ECOSYSTEMS

Legacies of Prehistoric Agricultural Practices Within Plant and Soil Properties Across an Arid Ecosystem

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ABSTRACT

Closely integrated research between archaeologists and ecologists provides a long-term view of human land use that is rare in the ecological literature, allowing for investigation of activities that lead to enduring environmental outcomes. This extended temporal perspective is particularly important in aridlands where succession occurs slowly and ecosystem processes are mediated by abiotic, geomorphic factors. Numerous studies show that impacts from ancient human actions can persist, but few have explored the types of practices or mechanisms that lead to either transient or long-term environmental change. We compared plant and soil properties and processes from a range of landscape patch types in the Sonoran Desert of the US Southwest that supported different, well-documented prehistoric farming practices from AD 750–1300. Our results show that the types of ancient human activities that leave long-term ecological legacies in aridlands are those that fundamentally alter ''slow variables'' such as soil properties that regulate the timing and supply of water. Prehistoric Hohokam floodwater-irrigation practices, but not dryland farming techniques, substantially altered soil texture, which was strongly associated with desert plant community and functional composition. However, prehistoric agriculture did not consistently alter long-term nutrient availability and thus had no impact on ''fast variables'' such as production of seasonal annual plants that are restricted to periods of ample rainfall. In this arid ecosystem, the inverse texture model explained patterns in plant functional composition at large scales, but is less predictive of production of short-lived desert annuals that experience a more mesic precipitation regime.

Key words: resilience; inverse texture hypothesis; Hohokam; dryland and runoff agriculture; winter desert annuals; anthropogenic landscapes.

INTRODUCTION

A growing number of studies have shown that historic and even prehistoric land use shapes the structure and functioning of ecosystems over decades to millennia (White and Oates 1999; Casperson and others 2000; Tilman and others 2000; Goodale and Aber 2001; Dupouey and others 2002; Dambrine and others 2007; Homburg and Sandor 2011). For example, the 200-year legacy of logging and agriculture followed by reforestation in the northeastern US continues to influence biodiversity, biogeochemical cycling, and ecosystem responses to interacting anthropogenic stressors (Foster and Aber 2004). Historic modification to soils from agricultural practices are evident even after native vegetation has reestablished, in part due to activities such as plowing that homogenized upper soil horizons and reset the pedogenic clock (Burke and others 1989; Davidson and Ackerman 1993; Compton and others 1998; Trimble 1999). Human activities in prehistory also significantly altered the environment, changing land cover, soil fertility, and biodiversity, with ecological consequences that affected human decision-making, demography, and social resilience (Denevan 1992; Redman 1999; Kirch 2005). Although less well-studied, some of these prehistoric activities also left long-lasting ecological legacies. For example, the extensive history of human land management in Europe, including grazing and fire, is thought underlie the unusually high species diversity of grasslands there (Bruun and others 2001; Partel and others 2007). Even tropical rainforests in the Amazon—once thought of as pristine—are now known to be structured in some areas by disturbance from settlements, major earthworks, and agricultural practices hundreds to thousands of years ago (Heckenberger and others 2003; Erickson 2006; McMichael and others 2012).

Although these studies show that outcomes of prehistoric human actions can endure, less is known about the types of actions, technologies, or biophysical factors that lead to either persistent or ephemeral land use signatures. Studies of modern ecosystems show that different types of agricultural practices and management decisions result in significantly different ecological outcomes (Robertson and others 2000; Gregory and others 2005; McLauchlan 2006). Furthermore, the effects of management practices vary among ecosystem types depending on climatic and soil factors that influence ecological dynamics. For example, no-till technology generally leads to lower soil carbon (C) losses compared to conventional tillage practices, and cropping in tropical moist climates results in four times as much C loss as in tropical dry climates (Ogle and others 2005; Batlle-Bayer and others 2010). Recently, James (2011) suggested that the ''geomorphic effectiveness'' of pre-Columbian agriculture in North America—the increase in large-scale sediment transport events such as erosion or deposition—was limited in most areas by the lack of specific technologies required for intensive land modification like those used in the Old World. However, notable exceptions were identified in several extraordinarily dense prehistoric settlements, including those located in arid and semi-arid regions of the US Southwest.

Southwestern landscapes were home to some of the largest prehistoric populations in North America, with tens of thousands of people living and farming from the Colorado Plateau down to northern Mexico from AD 800 to 1500 (Doolittle 1992; Hill and others 2004). Along the rivers in central and southern Arizona were the Hohokam, most widely known for their engineering skills in building hundreds of kilometers of canals for the growth of maize and cotton in ''one of the largest ever traditional irrigation systems in human history'' (Butzer 1990, p. 40). To supplement production from irrigated fields, the Hohokam also cultivated plants in upland regions using dryland, runoff techniques common to other prehistoric Southwestern communities, including construction of rock alignments, terraces, and check dams to slow overland water runoff and capture sediment (Doolittle 1992; Homburg and others 2004). Cultural landscapes such as these are extensive in the US Southwest and elsewhere, yet it is unclear which type of anthropogenic modifications result in ecological patterns that are still visible today, and which create short-term changes that fade and disappear. Few studies have explored the legacies of ancient irrigation farming on modern ecosystem properties, despite their prevalence and importance to the structure of early societies (Kirch 1977; Gelburd 1985; Huckleberry 1992; Davis and others 2000; Nordt and others 2004; Briggs and others 2006). Moreover, existing research on early runoff agricultural fields across a range of different sites in the US Southwest show inconsistently that soils associated with water-control features remain more fertile, more depleted, or no different than soils that were not modified or farmed (Sandor and Eash 1991; Sullivan 2000; Homburg and Sandor 1997; Homburg and Sandor 2011). To more clearly evaluate the long-term effects of different prehistoric agricultural practices on modern ecological properties, comprehensive, within-site comparative

studies are needed across a range of cultural and environmental settings.

The suite of agricultural technologies utilized by the Hohokam was designed to modify geomorphic properties across topographically variable landscapes to minimize risk and maximize water and nutrient delivery to crops (Sandor 1995; Doolittle 2000). This diversity of strategies may have led to spatial variation in slow, soil-forming state factors that continues to drive landscape patterns in modern ecosystem function (Jenny 1941; Holliday 2004; Chapin and others 2006; McLauchlan 2006). Ecological resilience, defined as the tendency of a system to return to its original configuration after a perturbation, can be overcome when stabilizing feedback loops are disrupted through changes in species abundance or disturbance regimes that modify soil resource supply (Holling 1973; Chapin and others 2006). As one of a handful of ecosystem-defining state factors, soil (as parent material) controls the availability of water and nutrients that limit biological processes in most terrestrial ecosystems (Amundson and Jenny 1997; Rao and Allen 2010; Ladwig and others 2012). Thus, changes to soil properties that regulate the timing and supply of these two factors may move an ecosystem to an alternate, persistent stable state by shifting the boundaries that limit fundamental ecological processes and properties like production and community composition.

In drylands, the amount and timing of precipitation regulates primary production across broad spatial and temporal scales, but soil properties such as rock cover, horizonation, and texture combine at smaller scales to influence how much water infiltrates and is held for plant communities or is lost to runoff or evaporation (Hamerlynck and others 2002; McAuliffe and others 2007). According to the inverse-texture hypothesis (Noy-Meir 1973), in arid regions (below ~370 mm annual rainfall; Sala and others 1988), coarse-textured soils support higher primary production than fine-textured soils because sandy soils allow infiltration of water to lower soil horizons where evaporative demand is low. For example, many prehistoric agriculturalists in the US Southwest that practiced upland runoff farming preferred to plant crops where clayey subsurface horizons lay beneath sandy surface horizons so that water from high-intensity summer rain events percolated deep enough to avoid evaporation yet was retained by deeper clay layers (Sandor and others 2007). In contrast, in ecosystems with abundant water supply (for example, >370 mm annual rainfall), coarse-textured soils should support lower rates of primary production than fine-textured soils because water drains quickly in sands, whereas matrices of silt and clay particles retain water near the surface where roots are concentrated (Noy-Meir 1973; Epstein and others 1997; Lane and others 1998; Fernandez-Illescas and others 2001; Caylor and others 2009; Yang and others 2009).

Hohokam irrigation strategies deposited fine-textured particles over originally sandy floodplains (Huckleberry 1992; Redman 1999; Schaafsma and Briggs 2007), and fine, silt-sized particles and organic matter can co-accumulate behind water retention structures used by runoff farmers in upland areas (Homburg and Sandor 2011). During the time when Hohokam people were farming around the northern Phoenix basin, flows along small rivers were likely more consistent (semi-permanent to intermittent), although the overall climate of the Sonoran Desert has been relatively stable over the last several thousand years (McAuliffe and Devender 1998; Phillips 1998; Huckleberry 2011). According to the inverse texture hypothesis, under more mesic conditions when floodwater events were more common and runoff was carefully managed, deposition of fine-textured sediments from Hohokam agricultural strategies may have been beneficial for crop growth. In addition to holding water in the rooting zone, fine-textured soils are often more fertile than coarse-textured soils in natural systems, supporting higher rates of N cycling, and larger pools of organic and available nutrients (Austin and others 2004). Nitrogen (N) and phosphorus (P) are thought to be secondarily limiting to primary producers in arid and semi-arid ecosystems, but nutrient supply likely regulates production when water is abundant, like during wet years, seasons, or days following rainfall (Hooper and Johnson 1999; Hall and others 2011). Under today's climate and flood regimes, however, the fine-textured soils that remain in former agricultural fields may now limit water infiltration due to high rates of evapotranspiration, and low water potentials that result may pose a serious challenge for growth of modern-day plant communities. In other words, the inverse texture hypothesis suggests that geomorphic modifications created by Hohokam irrigation farmers to promote crop success when water was more abundant (Graybill 1989; Larson and others 1996), may have fundamentally altered soil properties in this arid ecosystem that now regulate long-term ecological patterns.

