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ANTHROPOGENIC SOIL CHANGE IN ANCIENT AND TRADITIONAL AGRICULTURAL FIELDS IN ARID TO SEMIARID REGIONS OF THE AMERICAS

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Soils form the foundation for agriculture and are changed by farming through active management and unintentionally. Soil change from agriculture ranges from wholesale transformation to ephemeral and subtle modification. The archaeological record of early agricultural systems holds information about soil change on centurial to millennial scales, with important implications for long-term soil condition and land use sustainability. Knowledge of early agricultural management can also be inferred from soils, including farming strategies in dynamic, challenging environments. This paper discusses soil change processes and outcomes mainly using studies of ancient and traditional agriculture in arid regions of the Americas. The potential and limitations of soil change research methods in ancient agriculture are also considered. Soil anthropogenic change involves complex and interactive physical, chemical, and biological processes across a wide range of spatial and time scales. Soil change outcomes in early agriculture relating to soil health and productivity vary from improvement to degradation. Soil productivity improvement commonly resulting from management includes soil-landscape physical stabilization for crops, increased topsoil thickness and plant-available water capacity, and improved soil tilth and fertility. Degradation commonly results from unintentional soil-geomorphic-ecosystem changes that cause accelerated erosion, destabilization of soil structure and compaction, and decreases in plant nutrients and soil fertility. Soil change outcomes vary across space and time in response to complex environmental, agricultural, and social factors.

Keywords: *soils and archaeology, anthropogenic soil change, ancient agriculture, traditional agroecosystem, ethnopedology*

Introduction

Soils are a crucial resource for agriculture and are changed by farming, either deliberately through management or unintentionally. Agriculture alters land directly and indirectly by changing soil properties and underlying soil processes, as well as changing geomorphic and hydrologic conditions and ecosystems. Soil change from agriculture ranges from complete transformation to ephemeral and subtle modification. In some cases, natural soils have been buried or even destroyed by erosion. We need to understand soil change because soil is basically a non-renewable resource on the human time scale (Montgomery 2007; Sandor et al. 2005). Rates and degree of human-caused soil change usually greatly exceed rates of natural soil formation. Long-lasting and even irreversible damage to land

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can result from misuse. Careful management is needed to conserve soils and their productivity.

The goal of this paper is to explore evidence for anthropogenic soil change in ancient agriculture. Ancient agricultural systems and soils are long-term sources of data on management strategies and land resource change. The record of early agriculture provides a deep-time perspective on land use and human-environmental interaction, responses to climate change, and anthropogenic soil processes. Many past and contemporary ancient cultures have farmed the same land on scales of centuries to millennia. Much can be learned from both the successes and failures of ancient peoples who have lived in a region for many generations. The deep-time perspective makes it possible to actually test for long-term land use sustainability (Sandor and Eash 1991).

Outcomes of soil change due to agriculture in terms of soil health and productivity vary from degradation to improvement and also include a number of intermediate or inconclusive cases (Homburg and Sandor 2011; Sandor and Homburg 2011, 2015). Dividing anthropogenic soil change into deliberate and unintended categories for the purpose of organizing this paper is somewhat artificial, because, in reality, soil change causes and consequences are interactive and complex. In many cases, soil management practices developed in response to unintended soil degradation in an iterative process.

This paper emphasizes arid regions of the Americas, thus highlighting those land properties related primarily to water supply for crops and secondarily to physical stability and nutrients. To illustrate the vast range of soil change, examples of irrigated and non-irrigated (dryland) agricultural systems are presented across different geographic regions (Figure 1), spatial and time scales, and levels of labor intensity. Because this is a synthesis rather than a comprehensive paper, please refer to the cited references to individual case studies for details in method and content that are briefly summarized here.

Challenges and Approaches to Measuring Soil Change in Ancient Agriculture

Ancient agricultural systems and soil change vary greatly in kind and scale (Sandor and Homburg 2016; Sandor et al. 2005). They have been studied at landscape to submicroscopic scales using a number of field and laboratory approaches (Holliday 2004; Lewis 2012). Recognizing, measuring, and interpreting soil change can be difficult for several reasons: the sheer complexity of soils and agroecosystem processes, post-agriculture soil change through continued soil development, environmental change, and later land use. Some studies reveal complex stratigraphy and land use history. In addition to these factors, there are also methodological challenges and the fact that relatively limited research has been conducted so far. While soils in more intensive agricultural systems bear clear marks of change, soil change in other situations can be very subtle. Soil change has been well-documented in some areas, but in other areas, ancient agricultural soils remain unrecognized or insufficiently characterized.

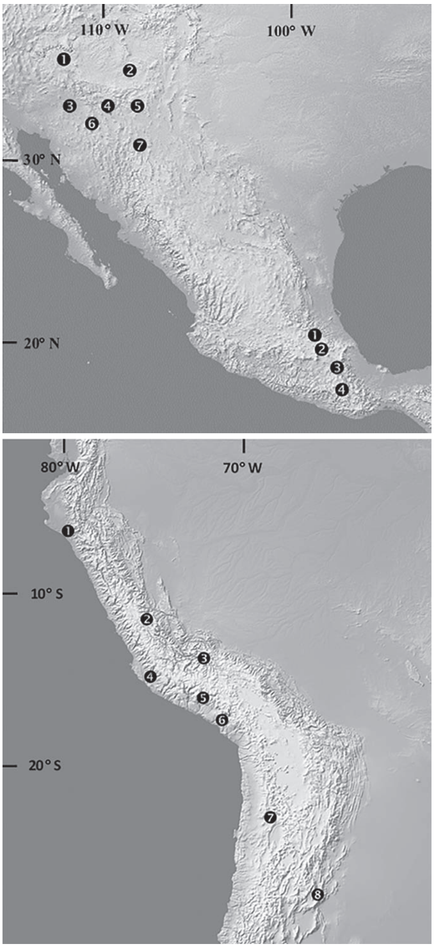
It is essential to consider the methods for studying anthropogenic soil change because the validity of data and interpretations depend on sound methods. Different approaches and challenges summarized here are covered more in Homburg and Sandor (2011) and Sandor and Homburg (2011, 2015, 2016). A main method used to study soil change directly is to compare agricultural soils and uncultivated reference or control soils in similar geomorphic settings. These natural reference soils are the baseline against which anthropogenic change is measured. This comparative approach is also known as a "space-for-time substitution" method (McLauchlan 2006) because the premise is that the nearby reference soils are similar to the original, unfarmed soils. This seems reasonable; however, the natural soils are unlikely to represent exactly what original soils were like prior to cultivation because soils are dynamic, forming and changing naturally over time. Soils are palimpsests, bearing the imprints of environmental change and multiple land uses in the many years between prehistoric agriculture and present observations. So the premise is modified to say that the natural soils actually represent what cultivated soils would be like now if they had not been farmed. Still, we think that, in some environments, the natural soils are close to the originals, for example, in arid regions, which tend to have slower rates of soil formation. Most comparative studies involve soils farmed during one discrete or undifferentiated period in the past. However, there are a few examples of anthrochronosequences in which soils farmed at multiple discrete periods have been identified, so paths of anthropogenic soil change can be traced.

