Biogeochemical Studies of a Native American Runoff Agroecosystem

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Research on soil fertility is presented in the context of runoff agriculture, a venerable farming system that has been used for millennia in arid to semiarid regions, where water is a major limiting resource for crop production. The agroecology of runoff farming was studied with the Zuni to evaluate nutrient and hydrologic processes, management, maize productivity, and soil quality in some of the oldest recognized fields in the United States. This ancient Southwest agriculture has functioned without conventional irrigation or fertilization by tapping into biogeochemical processes in natural watersheds connected to fields. Carefully placed fields are managed on alluvial fans and other valley margin landforms to intercept runoff and associated sediment and organic debris transported from adjoining forested uplands. We report on research to evaluate and link nitrogen and phosphorus, two key nutrients for crop production, in watershed, soil, and crop components of this agroecosystem. Nutrient data have been collected by observational and experimental methods for each component and the transport of nutrients from watershed to field to maize. The condition of Zuni agricultural soils suggests that their knowledge and management of soils contributed to effective conservation. This study and others indicate the need for further long-term monitoring and experimental research on watersheds, runoff processes, field soils, and crops across a range of arid to semiarid ecosystems. © 2007 Wiley Periodicals, Inc.

INTRODUCTION

Soil fertility evaluation is an important application of soil chemistry in agricultural archaeology. Studies of soil nutrients can help to reconstruct and evaluate past agricultural strategies and management practices, crop production, change in agriculture through time, and environmental impacts of past societies and their agriculture. This kind of research provides a useful approach for assessing agroecosystem function and sustainability in ancient and traditional farming systems. The soil sampling and analytical methods used in this study are directly applicable to geoar-

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chaeological investigations of the effects of ancient agriculture on landscapes, especially in arid and semiarid regions, where altered soil properties tend to persist for long periods.

Research on soil fertility is presented in the context of runoff agriculture, a venerable farming system that has been used for several thousand years in arid to semiarid regions of Africa, the Near East, central Asia, and the Americas, where water is a major limiting resource for crop production (e.g., Bryan, 1929; Evenari et al., 1982; Dennell, 1985; Gilbertson and Hunt, 1996; Doolittle, 2000; Sandor, 2006; Sandor et al., 2006). A remarkable characteristic of runoff agriculture is that crops have been grown successfully for millennia in arid lands without conventional irrigation or fertilizer inputs. How is this possible? The basic purpose and function that the many variations of runoff agriculture share is to increase water for crops by retaining surface storm water flow generated from watersheds. Fields are strategically placed on certain landscape positions and soils adjoining upland watersheds to intercept and manage incoming runoff from overland and ephemeral channel flow. A key, but less studied, aspect of runoff agriculture is that not only is it a method for boosting water supply, but also for building and replenishing soil fertility and renewing favorable hydrologic properties. Runoff involves both water and the transport of nutrient-rich organic matter and sediments from watershed to field. The influx of sediment and organic debris is very important to long-term sustained agricultural productivity, as well as watershed conservation.

Runoff agriculture is distinctive as a crop-production system that is closely linked with, and taps into, natural watershed and biogeochemical processes (Sandor et al., 2002; Norton et al., 2003). The term *biogeochemistry* refers to the cycling of nutrients among the atmosphere, lithosphere, and soil and biological components of ecosystems. In the context of runoff agriculture, this relates to the nutrient processes and relationships in an integrated agroecosystem comprising watershed soils and plants (and other organisms), and field soils and crops.

An investigation into traditional runoff agricultural systems developed by native peoples in the North American Southwest over many centuries is presented as a case study. We have conducted studies in both archaeological and current agricultural contexts in the Southwest, but here mostly focus on studies of historical and contemporary agriculture conducted in cooperation with the Zuni Indian Tribe in New Mexico.

There are two objectives in this study. First, we wish to investigate soil fertility and nutrient dynamics in traditional Zuni runoff agriculture, from watershed to field to crop. Nitrogen and phosphorus, two major plant nutrients that most often limit crop production, are emphasized. Research is still in the early stages of elucidating the complex nutrient relationships and processes in this agroecosystem. Second, we wish to evaluate effects of long-term agriculture on soil properties and productivity in relation to land-use sustainability. Archaeological evidence indicates that many Zuni runoff fields have been farmed for about 1000 years or longer, making them among the oldest identified fields in the United States. The age and continuity of these sites make it possible to greatly extend the time perspective on the impacts of agriculture on soil resources. These ancient fields are important resources for evaluating the condition of agricultural soils at time scales envisioned in the concept of agricultural sustainability (Sandor and Eash, 1991).

Zuni and Southwest American Indian Agriculture

The Zuni are among several American Indian peoples in the Southwest renown for runoff agriculture, including other Pueblos and the Navajo on the Colorado Plateau, and the Tohono O'odham and Rarámuri in the Basin and Range region of southern Arizona and northern Mexico (Figure 1; Doolittle, 2000). One of 19 Pueblo groups, the Zuni have strong cultural ties with the Hopi, another western Pueblo people that live on the Colorado Plateau, whose skills in growing maize (Zea mays L.) and other crops in arid lands are also well known (Hack, 1942; Bradfield, 1971; Dominguez and Kolm, 2005). The Zuni and Hopi have a record of agriculture extending well back into prehistory, associated with cultures known archaeologically as the Ancestral Pueblo (Anasazi) and Mogollon (Cordell, 1997).

The Zuni Indian Reservation is located in the arid to semiarid mesa country of the southeastern Colorado Plateau, at 1838–2347 m in elevation. Zuni farms are at relatively high elevations, higher than most modern mainstream agriculture in the Southwest region (Sandor, 1995). Field location with respect to elevation is likely an optimization between precipitation and temperature, which are inversely related variables with elevation. Thus, fields are at relatively high elevations to maximize precipitation, but low enough to permit a sufficient frost-free period for the growing season. Topography is controlled by mainly flat-lying to gently dipping strata of uplifted, mostly Mesozoic sedimentary rocks with variable resistance to erosion. Mesas are separated by narrow canyons to broad alluvial valleys. Traditional runoff agriculture is practiced mainly on alluvial fans where tributary ephemeral streams emerge from mesa uplands (Figures 2–4). Some runoff fields also occur in uplands, and use of upland sites for agriculture probably was more prevalent in the past (Kintigh, 1985; Maxwell, 2000). Native vegetation generally consists of pinyon-juniper-oak (*Pinus edulis* Engelm.—*Juniperus* spp.—mostly *Quercus gambeii* Nutt.) woodlands and shrubs on mesa uplands, and semiarid grasses and shrubs in valleys. Precipitation is extremely variable, averaging 300–400 mm annually. May and June are usually dry, whereas over half the annual precipitation falls from July to September, often as intense localized thunderstorms. More frequent but less intense, non-runoff-producing rains occur as frontal systems or on fringes of localized thunderstorms and are also critical to growth of the current year's crop. It is upon these monsoon rains that runoff agriculture, and soil rejuvenation and long-term sustainability, depend. Developed soils grade from Aridisols and Alfisols in the drier western area to Mollisols and Alfisols in higher eastern valleys of the Reservation (Zschetzsche, 2005).

The Zuni area comprises one of the most continuously inhabited and cultivated lands of the Southwest (Kintigh, 1985; Maxwell, 2000). Maize radiocarbon dated to about 2200 yr B.P. has been found at Zuni, and archaeological ceramics indicate that many Zuni runoff fields date to A.D. 1050–1150 (Pueblo II) and possibly older (Homburg, 2000). Agricultural canal features dating to 2000–3000 yr B.P. have been recognized at Zuni (Damp et al., 2002). Charred maize dating to about 4000 yr B.P.

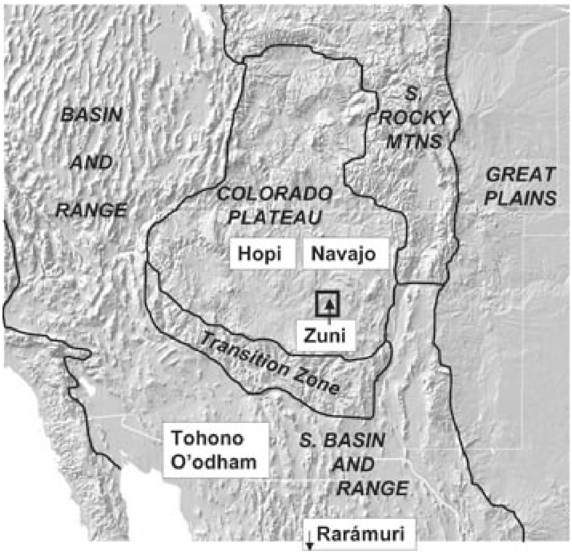

Figure 1. Southwest physiographic regions and main American Indian peoples that practice runoff agriculture. Map base from http://fermi.jhuapl.edu

was recovered just south of Zuni (Huber, 2005). Historic records provide evidence of productivity and attest to Zuni agricultural expertise (Figure 2a–b; Cushing, 1920; Stewart and Donnelly, 1943; Ferguson and Hart, 1985; Kintigh, 1985; Hart, 1995). For example, Coronado described the Zuni as having great stores of maize, and Zuni supplied the U.S. army in the region with maize during the mid-1800s, when there were estimated to be over 4000 ha under mainly nonirrigated production. The Zuni also mastered other forms of agriculture, ranging from fine-gridded "waffle" gardens, to peach production on sand dunes, to floodwater farming of larger watersheds, and irrigation agriculture (Perramond, 1994; Brandt, 1995; Doolittle, 2000; Maxwell, 2000). Besides the staple maize, a variety of native (e.g., beans [*Phaseolus* spp.], squash [*Cucurbita* spp.]) and introduced crops (e.g., wheat [*Triticum aestivum* L.] and alfalfa [*Medicago sativa* L].) are grown (Bohrer, 1960; Manolescu, 1994; Brandt, 1995; Muenchrath et al., 2002). Sheep and cattle production became important during the historic period and continues today. With the intent to assimilate Zuni into the irrigated agriculture norm of the western U.S. (Perramond, 1994; Cleveland et al., 1995), early-20th-century government programs initiated irrigation projects that shifted agriculture from primarily traditional valley margin fields to floodplains, which tend to have poorer soils (including highly clayey or sodic soils) and are more freeze-prone. Although greatly reduced in scope, traditional agriculture is still practiced at Zuni and revitalization efforts have been undertaken by the Zuni Conservation Project and the Zuni Sustainable Agriculture Project (Cleveland et al., 1995; Muenchrath et al., 2002).

Figure 2a. Long-term continuity of agriculture at Zuni and common settings for runoff agriculture. Runoff maize field near Corn Mountain (Dowa Yalanne) at Zuni in 1913 (Collins, 1914).

Figure 2b. Long-term continuity of agriculture at Zuni and common settings for runoff agriculture. Maize field in similar location in 1994.