Here, we compare the ecological legacies of different, well-documented prehistoric farming practices in the southwestern US that supported active

agricultural communities from AD 750 to 1300. The location of our research is within and surrounding Hohokam agricultural fields in the arid Sonoran Desert of the northern Phoenix basin, AZ. We compared plant and soil properties and processes over multiple years across two cropping strategies associated with four, common landscape patch types: prehistoric fields that were used intensively for floodwater-irrigated agriculture; areas behind rock alignments likely used for supplementary upland runoff cultivation, and less intensively used areas that surround both of these agricultural features (non-irrigated areas and between rock alignments) (see photos in Appendix A1 and A2). This unique design, accessible only through the archaeological record, provides us with an understanding of the relative importance of diverse human actions as drivers of long-term ecological patterns. We predicted that farmed soils within formerly floodwater-irrigated fields and behind alignments would be composed of finer-textured particles that support higher rates of nutrient cycling compared to soils that were not farmed. Furthermore, we expected this legacy would be strongest in the intensively cultivated floodwater-irrigated fields. However, following from the inverse texture hypothesis in this arid ecosystem, we expected that finer-textured soils associated with prehistoric agriculture would ultimately support lower primary productivity and different plant communities than non-farmed soils.

METHODS

### Site Description, Archaeological History, and Experimental Design

Site Description

The Cave Creek archaeological complex lies in the northern Sonoran Desert on state trust land, at the transition between the Phoenix Basin and the mountainous uplands of central Arizona (Figure 1). The study area is at approximately 560 m in elevation on relatively flat terrain (0°–1°), and is adjacent to Cave Creek, a S-SW flowing intermittent stream. The geology of the region is composed mostly of Quaternary alluvium from nearby mountain ranges of diverse lithologies, including metamorphosed volcanic and metasedimentary rocks (Leighty and Holloway 1998). Soils on the western side of the creek are Holocene-aged surfaces that have been influenced by flooding. The Hohokam flood-irrigated fields are slightly elevated due to ''soil building'' (that is, deposition) and are outside of the active floodplain, as canals were re-

quired to deliver sediment to the agricultural fields (Schaafsma and Briggs 2007; Huckleberry 2011; see photos in Appendix A). Although the channel of Cave Creek is around 3 m below the western bank, the soils between floodwater-irrigated fields may have experienced flooding during large storm events since the site was abandoned (although there was no evidence of overbank flooding during our study period). Soils from the floodwater-irrigated fields and between-field locations on the western side of Cave Creek are structurally quite different from one another, but they are grouped together by the NRCS as sandy loams within the Antho-Carrizo-Maripo complex (coarse-loamy, mixed, superactive, calcareous, hyperthermic Typic Torrifluvents; NRCS 2013). Soils on the east side of the creek are older, Pleistocene-aged surfaces that are part of the Carefree series (fine, mixed, superactive, hyperthermic Vertic Haplargids; NRCS 2013). These soils are also outside of the active floodplain (current, and during Hohokam occupation). Descriptions of soil profiles for these locations are given in Appendix B.

Precipitation in the northern Sonoran Desert is bimodal, with the majority of rainfall occurring during lower-intensity, longer-duration storms in winter and high-intensity, short-duration summer monsoons. Rainfall at the study site averages 211 mm per year (for 1993–2012; FCDMC 2012a), with a mean annual temperature of 22°C (for 2006–2011; FCDMC 2012b). Abundant pollen from cottonwood (*Populus* sp.), willow (*Salix* sp.), cattail (*Typha* sp.), and sedge (Cyperacea) have been found near the study site and other local catchments—even at distances away from the current channel (Phillips 1998). Along with geomorphic evidence, these patterns indicate that flows in small rivers were likely more consistent during the time of Hohokam occupation than today (Phillips 1998). Currently, perennial vegetation is typical of lower elevations in the Sonoran Desert, consisting of palo verde (*Parkinsonia microphylla* Torr.), ironwood (*Olneya tesota* A. Gray), creosote bush [*Larrea tridentata* (DC.) Coville], bursage [*Ambrosia deltoidea* (Torr.) Payne], saguaro [*Carnegiea gigantea* (Engelm.) Britton & Rose], and a variety of smaller cacti and shrubs. Diverse annual herbaceous plant communities occur in this region after sufficient winter-spring rainfall, composing up to 50% of estimated annual net primary production during wet seasons (Shen and others 2005). Modern land use includes cattle grazing, hunting, and other recreational activities. Grazing within the Cave Creek region during the time of sampling was minimal, at 35 cattle across 4,654 ha per year
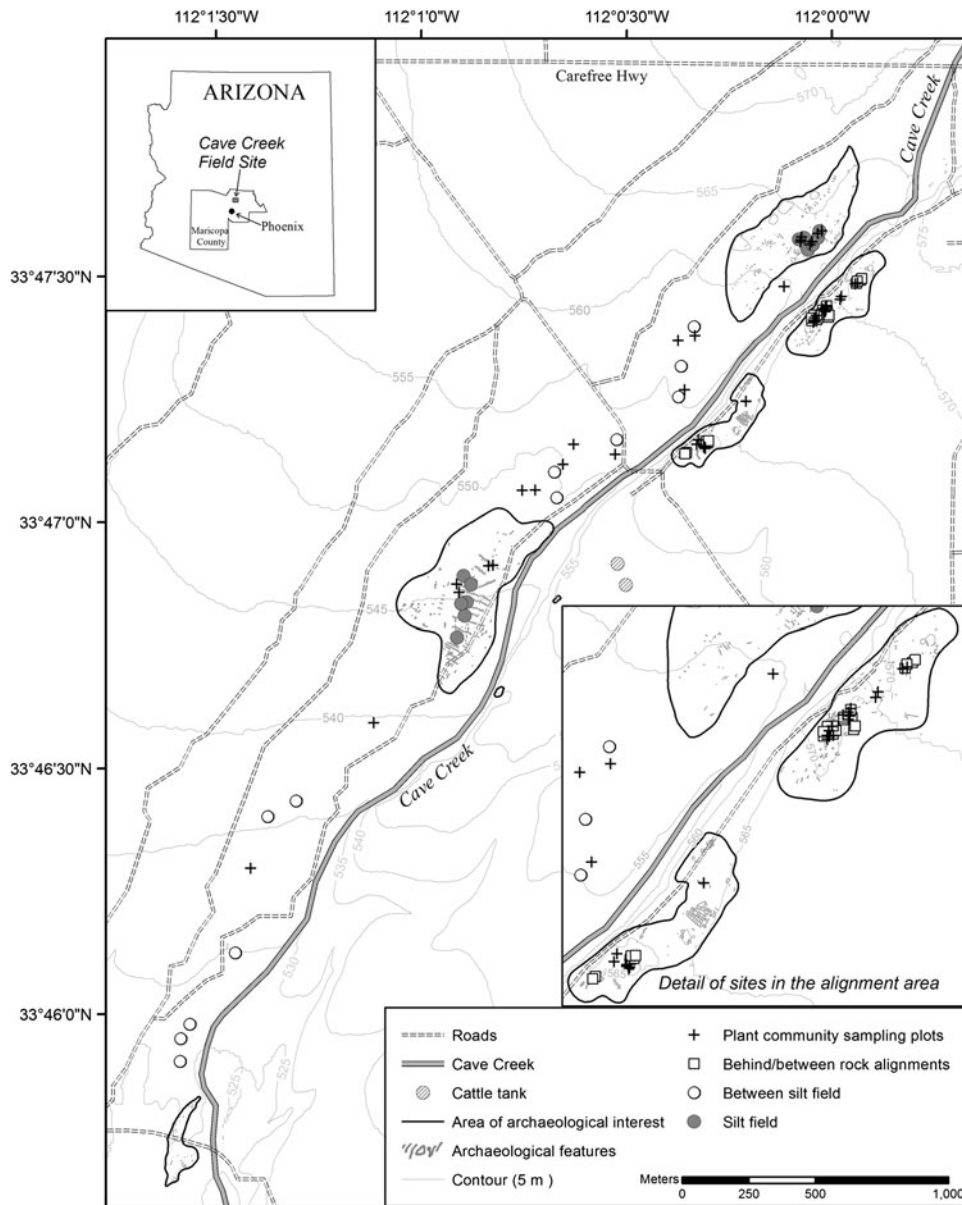
Figure 1. The Cave Creek archaeological complex in central Arizona. Our experimental design captured four distinct landscape patches that represent two types of Hohokam agricultural strategies and two areas located between these areas that have received less direct human impact. These landscape patches include: Rock alignments that were likely used as water-retention features for runoff cropping (''Behind alignments''); floodwater-irrigated agricultural fields ('Silt fields); areas less intensively used between anthropogenic rock alignments (''Between alignments''); and areas of native desert between floodwater-irrigated fields that contain no evidence of irrigation farming (''Between silt fields'').

