DISSERTATION

THE IMPACTS OF LONG-TERM CULTIVATION ON SOIL DEGRADATION IN THE SAN LUIS VALLEY, COLORADO

Submitted by

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ABSTRACT

THE IMPACTS OF LONG-TERM CULTIVATION ON SOIL DEGRADATION IN THE SAN LUIS VALLEY, COLORADO

Essentially all agricultural lands globally are under pressure to meet the food demands of an additional 2 billion people over the next 20 years. All of the agroecosystems possess limitations that constrain their ability to optimize production, however, these limitations are magnified in semi-arid regions where permanent, seasonal or periodic moisture deficiency results in evaporation and transpiration rates that exceed precipitation. Traditional cultivation practices that utilize modern technology have resulted in substantial amounts of soil loss through wind and water erosion, decreased soil organic matter, reduction in soil water-holding capacity, and alterations to the microbial community composition. Cultivation also affects soil chemical processes and conditions (e.g., pH, cation exchange complexes, electric conductivity, and sodium adsorption ratio) that can lead to further soil degradation. Changes in one or more of these properties often have direct or indirect effects on the fertility of soils, which influence resiliency and soil health. While research has clearly established the most common modifications to soil systems from cultivation, further investigation is needed in semi-arid regions to identify the critical links between physical, chemical, and biological properties that regulate resiliency and soil degradation.

In establishing these critical links, I evaluated the importance of parent material (basalt versus granite) in assessing the impacts on the physical, chemical, and biogeochemical soil properties as a function of cultivation, specifically sprinkler and flood irrigation. I also distinguished microbial community composition by parent material and land use and identified key soil properties that regulate changes in microbial community structure by sampling native and cultivated soils in the San Luis Valley (SLV), located in the South Central part of Colorado. The SLV is a high elevation semi-arid agroecosystem with basalt and granite substrates, that receives 177 mm of precipitation annually and the potential evapotranspiration that exceeds 1016 mm. The SLV has also has a 150-year history of irrigated agriculture practices, which add an additional 153 to 1226 mm of water during the growing season. This alters the natural climate and possibly results in some degree of land degradation.

Overall, the results indicate the importance of parent material (basalt vs. granite), as a soil forming factor in assessing the impact of cultivation on soil degradation processes. The initial clay percent in the native soils was 20% for basalt and 18% for granite. The additional accumulation of clay from irrigation was slightly higher for basalt soil, (22%) and 20% for granite soils. Soils derived from basalt have greater quantities of the major cations while soils derived from granite have lower quantities and a poor nutrient status. Soils derived from basalt have greater percentage of soil organic carbon in the soil surface horizons than soils derived from granite. The uncultivated soils derived from basalt classify as saline-sodic while those derived from granite were consistently non-saline, non-sodic.

As a function of irrigation, the nutrient concentrations of calcium, magnesium, sodium, potassium, chloride and sulfate were reduced in basalt soils while concentrations increased in granite. In addition, the greatest accumulation of clay and soil organic carbon occurred in granite soils with flood irrigation which resulted in similar concentrations as the basalt soils. Also, basalt soils re-classified as non-saline and non-sodic while those derived from granite remain consistently non-saline non-sodic. These results demonstrate a convergence among the basalt and granite soil properties as a function of land use.

Using the ester-linked fatty acid methyl ester (EL-FAMEs), which evaluates differences among soil microbial community composition based on the condition variables of parent material (granite and basalt) and treatments (control, sprinkler, and flood). The results indicated that total microbial biomass and the stress ratios differed between basalt and granite with flood irrigation and the most variation was observed in the basalt-flooded soils. The fungi-to-bacteria ratios were the same in basalt and granite soils and both irrigation types (sprinkler and flood).

Arbuscular Mycorrhizal (AM) Fungi did not differ between basalt and granite, however, the concentrations of AM fungi increased in irrigated soils, suggesting alfalfa and pasture hay grasses nurture root biomass. The correlations analysis identified pH, magnesium, sodium, potassium, chloride, and organic carbon as being the primary soil properties associated with the microbial communities in both soils and treatment types. The results from the sensitivity model for microbial communities in granite soils indicated changes in these soil properties were more pronounced pH, magnesium, sodium, potassium, chloride, and soil organic carbon in both sprinkler and flood irrigation. While the microbial communities in basalt soils were sensitive to pH and soil organic carbon in both irrigation practices; the responses were negligible compared to granite soils. Physical soil properties were not significant in determining correlations or sensitivities among the microbial communities.

Overall, my data revealed the importance of communally evaluating the physical, chemical, and biological properties in determining the key properties that collectively regulate resiliency and indicate soil degradation. The key indicators in this study are soil texture, bulk density, clay, soil organic matter, sodium, chloride, sulfate, and AM Fungi microbial communities, which provide a benchmark for quantifying the magnitude and directional change of soils in cultivated systems with respect to their native counterparts. The findings revealed that long-term cultivation in the SLV has not degraded the soils according to the indices used. The parameters used this study improve the understanding of long-term irrigation impacts on agroecosystems in arid and semi-arid regions by linking the substrate properties with the soil-forming factors and irrigated water quality. This study provides the key information that can be used as a matrix by which to evaluate the impacts of climate change and a growing global population in other water-limited regions.

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CHAPTER 1

INTRODUCTION AND DISSERTATION OBJECTIVES

1.1 Background

Agroecosystems cover more than 28% of the global land area (Ward 2000). Essentially all agricultural land possesses limitations that constrain their ability to optimize production, however, these limitations are magnified in the reported 44% of agroecosystems occupying drylands (The United Nations reported in 2010). Food and Agriculture Organization of the United Nations (FAO 2000a) defined drylands as those regions classified climatically as arid, semi-arid, or dry sub humid, based on the length of the growing period for annual crops. The World Resources Report 2000-2001 estimated that about two-thirds of these agroecosystems have been degraded in the past 50 years. The driving forces of degradation are wind and water erosion, salinization, compaction, nutrient depletion, and biological degradation. Yet, these agroecosystems are under increasing pressure as drylands, which have traditionally been used for livestock, are progressively being transformed into cropland to meet the food needs of an additional 2 billion people over the next 20 years (Beinroth et al., 2007).

Drylands include arid and semi-arid regions, where permanent, seasonal or periodic moisture deficiency results in evaporation and transpiration rates that exceed the amount of precipitation. These environmental variables influence the soil properties composition and characteristics which elicits the behavior of soil system in terms of resiliency and health. The health of these soils is important to look at in terms of the long-term sustainability in dryland agroecosystems. The variables that define soil health influence nutrient cycling, plant production, biological communities, and the formation of stable aggregate that reduce the risks of soil erosion and increase water infiltrations (Lehman et al., 2015).

The San Luis Valley (SLV) located in the South Central part of Colorado is a high elevation desert, with basalt and granite substrates, that receives 177 mm of precipitation annually and the potential evapotranspiration that exceeds 1016 mm. In addition, the SLV has a 150-year history of agriculture activity. The intrinsic soil system and extrinsic environmental conditions within the SLV region provide a unique setting to examine the processes that influence the directional changes in soil properties that influence soil health and degradation processes.

The soil system is defined by the soil-forming factors of climate, organisms, relief, parent material, and humans over time (Jenny, 1941). Therefore, all physical, chemical, and biological properties create unique combinations of characteristics that are important indicators of resiliency and soil health (Beinroth et al., 2007; Lehman et al., 2015). Resilience is defined as the land ability to recover from a disturbance. The current disturbance is the pressure to produce more food due to the swelling population.