In Zuni and other traditional Southwest runoff agriculture, small permeable stone or brush dam structures have been used to manage and distribute watershed runoff and sediment (Figure 2c–d). These small dams are multifunctional (Sandor, 1995; Doolittle, 2000). They commonly serve as agricultural terraces, decreasing slope angle and length, thereby encouraging runoff retention and sedimentation, and replenishing

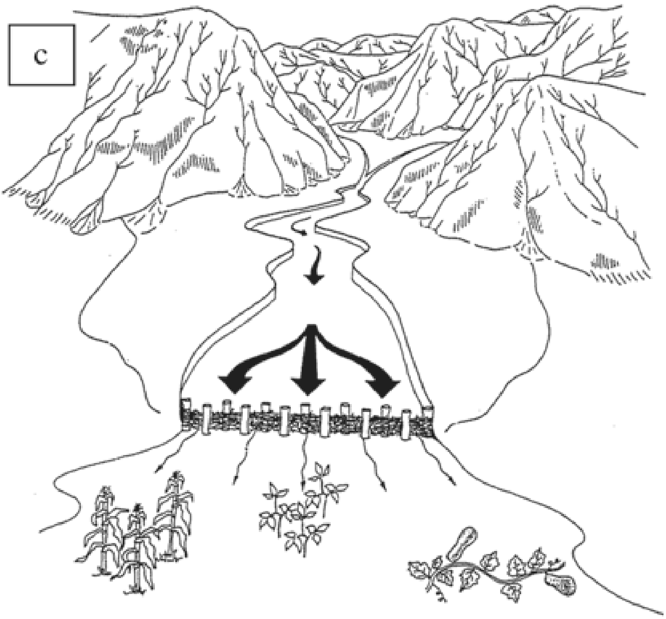

Figure 2c. Long-term continuity of agriculture at Zuni and common settings for runoff agriculture. Diagram of runoff agriculture (modified from Nabhan, 1984, by Pawluk, 1995).

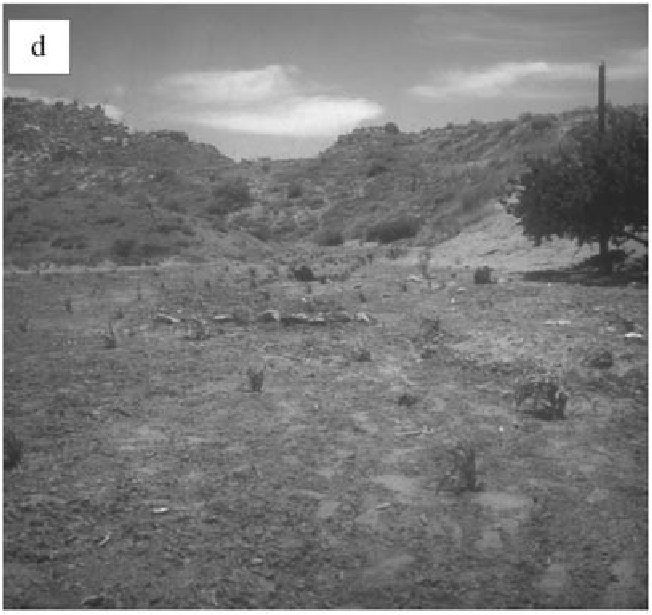

Figure 2d. Long-term continuity of agriculture at Zuni and common settings for runoff agriculture. Hopi runoff maize field on alluvial fan in 1976, early in growing season. Note small dams used for runoff management.

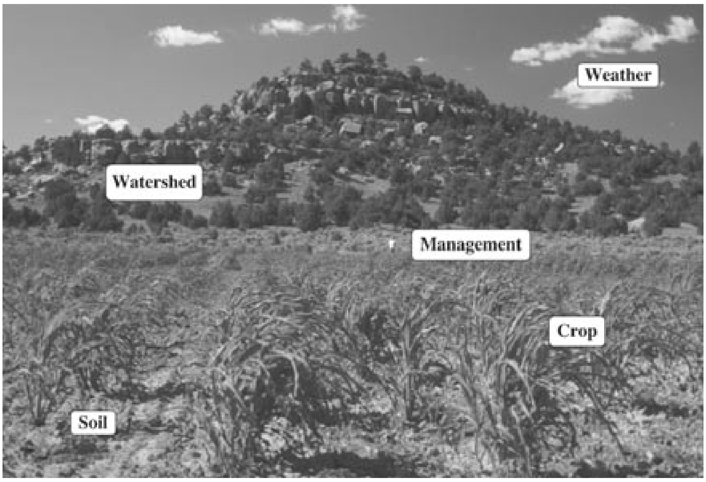

Figure 3. Runoff agriculture components.

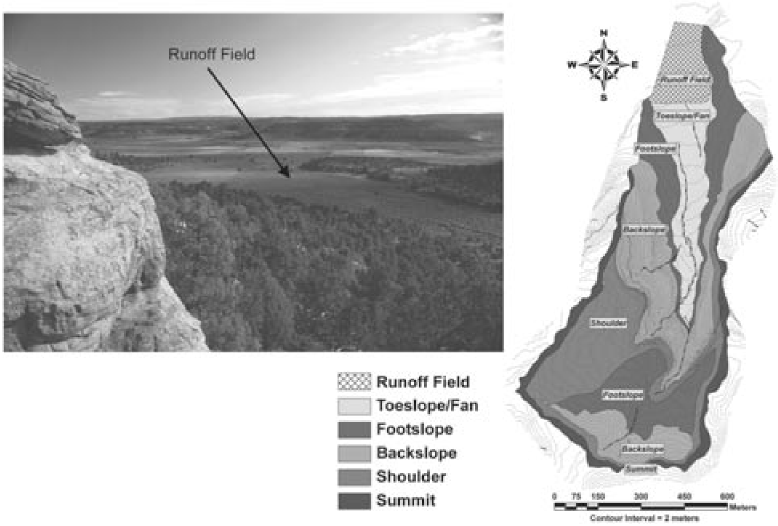

Figure 4. Zuni runoff field and watershed—Sanchez site (also see Figures 6b, 8a, 8c, and 9). Mapped field (from Norton et al., 2003) is visible in middle ground of photo.

soils. Also, dams are often placed upstream from fields to reduce erosive power and to manage the location of the stream power threshold where flow changes from erosive to depositional. The ephemeral dams can be readily reconfigured, enabling farmers to respond quickly to dynamic conditions of runoff events (Norton et al., 2002).

Traditionally, farmers prepared new fields by building dams a year or more before cropping (Cushing, 1920), allowing time for runoff deposition and subsequent soil incorporation and decomposition of fresh sediment and organic matter inputs. This illustrates the emphasis on runoff as a soil and nutrient resource, as well as a water resource. Although dams are not used much today in the Southwest (though they are in other regions of runoff agriculture), runoff input is still important and partly managed by tillage. Soil fertility renewal by runoff and its management is a key process in the Southwest because direct application of fertilizer materials (e.g., manure, ashes) was apparently not a widespread indigenous practice in this region (review in Sandor, 1995).

FIELD AND LABORATORY RESEARCH METHODS

Agroecological research concentrated on the eastern part of the Zuni Reservation; other areas were studied but to a lesser degree. To characterize runoff agricultural soils and test for soil changes, presently cultivated and abandoned agricultural soils documented to have been farmed during the 20th century were compared with soils not farmed during this time. Agricultural land-use information was obtained from archaeological records, historical documents, aerial photos (1934–present), inventories of agricultural sites, and interviews with farmers. To compare soils at both detailed and broad scales, a dual sampling method was used. For wide coverage, an "extensive" sampling consisted of 29 sites across the study area, including 9–10 sites each of cultivated, abandoned, and uncultivated soils. For more controlled, detailed comparisons within agricultural sites, an "intensive" soil sampling was undertaken at three adjacent pairs of cultivated/uncultivated sites located near traditional farming villages. Watershed ecosystem, meteorological, and maize production research was also conducted at "intensive" study sites. Altogether, study sites represent an approximately 30% sample of known runoff fields in the eastern Zuni study area. Field and lab methods used in this multidisciplinary study are detailed in Norton (1996, 2000), Havener (1999), Homburg (2000), Sandor et al. (2000), Muenchrath et al. (2002), Norton et al. (2002, 2003, in press a, in press b), and Homburg et al. (2005). The rationale and limitations of paired-site methodology in studies of ancient agriculture are discussed in Sandor and Eash (1991). Knowledge of soils, geomorphology, and agriculture was studied through interviews with a number of Zuni farmers over several years using ethnoscientific methods (Pawluk, 1995).

ZUNI RUNOFF AGROECOSYSTEM: COMPONENTS AND CONNECTIONS

Our presentation of research findings on the soil fertility of Zuni runoff agriculture is organized by agroecosystem components and linkages. A simplified conception includes the watershed (and weather), field, and crop components, and the transport of runoff and nutrients from watershed to field to crop (Figure 3). This study is intended as a first step toward integrating more specific project studies of these components and linkages into a whole picture. Within this overview, data illustrative of each segment are briefly presented along with references that provide more detail. Analyses and writing on several aspects of the project are in progress. Because this runoff agroecosystem is so complex and research is still at a relatively early stage, gaps and further steps needed to advance understanding are identified.

Watershed and Weather Component

The viability of runoff agriculture depends on watersheds to which the fields are connected. To begin to evaluate watershed nutrient and water inputs to agriculture, studies of vegetation, soil, hydrology, and geomorphology have been conducted in three watersheds of intensively sampled traditional fields (Norton, 2000; Norton et al., 2003, in press a, in press b).

Watershed vegetation distributions are complex, but generally consist of pinyon pine-juniper-oak woodlands and shrubs on mesa uplands and grasses and shrubs in valleys (Figures 3–5). The mosaic of patchy vegetation cover and corresponding soil variability has been characterized in ecological terms as "islands of fertility" (Skujins, 1991; Reid et al., 1999; Norton et al., 2003). Characterization and mapping of mesa to valley slope positions and vegetation have provided information about nutrient storage and distribution in watersheds (Figures 4 and 5). The steeper backslopes compose the largest area of most watersheds (average 37%), and also contain the most dense woodland vegetation and organic litter horizon thickness (Figure 5; Norton et al., 2003), and, therefore, much of the organic matter and nutrient storage in the watershed. In addition to cover and vegetation mapping, organic horizon thickness and density by plant species have been measured in two watersheds. However, nutrient contents of the natural vegetation and organic horizons have not yet been analyzed. Organic carbon, nitrogen, and phosphorus in upper mineral horizons of watershed soils (which are subject to long-term episodic movement) have been measured (Norton et al., 2003), but a nutrient inventory awaits further work. It is evident that watersheds hold major nutrient pools that can fertilize fields downslope. A next step would be to use the data in conjunction with data and models from other nutrient and hydrologic studies of Southwest watersheds (e.g., work of the USDA-ARS Southwest Watershed Research Center; Nabhan, 1984; Klemmedson, 1991; Rhode, 1995; Reid et al., 1999; Dominguez and Kolm, 2005) to estimate and model nutrient storage capacity in watersheds, and potential availability to fields over time.

