Eolian Deposition and Soil Fertility in a Prehistoric Agricultural Complex in Central Arizona

by

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ABSTRACT

Prehistoric farmers in the semi-arid American Southwest were challenged by marked spatial and temporal variation in, and overall low levels of, precipitation with which to grow their crops. One strategy they employed was to modify their landscape with rock alignments in order to concentrate surface water flow on their fields. A second challenge that has been less focused on by archaeologists is the need to maintain soil fertility by replenishing nutrients removed from the soil by agricultural crops. Numerous studies have shown that rock alignments can result in long-lasting impacts on soil properties and fertility. However, the direction and magnitude of change is highly variable. While previous work has emphasized the importance of overland flow in replenishing soil nutrient pools, none have investigated the influence of eolian deposition as a contributor of mineral-derived nutrients. This thesis explores the effects of the construction of rock alignments, agricultural harvest, and eolian deposition on soil properties and fertility on Perry Mesa within the Agua Fria National Monument. This site experienced dramatic population increase in the late 1200s and marked depopulation in the early 1400s. Since that time, although agriculture ceased, the rock alignments have remains, continuing to influence runoff and sediment deposition.

In the summer of 2009, I investigated deep soil properties and mineral-derived nutrients on fields near Pueblo La Plata, one of the largest pueblos on Perry Mesa. To examine the effects of rock alignments and agricultural harvest independent of one another, I sampled soils from replicated plots behind alignments paired with nearby plots that are not bordered by an alignment in both areas of high and low prehistoric agricultural intensity. I investigated soil provenance and the influence of deposition on mineral-derived nutrients through analysis of the chemical composition of the soil, bedrock and dust.

Agricultural rock alignments were significantly associated with differences in soil texture, but neither rock alignments nor agricultural history were associated with significant differences in mineral-derived nutrients. Instead, eolian deposition may explain why nutrient pools are similar across agricultural history and rock alignment presence. Eolian deposition homogenized the surface soil, reducing the spatial heterogeneity of soils. Dust is important both as a parent material to the soils on Perry Mesa, and also a source of mineral-derived nutrients. This investigation suggests that prehistoric agriculture on Perry Mesa was not likely limited by long term soil fertility, but instead could have been sustained by eolian inputs.

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INTRODUCTION

Human population dynamics are shaped by external environmental drivers such as climate or soil fertility, social drivers such as conflict and cooperation, and combined social-ecological factors, as humans respond to and modify environmental conditions (Ensor et al., 2003; Vitousek et al. 2004; Hunt et al., 2005). In the arid and semi-arid ecosystems of the American Southwest, climate, arable land and water availability have played important roles in prehistoric human migration and settlement patterns (Fish & Fish 1992; Ingram, 2010). For example, severe droughts appear to have contributed to the abandonment of the San Juan Basin and the Four Corners Region in the 12th and 13th centuries AD (Benson et al., 2007). However, people also respond with actions that can either ameliorate or exacerbate the availability of limiting resources. For instance, while crop success in upland regions was ultimately limited by precipitation, prehistoric people actively manipulated topography and surface rock distribution to maximize surface runoff onto fields (Sandor et al., 1990; Sullivan, 2000; Norton et al., 2003). Although these behaviors and others mitigated the negative impacts of climate variability, in some cases, they also intensified environmental limitations through soil nutrient depletion and erosion (Sandor et al., 1990; Sullivan, 2000).

The prehistoric population within central Arizona underwent dramatic changes from 1200AD to the mid 1400s AD, prior to European contact. While most settlements the US Southwest were declining in population in the late 1200's, settlements began to expand in size in and around the Verde Valley, a region characterized by broad, high elevation plateaus incised by deep canyons from tributaries of the Verde River and bounded to the north by the Mogollon Rim of the Colorado Plateau. One of these sites was on the top of Perry Mesa, located 80 km north of the Phoenix Basin at 1350 m in elevation where people constructed multi-room pueblos situated on the plateau perimeter (Stone, 2000; Kruse-Peeples et al. 2009). Over the next 100 years, the population rapidly expanded and the number of rooms more than tripled (Ingram 2010), but in the early to mid 1400s, Perry Mesa was abandoned by its inhabitants. Wilcox et al. (2001) posited that political conflict between Verde Valley inhabitants, the 'Verde Confederacy', and Hohokam populations to the south drove both settlement and the abandonment of the region. However, recent examination of trade routes by Kelly et al. (2010) suggests lower connectivity and coordination between settlements than expected by the Verde Confederacy model. Also, Kruse (2007) suggests that the large tracts of uninhabited land surrounding the pueblos served an agrarian purpose, rather than a defensive one.

The reasons behind the abandonment of Perry Mesa are not well understood. On the on hand, social isolation in the context of increasing population aggregation at a few places (e.g. the Hopi Mesas) may have been a driver (Bernardi & Brown, 2004). On the other hand, a hypothesis, supported by evidence from other prehistoric settlements in the Southwest, is that population decline on Perry Mesa was due to rapid agricultural intensification that degraded soil properties and fertility. Previous studies have demonstrated that prehistoric construction and farming of runoff agricultural fields led to long-term changes in soil properties, depending on soil-forming state factors and variation in human activity. For example, in the Mimbres area of New Mexico, long-term cultivation of runoff agriculture in grasslands resulted in nutrient depletion and accelerated erosion rates that persist eight centuries after abandonment (Sandor et al., 1990). In contrast, Homburg et al. (2005) showed that New Mexican Zuni field soils located downhill from organic matter-rich, upland forests are more fertile than uncultivated soils despite a millennium of agricultural activity. In prehistoric settlements in the Grand Canyon, cultivated Mollisols from nutrient-rich grasslands were depleted of organic matter and phosphorus, while cultivated Aridisols from nutrient poor pinyon-juniper woodlands were enriched in available calcium and had higher cation exchange capacity (Sullivan, 2000). With no upland area to draw from, the gentle, grassland slopes of Perry Mesa may have been vulnerable to soil fertility loss over time in the face of rapid intensification of runoff agriculture. Thus, losses in soil fertility over time may have played a role in population decline.

Previous archaeological work in arid and semi-arid agricultural systems has emphasized the importance of nutrient replenishment through runoff or overland flow as a prerequisite for sustainable agricultural production (Nabhan, 1979; Norton et al., 2003; Homburg et al., 2005). However, eolian deposition – input of material from wind – is another well known process that contributes to dryland soil properties, including soil mass, the formation of desert varnish and pavements, and the distribution of carbonate and clays (Lattman, 1973; Yaalon & Ganor, 1973; McFadden et al., 1987; Van der Hoven & Quade, 2002). Recent evidence suggests that atmospheric inputs of mineral-derived nutrients such as phosphorus (P) and potassium (K) in dust can be important as supplements for plant growth in various ecosystems (Swap et al. 1992; Chadwick et al., 1999; Reynolds et al., 2001; Soderberg and Compton, 2007; Lequy et al., 2012). Soils formed from eolian-derived loess mantles have been identified in the Southwest (Wells et al., 1985; McFadden et al., 1986), and prehistoric farmers are known to have taken advantage of the fertile loess on mesa tops in the Four Corners area (Arrhenius & Bonatti, 1965). However, despite its ecological importance, the implications of eolian deposition as a supplement for agricultural production have yet to be considered in southwestern archaeology.

In this study, I explored the effects of agricultural activity and environmental factors of topography and eolian deposition on deep soil properties near prehistoric settlements on Perry Mesa in central Arizona. Specifically, I asked:

(1) How does alteration in slope, either through human construction of rock alignments on agricultural fields or the natural presence of such alignments near the edges of the mesa, affect deep soil properties in this semi-arid grassland?

(2) Could dust have been an important source of mineral-derived nutrients for prehistoric crops?

(3) Did prehistoric agricultural harvest permanently deplete mineral-derived nutrients?

The effects of slope on soil properties have been thoroughly studied and patterns of surface flow, infiltration, and material deposition across hill slopes are well understood. I hypothesized that rock alignments, either natural or those constructed by prehistoric farmers for runoff control, reduce the slope on hillsides, resulting in predictable patterns in soil properties behind alignments. Soils behind alignments should be deeper, contain more organic matter and finer-textured particles, and exhibit higher water holding capacity. I hypothesize that eolian deposition is a major source of soil mass on Perry Mesa and could have been an important source of mineral-derived nutrients for crops. Agricultural fields on the mesa had no uplands to replenish nutrients through overland flow, and eolian deposition is known to modify soil properties in dryland ecosystems. Deposition may have replenished mineral-derived nutrients on annual or decadal timescales, influencing the sustainability of prehistoric agriculture. Finally, I do not expect the effects of prehistoric agricultural harvest to be detectable in modern soils properties, in part due to the short duration of habitation.

METHODS

Study Site

Today, Perry Mesa is located within the Agua Fria National Monument and Tonto National Forest, located at 1350 m in elevation, 80 km north of the Phoenix Basin in Arizona (Figure 1). The top of Perry Mesa is characterized by gently sloping hills (0-2%) and a semi-arid grassland that receives 300-400 mm precipitation annually (Maricopa County Flood Control, 2011). Dominant species include the perennial grass *Pleuraphis mutica* Buckley and the shrub *Acacia gregii* Gray. Soils in the region are characterized as Vertisols of the Springerville series (fine, montmorillonitic, mesic Arid Haplusterts; USDA- NRCS 1997) and overlay a 10 million year old basalt flow, the Hickey Formation (Leighty, 2007).

My study site was located along a portion of the western edge of Perry Mesa near the ruins of the 70-75 room structure of Pueblo La Plata, one of the seven largest pueblos on the mesa (Kruse-Peeples et al., 2009). On southern facing slopes within 0.5 km of the pueblo, archaeologists identified constructed rock alignments (Kruse, 2005). This area bears further evidence of prehistoric agriculture, including a high density of artifacts and the presence of maize pollen (Kruse-Peeples et al., 2009; Smith, 2009). Further from Pueblo La Plata, 1 km south and separated from the pueblo by a gorge, is an area that lacks large room blocks and agricultural alignments, and supports a low density of artifacts. These characteristics suggest that – while this area was accessible to habitants at Pueblo La Plat – it was less intensely farmed than the field systems near the pueblo or not farmed at all (Kruse-Peeples et al., 2009).

Beginning in the mid 1870s, more than four centuries after the prehistoric abandonment of the settlements on Perry Mesa, cattle, horses and sheep were introduced onto the Mesa. The region has since been grazed, and historic land management included both fire suppression, and – most recently – prescribed burns (Briggs et al., 2005). To minimize the confounding factors of modern land management practices, I selected sites that share common historic land use characteristics including similar recorded grazing densities and fire management.

The Bureau of Land Management (BLM) had an approximate stocking rate of 381 cattle on 70,900 acres per year prior to 2007, when grazing ended (Trujillo 2011). The former agricultural area is located closer to a cattle tank (0.5-0.75 km distance) than the non agricultural area (1-1.5 km distance); however, in dryland systems, the most severe impacts of low-density cattle on soil and plant properties are usually within 0.5 km of the water source (Nash et al., 1999; Adler and Hall, 2005). Thus, we can assume the impacts from grazing on the two sites are similar

Experimental Design

Previous studies of the biophysical legacies of prehistoric dryland agriculture have often used a paired sampling design, comparing soils behind rock alignments within cultivated fields to soils in uncultivated areas without rock alignments (Sandor et al., 1990; Sullivan, 2000; Homburg et al., 2005). However, this design confounds the direct effects of active agricultural harvest from the indirect effects of rock alignments – and thus a change in slope – on soil properties. To test the independent effects of these two processes, I followed a design used by Trujillo (2011), sampling soils from replicated plots behind alignments paired with nearby plots that are not bordered by an alignment in both areas of high and low prehistoric agricultural intensity. The alignments in the area of low to no agricultural intensity were natural alignments towards the edge of the mesa. Specifically, I sampled soils in the agricultural area within 0.5 km of Pueblo La Plata (hereafter referred to as “Near”) and compared these to soils sampled in the less intensively used area 1 km to the south of Pueblo La Plata (hereafter as “Far”). To compare the effects of rock alignments on soil properties independent of agricultural activity, I selected three plots in each area that were either directly upslope of rock alignments (“Rock alignment”), or not behind alignments (“No alignment”) (Figure 1). In total, I sampled across a replicated 2 x 2 factorial design that included the independent factors of agricultural history (‘Distance’, near and far) and feature (‘Alignment’, rock alignment and no alignment). Within each factor of this design, I randomly chose a subset of three replicate plots from a larger group of 15 replicate plots established by Trujillo (2011) for a total of 12 plots.

Soil characterization and sampling

In the summer and fall of 2009 (June – November), I excavated 1 m^2 soil pits down to bedrock at each of the 12 plots, avoiding areas of previous surface soil sampling that were marked by nails. I recorded soil properties (depth, structure, texture, root density, color and reaction) in the field using standard NRCS methods (Schoeneberger et al., 2002) and characterized horizons based on structure, root density and texture. I collected soil samples by horizon or every 10 cm within horizons that were thicker than 15 cm. Following field collection, I transported soil samples to Arizona State University for laboratory analysis.

