Seasonality and Ecosystem Response in Two Prehistoric Agricultural Regions of Central Arizona

by

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ABSTRACT

Around the globe, prehistoric agriculture has impacted the environment in ways that are observable today. Prehistoric farmers in the Southwestern US modified the landscape with rock alignments to support rain fed agriculture in this semi-arid region. Numerous studies have shown that former agricultural fields are ecologically different than areas that have not been farmed. This thesis explores the independent effects of the manipulation of rocks into alignments, prehistoric farming, and season on soil properties in two areas with a history of prehistoric agriculture in central Arizona, Pueblo la Plata within the Agua Fria National Monument (AFNM), and an archaeological site north of the Phoenix basin along Cave Creek (CC).

During spring, summer, and fall of 2008, soil properties were compared across three landscape features: 1) agricultural rock alignments that were near the archaeological site 2) geologically formed rock alignments that were located 0.5-1 km away from settlements; and 3) areas both near and far from settlements where rock alignments were absent. Annual herbaceous plant biomass was also collected in each location. To explore the effect of alignment and surface soil geomorphology on soil and plant properties, the physical properties of alignments and surface soils were measured.

At AFNM, presence of rock alignments, distance from archaeological settlement, and time of year were significantly associated with soil physical properties and nutrient concentration. Patterns of potential nitrogen mineralization rates (pNmin) and herbaceous plant growth varied spatially and temporally. In contrast, at CC, time of year is the only factor associated with soil physical properties, while patterns of pNmin are associated with distance from archaeological features and time of year, and biomass was associated with the presence of alignments.

In two areas of central Arizona, topographic modification and seasonality affect current ecological processes and soil properties in distinctly different ways. At AFNM, relatively well-built rock alignments have altered soil properties and processes while less-intact alignments at CC have left few legacies. By exploring the effects of season and landscape modification on soil properties and processes, the effects of prehistoric agriculture on current arid and semi-arid ecosystems can be better understood.

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INTRODUCTION

Agriculture began approximately 10,000 years ago in multiple places around the globe (Glemin and Bataillon 2009, Harlan 1971, Smith 1989). As the cultivation of crops expanded and intensified, agricultural practices created environmental impacts that are observable today (McLauchlan 2006, Foster et al. 2003, Whitmore and Turner 1992). In some cases, agricultural legacies enhanced soil quality. For instance, in agricultural areas where manure, charcoal, or other organic additions were incorporated into the soil, soil organic carbon was elevated for 130-1000 years after abandonment (Johnson 1986, Sandor and Eash 1995, Springbob and Kirchmann 2002, Glaser et al. 2000). In other places, agriculture degraded soil fertility. For example, concentrations of soil phosphorus and calcium were lower in farmed soils compared to non farmed soils within the dryland agricultural systems of pre-contact Hawai'i, (Kirch et al. 2005), and irrigation led to salinization in arid Mesopotamia (Jacobson and Adam 1958, Gelbund 1963). Although we can make some generalizations based on previous research, the effects of prehistoric agriculture on the landscape depends on the physical and biological factors of the location of agriculture (i.e., climate, topography, soil), the type of agricultural method practiced, and duration of agricultural production.

In order to cope with unfavorable environmental conditions, prehistoric farmers modified the landscape to mitigate climatic variation and improve soil conditions (McLauchlan 2006, Foster et al. 2003, Whitmore and Turner 1992). For example, prehistoric agricultural techniques in the arid Southwestern United States encompassed a diversity of approaches that were designed to provide and retain water for crops such as; flood irrigation, mulch cover, runoff capture, and terrace formation (Masse 1981, Ort et al. 2008, Doolittle 1992, Sandor et al. 1990). In this research, I focus on the specific method of runoff capture identified as agricultural terracing, which was a prominent technique in the Southwestern US. Agricultural terraces were built by “placing lines of stone across shallow hill slopes and ephemeral stream channels” (Sandor et al. 1990). These rock alignments slowed overland runoff from seasonal rainfall and directed water to crops (Doolittle 1992).

Water availability often limits both natural and agricultural productivity in arid and semi-arid regions (Noy-Meir 1973, Sala et al. 1988, Austin et al. 2004, Reynolds et al. 2004, Collins et al. 2008). Therefore, small-scale landscape alterations such as agricultural terracing may increase long-term primary productivity by increasing water availability and biological nutrient cycling (Norton 2007, Norton et al. 2003, and Sandor et al. 2007). For example, in western New Mexico, Zuni agricultural systems that have used runoff capture for millennia are the most fertile on colluvial/alluvial toeslopes. In these systems, permeable stone and brush structures are able to capture and direct precipitation runoff, nutrients and sediment (Norton et al. 2003, Sandor et al. 2007). However, such improvements were not universal. For instance, in the terraced regions of Mimbres, New Mexico, similar rain fed agricultural features resulted in erosion, compaction, and lower concentrations of soil organic matter and nutrients (Sandor et al. 1990). The factors that control this variation remain unclear since it is difficult to separate various ecological and anthropogenic drivers of landscape patterns. In order to investigate the legacies of prehistoric agriculture within modern arid ecosystems the individual and interactive effects of natural ecological process and prehistoric agriculture should be considered.

Desert ecological processes are regulated by sporadic precipitation events that create ‘pulses’ of plant growth and ‘reserves’ of remnant plant productivity (seeds) when water is exhausted (Noy-Meir 1973, Sala et al. 1988, Reynolds et al. 2004, Collins et al. 2008). However this response is modulated by water holding capacity, which – in arid ecosystems – is a direct function of soil texture. The 'inverse texture hypothesis' suggests that coarser-textured soil should yield greater plant productivity than finer-textured soils in arid systems because of deeper water infiltration and subsequent reduced water loss from evaporation (Noy-Meir 1973, Sala et al. 1988). Austin et al. (2004) further suggested that higher water-holding capacities of finer-textured soils would lead to larger pools of organic matter and higher rates of nitrogen return to plants via microbial mineralization of organic matter (nitrogen mineralization = microbial conversion of organic N to plant-available NH_4^+) compared to coarse-textured soil in regions that received similar rates of precipitation. These apparently contradictory hypotheses suggest that primary production and soil nutrient cycling are decoupled in arid systems, where coarser-textured soils support greater plant productivity but lower rates of nitrogen mineralization. Conversely, finer-textured soils should support lower primary productivity but higher rates of nitrogen mineralization. Thus, modification of soil texture by prehistoric agricultural practices may leave long-lasting legacies in soils and plant communities of arid ecosystems.

Previous research on legacies of prehistoric agriculture in the US Southwest has focused on the effects of farming generally by characterizing soil properties on and off prehistoric fields at one point in time (Briggs et al. 2006, Sandor et al. 1986a, 1986b, 1986c). However, soil properties in arid ecosystems are characteristically heterogeneous both spatially and temporally, depending on vegetation characteristics, rock cover, and precipitation pulses (Noy-Meir 1973, Ogle and Reynolds 2004, Reynolds et al. 2004, Schwinning and Sala 2004, Augustine 2010, Sala and Lauenroth 1982, Collins et al. 2008, Abrahams and Parson 1991, Heisler-White et al. 2008). Furthermore, physical characteristics of rock structures and agricultural fields are highly variable depending on the extent of alignment construction and the slope of the landscape. In this study I separately explore the importance of rock alignment construction and farming activity on soil and plant properties over one year in two semi-arid regions of prehistoric agriculture in central Arizona.

I hypothesized that rock alignments would contribute directly to ecological processes through their effects on soil properties. I expected that the change in slope incurred by the rock alignment would slow overland flow and deposit fine textured materials. Soils behind alignments would be finer in texture than soils not associated with alignments, due to pedogenic processes associated with colluvial and alluvial deposition on hill slopes (Norton et al. 2003, Dalrymple et al. 1968). Additionally, fine-textured soils associated with rock alignments would contribute to higher soil water holding capacity, as well as higher moisture dependent soil physical properties and nutrient concentrations compared to coarse-textured soils. Additionally, these effects would persist across all seasons. Second, I hypothesized that soil texture would be significantly associated with nutrient cycling and plant growth and these effects would endure across all seasons as well. Specifically, I expected that potential nitrogen mineralization rates would be higher on fine-textured soils behind rock formations and plant biomass would be lower compared to coarse-textured soils in areas not used for prehistoric agriculture. Finally, I expected rock alignments to have similar impacts on soils in two different dryland ecosystems in Arizona that have been farmed by prehistoric people, higher elevation desert grasslands within the Agua Fria National Monument, and Sonoran Desert ecosystems in the north Phoenix basin along Cave Creek.

METHODS

Study areas

To explore the importance of rock alignments and farming on soil and plant properties, I selected two prehistoric agricultural sites in central Arizona for my study: a collection of rock alignments near Pueblo la Plata within the Agua Fria National

Monument and a number of agricultural rock alignments near Cave Creek (Figs. 1 and 2). Each region was selected based on the presence of dryland field systems with rock alignments and detailed archaeological history. The physical attributes and histories of each site are presented below.

Agua Fria National Monument (AFNM)

The Agua Fria National Monument is located 80 km north of the Phoenix Basin in central Arizona, USA (34 14'52. 69" N, 112 02'17. 90" W)(Fig. 1).The site is located at an elevation of 1,115 m and receives 300-400 mm precipitation annually (Maricopa County Flood Control 2010 and NCDC 2010). The study site is located in the central portion of AFNM east of the Agua Fria River on Perry Mesa. The mesa-top is characterized by hills and semi-arid desert grassland with soils derived from granite, basalt or wind-transported material (Nakase et al. in prep; Wendt et al. 1976). Soils are characterized as fine, montmorillonitic, mesic Aridic Haplusterts from the Springerville-Cabezon complex and as fine, montmorillonitic, thermic Typic Chromusterts within the Rimrock-Graham complex (USDA-NRCS 1997).

Around A.D. 1280 -1400, the people whom archaeologists have classified as the Perry Mesa Tradition (Stone 2000) inhabited central Arizona (Wilcox and Holmlund 2007). These populations built several pueblos or villages (80-100 rooms each) that reached their greatest extent during the late 1200s and early 1300s (Wilcox et. al 2001a, 2001b). Many of these villages are associated with sizable agricultural areas (Kruse 2007) with rock alignments that likely were used for maize cultivation (Fish et al. 1975, Gumerman et al. 1975, Heuett and Long Jr. 1996, North 2002, Doolittle 2000).