(W. Sommers, AZ State Land Dept., personal communication).

Archaeological History

The Hohokam people lived in large villages throughout central and southern Arizona between AD 0–1450, reaching their largest extent during the Sedentary Period, AD 950–1150 (Hill and others 2004). Most of the Hohokam population was concentrated in large irrigation communities along the Salt and Gila Rivers in the Phoenix Basin, but smaller villages and floodwater irrigation systems were also located along ephemeral watercourses in regions north of the basin called the ''Northern Periphery'', including Cave Creek (Hackbarth and others 2002). Occupation of the Northern Periphery began as early as 350 AD but was limited to small villages of a few families until the Sedentary Period, when several larger villages and extensive field systems were established (Hackbarth and others 2002). No large village sites, and only a few small rancherías, persisted in this region after AD 1150, and it was largely unoccupied by around AD 1275 (Rodgers 1977; Henderson and Rodgers 1979; Wenker 2002; Schaafsma and Briggs 2007; Huckleberry 2011).

On the western, Holocene-aged side of Cave Creek, the Hohokam farmers practiced floodwater agriculture, creating several large, fields through deposition of silt-sized particles delivered to the

fields by earthen canals (Bryan 1929; Phillips 1998; Schaafsma and Briggs 2007; Appendix A1). These ''silt fields'' are composed of soils with a relatively uniform silty texture from the surface to around 80–90 cm, below which are sandy sediments (Appendix B). Silt fields are located parallel to the stream bed, are roughly 1–18 ha in size, and are separated from one another by areas of desert that were not irrigated. Pollen and macrobotanical evidence from the irrigated fields and nearby habitation sites show that Hohokam agriculturalists cultivated cotton, corn, beans, squash, tobacco, and numerous herbaceous plants (Phillips 1998; Schaafsma and Briggs 2007). Recent geoarchaeological evidence from ceramics and charcoal ^{14}C dates the deposition of these fields to AD 750–1150, with abandonment occurring about AD 1200 (Phillips 1998; Huckleberry 2011). Prehistoric ceramics from small village and ranchería sites located within 1,500 m upstream of the Cave Creek sites are also consistent with these dates (Clark and others 1999; Wenker 2002). Archaeological evidence indicates that no additional farming occurred on this location since abandonment around 700–800 years ago. Although not used in this study, nearby the silt fields on the western side of the creek are dryland agricultural features known as ''grid gardens'', which were presumably used to concentrate rainfall for crops (see photo in Appendix A3; Doolittle 2004).

In an earlier study at this site, Briggs and others 2006 described significant differences in soil texture and plant community structure between areas within the flood-irrigated silt fields and the non-farmed areas surrounding fields, including a loss of woody plant diversity and biomass. Only one woody plant species grows in floodwater-irrigated silt fields, creosote bush (*Larrea tridentata*), and these individuals are less abundant and smaller than in the surrounding areas in between silt fields that support about 7 species of shrubs and cacti.

On the eastern side of Cave Creek at a slightly higher elevation (by ~10 m) where river water could not be transported for irrigation, the Hohokam practiced upland runoff farming using rock alignments to concentrate runoff water and sediment (Phillips 1998, 2002; Schaafsma and Briggs 2007). Numerous prehistoric artifacts have been identified in this area, alongside more than one hundred discontinuous rock alignments that usually consist of ''a single linear arrangement of rocks, of various sizes, that are one to several courses in width and generally only one course in height'' (Rankin 1989, p. 956). Pollen analyses revealed

similar botanical assemblages in soil collected behind alignments and between alignments, and there was no evidence of pollen from cultigens such as maize (Smith 2009; but see Appendix C). It is likely that these alignments were used less intensively than fields used for floodwater farming, for either staple crops or potentially to ''encourage'' native plants such as cholla (*Cylindropuntia* spp.), agave (*Agave* spp.), and a variety of native desert annuals—a number of which were domesticated (for example, *Plantago* spp.)—that were used for food or other economic purposes (Bohrer and others 1969; Miksicek 1983; Fish 1984; Bohrer 1991; Doolittle 2000; Appendix D).

Experimental Design

We investigated whether prehistoric agricultural practices differed in the strength of the ecological legacy left behind by comparing soils and plant properties and processes within the Cave Creek archaeological complex across two types of agricultural strategies. These different strategies were associated with four types of landscape patch types that are also common to other prehistorically cultivated regions in drylands, including (1) patches in between anthropogenic rock alignments (''between alignments''), (2) patches directly upslope from rock alignments that were likely used as water-retention features for runoff agriculture (''behind alignments''), (3) areas of native desert between flooded fields that contain no evidence of farming (''between silt fields''), and (4) formerly floodwater-irrigated agricultural fields (''silt fields''; see photos in Appendix A). For soils, 12 replicate plots of each landscape patch type were identified randomly across the Cave Creek archaeological complex in areas that were located more than 20 m from a road. For vegetation communities, 11 plots were selected with the same criteria. Plots on the west side of the creek were split across the two largest silt fields and ''between silt field'' areas within the complex and then chosen at random. Rock alignment plots were chosen by archaeologists from a larger group of constructed agricultural features identified on the east side of Cave Creek using visual identification in the field (alignments that were likely anthropogenic; Figure 1; Phillips 1998). The ''between alignment'' areas were not bounded by a linear arrangement of rocks and were located 5 m to the east of chosen alignment plots (or to the west if leguminous trees were encountered). All plots were located more than 1 m from the drip line of a shrub and more than 5 m from leguminous trees.

Sampling and Analysis of Soil and Vegetation

Soil Sampling and Analyses

Surface soils (0–5 cm depth) were sampled from all sites four times, during spring after winter rains (March–April 2008), during the pre-monsoon period of summer (June 2008), during the dry period after the monsoon rains in fall (October 2008), and an additional time in spring 2010. Relatively shallow depths were sampled for biogeochemical variables because microbial activity in arid ecosystems attenuates quickly below the first several mm of soil, and resources in surface soils are important for low-stature, winter annual plant communities that grow in the Sonoran Desert (Schenk and Jackson 2002; Belnap and others 2003). During each sampling event, two surface soil cores were taken from each plot and pooled. In the ''behind alignment'' plots, soil cores were taken 10 cm upslope from the upper edge of rock alignment. For areas without alignments, sites for soil sampling were chosen randomly, at least 1 m away from one another. Nails were placed in holes after sample collection to prevent sampling in the same place the next season. Soils were transported on ice to ASU for overnight storage and were sieved to 2 mm within 24 h. In addition to soil cores, we measured surface and alignment rock cover across all feature types using a 1 m^2 quadrat (centered in the middle of the plot or the alignment) and assigned to one of 6 percentage classes: less than 1, 1–10, 10–25, 25–50, 50–75, and 75–100%. Rocks were also categorized into four size classes: gravel (<7.6 cm diameter), cobbles (7.6–25 cm), stones (25–60 cm), and boulders (>60 cm) (Schoeneberger 2002).

Sieved soils were analyzed for a suite of physical and biogeochemical properties using standard methods described in Hall and others, (2011) and further detailed in Appendix C, including soil particle size (hydrometer following removal of carbonate); soil moisture (gravimetric); water-holding capacity (WHC; 24 h drain time), soil organic matter (mass loss following combustion); pH and electrical conductivity (saturated paste); extractable ammonium and nitrate (NH_4^+–N, NO_2^- + NO_3^-–N; 2 M KCl extraction); extractable phosphate (PO_4^3–P; 0.5 M $NaHCO_3$ extraction); potential rates of net N mineralization and nitrification (incubation at 60% WHC for 10 days); effective cation exchange capacity (ECEC; 1 M ammonium acetate); and bulk density (subtracting volume and weight of coarse fragments). A subset of soil samples (four of the 15 replicates each of silt fields, between silt fields, and behind alignment locations) was analyzed for total C and N (%).

Vegetation Sampling and Analyses

Annual herbaceous aboveground plant biomass was measured during the springs of 2008, 2009, and 2010 (March–April) within two 50 cm × 20 cm (100 cm^2) subplots per replicate of each landscape patch type. Subplot biomass was pooled within each replicate plot. Sub-plots were located ~10–20 cm upslope from (behind) rock alignments, at least 50 cm away from soil cores. Herbaceous vegetation was clipped at ground level, transported to ASU, and dried at 60°C for 48 h before being weighed. Nails were driven into the soil at each of the quadrat corners after the harvest. Subplots the following season were located at least 10 cm away from formerly clipped plots. To evaluate the effects of soil fertility of different landscape patch types on plant chemistry, we analyzed tissue C, N, and P content from green stems and leaves of 5–6 individuals of the common annual forb, *Plantago ovata* Forssk (Appendix C).