In water-limited ecosystems of the world, the major differentiating factors in soil formation are climate, vegetation, and biological activity (Verheye 2006). Precipitation in drylands is generally characterized by irregular distribution of moisture and intense and prolonged periods of drought, which is enhanced by low air humidity, high solar radiation, and high air temperature. The temperatures are generally high with large diurnal variations, which influences biological activity and may increase the potential for mechanical and physical weathering processes. Thus, soil properties present in these ecosystems are the result of limited dissolution of primary minerals (Verheye 2006; Birkland 1974).

The natural vegetation in water-limited areas is primarily xerophytic and sclerophytic vegetation that are regulated by precipitation quantity and distribution, but also by the edaphic conditions (e.g., texture, depth, salinity), and local topographic conditions that influence the moisture content in the biologically active zone (e.g., root zone) (Verheye 2006). The vegetative communities of water-limited ecosystems provide below ground inputs to the Soil Organic

Matter (SOM) pool. Other biological activity from insects, lizards, snakes, and rodents play important roles in mixing of soil materials to the deeper soil layers where moisture remains relatively high and temperature fluctuations are reduced. Microbial activity mirrors patterns of available water and temperature that regulate plant growth (Verheye 2006).

These soil forming factors and the transformations of individual organic and inorganic compounds through oxidation, reduction, hydrolysis, chelation, and crystallization (Wilding et al., 1983) result in the amalgamation of processes that alter the initial state of materials. Even in the most water limited of systems these sets of processes result in a broad array of soil orders, namely, Entisols, Aridsols, Mollisols, Alfisols, and Vertisols. These soils have morphologies that typically reflect less chemical and physical weathering, slow rates of soil formation processes, coarse texture, shallow profiles, abrupt boundary changes. In addition, these soils have accumulations of calcium and salt through aeolian deposition and subsequent retention of soluble salts and carbonates from weathered parent material (Birkland 1974).

Simonson (1959) presented a soil development model that includes concepts of gains, losses, translocations, and transformations of materials. This approach requires a knowledge of the initial state of soil system (e.g., parent material) and allows for evaluation of the overall net changes in soil constituents (e.g., clay) to assess the rates of processes important to soil development (Wilding et al., 1983). In general, the pedogenic processes that predominate in arid and semi-arid regions, are calcification, salinization, and alkalization that influence the translocation of calcium carbonates, soluble salts and sodium ions.

Anthropogenic activities influence the soils ability to function within an ecosystem and major changes in these process from external drivers (e.g., climate and land use change) may result in some degree of land degradation. Soil degradation is often linked to non-sustainable actions or loss of resilience (Gabriels and Cornelis 2008).

The most significant land use change on the planet has come as a direct result of the increasing global population. As more demand is placed on cultivation practices, the resiliency of our soil resources is tested. Traditional cultivation practices that utilize modern technology (e.g., mechanical equipment, manufactured fertilizers, and irrigation have resulted in massive amounts of soil loss through wind and water erosion, decreases in SOM content, observable reduction in soil water-holding capacity and alterations in the microbial community composition. In addition, cultivation also affects soil chemical processes and conditions (e.g., pH, cation exchange complexes, electric conductivity, and sodium adsorption ratio) that can lead to further soil degradation. Changes in one or more of these properties often have direct or indirect effects on the fertility of soils, which can lead to a decrease in soil health and productivity (Lal 2006).

Soil health and resiliency can also be linked to the microbial community composition, which plays a fundamental role in the cycling of nutrients and retention and loss of organic matter in the soil. Thus, it is important to understand the microbial responses to changes in their environmental condition, such as the concentrations of salts and the water content of the soil.

It is clear that further investigation is needed to identify the critical limits of the physical, chemical, and biological properties beyond which soil resiliency is severely and irretrievably jeopardized. The complexity of arid and semi-arid regions provides a pathway by which these critical links can be discovered and directional change in soil properties can be observed as a result of historical land use.

The expectations of soil health and resiliency within the SLV will be governed by the two parent materials (basalt and granite). The initial state of these soil systems will be evaluated by examining the physical, chemical and biogeochemical properties as a function of the parent material. Specifically, the chemical structure of basalt and granite will dictate the ion concentrations in the derived soils; basalt soils will have higher concentrations than granitic soils. Evaluating soil properties collectively will identify which properties will be altered as a function of irrigated agriculture and provide indicators that trend towards degradation or resiliency. I hypothesize that soil health will be a function of the major cation concentrations, soil organic matter percentage and microbial community composition, and will be the primary indicators of soil degradation. The ion concentrations will decrease slightly in basalt soils due to row crop production but the changes will be offset due to increases in weathering of basalt parent material. Granite soils will increase in ion concentrations due to increase in weathering but will be offset by their coarser texture, which will allow for more leaching of nutrients from the system. Therefore, the impacts on both soil types from long-term irrigated agriculture should be similar.

1.2 Research Goals and Objectives

The research presented here intends to broaden the knowledge of anthropogenic impacts in cultured systems (e.g., irrigation) and the environmental controls that affect the progression of soil degradation in the high desert, semi-arid region of the SLV located in south central Colorado. Two questions are addressed: 1) what are the critical links between the conditioning variables and pedogenic processes that influence soil degradation, and 2) what are the critical physical, chemical, and biogeochemical controls that regulate soil degradation?

The specific objectives for this research are:

1) to evaluate the importance of parent material (basalt vs. granite) in assessing the impacts of cultivation on soil degradation
2) to evaluate the influence of cultivation, specifically sprinkler and flood irrigation, as a function of parent material (basalt and granite) on key soil properties
3) to distinguish microbial community composition by parent material and land use and to identify the key soil properties (physical, chemical, and biogeochemical) that regulate the changes in microbial community composition that may influence soil degradation

1.3 Dissertation Format

My dissertation contains five chapters. Chapter 1 provides an overall introduction including overarching objectives for the research. Chapters 2, 3, and 4 were organized and written as separate manuscripts that will be considered for publication. Each manuscript has its own introduction, methods and conclusion sections, which contain a review of the literature relevant to the subject matter. Thus, the introduction and literature review in chapter 1, as well as the general conclusion chapter 5, are brief and only provide an overview of the entire dissertation and encapsulate the results from the three manuscript chapters.

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CHAPTER 2

PEDOLOGY OF NATIVE SITES

2.1 Introduction

Soils contain mineral and organic materials, water, air, and living biota. They are the manifestation of the combined effects of 1) additions to the ground surface, 2) transformations within the soils, 3) vertical transfers within the soil, and 4) removals from the soil (Simonson 1953). Pedology provides the frame work to examine these characteristics as a reflection of the soils internal characteristics, function and resiliency, present and past processes, and conditions of formation (Mitchell et al., 2005).

Soil formation processes are conditioned by soil forming factors, namely, climate, organism, parent material, relief, time, and humans (Jenny 1941, 1980). In general, parent material conditions soil processes and properties to a greater degree in drier regions and in the initial stages of soil development. The more active soil forming factors, namely, climate, vegetation, and biological activity are considered the major differentiating factors across a broader range of environmental conditions (Birkland 1974; Verheye 2008).