My study site was located near Pueblo la Plata (Site No. NA 11648), which is in close proximity (~300m) to a 10 ha area of agricultural terraces (Site No. AZ N:12:135; ASM) (Kruse 2007). Based on conversations with archaeologists, I assumed that rock alignments in this area were human-made for agricultural purposes and will refer to this sampling location as 'Near.' Southwest from Pueblo la Plata (0.5 – 1 km) on an adjacent mesa top, there is less evidence of agricultural activity (Kruse-Peeples et al. 2009) and naturally formed rock alignments; I refer to this area as 'Far' from the Pueblo. The entire site is located on a 0-2% slope, facing south-southwest.

Cave Creek (CC)

Cave Creek, Arizona USA (33 46'45.32" N, 112 00'44.09" W) is located within the northern Phoenix basin (Fig. 2). The site is located on Arizona State Trust Land at an elevation of 547 m and receives 150-250 mm precipitation annually (Maricopa County Flood Control 2010 and AZMET 2010). Cave Creek is an ephemeral stream located on an alluvial fan with upper terrace and basin-floor deposits. In areas to the north and west of the site, geomorphology is composed of metamorphosed volcanic rocks and metasedimentary rocks, mostly derived from sandstone and shale, with minor amounts of conglomerate and carbonate rock (Richard et al. 2000).

From A.D. 0 -1450, people whom archaeologists refer to as the Hohokam were present in the Phoenix basin (Hackbarth 2002). The Hohokam are best known for their extensive canal construction (Haury 1976, Gregory 1991, Doyel 1991, Doolittle 1992). Prehistoric sites along Cave Creek in the north Phoenix Basin contain sizable, canal-irrigated agricultural fields that were used primarily for maize cultivation (Phillips 1998, Schaafsma and Briggs 2007). Additionally there are areas that contain rain fed rock alignments and grid gardens that were used to supplement maize production (Site Nos. AZ T:4:74 and AZ T:4:76; Phillips 1998).

I infer that rock alignments within sites AZ T:4:74 and AZ T:4:76 were built and used for agriculture by humans and will refer to this area as 'Near' (i.e. near archaeological sites). These sites are 0.8 to 1.5 km southwest from habitation sites in the area (Site Nos. AZ U:1:11 (ASM), AZ U:1:159 (ASM), AZ U:1:309 (ASM), and AZ U:1:310 (ASM). Approximately 0.5-1 km southwest from sites AZ T:4:74 and AZ T:4:76 is an area that has less archaeological evidence (Site Nos. AZ T:4:94 and AZ T:4:95) and contains naturally formed rock alignments. I refer to this area as 'Far' (i.e., far from abundant archaeological evidence; Fig. 2). The entire site is located on a 0-2% slope, facing north-northwest.

Grazing history at AFNM and CC

Cattle were introduced in the AFNM area around the mid-1870s and the earliest records of grazing near the CC field site date to the 1920s; however, little is known about the densities of livestock during those times. AFNM previously had a stocking rate of 381 cattle on approximately 70,900 acres per year. The Bureau of Land Management (BLM) stopped grazing in 2007. Currently CC has a rate of 35 animal units (cattle) on approximately 11,500 acres per year (Sommers 2010). Since the acquisition and subsequent regulation of these lands by state and federal agencies, comprehensive range management plans are in place to ensure environmental protection against overgrazing. Because grazing has occurred across both landscapes, and because I make relative comparisons between feature types within each landscape, I assume it will not be a confounding factor in my analysis.

Experimental design

To separate various ecological and anthropogenic drivers of landscape patterns in arid and semi-arid systems, I selected an experimental design that controlled for both prehistoric agricultural activity and presence or absence of rock alignments with four 'landscape types'. To explore the effect of humans/agriculture, I collected soil and plant samples: 1) near (<0.5km) the archeological site (assumed to have relatively high prehistoric human impact) and 2) far (0.5-1km) from the archeological site (assumed to have less human impact). To explore the effects of rock alignments, I collected soil and plant samples: 3) behind the rock alignments where water and soil would collect and 4) from areas with no rock alignments within each ‘near’ and ‘far’ location. For clarity and consistency with archaeological evidence, rock alignments near the archaeological site were referred to as ‘anthropogenic’ indicating that they were constructed by humans. Additionally, rock alignments far from the archaeological site were referred to as ‘natural,’ indicating that they were formed by geomorphic processes.

Fifteen replicates of each landscape type were established at each site (AFNM and CC), for a total of 120 plots. Plots were approximately 4 x 2 m, half of which was used for plant biomass collection while the other half was used for soil sampling. Soil samples were collected three times in 2008 over the period from February to October. Above ground biomass of herbaceous annual plant species was collected at peak growth in the spring (April) and fall (October) of 2008 at AFNM and during the spring (March) at CC to estimate net primary productivity of this plant community. No perennial vegetation was collected.

Rock alignment and non-alignment area characterization

To describe rock alignments and physical characteristics of the prehistoric agricultural areas, I collected data on slope, surface rock cover, and alignment characteristics (geometry, density of rocks) from each plot within each site. The ‘planting surface’ of natural and anthropogenic rock alignments was measured as the area directly behind the rock alignment bounded by the next rock alignment or break on the hill slope. Slope was measured on the planting surface by using a stadia rod and clinometer between the outer edge of the planting surface and 5 meters upslope. Rock and vegetation cover were assigned to one of 6 percentage classes using a 1m^2 quadrat (<1%, 1-10%, 10-25%, 25-50%, 50-75%, 75-100%). Rocks were categorized into four sizes: gravel (<7.6 cm), cobbles (7.6-25 cm), stones (25-60 cm), and boulders (>60 cm) (Schoeneberger et al. 2002).

Length, width, and height of rock alignments were recorded in number of courses (rocks) and in cm, as well as length and width of the planting surface. To determine the density of rocks within the alignment, six meter-long segments of the alignment were used to classify the percentage of rocks by size. The total percentage of rock within the alignment was subtracted from 100% to estimate the percentage of soil and/or vegetation within the alignment.

Soil and plant biomass sampling

In order to account for soil heterogeneity and preserve the archaeological and geologic features, two soil cores (0-7 cm depth at AFNM, 0-5 cm depth at CC) were taken from each plot during February-March, June, and September-October. Soil samples were taken at least 1 m away from any nitrogen-fixing shrubs such as *Acacia greggii* A. Gray (cat claw acacia) and *Prosopis velutina* Wooton (mesquite). Soil cores were taken from the center and at the east end of the alignment approximately 10 cm from the inside edge. For non-alignment areas, cores were taken approximately 1 meter away from one another. Soil cores were pooled in the field by plot (2 cores per plot, 15 plots per landscape type) and transported on ice to Arizona State University (ASU) for overnight storage. Soils were sieved to <2 mm within 24 hours of collection.

In the spring at both locations, annual plant biomass was sampled within two 50 × 20 cm (1000 cm^2) subplots. Vegetation was clipped to the soil surface using scissors, transported to ASU, and dried at 60°C for 48 hrs prior to being weighed (USDA-NRCS 1997). In the fall at AFNM an additional two subplots were collected approximately 10 cm away and parallel to the spring subplot. Precipitation data were recorded daily for the growing season at both AFNM and CC using regional precipitation stations. Stations were approximately 0.4 to 12 km away from sampling locations in areas of similar elevation. At AFNM data were collected from the following sensors: Sunset Point (ID No. 5730) and Horseshoe Ranch (ID No. 5745) from the Flood Control District of Maricopa County (Maricopa County Flood Control 2010); and the Cordes Junction Weather Station (ID No. 022109) from the National Climate Data Center (NCDC 2010). At Cave Creek (CC) precipitation data were collected from the Cave Creek Landfill sensor (ID No. 4915) and Desert Mountain School sensor (ID No. 4875) also from the Flood Control District of Maricopa County (Maricopa County Flood Control 2010) and the Desert Ridge sensor from the City of Phoenix Water Conservation Department (AZMET 2010). Precipitation data were averaged from the multiple sensors at each site to obtain the mean daily precipitation amount. Daily amounts were summed for monthly and yearly analysis.

Soil analysis

Sieved soils were analyzed for a suite of physical and biogeochemical properties using Central Arizona–Phoenix, Long Term Ecological Research (CAP LTER) standard protocols (http://caplter.asu.edu/). Soil particle size (texture) was determined using the hydrometer method (100 mL of 50 g/L sodium hexametaphosphate in 40 g of soil), followed by sieving (to 53 µm) for sand content and calculating silt content by difference. To determine water holding capacity (WHC (%)), 20 g of soil was saturated with water and weighed after 24-hr drain time through a GF-A filter. WHC was calculated as: $\theta_g = (W_{ms}-W_{ds}/ W_{ds}) \times 100$; where W_{ms} is the mass of the moist soil and W_{ds} is the mass of the soil dried at 105° C for 24 hours. Gravimetric soil moisture (g/g dry soil) was determined by drying 30 g of soil for 24 hours at 105°C and calculated as: $W_g = W_{ms}-W_{ds}/ W_{ds}$;where W_{ms} is the mass of the fresh (moist) soil and W_{ds} is the mass of the soil dried at 105° C for 24 hours.

Soil organic matter (SOM) (g organic matter per 100 g of dry soil; %) was estimated by the loss-on-ignition method as ash-free dry mass following combustion of oven-dried soils for 4 hours at 550°C. To determine pH, 30 mL of nanopure water was added to 15 g of soil; the slurries were measured using a portable pH meter after 30 minutes (VWR sympHony, Bristol, Connecticut, USA). Electrical conductivity (EC (µmhos/cm)) was measured by adding 30 mL of nanopure water to 15 g of soil; EC was measured with a portable conductivity meter (HACH miniconductivity, Ames Iowa) after 30 minutes. Effective Cation Exchange Capacity (ECEC ($cmol_c$/kg)) was determined using 10 g of soil extracted with 50 mL of 1 M ammonium acetate adjusted to pH 7; the slurry was filtered through pre-leached Whatman no. 42 filters and then frozen immediately for later analysis. Ammonium acetate extracts were analyzed for potassium, calcium, magnesium, and sodium with inductively coupled plasma-optical emission spectrometry (ICP-OES) (Thermo iCAP 6300, Waltham, Massachusetts, USA). ECEC was calculated as: (cmol element/kg soil) = exch K^++ exch Ca^{2+}+ exch Mg $^{2+}$+ exch Na^+. Results were reported in centimoles of charge per kilogram (Sumner and Miller 1996).