Relative soil change can be evaluated among soils within the same agricultural system but in different internal contexts (e.g., interiors and edges of rock grid fields) or time periods (e.g., abandoned and still-farmed ancient fields). In some cases, it is possible to infer soil change from the agricultural soils themselves, if they exhibit properties far out of the range of natural soils. Proxy and off-site data have also been used. One famous example is the use of crop records to infer soil salt buildup in Mesopotamia (Montgomery 2007). Many studies world-wide have inferred accelerated soil erosion from ancient agriculture. These are based on erosion signatures in fields and especially on stratigraphic records of massive sedimentation and buried soils downslope from fields (McAuliffe et al. 2001; McClung de Tapia 2012; Montgomery 2007).

All these methods have their limitations. They are not necessarily mutually exclusive; in fact, multiple approaches strengthen research.

Soil Change from Ancient Agricultural Management

Soil change through deliberate management ultimately relates to how management changes soils and landscapes to meet crop needs, reduces constraints to production, and counteracts hazards. The fundamental goals of management are to enhance or even create soils to make agriculture possible, increase the probability of successful crop production, improve soil productivity, maintain yield stability, and achieve sustainability. For agriculture in arid to semiarid environments, water supply to crops, including amounts, timing, and



US Southwest and Northwestern Mexico
1. Coconino Plateau and Grand Canyon: Berlin et al. 1977, 1990; Davis et al. 2000; Edwards 2002; Sullivan 2000.
2. Zuni: Homburg et al. 2005; Norton et al. 2007; Sandor et al. 2007.
3. Phoenix Basin and vicinity: Hall et al. 2013; Huckleberry 1992; Kruse-Peeples et al. 2009; Means 1901; Nakase et al. 2014; Schaafsma and Briggs 2007; Strawhacker 2013; Woodson et al. 2015.
4. Safford Basin: Homburg et al. 2004.
5. Mimbres Region: Sandor et al. 1986, 1990.
6. Tucson Basin: Homburg 2015.
7. Casas Grandes, Chihuahua: Herold 1970; Homburg et al. 2011.

Central Mexico
1. Teotihuacan: Sánchez-Pérez et al. 2013; McClung de Tapia 2012.
2. Tlaxcala: Borejsza et al. 2008.
3. Tehuacán Valley: McAuliffe et al. 2001.
4. Oaxaca: Pérez-Rodríguez and Anderson 2013.

South America (Peru, Chile, Argentina)
1. Northwest coastal Peru: Nordt et al. 2004.
2. Paca Valley (Upper Mantaro Valley), Junín Region, Peru: Goodman-Elgar 2008.
3. Cuzco Region, Peru: Keeley 1985.
4. Palpa Valley, Ica Region, Peru: Hesse and Baade 2009.
5. Colca Valley, Peru: Sandor and Eash 1995.
6. Wawakiki, Moquegua Region, Peru: Zaro and Umire-Alvarez 2005.
7. High-altitude Atacama Desert, Chile: Keely 1988; Sandor et al. 2015.
8. Northwestern Argentina, Tucumán Province: Sampietro Vattuone et al. 2011.

Figure 1. Locations of examples of agricultural soil change studies in arid and semiarid regions of the Americas. Map base from Natural Earth.

control, is a key priority. Other crop productivity factors improved by soil-landscape management include erosion control, physical stability, nutrient supply, and microclimate conditions, such as temperature and wind. Management practices are emplaced to protect crops from climate and hydrologic extremes, such as drought, flooding, freezes, and heat stress, as well as from animal predation. They also serve to combat injury from excessive salt and sodium. Many management practices likely developed in response to human-induced degradation processes, such as accelerated erosion and salinization.

Although it is not always certain that particular soil changes involved pre-planned management decisions, it is likely that farmers realized the benefits and, in effect, they became management tools. A rich heritage of knowledge about agricultural and soil management has been developed by traditional farmers over many generations in arid environments of the Americas (Barrera-Bassols and Zinck 2000; Nabhan 2013; Pérez Rodríguez and Anderson 2013; Sampietro

Vattuone et al. 2008; Sandor et al. 2006; WinklerPrins and Barrera-Bassols 2004; WinklerPrins and Sandor 2003).

In this discussion, management-driven soil-landscape change is organized by topographic variables, soil physical and morphological properties, and soil chemical and biological properties, though, in reality, these factors are interactive components of a broader soil-geomorphic system. Case studies illustrating these factors are summarized in Table 1.

Soil-Geomorphic and Soil Physical Change

Physical soil management changes in soil surfaces and topography in arid land agriculture are primarily intended to increase and control water supply to crops, moderate temperature, create or promote crop physical stability, increase soil volume for crop rooting (and so increase water and nutrient uptake capacities), and to protect soils from excessive erosion.