Several characteristics impart effective runoff production to these watersheds, including steep hillslopes, bedrock outcrops, patchy vegetation cover, and soils with subsurface layers of clay accumulation (argillic horizons). A notable trait of watersheds used for runoff agriculture in the Southwest is that they are generally unmodified, except for the construction of erosion control dams near fields (Doolittle, 2000). In contrast, alteration of watershed surfaces and soils to enhance runoff to fields has been reported in other regions. One example is from the Negev Desert, where ancient farmers successfully used runoff to augment the annual 100-mm rainfall by rearranging rock fragments on slopes, which caused soil crusts to form that increased runoff to fields (Evenari et al., 1982). Another example is the deliberate removal of vegetation in watersheds in Mexico to encourage soil erosion and sediment transport to replenish fertility in agricultural soils downslope (Bocco, 1991; Doolittle, 2000).

To measure runoff amounts and composition, sediment traps were installed and monitored in watersheds (Norton, 2000; Norton et al., in press a, in press b). Sediment traps with 20-m^2 catchments were placed in different slope positions with common plant species combinations (Figure 6a). Results from this and other hydrologic mon-

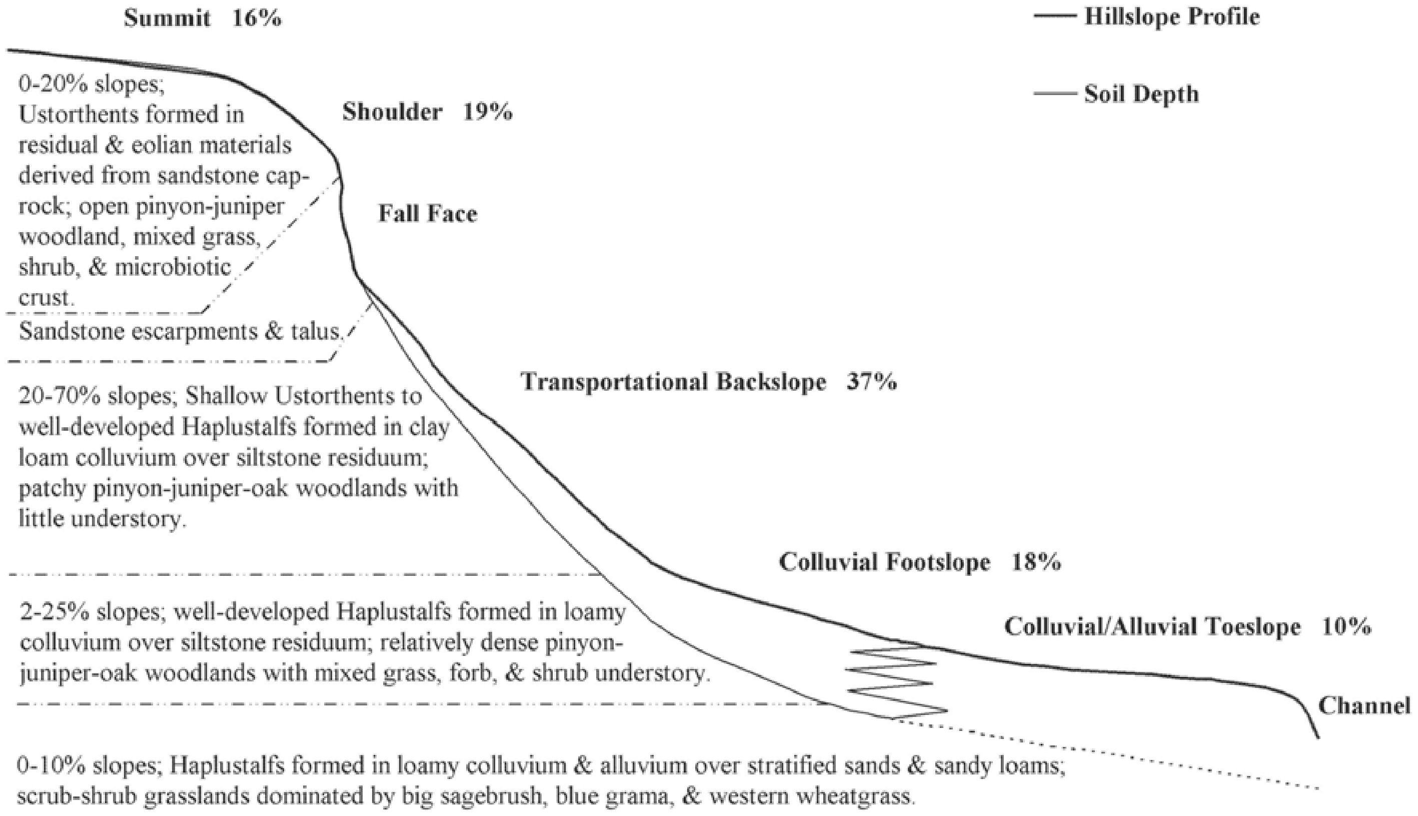

Figure 5. General cross-section of a mesa hillslope, and average areal extent of slope positions (%) for three watersheds of Zuni runoff agriculture fields (from Norton et al., 2003, Figure 2 and Table 2).

itoring indicate that runoff events are common in the Southwest during summer thunderstorms; however, they have a high spatial and temporal variability. During a given summer, runoff events on hillslopes usually occur several times, but only a few are large enough to generate flow to agricultural fields, and some fields may not receive runoff in a given summer (Norton, 2000; Norton et al., 2001, in press a, in press b). Several factors influence the location and amount of runoff. Besides rain intensity, duration, and antecedent soil moisture, watershed size and other geomorphic and climate variables are important factors (see discussion in Sandor et al., 1990; Sandor, 1995). Patterns of watershed area to field ratios (average about 20–25:1), similar to those reported in runoff agriculture literature elsewhere in the Southwest and Near East (Hack, 1942; Evenari et al., 1982; Rhode, 1995; Homburg, 2000), suggest that this is also an important management consideration.

Nutrients are transported from watersheds toward fields as solutes in runoff, and in sediments and organic debris carried by runoff. Soil morphology and sediment transport data suggest that although subsurface soil horizons in Zuni watersheds mostly remain stable, surface horizons are more easily mobilized, and episodically contribute organic matter and sediment to fields. Small, frequent hillslope runoff events incrementally move sediment and organic matter downslope, where they accumulate. Larger, less frequent runoff events episodically flush accumulated materials from uplands to alluvial fans and fields through overland and ephemeral channel flow (Figure 6 b–c). Farmers report that major runoff events can cause crop damage, but recognize the long-term benefits of soil renewal. With active management of runoff that was practiced traditionally, runoff events could be controlled and were more immediately beneficial in supplying water to crops.

Meteorological data from the Zuni study (White and Thomas, 1999), including rainfall frequency, amount, and chemical composition, suggest that atmospheric contributions of nutrients are minor relative to those of watershed sediments, though these soluble nutrients would be more immediately available to crops. Nitrate-nitrogen ranged from 0.1 to 0.5 mg/L and phosphate-phosphorus from 0.02 to0.06 mg/L of rain water. The possible contributions of nitrogen by lightning fixation, possibly more significant than previously thought (Franzblau and Popp, 1989), should be investigated in Southwest areas, such as Zuni, where lightning storms are common.

Sediments and organic debris are transported along with the runoff in pulses. Varying amounts enter, and are retained in, agricultural fields. These materials are differentially transported toward the fields, and arrive in different stages of decomposition, essentially a “traveling compost.” We observed organic-rich materials from runoff events in clusters (“nuggets”) and various stages of decomposition en route to, and within, agricultural fields (Figure 6b–c; also see Norton, 2000; Norton et al., in press a, in press b). In runoff experiments north of Zuni, Hubbell and Gardner (1950) measured much greater amounts of organic matter and bacteria in runoff relative to soils where runoff originated.

Smaller sediment traps (1-m^2 catchment) were placed in association with single plant species or other cover types (Norton et al., 2006). One cover type of special interest consists of symbiotic biological crusts that fix nitrogen. Nitrogen-fixing shrubs, such as mountain mahogany (Cercocarpus montanus Raf.), are also common in the

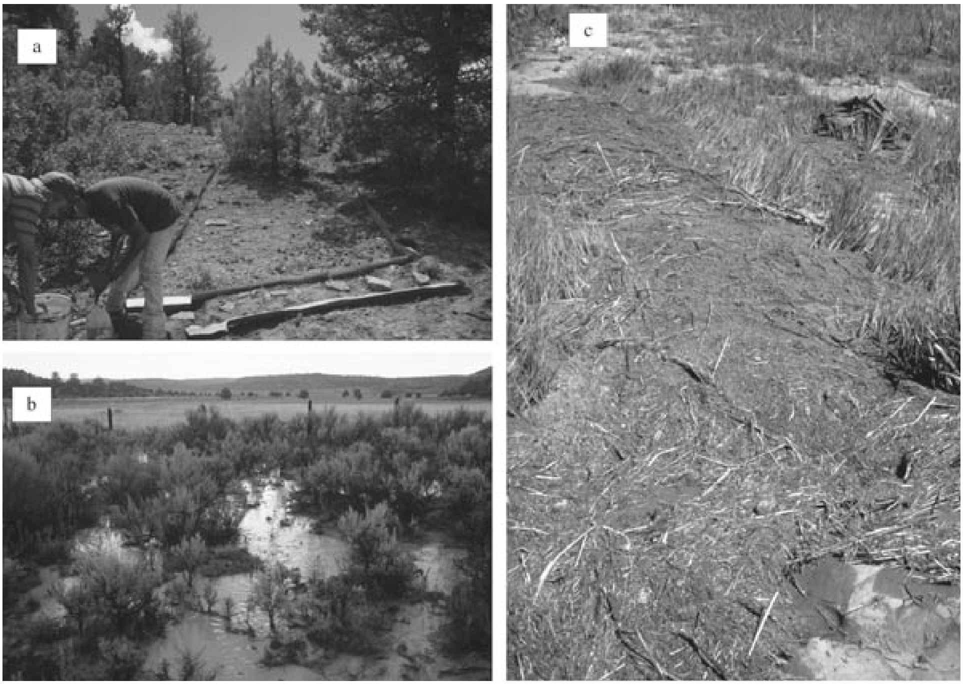

Figure 6. Photos of runoff agriculture watershed component at Zuni. (a) Watershed sediment trap (20 m^2) on backslope, Weekoty Field watershed. (b) Runoff entering Sanchez wheat field during 13-mm rainfall. Note sediment and organic matter in runoff. (c) Organic matter–rich runoff debris in abandoned runoff field.

watersheds. The function of these organisms in soil fertility and ecosystem productivity in the Southwest has been studied by a number of researchers (Klemmedson and Weinhold, 1991; Berry, 1995; Belnap, 2003). More soil biology and ecology studies of watersheds and fields are needed to learn more about potential nutrient contributions from plant and microbial species in runoff agriculture.

Watershed distribution and change in composition of carbon, nitrogen, and phosphorus during runoff transport toward fields are illustrated in Figure 7. Carbon-nitrogen (C:N) ratio data show increasing decomposition of organic matter and mineralization of nitrogen and phosphorus from the backslope woodland source during downslope transport. Plant-available forms of nitrogen and phosphorus also increase downslope. Runoff plays an essential role in moistening dry soil, which activates microbial decomposition of organic matter, thereby producing and releasing plant-available nutrients (Norton et al., 2003).