In arid and semi-arid regions the conditions for soil formations are driven by the mineral and elemental composition of the parent material and the intensity and duration of the weathering. As a consequence, sand and silt fractions tend to be composed mainly of inherited primary minerals, while clay fractions are dominated by secondary minerals, either formed *in-situ* or transported from other environments (Karathanasis 2007). In high elevation arid to semi-arid regimes climate is characterized by low precipitation and variable day and night temperatures. The moisture supplied to the soil from rain/snow is offset by evaporation, low air humidity, high solar radiation, and high air temperature. The result is limited dissolution of soluble primary minerals, and the development of soil profiles with properties that reflect these environmental conditions (Verheye 2008).

Numerous processes that drive soil formation may take place simultaneously or in sequence and mutually reinforce or contradict one another (Buol et al., 2003; Simonson 1959). These processes fall into four generalized categories, namely, gains, losses, translocations, and transformations that support the differentiation of horizons within a soil profile (Simonson 1959; Schatzel et al., 2005). In addition, the multitude of processes that drive soil formation are and can be combined into "bundles" (Schatzel et al., 2005) of pedogenic processes, of which six are considered to be highly relevant to the study of soils in arid and semi-arid regions: 1) calcification, 2) de-calcification, 3) salinization, 4) de-salinization, 5) alkalization, and 6) de-alkalization (Wilding et al., 1983).

In general, the soils in arid-regions commonly have low levels of organic matter, slightly acid to alkaline reaction (pH) in the surface, calcium carbonate accumulation, coarse to medium texture, low biological activity and weak to moderate profile development (e.g., soil structure) . Soluble salts are also present in quantities sufficient to influence agricultural plants, particularly in poorly drained depression and in irrigated areas (Barrows 1991).

The parent material influences many soil properties. Mineral structure and elemental composition plays a major role in the resistance of the parent materials to weathering. Basalt is an igneous rock with very small crystals, darker in color (black, very dark gray or light gray); and some contain gas bubbles. The weathering behavior depends on the crystallinity and mineral composition; basalt can weather fairly rapidly, due to chemical and physical weather processes. The most abundant minerals are feldspars (iron and magnesium silicate), olivine (magnesium iron silicate), and amphibole and pyroxenes (iron, magnesium, silicon, calcium, and sodium silicate). The weathering of basalt, tends to generate finer textured alkaline soils that are generally nutrient rich (Velde and Meunier 2008).

Granite is an igneous rock completely crystallized; large, well-formed interlocking crystals, no preferred crystal orientation; fairly light in color (white, gray, and pink). The most dominant minerals are quartz (silicon and oxygen), feldspar (rich in iron and magnesium), and biotite (silicate minerals). The quartz-rich material tends to produce sandier textures, poorly buffered, acidic soils of low nutrient status (Velde and Meunier 2008).

Soils are an amalgamation of processes and properties that are unique in their functions and response to land use changes. Soils formed within semi-arid and arid landscapes are especially vulnerable to degradation due to an acceleration of natural degradation processes by increasing frequency of extreme climatic events, natural disasters, and of course a host of human activities with the onset of the Anthropocene (Steffen et al., 2007; Pimentel 2006). These vulnerabilities necessitate the importance of understanding the properties of soils within ecosystems that can be used to evaluate their resiliency and degradation processes. The overarching goal of this study is to evaluate the importance of parent material (i.e., granite and basalt) in assessing the impacts of cultivation on soil degradation processes in high elevation arid ecosystems of the south central Colorado. This chapter will report on the characterization of the control sites linking parent materials to soil properties and establishing the benchmark for evaluating cultivation impacts in later chapters.

2.2 Experimental Design

Study Area

The San Luis Valley (SLV) is located in the South Central part of Colorado. The climate is arid and characterized by cold winters, moderate summers, abundant sunshine, and prevailing winds are in the south to northeast direction. The valley is a high elevation desert with a base elevation of 2147 m. The Sangre de Cristo Mountains flanks the east side of the valley and the San Juan Mountains boarder the west. These mountains range in elevations from 2449 to 4372 m, creating a rain shadow effect, which reduces the amount of precipitation that reaches the valley floor. The mean annual precipitation is < 228 mm annually, and most of the valley receives 177 mm annually with the potential evapotranspiration exceeding 1016 mm (Emery et al., 2013). The surrounding mountains, however, receive 762-1219 mm annually, which is the major source of water for the area (McNoldy and Doesken, 2007). The average annual temperature is approximately 5°C, with extremes of -45°C and 32°C (Emery et al., 2013).

The San Juan Mountains are mafic and composed primarily of basaltic volcanic flows, tuffs and breccias and the Sangre de Cristo Mountains are felsic and composed primarily of granitic rocks. The valley is underlain by as much as 3657 meters of clay, silt, sand, and gravel derived from the surrounding mountain ranges, and interbedded volcanic flows and tuffs. The alluvial fan deposits that form the conduits between the bordering mountains and the valley floor are coarse and permeable near their tops and grade to fine grained, less permeable deposits toward the center of the valley floor (Emery 2013).

Experimental Design and Identification of field sites

Field sites were selected on the basis of the state factor model (Jenny 1994), in which the variability of relief, climate and time were minimized and parent material variations were tested. Parent material was assessed as the independent variable conditioning soil properties. Field sites were restricted to the south central part of the San Luis Valley where the geographic feature of the Rio Grande River and HWY 160 was used as the division between the east and west sides, and the north and south side of the SLV, respectively. To control for relief an elevation gradient constrained the study area to the valley floor, between 2147 – 2351 m, and slope to less than 2%. A combination of geospatial analyses including a Geographical Information System (GIS) was used along with interviews and field observations to identify prospective locations where cultivation practices had not occurred (for control sites) on the soil parent material of interest. Areas of interest were refined by intersecting the 2010 common land units, 2011 LiDAR 10m hill shade, slope and elevation, NDVI vegetation data, Colorado

Geological Survey and United States Geological Survey geology maps, and ESRI™ base map imagery. These analyses isolated the areas within the SLV where both parent material-land use combinations could be found consistent with our project goals. The entire study area is approximately 2.14 km^2 (1.26 km^2 on the west .87 km^2 on the east) (Figure 2.1).

Control pedons were selected from areas that historically were not influenced by agricultural practices and were in close proximity (<0.5 miles, 805 meters) to cultivated sites. Based on the criteria established in our experimental design we located and sampled 14 control pedons derived from basalt and 9 control pedons from granite, which equates to 23 pedons and 117 horizons sampled from the control sites (Table 2.1).

Table 2.1: Sampling design for the control pedons, the number of pedons sampled by parent material and treatment.