Soil properties and nutrient analyses

Sieved soils were analyzed in the laboratory for a suite of physical and chemical properties using methods from the Soil Society of America. Samples were sieved to 2 mm to remove rock fragments. Soil organic matter (%) was determined by the loss-on-ignition method as ash-free dry mass following combustion of 30 g of oven-dried soils for 6 hours at 550°C (Sparks, 1996b). I measured water-holding capacity (WHC) as the percent of water held in 20 g of soil after saturation and 24 hours of draining through a GF-A filter. I analyzed soil particle size through the sieve hydrometer method, determining clay content (%) through the hydrometer method (40 g soil in 100 mL of 50 g/L sodium hexametaphosphate) followed by sieving to 53 µm to measure sand content (%) and calculating silt content (%) by difference (Dane & Topp 2002). To measure the bulk density ($g\ cm^{-3}$), I removed and weighed intact soil peds, coated them with saran and estimated volume by water displacement (Dane & Topp 2002). For soils that would not remain intact as peds, I removed known volumes of soil with a core and subtracted the weight and volume of coarse fragments (>2 mm) in the lab (Dane & Topp 2002). Nitrate+ nitrite (summed as $\mu g\ NO_3^-\ g^{-1}$ dry soil) and ammonium ($\mu g\ NH_4^+\ g^{-1}$ dry soil) were extracted from 10 g of soil with 50 mL of 2M KCl (Sparks, 1996c) and measured colormetrically by flow injection analysis on a Lachat Quickem 8000 (ASU, Tempe AZ). Potential net nitrification ($\mu g\ NO_3^-\ g^{-1}\ d^{-1}$) and potential net nitrogen mineralization were determined by comparing nitrate and ammonium concentrations before and after incubating soils for ten days at 60% WHC (Weaver et al., 1994). Phosphate ($\mu g\ PO_4^{3-}\ g^{-1}$ dry soil) was extracted from 2 g of dry soil with 40 mL 0.5M $NaHCO_3$ (Sparks, 1996a) then measured by segmented flow analysis on a Bran-LuebbeTraacs 800 Autoanalyzer (ASU, Tempe AZ).

Analysis of soil and parent material chemical composition

I compared the chemical compositions of soils and parent material to evaluate the sources of mineral-derived nutrients. Ratios of rare earth elements (REE) such as lanthanum (La) through lutetium (Lu) have been used in provenance studies as a method to fingerprint soils to determine the origin of parent material (Taylor & McLennan, 1985; McLennan 1989; Muhs et al., 2008). Chondrite normalized ratios of lanthanum and ytterbium (La_N/Yb_N) and ratios of europium anomalies (Eu_N/Eu^*) vary between rock types. I compared the chemical composition of soil from all horizons, bedrock from the bottom of each pit, and samples of wind-derived dust from surface traps. The weathering rinds from samples of bedrock were removed with a rock saw at ASU prior to chemical analyses. I collected dust samples over an two year period from dust collectors located at the agricultural and non agricultural areas near Pueblo La Plata where my soil pits were located, and from an additional prehistoric agricultural site (Bull Tank Field) located 3 km south west of Pueblo La Plata. At each of the three sites, the dust collectors were located at the top of the slopes at least 50 m apart from one another to account for the patchiness of the monsoon rains. Four collectors were installed 2 m off the ground following the design of Reheis and Kihl (1995). Additionally, I installed two collectors at 1 m height to test whether height of the collector affects the rate of dust collected. Thus, in total, I installed 18 dust collectors on Perry Mesa. The dust collectors were constructed by mounting a teflon-coated cake pan atop a PVC pole. In the cake pan, ¼ inch mesh was set 5 cm below the rim and then covered with a layer of glass marbles. To discourage use as perches, I attached bird spikes to the edges of the collectors.

I installed the dust traps in September 2009 and collected the sediment in August 2010 (11 months total duration) and again in September 2011 (13 months total duration). To collect the sediment, I rinsed the pans and marbles with deionized water into polyethylene bottles and oven dried the samples at 105 °C. I pooled all the dust samples within each collection height to obtain the minimum required mass for the chemical analyses. I sent samples of soil, rock and dust to ALS Chemex in Reno, Nevada where they were pulverized to pass through a 75 µm mesh, then analyzed for major elements and rare earth elements by ICP-AES and ICP-MS, respectively, following lithium borate fusion. Major elements were reported as percentages and rare earth elements were reported as parts per million (ppm; Appendix 10).

For analyses of soil properties and nutrients, I grouped data by the depth of the midpoint of the sample collected (0-5 cm, 5-10 cm, 10-25 cm, and ≥25 cm) and compared these results to values derived from binning instead by horizon. I compared the content of the mineral-derived nutrients P – total and extractable – and total K by integrating concentrations by depth both within horizons and across the entire soil profile. For each horizon, concentrations were multiplied by bulk density and depth, then horizon pools were summed to obtain the pool of the entire soil profile (g m^{-2}). I used the ‘hybrid’ bulk density (Throop et al., 2012) for this calculation, which is the mass of the fine earth fraction (<2 mm) divided by volume of the fine earth fraction and rock fragments, in order to account for the volume taken up rock fragments. The assumption that the soil column is 100% fine earth fraction can lead to the overestimation of nutrient pools, particularly in the rocky soils characteristic of semi-arid ecosystems. I did not analyze the effect of agriculture or alignment on soil nitrogen (N) pools or transformations because distribution of this element varies depending on biological activity and samples from different replicate sites were collected during different times of the year under variable temperature and soil moisture conditions.

Chemical changes in mineral-derived nutrients

Evaluation of element pools is a method that has been used to assess enrichment or depletion of mineral-derived nutrients in soil (Sandor et al., 1990; Sullivan, 2000; Norton et al., 2003). However, this method does not distinguish changes in mineral-derived nutrient content due to chemical processes such as agricultural harvest from physical processes, such as erosion (Brimhall et al., 1992). In order to investigate the chemical loss of mineral-derived nutrients from agricultural harvest, I used a mass balance approach by calculating tau (τ). This analysis references mobile elements to immobile elements in weathered material (soil) and parent material to assess the proportion of the element lost or gained through chemical, rather than physical, processes (Chadwick et al., 1990; Brimhall et al., 1992). Tau is defined as:

$$\tau_{j,w} = [(C_{j,w}/C_{j,p}) \text{ x } (C_{i,p}/C_{i,w})] -1$$

where C_j is the concentration of element *j*, C_i is the concentration of a geologically immobile index element *i*, *w* refers to the weathered material, and *p* refers to the parent material. In my analyses I used niobium (Nb) as the immobile index element (*i*) as it has been shown to be consistently immobile across weathering intensities and soil mineral compositions (Kurtz et al., 2000). A positive τ means there is a chemical gain of an element relative to the parent material while a negative τ means there has been a chemical loss of an element (Kurtz et al., 2000). While agriculture can drive the loss of mineral-derived nutrients, abiotic processes such as leaching can do so as well. In order to determine whether losses are due to agricultural withdraw or abiotic processes, I compared cations strongly cycled by plants (P, K, and calcium [Ca]) to cations that are less strongly cycled by vegetation (aluminum [Al], iron [Fe], and sodium [Na]).

In order to investigate the contributions of bedrock and dust to Perry Mesa soil mass and composition, I analyzed the mass balance of silica (Si) as well as the REE composition. Since silica readily weathers from minerals, enrichment of silica relative to bedrock suggests an additional source of soil material. I compared REE ratios of dust, rock, and soil grouped by depth intervals. Since I was not testing the effects of distance from the pueblo or presence of alignments on the chemical composition of soils and parent material, I pooled all soil data together and grouped by similar midpoint depth. The number of data replicates for REE analysis was 5 as it allowed for a more detailed examination of chemical distribution with depth.

Statistical Analysis

I used SPSS 20 software for all of my statistical analyses. To compare soil properties (clay and sand content, soil organic matter, WHC) and nutrients (total P, extractable P, τ_P) by agricultural history and the presence of rock alignments, I conducted a two-way ANOVA across the entire soil profile, and within each depth or horizon interval using distance (near or far) and presence of rock alignments (alignment or no alignment) as fixed variables. In order to investigate the contribution of dust and bedrock to soil mass, I conducted one-way ANOVA with post-hoc Tukey tests within each depth interval with mineral type (soil, rock, or dust) as the independent variable and τ_{Si} referenced to rock and dust and REE ratios as the dependent variables.

The assumptions of normality and homogeneity of variance were tested for all analyses prior to ANOVA analyses. Normality was tested using the Sharpiro-Wilk test and evaluating histograms while homogeneity of variance was tested using the Levene test. If the assumptions were violated, the data were transformed according to the ladder of power (Velleman & Hoaglin, 1981) and retested until the assumptions were met. In the few cases that the assumptions were not met through transformation (10 cases in 180 total analyses), I compared the outcomes from the two-way ANOVAs with sequential one-way non-parametric Mann Whitney tests and found no change in significance. Sequential hypothesis tests of significance are subject to increasing probability of Type 1 error (a null hypotheses will be rejected when it is true) with each additional statistical test performed. One method to reduce this Type 1 error is to divide the alpha by the total number of tests performed, also known as the Bonferroni correction (Holm 1979). However, Bonferroni corrections also reduce the power of statistical tests and can leave studies with small sample sizes vulnerable to high levels of Type II error (Cabin & Mitchell, 2000; Nakagawa, 2004). Thus, due the low replication in my experimental design, I did not adjust my a priori alpha value ($\alpha = 0.05$) but instead interpret p-values close to 0.05 with caution.

RESULTS

Prehistoric human activity and eolian deposition have both influenced soils on Perry Mesa, but in different ways. Agricultural activity was associated with changes in deep soil texture through the intentional construction of agricultural rock alignments, but farmed sites showed no evidence of augmentation or depletion of soil fertility. Instead, eolian deposition likely drives the abundance and distribution of mineral-derived nutrients in Perry Mesa soils. Chemical analyses suggest that soils on the mesa are largely derived from dust. The rate of deposition and the characteristics of the wind-deposited material support the hypothesis that eolian deposition could have replenished mineral-derived nutrients on a human time scale.

Field-characterized soil profiles

All soil profiles described in the field shared common horizons, structure and root distribution. However, while rock alignments had no effect on visual horizon properties, surface soil characteristics were significantly associated with agricultural history. All soils contained a 3 to 11 cm thick A horizon with fine granular structure, an upper B_t horizon with sub-angular to angular blocky structure ranging from 3-30 cm depth, and a lower B_t horizon with massive structure that ranged from 30-75 cm in depth (Appendices 1-2). Very fine and fine roots were concentrated in the A and upper B_t horizons, with a lower density of very fine roots reaching bedrock in the lower B_t horizons along vertic cracks. Rock fragments were high in concentration at the surface of soils (over 50% in the A horizons) then fell to approximately 20% or less in the B_t horizons. The soils with an agricultural history near Pueblo La Plata had A horizons that were on average twice as thick as those in soils with no agricultural history (two-way ANOVA; distance, $p = 0.04$; Table 1). Former agricultural soils near the pueblo also supported a lower surface cover of boulders (distance, $p=0.01$; Table 2) and stones (distance, $p=0.03$) than non-agricultural soils further away.

Soil properties

The alteration of slope, through intentional construction of rock alignments or due to the natural occurrence of alignments at the edge of the mesa, resulted in subtle but significant impacts on deep soil properties. The presence of rock alignments, whether natural or anthropogenic, was not significantly associated with soil depth, horizon thickness, or soil organic matter when analyzed by depth or horizon (Table 1; Appendices 6-9). However, texture in subsurface soils (>10 cm) was significantly affected by rock alignments, depending on agricultural history.

Deep soils behind natural alignments had 5-10% higher clay content than adjacent soils without rock alignments while deep soils behind agricultural alignments had 5-10% less clay than adjacent non-alignment areas (Table 1; Figure 2a). This interactive effect of agricultural history on soil clay content behind alignments was consistent in the upper and lower B_t horizons (Table 1), and in the grouped A and upper B_t horizons that represent the likely rooting zone for vegetation in this ecosystem (distance*alignment, $p=0.01$). Average soil texture in the upper B_t horizon behind natural alignments is classified as a silty clay loam, which is finer than the silt loam texture in non-alignment soils. However, in former prehistoric agricultural soils, the average soil texture behind constructed rock alignments is a silty clay loam, which is coarser than silty clays of the non-alignment areas (Table 1.)

Although there are several sources of error associated with the use of the hydrometer to measure clay content, I minimized error through consistent methods. The hydrometer method tends to overestimate clay content, but it is still an appropriate method to use when comparing the clay content of soils relative to one another (Di Stefano et al., 2010). The temperature correction for the hydrometer is not consistent at extreme temperatures or with variation of the amount of soil used (Richter, 1931), but if temperature is controlled to within ±5°C and a blank is measured to compensate for temperature effects, the error in the calculated clay fraction is less than 1% clay (Gee & Bauder, 1979). The amount of soil I used did not vary and the temperature was consistent across all samples and within 4°C of the 20°C standard. Further error results from the misreading of the hydrometer, which can cause as much as 2.5% error in clay content (Gee & Bauder, 1979). Unpublished data from Trujillo et al. (2011) showed that clay content of subsamples from homogenized Perry Mesa soil varied in clay content an average of 3% (±2% standard deviation). As the differences in clay content found in this study were 5% or greater, I have confidence in the pattern in clay content in subsurface soils.

While the difference in clay content was consistent for subsurface soils whether grouped by depth or horizon, differences in the content of silt and sand were less predictable. Below 25 cm depth, soils behind agricultural alignments had 3-5% more sand than adjacent non-alignment soil, while soils behind natural alignments had 3-5% less sand (distance*alignment, p=0.01; Appendix 9). Differences in silt content were similar in direction and magnitude in the lower B_t horizons (agricultural distance*alignment, p=0.02; Table 1).

Despite differences in soil texture, when analyzed by depth, soils behind rock alignments had similar WHC as soils without rock alignments (Figure 2b). However, when analyzed by horizon, soils in the lower B_t horizon behind agricultural alignments had the capacity to hold less water than adjacent non-alignment soils, while those behind natural rock alignments could hold more (distance*alignment, p=0.03; Table 1).