Terracing is among the most visible and intensive kinds of management in ancient agricultural landscapes. Terracing involves segmenting slopes into topographic steps and has been used extensively in sloping terrain to create stable, nearly level fields and to manage water (Denevan 2001; Donkin 1979; Doolittle 2000; Sandor 2006; Sandor and Homburg 2016). The stepped topography resulting from terrace wall construction and sediment filling is generally characterized by reduced field slope angle and length. Along with creating a stable topographic base for crops, functions of terracing include soil retention and erosion control, soil building by construction filling or sedimentation, microclimatic modification, and water control ranging from runoff management to irrigation and drainage. Intensively terraced irrigated landscapes are especially prevalent in the Andes and parts of Mexico. The Colca Valley, Peru, is an example of monumental bench terracing and irrigation, in which much of the land below 4000 m elevation has been transformed into a terraced landscape (Denevan 2001; Sandor and Eash 1995; Sandor et al. 2006; Treacy 1989; Figure 2). Terrace agriculture in the Colca Valley has been practiced for over 1500 years and continues today. Terracing in the Andes has been practiced for at least 4000 years (Denevan 2001) and there is evidence for irrigation as early as 6700 yrs BP (Dillehay et al. 2005). Intricately constructed canals woven as passages through flights of durable stone terraces constitute a monumental and enduring transformation of soils and landscape in the Colca Valley and other terrace systems in the Andes and Mesoamerica.

Beneath terraced surfaces, soils have been altered to improve production (Figure 2). One of the most distinctive morphological features of terraced soils is increased surface horizon (A horizon) thickness resulting directly from accumulation of material upslope of terrace walls either by hand-filling or sedimentation. The amount of soil thickening within each terrace varies because of the wedge-shaped geometry common in terraced soil fills, wherein fills are thickest nearest the terraced wall and decrease upslope (Sandor 2006). In the case of the Colca Valley, A horizon thickening mostly ranges from 0.3 to 1 m and the range reported elsewhere is a few centimeters to several meters. Other positive physical soil changes resulting from management are more stable granular soil structure, increased macroporosity, and reduced bulk density

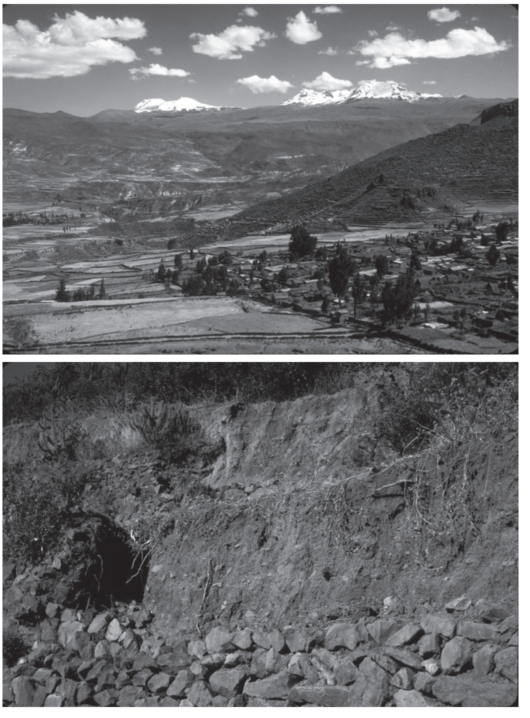


Figure 2. Terraced landscape and soil in the Colca Valley, Peru (upper photo). Thick anthropogenic, organic matter-rich soil exposed where agricultural terrace wall partially removed by farmers for repair (lower photo).

(Sandor and Eash 1991, 1995). These structural changes are imparted by careful management practices, such as long-term organic matter additions and tillage practices that minimize soil disturbance. Anthropogenic changes in the fine earth texture of soils were not observed in the Colca Valley, but gravels were emplaced in soils just upslope of terrace walls to aid water drainage and prevent excess pressure on terrace walls. In prehispanic terraces in Chile, rock fragments were removed from upper soil horizons (Sandor et al. 2015). All the physical soil changes described enhance crop production by increasing topsoil volume and tilth that can be exploited by roots, thereby increasing and facilitating water and nutrient uptake. Specific alteration of soil physical properties for management in terraced soils in the Americas has also been reported by Field (1966), Keeley (1985, 1988), and Sampietro Vattuone et al. (2011, 2014). Some studies of ancient agricultural terraces have revealed complex stratigraphy, with multiple soils and paleosols, indicating multiple use and reconfiguration of terraces during different time periods (Borejsza et al. 2008; Branch et al. 2007; Pérez Rodríguez and Anderson 2013; Sánchez-Pérez et al. 2013; Zaro and Umire Alvarez 2005).

Another form of intensive soil change in ancient agriculture is the development of greatly thickened soils through long-term accumulation of suspended sediment in fields from irrigation canals. This sedimentation process

Table 1. Examples of soil change due to deliberate management inferred in ancient fields in arid and semiarid regions of the Americas.

Location/Age	Soil change	Management purpose
	Soil-geomorphic change	
Colca Valley, Peru, past 1500+ years; high Atacama Desert, Chile (e.g., Turi Basin), mainly ca. AD 950–1532, also to historic	Terraced slopes	Slope stability, irrigation and distribution of limited irrigation water, temperature control/ moderation
American SW (including northern Mexico), prehistoric and historic in some areas, mostly since ca. AD 1000	Dryland terracing	Erosion control, runoff retention and control, and water distribution
American SW, prehistoric, mostly since ca. AD 1000	Other dryland surface rock configurations (lithic mulch, rock grids, rock piles)	Moisture retention, reduced water loss from evaporation, increased water infiltration, erosion control, physical stability and protection, temperature moderation
	Soil physical and morphological change	
Colca Valley, Peru; Peru south coast, ca. AD 900 to end of Inka period	Thickened upper soil horizons through terracing. Soil structure and pore changes.	Increased soil volume for water, nutrients, and physical stability. Improved soil tilth for plant-available water capacity, water movement, root growth.
Middle Gila River Valley, Arizona, ca. AD 450–1450; Peru south coast, > 3500 yrs BP into historic.	Thickening upper soil horizons through irrigation sediment (irragric horizons). Possible soil texture change.	Increased soil volume for water, nutrients, and physical stability
High Atacama Desert, Chile	Removal of rock fragments from upper soil horizons	Increased soil volume for roots, water, and nutrients.
	Soil chemical and biological change	
Middle Gila River Valley, Arizona; Peru north coast, probably ca. AD 900–1532	Decreased salt, sodium, and pH	Reduce hazard of crop damage caused by excess salt and sodium accumulation from irrigation