Data collected on the nutrient composition of runoff sediments that can reach fields are shown in Table I. Data from this and other studies of present-day and archaeological fields (Sandor, 1983; Nabhan, 1984; Wilken, 1987) indicate that runoff sediments tend to be rich in organic matter, nitrogen, and phosphorus compared to

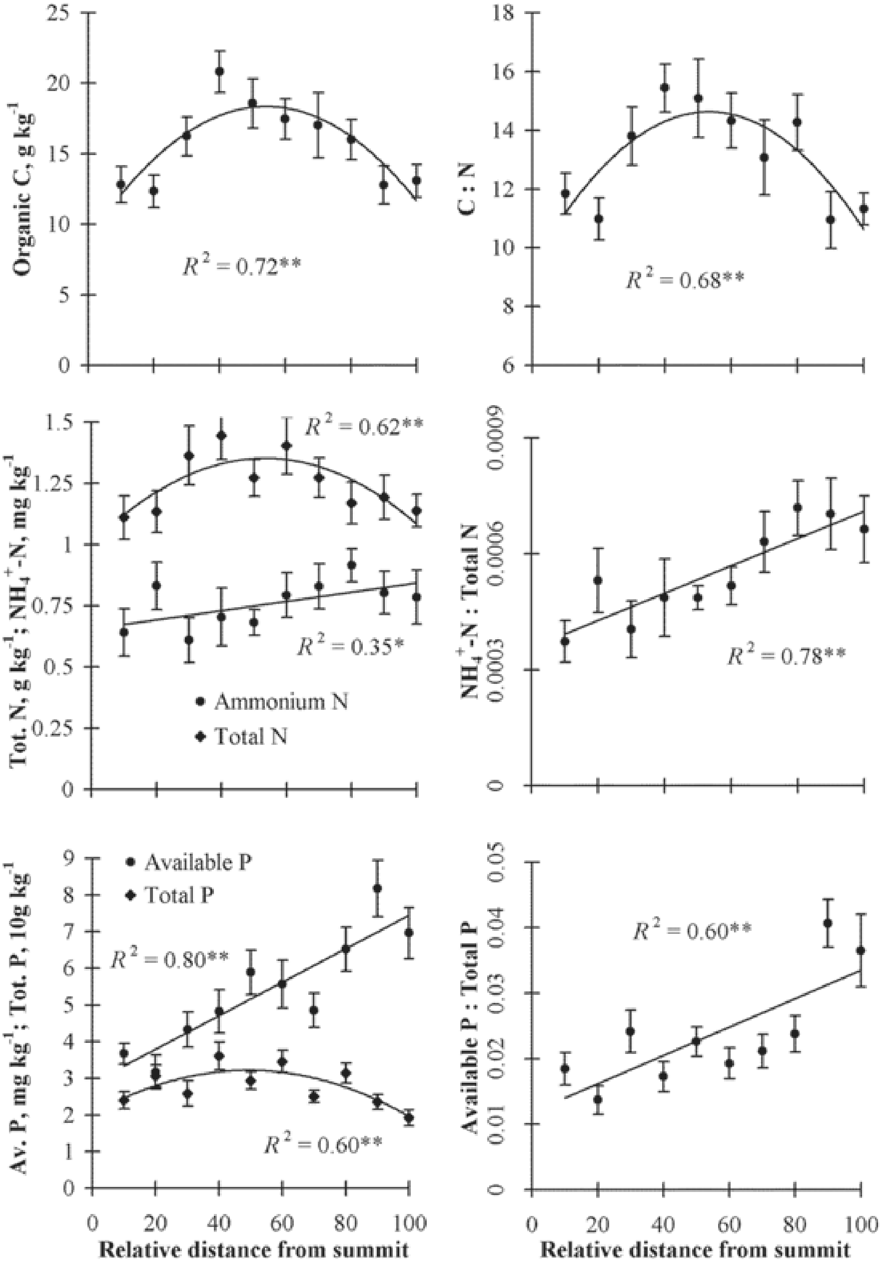

Figure 7. Organic matter and nutrient trends along watershed hillslopes connected to Zuni agricultural fields (from Norton et al., 2003). Backslopes extend from ~27 to 55 and toeslopes from 89 to 100 relative distance units along the x-axis. Each point is an average of 10 distance units from a composite of three Zuni watersheds. Error bars are standard errors. Regression lines: *, **, significant at the 0.05 and 0.005 probability levels, respectively.

Table I. Comparison of organic matter and nutrients in runoff sediment and field surface soil.

Site	Organic Carbon (g/kg)		Total Nitrogen (g/kg)		Total Phosphorus (mg/kg)	
	Runoff Sediment	Soil	Runoff Sediment	Soil	Runoff Sediment	Soil
Laate site 1996–1997 5 runoff events	14 (3)	8 (1)	1.6 (0.3)	0.8 (0.1)	548 (16) (2 events 1996)	429 (49)
Weekoty site 1998 1 runoff event	26	11 (1)	1.8	0.9 (0.1)	469	268 (54)

Note. Data are means (standard deviations in parentheses) of runoff sediment samples taken just upslope of fields after different runoff events, and 25 surface soil samples (0–15 cm depth) from each corresponding field and maize experiment site.

field soil A horizons, supporting the hypothesis that runoff is an important source of nutrient replenishment for agricultural soils. The runoff nutrients shown in Table I are from sediments only and do not include contributions from the coarse organic material or liquid portion of runoff also transported into fields. Even so, nutrient inputs from runoff events may not balance crop removal of nutrients, so that fallowing and other strategies are likely needed to maintain long-term soil fertility.

Nitrogen mineralization studies of runoff debris and field soils suggest that runoff debris may require further decomposition to increase nutrient availability to crops (Thomas and White, 1999b). Excess amounts of runoff sediment can also be detrimental to crop growth (Forbes, 1906; Hubbell and Gardner, 1950; Hillel, 1991). These factors may partly explain why Zuni farmers traditionally waited some time after initiating runoff fields to grow crops (Cushing, 1920; also see Wilken, 1987, regarding runoff management in Mexico). However, the immediate value of runoff for plant growth, both in terms of nutrients as well as water, is also evident from speaking with farmers and other studies (Nabhan, 1984; Wilken, 1987; Sandor et al., 2002). The fertilizing effect of runoff is more well known in flood recession and floodwater agriculture in larger stream valleys (e.g., Berger, 1898; Forbes, 1906; Castetter and Bell, 1951; Jenny, 1962; Hillel, 1991; Doolittle, 2000). Continued integrated studies of runoff in an array of geomorphic settings would help to further advance understanding about the near- to long-term effects of runoff water and nutrient inputs, quantity and quality of nutrient additions, rates of decomposition and nutrient availability for crops, and relationships between moisture and nutrient decomposition and availability.

Zuni farmers recognize the value of runoff material for growing crops, and part of their field location and management strategies involve directing it into the field (Pawluk, 1995; Norton et al., 2001; Sandor et al., 2002). In fact, they collect organic runoff debris in road ditches after storms and take it in their pickup trucks to home gardens. Knowledge of the watershed's role in contributing sediments and organic matter to replenish agricultural soil fertility is encapsulated in the Zuni term *danaya* *so:we*, which translates into forest sand or soil, or simply “tree soil.” Tree soil describes the plant litter and topsoil (O and upper A horizons) transported by runoff from uplands to fields. Different types of tree soil and their value are recognized (e.g., juniper is considered favorable, and one farmer referred to “oak soil,” which is especially dark and organic matter–rich (Norton, 2000; Norton et al., 2006; also see Klemmedson, 1991, concerning positive effect of Gambel oak on soil fertility in Arizona pine forests). Other Southwest American Indians practicing runoff agriculture have parallel concepts about organic runoff debris, including its components and states (e.g., Nabhan, 1984). Other Zuni terms relate to the importance of runoff sediment in improving and maintaining soils, and contain concepts about runoff processes (Sandor et al., 2002). Fresh sandy to loamy deposits are particularly valued by farmers because they improve the ability of surface soils to take in water (Norton et al., 2001). Ethnographic and historic reports on Southwest runoff agriculture discuss the importance of flood deposition in maintaining soil fertility, and farmers’ knowledge of this function (review in Sandor, 1995). They view erosion/sedimentation processes as favorable, managing sediment as resource, in contrast with the conventional negative view of erosion and sedimentation as environmental degradation (Wilken, 1987; Bocco, 1991). In addition to their agricultural significance, these indigenous concepts and associated soils are relevant to conserving hydrologic and ecological functions of watersheds (Norton et al., 2003).

Field Soil Component

Soils in agricultural fields function as the crop-growing medium, and in the context of runoff agriculture as the receiver and retainer of water and nutrient inputs for crops. Findings pertaining to inputs of runoff sediment and nutrients into agricultural soils are briefly summarized. Both natural soil properties and runoff processes, and those modified by management, affect soil nutrient conditions. Runoff management can be conceived in terms of placing fields in favorable positions for deposition, and enhancing natural hydrologic processes.

A distinctive feature of soils used for runoff agriculture is that they generally have thicker surface horizons than historically uncultivated soils used as references (Figure 8a and Table II; Homburg et al., 2005). We infer that this is due, at least in part, to greater inputs of sediment from runoff processes. Thickening has been enhanced by the placement of fields at natural areas of deposition on alluvial fans, and during long-term runoff agricultural management. Remnants of small dams, likely to have encouraged soil thickening, have been observed upslope from Zuni fields, and some are visible in 1935–1937 aerial photos. Topsoil thickening over time is also indicated by the common presence of buried soil horizons (as illustrated in Figure 8a).