Eolian deposition as a source of soil mass

Evidence from dust collections and chemical analyses suggests that eolian deposition is an important source of soil mass on Perry Mesa. Approximately 2.7

g $m^{-2}$was deposited on Perry Mesa in 2010 and ~14 g m^{-2} fell in 2011 (Table 3). Although inter-annual variation in climate is characteristically high in dryland regions, these rates are within the range of modern dust deposition in other areas of the US Southwest (1 – 60 g m^{-2}; Table 4). The role of dust as a parent material is clear from the mass balance of Si and the REE patterns throughout the soil profile. When referenced to bedrock, soils are enriched in Si at every depth, suggesting an additional source of soil minerals (Figure 3a). In contrast, there is a net depletion of silica when soils are referenced to dust as is expected from chemical leaching of this mobile element (Figure 3b), supporting the hypothesis that dust is a source of soil mass. The REE composition of the soil compared to the dust and bedrock further supports this hypothesis. The ratios of La_N/Yb_N and Eu_N/Eu^* of the soils on Perry Mesa are significantly different to that of bedrock but not significantly different than those of dust (Figure 4). This pattern remains consistent with depth (Figure 5).

Mineral-derived nutrients and major cations

Based on both nutrient pool and mass balance methods, the availability of mineral-derived nutrients was not significantly associated with prehistoric agricultural use. Soil P content – both the total and extractable pools – was not related to agricultural history or the presence of rock alignments when depth-integrated across the soil column (Table 5). Total P concentrations also did not differ with agricultural history or presence of rock alignments in any horizon (Appendix 10). When P content is referenced to the immobile element Nb and compared to either bedrock or dust, there is a net chemical loss throughout the soil depth, but no significant differences in the magnitude of that loss with agricultural use or alignment at any depth (Figure 6). Soils across the mesa are also depleted of the mobile elements K and Ca relative to bedrock or dust, but when referenced to dust there is a 5-10% greater depletion in the upper B_t horizons in former agricultural soils near the pueblo compared to far from the pueblo (Table 6). This pattern of depletion in the upper B_t horizons also occurs with iron (Fe) and sodium (Na) (Table 6) which are not cycled as strongly by plants, as P, K, or Ca, suggesting that the greater cation depletion in former agricultural soils is due to abiotic, rather than biotic, (i.e. crop uptake) processes.

Mineral-derived nutrients from eolian deposition

Eolian deposition of material to Perry Mesa is a source of soil mass and mineral-derived nutrients on time scales that may have been important to prehistoric agricultural production. Concentrations of the biologically important elements P and K in the dust collected were significantly higher than in the soils (Table 7). Dust had four to five times more P and 10-25% K than soils. In total, dust deposition added approximately 30 mg m^{-2} of P, 300 mg m^{-2} of K, and 360 mg m^{-2} Ca to Perry Mesa soils during a two-year period between 2010 and 2011 (Table 7).

DISCUSSION

Evidence of prehistoric agricultural activity on Perry Mesa persists six centuries after abandonment. The indirect effect of landscape modification through the construction, maintenance, and use of rock alignments for runoff control decreased soil clay content in ways that may have affected agricultural production in these vertic, shrink-swell soils. However, based on analyses conducted in this study, there is no evidence that agricultural production depleted soil nutrients over the long-term. Furthermore, my results suggest that eolian deposition was important ecological process that contributed to soil properties and fertility before, during and in the centuries since human occupation.

Rock alignments and soil properties

Contrary to my predictions, the presence of rock alignments – whether natural or anthropogenic – did not alter soil properties in consistent ways. As expected from previous findings on hill slopes (Jenny, 1941; Phillips & MacMahon, 1978; Sandor et al., 1986; Norton et al., 2003), soil behind natural alignments was more clayey than soils not bounded by alignments, but soil behind human-formed alignments was generally coarser in texture, containing more silt and sand and less clay. Kruse-Peeples (in prep) found a similar pattern in a nearby prehistoric agricultural field on Perry Mesa (Bull Tank fields) where soils behind rock alignments were coarser than unbounded soils. Kruse-Peeples hypothesized that as soils high in clay content have been shown to lose fines during storms (Pathack et al. 2004), fines were suspended and floated off the planting surfaces behind alignments during rain events. Also, prehistoric farmers likely maintained the constructed rock alignments so their effectiveness as barriers to runoff and erosion was diminished after abandonment. Erosion since abandonment may have driven further loss of clay particles behind constructed rock alignments.

In the silty clay vertic soils of Perry Mesa, alteration of soil texture behind constructed rock alignments in favor of more coarse-sized particles may have had important implications for prehistoric agricultural productivity. In soils with high clay content, plants have difficulty extracting tightly-held water from fine particle surfaces (Cosby et al., 1984; Dodd & Laurenroth 1997). Also, fine-textured surface soils reduce the rate and depth of infiltration, resulting in more rapid evaporation and lower primary production in water limited ecosystems (Noy-Meir, 1973; Sala et al., 1988). Not only does soil texture influence plant available water, but clay type and content also drive the shrink-swell characteristic of vertic soils (Zien El Abedine & Robinson, 1971; Ross, 1978; Thomas et al., 1998; Chertkov, 2003). As root exposure to air can cause water stress in plants, a reduction in the frequency and duration of soil crack formation could have been beneficial to crop production.

Eolian deposition and soil provenance

Although I expected eolian deposition of material to contribute a significant fraction of soil mass in these semi-arid landscapes, the results of the chemical analyses suggest that soils on Perry Mesa are largely derived from dust. I expected soil profiles in this system to show a net depletion of Si relative to bedrock, as this element is one of the most mobile elements in soils and is lost from terrestrial systems through weathering (Ruxton, 1968; Conley 2002). In semi-arid grasslands, an enrichment of Si at the top of the soil column is not unexpected as it is redistributed to the surface through biological pumping (Blecker et al., 2006), but if bedrock is the sole source of soil mass, we would expect either no change or a net depletion of silica relative to rock when integrating the entire soil column. Instead, soils across all sites are enriched in Si relative to the andesitic rock beneath them – suggesting an alternative source of soil mass – and the elemental composition of the soils matches that of dust more closely than that of bedrock. Additionally, if bedrock was a major contributor to soil mass, I would expect that the chemical composition of soils would be more similar to that of bedrock at depth. In all soils examined here, however, the dust signature is consistent from the soil surface to depth. While this pattern may be due in part to pedoturbation from the shrinking and swelling of clays that vertically homogenize soil chemistry, the absence of bedrock elemental signatures altogether provides strong evidence for the overwhelming influence of dust on the composition and mass of these soils.

The influence of agriculture and eolian deposition on nutrient distribution

While human construction of rock alignments had lasting effects on Perry Mesa soil properties, there is no evidence for a reduction of mineral-derived nutrients from agricultural harvest. Based on estimated crop yields, P content of maize and duration of agriculture (Table 8), the maximum P withdrawn by crop harvest over 150 years would have reduced the soil P pool by 10 g m^{-2}. However, this maximum P withdraw is an unlikely scenario. In this semi arid climate, it is likely that N would have limited crop production before P. Also, fields may not have been utilized the entire duration of Pueblo La Plata's habitation. Kruse (2007) hypothesized that the wide tracts of available land surrounding pueblos allowed prehistoric farmers to let fields periodically lay fallow. Finally, the similarity in nutrient pools across agricultural history and rock alignment presence may result in part from the short duration (~150 years) of habitation on Perry Mesa and long periods (~600 years) since abandonment. Dust deposition may have spatially homogenized the distribution of mineral-derived nutrients. The constant addition of dust, coupled with other adaptive agricultural strategies renders a depletion of mineral-derived nutrients unlikely to be detected.

Eolian deposition and prehistoric agriculture

Eolian deposition of material provides unique benefits for prehistoric farmers. Rather than soil weathering from the bottom of the soil column, new material is deposited on the top of the soil column – directly into the rooting zone of crops. Nutrients are readily weathered from due to the high surface area to volume ratio and wind-transported material tends to be enriched in plant important nutrients (Li et al, 2007; Lawrence & Neff, 2009). Indeed, the dust collected on Perry Mesa had higher P and K content than the soils. P adsorption to Fe oxides can reduce plant available P. However, P adsorption is reduced when ratios of P to Fe oxides are high and pH is neutral (Eghball et al., 1995;

Brennan et al 2008). Although I was unable to test the pH of the dust, the soil pH ranged from 6.5-8. The characteristics of eolian deposited sediments are ideal for agricultural supplementation.

The importance of eolian deposition as a source of mineral-derived nutrients to farmers depends on whether P input from eolian deposition could have replenished the soil pool on a human time scale. The annual P deposition rate calculated from the dust collected (20 mg m^{-2} yr^{-1}, Table 7) in this study would not have replenished maximum P withdraw from crop harvest annually (70 mg m^{-2} yr^{-1}, Table 8). However, the deposition rates measured do not reflect the influence of less frequent, large dust events. Large dust events are defined by the reduction of visibility to less than 11.3 km (Nickling & Brazel 1984). These events can deposit 2 – 5 g m^{-2}, but do not occur every year (Table 9). Incorporating representative large dust event frequencies and sizes rapidly increases the estimated annual P deposition rates (Table 9). Even the contribution of large dust events with low frequency and size nearly doubles the average annual rate of P deposition. P deposition based on the higher range of large dust event frequencies and sizes (83 mg m^{-2} yr^{-1}) could offset even maximum P withdraw from crop harvest (70 mg m^{-2} yr^{-1}). However, as previously discussed, maximum P withdraw from harvest was unlikely. Together, my results suggest that – while prehistoric farmers on Perry Mesa were unable to benefit from nutrient rich runoff from forested uplands like other agriculturalists in the southwestern US – eolian deposition would have been an important process in maintaining soil fertility for crop production.

CONCLUSION

The prehistoric inhabitants of Perry Mesa responded to ecological driving forces, such as precipitation variability, by constructing rock alignments to manage surface flow and enhance agricultural production. By altering the topography at this small scale, they inadvertently impacted deep soil texture in a way that may have further benefitted their crops. I found no evidence that farmers depleted mineral-derived nutrients through agricultural harvest. It is possible that prehistoric nutrient depletion would not detectable after six centuries of deposition homogenized the spatial distribution of mineral-derived nutrients. However, eolian deposition and other agricultural strategies may have prevented mineral-derived nutrients from becoming limiting. Nutrient limitations to crops may have been avoided either by agricultural strategies, such as leaving fields fallow, replenishment of mineral-derived nutrients from eolian deposition, or both. This investigation suggests that prehistoric agriculture on Perry Mesa was not likely limited by long term soil fertility, but instead could have been sustained by eolian inputs.

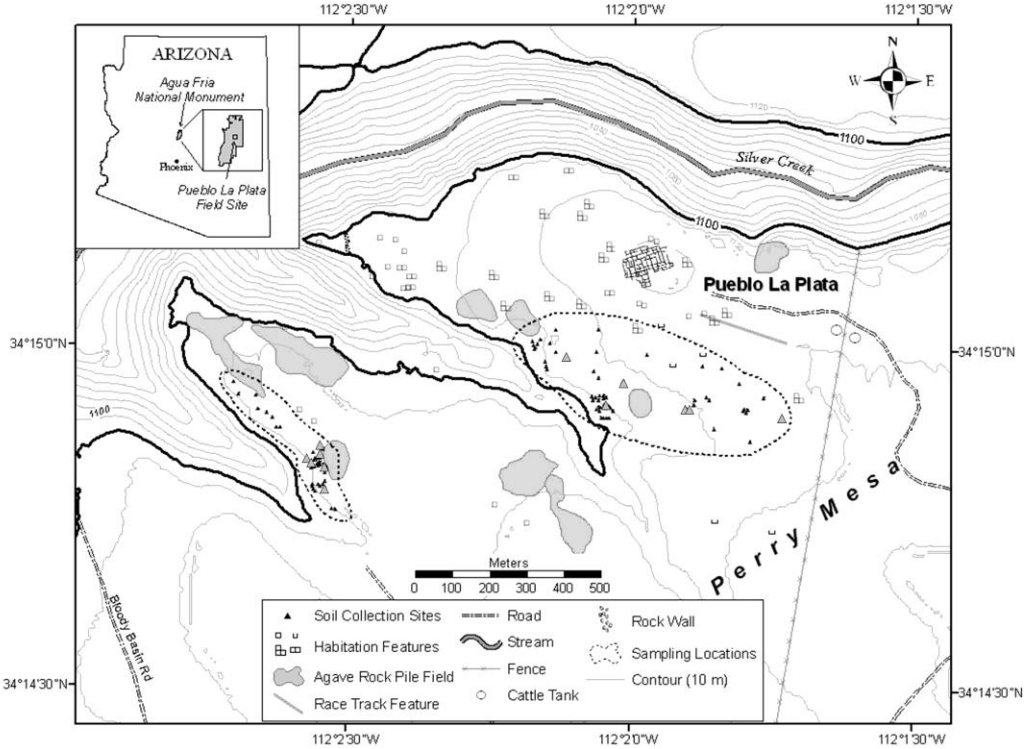

Figure 1. Map of sampling sites in agricultural (rightmost dotted ellipse) and non agricultural (leftmost dotted ellipse) areas near Pueblo La Plata in the Agua Fria National Monument, AZ. In this study, deep soil properties were analyzed within 12 plots (large grey triangles) randomly chosen from a subset of 60 sites studied by Trujillo (2011) (small black triangles).