Ammonium (µg NH_4^+-N·g^{-1} dry soil) and nitrate + nitrite (summed as µg NO_3^--N·g^{-1} dry soil) concentrations were measured using 10 g of soil extracted in 50 mL of 2M KCl by shaking for 1 hour and filtering through pre-leached Whatman #42 ashless filters. The extracts were frozen until colorimetric analysis using a Lachat Quickem 8000 autoanalyzer. Potential rates of net N mineralization and net nitrification were assessed by incubating 10 g of soil in the dark at 20°C for 10 days at 60% WHC, followed by extraction with 2M KCl and colorimetric analysis as described above. Rates of potential net N mineralization and net nitrification were calculated as the difference in the sum of NH_4^+ and NO_3^-, or NO_3^- alone, respectively, before and after incubation divided by the number of incubation days (reported as µg N g^{-1} d^{-1}).

Phosphate (µg PO_4^{3-}P·g^{-1} dry soil) concentration was measured using 2 g of soil extracted in 40 mL of 0.5M $NaHCO_3$ by shaking for 1 hour and filtering through pre-leached Whatman #42 ashless filters. The extracts were frozen until colorimetric analysis using a Bran-Luebbe Traacs 800 Autoanalyzer.

Data analysis

PASW 18 software was used for all statistical analyses. When necessary, data were transformed ($\log_{10}$, modified square root [where $x' = (x+1)^{½}$], cube root) to meet the assumptions of normality and homoscedasticity. Data from each site (AFNM and CC) were analyzed separately.

Feature metrics:

To examine the differences between the alignments (near and far from archaeological sites) individual metrics from each alignment were analyzed with an Independent samples t-test and Bonferroni corrected by the number of tests used per analysis (alpha (α) = 0.05 / 10 alignment characteristics = 0.005). Characteristics included length, width, height, percentage of gravel, cobble, stones and boulders within the alignment, total amount of rocks within the alignment, total amount of rocks on the planting surface and the change in slope. To compare surface properties (change in slope, total surface rock cover) between alignments and non-alignment areas, a two-way ANOVA was performed using distance (near or far), and presence of rock alignment (alignment or non-alignment) as fixed factors and Bonferroni corrected by the two variables tested (α = 0.05 / 2 = 0.02). Additionally, alignments and surface properties at AFNM and CC were compared using Independent samples t-test and Bonferroni corrected by the number of tests used per analysis (alpha (α) = 0.05 / 9 alignment characteristics = 0.005). Only nine characteristics were included because boulders were not present at Cave Creek.

Soil properties:

To compare seasonally averaged soil properties (clay and sand fraction, pH, effective cation exchange capacity (ECEC), water holding capacity (WHC)) between alignments and non-alignment areas, a two-way ANOVA was performed using distance (near or far), and presence of rock alignment (alignment or non- alignment) as fixed factors and Bonferroni corrected by the 5 variables tested ($\alpha = 0.05 / 5 = 0.01$). Additionally, I used a three-way ANOVA to explore the effects of season (spring, summer, fall at AFNM; summer and fall only at CC), distance to archaeological site (near or far), and presence of rock alignment (alignment or non-alignment) on plant biomass and a suite of soil properties that varied seasonally. Soil variables include nutrient concentration (extractable inorganic nitrogen (TIN) and phosphorous (PO_4^{3+}), gravimetric moisture, soil organic matter (SOM), and potential nitrogen mineralization (pNmin)). Alpha values used in these three-way ANOVA tests were Bonferroni corrected to $\alpha=0.05/6=0.008$ to account for the six different ANOVA tests used in this group of analyses. Post hoc Tukeys HSD tests were used to explore differences in soil properties between seasons and differences between alignment (natural and anthropogenic) and non-alignment areas within season. When three-way ANOVA results yielded interactions that were significant, a post-hoc two-way or one- way ANOVA was performed using presence of rock alignment and/or distance to archaeological features to better understand the interaction.

At CC in spring 2008, no data were collected from non-alignment areas that were far from the archaeological site, thus I used a one-way ANOVA with presence of rock alignment (alignment or non- alignment) as the only factor in order to examine the six seasonal soil variables described above and herbaceous plant biomass for that season (six sequential ANOVA tests; $\alpha=0.05/6=0.008$).

For each season individually (spring, summer and fall) and throughout the year (averaged across all seasons), stepwise multiple linear regression was used to determine the effect of non-correlated soil properties (pH, SOM, WHC, TIN, pNmin (included for biomass only), PO_4^{3+} concentrations, soil moisture, sand and clay fraction) and alignment and non-alignment characteristics (surface cover of rocks and slope change) on pNmin and annual herbaceous plant production. These variables were selected based on hypotheses that suggest that texture, nutrient concentration and surface soil characteristics influence pNmin and plant productivity (Austin et al. 2004, Hook and Burke 2000). In PASW, collinearity diagnostics were performed to provide condition indices, which indicate multicollinearity when above 30 (Belsley et al. 1980). From the regression analysis, the adjusted coefficient of determination (r^2) and the p-value were used to evaluate the strength of the entire model on the independent variables of potential nitrogen mineralization rates and biomass. Standardized coefficients (β) were used to evaluate the strength of individual dependent variables within each model.

RESULTS

R*ock alignment and non-alignment area characterization and soil properties*

Agua Fria National Monument (AFNM)

Human constructed rock alignments near the pueblo and natural alignments far from the pueblo are physically different from one another. Anthropogenic alignments are longer ($p = 0.001$), taller ($p = 0.005$), and characterized by a larger proportion of stones (25-60 cm; $p = 0.002$) compared to natural alignments (Table 1). In contrast, both types of rock alignments (natural and anthropogenic) contain an approximate 60:40 ratio of rock to soil and create a similar change in slope on the landscape ($p=0.66$). The planting surfaces behind both types of rock alignments and non-alignment areas had similar surface rock cover ($p=0.35$). Natural and anthropogenic rock alignments created a greater change in slope compared to non-alignment areas both near and far from the pueblo ($p<0.001$).

Distance from the Pueblo and presence of alignments were significantly associated with soil physical properties (Tables 3-5). In general soils near the pueblo (rock alignment and non-alignment areas together) contained a larger fraction of clay ($p<0.001$) (less coarse) and exhibited higher water holding capacity (WHC) ($p<0.001$), higher effective cation exchange capacity (ECEC) ($p<0.001$), and higher pH ($p<0.001$) compared to areas further away. Soils collected behind both types of alignments (natural and anthropogenic) contained a lower fraction of clay ($p<0.001$) (more coarse), and exhibited lower WHC ($p<0.001$) and ECEC ($p<0.001$) compared to soils collected in non-alignment areas. After Bonferroni Corrections, sand was not significantly different between distances (near/far) ($p=0.01$) or between alignment and non-alignment areas ($p=0.05$), though trends indicated that soils far from the Pueblo and behind both types of rock alignments (natural and anthropogenic) contained a greater sand fraction than areas closer to the Pueblo and soils in non-alignment areas.

Season, distance from the Pueblo, and the presence or absence of rock alignments were significantly associated with soil water and nutrient concentration (Tables 3-5), with season the most important of the three factors. Soil moisture varied by season but was greatest in the spring and fall ($p<0.001$). Soil moisture content was greater near the Pueblo and in non-alignment areas where textures were less coarse compared to soils further away from the Pueblo or behind natural and anthropogenic rock alignments ($p<0.001$). Total inorganic nitrogen (TIN) concentration was highest in the spring across all treatments ($p<0.001$) but was not associated with distance from the Pueblo ($p=0.04$) or rock alignments ($p=0.32$). After Bonferroni corrections soil organic matter (SOM) and phosphate (PO_4^{3+}) concentrations were not significantly different between treatments

(SOM: p=0.282; PO_4^{3+}: p=0.853) or seasons (SOM: p=0.569; PO_4^{3+}: p=0.144) (Table 3-5).

Cave Creek (CC)

Similar to AFNM, rock alignment characterization differed between natural and anthropogenic alignments at CC. Anthropogenic rock alignments are longer (p=0.002) and taller (p<0.005) than naturally formed alignments further away (Table 2). Additionally, anthropogenic rock alignments are characterized by a larger proportion of cobble (7.6-25cm; p=0.004) and composed of a 50:50 ratio of rock to soil compared to a 60:40 ratio of rock in alignments far from the archaeological site (p=0.001). Natural and human constructed rock alignments had a similar composition of gravel (p=0.62), stones (p=0.58), and did not significantly alter the slope of the landscape (p=0.34). The planting surface behind both natural and anthropogenic rock alignments had lower quantities of rock surface cover compared to non-alignment areas (p<0.001). Both rock alignments (natural and anthropogenic) exhibited a similar change in the slope to non-alignment areas (p=0.45).

In contrast to the patterns I observed at AFNM and my second and third hypothesis, a majority of soil physical properties were not associated with rock alignments. The sand fraction was the only soil variable significantly influenced by distance from the archaeological site and presence of rock alignments. Soils near the archaeological site (anthropogenic alignment and non-alignment areas together) contained a greater sand fraction (more coarse) compared to soils further away (p=0.003) and soils behind all alignments (natural and anthropogenic) contained a lower sand fraction (less coarse) compared to non-alignment areas (p=0.003). The clay fraction, WHC, ECEC and pH were not significantly different between distances from the archaeological site (near/far) (clay fraction: p=0.319, WHC: p=0.322, ECEC: p=0.660

and pH: p=0.500) or between alignment and non-alignment areas (clay fraction: p=0.127, WHC: p=0.131, ECEC: p=0.335 and pH: p=0.439).