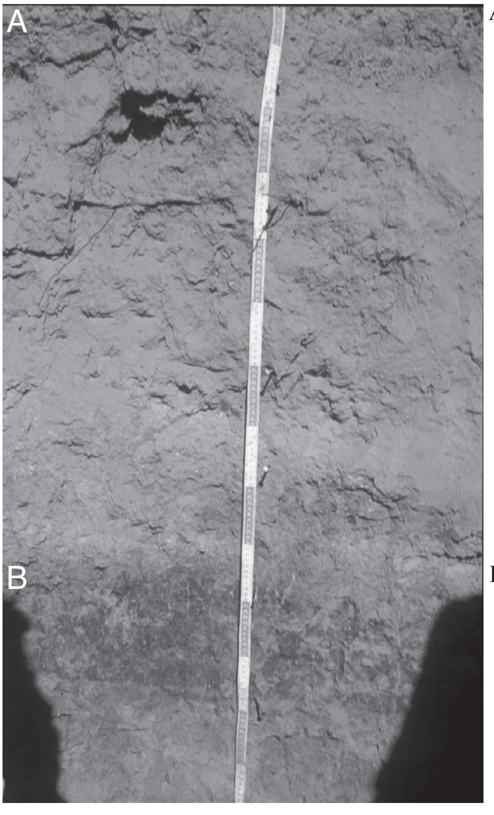
Table 1. Continued.

Location/Age	Soil change	Management purpose
American SW several examples prehistoric to historic	Nutrient increase or minimal/ no nutrient loss	Nutrient replenishment through managed runoff and eolian processes (e.g., nitrogen, phosphorus to offset losses during crop uptake)
Colca Valley, Peru	Increased organic carbon and nutrient concentrations and quantities	Nutrient inputs through direct fertilization with manure and other materials
Colca Valley, Peru; Zuni, New Mexico, at least 1000 years	Increased soil enzyme, mycorrhizae, and other biological activity	Indirect result of fertilization through direct inputs or management of irrigation or runoff water

Dick et al. 1994; Hesse and Baade 2009; Homburg and Sandor 2011; Homburg et al. 2004, 2005; Lightfoot 1996; Nakase et al. 2014; Nordt et al. 2004; Sandor and Eash 1995; Sandor and Homburg 2015; Sandor et al. 2007, 2015; Woodson et al. 2015

See the following for more examples: Adams 2004; Arrhenius 1963; Baade 2012; Branch et al. 2007; Brooks 1998; Denevan 2001; Donkin 1979; Doolittle 2000; Field 1966; Hall et al. 2013; Herold 1970; Herold and Miller 1995; Huckleberry 1992; Homburg 2015; Keeley 1985, 1988; Kruse-Peeples et al. 2009; Macphail 2015; Nabhan 2013; Norton et al. 2007; Pérez Rodríguez and Anderson 2013; Sampietro Vattuone et al. 2011, 2014; Sánchez-Pérez et al. 2013; Sandor and Eash 1991; Schaafsma and Briggs 2007; Strawhacker 2013; Sullivan 2000; Treacy 1989; White et al. 1998; Wilken 1987; Winterhalder et al. 1974; Zaro and Umire Alvarez 2005; Zimmerer 1994.

over centuries results in the formation of thick anthropogenic "irragric" horizons, whose uniform textures are commonly rich in fine particles (fine sands, silts, or clays). While irragric horizons cannot always be unequivocally attributed to deliberate management, they commonly improve soils for agriculture by increasing topsoil volume, replenishing soil fertility, and reducing soil salinity. Awareness of the benefits of moderate sedimentation in traditional agricultural fields in renewing and improving soils and crop production indicates that, in many cases, this is intentional management (Doolittle 2000; Nabhan and Sheridan 1977; Russell 1908; Williams 1981). However, a balance between the benefits of slight to moderate sedimentation and the detrimental effects of excess sedimentation was not easy to achieve (e.g., Dart 1986; Woodson et al. 2015). An example of an irragric soil is that developed in fields in the Gila River Valley in the Phoenix Basin from about AD 450–1450 by the Hohokam, whose remarkable canal irrigation systems—the largest in the Americas north of Peru—are renowned for their monumental scale and skilled engineering (Doolittle 2000; Fish and Fish 2007). In this case, a silt-rich irragric horizon about 77 cm thick with favorable properties for agriculture buries a natural clay-enriched argillic horizon on a Pleistocene stream terrace (Woodson et al. 2015; Figure 3). Other examples of irragric soils in ancient fields in the American Southwest have been reported (Hall et al. 2013; Homburg 2015; Huckleberry 1992; Means 1901; Schaafsma and Briggs 2007). Along the south coast of Peru, irragric soils dating to more than 3500 yrs BP and up to 4 m thick were documented by Hesse and Baade (2009).



A. Light-colored mantle of silt loam is an anthropogenic irragric soil horizon developed in sediment deposited during long-term canal irrigation, ca. AD 750–1450.

B. Natural soil horizon of clay accumulation (argillic horizon) on Pleistocene river terrace buried by the irragric horizon.

Location Relative to Irrigated Fields	Electrical Conductivity (EC) (dS m^{-1})	Sodium Adsorption Ratio (SAR)	pH
Inside	14*	25***	8.1***
Adjacent	20	65	8.6
Well-Outside	21	57	8.5

Figure 3. Prehistoric irragric soil and chemical properties related to salt management. Snaketown canal-field system, middle Gila River Valley, Arizona. Photo scale is divided into 10 cm bands. In the table, numbers shown are means of soil samples from inside, adjacent to, and outside of the prehistoric irrigated field area. Asterisks indicate statistically significant differences among locations with the Kruskal–Wallis test at the following probability levels: *$P < 0.05$, ***$P < 0.001$. See Woodson et al. (2015) for more information.