Number of Pedons Sampled	Parent Material	Treatments
9	Granite	Control
14	Basalt	Control

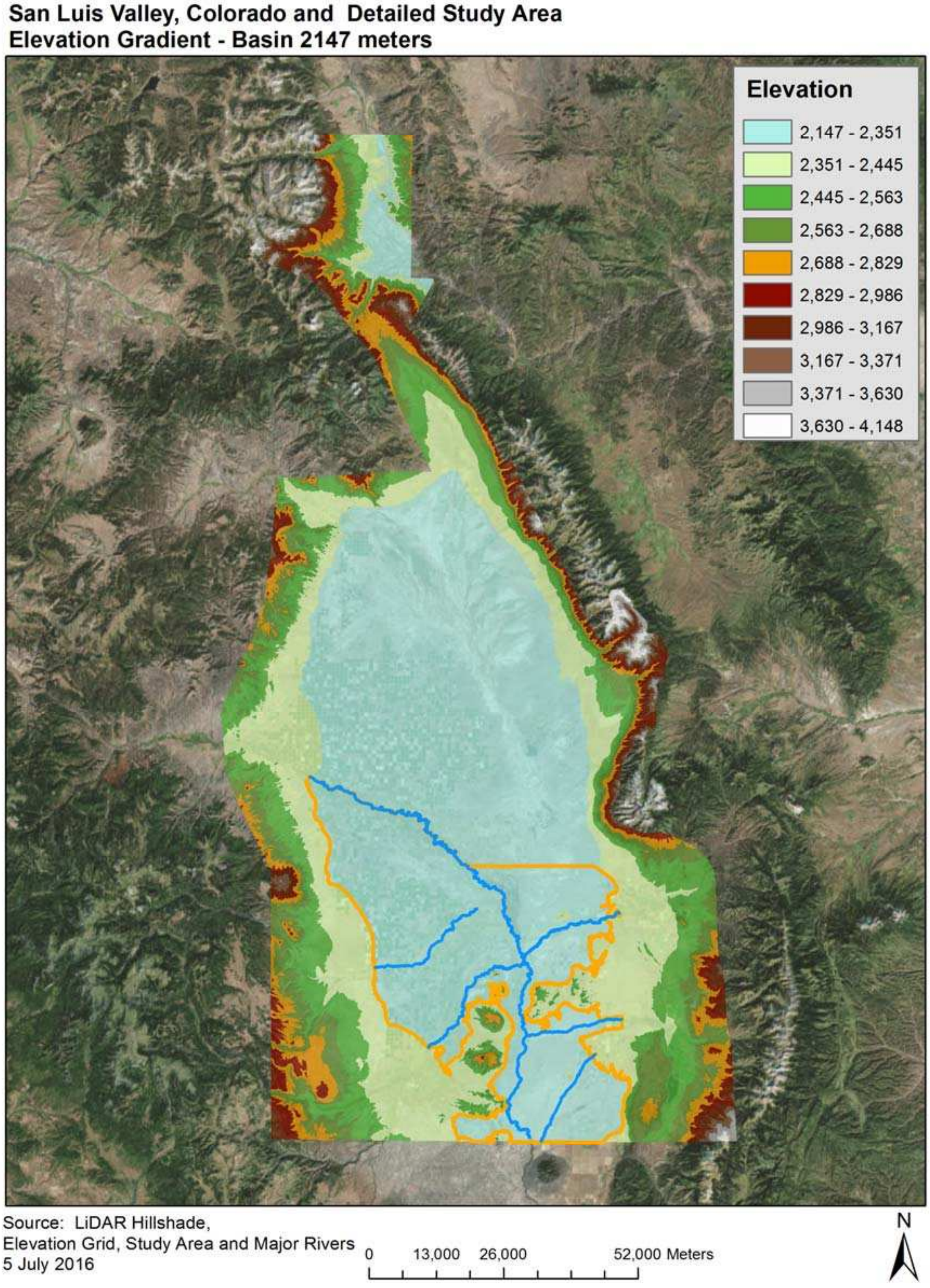
Total number of samples used for analysis was117 horizons from 23 pedons

Site Characteristics

Soils derived from basalt were located in Rio Grande County, Alamosa County, and Conejos County, CO, west of the Rio Grande River. Soils derived from granite were located in Costilla County, CO east of the Rio Grande River. Soil derived from basalt and granite have the same three major land uses - sprinkler and flood irrigation treatments and controls (non-cultivated sites).

The dominate vegetation for the majority of the basalt controls were Greasewood (*Sarcobatus vermiculatus*), greene's rabbitbrush (*Chrysothamnus greenei*), salt grass (*Distichlis spicata* (L.), and blue gramma (*Bouteloua gracilis*) (Dixon 2012). Site observation indicated mature vegetation with no previous recorded evidence of agriculture practices and confirmed by the land owners. The dominate vegetation for the majority of the granite controls were Greasewood (*Sarcobatus vermiculatus*) and salt grass (*Distichlis spicatai* (L.) (Dixon 2012). Site observation indicated mature vegetation with no previous recorded evidence of agriculture practices and confirmed by the land owners.

The soil characteristics from the basalt parent material are described in Table 2.2, which represents three of the 14 control soils sampled. Table 2.3 lists the soil characteristics from the granite parent material, three of the nine controls.



San Luis Valley, Colorado and Detailed Study Area
Elevation Gradient - Basin 2147 meters

Source: LiDAR Hillshade,
Elevation Grid, Study Area and Major Rivers
5 July 2016

Figure 2.1: The detailed elevation gradient extracted from the 10m LiDAR imagery for the San Luis Valley. The study are is approximately 2.14 km^2 - 1.26 km^2 on the west .87 km^2 on the east, with respect to the Rio Grande River as outlined in orange.

2.3 Methods

Field Methods

Soils samples were collected using a hand auger. Depths to the parent material varied by site and ranged from 90 to 120 cm. Soils were described morphologically and sampled by genetic horizon in accordance with the NRCS Field Book for Describing and Sampling Soils, version 3.0 (Schoeneberger et al., 2012). The plant community composition of the all control sites included sagebrush, greasewood, rubber rabbit brush, Greene's rabbit brush, grassland, and shrub-steppe communities (Dixon 2012). Soil sampling was conducted between Aug – Nov 2014.

Soil analysis

All soil samples were air-dried and sieved to < 2mm. Soil particle size analysis was performed using the modified 2-hour hydrometer method (Gee and Bauder 1986). Soil pH in saturated soil paste for Saline Sodic soil were measured using the saturated paste method, Handbook 60, method 2, using an Oaklon™ pH 2700 meter. Electric Conductivity (EC) was determined using the Electric Conductivity Extraction method in saturated soil paste extraction, Handbook 60, method 2, for saline sodic soil and YSI Model 35 Conductance Meter. Cation Exchange Capacity (CEC) was measured using the displacement (pH 8.2) method, NRCS, Soil Survey Investigation Report No. 42. Version 4.0. Method 4B4b (modified). The CEC ionic concentration was analyzed using the Inductive Coupled Plasma Optical Emission Spectrometer (ICP-OES) Optima 7300 DV, Perkin Elmer. Exchangeable Cations and Exchangeable Sodium Percent (ESP) was measure using Handbook 60, method 18 and 20b and the ionic concentration was analyzed using the ICP-OES Optima 7300 DV. Sodium Adsorption ratio (SAR) was measured using the Handbook 60, method 2. The SAR ionic concentration was analyzed using the ICP-OES Optima 7300 DV. Anion concentrations were measured using the saturated paste method, Handbook 60, method 2. Anion concentration were analyzed with the Ion Chromatography System Dionex ICS-1100. Carbonate and

Bicarbonate was measured using the Titration with Acid Handbook 60, method 12. Total carbon (C) and nitrogen (N) were determined on finely ground soil, and then analyzed with a LECO-TruSpec ® CN628 Elemental Combustion Analyzer (St Joseph, MI, USA).