At CC, in dissimilarity with AFNM, soil properties and nutrient concentrations were not associated with soil texture. Rather proximity and seasonality influenced these patterns on the landscape. During the spring, no data were collected from non-alignment areas that were far from the archaeological site, thus spring data were analyzed separately from summer and fall for all soil properties, nutrient cycling and biomass response variables. In the spring, nutrient and soil moisture concentrations associated with natural and anthropogenic rock alignments were not significantly different from the non-alignment area (PO_4^{3+} conc. (p=0.01), TIN (p=0.60), SOM (p=0.68) and soil moisture (p=0.31)).

During the summer and fall, soil nutrient concentrations and water availability were influenced by distance from the archaeological sites rather than presence of rock alignments and varied seasonally (Tables 6-8). For example, PO_4^{3+} concentrations were greater in the fall compared to summer (p=0.005) and were greater far from the archaeological site compared to near (p=0.001). TIN was greatest in the fall across all treatments (near and far, alignment and non-alignment) (p=0.001). In contrast, SOM was greater in the summer compared to the fall across all treatment types ($p<0.001$). Soil moisture was affected differentially by distance to the archaeological site depending on the season (two-way interaction, p=0.001). Soil moisture was greater in the fall compared to the summer ($p<0.001$) and greater in areas further from the archaeological site in the fall (p = 0.003).

Comparison of alignments between AFNM and CC

Natural and anthropogenic rock alignments are relatively well built at AFNM compared to CC. Rock alignments at AFNM are wider ($p<0.001$) and taller ($p< 0.001$), and composed of more stone sized rocks ($p < 0.001$) than rock alignments at CC. In contrast, alignments at CC are composed of greater amounts of gravel ($p < 0.001$) and cobble ($p < 0.001$) than AFNM. Alignments at AFNM are composed of at 60:40 ratio of rock to soil compared to a 40:60 ratio at CC ($p<0.001$). Additionally, the planting surface behind rock alignments at AFNM had greater amounts of rock surface cover ($p<0.001$) and created a greater change in the slope ($p<0.001$) compared to CC.

Nutrient cycling and plant production

AFNM

Patterns of potential nitrogen mineralization rates (pNmin) and net primary productivity varied both spatially and temporally at AFNM (Fig. 3 and 4). Rates of pNmin were lower on alignments (natural and anthropogenic) compared to non-alignment areas (Fig. 3; 3-way ANOVA, alignment: $p < 0.001$). Rates were similar in the summer and fall and significantly lower than rates in spring (3-way ANOVA w/ post-hoc Tukey, season: $p < 0.001$). Post-hoc Tukey analyses within each season revealed that rates of pNmin were not different between natural and anthropogenic alignments and non-alignment areas.

For all of 2008, multiple regression revealed that pNmin was significantly but weakly predicted by TIN, WHC, and sand fraction within soils ($r^2 = 0.13$; $p < 0.001$; β(TIN)= -0.267; β(WHC)=0.306; β(% Sand)=0.345). Regression analysis of spring 2008 data alone indicates that pNmin was significantly predicted by WHC and sand fraction (r^2=0.21; $p<0.001$; β(WHC)=0.395; β(% Sand)=0.529), while summer pNmin was significantly but weakly predicted by TIN and WHC (r^2=0.12; p=0.008; β(TIN)=0.357; β(WHC)=0.303). None of the soil and landscape variables was significantly associated with pNmin during the fall.

Production of annual herbaceous plants was affected differentially by presence of alignments and distance to the Pueblo depending on the season (three-way interaction, $p = 0.004$; Fig. 4). Analysis of each season separately revealed that in the spring, production was highest near the pueblo compared to further away ($p=0.003$). The total amount of precipitation from October 2007 to May 2008 was approximately ~278 mm (Table 9). It appeared that production was lower on alignment areas compared to non-alignment areas, although this pattern was not statistically significant ($p=0.67$). Additionally, post-hoc Tukey analyses within each season revealed that production of annual herbaceous plants was not different between natural and anthropogenic alignments and non-alignment areas.

During the fall, soils behind anthropogenically constructed rock alignments near the pueblo and soils from non-alignment areas far from the pueblo supported the greatest amounts of biomass ($p=0.02$) (Fig. 4). Precipitation for the summer was ~100 mm from June to October 2008. Across both seasons, above ground productivity was predicted by TIN, SOM, and clay fraction, (multiple regression, $r^2 = 0.398$, $p < 0.001$; $\beta(\text{TIN})= -0.562$; $\beta(\text{SOM})=0.193$; $\beta(\text{\% Clay})=0.172$). In the spring, regression analysis revealed that soil moisture is the most important factor related to primary production ($r^2 = 0.275$, $p < 0.001$; $\beta=0.536$). None of the soil and landscape variables was significantly associated with primary production of herbaceous annuals during the fall.

CC

In contrast to my second and third hypotheses as well as the patterns I observed at AFNM, pNmin did not exhibit a specific pattern throughout the year at CC. For spring 2008, pNmin was highest in the fine-textured soils that occurred behind the natural and anthropogenic rock alignments compared to the single non- alignment area ($p=0.001$) (Fig. 5). Multiple regression analysis found that 39% of the variability in pNmin is determined by a combination of TIN and PO_4^{3+} ($p<0.001$; β(TIN)= 0.402; $\beta(PO_4^{3+})$=0.443).

In the summer and fall, pNmin was affected differentially by distance to the archaeological site depending on the season (two-way interaction, $p<0.001$). Analysis of each season separately showed that in the summer, soils far from the archaeological site had a lower capacity to provide plant-available nitrogen than soils near the archaeological site ($p=0.008$). The pattern was reversed in Fall 2008, where pNmin in soils far from the archaeological site was higher than in soils near the archaeological site (Fig. 5; $p<0.001$). Post-hoc Tukey analyses within season revealed that rates of pNmin were not different between natural and anthropogenic alignments and non-alignment areas in the summer, but in the fall, rates of pNmin were different between areas near the archaeological site and areas far from the archaeological site. Exploring predictors of these patterns with multiple regression revealed that for combined fall and summer pNmin rates, 10% of the variability was determined solely by soil moisture ($p<0.001$; β(soil moisture)= 0.334), while no other variables were significant predictors. Regression analysis from soils collected in summer revealed that none of the soil or landscape variables were significantly associated with nitrogen availability. In soils collected in the fall, PO_4^{3+} and SOM together were associated with 25% of the variability in pNmin ($p<0.001$; β (SOM) =0.293: β (PO_4^{3+})=0.367).

Production of annual herbaceous plants was only measured in the spring. The total amount of precipitation from October 2007 to May 2008 was approximately 167 mm of precipitation at CC (Table 9). Biomass was greater on both natural and anthropogenic rock alignments compared to the non-alignment area ($p=0.007$; Fig. 6). 33% of the variability within biomass was significantly explained by only soil moisture ($p<0.001$; β= 0.588).

Discussion

Physical structure of rock alignments affects soil texture

Agua Fria National Monument (AFNM)

Rock alignments altered surface topography around Pueblo la Plata. Rock alignments composed of stone-sized rocks (25-60 cm), placed in a curvilinear manner decreased the slope enough to alter physical soil properties and processes. Soils behind rock alignments (both natural and anthropogenic) contain coarser textured soils (decreased clay fraction) than the surrounding non-alignment areas. The transition from fine to coarse composition of soils on rock alignments is contrary to traditional hill slope soil formation, which suggests that fine-textured material will be transported down slope. It is possible that the change in slope created by rock alignment construction did in fact generate a finer planting surface initially. Perry Mesa soils, however, are vertisols (>30 % clay content; USDA 2011) and in small agricultural watersheds composed of vertisols it is common to have large losses of clay particles due to surface flow during storm events (Pathak et al. 2004). Throughout time, any accumulation of fine material may have slowly decreased because of surface runoff and has left coarse material behind.

Cave Creek (CC)

At Cave Creek, both natural and anthropogenic alignments do not significantly alter slope across the landscape, and of the numerous soil physical properties observed; only the sand fraction was different (lower) behind rock alignments compared to non-alignment areas. Soils that were less coarse on the planting surface may be contributed to rock alignments, however this pattern is also attributed to natural colluvial and alluvial deposition on hill slopes (Norton et al. 2003, Dalrymple et al. 1968). Rock alignment areas at CC were used for supplementary agriculture, possibly beans or agave rather than maize (Smith 2009). The less intensive nature of agricultural practices could explain why only very subtle changes to soil properties were observed between alignment and non-alignment areas.

Response of nutrient processes and plant production to modified soil physical properties

AFNM

Differences in soil texture behind rock alignments were associated with soil and plant ecological properties. Finer-textured soils from non-alignment areas have a higher water holding capacity (60-70%) compared to soils behind alignments (50-55%), and finer-textured soils were associated with higher rates of potential nitrogen mineralization (pNmin) (pNmin of soils behind both natural and anthropogenic alignments < non-alignment soils). These patterns of pNmin across landscape types support the hypothesis of Austin et al. (2004), which suggests that pNmin is controlled by soil texture. Furthermore, these patterns suggest that the presence of rock alignments has decreased the soils' capacity to provide nitrogen to plants through the microbial process of nitrogen mineralization. Additionally, these patterns could be influenced by prehistoric use as it is not certain that naturally formed terraces were not used for agriculture.

Net primary production also appeared to be related to soil texture, although weakly, as results supported predictions from the inverse texture hypothesis. AFNM received approximately 360 mm of precipitation for 2008 (January-December) (Maricopa County Flood Control 2010 and NCDC 2010), placing it near the fulcrum of change in the inverse texture model (Sala et al. 1988). Sala et al. (1988) suggested that soils in regions that receive greater than ~370 mm of precipitation annually will be more productive on finer-textured soil compared to coarse soils. Generally all the soils near Pueblo la Plata were finer in texture and had greater amounts of biomass compared to the areas far from the pueblo that were coarser in texture. Additionally, spring biomass tended to be higher on finer-textured, non- alignment areas compared to coarser-textured natural and anthropogenic alignments (though not significantly). The combination of slightly lower biomass behind both rock alignments in conjunction with coarser soil textures also provides support for the inverse texture hypothesis at AFNM.