Subtle, yet widespread, cases of landscapes and soils physically altered by prehistoric agricultural management are also evident. An example is the extensive and diverse dryland agricultural fields in the American Southwest and northern Mexico located in valley margin and upland environments (Adams 2004; Doolittle 2000; Herold 1970; Sandor and Homburg 2015). Some of these fields are identified from terracing and other rock configurations used to create and manage the fields. Examples of these landscape modifications using rock

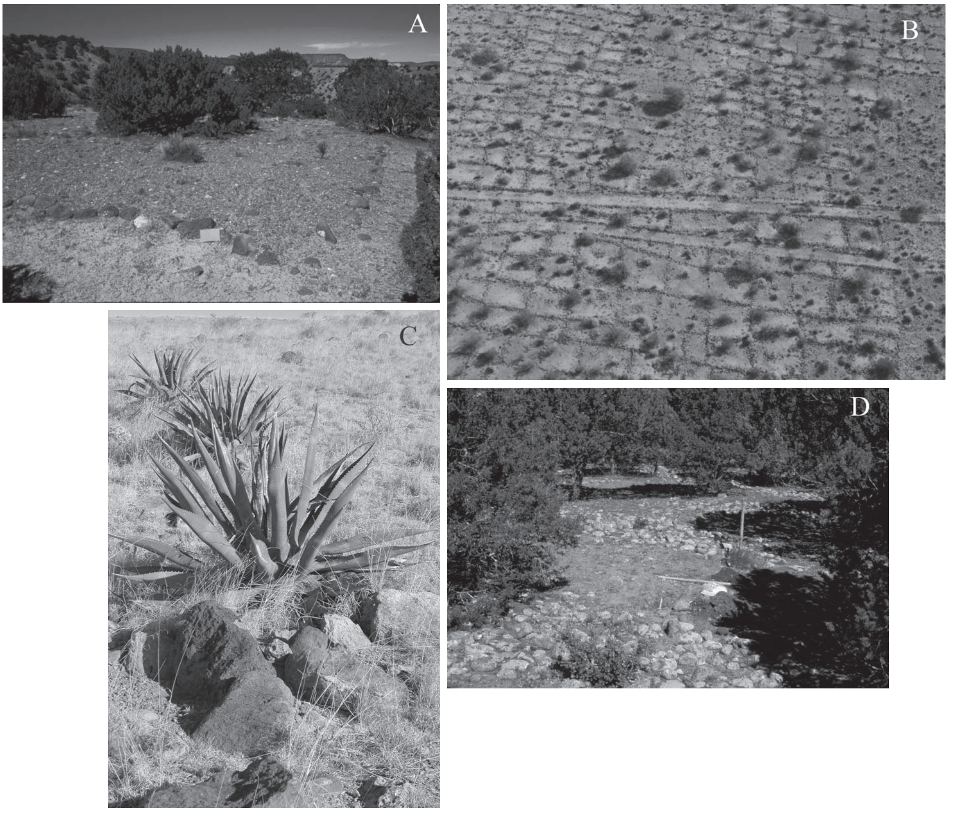


Figure 4. Prehistoric dryland agricultural fields in the American Southwest managed with rock configurations. A - Lithic mulch field, Chama River Valley, northern New Mexico; B - Grid fields, Gila River Valley near Safford, eastern Arizona. Average grid size is about 22 m^2 (Doolittle and Neely 2004). Aerial photo by James A. Neely; C - Rock pile field and agave near Casas Grandes, Chihuahua, Mexico; D - Terraces for runoff agriculture, Sapillo Valley (near Mimbres Valley), southwestern New Mexico.

alignments are terraces, grids, piles, and lithic mulch fields (Figure 4). However, these structures were not always used, so it is likely that many early dryland fields remain unrecognized.

Because water is the most limiting resource in arid land agriculture, a key function of rock configuration fields relates to water conservation. For example, rock piles helped retain soil moisture for agave and other desert crops by reducing evaporation (Fish and Fish 2014; Homburg and Sandor 2011). Lithic mulch fields operated on a similar basis and another likely primary purpose of lithic mulch in the extensive fields of the northern Rio Grande region in New Mexico was to moderate temperature—especially to promote warmer spring temperatures in the soil during the early growing season at the higher latitudes and elevations of the northern Southwest (Anscheutz 1998; Lightfoot 1996; White et al. 1998).

The most widespread kind of dryland agriculture in the Southwest and other arid regions is runoff farming. An important achievement of runoff agriculture is its ability to supply water and nutrient needs to crops without conventional irrigation or fertilization. This is done by connecting fields to hydrologic and ecosystem processes in watersheds. Fields are carefully placed and managed on certain landscape positions, such as alluvial fans, to intercept storm runoff and associated sediment and organic debris transported from adjoining uplands. Within fields, terracing or analogous management boosts water retention by reducing slope angle and length and by encouraging sedimentation. The sediment becomes a thicker topsoil with a desirable loamy to sandy texture that increases water infiltration, rooting volume, and thus water-holding capacity for plant use. In some cases, erosion of soils in watersheds was used as a management tool to encourage sediment deposition in fields downslope (Doolittle 2000). In-depth knowledge among traditional farmers about soil, geomorphic, hydrological, and ecological processes involved in runoff agriculture in the American Southwest and Mexico has been recorded in some studies (e.g., Nabhan 2013; Nabhan and Sheridan 1977; Pawluk 1995; Sandor et al. 2007).

Soil Chemical and Biological Change

Management of soil chemical and biological properties in arid land agriculture is primarily intended to enhance or replenish nutrients removed from soil by crops and to protect soils from accumulating excess salt and sodium that harm crops.