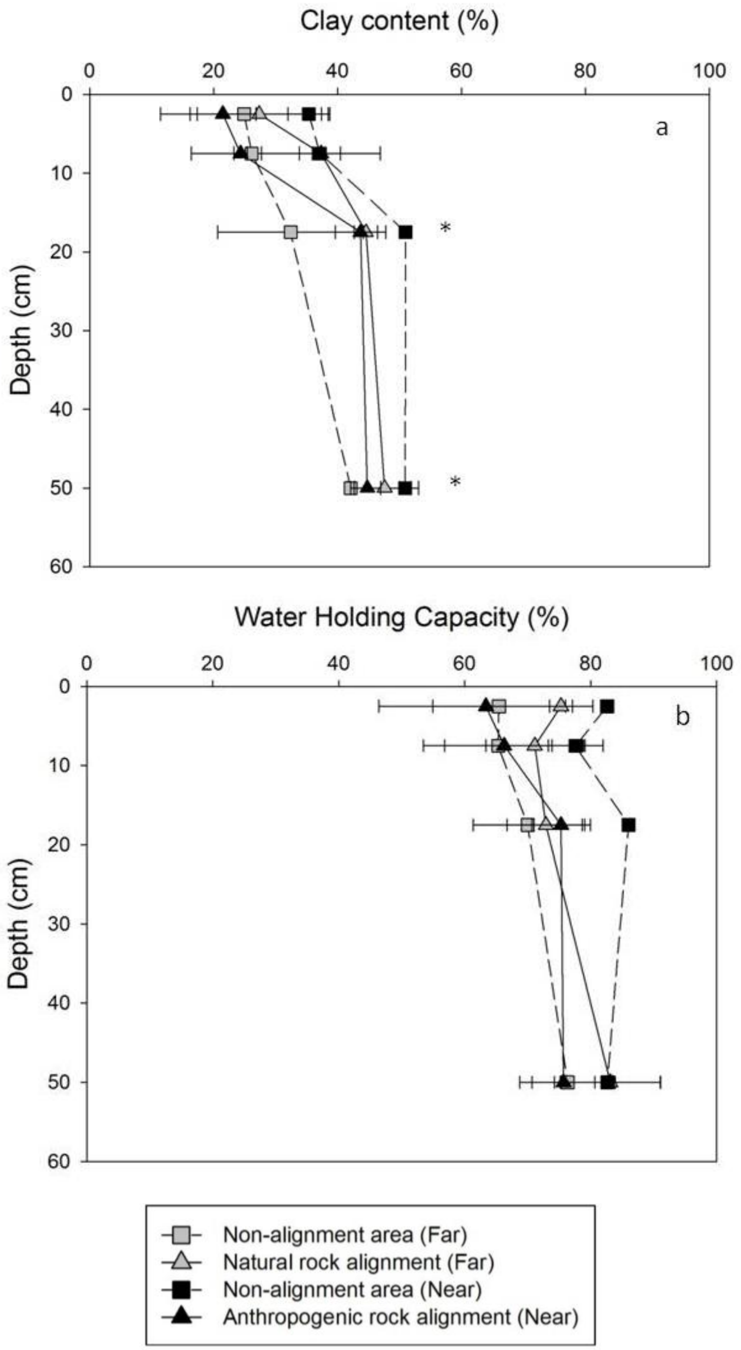

Figure 2. (a) Clay content with soil depth. Error bars are ± 1 standard deviation. Asterisks indicate significant interaction between agricultural history and presence of rock alignments at depths 10 cm to 25 cm (two-way ANOVA; distance*alignment, p = 0.05) and >25 cm (distance*alignment, p = 0.01). (b) WHC with soil depth. Neither alignment nor agricultural distance had significant effects on WHC, despite measurable changes in clay content (distance*alignment, p = 0.06).

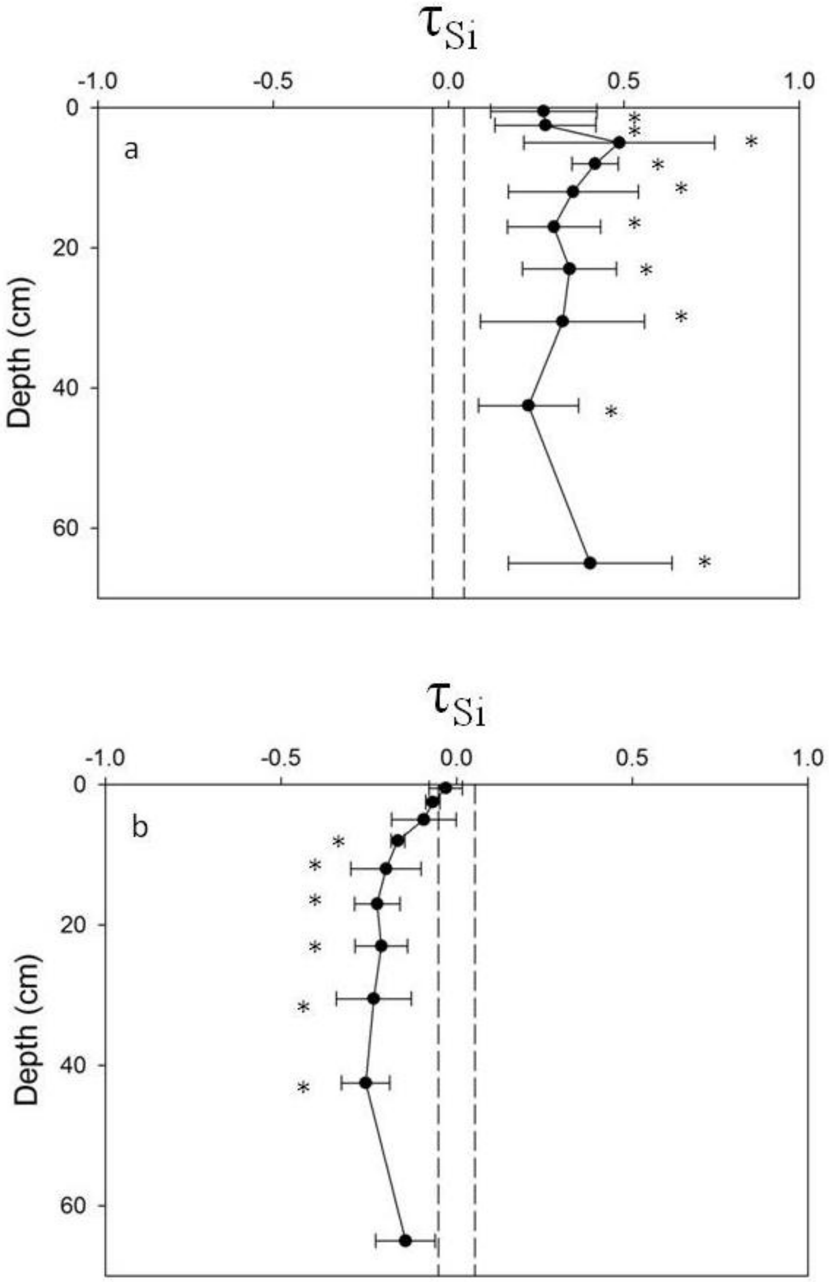

Figure 3. Tau silica, the proportion of chemical gain (>0) or loss (<0) of silica in soils referenced to (a) bedrock and (b) dust. Error bars are ± 1 standard deviation, asterisks indicate significant difference from 0 (rock or dust). Two-sample t-test, $p<0.05$. The dashed lines are +1 and – 1 standard deviation around the mean of 0.

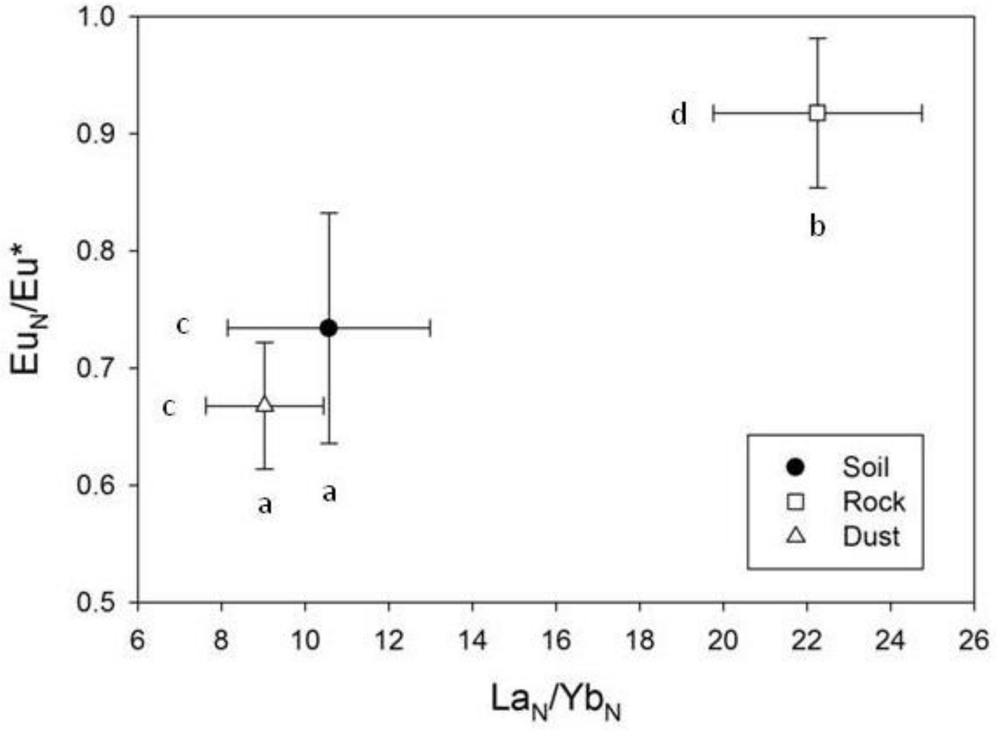

Figure 4. Chondrite normalized ratios of La_N/Yb_N versus Eu_N/Eu^*. Error bars are ±95% confidence interval. Letters indicate significant differences between minerals (one-way ANOVAs conducted on each ratio separately).

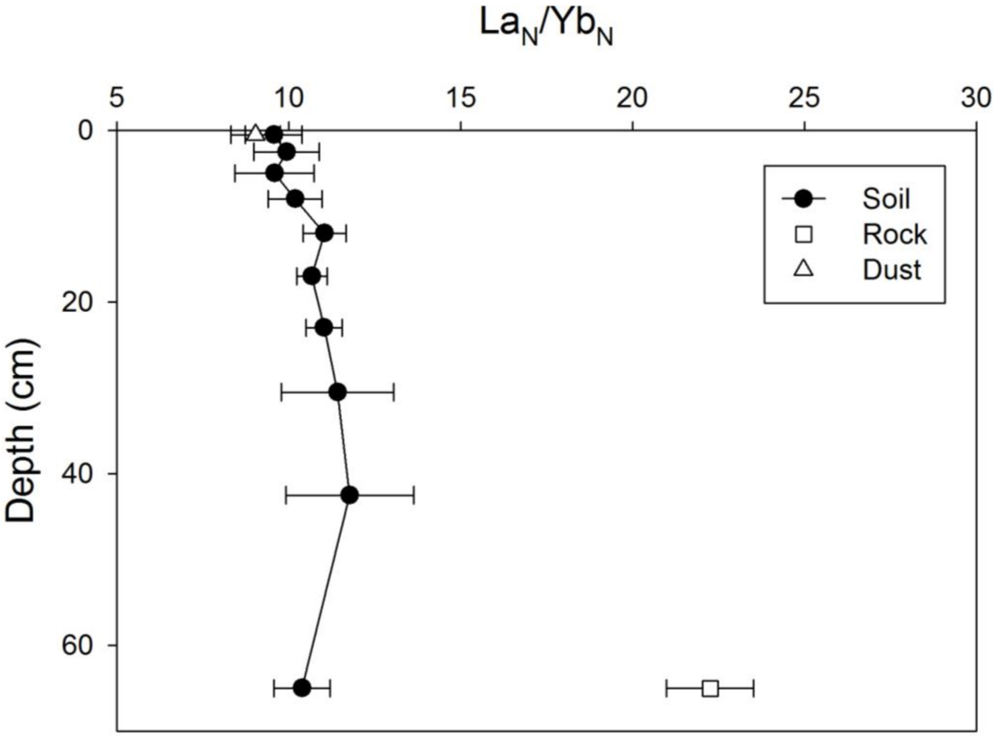

Figure 5. Chondrite normalized ratios of La vs. Yb with depth. Error bars are ±1 standard deviation. Note the dust samples (open triangles) are from the soil surface (0 cm) and rock samples (open square) are from bottom (65 cm) of the soil pits.