Total calcium carbonate content was determined by measuring the CO_2 released using the Inorganic Carbon Analysis by Modified Pressure-Calcimeter Method (Sherrod et al., 2002). Each sample was finely ground and passed through 200-um sieve. Samples were transferred to a Wheaton serum bottle, in which a 2-ml (.50 dram) auto sampler vial was inserted containing 2-ml of the acid reagent of 6 M HCl containing 3% by weight of $FeCl_2*4H_2O$. The hydrochloric acid evolved CO_2 during a 2 to 24-hour period at which time, the pressure inside was measured using the pressure transducers and voltage meter. Measured values were converted to concentration of inorganic carbon using a calibration curve generated from known concentration of $CaCO_3$ standards. The quantities of Soil Organic Carbon (SOC) was determined by difference (total C – inorganic C = organic C). Bulk density was estimated by method outlined in Rawls (1983).

Particle density of granite 2.65 g/cm^3 (Crawford 2013) and particle density of basalt 2.79 g/cm^3 (Hyndman and Dury 1977).

Statistical Analyses

Based on the experimental design these data were generated and summarized in groups; 23 locations representing the control pedons on two parent material, basalt and granite. All statistical analyses were performed in R 3.2.3 (R Core Team 2015). Principle component analysis used the inherit prcomp method in R. The inherit ANOVA aov method in R was used to evaluate results from the mass balance data and to evaluate the R^2 values of the parameters entered into the linear model. To evaluate the statistical significance of the liner mixed-effects model, the lsmeans from lsmeans-package was used, the parameter were a confidence level of 0.95, p value adjustment used the tukey method for comparing a family of 18 estimates and the significance level used was alpha = 0.05 (Lenth 2016) and the MuMIn (Barton 2016). The linear mixed-effect model describes the relationship between a response variable and independent variables. The mixed-effects portion of the model consists of two parts, fixed effects and random effects. Fixed-effects terms are usually the conventional linear regression part, and the random effects are associated with individual experimental units drawn at random from a population. The random effects have prior distributions whereas fixed effects do not. Mixed-effects models can represent the covariance structure related to the grouping of data by associating the common random effects to observations that have the same level of a grouping variable (R Core Team 2015). The linear mixed effects model used the lme4 package (Bates et al., 2015), and MASS package (Venables et al., 2002); 0.95 confidence intervals for analyzing mixed effect regression models were determined using the merTools package (Knowles and Frederick 2016). Parent and parcel grouping described how the treatment and control soils were grouped together for analysis were considered random variables and the soil properties were fixed. The linear mixed effect model analyzed the response variable with the interaction of the parent material and the control treatment. Significance was determined at $P \leq 0.05$.

2.4 Results and Discussion

Soil Morphological and Physical Properties

The morphological properties of soils derived from basalt were similar with respect to the presence of master horizons, soil depth and color. Accumulation of exchangeable sodium and soluble salts (e.g. more soluble than gypsum) were present in both the A and B horizons. The average accumulation of $CaCO_3$ within the profile was 4% and occurred in all pedons (Table 2.2).

The characteristics of soil derived from granite were similar with respect to master horizons, depth and color. Accumulation of exchangeable sodium and salts, more soluble salts (e.g., more soluble than gypsum) were not present in the control pedons. Slightly higher accumulations of $CaCO_3$ (5.5%) were only present in a few of the pedons. In general, the soil profiles lacked soil development with weakly developed Bt horizons (Table 2.3).

Table 2.2: Morphological properties from soils derived from basalt, the abbreviations are defined as basalt control (BC),. Environmental variables are elevation, slope %; soil profile characteristic - horizonation depth in centimeters, texture based on NRCS abbreviations, and Munsell moist color value Hue/Chroma, San Luis Valley, CO

Location	**Elevation (m)**	**Slope %**	**Horizon**	**Depth (cm)**	**Texture**	**Munsell* Moist Color**
BC-1	2305	0.54	Anz	0-5	SL	10YR 3/2
			Btkz	5-46	SCL	10YR 2/1
			Bkz	46-81	SL	10YR 3/1
			BC	81-112	LS	7.5YR 3/1
			Ck	112-132	SL	7.5YR 4/2
BC-6	2290	0.18	A	0–3	SL	7.5YR 3/2
			Btkz	3-25	SL	7.5YR 4/4
			Bt1	25-56	SL	7.5YR 4/4
			Bt2	56-69	SL	10YR 5/3
			BC	69-99	SL	10YR 4/3
			C1	99-130	SL	10YR 3/3
			C2	130-142	S	
BC-11	2324	0.56	Anz	0-3	SCL	7.5YR 3/3
			BAnz	3-18	SCL	7.5YR 4/3
			Btknz	18-51	SCL	7.5YR 6/4
			Bk	51-102	SCL	7.5YR 7/4
			BCK1	102-127	SCL	7.5YR 6/4
			BCK2	127-147	SCL	7.5YR 5/4

*Munsell soil colors standards, texture abbreviations: SCL – Sandy Clay Loam, SL – Sandy Loam, LS – Loamy Sand, L - Loam, SC – Sandy Clay

Table 2.3: Morphological properties from soils derived from granite, the abbreviations are defined as granite control (GC),. Environmental variables are elevation, slope %; soil profile characteristic - horizonation depth in centimeters, texture based on NRCS abbreviations, and Munsell moist color value Hue/Chroma, San Luis Valley, CO

Location	**Elevation (m)**	**Slope %**	**Horizon**	**Depth (cm)**	**Texture**	**Munsell* Moist Color**
GC-3	2362	0.55	A	0-8	SL	7.5YR 4/4
			AB	8-28	SL	7.5YR 4/4
			Btk	28-61	SCL	7.5YR 7/2
			Bk	61-69	SCL	7.5YR 7/2
			BCk	69-94	SCL	7.5YR 7/3
GC-7	2292	0.41	A	0-3	SL	7.5YR 3/3
			Bw	3-23	SL	7.5YR 4/3
			Btk	23-38	SCL	7.5YR 6/3
			BCk	38-46	SCL	7.5YR 6/4
			2Btk	46-56	SCL	7.5YR 7/3
GC-9	2338	0.95	A	0-5	SL	7.5YR 4/3
			AB	5-23	SL	7.5YR 3/2
			Bw	23-46	SL	7.5YR 4/4
			Bk	46-58	SL	7.5YR 5/4
			CBK	58-60	SL	

* Munsell soil colors standards, texture abbreviations: SCL – Sandy Clay Loam, SL – Sandy Loam, LS – Loamy Sand, L - Loam, SC – Sandy Clay

Modeling of Soil Properties

We evaluated 15 soil properties to establish the differences between soils derived from basalt and granite in order to create the bench mark soils property parameters that will be used for further evaluation in Chapter 3, which examines the influence of irrigation. Table 2.4 outlines the properties by each category.

Table 2.4: The type of soil analysis performed by category – Physical, chemical and biogeochemical for the soils derived from basalt and granite

Physical	**Chemical**	**Biogeochemical**
Sand *	pH *	Calcium Carbonate *ǂ
Silt *	Electric Conductivity (ECe) *	Soil Organic Carbon *ǂ
Clay* ǂ	Sodium Adsorption Ratio (SAR) *	Total Carbon ł
Soil Bulk Density *ǂ	Exchangeable Sodium Percent (ESP) *	Total Nitrogen ǂ
Soil Bulk Density Ratio ǂ	Exchangeable Base Cations and Anions *	C:N ratio ǂ
	Cation Exchange Capacity *ǂ	

* Linear mixed effect model analysis
ǂ ANOVA mass data or average analysis

Modeling of Soil Properties

The principle component analysis, which is widely used to reduce the dimensionality among data sets, was used to quantify the variation among the 23 control pedons from soils derived from basalt and granite. The soil properties were separated into three groups, physical properties –sand, silt, and clay; chemical properties – pH, major cations calcium (Ca), magnesium (Mg), sodium (Na), potassium (K), anions chloride (Cl) and sulfate (SO_4), and biogeochemical properties of calcium carbonate ($CaCO_3$) % and soil organic carbon (OC) %. This process eliminated the correlated values from the full data set represented in Table 2.4.