Chemical and biological changes in ancient agricultural soils resulting from management have been inferred in a few studies (Table 1). In the Colca Valley, Peru, higher levels of organic carbon, nitrogen, and phosphorus were found in agricultural soils compared with uncultivated soils (Sandor and Eash 1991, 1995; Figure 5). Extraordinary levels of phosphorus were found in some subsurface horizons of agricultural soils, indicating additions of P-rich fertilizer materials and significant downward movement of phosphorus over centuries. Higher soil enzyme activity associated with nitrogen and phosphorus metabolism was also detected (Dick et al. 1994). These soil changes were attributed to the long-standing Andean practice of fertilization with animal manure and other materials, including sea-bird guano. Increases in soil nutrients in traditional Andean agricultural soils fertilized with manure were also measured by Winterhalder et al. (1974). These practices and others—such as crop rotation, fallowing, diverse intercropping, and use of nitrogen-fixing legumes—have been instrumental in conserving and improving soils. These show long-term soil care resulting from deliberate fertilization and organic matter management. The substantial knowledge underlying this impressive management is exemplified in the traditional soil classification system in the Colca Valley (Sandor and Furbee 1996; Sandor et al. 2006).

In other arid regions of the Americas, such as the North American Southwest, where there is little evidence for direct application of fertilizer materials, higher levels of nutrients have not been consistently detected in ancient fields. However, there is soil and ethnographic evidence of nutrient replenishment by watershed hydrologic processes in agricultural systems that use runoff. Runoff management not only increases water supply for crops, it also creates new soil and replenishes fertility as runoff delivers fresh nutrients. Studies of watersheds and linked fields at Zuni documented soil build-up and maintenance of soil nutrients (Homburg et al. 2005; Norton et al. 2007; Sandor et al. 2007). Studies in ethnoecology and ethnopedology indicate that traditional farmers in the Southwest and Mexico are well-aware that runoff inputs maintain and enrich soils (Nabhan 2013; Pawluk 1995; Sandor et al. 2007; Wilken 1987). Agricultural experiments with runoff and monitoring runoff materials in agricultural watersheds have provided data about the processes of nutrient decomposition and availability to crops, as well as the effects of nutrients in runoff on crop productivity (Hubbell and Gardner 1950; Norton et al. 2007). A few studies of soil biological activity point to the importance of nitrogen-fixing organisms and plants, mycorrhizal fungi, and biological crusts in maintaining soil fertility in traditional agricultural systems (Berry 1995; Havener 1999; Norton et al. 2007). Inputs of nutrients to soils through eolian dust have also been found (Nakase et al. 2014) and recognition of wind transport of sediment in replenishing soil has been reported ethnographically (Cushing 1920; Ferguson 1985; Pawluk 1995).

Controlling salt is an aspect of soil chemical property management especially important in arid lands. Salt and sodium accumulation and associated high pH are a major hazard in past and present irrigation agriculture that can seriously damage land (Brady and Weil 2008). Crop tolerance to salt and sodium is variable: among major crops of the Americas, beans (*Phaseolus* spp.) are highly sensitive, cotton (*Gossypium hirsutum*) is more tolerant, and maize (*Zea mays*) is intermediate. Damaging effects of salt in early agriculture have been inferred in other world regions, such as Mesopotamia (commonly accepted as true, though some controversy exists), and salinization has been implicated as a factor in the demise of the Hohokam in the American Southwest (Diamond 2005; Reisner 1986). However, these assertions are not based on direct soil evidence. Evidence from a recent study of Hohokam irrigated soils from the Snaketown canal-field system along the middle Gila River Valley indicates that salt, sodium, and pH are actually lower in the irrigated soils compared with adjacent similar land outside the system, although there are salt levels that need to be managed (Woodson et al. 2015; Figure 3). Lower salt and sodium in the Hohokam fields can be attributed to two factors: 1) the younger age of the anthropogenic soil so that there was less time for salt accumulation and 2) the leaching of salts by applied irrigation water. While it is not certain that this is due to deliberate management, indirect evidence for management of salt is: 1) that the Snaketown irrigation system functioned for a long time (7–10 centuries) and 2) an ethnographic record of careful salt management among historic Indian farmers in the area. More research is needed, but the longevity of the Hohokam irrigation systems on the order of a millennium suggests that they were able to manage salinity problems (Ackerly 1988).

Unintentional Soil Change Resulting from Ancient Agriculture

Whereas the outcomes of soil change due to agricultural management are intended to enhance soils and landscapes for crop production and conserve soil