Predictors of net primary productivity of annual herbaceous plants include a combination of nitrogen concentration, organic matter, and soil texture indicating that a combination of ecological factors (nitrogen concentration, SOM) and anthropogenic manipulations (construction of rock alignments that changed soil texture) influence biomass on Perry Mesa. However, across the landscape, water is a limiting factor and the greater amount of plant biomass in the spring could be attributed to greater amounts of precipitation during that season (~278 mm from October 2007-May 2008 vs. ~100 mm from June to October). Desert annual plants increase in species richness and productivity with higher water availability (Knapp and Smith 2001, Schmida 1985, Ward & Olsvig-Whittaker 1993, Kutiel et al. 2000, Xia et al. 2010).

CC

In the spring at CC, soil texture was significantly associated with pNmin. The pNmin was greater on natural and anthropogenic rock alignments compared to the non-alignment area. This pattern supports the hypothesis presented by Austin et al. (2004) which suggests that finer textured soils should yield greater rates of pNmin.

However, during the summer and fall soil texture was not associated pNmin in any consistent way. In the summer, pNmin rates were similar in areas far from the archaeological site (natural alignment and non- alignment areas) and much lower than areas near the archaeological site (anthropogenic alignment and non-alignment areas). During the fall, pNmin rates were lower in areas near the archaeological site compared areas further away. These patterns do not support the hypothesis presented by Austin et al. (2004), rather they suggest that other factors should to be considered as well. For example, summer and fall regression analyses indicate that soil moisture predicts pNmin, yet soil moisture was not associated with soil texture. It is likely that soil properties across CC are responding to seasonal change in precipitation. Summer was relatively moist in 2008 (~135 mm of precipitation from June-August) and the minimal episodic rainfall events in the fall (~41 mm of precipitation from September to November) may have triggered rapid nitrogen mineralization and immobilization (Schimel and Parton 1986).

Net primary productivity at CC was significantly influenced by the presence of rock alignments. Natural and anthropogenic alignments have greater amounts of biomass compared to the non-alignment area and regression analyses suggest that biomass was predicted by soil moisture. Approximately 167 mm of precipitation fell at CC before harvest and according to the inverse texture hypothesis for ecosystems below 370 mm of rainfall, finer-textured soils yield lower rates of production compared to coarser-textured soils (Sala et al. 1988). However, at CC, this hypothesis was not supported. It is possible that the combination of finer soils with flatter surfaces (no slope change) and water amount could have allowed water to pool and slowly infiltrate for plant use and allow for greater productivity on the planting surface of alignment areas at CC.

AFNM and CC comparisons

AFNM and CC differ with regard to the construction of rock alignments and the ecological response on the landscape to these formations. Rock alignments at AFNM are better built in comparison to alignments at CC because they are taller, wider and composed of greater amounts of rocks (60:40 ratio of rock to soil) than those present at CC. At AFNM, distinct patterns emerge on the landscape. Natural and anthropogenic rock alignments are coarser in texture and in the summer and fall the potential nitrogen mineralization rate is consistently lower on natural and anthropogenic alignments compared to the non-alignment area. In contrast, at CC, only subtle differences are associated with alignment features and soil properties and processes.

The better constructed terraces at AFNM coupled with the strong record of prehistoric agricultural use (Fish et al. 1975, Gumerman et al. 1975, Heuett and Long Jr. 1996, North 2002, Doolittle 2000) could be responsible for the differences between soil texture and nutrient fluxes on rock alignment and non-alignment areas. At CC, the primary prehistoric agricultural method used was irrigated cropland (Hackbarth 2002). The less-constructed rock alignments were supplemental in use at CC and may have resulted in minimal differences between rock alignments and non-alignment areas at this site.

CONCLUSIONS

In two areas of central Arizona, landscape modification from prehistoric agriculture affects soil texture and ecosystem processes and properties, even today. At the beginning of my experiment, I hypothesized that the physical structure of alignments would contribute directly to ecological processes through their effects on soil texture and expected that the change in slope incurred by the rock alignment would slow overland flow and deposit fine textured materials. I discovered that rock alignments altered soil particle size at both sites, although not always as predicted. At AFNM the clay fraction of soils on natural and anthropogenic rock alignments is lower than on the surrounding non alignment areas. At Cave Creek, natural and anthropogenic rock alignments had a lower sand fraction compared to surrounding desert soils.

Soil texture controls water dynamics and supporting ecosystem processes in arid and semi-arid environments. Therefore, I hypothesized that alterations in soil texture would be significantly associated with nutrient cycling and plant growth, and that these effects would endure across all seasons. In agreement with Austin et al. (2004), I found that pNmin was related to soil texture at AFNM. Additionally, patterns of biomass support the inverse texture hypothesis at AFNM but not at CC (Sala et al. 1988), where finer-textured soils supported higher annual herbaceous plant production. Incorporating a seasonal dimension into ecosystem research adds additional complexity to understanding agricultural legacies. I found that patterns in soil properties and processes varied throughout the year, suggesting the importance of incorporating seasonal measurements into my study when investigating the effects of prehistoric impacts on the landscape. Exploring seasonal variation allowed me to better understand the dynamic processes taking place within the landscape that may have been overlooked if I had only examined one point in time.

Finally, I expected rock alignments at AFNM and CC to have similar impacts on soils. In contrast, I found that rock alignments at AFNM and CC have very different impacts on soils. Rock alignments at AFNM were used extensively for maize agriculture, while alignments at CC were supplemental to irrigated farming. The difference in use could be responsible for the dissimilarity in current landscape pattern.

My thesis suggests that topographic modification that occurred hundreds (anthropogenic terraces) or possibly millions of years ago (natural terraces) can affect current ecological processes through the indirect manipulation of soil particle size. Furthermore, the combination of landscape modification, ecosystem properties and processes and seasonal dynamics provides a general template for understanding the effects of prehistoric agriculture on current landscape structure and function.

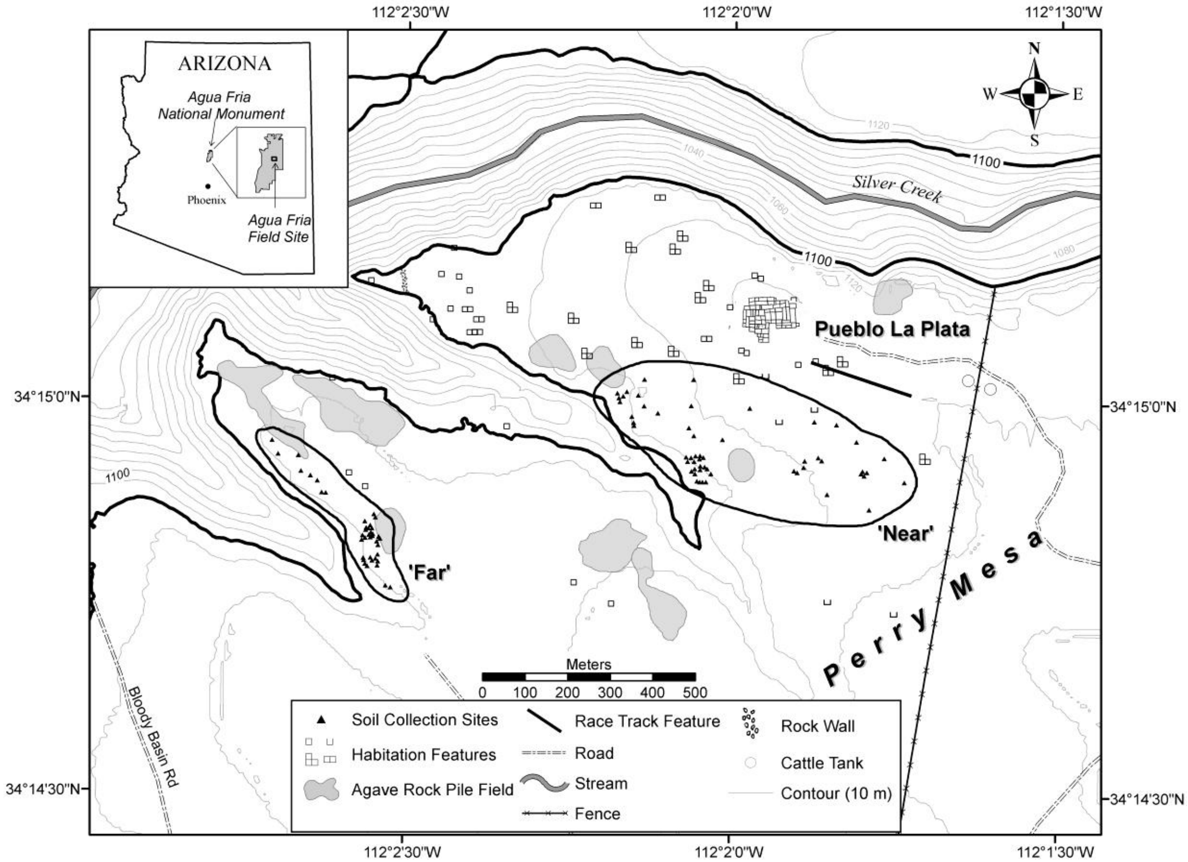

FIG. 1. Map of sampling locations at Pueblo la Plata within the Agua Fria National Monument.