In March of 2008, we randomly chose additional plots in spaces between plant canopies in each landscape patch type to estimate herbaceous plant species composition and cover. On the western side of the creek, we selected 11 plots per patch type that were located more than 20 m from roads. In the two landscape patch types on the eastern side of Cave Creek where the availability of constructed alignments limited our choices, some of these additional community composition plots were located behind the same alignment used for soil and biomass sampling. In these cases, we estimated plant cover more than 1 m away from where soils and biomass were collected. At peak biomass, we estimated percent cover of all herbaceous species within each plot using a 0.5 × 0.5 m^2 quadrat with a wire crossing at 0.25 m on each side. Quadrats were oriented so the front edge was parallel to the alignment (in alignment plots) or along cardinal directions (plots without alignments). Percent cover for each species was estimated using a modified Daubenmire cover scale with six categories, including less than 1% (coded as = 0.5%); 1–10% (5%); 10–25% (17.5%); 25–50% (37.5%); 50–75% (67.5%), and 75–100% (87.5%).

Data Analysis

Statistical tests were conducted using SPSS 20.0 for Mac (SPSS 2011). All data with non-normal distributions were transformed before parametric

analyses to satisfy linear model assumptions. Normality was determined by viewing histograms and calculating if skew and kurtosis z-scores (z = skew/SE_{skew}) were within the range of ± 2 (95% confidence interval; Field and Miles 2010). For analysis of seasonal ecological properties (inorganic N and P pools, potential net N mineralization and nitrification, soil moisture, and herbaceous plant biomass), one-way multivariate analysis of variance (MANOVA) tests were performed with all relevant seasons as the dependent variables and landscape patch type as the independent variable, and using Pillai's trace statistic to assess multivariate significance. The homogeneity of variance assumption for each dependent variable was assessed using Levene's test; if data were heteroscedastic even after transformation, we compared means using a univariate Welch's F test with post-hoc Games–Howell test. Alpha values for the post-hoc univariate tests on each dependent variable were Bonferroni corrected from 0.05 by the number of variables examined (for example, for seasonal soil properties, α = 0.05/4 seasons = 0.0125). To assess the effect of landscape patch type on combined soil properties, factor analysis (PCA) was applied to the correlation matrix of soil physical variables as well as those associated closely with biotic processes (total extractable inorganic N and P pools, and potential rates of net N mineralization assessed during Spring 2008; see variables in Table 2; Appendix E). Backward stepwise multiple regression analysis was conducted to determine the relationship between soil texture and ecological variables. Dependent variables were potential net N mineralization, herbaceous biomass, and total inorganic N and extractable P pools. Independent variables in the regression (% sand, % clay) were checked for collinearity by running a full model and eliminating variables (a) if they had a tolerance below 0.2 and (b) if two variables had a variance proportion of 0.50 or higher with a condition index greater than 30 (Weiner and others 2003).

Species diversity metrics were calculated on untransformed data. Individual-based species accumulation curves (Gotelli and Colwell 2001) were plotted by feature type in EstimateS 8.2.0 for Mac (Colwell 2011) using percent cover as a proxy for number of individuals. Richness was estimated based on the ICE and Chao 2 estimators after 50 randomization runs without replacement (Colwell 2011). Similarities or differences in richness between feature types were estimated based on overlap of 95% confidence intervals on the species accumulation curves (Barlow and others 2007). Species density (# species per quadrat), Shannon–Weiner

diversity (H'), and Shannon–Weiner evenness were calculated using PC-ORD 6 (McCune and Mefford 2011). We also explored differences in community composition among feature types using non-metric multidimensional scaling (NMDS) ordination in PC-ORD using the Sorensen (Bray-Curtis) distance metric on square-root transformed cover data with rare species removed (< 5% in all sample plots; see Appendix C). To test whether plant community composition between feature types was significantly different from one another, and which species were most responsible for dissimilarity between feature types, we performed a one-way, non-parametric analysis of similarity test (ANOSIM; Clarke 1993) followed by a similarity percentage analysis (SIMPER) in PAST 1.94b (Hammer and others 2001; Appendix C).

RESULTS

Within the arid ecosystems alongside Cave Creek, AZ, prehistoric farmers left ecological legacies that continue 700 years after site abandonment. However, the strength of the legacy depends both on the type of agricultural practice used, the ecological variable considered, and continuing, post-depositional surficial processes. As expected, prehistoric floodwater irrigation practices produced silty soils from formerly sandy substrates that supported a plant community similar in composition to fine-textured surface soils in the dryland farmed area. However, the change in texture associated with floodwater farming was not as tightly associated with nutrient availability: silt field soils were often less fertile than soils of similar texture located in other patch types near Cave Creek. In contrast, plant and surface soil properties behind rock alignments that were used passively—and perhaps ephemerally—for runoff control were not significantly different from nearby patches that were not bound by alignments. Contrary to that expected based on the inverse texture hypothesis, growth of spring herbaceous plants was positively related to clay content, but the link between texture and production was the highest when less-fertile flood-irrigated silt fields were excluded from the analysis. Aboveground herbaceous plant production was highest on fine-textured soils during the dry spring of 2009, but was more closely related to nutrient availability—not agricultural practice—in the wet spring of 2010.

Soil Properties

Soils within the agricultural landscapes of the Cave Creek archaeological complex varied significantly

by patch type, especially those properties related to water retention and fertility. Non-agricultural soils located between silt fields were sandy, had low capacity to hold water or cations (lower water-holding capacity, electrical conductivity, and effective CEC relative to other patch types), contained small pools of organic matter, and supported the lowest potential rates of N cycling of the four feature types (Figures 2, 3; Tables 1, 2, Appendix E). As expected, surface soils became finer-textured silt loams with floodwater irrigation (''silt fields''), supporting less surface gravel, higher organic matter and carbon concentrations, and higher cation exchange capacity, electrical conductivity, and water-holding capacity than their non-farmed predecessors (''between silt fields''). Clay content and water retention of floodwater-irrigated soils that were located on the Holocene-aged bank near the stream closely resembled much older, Pleistocene-aged loam soils on the eastern, upper bank above Cave Creek where dryland alignments were located (Table 1). However, despite dramatic changes in soil texture, flood-irrigated silt field soils were not consistently more fertile than non-farmed (between silt field) soils as expected (Figure 2; Table 2). Soils in silt fields were relatively alkaline and had higher concentrations of inorganic N than between-silt field locations during both spring 2008 and spring 2010, but they supported relatively low phosphate content and rates of potential net N
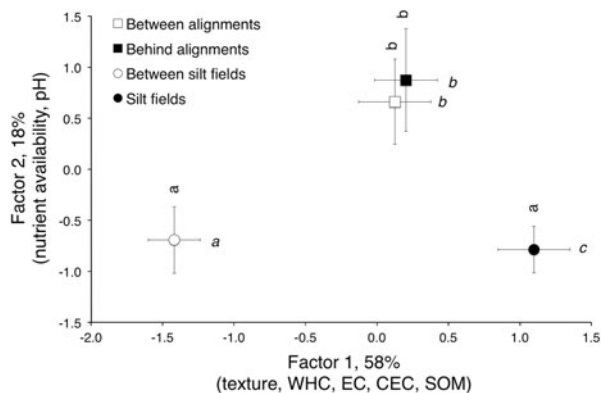
Figure 2. Principal components analysis of soil properties from spring 2008 across the four landscape patch types used in this study. *Error bars* are ±95% confidence intervals. Factor 1 represents most of the variance in the independent variables, composed of properties related to soil texture (''slow variables''). Factor 2 represents properties related to soil fertility (''fast variables''). Lowercase letters represent significant differences between patch types across Factor 1 (italic, horizontal), and Factor 2 (non-italic, vertical), α = 0.025. Factor loadings and results from MANOVA shown in Table 2.

transformations that were statistically similar in magnitude to the coarse-textured areas between fields (Figure 3; Appendix E).

Unlike the outcomes from long-term floodwater irrigation, dryland farming did not leave any measurable, enduring legacies in plant or surface soil properties or processes: surface soil texture between and behind rock alignments on the older, upper bank above Cave Creek was classified as loam with statistically similar ecological properties and processes (Tables 1, 2; Figures 2, 3; Appendix E). Surface soil properties behind alignments were not statistically different even from more distant soils on the same geologic substrate (also on the east side of the creek) located approximately 1 km to the south of our study site (Trujillo 2011). The density of rock cover in the alignments ranged from 36 to 62% and was not significantly associated with soil texture, pH, water-holding capacity, or organic matter content of soils behind them. N cycling rates on the upper, eastern bank of Cave Creek were the highest among all the feature types: rates of potential N mineralization and nitrification were on average twice the magnitude of rates on the younger, lower bank where floodwater irrigation farming was practiced (Figure 3, Appendix E).

Herbaceous Aboveground Primary Production and Plant Tissue Nutrients

Over the 2 years of this study, annual herbaceous aboveground production was strongly related to the amount of winter-spring precipitation received at the site, but was not related to prehistoric farming practice. The winters of 2008, 2009, and 2010 were moderate (167 mm), dry (100 mm), and wet (203 mm), respectively (Figure 4). Correspondingly, average growth of spring annual plant species across the Cave Creek archaeological complex was the highest in the wet spring of 2010 (112 g biomass m^{-2}) and lowest in the dry spring of 2009 (53 g m^{-2}; Figure 4).