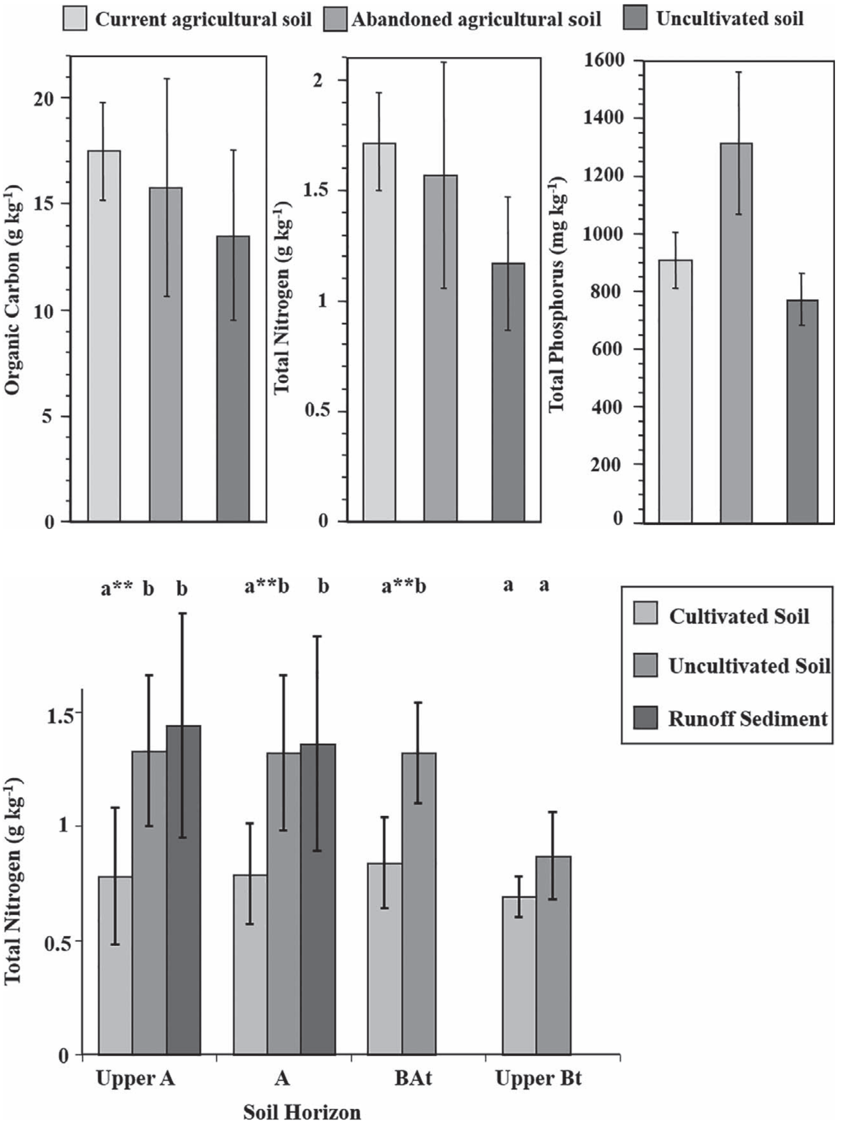


Figure 5. Examples of soil chemical change in ancient agricultural soils.
Upper graph: comparison of organic carbon, total nitrogen, and total phosphorus in terraced agricultural and uncultivated upper A horizons in the Colca Valley, Peru. Bars are means (lines within bars show ± 1 standard deviation) from each sample group. Mean differences are statistically significant minimally at the 0.05 probability level in all cases except between current and abandoned agricultural soils for organic carbon and total nitrogen. See Sandor and Eash (1991, 1995) for more information.
Lower graph: comparison of total nitrogen in uncultivated and Mimbres prehistoric agricultural soils. Bars are means (lines within bars show ± 1 standard deviation) from prehistoric cultivated soil, uncultivated soil, and recent runoff sediment sample groups. ** = significant overall differences among sample groups at the 0.01 probability level. Different letters indicate individual mean differences at the 0.05 probability level. Refer to Sandor et al. (1986, 1990) for more information.

resources, unintentional soil change that accompanies agriculture usually has negative consequences for soil productivity and quality. Such soil degradation often results from lack of management or mismanagement of land resources. It is likely that most management practices developed in response to soil-landscape degradation that threatened crop productivity. Because of the complex nature of soil, climate, and other environmental change, management response to degradation most likely developed in an incremental, iterative way. In some cases, fields may have been abandoned before management was successfully implemented or when degradative processes overwhelmed attempts at management to stem and repair land damage. Cases of unintentional soil, landscape, and ecosystem change from ancient agriculture are summarized in Table 2.

Unintended Soil-Geomorphic, Ecological, and Soil Physical Change

Unintended landscape and physical soil degradation from agriculture documented in ancient fields in arid lands mainly involves accelerated erosion (by wind, water, and mass movement) that can remove soil, particularly valuable topsoils. Other deleterious impacts recognized in ancient agricultural fields are compaction and soil structural degradation that restricts root growth and reduces water and nutrients available to plants. Accelerated erosion (including that following abandonment of ancient agricultural terraces) and other physical soil degradation, such as soil compaction, have been reported in several studies in Mexico (Borejsza et al. 2008; McAuliffe et al. 2001; McClung de Tapia 2012; Sánchez-Pérez et al. 2013), Peru (Goodman-Elgar 2008; Inbar and Llerena 2000; Zaro et al. 2008), and the American Southwest (Kruse-Peeples et al. 2009).

One case of such degradation is in prehistoric upland agricultural fields in the Mimbres region of New Mexico (Sandor and Homburg 2015; Sandor et al. 1986, 1990). These fields mainly date to the Mimbres Classic period (AD 1000–1130), based on archaeological evidence of association with nearby small pueblos and ceramic sherds within terraced soils. This dryland agriculture used a series of low rock terraces to capture runoff from summer monsoon storms. Testing for soil change was possible because intact fields could be identified, control areas were available, and post-agriculture land use was relatively minimal. Soils were sampled in transects across agricultural and unfarmed areas with similar geomorphic settings. Using the comparative approach, major soil-landscape changes from agriculture were inferred, namely long-term soil and ecosystem degradation. Widespread gully and sheet erosion was observed in the agricultural area but not within the unfarmed reference areas. Evidence that accelerated erosion began during prehistoric agriculture is that terraces are breached by gullies, showing that terracing came first, and attempts by prehistoric farmers to repair the damage are shown by rock dams built within gullies. Long-term anthropogenic ecosystem change involving reduced grass cover contributed to the accelerated erosion, which continues to the present. Besides erosion, degradation of soil physical properties within fields is also apparent. Upper soil horizons have suffered structural

Table 2. Examples of unintentional soil change inferred in ancient agricultural fields in arid and semiarid regions of the Americas.