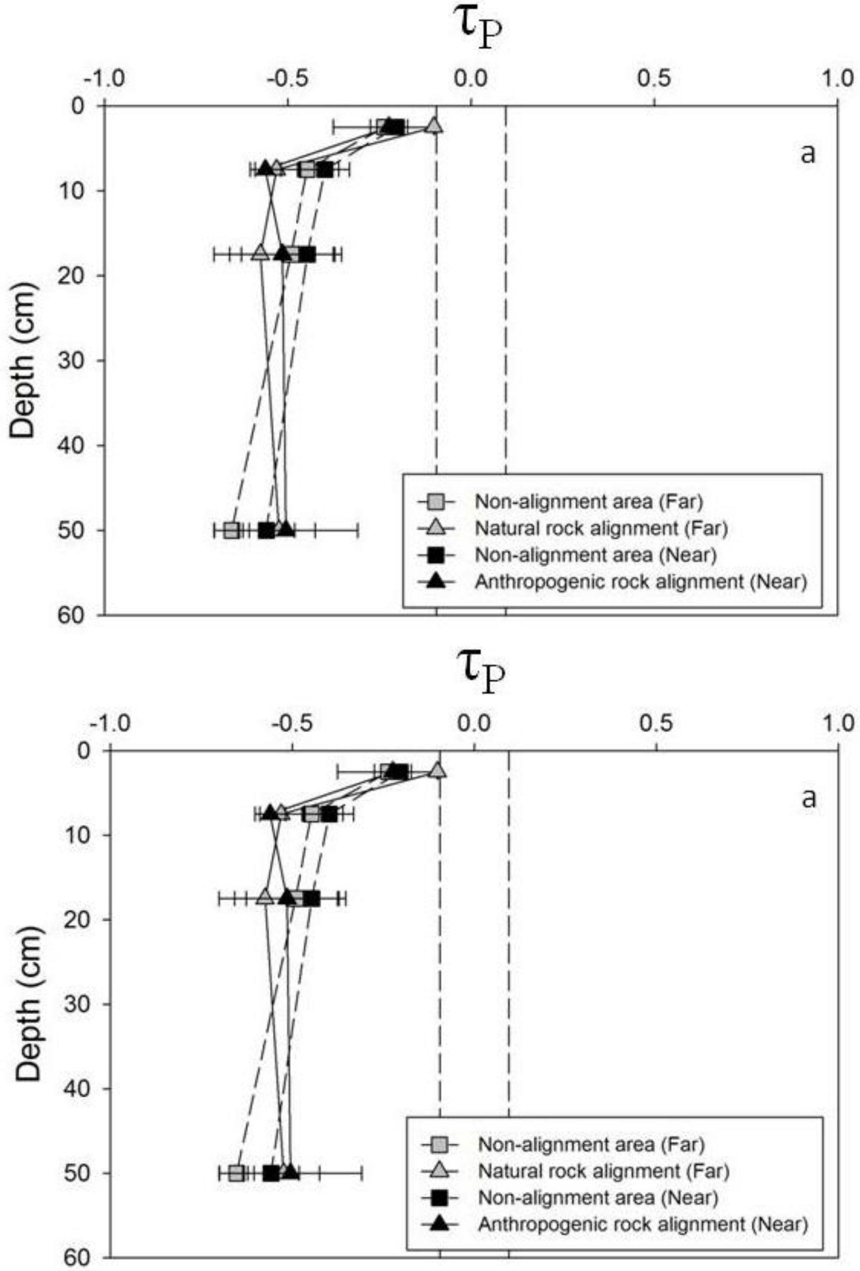

Figure 6. Tau P, the proportion of chemical gain (>0) or loss (<0) of P in soils referenced to (a) bedrock and (b) dust. For either case, there were no significant differences in τ_P by agricultural history or presence of rock alignments at any depth. Error bars are ± 1 standard deviation. As τ was calculated based on the mean values of the rock and dust chemistry, the dotted lines are + 1 and – 1 standard deviation around the mean of 0.

Table 1: Soil properties by horizon. P-values less than 0.05 highlighted in **bold**.

		Horizon thickness (cm)		Soil Organic Matter (%)		Sand content (%)		Silt content (%)		Clay content (%)		WHC (%)		Soil Texture †
Horizon		Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	
A	No alignment (Far)	2.3	0.6	5.70	0.46	17.7	2.9	57.4	16.0	25.0	13.5	65	11	SL
	Natural alignment (Far)	2.3	0.6	6.32	1.63	11.4	4.8	61.3	6.2	27.4	10.0	75	2	SCL
	No alignment (Near)	8.0	4.4	5.25	1.34	12.7	1.4	49.9	3.7	37.4	2.4	79	4	SCL
	Agricultural alignment (Near)	4.0	2.7	5.62	0.33	12.5	2.9	66.0	2.4	21.5	5.3	63	17	SL
	Two-way ANOVA p-values													
	Distance	***0.04***		*0.40*		*0.33*		*0.80*		*0.54*		*0.88*		
	Alignment	*0.22*		*0.46*		*0.12*		*0.09*		*0.23*		*0.63*		
	*Distance * Alignment*	*0.22*		*0.86*		*0.15*		*0.27*		*0.11*		*0.06*		
Upper B_t	No alignment (Far)	11.0	5.6	4.82	0.93	14.1	3.1	59.7	8.9	26.2	9.7	66	7	SL
	Natural alignment (Far)	9.7	2.5	4.68	0.77	8.8	4.6	53.9	5.3	37.3	9.6	71	8	SCL
	No alignment (Near)	21.3	11.9	4.65	0.72	7.5	2.7	41.8	3.4	50.7	0.8	83	6	SC
	Agricultural alignment (Near)	17.0	6.6	4.73	0.31	8.0	2.9	43.7	15.7	33.6	10.6	73	8	SCL
	Two-way ANOVA p-values													
	Distance	*0.07*		*0.90*		*0.10*		*0.34*		*0.07*		*0.05*		
	Alignment	*0.53*		*0.94*		*0.26*		*0.73*		*0.56*		*0.56*		
	*Distance * Alignment*	*0.73*		*0.79*		*0.18*		*0.50*		***0.02***		*0.17*		
Lower B_t	No alignment (Far)	30.7	19.8	4.59	0.34	9.3	1.2	49.5	1.2	41.2	0.6	74	6	SC
	Natural alignment (Far)	48.0	19.1	4.41	0.45	6.4	1.6	46.7	4.7	46.9	3.2	80	7	SC
	No alignment (Near)	29.0	12.5	4.56	1.13	7.0	2.0	40.8	3.4	52.2	1.5	88	4	SC
	Agricultural alignment (Near)	29.7	17.4	4.78	0.71	8.9	2.4	48.3	0.9	42.9	1.6	76	5	SC
	Two-way ANOVA p-values													
	Distance	*0.35*		*0.69*		*0.95*		*0.07*		***0.01***		*0.20*		
	Alignment	*0.40*		*0.95*		*0.66*		*0.22*		*0.14*		*0.35*		
	*Distance * Alignment*	*0.43*		*0.63*		*0.06*		***0.02***		***<0.01***		***0.03***		

† Abbreviations: SC silty clay; SCL, silty clay loam; SL, silt loam.

Table 2: Soil depth and surface rock cover. P-values less than 0.05 highlighted in **bold**. N=3 replicate pits per factor.

	Total soil depth (cm)		Total surface rock cover (%)		Boulder cover (%)		Stone cover (%)		Cobble cover (%)		Gravel cover (%)	
	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
No alignment (Far)	44	18	57	25	8	3	17	6	20	6	12	4
Natural alignment (Far)	60	18	75	13	13	6	22	10	27	3	13	3
No alignment (Near)	58	18	60	13	2	3	7	6	32	7	20	10
Agricultural alignment (Near)	51	18	53	11	3	4	8	4	25	5	18	3
Two-way ANOVA p-values												
Distance	*0.82*		*0.40*		***0.01***		***0.03***		*0.42*		*0.37*	
Alignment	*0.70*		*0.62*		*0.27*		*0.53*		*0.99*		*0.95*	
*Distance * Alignment*	*0.29*		*0.26*		*0.42*		*0.65*		*0.29*		*0.76*	

Table 3. Dust deposition rates on Perry Mesa. N=12.

	Deposition rates (g m^{-2} yr^{-1})	
Collection dates	Mean	Std. Dev.
September 2009-August 2010	2.66	1.79
August 2010-September 2011	13.6	3.40

Table 4. Annual deposition rates and large dust event frequency and size in the Southwest US.

Annual dust deposition

Location	Annual deposition (g m^{-2})	Citation
Phoenix, AZ	54	Pewe et al., 1981
Las Cruces, NM	10 – 60	Gile & Grossman, 1979
Mesa Verde, CO	36	Arrhenius and Bonatti, 1965
San Juan Range, CO	12.5	Lawrence & Neff, 2009
Edwards plateau, TX	12	Rabenhorst et al., 1984
Mojave Desert, NV & CA	11	Reheis 2006
Front Range, CO	6	Ley et al., 2004

Large dust event frequencies

Location	Average number per year	Citation
California Deserts	18.0	Bach et al., 1996
Coachella, CA	37.8	Bach et al., 1996
Yuma, AZ	9.4	Nickling & Brazel, 1984
Phoenix, AZ	6.6	Nickling & Brazel, 1984
Winslow, AZ	1.8	Nickling & Brazel, 1984
Tucson, AZ	0.9	Nickling & Brazel, 1984

Large dust event size

Location	Event Size (g m^{-2})	Citation
Texas/Oklahoma	4.65	Prokopovich, 1954
Phoenix, AZ	3.85	Pewe et al., 1981
San Juan Range, CO	2	Lawrence et al., 2010

Table 5. Total soil pools of mineral-derived nutrients and cations.

	No alignment (Far)		Natural alignment (Far)		No alignment (Near)		Agricultural alignment (Near)		*Two-Way ANOVA p-values*		
	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	*Distance*	*Alignment*	*Distance * Alignment*
PO_4^{3-} (g m^{-2})	3.51	2.39	2.61	1.45	3.71	2.08	4.13	2.39	*0.50*	*0.85*	*0.60*
P (g m^{-2})	370	307	437	220	340	122	379	203	*0.74*	*0.69*	*0.92*
Si (kg m^{-2})	239	118	309	91	267	114	238	94	*0.73*	*0.75*	*0.43*
Al (kg m^{-2})	59	32	77	25	71	25	60	22	*0.86*	*0.85*	*0.36*
Fe (kg m^{-2})	30	17	40	15	38	14	32	12	*0.92*	*0.83*	*0.38*
Ca (kg m^{-2})	11	7	14	4	14	6	11	4	*0.98*	*0.95*	*0.32*
Na (kg m^{-2})	8.48	4.46	9.90	3.40	7.77	2.65	7.95	3.01	*0.52*	*0.70*	*0.76*
K (kg m^{-2})	11.61	4.66	14.55	4.45	12.61	5.88	12.27	4.74	*0.83*	*0.66*	*0.58*
Mg (kg m^{-2})	8.57	5.60	11.03	3.36	12.33	4.72	9.58	3.91	*0.67*	*0.96*	*0.34*

Table 6. Proportion of chemical gains or losses (τ) of mineral-derived nutrients and cations relative to dust. P-values less than 0.05 highlighted in **bold**.

		No alignment (Far)		Natural alignment (Far)		No alignment (Near)		Agricultural alignment (Near)		*Two-way ANOVA p-values*		
		Mean	S. D.	Mean	S. D.	Mean	S. D.	Mean	S. D.	*Distance*	*Alignment*	*Dist.*Align.*
A	τ Si	-0.02	0.06	-0.05	0.02	-0.11	0.04	-0.07	0.02	***0.04***	*0.89*	*0.16*
	τ Al	-0.10	0.08	-0.09	0.06	-0.12	0.01	-0.14	0.02	*0.27*	*0.98*	*0.64*
	τ Fe	-0.16	0.10	-0.14	0.10	-0.22	0.09	-0.18	0.03	*0.30*	*0.55*	*0.86*
	τ Ca	-0.30	0.17	-0.23	0.17	-0.46	0.22	-0.34	0.06	*0.20*	*0.37*	*0.83*
	τ Na	-0.20	0.11	-0.17	0.13	-0.24	0.09	-0.21	0.07	*0.51*	*0.65*	*0.97*
	τ K	-0.22	0.15	-0.19	0.14	-0.41	0.19	-0.28	0.03	*0.11*	*0.32*	*0.53*
	τ Mg	-0.21	0.15	-0.17	0.12	-0.35	0.12	-0.26	0.02	*0.12*	*0.34*	*0.70*
	τ P	-0.38	0.22	-0.26	0.18	-0.55	0.24	-0.41	0.07	*0.18*	*0.27*	*0.95*
Upper Bt	τ Si	-0.08	0.07	-0.18	0.01	-0.18	0.10	-0.23	0.07	*0.07*	*0.14*	*0.11*
	τ Al	-0.16	0.06	-0.22	0.04	-0.15	0.06	-0.23	0.07	*0.07*	*0.86*	*0.06*
	τ Fe	-0.28	0.04	-0.33	0.03	-0.26	0.05	-0.33	0.05	***0.05***	*0.76*	***0.04***
	τ Ca	-0.59	0.04	-0.59	0.05	-0.57	0.09	-0.64	0.04	***0.04***	*0.74*	*0.38*
	τ Na	-0.39	0.04	-0.42	0.04	-0.31	0.03	-0.39	0.04	***0.04***	***0.03***	***0.05***
	τ K	-0.45	0.04	-0.50	0.04	-0.55	0.09	-0.55	0.04	***0.04***	*0.06*	*0.45*
	τ Mg	-0.44	0.05	-0.48	0.03	-0.49	0.07	-0.52	0.06	*0.06*	*0.21*	*0.27*
	τ P	-0.73	0.04	-0.71	0.07	-0.71	0.13	-0.77	0.05	*0.06*	*0.62*	*0.63*
Lower Bt	τ Si	-0.21	0.08	-0.24	0.07	-0.22	0.11	-0.23	0.09	*0.98*	*0.73*	*0.88*
	τ Al	-0.16	0.08	-0.23	0.05	-0.16	0.04	-0.19	0.06	*0.49*	*0.21*	*0.62*
	τ Fe	-0.31	0.05	-0.32	0.07	-0.26	0.06	-0.28	0.05	*0.21*	*0.69*	*0.92*
	τ Ca	-0.70	0.02	-0.61	0.12	-0.57	0.10	-0.60	0.17	*0.28*	*0.66*	*0.32*
	τ Na	-0.46	0.02	-0.43	0.09	-0.30	0.04	-0.35	0.07	***0.01***	*0.84*	*0.34*
	τ K	-0.59	0.04	-0.56	0.11	-0.56	0.05	-0.54	0.16	*0.73*	*0.84*	*0.84*
	τ Mg	-0.57	0.07	-0.54	0.12	-0.52	0.02	-0.50	0.15	*0.43*	*0.75*	*0.90*
	τ P	-0.86	0.02	-0.75	0.16	-0.75	0.12	-0.72	0.22	*0.45*	*0.50*	*0.51*

Table 7. Mineral-derived nutrient content in dust and soils. P-values less than 0.05 highlighted in **bold.** N=12.