Herbaceous plant growth was associated with landscape patch type (MANOVA, $p < 0.001$), although univariate tests confirmed this effect was significant only in spring 2009 when differences were small ($p = 0.01$; partial $\eta^2 = 0.23$), and spring 2010 when differences were large ($p < 0.001$; partial $\eta^2 = 0.40$; Figure 4, Appendix E). In the wet spring of 2010, biomass was on average 80% higher within the more fertile, geologically-older alignment area on the eastern, upper banks of the creek relative to the lower, streamside soils on the west side of the creek, regardless of texture or agricultural history (Figure 4). In general, across
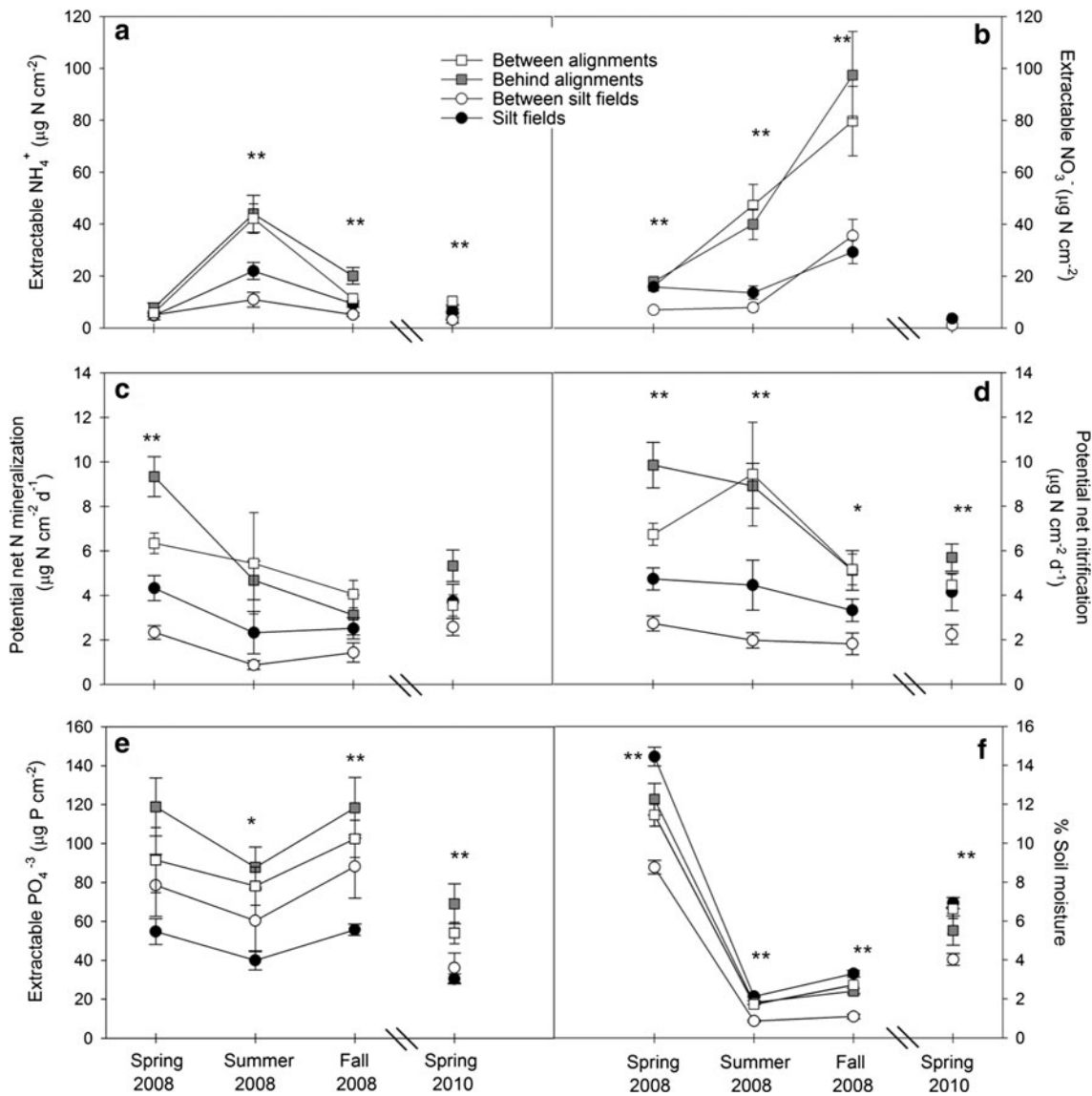
Figure 3. Seasonal variation in soil properties and processes across landscape patch types. *Error bars* are ±1 standard error. Statistics are from MANOVA tests; *$p \leq 0.01$, **$p \leq 0.001$. See descriptive statistics and multiple comparisons results in Appendix E.

the wide range of precipitation levels received from 2008 to 2010, prehistoric agricultural practices did not leave long-lasting signatures in spring herbaceous plant growth. Aboveground production did not differ between and behind rock alignments, nor between the coarse-textured "between silt field" soils and the fine-textured soils within silt fields.

Although agricultural history did not have any measurable effect on herbaceous plant production, plant tissue chemistry (assessed in spring 2008), was significantly affected by floodwater irrigation practices (Table 1). Tissue P of the annual forb, *Plantago ovata*, was the highest in the sandy soil in

between silt fields and declined by 50% with changes in texture associated with irrigation. Similarly, foliar N:P ratios in the sandy soil between silt fields were lowest of all the feature types and increased with floodwater irrigation. In contrast, similar to patterns in other ecological variables studied, dryland runoff farming had no long-term effect on plant tissue nutrients. Soils in the alignment area had the highest N:P and C:P ratios of all the feature types (Table 1), but plant tissue chemistry did not differ in soils located between or behind rock alignments used for runoff farming. Landscape patch type was not associated with *Plantago ovata* tissue N content nor C:N ratio.

Table 1. Physical Properties of Surface Soils and Plant Tissue Nutrients Across the Cave Creek Archaeological Complex

| | Landscape feature type | | | | | | | | | | | | Feature comparison[3] | |
| | Between alignments | | | Behind alignments | | | Between silt fields | | | Silt fields | | | | |
Variable	Mean	SE	Sig.[1]	Mean	SE	Sig.	Mean	SE	Sig.	Mean	SE	Sig.	Statistic	p
Physical soil properties														
pH	7.6	0.2	a	8.0	0.1	ac	8.6	0.1	b	8.6	0.0	bc	23.3	<0.001
WHC (%)	51.5	1.6	a	49.9	1.5	a	32.0	1.0	b	52.9	1.4	a	35.4	<0.001
SOM (%)	3.1	0.1	ac	3.0	0.1	a	2.0	0.1	b	3.4	0.1	c	42.8	<0.001
Total soil C (%)[2]	No sample			0.8	0.2	a	0.4	0.1	b	0.7	0.03	a	7.9	0.01
Total soil N (%)	No sample			0.09	0.01	a	0.04	0.003	b	0.06	0.01	c	20.3	<0.001
Soil C:N	No sample			8.7	0.9	a	9.1	1.2	a	11.6	1.2	a	1.97	0.20
EC (μmhos/cm)	558	31	a	613	35	a	260	15	b	608	46	a	32.5	<0.001
ECEC (cmol/kg)	16.0	0.7	a	15.8	0.7	a	8.3	0.3	b	19.9	0.4	c	81.4	<0.001
Particle size	Loam			Loam			Sandy loam			Silt loam				
Sand (%)	42.9	1.5	a	37.8	1.1	a	70.3	3.0	b	28.5	1.5	c	79.4	<0.001
Silt (%)	38.2	1.4	a	43.3	1.3	a	19.7	2.9	b	54.9	1.3	c	72.1	<0.001
Clay (%)	19.0	1.4	a	18.9	1.0	a	10.0	0.6	b	16.7	0.7	a	18.5	<0.001
Plant nutrients														
Tissue N (%)	2.3	0.1	a	2.2	0.1	a	2.0	0.2	a	2.3	0.2	a	2.8	0.42
Tissue P (%)	0.1	0.0	a	0.1	0.0	a	0.2	0.0	b	0.1	0.0	a	15.3	<0.001
C:N	18.2	0.8	a	18.4	0.5	a	22.7	2.1	a	18.9	1.5	a	4.74	0.19
N:P	22.2	1.2	ac	23.1	1.4	a	12.3	1.4	b	18.1	1.0	c	14.9	<0.001
C:P	402.4	25.1	ac	426.3	29.2	a	257.4	16.2	b	330.2	15.1	bc	11.3	<0.001
Surface rock cover														
Gravel (%)	14.9	1.4	a	10.0	1.1	a	6.1	1.6	b	1.8	0.3	c	37.2	<0.001
Cobbles (%)	20.9	4.1	a	7.2	1.7	a	0.2	0.2	b	0.2	0.2	b	30.3	<0.001
Stones (%)	5.4	2.7	a	1.3	1.3	ab	0.0	0.0	b	0.0	0.0	b	12	0.007
Bare ground (%)	58.8	5.3	a	81.6	2.6	ab	93.7	1.6	bc	98.1	0.3	c	37.3	<0.001

pH, WHC, SOM, total soil C and N, and particle size determined from cores collected in February 2008. Electrical conductivity and effective CEC determined from cores collected in September 2008.
WHC = Water-holding capacity (% gravimetric moisture); SOM = soil organic matter, EC = electrical conductivity, ECEC = effective cation exchange capacity, N = 12 Plots per Landscape Patch Type.
[1]Different lowercase letters represent statistically significant differences between landscape patch types.
[2]Total C and N analyses performed on a subset of four plots per landscape patch type.
[3]Comparison of soil properties by landscape feature type performed with one-way ANOVA (statistic = F) with post-hoc Tukey tests except pH, % foliar N, foliar C:N, cobbles, stones, and bare ground which were analyzed using the non-parametric Kruskal–Wallis independent sample test (statistic = K) with post hoc multiple comparisons tests.