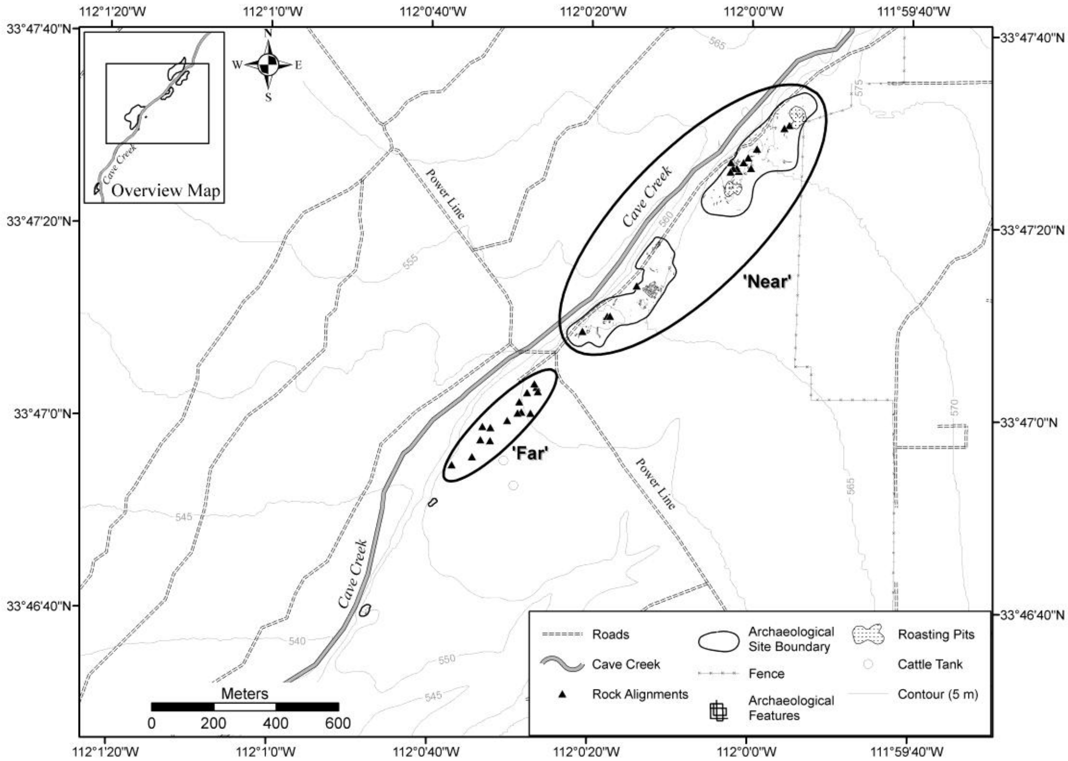

FIG. 2. Map of sampling location at Cave Creek, located in central Arizona on State Trust Land.

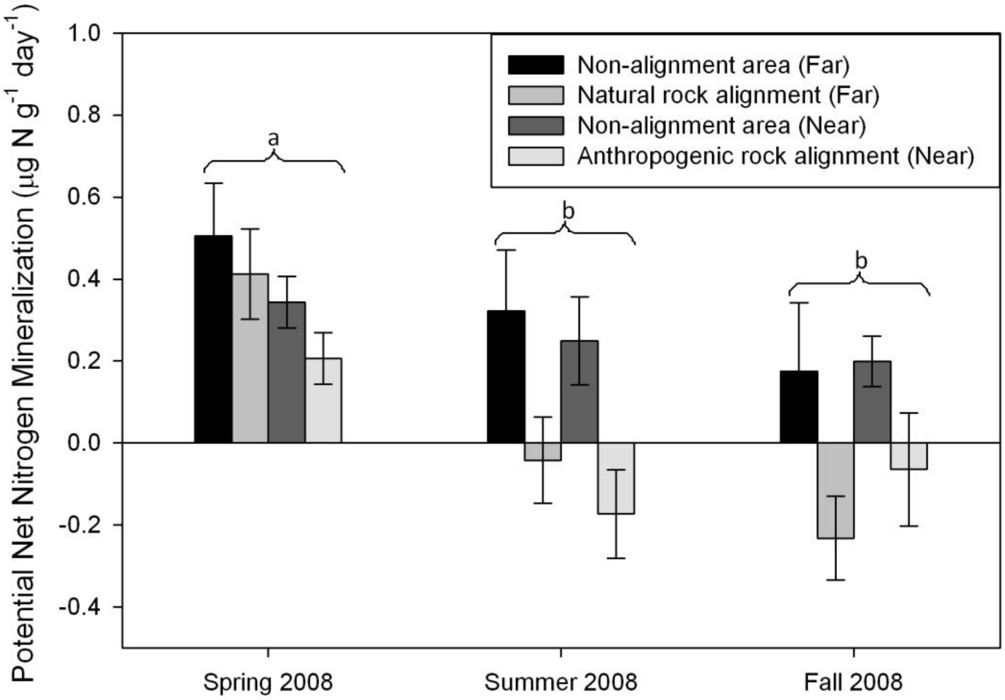

FIG. 3. Potential nitrogen mineralization throughout 2008 at Agua Fria National Monument (AFNM). Error bars are ±1standard error, letters indicate significant differences between seasons. Three-way ANOVA: Season: $p<0.001$, Distance to pueblo (near or far): $p=0.34$, Presence of alignment: $p<0.001$. No higher order interactions were significant.

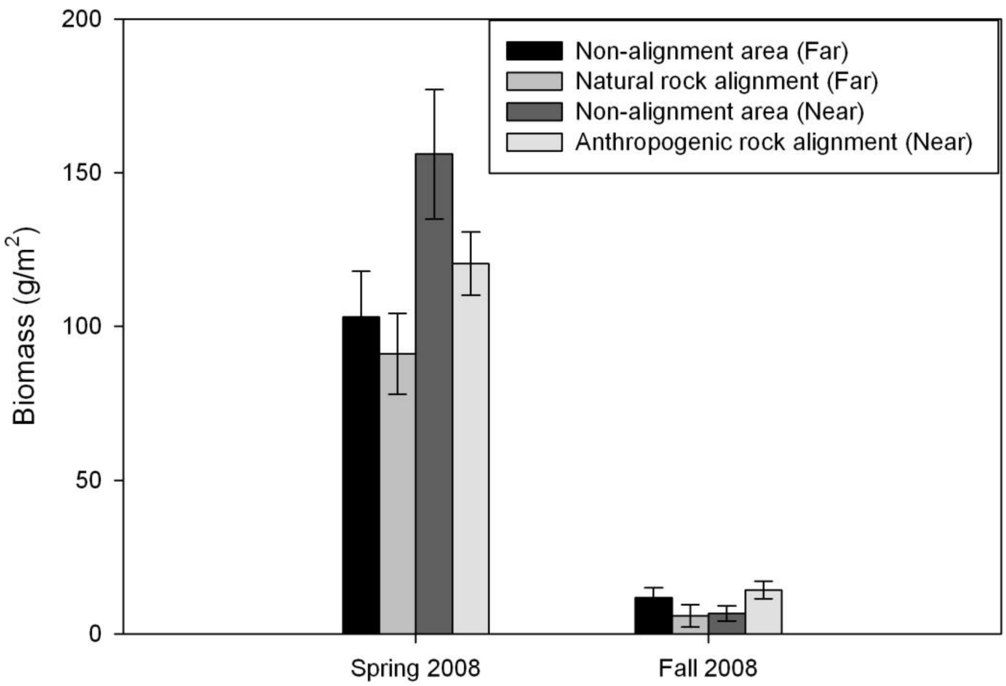

FIG. 4. Biomass of herbaceous annual plants collected throughout 2008 at Agua Fria National Monument (AFNM). Error bars are ±1 standard error. Three-way ANOVA: Season: $p<0.001$, Distance to pueblo (near or far): $p=0.01$, Presence of alignment: $p=0.73$, Season x Distance x Alignment: $p=0.004$.

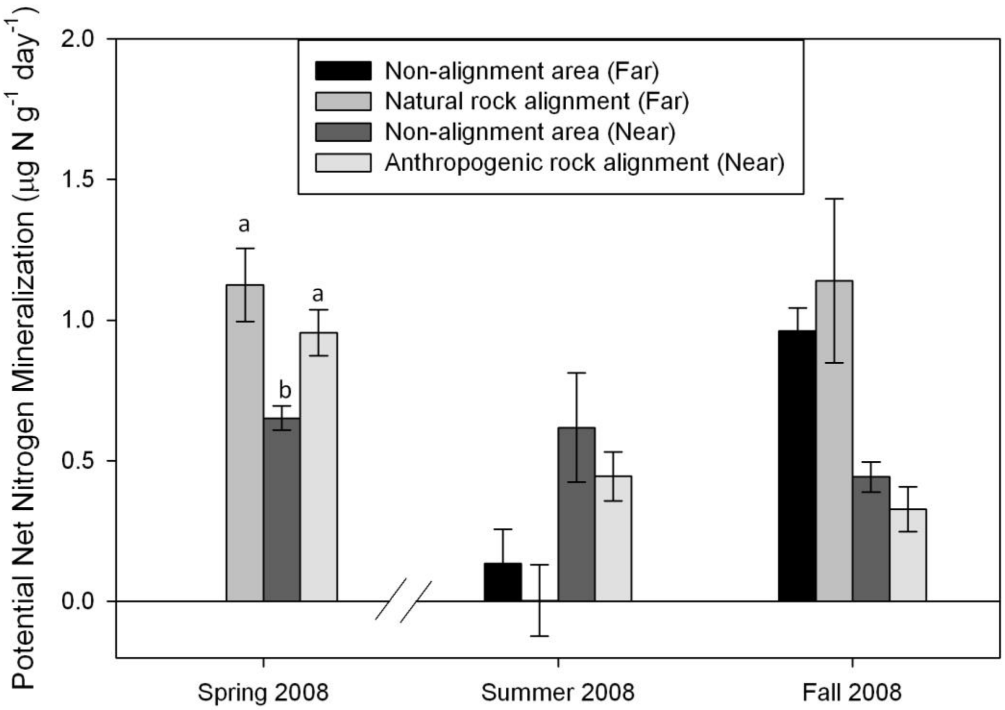

FIG. 5. Potential nitrogen mineralization throughout 2008 at Cave Creek (CC). Error bars are ±1 standard error, letters indicate significant differences between non-alignment and alignment areas in the spring. Spring: One-way ANOVA: Presence of alignment: $p<0.001$. Fall and summer: Three-way ANOVA: Season: $p<0.001$, Distance to pueblo (near or far): $p=0.35$, Presence of alignment: $p=0.76$, Season x Distance: $p<0.001$.