Collectively, the soil properties clustered by parent material in Figure 2.2 A, PCoA 1 explained 38% and PCoA 2 explained 21%, for a total of 59% of the variation of these data were explained. Large, positive coefficients indicated the enriching soil properties were located on the positive side of the PCoA axis. Large, negative coefficients indicate the soil properties that are enriched are found on the negative side of the PCoA axis (Figure 2.2 A). The clustering pattern of parent material and horizon (Figure 2.2 B) showed a similar distribution pattern of the soil properties and indicated which horizons behaved similarly. The variances explained for Figure 2.2 B were the same as Figure 2.2 A.

The soil property with the positive eigenvector coefficient for PCoA 1 in Figure 2.2 A and Figure 2.2 B was sand. In contrast, the soil properties with negative eigenvector coefficients for PCoA 1, and more associated with properties to the left of PCoA 1, included sodium, potassium, chloride, sulfate, calcium, magnesium, pH, clay, organic carbon and calcium carbonate (Appendices 1).

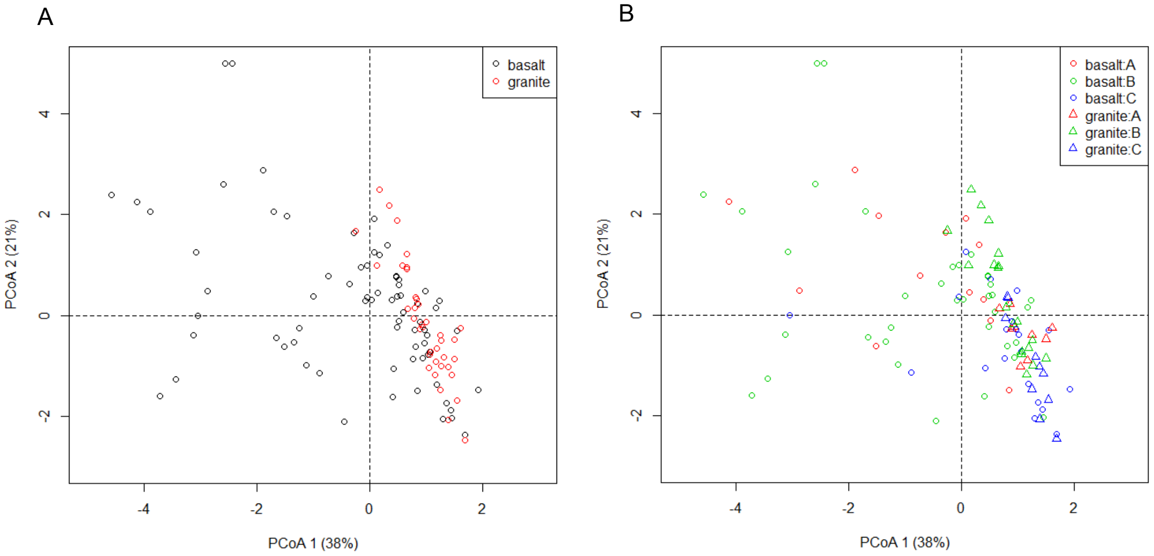


Figure 2.2: The distribution of the principle component analysis in soil derived from granite and basalt (A) by parent material and (B) by parent material and horizon. The percent variance explained by each principal component (PCoA) is shown in parentheses.

Principal component analysis was also used to explain the variation in the soil properties as a function of parent material. The soil properties derived from basalt Figure 2.3, PCoA 1 explained 37% and PCoA 2 explained 24%, for a total of 51% of the variation of these data were explained. Soil properties with the most positive eigenvectors coefficients for PCoA 1 were of clay, pH, calcium carbonate, organic carbon, calcium, magnesium, sodium, potassium, chloride, and sulfate. In contrast, the soil property with a negative eigenvector coefficient for PCoA 1 was sand (Appendices 2).

The soil properties derived from granite Figure 2.4, PCoA 1 explained 47% and PCoA 2 explained 21%, for a total of 68% of the variation of these data were explained. Soil properties with the most positive eigenvectors coefficients for PCoA 1 were of sand, organic carbon, and potassium. In contrast, the soil properties with a negative eigenvector coefficients for PCoA 1 were pH, clay, calcium carbonate, calcium, magnesium, sodium, chloride, and sulfate (Appendices 3).

The soil properties derived from basalt have distinctive clustering patterns among chloride and sulfate, sodium and potassium, calcium carbonate and organic carbon, and calcium and clay. In contrast, the clusters observed among the soil properties derived from granite were pH, clay, and calcium carbonate, sand and potassium, and magnesium, sodium, chloride, and calcium. This suggests that specific properties behave similarly under specific conditions, it also validates the nutrient content and texture are directly related to the parent mineral arrangement and structure.

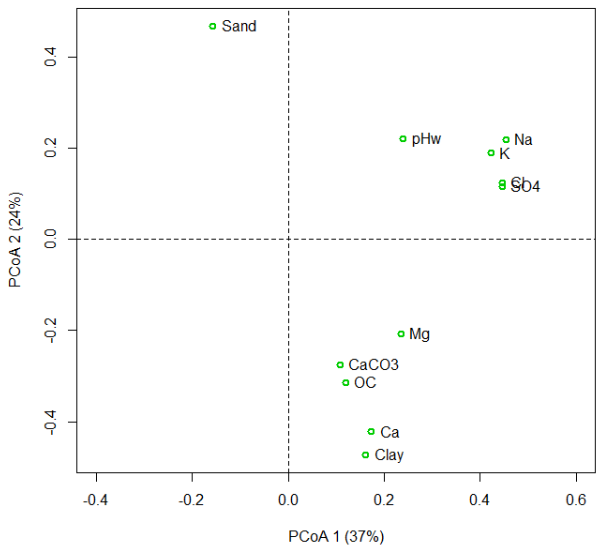


Figure 2.3: Principle Component Analysis of the soil properties derived from basalt. The percent variance explained by each principal component (PCoA) is shown in parentheses.