	Dust ($mg\ g^{-1}$)		Soil in A Horizon ($mg\ g^{-1}$)		*Two-sample t-test*	Annual Deposition ($g\ m^{-2}\ yr^{-1}$)	
	Mean	Std. Dev.	Mean	Std. Dev.	*p-value*	Mean	Std. Dev.
Si	190	14	295	10	*0.54*	1.44	1.17
Al	47	5	63	5	*0.82*	0.35	0.29
Fe	29	9	33	3	***<0.01***	0.22	0.19
Ca	24	0	12	1	*0.10*	0.18	0.01
Mg	10	1	10	2	*0.27*	0.08	0.06
Na	13	1	15	1	*0.61*	0.10	0.08
K	18	0	10	1	***0.04***	0.14	0.01
P	1.94	0.52	0.49	0.12	***<0.01***	0.02	0.01

Table 8. Estimated rates of P withdraw due to crop production.

Potential P withdraw (maximum)	Values	Citations
Duration of habitation (years)	50	Stone et al., 2000
Potential maize yield ($kg\ ha^{-1}\ yr^{-1}$)	58	Van West, 1990
P content of maize ($g\ P\ kg^{-1}$ maize)	4.44	Sandor, unpublished
Annual withdraw ($g\ P\ m^{-2}$)	0.07	
Total withdraw over 150 years ($g\ P\ m^{-2}$)	10	

Table 9. Estimated P deposition incorporating large dust event frequency and size.

Average frequency of dust events (# yr^{-1})	Average dust event size (g m^{-2})	Average annual P deposition (mg m^{-2})
0	0	20
1.8	2	35
1.8	4	45
3	2	42
3	4	60
5	2	54
5	4	83

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APPENDIX A

DATA COLLECTED APRIL – NOVEMBER 2009

Appendix 1. Soil profile descriptions in non-agricultural area far from Pueblo La Plata.

	Horizon	Thickness (cm)	Color Moist	Structure Grade	Size	Type	Soil Texture	% Rock	Roots VF	F	M	Boundary
No alignment (Far)												
GCS 4	A	2	10YR 3/4	Wk	F	Gr	Silt Loam	60	C	C		AS
	Upper Bt	17	10YR 3/4	Mod	F	Sbk	Silt Loam	15	C	C		CS
	Lower Bt	13	10YR 3/6			Ma	Silty Clay	5	Few	Few		AW
GCS 6	A	2	10YR/34	Wk	VF/F	Gr	Silt Loam	80	C	C		AS
	Upper Bt	6	10YR 3/4	Mod	F/M	Sbk	Silty Clay Loam	20	C	Few		AS
	Lower Bt	27	10YR 3/4			Ma	Silty Clay	5	C	C		VW
GCS 7	A	3	10YR 3/2	Mod	F	Gr	Silty Clay Loam	30	C	C		AS
	Upper Bt	10	10YR 3/2	Mod	F	Sbk	Silt Loam	15	C	Few		AS
	Lower Bt	52	10YR 3/2			Ma	Silty Clay	2	Few			VW
Natural alignment (Far)												
NTS 6	A	2	10YR 3/3	Wk	F	Gr	Silty Clay Loam	85	C	C		AS
	Upper Bt	7	10YR 3/3	Mod	F	Sbk	Silty Clay	30	C	Few		AS
	Lower Bt	21	10YR 3/3			Ma	Silty Clay	35	Few			VW
NTS 10	A	2	10YR 3/4	Mod	F	Gr	Silt Loam	40	C	C		AS
	Upper Bt	10	10YR 3/4	Mod	F/M	Sbk	Silty Clay	15	C			CS
	Lower Bt	68	10YR 3/4			Ma	Silty Clay	2	Few			VW
NTS 14	A	3	10YR 3/6	Wk	F	Gr	Silt Loam	80	C	C		AS
	Upper Bt	12	10YR 3/6	Mod	F/M	Sbk	Silt Loam	20	C	Few		AS
	Lower Bt	30	10YR 3/6			Ma	Silty Clay	10	Few			VW

†Abbreviations: Abk, angular blocky; AS, abrupt smooth; C, common; CS, clear smooth; F, fine; Gr, granular; M, medium; Ma, massive; Mod, moderate; Sbk, subangular blocky; St, strong; VC, very coarse; VF, very fine; VW, very abrupt wavy; Wk, weak.

Appendix 2. Soil profile descriptions in agricultural area near Pueblo La Plata. †

	Horizon	Thickness (cm)	Color Moist	Grade	Structure Size	Type	Soil Texture	% Rock	Roots VF	F	M	Boundary
No alignment (Near)												
LPC 12	A	10	7.5YR 4/3	Mod	F/M	Gr, Sbk	Silty Clay Loam	45	C	C		AS
	Upper Bt	33	7.5YR 4/3	St	Coarse	Abk	Silty Clay	5	C	Few		DS
	Lower Bt	32	5YR 4/3			Ma	Silty Clay	5	C	Few		VW
LPC 2-3	A	3	10YR 3/4	Mod	F	Gr	Silty Clay Loam	60	C	C		AS
	Upper Bt	16	10YR 3/4	Mod	F	Sbk	Silty Clay	20	C	Few		CS
	Lower Bt	41	10YR 3/1			Ma	Silty Clay	30	Few			AW
LPC 2-6	A	11	10YR 3/6	Mod	F	Gr, Sbk	Silty Clay Loam	45	C	C		AS
	Upper Bt	13	10YR 3/6	Mod	Coarse	Sbk	Clay	35	Few			AS
	Lower Bt	16	10YR 3/6			Ma	Clay	20	Few			VW
Agricultural alignment (Near)												
ST 2	A	7	10YR 2/2	Mod	F/M	Gr, Sbk	Silt Loam	50	C	C	C	AS
	Upper Bt	10	10YR 2/2	Mod	F	Sbk	Silty Clay	20	C	C		CS
	Lower Bt	38	10YR 3/2			Ma	Silty Clay	45	Few	Few	Few	VW
ST 4	A	3	10YR 3/6	Mod	F	Gr, Sbk	Silt Loam	45	C	C		AS
	Upper Bt	11	10YR 3/6	Mod	F	Sbk	Silty Clay Loam	10	Few	Few	Few	CS
	Lower Bt	48	10YR 3/4			Ma	Silty Clay	5	Few			VW
ST 13	A	2	10YR 3/6	Mod	VF/F	Gr	Silt Loam	60	C	C		AS
	Upper Bt	18	10YR 3/6	Mod	F	Sbk	Silt Loam	10	C	Few		CS
	Lower Bt	10	10YR 3/6			Ma	Silty Clay	8	Few	Few		VW

†Abbreviations: Abk, angular blocky; AS, abrupt smooth; C, common; CS, clear smooth; F, fine; Gr, granular; M, medium; Ma, massive; Mod, moderate; Sbk, subangular blocky; St, strong; VC, very coarse; VF, very fine; VW, very abrupt wavy; Wk, weak.

Appendix 3. Soil properties of the A horizon at Pueblo La Plata.

A horizon	No alignment (Far)		Natural alignment (Far)		No alignment (Near)		Agricultural alignment (Near)	
Variable	Mean	Std. Dev	Mean	Std. Dev	Mean	Std. Dev	Mean	Std. Dev
Horizon Thickness (cm)	2.33	0.58	2.33	0.58	8.00	4.36	4.00	2.65
pH	6.82	0.35	6.73	0.62	7.37	0.16	7.00	0.55
Soil organic matter (%)	5.70	0.46	6.32	1.63	5.25	1.34	5.62	0.33
WHC (%)	65.47	10.51	75.31	1.83	79.24	4.16	63.40	16.98
Sand fraction (%)	17.68	2.89	11.39	4.75	12.70	1.37	12.48	2.94
Silt fraction (%)	57.37	15.95	61.25	6.19	49.93	3.66	66.02	2.37
Clay fraction (%)	24.95	13.53	27.36	10.04	37.37	2.35	21.50	5.31
Bulk density (g cm^{-3})	1.28	0.03	1.23	0.13	1.33	0.21	1.18	0.09
Phosphate (PO_4^{3-}) (µg g^{-1} dry soil)	30.95	8.02	28.14	17.42	23.14	15.82	32.12	7.41
Total P (µg g^{-1} dry soil)	407	50	553	220	480	87	538	67
Nitrate+nitrite (NO_3^- + NO_2^-) (µg g^{-1} dry soil)	2.79	1.82	1.73	1.44	2.39	1.75	2.86	3.25
Ammonium (NH^{4+}) (µg g^{-1} dry soil)	3.93	1.51	3.56	1.65	1.28	1.29	2.74	1.88
Total inorganic N (µg g^{-1} dry soil)	6.72	3.29	5.29	3.02	3.67	2.75	5.60	5.11
Potential nitrogen mineralization (µg g^{-1} day^{-1})	-0.23	0.47	-0.23	0.29	0.45	0.52	0.48	1.06
Potential net nitrification (µg g^{-1} day^{-1})	0.13	0.35	0.07	0.12	0.50	0.62	0.75	1.23

Appendix 4. Soil properties of the upper B_t horizon at Pueblo La Plata.

Upper B_t Horizon	No alignment (Far)		Natural alignment (Far)		No alignment (Near)		Agricultural alignment (Near)	
Variable	Mean	Std. Dev	Mean	Std. Dev	Mean	Std. Dev	Mean	Std. Dev
Horizon Thickness (cm)	11.00	5.57	9.67	2.52	21.33	11.93	17.00	6.56
pH	6.98	0.20	6.71	0.77	7.70	0.63	6.81	1.05
Soil organic matter (%)	4.82	0.93	4.68	0.77	4.65	0.72	4.73	0.31
WHC (%)	66.46	6.64	71.13	7.76	82.77	5.69	73.13	7.82
Sand fraction (%)	14.11	3.08	8.80	4.62	7.49	2.73	7.96	2.89
Silt fraction (%)	59.69	8.89	53.86	5.28	41.76	3.44	43.66	15.72
Clay fraction (%)	26.21	9.71	37.34	9.58	50.74	0.78	33.57	10.58
Bulk density (g cm^{-3})	1.81	0.05	1.71	0.05	1.75	0.19	1.65	0.13
Phosphate (PO_4^{3-}) (µg g^{-1} dry soil)	9.66	8.92	5.56	3.73	3.28	3.81	7.53	5.19
Total P (µg g^{-1} dry soil)	445	101	349	76	407	50	413	36
Nitrate+nitrite (NO_3^- + NO_2^-) (µg g^{-1} dry soil)	0.80	0.49	0.74	0.76	1.40	1.20	1.46	1.60
Ammonium (NH^{4+}) (µg g^{-1} dry soil)	1.11	0.03	1.26	0.46	0.24	0.13	0.95	0.67
Total inorganic N (µg g^{-1} dry soil)	1.91	0.47	2.00	0.92	1.65	1.29	2.41	2.26
Potential nitrogen mineralization (µg g^{-1} day^{-1})	0.21	0.27	0.30	0.19	0.16	0.14	0.44	0.11
Potential net nitrification (µg g^{-1} day^{-1})	0.31	0.26	0.40	0.26	0.18	0.15	0.53	0.17

Appendix 5. Soil properties of the lower B_t horizon at Pueblo La Plata.

Lower B_t Horizon	No alignment (Far)		Natural alignment (Far)		No alignment (Near)		Agricultural alignment (Near)	
Variable	Mean	Std. Dev	Mean	Std. Dev	Mean	Std. Dev	Mean	Std. Dev
Horizon Thickness (cm)	30.67	19.76	48.00	19.08	29.00	12.53	29.67	17.39
pH	7.46	0.38	7.50	0.85	7.80	0.83	7.06	1.02
Soil organic matter (%)	4.59	0.34	4.41	0.45	4.56	1.13	4.78	0.71
WHC (%)	74.40	6.24	79.88	6.65	87.56	4.33	75.67	4.84
Sand fraction (%)	9.27	1.24	6.41	1.61	6.97	1.96	8.85	2.40
Silt fraction (%)	49.54	1.22	46.73	4.71	40.84	3.39	48.29	0.95
Clay fraction (%)	41.19	0.62	46.86	3.16	52.19	1.45	42.86	1.60
Bulk density (g cm^{-3})	1.91	0.24	1.88	0.03	1.68	0.19	1.72	0.15
Phosphate (PO_4^{3-}) (µg g^{-1} dry soil)	1.47	0.65	0.86	0.21	1.16	1.43	1.26	0.72
Total P (µg g^{-1} dry soil)	377	147	383	85	291	50	436	115
Nitrate+nitrite (NO_3^- + NO_2^-) (µg g^{-1} dry soil)	0.66	0.35	0.26	0.23	0.56	0.25	0.69	0.57
Ammonium (NH^{4+}) (µg g^{-1} dry soil)	0.75	0.01	0.73	0.65	0.35	0.32	0.36	0.31
Total inorganic N (µg g^{-1} dry soil)	1.41	0.35	0.99	0.83	0.91	0.55	1.05	0.51
Potential nitrogen mineralization (µg g^{-1} day^{-1})	0.33	0.07	0.25	0.22	0.17	0.14	0.15	0.09
Potential net nitrification (µg g^{-1} day^{-1})	0.39	0.08	0.31	0.27	0.17	0.12	0.17	0.05

Appendix 6. Soil properties between depths of 0 cm to 5 cm at Pueblo La Plata.