This and other studies indicate that an important benefit of thickened A horizons is increased water retention for crop use, especially when permeable sandy to loamy A horizons are underlain by natural horizons of clay accumulation (argillic horizons) or other layers that help retain infiltrated water in the root zone (Sandor et al., 1990; Sandor, 1995; Muenchrath et al., 2002; Homburg et al., 2004; Dominguez and Kolm, 2005). Besides the hydrologic benefits of A-horizon thickening, runoff deposition

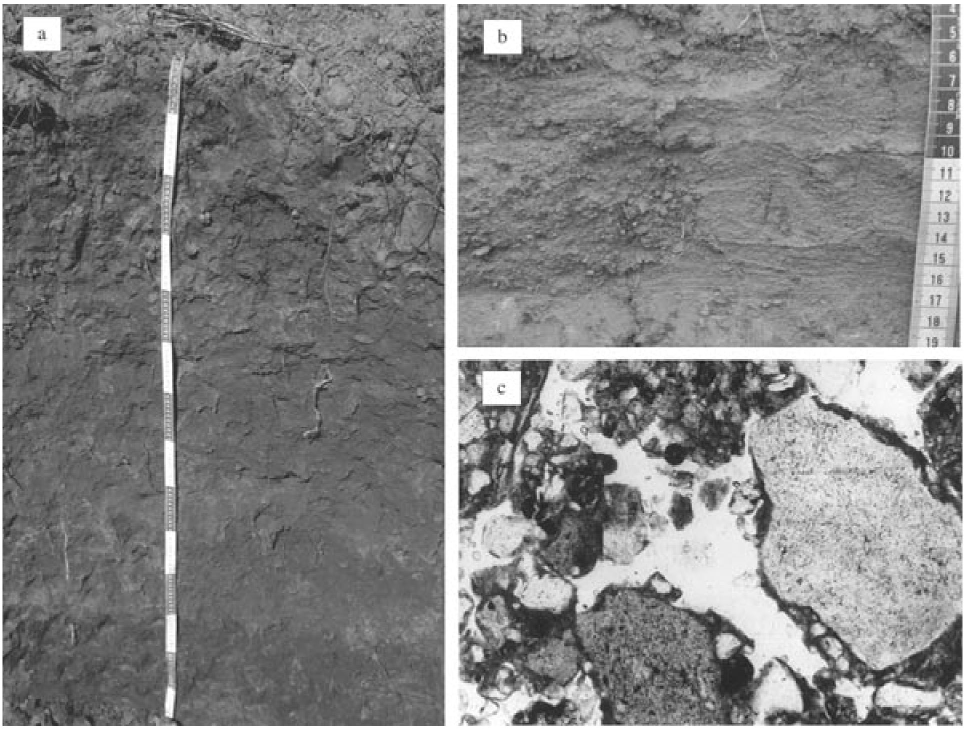

Figure 8. Runoff agricultural soils at Zuni. (a) Upper Sanchez Field (also see Figure 9): thickened surface horizon overlying buried soil near base of profile. Scale tape bands mark 10-cm intervals. (b) Laminated runoff sediments in surface horizon of abandoned agricultural soil. Scale in cm. (c) Micromorphology of soils in runoff fields. Note dark organic matter rich coatings on mineral grains and aggregates in A horizon. Thin-section frame length 7 mm; plane-polarized light.

adds fresh mineral and organic soil material, thereby replenishing soil nutrients, both in terms of quantity and quality, as previously discussed with regard to “tree soil.” Maps of depth to the natural subsurface illuvial clay accumulation in two intensively sampled runoff fields and upslope alluvial fans show the greatest buildup of material in fields and just upslope where dams were located (Figure 9 shows one example).

Effects of runoff sedimentation and management relevant to soil fertility are also evident in other soil morphological properties. Fine stratification of sediments was observed in surface horizons of some current and abandoned runoff soils (Figure 8b). These laminated sediments are preserved only in a few fields because they are easily erased by plowing and soil-formation processes, such as bioturbation and structure development. Fine sediment stratification was also observed by Damp and Kendrick (2000) in older buried agricultural fields at Zuni. Soil micromorphology studies show more organic coatings in A horizons of runoff fields (Figure 8c). These are sources of increased organic matter and associated nutrients for crops. The coatings may be associated with another finding, namely unusually high positive correlations between silt and organic matter (including nitrogen) in a number of runoff

Table II. Comparison of thickness and silt/organic carbon correlations for cultivated, abandoned (formerly cultivated), and uncultivated soil A-horizons.

Land Use	A-Horizon Thickness (cm)	Silt/Organic Carbon Correlation (r)
Cultivated	19 (6) a	0.88**
Abandoned	13 (3) b	0.42
Uncultivated	9 (4) c	0.26

Note. For A-horizon thickness, means (standard deviations in parentheses) are shown for 29 extensive sample sites. Silt/organic carbon correlations are for 0–15 cm depth at the 29 extensive sample sites. A horizon thickness values followed by different letters are significantly different at the 0.05 probability level; the silt/organic carbon correlation coefficient followed by ** is significant at the 0.01 probability level. Data from Homburg (2000).

fields, which may reflect cotransport of silt and organic debris common with runoff processes (Table II; Nabhan, 1984; Norton, 1996; Homburg et al., 2005).

Overall, data from this project suggest that nitrogen and phosphorus levels of Zuni runoff agricultural soils are sufficient to meet crop needs (Table III; Homburg et al., 2005; also see the next section on maize). In conjunction with soil chemistry studies, soil biology is a key area relating to soil nutrient dynamics that deserves much more study in relation to past and present runoff agriculture. Nitrogen mineralization studies in relation to runoff sediments and comparisons of cultivated and uncultivated Zuni soils (Thomas and White, 1999a, 1999b) are discussed in other sections. Work by soil biologists suggests increased arbuscular mycorrhizal activity in Zuni maize (Table IV; Havener, 1999). Mycorrhizae are symbiotic associations between certain soil fungi and roots that increase water and nutrient uptake by increasing effective root area, and that also facilitate the uptake of phosphorus and other nutrients.

Crop Component

The bottom line of any agriculture is crop production. In the context of runoff agriculture, production reflects the integration of weather, watershed, soil, management, and all other components of the system. To begin to evaluate crop production and the effects of runoff inputs on soil fertility and plant nutrition, observational and experimental studies were conducted at Zuni. Results of the observational study of four Zuni runoff fields are reported in Muenchrath et al. (2002). The controlled experiment was conducted over a 2-year period (1997–1998) within two fallow traditional fields on alluvial fans (Figure 10). The experiment focused on maize, specifically using a traditional Zuni blue corn and two commercial hybrid maize varieties. Experimental runoff treatments were applied to plots after collecting runoff water and sediments during storms in catchments placed in the fields' watersheds (Figure 10a). To partially separate out the effects of runoff water from those of the sediments, the two runoff treatments were the runoff water (plus suspended load) and runoff water plus sediments that settled out in the reservoirs. The three control treatments were rainfed only, conventional irrigation water to the extent of runoff applied, and irrigation plus synthetic N and P fertilizer to ensure that water and nutrients were nonlimiting. Because of

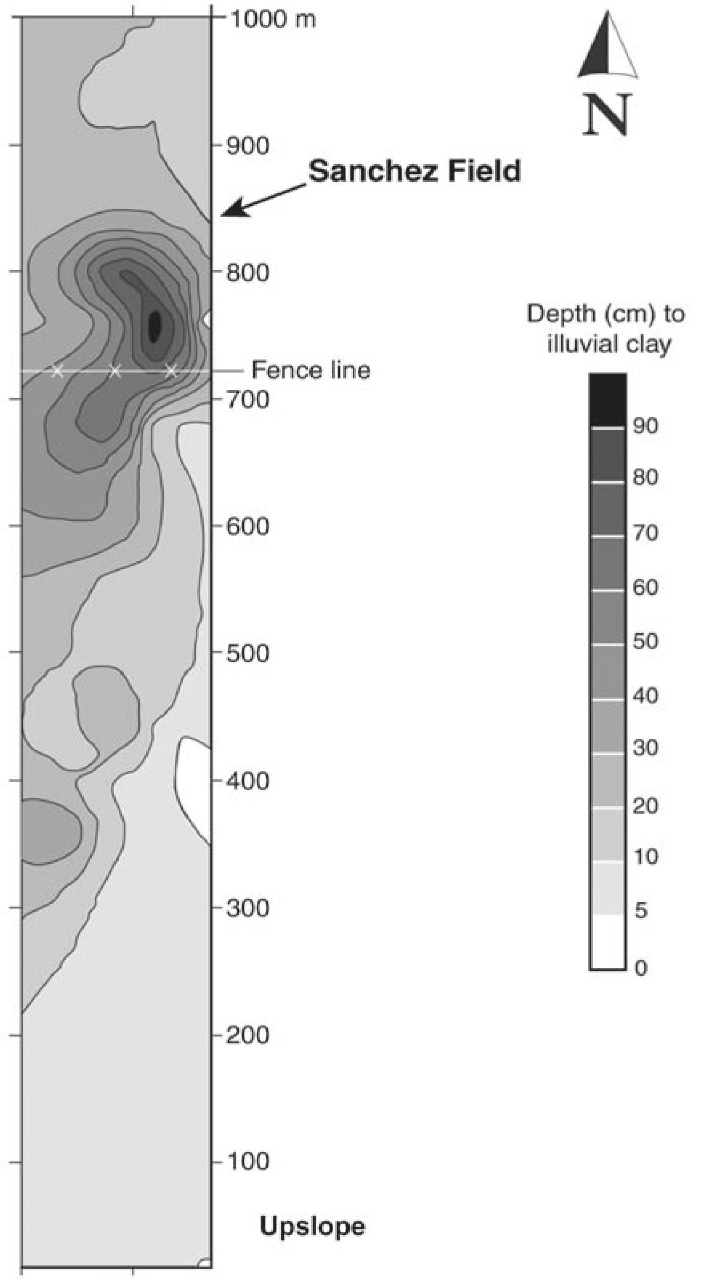

Figure 9. Contour map of surface-horizon thickness in a runoff field, and alluvial fan watershed upslope. Upper boundary of current field is the horizontal line at about 720 m distance. Data indicate most alluvial deposition at upper part of field and just upslope. Same field as shown in Figures 4, 6b, and 8a. Figure redrawn by Peg Robbins.

Table III. Comparison of surface soil chemical properties (0–15 cm depth in A horizons) among cultivated soils, abandoned agricultural soils, and uncultivated soils.

Land Use	Organic Carbon (g/kg)	Total Nitrogen (g/kg)	Total Phosphorus (mg/kg)	Available Phosphorus (mg/kg)
Cultivated	12 (5)	0.9 (0.3)	294 (72)	10 (5)
Abandoned	13 (6)	1.1 (0.4)	296 (50)	12 (5)
Uncultivated	13 (7)	1.0 (0.4)	322 (94)	14 (5)

Note. Data are means (standard deviations in parentheses) for 29 extensive sample sites. There are no significant differences at the 0.05 probability level between soils for any of these soil properties. Data from Homburg (2000).

Table IV. Arbuscular mycorrhizal formation in maize experiment (Laate site, 1997).

Maize Type	June	August	October	Combined
Zuni	51a	90a	53a	59a
Hybrid	27b	50b	49a	50b

Note. Values are % of 1-mm root segments with mycorrhizal infection. Different letters indicate values for maize type and are significantly different at the 0.05 probability level. Data from Havener (1999).

variability in runoff events (and challenges of an *in situ* experiment), the times and amounts of runoff that could be applied varied with each site and year. Results were obtained for 3 site-years, with runoff application results obtained for 2 site-years, 1 year at each of the two sites.

Several physiological and production measurements were made, and those especially relevant to biogeochemical studies included soil nutrient analyses, assays of soil nitrogen mineralization and arbuscular mycorrhizal formation, grain and aboveground biomass production, and nutrient composition of leaf and grain. Soil data were generally inconclusive in terms of connecting soil nutrient levels to maize composition and production within each experimental field. This may partly relate to the experiment fields having been fallow for a number of years prior to the study. Also, several years of experiments and monitoring would likely be needed to detect significant changes in soil nutrient levels from runoff and fertilizer additions and to observe soil-crop fertility relationships. Positive relationships between nitrogen, phosphorus, and manganese levels in soils and maize were found in a controlled greenhouse experiment growing an ancient Southwest maize cultivar (chapalote) in soil from a prehistoric runoff agricultural site and nearby uncultivated soil in southwestern New Mexico (Sandor and Gersper, 1988).