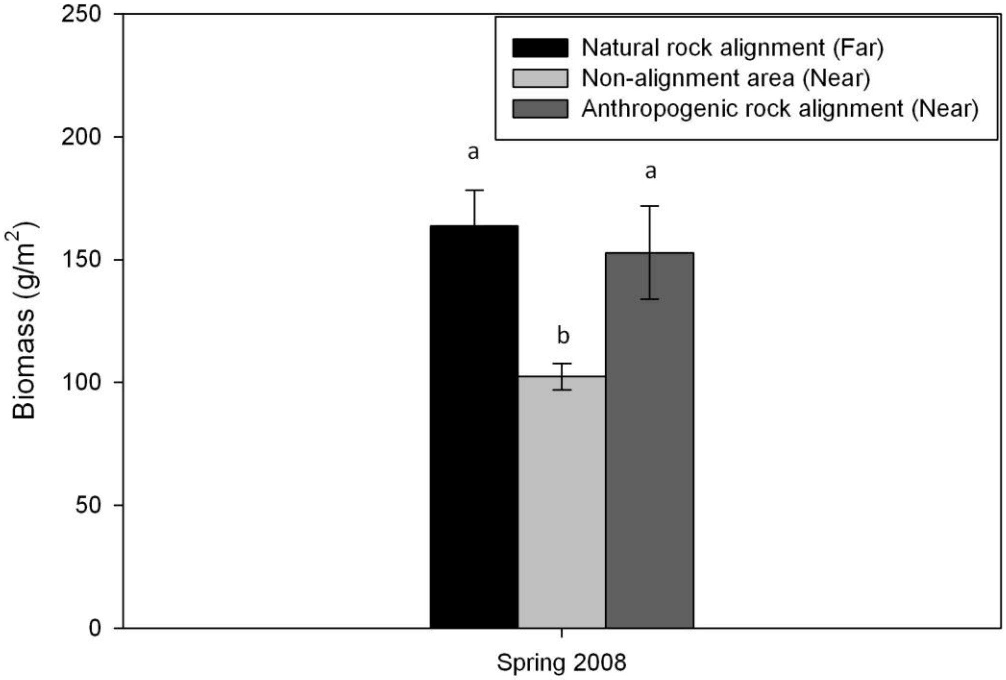

FIG. 6. Biomass of herbaceous annual plants collected during Spring 2008 at Cave Creek. Error bars are ±1 standard error and letters indicate significant differences between non-alignment and alignment areas.

TABLE 1. Agua Fria National Monument (AFNM) rock alignment and non- alignment area characterization.

	Non-alignment area (Far)		Natural rock alignment (Far)		Non-alignment area (Near)		Anthropogenic rock alignment (Near)	
Variable	Mean	Std. Dev	Mean	Std. Dev	Mean	Std. Dev	Mean	Std. Dev
Alignment Length (m)			4.22**	0.86			6.97**	2.71
Alignment Width (m)			0.82	0.40			0.90	0.37
Alignment Height (m)			0.14**	0.08			0.23**	0.09
Number of Courses High			1.20	0.41			1.47	0.52
Number of Courses Wide			1.40	0.63			2.00	0.85
Total Rock in the alignment (%)			64.84	13.78			67.25	15.05
Total Soil in the alignment (%)			35.16	13.78			32.75	15.05
Planting surface Length (m)			2.89	0.64			5.93	2.48
Planting Surface Width (m)			2.84	0.98			3.42	0.81
Surface Cover of Rocks	43.47	18.21	45.73	14.05	38.00	16.74	38.93	12.41
Slope Change	0.33*	0.41	0.61*	0.61	0.37*	0.57	1.00*	0.50
Alignment Gravel (<7.6cm) (%)			2.60	1.88			5.86	4.83
Alignment Cobbles (7.6-25cm) (%)			8.89	7.86			13.65	8.90
Alignment Stones (25-60cm) (%)			17.89**	9.67			34.86**	13.63
Alignment Boulders (>60cm) (%)			35.46	16.82			12.88	16.02
Alignment Dirt/Veg (%)			35.16	13.78			32.75	15.05
Planting surface Gravel (<7.6cm) (%)			7.87	5.85			11.73	10.46
Planting surface Cobbles (7.6-25cm) (%)			15.13	7.00			12.40	6.27
Planting surface Stones (25-60cm) (%)			21.07	12.16			13.47	11.35
Planting surface Boulders (>60cm) (%)			1.67	4.50			1.33	5.16
Planting surface Dirt/Veg (%)			54.27	14.05			61.07	12.41
Slope (%)	-0.95	0.60	-0.62	0.54	-1.62	1.12	-1.00	0.50
5 m up-slope (%)	-0.95	0.48	-1.10	0.55	-1.74	1.37	-2.00	0.63

Note: *, ** Feature metrics differ between rock alignments near or far at the $p<0.005$ (**) level or rock alignments and non- alignment areas at the $p<0.02$ (*) level. Blank space indicates that no data were collected

TABLE 2. Cave Creek (CC) rock alignment and non- alignment area characterization.

	Non-alignment area (Far)		Natural rock alignment (Far)		Non-alignment area (Near)		Anthropogenic rock alignment (Near)	
Variable	Mean	Std. Dev	Mean	Std. Dev	Mean	Std. Dev	Mean	Std. Dev
Alignment Length (m)			4.48**	1.00			6.01**	1.40
Alignment Width (m)			0.48	0.15			0.60	0.21
Alignment Height (m)			0.01**	0.01			0.05**	0.02
Number of Courses High			1.00	0.00			1.07	0.26
Number of Courses Wide			1.67	0.62			2.13	0.64
Total Rock in the alignment (%)			37.09**	7.66			50.00**	11.26
Total Soil in the alignment (%)			62.91	7.66			50.00	11.26
Planting surface Length (m)			4.04	0.86			5.34	1.23
Planting Surface Width (m)			3.37	1.26			3.52	0.92
Surface Cover of Rocks	30.40*	15.36	13.13*	9.34	38.20*	18.19	17.93*	8.33
Slope Change	0.15	0.21	0.18	0.15	0.13	0.13	0.17	0.23
Alignment Gravel (<7.6cm) (%)			11.04	4.87			12.19	5.98
Alignment Cobbles (7.6-25cm) (%)			17.92**	8.56			28.73**	9.03
Alignment Stones (25-60cm) (%)			7.94	8.55			9.08	7.44
Alignment Boulders (>60cm) (%)			0.19	0.73			0.00	0.00
Alignment Dirt/Veg (%)			62.91	7.66			50.00	11.26
Planting surface Gravel (<7.6cm) (%)			6.40	4.22			9.80	4.06
Planting surface Cobbles (7.6-25cm) (%)			6.13	6.85			7.13	5.28
Planting surface Stones (25-60cm) (%)			0.60	1.68			1.00	3.87
Planting surface Boulders (>60cm) (%)			0.00	0.00			0.00	0.00
Planting surface Dirt/Veg (%)			86.87	9.34			82.07	8.33
Slope (%)	-0.33	0.31	-0.25	0.23	-0.23	0.15	-0.12	0.13
5 m up-slope (%)	-0.32	0.24	-0.27	0.24	-0.30	0.17	-0.25	0.23

Note: *, ** Feature metrics differ between rock alignments near or far at the p<0.005(**) level or rock alignments and non- alignment areas at the p<0.02 (*) level. Blank space indicates that no data were collected

TABLE 3. Agua Fria National Monument (AFNM) soil properties and ecosystem dynamics for Spring 2008 at Pueblo la Plata across the landscape.

Spring 2008	Non-alignment area (Far)		Natural rock alignment (Far)		Non-alignment area (Near)		Anthropogenic rock alignment (Near)	
Variable	Mean	Std. Dev	Mean	Std. Dev	Mean	Std. Dev	Mean	Std. Dev
pH	7.20	0.37	7.05	0.22	7.56	0.28	7.26	0.26
Soil Organic Matter (SOM) (%)	4.92	0.84	4.47	0.62	4.38	0.62	4.90	0.76
Water Holding Capacity (WHC) (%)	60.06	10.32	48.87	7.67	71.03	6.38	55.59	9.59
Nitrate (NO^{3-}) (µg g^{-1}dry soil)	0.59	0.30	1.67	1.34	0.79	0.55	1.01	0.73
Ammonium (NH_4^+) (µg g^{-1}dry soil)	2.99	0.75	3.18	1.70	2.60	0.72	3.20	1.00
Total Inorganic Nitrogen (TIN) (µg g^{-1} dry soil)	3.58	0.78	4.85	1.86	3.39	1.02	4.21	1.61
Potential Nitrogen Mineralization (N-Min) (µg g^{-1}day^{-1})	0.50	0.50	0.41	0.42	0.34	0.25	0.21	0.24
Nitrification (µg g^{-1}day^{-1})	0.80	0.51	0.73	0.55	0.60	0.28	0.53	0.31
Phosphate (PO_4^{3-}) (µg g^{-1}dry soil)	12.89	6.25	10.78	5.96	10.99	3.89	12.58	7.92
Soil Moisture (%)	6.10	1.70	4.90	1.90	8.90	1.70	6.80	1.70
Sand Fraction (% Sand)	15.84	5.67	19.96	6.98	10.68	4.01	11.83	5.94
Silt Fraction (% Silt)	46.08	5.90	44.39	4.31	46.34	5.29	50.47	4.55
Clay Fraction (% Clay)	38.08	8.08	35.65	9.26	42.98	5.66	37.70	7.67
Biomass (g/m^2)	96.19	59.73	91.12	50.69	156.06	81.54	120.43	39.75

TABLE 4. Agua Fria National Monument (AFNM) soil properties and ecosystem dynamics for Summer 2008 at Pueblo la Plata across the landscape.

Summer 2008	Non-alignment area (Far)		Natural rock alignment (Far)		Non-alignment area (Near)		Anthropogenic rock alignment (Near)	
Variable	Mean	Std. Dev	Mean	Std. Dev	Mean	Std. Dev	Mean	Std. Dev
pH	6.72	0.29	6.59	0.24	7.42	0.20	7.26	0.26
Soil Organic Matter (SOM) (%)	4.87	0.74	4.94	1.60	4.57	0.77	4.90	0.76
Water Holding Capacity (WHC) (%)	60.06	10.32	48.87	7.67	71.03	6.38	55.59	9.59
Nitrate (NO^{3-}) (µg g^{-1}dry soil)	4.04	1.83	4.01	1.73	3.04	0.89	1.01	0.73
Ammonium (NH_4^+) (µg g^{-1}dry soil)	3.01	0.91	2.88	0.99	2.39	0.81	3.20	1.00
Total Inorganic Nitrogen (TIN) (µg g^{-1} dry soil)	7.05	2.41	6.89	2.14	5.43	1.62	4.21	1.61
Potential Nitrogen Mineralization (N-Min) (µg $g^{-1}$$day^{-1}$)	0.32	0.58	-0.04	0.41	0.25	0.41	0.21	0.24
Nitrification (µg $g^{-1}$$day^{-1}$)	0.59	0.60	0.23	0.41	0.47	0.45	0.53	0.31
Phosphate (PO_4^{3-}) (µg g^{-1}dry soil)	11.86	7.85	10.21	5.00	8.92	3.62	12.58	7.92
Soil Moisture (%)	3.20	0.90	3.00	1.60	4.70	1.10	6.80	1.70
Sand Fraction (% Sand)	15.65	5.99	17.78	7.35	11.01	4.05	11.83	5.94
Silt Fraction (% Silt)	54.25	3.24	54.22	5.50	54.79	2.98	50.47	4.55
Clay Fraction (% Clay)	30.09	7.14	28.00	10.78	34.20	5.06	37.70	7.67

TABLE 5. Agua Fria National Monument (AFNM) soil properties and ecosystem dynamics for Fall 2008 at Pueblo la Plata across the landscape.