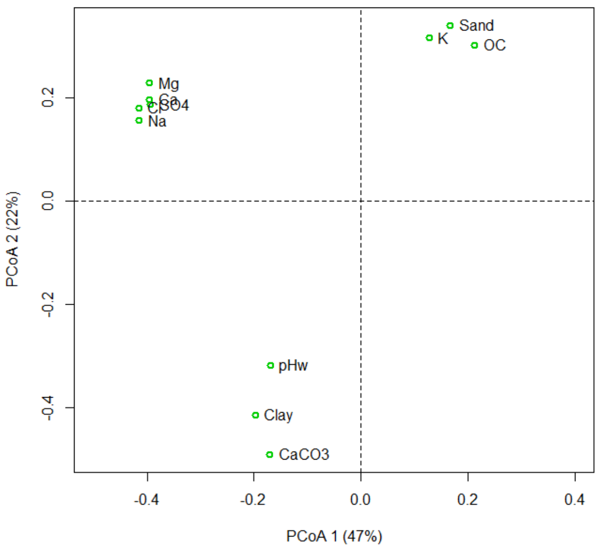


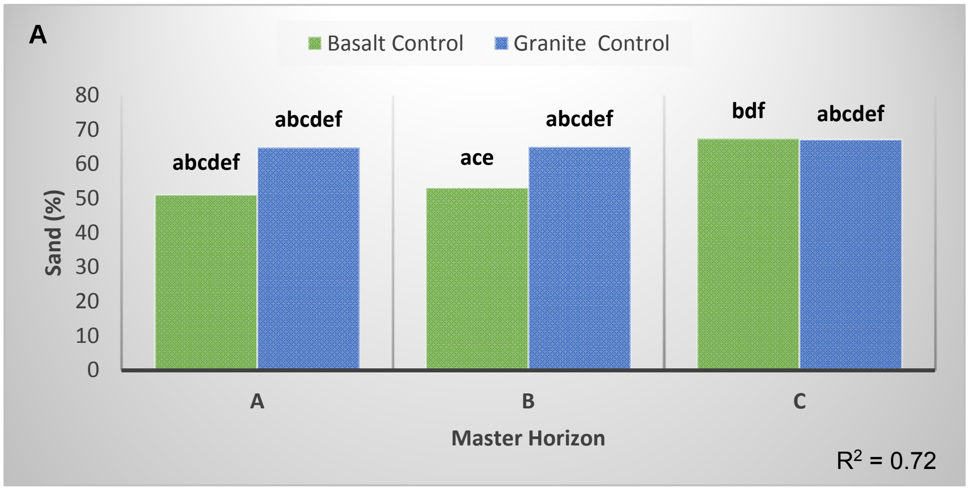
Figure 2.4: Principle Component Analysis of the soil properties derived from granite. The percent variance explained by each principal component (PCoA) is shown in parentheses.

Linear Mixed-Effects Model

We initially looked at the data using the linear mixed effect model approach to evaluate the difference between the parent materials within the different categories (physical, chemical and biogeochemical) by master horizons. The statistical differences within the model were evaluated by using a 0.95 confidence level, the P value adjustment was done by using the Tukey method that compared 18 family estimates (the controls were a displayed separately from the treatments in this chapter), and the alpha significance level was 0.05. Results from the linear mixed effects model are indicated by the asterisk in Table 2.4

Soil derived from granite were statistically different than soils derived from basalt and the differences between the two parent materials throughout the majority of the profile. Sand was statistically the same in the A horizon of both parent material and differed in both the B and C horizons (Figure 2.5 A). Silt was statistically different primarily in the A and B horizons in soils derived from basalt and statistically similar in the same horizons in soils derived from granite.

The C horizon was statically the same for both parent materials (Figure 2.5 B). Clay was statically different in soils derived from basalt than granite and were statically different among the horizons. Clay in soils derived from granite were statistically the same throughout the profile. There was a variation in the clay content in the C horizon showed an increase of clay accumulation in soils derived from granite than basalt and is likely due the greater depth of leaching in the coarser textured matrix of the soils (Figure 2.5 C). These results indicate that mineral weathering and argillic horizon formation are relatively slow, which varies with the parent material and climatic conditions (Presley et al., 2004). Birkland (1999) and Buol et al. (2003) indicate that these processes in general occur on the order of thousands of years. Therefore, we would expect a greater percentages of clay in soils derived from basalt, due to the feldspar minerals and the release of 2:1 clays from the biotite minerals in granite; neither condition were observed in the clay content or the cation exchange capacity values in Figure 2.6 H. These difference will also influence infiltration rates during precipitation events, and subsequently, the depth of percolation and evaporative losses. Thus, these results indicate that the soil in the SLV are relatively young and lack significant differentiation among their physical properties.



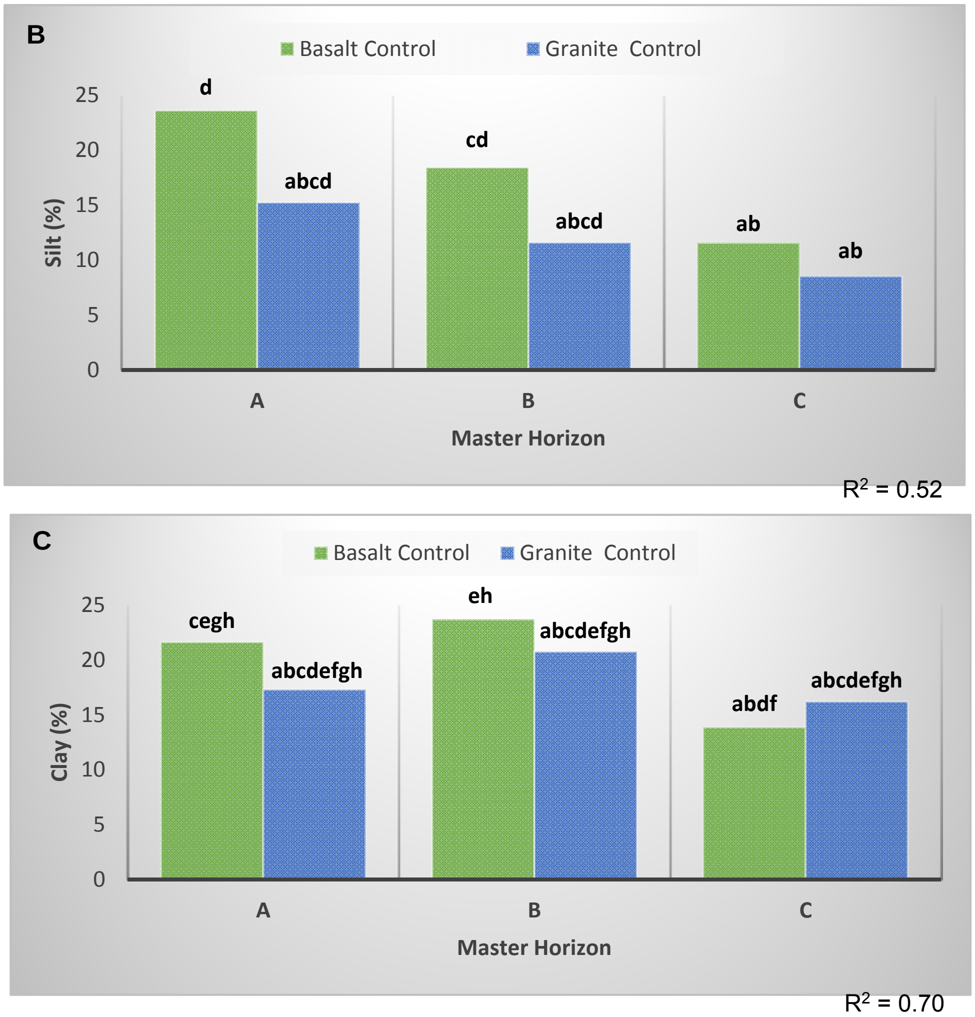


Figure 2.5: Comparing the physical soil properties from soils derived from basalt and granite within each master horizon; (A) Sand, (B) Silt and (C) Clay from the Linear Mixed Model. The interaction between of parent material and the master horizons in the linear model were significant $P \leq 0.05$. The lsmeans with different letters are significantly different (Tukey's).