Relationships Between Soil Texture and Ecological Properties and Processes

Contrary to our predictions based on the inverse texture hypothesis in this arid ecosystem, clay content was significantly and positively associated with herbaceous plant growth, moderately in 2008 and 2009, and more strongly in the wet spring of 2010 (Table 3). When less-fertile silt fields were removed from the analyses, annual biomass was strongly and negatively related to sand content during 2010 when differences between landscape patch types were strongest (Table 3; Figure 5A).

Across all landscape patch types, including both agricultural and non-modified areas, soil texture was related to nutrient pools and cycling only for some variables and during some seasons (Table 3). In these cases, clay content was positively associated (or sand content negatively associated) with total inorganic N pools and potential net N mineralization as expected. However—as with aboveground herbaceous plant growth—the strength of the association between soil texture and nutrient availability was highest in soils that were not floodwater irrigated (Table 3; Figure 5B).

Spring Herbaceous Plant Species Diversity and Community Composition

Prehistoric agricultural practices in the Cave Creek archaeological complex did not alter plant species diversity of winter/spring annuals, but floodwater

Table 2. Principal Components Analysis of Soil Properties from Spring 2008, C ollected Across Patch Types Within the Cave Creek Archaeological Complex

Variable	Rotated factor loadings		Extraction communality	Transformation used
	Factor 1	Factor 2		
Sand (%)	**−0.96**	−0.03	0.92	$Log_{10}(x)$
Silt (%)	**0.91**	−0.01	0.83	x
Clay (%)	**0.63**	0.55	0.69	x
WHC (g g^{-1})	**0.84**	0.36	0.83	x^2
Effective CEC (cmol charge kg^{-1})	**0.96**	0.03	0.92	x
Electrical conductivity (μmhos cm^{-1})	**0.82**	0.30	0.77	x
SOM (%)	**0.91**	0.19	0.87	x
Potential net N min (μg N cm^{-2} d^{-1})	0.34	**0.82**	0.79	$\sqrt{(x)}$
Extractable inorganic N (μg N cm^{-2})	0.43	**0.65**	0.60	$Log_{10}(x)$
pH	−0.10	**−0.77**	0.61	x^3
Extractable PO$_4^{-3}$ (μg P cm^{-2})	−0.27	**0.67**	0.52	$\sqrt{(x)}$
Eigenvalue	6.3	2.0		
Fraction of variance explained (%)	57.5	18.4		
MANOVA, p value	<0.001	<0.001		

Bold values indicate statistically significant
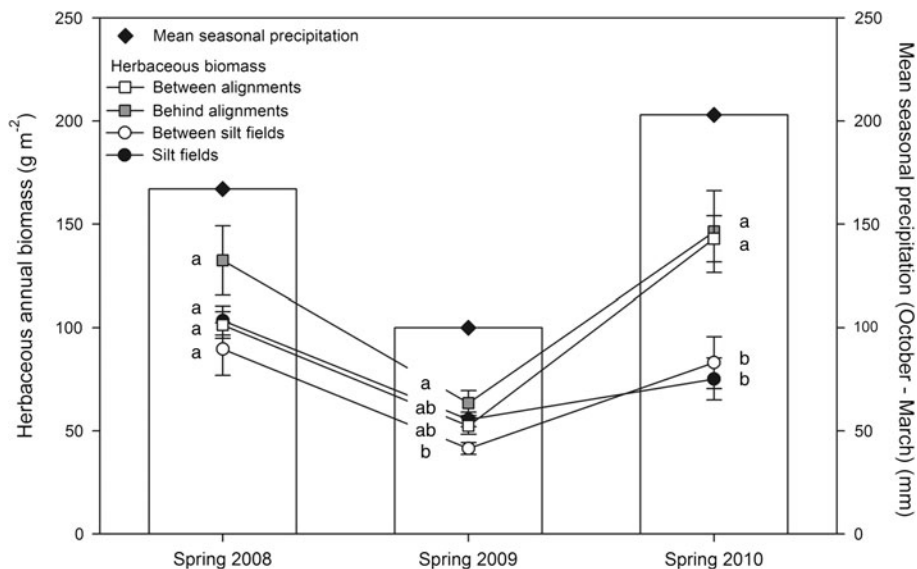
Figure 4. Seasonal variation in aboveground biomass of herbaceous annuals (g m^{-2}) across landscape patch types. *Error bars* are ±1 standard error. *Lowercase letters* represent significant differences between patch types within years (MANOVA with post-hoc univariate Tukey; Appendix E).

irrigation resulted in distinct plant communities that were related to soil texture. Mean species richness ranged from 19 between agricultural rock alignments to 42 in between silt fields, but richness, Shannon-Weiner diversity, and evenness were not significantly different among patch types (Figure 6; Table 4). On a plot scale, species density ranged from 7 to 9 species per 0.25 m^2 quadrat and was around 30% higher on the finer-textured soils (between alignments, silt fields) compared to the coarser-textured soils between silt fields (Table 4). As predicted, differences in plant community composition between landscape patch types reflected underlying soil textural differences associated with agriculture. NMDS analyses (stress = 12.1) showed clear distinction between communities growing on the coarser-textured sandy loam surface soils located between silt fields and communities growing on the finer-textured loamy and silt loam surface soils within the other patch types, including the floodwater-irrigated silt fields (Figure 7). The separation between the communities occurred primarily along axis 1, which represented the highest amount of variance

Table 3. Statistical Results From Linear Regressions of Ecological Variables with Texture (% Sand, % Clay[1])

	All landscape patch types				Excluding irrigated silt fields				
	Predictor variable	Std. β	r^2	ρ	Predictor variable	Std. β	r^2	ρ	Transformation used
Herbaceous biomass (g cm^{-2})									
Spring 2008	Clay	0.40	0.14	0.01	Clay	0.42	0.15	0.01	$Log_{10}(x)$
Spring 2009	Clay	0.40	0.14	0.01	Clay	0.43	0.16	0.01	$Log_{10}(x)$
Spring 2010	Clay	0.52	0.26	<0.001	Sand	−0.66	0.43	<0.001	$Log_{10}(x)$
Potential net N mineralization(μg N cm^{-2} d^{-1})									
Spring 2008	Clay	0.56	0.30	<0.001	Sand	−0.74	0.54	<0.001	$\sqrt{(x)}$
Summer 2008	–	–	–	–	–	–	–	–	X
Fall 2008	–	–	–	–	–	–	–	–	X
Spring 2010	Sand	−0.32	0.09	0.03	Sand	−0.45	0.18	0.01	X
Total inorganic (μg N cm^{-2})									
Spring 2008	Sand	−0.52	0.25	<0.001	Sand	−0.70	0.47	<0.001	$Log_{10}(x)$
Summer 2008	Clay	0.77	0.58	<0.001	Sand	−0.44	0.64	<0.001	$Log_{10}(x)$
					Clay	0.41			
Fall 2008					Sand	−0.63	0.38	<0.001	$Log_{10}(x)$
Spring 2010	Sand	−0.43	0.17	<0.01	Sand	−0.51	0.24	<0.01	$\sqrt{(x)}$
Extractable PO$_4^{-3}$ (μg P cm^{-2})									X
Spring 2008									$\sqrt{(x)}$
Summer 2008	Clay	0.34	0.10	0.02	Sand	−0.42	0.15	0.01	X
Fall 2008					Sand	−0.44	0.17	0.01	$Log_{10}(x)$
Spring 2010					Sand	−0.44	0.17	0.01	$\sqrt{(X)}$

[1]*Sand and silt content were highly correlated, so only % sand and % clay were used in models.*
*– = neither sand nor clay content was related to variable, α = 0.0167 for biomass, 0.0125 for all others.*
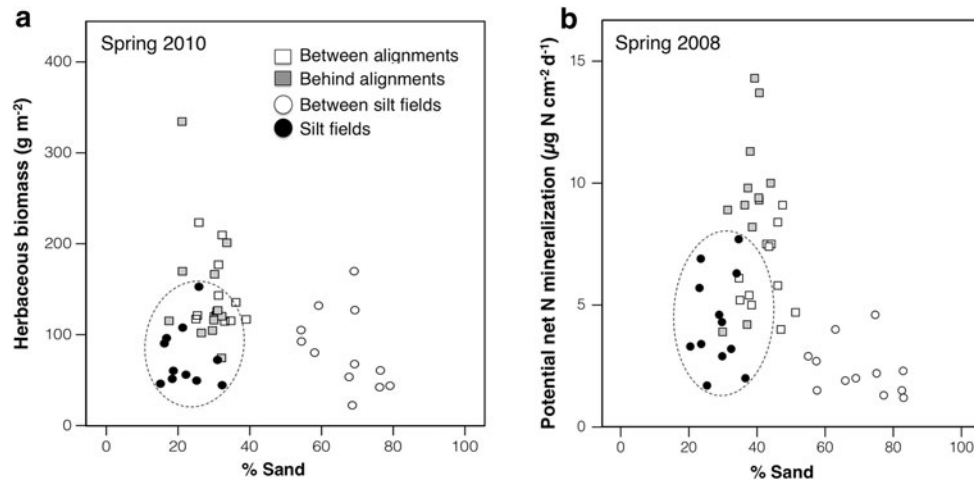
Figure 5. Relationship between soil texture and **A** aboveground herbaceous biomass (spring 2010 shown), and **B** soil N availability as estimated by rates of potential net N mineralization (spring 2008 shown). Statistics in Table 3. Note the strength of the relationship between sand content and these two variables increases when floodwater irrigated silt fields (*dotted ellipses*) are not included in the analyses.