Fall 2008	Non-alignment area (Far)		Natural rock alignment (Far)		Non-alignment area (Near)		Anthropogenic rock alignment (Near)	
Variable	Mean	Std. Dev	Mean	Std. Dev	Mean	Std. Dev	Mean	Std. Dev
pH	6.85	0.37	7.09	0.26	7.27	0.37	7.27	0.27
Soil Organic Matter (SOM) (%)	4.81	1.13	4.83	0.62	4.71	0.86	4.86	0.62
Water Holding Capacity (WHC) (%)	60.06	10.32	48.87	7.67	73.55	6.87	55.59	9.59
Nitrate (NO^{3-}) (µg g^{-1}dry soil)	23.22	14.02	18.10	6.97	19.54	8.02	21.96	12.66
Ammonium (NH_4^+) (µg g^{-1}dry soil)	1.30	1.09	1.68	1.64	1.35	1.60	0.58	0.25
Total Inorganic Nitrogen (TIN) (µg g^{-1} dry soil)	24.52	13.92	19.78	8.00	20.89	8.57	22.54	12.65
Potential Nitrogen Mineralization (N-Min) (µg $g^{-1}day^{-1}$)	0.18	0.65	-0.23	0.40	0.20	0.24	-0.07	0.54
Nitrification (µg $g^{-1}day^{-1}$)	0.30	0.65	-0.06	0.46	0.34	0.27	-0.01	0.55
Phosphate (PO_4^{3-}) (µg g^{-1}dry soil)	10.99	7.66	12.04	3.55	13.42	5.22	13.72	7.88
Soil Moisture (%)	6.50	1.60	6.50	1.70	9.00	1.60	8.10	2.20
Sand Fraction (% Sand)	13.58	4.97	16.93	6.60	13.48	4.64	17.33	5.37
Silt Fraction (% Silt)	57.46	3.67	56.31	3.98	51.11	3.09	51.78	4.13
Clay Fraction (% Clay)	28.97	7.70	26.77	8.16	35.41	5.87	30.89	7.44
Effective Cation Exchange Capacity (ECEC) ($cmol_c$/kg soil)	23.46	5.77	19.42	6.81	33.07	6.68	24.36	5.96
Electrical conductivity (EC) (µmhos/cm)	125.60	56.76	76.80	26.55	89.80	24.69	82.20	33.86
Biomass (g/m^2)	11.85	12.22	5.85	14.15	6.58	9.52	14.27	11.22

TABLE 6. Cave Creek (CC) soil properties and ecosystem dynamics for Spring 2008 across the landscape.

Spring 2008	Non-alignment area (Far)		Natural rock alignment (Far)		Non-alignment area (Near)		Anthropogenic rock alignment (Near)	
Variable	Mean	Std. Dev	Mean	Std. Dev	Mean	Std. Dev	Mean	Std. Dev
pH			8.32	0.42	7.73	0.59	8.06	0.49
Soil Organic Matter (SOM) (%)			3.20	0.48	3.07	0.22	3.07	0.43
Water Holding Capacity (WHC) (%)			45.75	6.26	42.06	5.34	42.09	5.60
Nitrate (NO^{3-}) (µg g^{-1}dry soil)			1.74	0.88	1.65	0.38	1.84	0.46
Ammonium (NH_4^+) (µg g^{-1}dry soil)			0.72	0.74	0.66	0.42	0.78	0.64
Total Inorganic Nitrogen (TIN) (µg g^{-1} dry soil)			2.46	1.38	2.31	0.63	2.62	0.98
Potential Nitrogen Mineralization (N-Min) (µg $g^{-1}day^{-1}$)			1.13	0.50	0.65	0.17	0.96	0.32
Nitrification (µg $g^{-1}day^{-1}$)			1.16	0.54	0.70	0.17	1.01	0.36
Phosphate (PO_4^{3-}) (µg g^{-1}dry soil)			18.00	8.49	9.06	5.67	12.70	5.63
Soil Moisture (%)			11.70	2.40	10.40	1.40	11.30	2.20
Sand Fraction (% Sand)			34.31	4.61	42.32	5.34	37.06	4.19
Silt Fraction (% Silt)			49.54	8.31	38.72	4.47	44.00	4.71
Clay Fraction (% Clay)			19.80	3.97	18.96	4.84	18.94	3.20
Biomass (g/m^2)			163.72	56.59	102.29	20.79	152.86	73.77

Note: Blank space indicates that no data were collected.

TABLE 7. Cave Creek (CC) soil properties and ecosystem dynamics for Summer 2008 across the landscape.

Summer 2008	Non-alignment area (Far)		Natural rock alignment (Far)		Non-alignment area (Near)		Anthropogenic rock alignment (Near)	
Variable	Mean	Std. Dev	Mean	Std. Dev	Mean	Std. Dev	Mean	Std. Dev
pH	7.93	0.26	7.89	0.40	8.01	0.27	8.00	0.27
Soil Organic Matter (SOM) (%)	3.29	0.33	3.29	0.87	2.85	0.29	3.20	0.65
Water Holding Capacity (WHC) (%)	41.27	4.54	45.75	6.26	42.06	5.34	42.09	5.60
Nitrate (NO^{3-}) (μg g^{-1}dry soil)	4.25	5.36	3.27	2.12	4.62	2.82	4.01	2.10
Ammonium (NH_4^+) (μg g^{-1}dry soil)	3.57	2.98	4.23	2.53	4.20	1.98	4.41	2.48
Total Inorganic Nitrogen (TIN) (μg g^{-1} dry soil)	7.82	8.15	7.50	4.25	8.82	4.62	8.42	4.38
Potential Nitrogen Mineralization (N-Min) (μg g^{-1}day^{-1})	0.14	0.47	0.00	0.49	0.62	0.75	0.45	0.34
Nitrification (μg g^{-1}day^{-1})	0.49	0.51	0.42	0.52	1.02	0.77	0.87	0.40
Phosphate (PO_4^{3-}) (μg g^{-1}dry soil)	12.03	6.11	17.73	13.19	8.71	3.85	9.04	3.63
Soil Moisture (%)	1.70	0.30	1.60	0.30	1.70	0.20	1.80	0.30
Sand Fraction (% Sand)	37.68	5.30	38.18	5.15	41.22	4.04	35.73	4.11
Silt Fraction (% Silt)	48.25	4.22	48.54	4.43	44.71	3.30	51.57	3.00
Clay Fraction (% Clay)	14.07	1.66	13.28	2.01	14.08	2.55	12.70	1.87

TABLE 8. Cave Creek (CC) soil properties and ecosystem dynamics for Fall 2008 across the landscape.

Fall 2008	Non-alignment area (Far)		Natural rock alignment (Far)		Non-alignment area (Near)		Anthropogenic rock alignment (Near)	
Variable	Mean	Std. Dev	Mean	Std. Dev	Mean	Std. Dev	Mean	Std. Dev
pH	7.87	0.43	7.72	0.42	8.18	0.33	7.96	0.34
Soil Organic Matter (SOM) (%)	2.77	0.33	2.82	0.44	2.64	0.25	2.79	0.37
Water Holding Capacity (WHC) (%)	41.27	4.54	45.75	6.26	42.06	5.34	42.09	5.60
Nitrate (NO^{3-}) (µg g^{-1}dry soil)	10.15	6.28	9.91	5.72	7.85	4.63	9.90	5.95
Ammonium (NH_4^+) (µg g^{-1}dry soil)	1.25	1.32	1.30	0.73	1.18	0.53	2.29	1.25
Total Inorganic Nitrogen (TIN) (µg g^{-1} dry soil)	11.41	7.09	11.21	6.09	9.03	4.94	12.19	6.66
Potential Nitrogen Mineralization (N-Min) (µg $g^{-1}$$day^{-1}$)	0.96	0.31	1.14	1.13	0.44	0.21	0.33	0.31
Nitrification (µg $g^{-1}$$day^{-1}$)	1.08	0.31	1.10	0.61	0.56	0.23	0.56	0.33
Phosphate (PO_4^{3-}) (µg g^{-1}dry soil)	13.68	5.94	20.00	11.49	10.95	3.39	13.31	7.25
Soil Moisture (%)	0.03	0.01	0.03	0.01	0.03	0.00	0.03	0.01
Sand Fraction (% Sand)	37.22	4.30	36.31	3.96	41.97	3.44	39.09	4.53
Silt Fraction (% Silt)	52.29	3.98	49.65	2.99	48.40	2.40	50.69	3.68
Clay Fraction (% Clay)	10.48	1.28	14.04	1.88	9.62	1.79	10.22	1.57
Effective Cation Exchange Capacity (ECEC) ($cmol_c$/kg soil)	16.26	2.54	15.11	3.37	15.30	2.20	15.27	2.67
Electrical conductivity (EC) (µmhos/cm)	110.87	24.62	100.13	43.18	90.33	21.50	100.67	37.41

TABLE 9. Precipitation amounts during the growing season at Agua Fria National Monument (AFNM) and Cave Creek (CC) prior to biomass harvest.

	Agua Fria National Monument (AFNM)	Cave Creek (CC)
Growing Season	Precipitation (mm)	Precipitation (mm)
October 2007- May 2008	278	100
June 2008-October 2008	167	

Note: Blank space indicates that no data were collected.

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