Depth 0cm to 5cm	No alignment (Far)		Natural alignment (Far)		No alignment (Near)		Agricultural alignment (Near)	
Variable	Mean	Std. Dev	Mean	Std. Dev	Mean	Std. Dev	Mean	Std. Dev
pH	6.82	0.35	6.73	0.62	7.32	0.01	7.00	0.55
Soil organic matter (%)	5.70	0.46	6.32	1.63	6.55	0.32	5.62	0.33
WHC (%)	65.5	10.5	75.3	1.8	82.6	0.3	63.4	17.0
Sand fraction (%)	17.68	2.89	11.39	4.75	11.94	0.21	12.48	2.94
Silt fraction (%)	57.37	15.95	61.25	6.19	51.50	11.97	66.02	2.37
Clay fraction (%)	24.95	13.53	27.36	10.04	36.31	3.39	21.50	5.31
Bulk density (g cm^{-3})	1.28	0.03	1.23	0.13	1.21	0.01	1.18	0.09
Phosphate (PO_4^{3-}) (µg g^{-1} dry soil)	30.95	8.02	28.14	17.42	34.37	9.93	32.12	7.41
Total P (µg g^{-1} dry soil)	407	50	553	220	546	31	538	67
Nitrate+nitrite (NO_3^- + NO_2^-) (µg g^{-1} dry soil)	2.79	1.82	1.73	1.44	1.38	1.92	2.86	3.25
Ammonium (NH^{4+}) (µg g^{-1} dry soil)	3.93	1.51	3.56	1.65	1.29	1.83	2.74	1.88
Total inorganic N (µg g^{-1} dry soil)	6.72	3.29	5.29	3.02	2.67	3.74	5.60	5.11
Potential nitrogen mineralization (µg g^{-1} day^{-1})	-0.23	0.47	-0.23	0.29	1.00	0.03	0.48	1.06
Potential net nitrification (µg g^{-1} day^{-1})	0.13	0.35	0.07	0.12	1.07	0.17	0.75	1.23

Appendix 7. Soil properties between depths of 5 cm to 10 cm at Pueblo La Plata.

Depth 5cm to 10 cm	No alignment (Far)		Natural alignment (Far)		No alignment (Near)		Agricultural alignment (Near)	
Variable	Mean	Std. Dev	Mean	Std. Dev	Mean	Std. Dev	Mean	Std. Dev
pH	6.69	0.33	6.71	0.77	7.41	0.21	6.48	1.53
Soil organic matter (%)	4.73	1.02	4.68	0.77	4.49	0.31	4.86	0.39
WHC (%)	65.4	8.5	71.1	7.8	77.6	4.4	66.3	12.8
Sand fraction (%)	14.94	2.79	8.80	4.62	12.88	1.89	9.55	5.17
Silt fraction (%)	58.91	7.77	53.86	5.28	49.95	5.17	43.88	25.20
Clay fraction (%)	26.15	9.77	37.34	9.58	37.17	3.29	24.35	1.06
Bulk density (g cm^{-3})	1.81	0.05	1.71	0.05	1.39	0.26	1.75	0.23
Phosphate (PO_4^{3-}) (µg g^{-1} dry soil)	10.66	7.96	5.56	3.73	14.01	0.88	14.57	6.81
Total P (µg g^{-1} dry soil)	436	115	349	76	458	93	415	93
Nitrate+nitrite (NO_3^- + NO_2^-) (µg g^{-1} dry soil)	0.91	0.51	0.74	0.76	2.23	2.44	2.32	2.44
Ammonium (NH^{4+}) (µg g^{-1} dry soil)	1.26	0.28	1.26	0.46	0.63	0.89	1.75	1.41
Total inorganic N (µg g^{-1} dry soil)	2.18	0.63	2.00	0.92	2.85	3.33	4.07	3.85
Potential nitrogen mineralization (µg g^{-1} day^{-1})	0.30	0.38	0.30	0.19	0.17	0.26	0.56	0.30
Potential net nitrification (µg g^{-1} day^{-1})	0.40	0.38	0.40	0.26	0.16	0.24	0.73	0.44

Appendix 8. Soil properties between depths of 10 cm to 25 cm at Pueblo La Plata.

Depth 10 cm to 25cm	No alignment (Far)		Natural alignment (Far)		No alignment (Near)		Agricultural alignment (Near)	
Variable	Mean	Std. Dev	Mean	Std. Dev	Mean	Std. Dev	Mean	Std. Dev
pH	7.48	0.42	7.45	1.05	7.34	0.70	7.05	1.04
Soil organic matter (%)	4.56	0.46	5.09	0.94	5.05	1.16	4.51	0.72
WHC (%)	70.0	7.6	71.8	8.0	86.0	8.4	75.5	5.0
Sand fraction (%)	10.47	1.11	6.87	1.15	8.84	1.16	8.42	2.38
Silt fraction (%)	57.11	1.71	48.13	6.60	40.17	2.09	47.53	4.51
Clay fraction (%)	32.42	0.60	45.00	5.46	50.99	0.94	44.05	2.14
Bulk density (g cm^{-3})	1.76	0.32	1.83	0.05	1.85	0.16	1.66	0.17
Phosphate (PO_4^{3-}) (µg g^{-1} dry soil)	1.92	0.37	0.94	0.11	4.70	1.34	2.21	0.33
Total P (µg g^{-1} dry soil)	466	91	360	94	436	66	458	91
Nitrate+nitrite ($NO_3^- + NO_2^-$) (µg g^{-1} dry soil)	0.62	0.31	0.26	0.39	1.97	0.27	0.95	0.56
Ammonium (NH^{4+}) (µg g^{-1} dry soil)	0.86	0.21	0.71	0.51	0.31	0.21	0.57	0.06
Total inorganic N (µg g^{-1} dry soil)	1.48	0.19	0.98	0.69	2.29	0.48	1.52	0.55
Potential nitrogen mineralization (µg g^{-1} day^{-1})	0.34	0.03	0.25	0.17	0.21	0.15	0.24	0.05
Potential net nitrification (µg g^{-1} day^{-1})	0.41	0.05	0.30	0.19	0.25	0.11	0.29	0.04

Appendix 9. Soil properties deeper than 25 cm at Pueblo La Plata.

Depth over 25cm	No alignment (Far)		Natural alignment (Far)		No alignment (Near)		Agricultural alignment (Near)	
Variable	Mean	Std. Dev	Mean	Std. Dev	Mean	Std. Dev	Mean	Std. Dev
pH	7.51	0.24	7.51	0.61	8.11	0.40	7.08	0.60
Soil organic matter (%)	4.48	0.27	3.78	0.54	4.45	0.67	4.79	0.41
WHC (%)	76.4	4.4	83.1	4.6	82.7	4.8	75.7	2.9
Sand fraction (%)	9.11	0.64	6.03	0.66	5.48	0.67	8.86	1.38
Silt fraction (%)	48.75	0.99	46.38	3.81	43.60	1.21	46.32	2.60
Clay fraction (%)	42.13	0.35	47.60	3.15	50.92	0.54	44.81	1.24
Bulk density (g cm^{-3})	2.02	0.19	1.90	0.03	1.62	0.09	1.70	0.10
Phosphate (PO_4^{3-}) (µg g^{-1} dry soil)	1.09	0.21	0.78	0.06	1.25	0.77	1.04	0.19
Total P (µg g^{-1} dry soil)	335	52	382	54	416	38	422	52
Nitrate+nitrite (NO_3^- + NO_2^-) (µg g^{-1} dry soil)	0.62	0.18	0.23	0.23	0.42	0.16	0.70	0.32
Ammonium (NH^{4+}) (µg g^{-1} dry soil)	0.66	0.12	0.64	0.29	0.19	0.12	0.23	0.04
Total inorganic N (µg g^{-1} dry soil)	1.28	0.11	0.87	0.40	0.62	0.28	0.93	0.31
Potential nitrogen mineralization (µg g^{-1} day^{-1})	0.31	0.02	0.24	0.10	0.14	0.09	0.17	0.03
Potential net nitrification (µg g^{-1} day^{-1})	0.36	0.03	0.28	0.11	0.11	0.06	0.18	0.03

Appendix 10. Mineral-derived nutrient and cation concentrations by horizon. P-values less than 0.05 highlighted in **bold**.

		No alignment (Far)		Natural alignment (Far)		No alignment (Near)		Agricultural alignment (Near)		*Two-way ANOVA p-values*		
	(ppm)	Mean	S. D.	Mean	S. D.	Mean	S. D.	Mean	S. D.	*Distance*	*Alignment*	*Dist.*Align.*
A	P	407	50	553	220	480	87	538	67	*0.70*	*0.20*	*0.56*
	Si	305242	7652	294179	2159	283116	8898	298698	5268	***0.05***	*0.57*	***0.01***
	Al	59454	1986	62717	5028	68716	2805	61747	3413	*0.07*	*0.39*	***0.04***
	Fe	30473	1373	31003	2453	35432	2575	33758	3186	***0.03***	*0.70*	*0.46*
	Ca	12221	1380	11673	109	12817	2254	13103	1190	*0.26*	*0.88*	*0.63*
	Na	11153	576	9941	1120	8754	927	10485	343	*0.08*	*0.59*	***0.01***
	K	15496	418	14832	789	14638	553	15441	659	*0.74*	*0.85*	*0.08*
	Mg	8804	1127	8724	764	11629	593	10674	2665	***0.03***	*0.57*	*0.63*
Upper Bt	P	445	101	349	76	407	50	413	36	*0.76*	*0.30*	*0.24*
	Si	299019	8183	293400	4588	279377	13494	283736	10296	***0.03***	*0.91*	*0.40*
	Al	66095	2373	67393	2915	73832	5840	70803	163	***0.02***	*0.68*	*0.31*
	Fe	33709	1101	34181	745	38165	4812	36973	1609	***0.04***	*0.82*	*0.60*
	Ca	12070	1449	11983	83	13103	1232	12813	857	*0.16*	*0.76*	*0.87*
	Na	10732	453	9620	1528	8086	519	9636	632	***0.04***	*0.68*	***0.03***
	K	15202	692	14306	1163	13642	1334	14850	913	*0.43*	*0.80*	*0.12*
	Mg	9361	1064	9608	502	12101	803	11390	2050	***0.01***	*0.76*	*0.53*
Lower Bt	P	377	147	383	85	291	50	436	115	*0.79*	*0.25*	*0.29*
	Si	282780	7224	281572	5657	268785	20800	281636	5963	*0.34*	*0.42*	*0.33*
	Al	73478	1911	70461	1933	75585	5708	73303	3705	*0.28*	*0.25*	*0.87*
	Fe	37144	871	36686	2984	40568	7896	38801	3671	*0.33*	*0.69*	*0.81*
	Ca	12132	1708	13042	1887	14949	3632	12841	771	*0.34*	*0.66*	*0.28*
	Na	9696	1064	8871	500	8122	456	9150	471	*0.13*	*0.80*	***0.04***
	K	14042	1613	13119	123	12517	2810	14458	377	*0.92*	*0.60*	*0.17*
	Mg	10066	1197	10174	369	13120	2068	11679	1706	***0.03***	*0.46*	*0.39*

Appendix 11. Proportion of chemical gains or losses (τ) of mineral-derived nutrients and cations relative to bedrock. P-values less than 0.05 highlighted in **bold**.

		No alignment (Far)		Natural alignment (Far)		No alignment (Near)		Agricultural alignment (Near)		*Two-way ANOVA p-values*		
		Mean	S. D.	Mean	S. D.	Mean	S. D.	Mean	S. D.	*Distance*	*Alignment*	*Dist.*Align.*
A	τ Si	0.34	0.16	0.18	0.17	0.34	0.28	0.29	0.09	*0.65*	*0.35*	*0.61*
	τ Al	0.07	0.03	0.03	0.05	0.15	0.14	0.04	0.03	*0.37*	*0.15*	*0.53*
	τ Fe	-0.01	0.02	-0.04	0.02	0.00	0.02	-0.02	0.02	*0.24*	*0.12*	*0.74*
	τ Ca	-0.26	0.15	-0.21	0.15	-0.41	0.20	-0.30	0.05	*0.21*	*0.37*	*0.78*
	τ Na	-0.27	0.15	-0.22	0.16	-0.36	0.15	-0.30	0.07	*0.34*	*0.46*	*0.98*
	τ K	-0.16	0.12	-0.15	0.11	-0.36	0.17	-0.22	0.02	*0.08*	*0.33*	*0.36*
	τ Mg	0.24	0.11	0.12	0.15	0.23	0.23	0.20	0.10	*0.72*	*0.41*	*0.61*
	τ P	-0.24	0.14	-0.10	0.00	-0.33	0.14	-0.23	0.05	*0.11*	*0.08*	*0.78*
Upper Bt	τ Si	0.57	0.14	0.33	0.09	0.36	0.29	0.32	0.12	*0.12*	*0.32*	*0.24*
	τ Al	0.20	0.08	0.07	0.07	0.19	0.12	0.11	0.10	*0.10*	*0.77*	*0.10*
	τ Fe	0.02	0.06	-0.08	0.03	0.02	0.01	-0.05	0.06	*0.06*	*0.44*	***0.01***
	τ Ca	-0.53	0.04	-0.53	0.04	-0.51	0.07	-0.57	0.03	***0.03***	*0.78*	*0.26*
	τ Na	-0.53	0.03	-0.53	0.05	-0.45	0.06	-0.53	0.03	***0.03***	*0.24*	*0.20*
	τ K	-0.35	0.04	-0.43	0.04	-0.49	0.08	-0.47	0.04	***0.04***	***0.02***	*0.31*
	τ Mg	0.39	0.15	0.15	0.09	0.17	0.25	0.21	0.13	*0.13*	*0.41*	*0.34*
	τ P	-0.45	0.08	-0.53	0.06	-0.49	0.09	-0.53	0.05	*0.06*	*0.58*	*0.16*
Lower Bt	τ Si	0.44	0.14	0.27	0.07	0.30	0.32	0.27	0.08	*0.51*	*0.39*	*0.51*
	τ Al	0.25	0.12	0.09	0.04	0.18	0.13	0.14	0.09	*0.94*	*0.10*	*0.28*
	τ Fe	0.03	0.07	-0.05	0.02	0.03	0.03	0.01	0.04	*0.30*	*0.07*	*0.30*
	τ Ca	-0.63	0.02	-0.55	0.11	-0.51	0.09	-0.54	0.15	*0.24*	*0.75*	*0.25*
	τ Na	-0.61	0.01	-0.55	0.12	-0.46	0.06	-0.48	0.11	*0.07*	*0.77*	*0.40*
	τ K	-0.50	0.05	-0.49	0.10	-0.50	0.02	-0.48	0.15	*0.91*	*0.95*	*0.96*
	τ Mg	0.24	0.21	0.06	0.06	0.11	0.32	0.14	0.08	*0.83*	*0.53*	*0.37*
	τ P	-0.61	0.10	-0.54	0.09	-0.60	0.09	-0.51	0.21	*0.84*	*0.32*	*0.97*

Appendix 12. Proportion of chemical gains or losses (τ) of major elements by depth referenced to bedrock.