As an example of production data for 1 site-year, Figure 11 shows yield on a per plant basis, with treatments arranged in order of increasing nutrient and water inputs. An interesting finding, corroborating observations of some traditional fields at Zuni (Manolescu, 1994; Norton, 2000) and Hopi (Dominguez and Kolm, 2005), is that maize can be produced without runoff-supplemented water, at least in years with enough stored soil moisture and precipitation. At this point, it is uncertain whether the greater production with the irrigation and fertilizer treatment can be attributed to a response to the extra water or nutrients, or both. However, the nitrogen and phosphorus levels

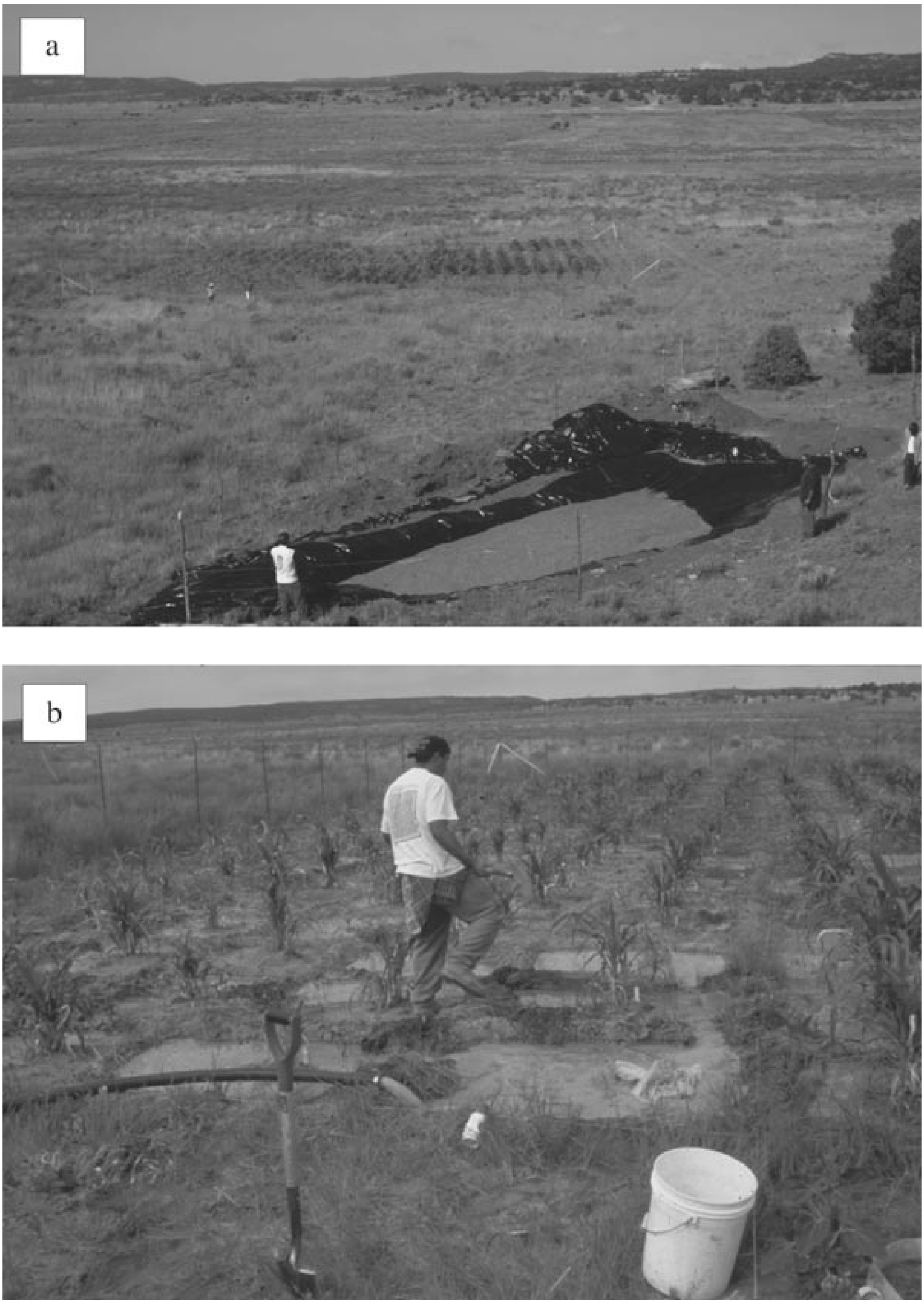

Figure 10. Photos of maize experiment at Laate site, 1997. (a) Runoff catchment for maize experiment and field downslope. (b) Applying runoff from catchment to maize plots.

in maize leaves and grain for all treatments are within the ranges for maize in well-fertilized soils of the Midwest United States (Cerrato and Blackmer, 1990, 1991; Mallarino et al., 1991), suggesting that the higher production is mostly due to water. So in answer to the question as to whether Zuni soils are fertile, our initial inference is that the basic soil fertility of these Zuni fields is adequate, perhaps especially so in these maize experiment fields because they had been fallow for several years. Zuni farmers and researchers have observed reduced maize growth and nutrient deficiency (chlorosis) after a few years of continuous production. At one traditional Zuni field showing nutrient deficiency after 4 years of maize production, maize growth was vigorous in an adjacent field in its second year of production after having not been farmed for a number of years, showing the importance of fallow and nutrient replenishment. Previous studies also suggest that traditional agricultural fields, though they appear to be located in marginal areas from the perspective of mainstream U.S. agriculture, are potentially productive and fertile, especially with nutrient replenishment by watershed runoff deposition (e.g., Sandor and Gersper, 1988; Norton et al., 2003).

Differences in nutrient composition and distribution between the cultivars have also been found (Figure 12). For example, in all 3 site-years, across treatments, the Zuni maize had a higher grain nitrogen content and a higher proportion of nitrogen in the grain than the leaf, compared to the hybrid. This suggests that the Zuni maize has a higher protein content and may be able to mobilize more nutrients to its grain. Similar differences were also found with respect to maize phosphorus at one site with lower natural soil phosphorus, but not at another site richer in soil phosphorus. This shows that Zuni soils vary in their natural fertility, in this case, due to differences in sedimentary rock composition.

Results from this study and others indicate that more long-term experimental and observational studies could provide valuable information in understanding ancient and traditional Southwest agricultural systems, and for applying that information to the development of more sustainable modern arid land agricultural systems. One area meriting further research that relates to nutrients and their cycling involves studies of other native Southwest crops, such as beans, which symbiotically fix atmospheric nitrogen and are commonly intercropped with maize in traditional fields (e.g., Bohrer, 1960; Manolescu, 1994; Muenchrath et al., 2002). Root studies are another area of research with major implications for soil and crop nutrition. One trait common to several Southwest maize cultivars is that they can be planted remarkably deep to germinate in moister soil and for other reasons (e.g., Collins, 1914; Muenchrath et al., 2002; Dominguez and Kolm, 2005). Recent work by Muenchrath and others (Bousselot, 2003) also suggests that traditional Southwest maize cultivars, including Zuni blue maize, have significantly higher root/shoot ratios compared with check maize lines from the Midwest United States. Greater ratios may increase the ability of these cultivars to meet their water and nutrient needs.

Long-Term Soil Change and Relevance to Sustainable Land Use

The ancient Zuni fields also made it possible to evaluate the fertility and condition of some of the oldest recognized agricultural soils in the United States. Although

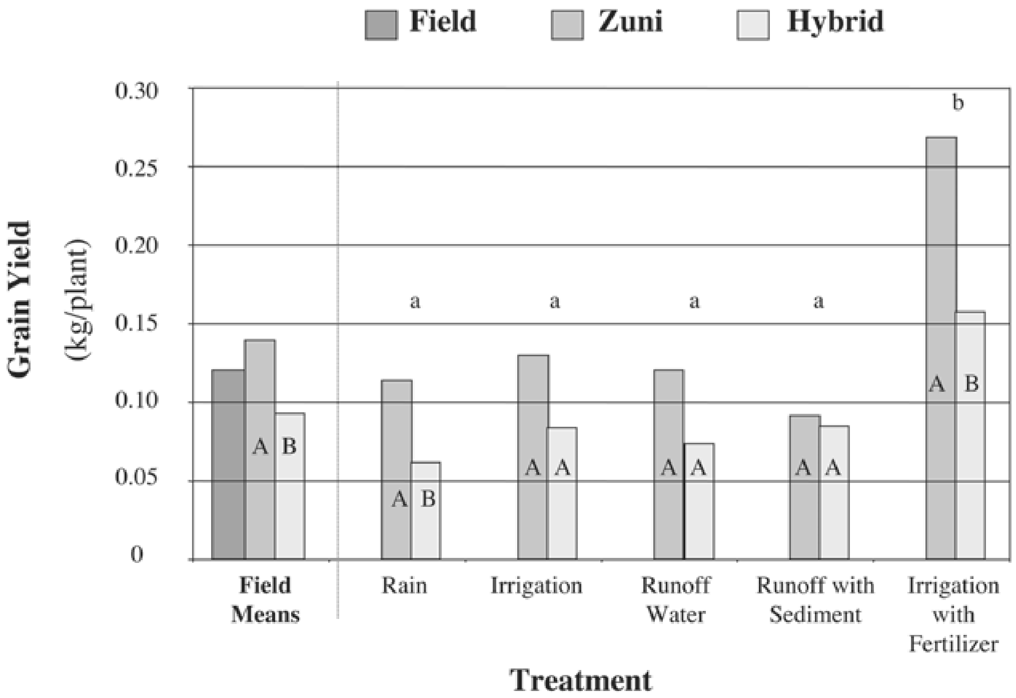

Figure 11. Mean grain yields of Zuni blue maize and commercial hybrid maize for 1997 Laate Field experiment. Different uppercase letters indicate significant differences between cultivars at the 0.05 probability level. Different lowercase letters indicate significant differences between treatments across cultivars at the 0.05 probability level.

agronomic experiments and soil monitoring considered “long term” have been running on time scales of decades to about one century, these ancient agricultural sites allow us to learn something about agricultural soils whose age, about 1000 years or older, is within a time frame more appropriate for evaluating sustainability (Sandor and Eash, 1991).

Both the intensive and extensive samples provide data about soil change, especially through use of historically uncultivated soils near, and matched to, cultivated fields as reference points for evaluating change in current and abandoned Zuni agricultural soils. It has proved difficult to identify with certainty truly uncultivated soils at Zuni, mainly due to the complex imprints of varied and long-term land use. The uncultivated soils can only be identified as not farmed during the period of historical documentation (approximately 20th century to present), meaning some may have been farmed in earlier historic or prehistoric periods. The association of prehistoric structures inferred to be field houses located near several uncultivated sites suggest prior cultivation (Homburg, 2000). Despite the problem of identifying true controls, worthwhile data for evaluating soil morphology, hydrology, chemistry, and biology have been obtained.