Location/Age/Context	Soil change	Probable cause(s) of soil change
	Soil-geomorphic change	
Mimbres region, New Mexico, dryland terrace agriculture, ca. AD 1000–1130	Accelerated sheet and gully erosion	Exposed soil from land clearance and loss of relict grass vegetation cover
Central Mexico and Peru (wide range of ages and sites)	Accelerated erosion: mass movement and water erosion; soil burial by eroded sediment	Land clearance and disturbance; abandonment of agricultural terraces
Hohokam, southern Arizona, canal irrigation	Potential excessive sedimentation	Irrigation from sediment-rich streams
	Soil physical and morphological change	
Mimbres region, New Mexico	Structural degradation, compaction	Decreased organic matter levels, lack of grass revegetation after agriculture
Paca Valley, Peru (since ca. 1000 yrs BP)	Downward translocation of silt and clay	Movement following tillage and/or tuber cultivation
	Soil chemical and biological change	
Mimbres region, New Mexico	Decreased organic carbon, nitrogen, phosphorus	Cultivation of sensitive soil-landscape and loss of grass cover, more removal of nutrients by crops than nutrient inputs
Coconino Plateau, Arizona (mainly 11th–13th century AD); Paca Valley, Peru (since 1000 yrs BP)	Soil organic matter and nutrient losses.	Crop removal of nutrients, and lack of soil organic matter management
Grand Canyon, Arizona; as early as 1300–3000 yrs BP	Salt accumulation	Long-term irrigation and possibly use of irrigation water with significant salt content
Colca Valley, Peru, past 1500+ years	Irregular distribution of phosphorus with depth	Long-term downward movement of fertilizer phosphorus

Table 2. Continued.

Location/Age/Context	Soil change	Probable cause(s) of soil change
High Atacama Desert, Chile, mainly ca. AD 950–1532	Increase in pH and carbonate	Irrigation with carbonate-rich water

Berlin et al. 1977; Borejsza et al. 2008; Dart 1986; Davis et al. 2000; Edwards 2002; Goodman-Elgar 2008; Homburg and Sandor 2011; Sampietro Vattuone et al. 2011; Sánchez-Pérez et al. 2013; Sandor and Eash 1995; Sandor and Homburg 2015; Sandor et al. 1986, 2015.

See the following for more examples: Arrhenius 1963; Berlin et al. 1990; Inbar and Llerena 2000; Keeley 1985, 1988; Kruse-Peeples et al. 2009; McAuliffe et al. 2001; McClung de Tapia 2012; Sampietro Vattuone et al. 2014; Sandor and Eash 1991; Sandor and Gersper 1988; Sandor et al. 1990; Sandor et al. 2015; Sullivan 2000; Zaro et al. 2008.

degradation and compaction, and lighter soil color reflects lower organic matter levels.

Unintended Soil Chemical and Biological Change

Degradation of soil fertility and biochemical properties from agriculture documented in ancient fields of arid lands mainly involves decreased levels of organic matter and nutrients, increased levels of salt and sodium, and accompanying changes in soil biology. In the prehistoric Mimbres case, biochemical degradation is expressed in the form of decreased organic matter and key nutrients nitrogen and phosphorus in upper soil horizons (Sandor and Homburg 2015; Sandor et al. 1986, 1990; Figure 5). Decline in soil organic matter is linked to the soil structural degradation and compaction. A controlled greenhouse experiment comparing prehistoric agricultural and unfarmed reference soils showed that maize growth and nitrogen content were reduced in the degraded agricultural soil (Sandor and Gersper 1988). Lack of soil recovery centuries after cultivation ended illustrates how degradation can persist for a long time in environments sensitive to disturbance, in this case about a millennium.

Other cases of soil organic matter and nutrient loss in ancient agricultural soils have been reported in the American Southwest (Berlin et al. 1977, 1990; Edwards 2002; Sullivan 2000) and the Andes (Goodman-Elgar 2008; Sampietro Vattuone et al. 2014). Anthropogenic salinization has been reported in prehistoric fields in the Grand Canyon by Davis et al. (2000).

A current study in the Atacama Desert of Chile (Sandor et al. 2015) provides an example where unintentional soil change is not necessarily all bad. In this hyper-arid climate, agriculture is only possible with irrigation, so ancient terraced agricultural soils can be compared with nearby natural soils upslope from the highest canal. One major soil change is an influx of calcium carbonate by long-term irrigation with calcareous spring water. The downside for crops is that the resulting higher pH lowers availability of plant nutrients, such as phosphorus. But a possible benefit of this carbonate for crops is increased soil water-holding capacity (Duniway et al. 2010; Georgen et al. 1991).

Conclusions and Future Research

Like the diversity of ancient agricultural systems and social and environmental settings in which they took root, anthropogenic soil change is also diverse and complex. As is evident from the broad range of examples presented here, this diversity holds both for soil change resulting from deliberate management and unintentional soil change. Some have thought that the variation is because the studies are "…unclear and even contradictory…" (Kohler 2012). While more research coverage and improvement in methods are always needed, variability in outcomes should be expected given the wide range of initial soil-geomorphic settings, ecosystems, climate conditions, and change, as well as variation in agricultural systems (kind, scale, intensity, and duration), social factors, and post-agricultural change processes. Because of the multiplicity of complex, interactive social, and environmental factors, applicability and predictability of soil change outcomes across regions should not be assumed. Although similarities and patterns exist between and within regions, each area and its factors must be also studied individually because there is no single universal response of soils to agriculture (Sandor 1995; Sandor and Homburg 2015).

Soil is a basic resource upon which past and present societies have depended for their sustenance. We are now in a time of unprecedented human-induced change in soils, climate, and environment. There is justified concern about the ability of land and water resources to meet world food needs. Even with the differences in scale and technology between past and present, many challenges in agriculture today are fundamentally like those faced by farmers since ancient times, such as obtaining enough water in a variable changing climate, sustainably meeting crop nutrient needs, and conserving soils. The deep time perspectives gained from studies of ancient agricultural soils are important to understanding the history of human-environmental relationships and relevant to agriculture today. Agricultural soils that have functioned on scales of centuries to millennia in a wide array of social and environmental contexts are unique sources of information about long-term effects of deliberate management practices and unintentional impacts of agriculture on soil processes, condition, and health. Data about long-term soil processes and responses to agricultural land use are valuable for developing productive and sustainable agricultural systems that can conserve land and water resources for future generations. The substantial experience and knowledge about agricultural strategies and soil management in arid lands among traditional peoples should also be recognized as a critical resource for the future of agriculture. We hope that further insights into ancient agricultural management and soil change will be gained with continued research and new analytical tools.

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