in the dataset among the three orthogonal axes derived from the analysis and was most strongly associated with soil texture. Despite overlap between three fine-textured patch types in the NMDS ordination, results from the ANOSIM test showed that plant community composition was statistically different between and behind alignments ($R = 0.5$; $p = 0.0001$; multiple comparisons, $p = 0.01$), as well as among other feature types (all other pairwise comparisons, $p < 0.001$). Based on SIMPER analyses, overall similarity in plant composition between feature types was the highest among those
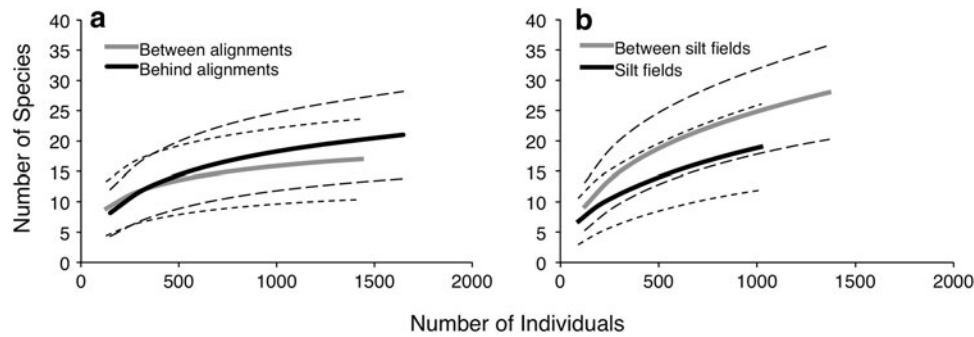
Figure 6. Individual-based species accumulation curves (*solid lines*) and 95% confidence intervals (*dotted lines*) for her-baceous species **A** between and behind alignments, and **B** between silt fields and silt fields at peak biomass in 2008. If confidence intervals overlap, species richness does not differ significantly between patch types. Note the relatively few number of individuals recorded in irrigated silt fields.

Table 4. Plant Species Diversity Metrics Across Landscape Patch Types at the Cave Creek Archaeological Complex

Patch type	Species richness		Species density (#sp/quadrat)			Species diversity (H′)			Evenness		
	ICE	Chao 2	Mean	SE	Sig.[1]	Mean	SE	Sig.	Mean	SE	Sig.
Between alignments	19.2	18.5	8.9	0.6	a	1.53	0.07	a	0.71	0.03	a
Behind alignments	26.3	30	8.2	0.6	ab	1.55	0.09	a	0.75	0.04	a
Between silt fields	41.2	43.1	9.3	0.5	a	1.67	0.06	a	0.76	0.03	a
Silt fields	32.3	29.7	6.8	0.4	b	1.40	0.09	a	0.74	0.04	a

ICE (incidence-based estimator) and Chao 2 are non-parametric species richness estimators.
[1]Results from one-way ANOVA, species metric (dependent) × patch type (independent). Lowercase letters represent significant differences within a column, α < 0.05. Species density: ANOVA, p = 0.01.
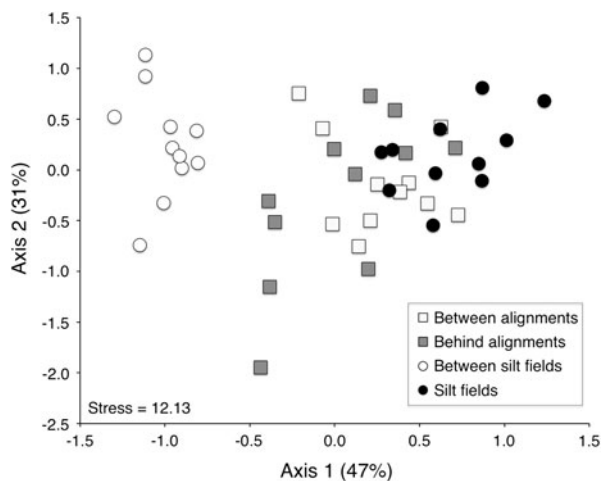
Figure 7. Results from NMDS ordination of herbaceous plant communities across the four landscape patch types in spring 2008. Axis 1 composed most of the variance of all three derived axes and was associated with sand content.

with fine soil texture, including the silt fields, be-tween alignment, and behind alignment patch types (46–55% dissimilarity; Table 5). In contrast,

the lowest compositional similarity occurred be-tween the sandy ''between silt field'' plots and the fine textured soils, including between alignments (62% dissimilarity), behind alignments (63% dis-similarity), and the silt fields (68% dissimilarity). Five species were responsible for approximately half of the dissimilarity between the coarse tex-tured ''between silt field'' patch type and the three, more fine-textured patch types (Table 5). Among these, native *Pectocarya recurvata* (curvenut comb-seed) and introduced *Erodium cicutarium* (redstem or common stork's bill) were the dominant species in sandy soils between silt fields, whereas native *Plantago ovata* (also known as *P. insularis*; desert Indian wheat) and native *Erodium texanum* (Texas stork's bill) dominated fractional plant cover in the fine-textured soils within the floodwater-irrigated silt fields (Appendix D).

DISCUSSION

Recent work in the field of ecological resilience has demonstrated that changes to ''slow'' variables such as soil properties can shift ecosystems toward

Table 5. Results from SIMPER Analyses Between Coarse-Textured (Between Silt Fields) and Finer-Textured Patch Types

| Species | Between silt fields vs. | | | |
	Between alignments	Behind alignments	Silt fields	
Overall dissimilarity (%)	62	63	68	
Species	% Contribution to dissimilarity			Relative abundance[1]
Pectocarya recurvata	13	12	17	BtwS ≫ BtwA = BhdA = Silt
Plantago ovata	10	11	13	BtwS ≪ BtwA = BhdA = Silt
Erodium texanum	13	3	13	BtwS = BhdA ≪ BtwA = Silt
Erodium cicutarium	10	11	10	BtwS = BhdA = BtwA = Silt
Schismus spp.	7	9	4	BtwS = BhdA = BtwA = Silt
Cumulative	53	46	57	

BtwS = Between silt fields; BtwA = Between alignments; BhdA = Behind alignments; Silt = Silt fields.
[1]Differences in relative abundance between patch types estimated from one-way ANOVA or Kruskal-Wallis non parametric tests (Appendix D).

alternate stable states that differ in their structure and function (Scheffer and Carpenter 2003). In support of this paradigm, results from this study suggest that the types of human activities that leave enduring ecological legacies in aridlands are those that modify fundamental soil properties that regulate water availability, the primary limiting resource to primary producers. In the Sonoran Desert site studied here, Hohokam irrigation practices that changed soil texture and raised fields above the active floodplain—but not alignments associated with runoff practices—substantially altered surface and deep soil texture, which continues to control water dynamics 700 years after abandonment. A change from coarse to fine-textured soils on formerly floodwater-irrigated fields is associated with a compositional change in desert plant communities. In support of the inverse texture hypothesis, perennial vegetation on former agricultural silt fields was composed of relatively small individuals of creosote bush (compared to a diverse assemblage of shrubs and cacti on sandy soils between silt fields), and winter annual communities that were dominated by a prehistorically encouraged species, desert Indian wheat (*P. ovata*). However, neither upland runoff farming practices nor floodwater agriculture were consistently associated with production of phenologically narrow, seasonal annual plants that are likely limited by "fast variables" such as nutrient availability because their activity is restricted to periods of sufficient rainfall.

Studies in other arid and semi-arid ecosystems have also documented cases of persistent ecological change due to agricultural practices that modified soil properties related to the timing and availability of water. For example, long-term irrigation of agriculture in ancient Mesopotamia salinized soils over vast areas, creating a suite of physico-chemical conditions that ultimately limited plant water uptake, productivity, and human-well being—conditions that remain even today (Jacobsen and Adams 1958). More recently, intensive grazing has transformed arid and semi-arid grasslands into patchy shrublands through positive feedback cycles that promote erosion, leading to numerous changes to soil properties that decrease water infiltration and fertility (Schlesinger and others 1990; Okin and others 2009). Even small changes in moisture availability in arid systems can influence vegetation communities over hundreds of years. For example, constructed rock piles and alignments in some Hohokam rain-fed fields in southern Arizona (~AD 750–1385) support higher densities of long-lived creosote bush than surrounding areas (Fish and others 2004).