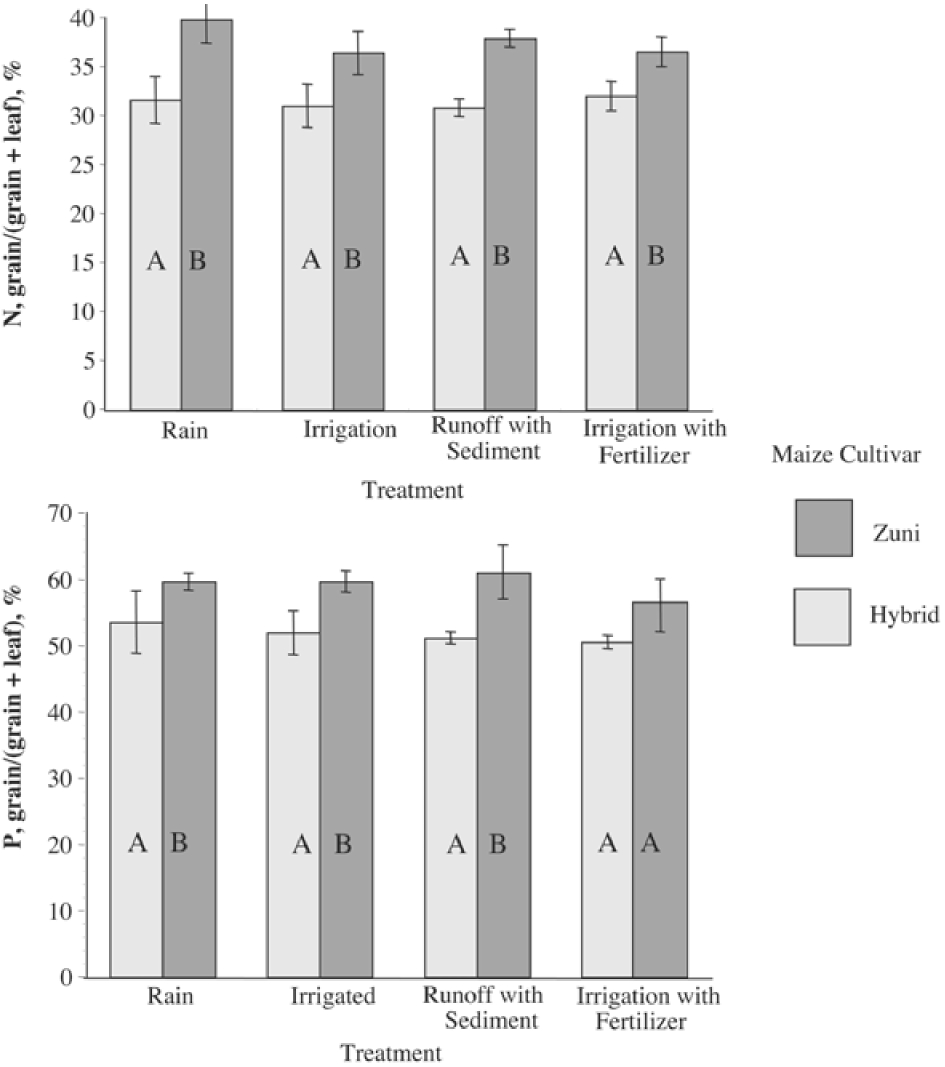

Figure 12. Nitrogen and phosphorus proportion in grain from maize experiment at Weekoty Field, 1998. Bars are means from replicated plots, expressed as percent by weight of grain plus leaves. Vertical lines within bars show ±1 standard deviation. Different uppercase letters indicate significant differences between Zuni blue maize and commercial hybrid maize within treatment at the 0.01 probability level, except for rain only treatment ($p < .001$) and irrigated + fertilized treatment ($p < .05$) for nitrogen.

Organic carbon, nitrogen, and total and plant-available phosphorus for cultivated, abandoned, and historically uncultivated upper A horizons are compared on a mass basis in Table III. No statistically significant differences were found, nor for comparisons of soil microbial biomass carbon (Havener, 1999) or potentially mineralizable nitrogen (Thomas and White, 1999b). On a mass/volume basis for A horizons, cultivated soils have higher organic matter and phosphorus levels than uncultivated soils primarily because of greater A-horizon thickness. These and other data already discussed suggest that overall, traditional Zuni agriculture has altered, but not degraded,soils (Homburg et al., 2005). This stands in contrast to clear trends toward decreased organic matter and microbial biomass with cultivation commonly reported in the literature for many modern agricultural fields under conventional cultivation (Sandor and Eash, 1991). The condition of traditional Zuni agricultural land after many centuries of farming suggests that their soil knowledge and care led to effective conservation of soil and water resources. Zuni certainly has experienced land degradation, but findings from this study suggest that the causes are probably not from traditional agriculture. For example, arroyo erosion has seriously damaged Zuni and other Southwest land during the past century. However, this is likely due to a combination of climate change, intrinsic geomorphic factors and natural erosion cycles, and later historic land-use problems (e.g., Balling and Wells, 1990; Gellis et al., 1995; Hart, 1995; Knox, 2001), rather than to traditional Zuni farming. In fact, traditional Zuni agricultural management has likely promoted erosion control and soil conservation (Stewart and Donnelly, 1943; Bull, 1997; Norton et al., 2002). Studies of other ancient agricultural soils in the Southwest show a range of consequences for soils, ranging from relatively stable to enhanced to degraded (Sandor et al., 1990; Homburg, 1994; Sandor, 1995; Homburg and Sandor, 1997; Sullivan, 2000). This illustrates how the experience of past and traditional societies can serve as a resource for evaluating long-term soil quality and land-use sustainability (Sandor and Eash, 1991; Kohler, 1992; Redman, 1999).

CONCLUSIONS

It is important to emphasize that although substantial hydrologic and nutrient/biogeochemical data on components and linkages in runoff agroecosystems have been collected and evaluated during this project at Zuni, clearly more work is needed on many aspects. Especially worthwhile would be longer-term monitoring and experimental work on watersheds, runoff processes, field soils, and crops across a wide range of Southwest agroecosystems. For example, comparative research on runoff agriculture between the Sonoran Desert/southern Basin and Range and this projects' work on the Colorado Plateau could generate valuable information.

Soil research into these systems is relevant in archaeology and resource management issues in agriculture, soil quality, and sustainable land use. Soil studies complement archaeological investigations to reconstruct and evaluate past agricultural strategies, agricultural productivity and change through time, and long-term condition of land resources. Ancient agricultural systems and joint studies in archaeology and soil science can make especially important contributions here in providing long-term perspectives on adaptations and strategies in arid land agriculture and land-use sustainability. These extended spatial and time perspectives on land use can support efforts to address today's critical problems in areas such as agricultural and biological diversity, agricultural development, global environmental change, water resources, soil quality, and land-resource conservation. Especially important, in this case, is that this traditional agriculture does not rely on energy-intensive inputs of fertilizers, but rather taps into natural watershed processes. With their coupled fields and natural watersheds, viable runoff agroecosystems create diverse landscape mosaics that maintain their essential biogeochemical functions.

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REFERENCES

Balling, R.C., & Wells, S.G. (1990). Historical rainfall patterns and arroyo activity within the Zuni River drainage basin, New Mexico. Annals of the Association of American Geographers, 80, 603–617.

Belnap, J. (2003). The world at your feet: Desert biological soil crusts. Frontiers in Ecology and the Environment, 1(4), 181–189.

Berger, J.M. (1898). Report of farmer in charge of Papagoes. Washington, DC: U.S. Government Printing Office.

Berry, A.M. (1995). Biological nitrogen fixation and soil fertility in Southwestern lands: Implications for Anasazi agriculture. In H.W. Toll (Ed.), Soil, water, biology, and belief in prehistoric and traditional Southwestern agriculture (pp. 139–143). Denver, CO: New Mexico Archaeological Council.

Bocco, G. (1991). Traditional knowledge for soil conservation in central Mexico. Journal of Soil and Water Conservation, 46, 346–348.

Bohrer, V.L. (1960). Zuni agriculture. El Palacio, 67, 181–202.

Bousselot, J.M. (2003). The emergence capabilities of maize landraces. Unpublished master's thesis, Iowa State University, Ames.

Bradfield, M. (1971). The changing pattern of Hopi agriculture. London: Royal Anthropological Institute of Great Britain and Ireland.

Brandt, C. (1995). Traditional agriculture on the Zuni Indian Reservation in the recent historic period. In H.W. Toll (Ed.), Soil, water, biology, and belief in prehistoric and traditional Southwestern agriculture (pp. 291–301). Denver, CO: New Mexico Archaeological Council.

Bryan, K. (1929). Floodwater farming. The Geographical Review, 19, 444–456.

Bull, W.B. (1997). Discontinuous ephemeral streams. Geomorphology, 19, 227–276.

Castetter, E.F., & Bell, W.H. (1951). Yuman Indian agriculture; Primitive subsistence on the lower Colorado and Gila Rivers. Albuquerque, NM: University of New Mexico Press.

Cerrato, M.E., & Blackmer, A.M. (1990). Relationships between grain nitrogen concentrations and the nitrogen status of corn. Agronomy Journal, 82(4), 744–749.

Cerrato, M.E., & Blackmer, A.M. (1991). Relationships between leaf nitrogen concentrations and the nitrogen status of corn. Journal of Production Agriculture, 4, 525–531.

Cleveland, D.A., Jr., F.B., Eriacho, D.F., Laahty, A., & Perramond, E. (1995). Zuni farming and United States government policy: The politics of biological and cultural diversity in agriculture. Agriculture and Human Values, 12(3), 2–18.

Collins, G.N. (1914). Pueblo Indian maize breeding. Journal of Heredity, 5, 255–268.

Cordell, L.S. (1997). Prehistory of the Southwest (2nd ed.). New York: Academic Press.

Cushing, F.H. (1920). Zuni breadstuff. New York: Heye Foundation.

Damp, J.E., Hall, S.A., & Smith, S. (2002). Early irrigation on the Colorado Plateau near Zuni Pueblo, New Mexico. American Antiquity, 67, 665–676.

Damp, J.E., & Kendrick, J.W. (2000). In Zuni emergent agriculture: Early irrigation on the Colorado Plateau. Paper presented at the VII Biennial Southwest Symposium, Santa Fe, NM.

Dennell, R.W. (1985). The archaeology of check dam farming in Tauran, Iran. In I.S. Farrington (Ed.), Prehistoric agriculture in the tropics (pp. 699–715). Oxford: British Archaeological Reports.

Dominguez, S., & Kolm, K.E. (2005). Beyond water harvesting: A soil hydrology perspective on traditional Southwestern agricultural technology. American Antiquity, 70, 732–765.

Doolittle, W.E. (2000). Cultivated landscapes of native North America. New York: Oxford University Press.

Evenari, M., Shanan, L., & Tadmor, N. (1982). The Negev: The challenge of a desert (2nd ed.). Cambridge, MA: Harvard University Press.

Ferguson, T.J., & Hart, E.R. (1985). A Zuni atlas. Norman, OK: University of Oklahoma Press.

Forbes, R.H. (1906). Irrigating sediments and their effects on crops. Tucson, AZ: University of Arizona Experiment Station.

Franzblau, E., & Popp, C.J. (1989). Nitrogen oxides produced from lighting. Journal of Geophysical Research, 94, 11089–11104.