Soil (n=5) Depth (cm)		τ_{Si}	τ_{Al}	τ_{Fe}	τ_{Ca}	τ_{Mg}	τ_{Na}	τ_{K}	τ_{Cr}	τ_{Ti}	τ_{Mn}	τ_{P}	τ_{Sr}	τ_{Ba}
0 to 1	Mean	0.27	0.07	-0.01	-0.25	-0.24	-0.18	0.20	-0.06	0.10	0.15	-0.16	-0.17	-0.20
	Std Dev	0.15	0.04	0.02	0.12	0.11	0.10	0.13	0.12	0.06	0.09	0.06	0.11	0.15
1 to 4	Mean	0.28	0.04	-0.03	-0.29	-0.30	-0.22	0.19	-0.02	0.09	0.18	-0.24	-0.21	-0.21
	Std Dev	0.14	0.04	0.02	0.11	0.11	0.07	0.11	0.05	0.06	0.11	0.10	0.09	0.12
4 to 6	Mean	0.49	0.18	0.00	-0.50	-0.47	-0.38	0.34	-0.19	0.19	0.23	-0.45	-0.39	-0.39
	Std Dev	0.27	0.11	0.05	0.10	0.09	0.10	0.25	0.17	0.14	0.23	0.08	0.12	0.20
6 to 10	Mean	0.42	0.10	-0.06	-0.56	-0.55	-0.42	0.25	-0.17	0.15	0.21	-0.53	-0.43	-0.41
	Std Dev	0.07	0.06	0.04	0.02	0.01	0.04	0.07	0.12	0.05	0.08	0.09	0.01	0.06
10 to 14	Mean	0.36	0.15	0.00	-0.56	-0.52	-0.47	0.21	-0.18	0.16	0.19	-0.52	-0.41	-0.38
	Std Dev	0.19	0.11	0.07	0.04	0.04	0.05	0.20	0.15	0.11	0.12	0.03	0.11	0.04
14 to 20	Mean	0.30	0.12	-0.01	-0.56	-0.53	-0.48	0.13	-0.23	0.11	0.09	-0.54	-0.41	-0.37
	Std Dev	0.13	0.08	0.04	0.08	0.09	0.08	0.12	0.14	0.07	0.07	0.10	0.04	0.05
20 to 26	Mean	0.35	0.17	0.00	-0.57	-0.54	-0.48	0.15	-0.20	0.14	0.18	-0.52	-0.48	-0.43
	Std Dev	0.13	0.12	0.08	0.12	0.11	0.10	0.13	0.19	0.09	0.14	0.21	0.12	0.11
26 to 35	Mean	0.32	0.19	0.03	-0.58	-0.54	-0.53	0.14	-0.26	0.12	0.05	-0.61	-0.48	-0.45
	Std Dev	0.23	0.09	0.04	0.03	0.05	0.06	0.25	0.09	0.08	0.13	0.05	0.07	0.19
35 to 50	Mean	0.23	0.12	-0.02	-0.54	-0.52	-0.50	0.01	-0.17	0.09	0.01	-0.54	-0.44	-0.40
	Std Dev	0.14	0.07	0.05	0.17	0.16	0.11	0.15	0.08	0.06	0.09	0.11	0.20	0.17
50 to 80	Mean	0.40	0.18	-0.02	-0.47	-0.46	-0.44	0.23	-0.25	0.11	0.08	-0.52	-0.45	-0.50
	Std Dev	0.23	0.13	0.04	0.11	0.12	0.13	0.21	0.06	0.07	0.05	0.18	0.16	0.24
Rock	Mean	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
(n=12)	Std Dev	0.04	0.04	0.05	0.12	0.12	0.05	0.13	0.14	0.04	0.06	0.09	0.08	0.15

Appendix 13. Proportion of chemical gains or losses (τ) of major elements by depth referenced to dust.

Soil (n=5) Depth (cm)		τ_{Si}	τ_{Al}	τ_{Fe}	τ_{Ca}	τ_{Mg}	τ_{Na}	τ_{K}	τ_{Cr}	τ_{Ti}	τ_{Mn}	τ_{P}	τ_{Sr}	τ_{Ba}
0 to 1	Mean	-0.03	-0.09	-0.14	-0.28	-0.17	-0.22	-0.19	0.19	-0.02	-0.04	-0.32	-0.12	-0.06
	Std Dev	0.05	0.05	0.07	0.13	0.09	0.12	0.09	0.17	0.04	0.03	0.14	0.10	0.15
1 to 4	Mean	-0.07	-0.13	-0.18	-0.33	-0.22	-0.27	-0.26	0.32	-0.05	-0.06	-0.40	-0.15	-0.01
	Std Dev	0.02	0.04	0.06	0.12	0.08	0.10	0.09	0.19	0.02	0.02	0.16	0.07	0.10
4 to 6	Mean	-0.09	-0.15	-0.27	-0.56	-0.34	-0.46	-0.41	0.26	-0.05	-0.14	-0.68	-0.30	-0.10
	Std Dev	0.09	0.04	0.05	0.11	0.07	0.10	0.06	0.30	0.08	0.13	0.12	0.12	0.28
6 to 10	Mean	-0.17	-0.23	-0.34	-0.62	-0.42	-0.50	-0.49	0.35	-0.10	-0.18	-0.76	-0.32	-0.09
	Std Dev	0.02	0.03	0.01	0.02	0.02	0.03	0.02	0.22	0.03	0.05	0.05	0.01	0.12
10 to 14	Mean	-0.20	-0.20	-0.30	-0.62	-0.38	-0.54	-0.51	0.35	-0.09	-0.19	-0.76	-0.31	-0.02
	Std Dev	0.10	0.07	0.05	0.04	0.05	0.04	0.06	0.29	0.08	0.06	0.04	0.13	0.07
14 to 20	Mean	-0.23	-0.21	-0.30	-0.62	-0.39	-0.55	-0.53	0.24	-0.13	-0.25	-0.76	-0.31	-0.02
	Std Dev	0.06	0.06	0.05	0.09	0.08	0.08	0.08	0.27	0.05	0.05	0.12	0.04	0.07
20 to 26	Mean	-0.21	-0.19	-0.30	-0.64	-0.40	-0.56	-0.54	0.32	-0.11	-0.20	-0.77	-0.38	-0.10
	Std Dev	0.07	0.08	0.07	0.13	0.09	0.12	0.12	0.31	0.07	0.10	0.18	0.11	0.12
26 to 35	Mean	-0.24	-0.18	-0.29	-0.65	-0.39	-0.60	-0.56	0.23	-0.13	-0.29	-0.81	-0.37	-0.12
	Std Dev	0.11	0.05	0.03	0.03	0.06	0.05	0.06	0.12	0.05	0.07	0.05	0.08	0.31
35 to 50	Mean	-0.26	-0.21	-0.30	-0.60	-0.39	-0.57	-0.56	0.33	-0.14	-0.30	-0.75	-0.35	-0.09
	Std Dev	0.07	0.06	0.09	0.18	0.13	0.13	0.13	0.18	0.04	0.07	0.19	0.20	0.13
50 to 80	Mean	-0.15	-0.15	-0.29	-0.54	-0.32	-0.51	-0.46	0.16	-0.12	-0.24	-0.71	-0.37	-0.29
	Std Dev	0.08	0.06	0.08	0.14	0.08	0.15	0.14	0.19	0.05	0.08	0.22	0.14	0.27
Dust	Mean	0.00	0.00	-0.01	0.01	0.00	0.00	0.01	0.01	0.01	0.00	0.03	-0.01	0.01
(n=2)	Std Dev	0.05	0.02	0.20	0.13	0.04	0.06	0.13	0.13	0.10	0.05	0.40	0.16	0.13

Appendix 14. Concentrations of major element oxides.

Soil (n=5) Depth (cm)		SiO_2 %	Al_2O_3 %	Fe_2O_3 %	CaO %	MgO %	Na_2O %	K_2O %	Cr_2O_3 %	TiO_2 %	MnO %	P_2O_5 %	SrO %	BaO %
0 to 1	Mean	64.10	11.78	4.99	1.65	1.61	1.34	1.84	0.03	0.87	0.12	0.12	0.03	0.10
	Std Dev	1.68	0.71	0.49	0.23	0.35	0.20	0.09	0.01	0.06	0.02	0.04	0.01	0.03
1 to 4	Mean	63.24	11.56	5.08	1.82	1.61	1.41	1.83	0.03	0.87	0.13	0.12	0.03	0.11
	Std Dev	1.64	0.63	0.44	0.18	0.26	0.09	0.08	0.01	0.03	0.01	0.01	0.00	0.02
4 to 6	Mean	62.78	12.79	5.34	1.64	1.68	1.28	1.80	0.02	0.88	0.12	0.09	0.03	0.10
	Std Dev	3.44	0.82	0.42	0.16	0.26	0.21	0.14	0.01	0.05	0.02	0.02	0.00	0.03
6 to 10	Mean	62.24	12.52	5.42	1.79	1.76	1.41	1.78	0.03	0.92	0.13	0.10	0.03	0.11
	Std Dev	2.29	0.34	0.17	0.12	0.30	0.13	0.10	0.01	0.05	0.01	0.02	0.00	0.02
10 to 14	Mean	61.38	13.17	5.67	1.71	1.68	1.24	1.70	0.02	0.90	0.11	0.09	0.03	0.11
	Std Dev	2.22	0.45	0.46	0.21	0.27	0.13	0.17	0.01	0.01	0.01	0.01	0.00	0.01
14 to 20	Mean	59.45	13.95	6.21	1.75	1.90	1.23	1.71	0.03	0.93	0.12	0.10	0.03	0.12
	Std Dev	1.63	1.06	0.24	0.13	0.33	0.08	0.12	0.01	0.02	0.01	0.01	0.01	0.01
20 to 26	Mean	59.56	13.70	6.17	1.88	1.94	1.24	1.59	0.03	0.92	0.12	0.11	0.03	0.11
	Std Dev	1.90	0.62	0.81	0.13	0.27	0.11	0.15	0.01	0.05	0.02	0.04	0.00	0.02
26 to 35	Mean	60.50	14.06	5.95	1.70	1.77	1.19	1.72	0.02	0.91	0.11	0.07	0.03	0.10
	Std Dev	1.90	0.62	0.81	0.13	0.27	0.11	0.15	0.01	0.05	0.02	0.04	0.00	0.02
35 to 50	Mean	57.86	14.20	6.40	2.01	1.98	1.16	1.45	0.03	0.94	0.11	0.09	0.03	0.13
	Std Dev	4.22	0.89	0.85	0.59	0.46	0.11	0.29	0.01	0.03	0.01	0.01	0.02	0.03
50 to 80	Mean	60.97	13.16	5.39	1.92	1.78	1.18	1.69	0.02	0.85	0.11	0.09	0.03	0.08
	Std Dev	1.62	0.16	0.22	0.35	0.11	0.09	0.11	0.01	0.04	0.01	0.03	0.01	0.03
Dust	Mean	40.55	8.81	4.56	3.34	1.68	1.80	2.21	0.01	0.53	0.08	0.45	0.03	0.06
(n=2)	Std Dev	3.04	0.93	1.48	0.00	0.15	0.12	0.00	0.00	0.01	0.01	0.12	0.01	0.00
Rock	Mean	55.38	14.66	7.52	6.59	6.09	3.63	1.81	0.05	1.01	0.13	0.32	0.08	0.27
(n = 12)	Std Dev	1.16	0.47	0.27	0.62	0.53	0.14	0.19	0.01	0.03	0.01	0.02	0.01	0.04

Appendix 16. Rare earth element composition.

Soil (n = 5)	Eu_N/Eu^*		La_N/Yb_N	
Depth (cm)	Mean	Std Dev.	Mean	Std Dev.
0 to 1	0.72	0.06	9.57	0.82
1 to 4	0.74	0.04	9.94	0.95
4 to 6	0.72	0.03	9.59	1.14
6 to 10	0.73	0.05	10.19	0.78
10 to 14	0.74	0.06	11.04	0.62
14 to 20	0.76	0.04	10.67	0.44
20 to 26	0.71	0.05	11.03	0.52
26 to 35	0.74	0.05	11.42	1.63
35 to 50	0.76	0.07	11.77	1.86
50 to 80	0.71	0.05	10.39	0.82
Dust (n = 2)	0.67	0.03	9.03	0.72
Rock (n = 12)	0.92	0.03	22.25	1.27