According to the inverse texture hypothesis, the uniform, fine particle size distribution of soils created by past floodwater irrigation practices should restrict primary productivity under arid conditions compared to more sandy substrates (Noy-Meir 1973; Sala and others 1988). Although we did not measure production of perennial vegetation, the relatively small aboveground biovolume and highly-spaced distribution of the single remaining woody species on silt fields (*L. tridentata*) strongly suggests that this shift in texture decreased perennial plant production as expected (Briggs and others 2006). Desert shrubs are thought to depend on deep water recharge facilitated by relatively coarse soil texture that promotes infiltration and moderates evaporative losses (Whitford 2002). In other areas of the Sonoran Desert, creosote bush grows

monodominantly on stable Holocene surfaces lacking thick subsurface clay horizons (McAuliffe 1994). In this case, the reduction of woody plant diversity and biomass on abandoned floodwater-irrigated fields may result in part from low water availability for more shallow-rooted perennial species such as *Ambrosia deltoidea* and cacti. In support of our observations, fine-textured soils have been shown to support lower diversity of perennial species compared to coarse-textured soils in other arid and semi-arid ecosystems due to the complex trade-off between water availability and water stress experienced by plants in these soil types, which creates a narrow range of optimal hydrologic conditions (Caylor and others 2009). Also, Lane and others, (1998) showed that shrubs contribute a larger fraction of primary production relative to herbaceous plant species in coarse versus fine textured soils across large precipitation gradient in the US Great Plains.

Contrary to our expectations, clay content was positively related to aboveground production of shallow-rooted, cool-season annual plants across the Cave Creek archaeological complex, even across a two-fold range in winter precipitation inputs between 2009 and 2010. Notably, this explanation is contrary to the inverse texture model, which appears to better explain patterns over annual time scales that may be more relevant to perennial plants. Surface soils with more silt and clay have higher water-holding capacity, which can limit water infiltration for shrubs and other deep-rooted species under arid conditions. However, during most years, water availability to Sonoran Desert annuals is likely quite high, as they complete their life cycle over the winter and early spring when the rate of potential evapotranspiration is at its lowest point of the year. As a result, this phenologically-limited functional group may be effectively located on the more wet end of the inverse texture curve, where clay content is positively related to production. Fine-textured soils are also thought to be more fertile than soils with more sand, supporting larger organic matter pools and faster rates of microbial N turnover (Austin and others 2004). Texture was also related to nutrient cycling in the soils studied here (for example, % sand negatively related to N mineralization) except for in the relatively alkaline, silty, former flood-irrigated agricultural field. Although silt fields had higher soil carbon and organic matter content than soils between silt fields, they were not consistently more fertile: textural changes associated with floodwater irrigation were not strongly associated with rates of potential net N mineralization from

organic matter, or inorganic P availability. The relatively high pH of silt field soil (pH 8.6) compared to fine-textured soil on the eastern side of the creek (pH 7.6–8.0) may restrict nutrient availability through chemical or biological mechanisms. Alternatively, soil organic matter in silty, floodwater-irrigated soils may be less available, or of lower quality, than other fine-textured soils at this site that supported relatively high rates of N turnover and production of herbaceous annual plant species. Bulk soil organic content is generally related to rates of N mineralization (Booth and others 2005; Ros 2012), but many studies emphasize that plant nutrient availability depends most on the quantity of the labile fraction of organic matter—which may or may not be related to the size of total soil C and N pools (Parton and others 1987; Christensen 2001; Piñeiro and others 2006).

When considered together, the relationship between herbaceous production, soil texture, and fertility across landscape patches at the Cave Creek archaeological complex suggest that water supply was sufficient during the winter-spring seasons—particularly during the wet spring of 2010—such that ''fast variables'' such as nutrient availability more strongly limited seasonal herbaceous plant growth. Co-limitation of herbaceous production by N and P was demonstrated in other areas of the Sonoran Desert during wet years within this same time period (Hall and others 2011), and has been documented in a range of arid and semi-arid ecosystems worldwide (Craine and others 2008; Allen and others 2009; Chen and others 2009).

Herbaceous annual vegetation across this Hohokam agricultural site was composed of common Sonoran Desert native and introduced species, some of which were used by early Southwestern people for food or other economic purposes (Hodgson 2001; Appendix D). Within this broader community palette, floodwater irrigation practices appear to have substantially altered species composition due to changes in soil texture, favoring taxa with higher seasonal water demand. Surface soil moisture was consistently higher within silt fields compared to areas between fields during all times of year, although it is likely that surface water potential in these fine-textured soils in summer and fall was sufficiently low to limit plant processes. However, for annual communities that are restricted to cool, high rainfall seasons in winter and spring, landscape patches with higher soil water-holding capacity are likely to favor growth of some species over others. The forb *Pectocarya recurvata* composed the largest fraction of cover in

sandy, non-irrigated areas between silt fields (∼33%), followed by an introduced species, *Erodium cicutarium* (23%). In contrast, *Plantago ovata* and *Erodium texanum*, a native relative of *E. cicutarium*, together composed around 50% of the total herbaceous cover on fine-textured floodwater-irrigated fields. Interestingly, in a long-term study in Sonoran Desert sites located around 230 km to the SE of ours, the abundance of *P. recurvata* and *E. cicutarium* has increased over the last three decades, whereas cover of *P. ovata* and *E. texanum* has declined (Venable 2007). This relationship has been attributed to decreased frequency of late fall/early winter, warm rain events—a pattern associated with modern climate change—favoring the growth of cold-adapted, relatively water-use efficient species like *P. recurvata* and *E. cicutarium* that can germinate when precipitation commences later in the winter (Kimball and others 2010).

The diverse physiological traits of Sonoran Desert annuals may drive the community patterns that we observed on and off silt fields in the moderately wet winter of 2008. If *P. ovata* and *E. texanum* require warmer and wetter conditions to germinate (Huxman and others 2008; Kimball and others 2011), then—as observed—the growth of these two species would be favored on finer-textured soils such as formerly floodwater-irrigated fields that retain surface moisture longer after rains. An alternative explanation for the relative distribution of Sonoran Desert annuals at this site is cultural: *P. ovata* and *E. texanum* are known to have been consumed by prehistoric Southwestern people as supplemental food resources (Rea 1997; Hodgson 2001). Thus, the patterns we observed may represent remnant communities of culturally important native plants that have propagated through time (Essl and others 2012), as has been suggested in this region for agave (Hodgson 2001).

Unlike floodwater irrigation practices, ephemeral, low-intensity runoff agricultural practices left no significant ecological legacies in this arid ecosystem. Surface soil properties and processes were similar behind and between alignments, and indistinguishable from soil taken from a geomorphologically similar but more distant area ∼0.5 km to the south. Through their attenuating effects on slope, many prehistoric runoff features such as rock alignments and terraces were designed to capture sediment and nutrients and promote water infiltration by slowing overland flow (Doolittle 1992; Denevan 2003). These processes are thought to underlie the formation of deeper, more alkaline and organic-rich A horizons found in other ancient cultivated runoff fields compared to nearby uncultivated areas (Sandor and Eash 1991; Sullivan 2000; Homburg and others 2004; Goodman-Elgar 2008). However, across sites in the US Southwest, Native American dryland agricultural practices have been shown to leave inconsistent legacies in soils, ranging from sites that are slightly enhanced to those that are degraded compared to control areas. Variability in outcomes from runoff technology likely occur due to variability in geomorphic setting (for example, slope, soil type), post-abandonment processes such as sediment deposition and deflation that are common in topographically diverse, upland areas, and cultivation practices including intensity of production and management (Sandor and others 1990, 2007; Homburg and Sandor 2011). In the Hohokam sites studied here, we measured surface soil properties only, hillslopes were shallow, and rock alignments were only one course high and porous, comprising 40–60% bare ground across the alignment itself. These low-profile features are consistent with the intended purpose of slowing rather than retaining rainfall (Sandor 2006). Prehistoric farmers in other arid and semi-arid ecosystems were thought to actively maintain the integrity of runoff agricultural features such as terraces and alignments, and are even thought to have encouraged run-on to fields by diverting water during storms (Doolittle 2000; Sandor and Homburg 2011). However, with high productivity floodwater-irrigated fields just across Cave Creek, the permeable rock alignments at this site were likely used passively by the Hohokam to encourage supplemental rather than staple agricultural crops (Adams 2004). Consequently, 700 years after abandonment, it is unlikely that surface soil behind the subtle rock alignments studied here would have maintained textural differences of a magnitude large enough to alter water or nutrient availability for plant and microbial processes.

CONCLUSIONS

Numerous studies across the interdisciplinary environmental-archaeological literature have shown that ancient human activities can persist and in fact underlie many landscape patterns we see today. Our study advances this perspective by showing that the most enduring signatures are those left by activities that change fundamental ''slow'' soil properties that regulate the timing and supply of belowground limiting resources. At the broadest scales, ecological processes in aridlands are limited by precipitation—but at scales relevant to plants and the people that cultivate them, primary production is limited by the availability of water and

nutrients, both of which are constrained by geomorphic properties such as topography and soil texture. In the abandoned Hohokam agricultural site studied here, floodwater irrigation practices left stronger ecological legacies than dryland runoff practices, primarily by developing fine-textured soils from originally sandy substrates. Plant community and functional composition was strongly associated with soil textural changes associated with prehistoric agriculture, likely a result of species sorting in response to water availability. In contrast, primary production of shallow-rooted, herbaceous winter annual species was related most strongly to ''fast variables'' such as the amount of seasonal precipitation across years and soil nutrient availability within wet years, with weaker associations with soil texture on former agricultural landscapes. Understanding the drivers of enduring versus ephemeral human impacts on ecological processes may help to mitigate long-term state changes and productivity loss in aridlands, particularly under increasing drought conditions associated with modern climate variability.

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