Gellis, A., Cheama, A., Laahty, V., & Lalio, S. (1995). Assessment of gully-control structures in the Rio Nutria watershed, Zuni Reservation, New Mexico. Water Resources Bulletin, 31, 633–646.

Gilbertson, D.D., & Hunt, C.O. (1996). Romano-Libyan agriculture: Walls and floodwater farming. In G. Barker (Ed.), Farming the desert: The UNESCO Libyan valleys archaeological survey (pp. 191–225). Paris: UNESCO Publishing, The Department of Antiquities, Society for Libyan Studies.

Hack, J.T. (1942). The changing physical environment of the Hopi Indians of Arizona. Cambridge, MA: Harvard University Press.

Hart, E.R. (Ed.). (1995). Zuni and the Courts: A struggle for sovereign land rights. Lawrence, KS: University of Kansas Press.

Havener, C.I. (1999). The influence of Zuni runoff agriculture on microbial populations in cultivated fields. Unpublished master's thesis, University of Wyoming, Laramie.

Hillel, D.J. (1991). Out of the Earth: Civilization and the life of the soil. Berkeley, CA: University of California Press.

Homburg, J.A. (1994). Soil fertility and prehistoric agriculture in the Tonto Basin. In R. Ciolek-Torrello & J.R. Welch (Eds.), The Roosevelt rural sites study (pp. 253–295). Tucson, AZ: Statistical Research.

Homburg, J.A. (2000). Anthropogenic influences on American Indian agricultural soils of the Southwestern United States. Unpublished doctoral dissertation, Iowa State University, Ames.

Homburg, J.A., & Sandor, J.A. (1997). An agronomic study of two Classic Period agricultural fields in the Horseshoe Basin. In S.M. Whittlesey, R. Ciolek-Torrello, & J.H. Altschul (Eds.), Vanishing River: Landscapes and lives of the lower Verde River, The Lower Verde Archaeological Project (pp. 127–147). Tucson, AZ: SRI Press.

Homburg, J.A., Sandor, J.A., & Lightfoot, D.R. (2004). Soil investigations. In W.E. Doolittle & J.A. Neely (Eds.), The Safford Valley grids: Prehistoric cultivation in the southern Arizona desert. Tucson, AZ: University of Arizona Press.

Homburg, J.A., Sandor, J.A., & Norton, J.B. (2005). Anthropogenic influences on Zuni soils. Geoarchaeology, 20, 661–693.

Hubbell, D.S., & Gardner, J.L. (1950). Effects of diverting sediment-laden runoff from arroyos to range and crop lands. Washington, DC: United States Department of Agriculture and New Mexico Agricultural Experiment Station.

Huber, E.K. (2005). Early maize at the Old Corn Site (LA 137258). In E.K. Huber & C.R.V. West (Eds.), Fence Lake Project: Archaeological Data Recovery in the New Mexico Transportation Corridor and First Five–Year Permit Area, Fence Lake Coal Mine Project, Catron County, New Mexico (Chapter 36, 36.1–36.33). Tucson, AZ: Statistical Research.

Jenny, H. (1962). Model of a rising nitrogen profile in Nile Valley alluvium and its agronomic and pedogenic implications. Soil Science Society of America Proceedings, 26, 588–591.

Kintigh, K.W. (1985). Settlement, subsistence, and society in late Zuni prehistory. Tucson, AZ: University of Arizona Press.

Klemmedson, J.O. (1991). Oak influence on nutrient availability in pine forests of central Arizona. Soil Science Society of America Journal, 55, 248–253.

Klemmedson, J.O., & Weinhold, B.J. (1991). Aspect and species influences on nitrogen and phosphorus availability in Arizona chaparral soils. Soil Science Society of America Journal, 55, 1735–1740.

Knox, J.C. (2001). Agriculture, erosion, sediment yields. In A.R. Orme (Ed.), The physical geography of North America (pp. 482–500). New York: Oxford University Press.

Kohler, T.A. (1992). Prehistoric human impact on the environment in the upland North American Southwest. Population and Environment, 13, 255–268.

Mallarino, A.M., Webb, J.R., & Blackmer, A.M. (1991). Corn and soybean yields during 11 years of phosphorus and potassium fertilization on a high-testing soil. Journal of Production Agriculture, 4, 312–317.

Manolescu, K. (1994). The culture of Zuni land technologies: An appendix for the Zuni Development Plan. Black Rock, NM: Zuni Conservation Project, Pueblo of Zuni.

Maxwell, T.D. (2000). Looking for adaptation: A comparative and engineering analysis of prehistoric agricultural technologies and techniques in the Southwest. Unpublished doctoral dissertation, University of New Mexico, Albuquerque.

Muenchrath, D.A., Kuratomi, M., Sandor, J.A., & Homburg, J.A. (2002). Observational study of maize production systems of Zuni farmers in semiarid New Mexico. Journal of Ethnobiology, 22, 1–33.

Nabhan, G.P. (1984). Soil fertility renewal and water harvesting in Sonoran Desert agriculture. Arid Lands Newsletter, 20, 21–28.

Norton, J.B. (1996). Soil, geomorphic, and ecological factors in Zuni runoff agriculture. Unpublished master's thesis, Iowa State University, Ames.

Norton, J.B. (2000). Agroecology, hydrology, and conservation of ephemeral streams and alluvial fans, Zuni Pueblo, New Mexico. Unpublished doctoral dissertation, University of Montana, Missoula.

Norton, J.B., Jr, F.B., Peynetsa, P., Quandelacy, W., & Siebert, S.F. (2002). Native American methods for conservation and restoration of semiarid ephemeral streams. Journal of Soil and Water Conservation, 57, 250–258.

Norton, J.B., Pawluk, R.R., & Sandor, J.A. (2001). Farmer–scientist collaboration for research and agricultural development on the Zuni Indian Reservation, New Mexico, USA. In W.A. Payne, D.R. Keeney, & S.C. Rao (Eds.), Sustainability of agricultural systems in transition (pp. 107–120). Madison, WI: American Society of Agronomy, Crop Science Society of America, Soil Science Society of America.

Norton, J.B., Sandor, J.A., & White, C.S. (2003). Hillslope soils and organic matter dynamics within a Native American agroecosystem on the Colorado Plateau. Soil Science Society of America Journal, 67, 225–234.

Norton, J.B., Sandor, J.A., & White, C.S. (in press a). Runoff and sediments from hillslope soils within a Native American agroecosystem. Soil Science Society of America Journal.

Norton, J.B., Sandor, J.A., & White, C.S. (in press b). Organic matter transformations through arroyos and alluvial fan soils within a Native American agroecosystem. Soil Science Society of America Journal.

Pawluk, R.R. (1995). Indigenous knowledge of soils and agriculture at Zuni Pueblo, New Mexico. Unpublished master's thesis, Iowa State University, Ames.

Perramond, E.P. (1994). An historical geography of Zuni agriculture. M.A. thesis. Baton Rouge: Louisiana State University.

Redman, C.L. (1999). Human impacts on ancient environments. Tucson, AZ: University of Arizona Press.

Reid, K.D., Wilcox, B.P., Brashears, D.D., & MacDonald, L. (1999). Runoff and erosion in a pinyon-juniper woodland: Influence of vegetation patches. Soil Science Society of America Journal, 63, 1869–1879.

Rhode, D. (1995). Estimating agricultural carrying capacity in the Zuni region, west-central New Mexico: A water allocation model. In H.W. Toll (Ed.), Soil, water, biology, and belief in prehistoric and traditional Southwestern agriculture (pp. 85–100). Denver, CO: New Mexico Archaeological Council.

Sandor, J.A. (1983). Soils at prehistoric agricultural terracing sites in New Mexico. Unpublished doctoral dissertation. Berkeley, CA: University of California.

Sandor, J.A. (1995). Searching soil for clues about Southwest prehistoric agriculture. In H.W. Toll (Ed.), Soil, water, biology, and belief in prehistoric and traditional Southwestern agriculture (pp. 119–137). Denver, CO: New Mexico Archaeological Council.

Sandor, J.A. (2006). Ancient agricultural terraces and soils. In B. Warkentin (Ed.), Footprints in the soil: People and ideas in soil history (pp. 505–534). Amsterdam: Elsevier.

Sandor, J.A., & Eash, N.S. (1991). Significance of ancient agricultural soils for long-term agronomic studies and sustainable agriculture research. Agronomy Journal, 83, 29–37.

Sandor, J.A., & Gersper, P.L. (1988). Evaluation of soil fertility in some prehistoric agricultural terraces in New Mexico. Agronomy Journal, 80, 846–850.

Sandor, J.A., Gersper, P.L., & Hawley, J.W. (1990). Prehistoric agricultural terraces and soils in the Mimbres area, New Mexico. World Archaeology, 22, 70–86.

Sandor, J.A., Norton, J.B., Muenchrath, D.A., White, C.S., Williams, S.E., & Ankeny, M.D. (2000). Ecosystem and soil studies of Native American agriculture. Final report to National Science Foundation (Grant No. 9528458). Ames, IA: Iowa State University.

Sandor, J.A., Norton, J.B., Pawluk, R.R., Homburg, J.A., Muenchrath, D.A., White, C.S., et al. (2002). Soil knowledge embodied in a Native American Runoff Agroecosystem. Transactions of the 17th World Congress of Soil Science, Bangkok, Thailand (CD-ROM).

Sandor, J.A., WinklerPrins, A.M.G.A., Barrera-Bassols, N., & Zinck, J.A. (2006). The heritage of soil knowledge among the world's cultures. In B. Warkentin (Ed.), Footprints in the soil: People and ideas in soil history (pp. 43–84). Amsterdam: Elsevier.

Skujins, J. (Ed.). (1991). Semiarid lands and deserts: Soil resource and reclamation. New York: Marcel Dekker.

Stewart, G.R., & Donnelly, M. (1943). Soil and Water Economy in the Pueblo Southwest I. Field studies at Mesa Verde and northern Arizona II. Evaluation of primitive methods of conservation. Scientific Monthly, 56, 31–44, 134–144.

Sullivan III, A.P. (2000). Effects of small-scale prehistoric runoff agriculture on soil fertility: The developing picture from upland terraces in the American Southwest. Geoarchaeology, 15, 291–313.

Thomas, C.J., & White, C.S. (1999a). The effects of a Zuni agricultural practice on potentially mineralizable nitrogen in western New Mexico. Paper presented at the annual meeting of the American Society of Agronomy.

Thomas, C.J., & White, C.S. (1999b). The effects of sediment addition to field soils on nitrogen mineralization potentials at Zuni, New Mexico. Paper presented at the annual meeting of the American Society of Agronomy.

White, C.S., & Thomas, C.J. (1999c). Nitrogen contributions from precipitation to a corn field at Zuni, New Mexico. Paper presented at the annual meeting of the American Society of Agronomy.

Wilken, G.C. (1987). Good farmers: Traditional agricultural resource management in Mexico and Central America. Berkeley, CA: University of California Press.

Zschetzsche, S.A. (2005). Soil survey of McKinley County Area, New Mexico. Washington, DC: USDA-NRCS.

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