Chemical Properties

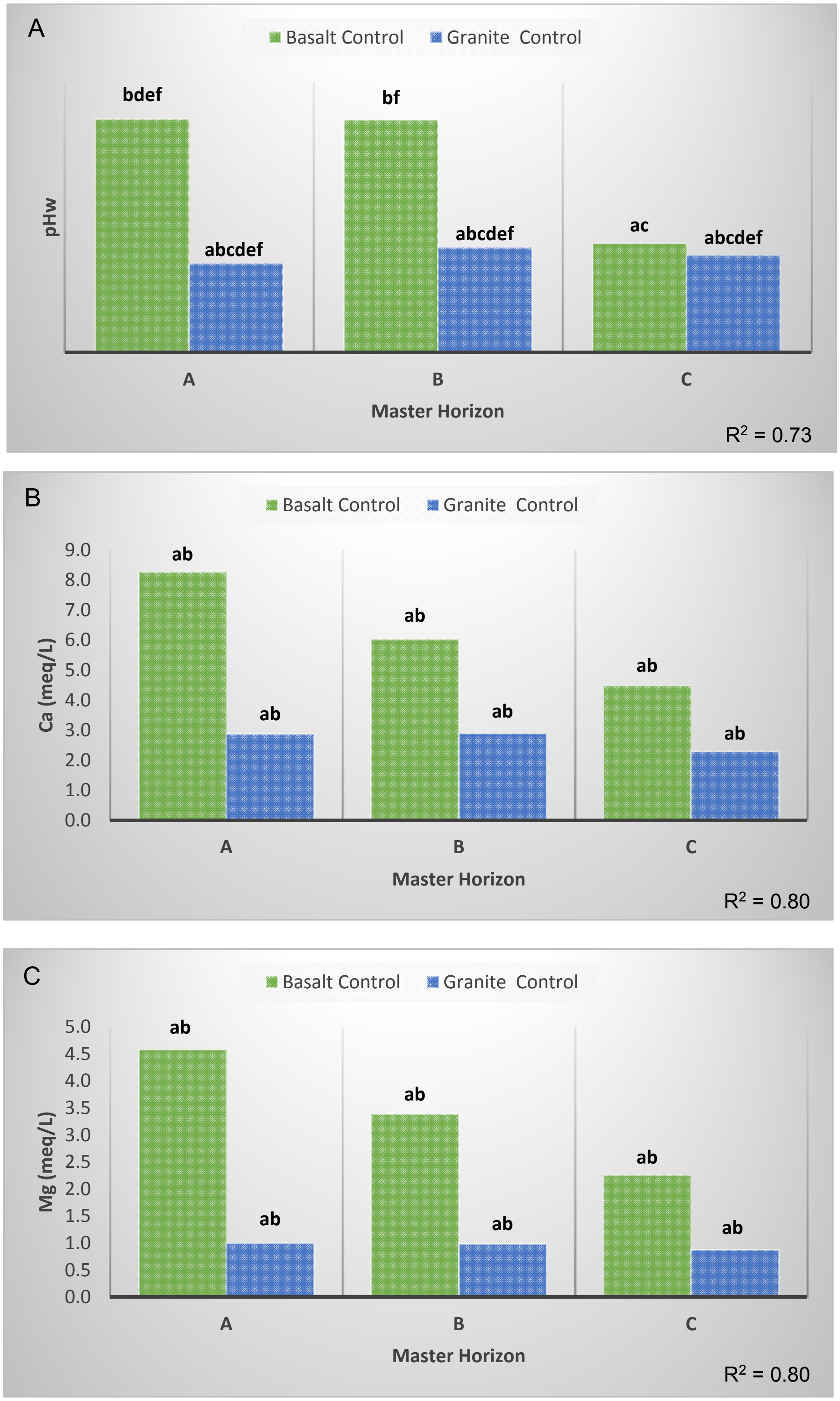
The soils derived from basalt had a higher pH range (7.6 to 8.1) than soils derived from granite throughout all master horizons, with both remaining in the neutral range. Soils derived from basalt were statistically different from soils derived from granite and were different among the horizons, while the granite soils remained the same throughout the profile (Figure 2.6 A). The calcium and magnesium concentrations were greater in the soils derived from basalt relative to soils derived from granite however, they were not statistically different between the two parent materials or throughout the profile (Figure 2.6 B - C). The sodium content was greater in soil derived from basalt than granite. The soils differed statistically between basalt and granite and differed among the horizons in basalt soils and were similar among the horizons for granite soils (Figure 2.6 D). Potassium was statistically different between basalt and granite soils and varied through the horizons in both soil types. The potassium content was higher in the soils derived from basalt than granite (Figure 2.6 E). The two anions Cl and SO_4 were significantly higher is soils derived from basalt than granite with higher concentrations generally found in the upper portions of the soil profile. However, the A and B horizons in basalt soils were statistically the similar for chloride and were statistically different from granite soils. Chloride in granite soils were similar in the A and B horizons as well and both soil types different in the C horizons (Figure 2.6 F-G). Sulfate in soils derived from basalt were statistically different from soils derived from granite. The A and B horizons were the same and differed in the C horizon of basalt soils. Granite soils showed variation in the A horizon and similarities in the B and C horizons for sulfate (Figure 2.6 G).

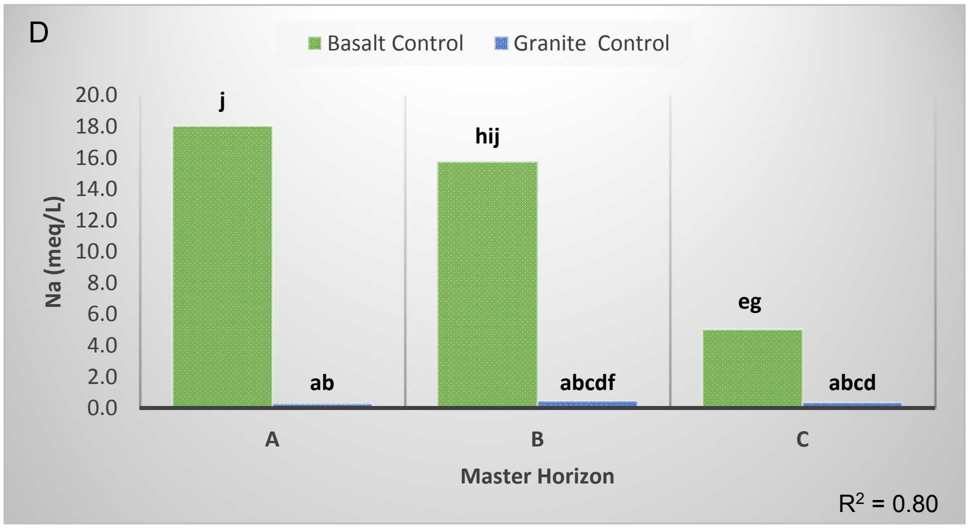
The results of the chemical analysis fall within the general range for values reported in semi-arid to arid regions of the western US (USDA NRCS 2012). The analyses of major cations shows a contrast between the parent materials; basalt soil have higher concentrations of major cations tending toward more fertile soils, and granite soils have lower concentrations leading to a poorer nutrient status. Soluble salt concentrations which are derived from secondary weathering of these soil materials from basalt. In addition, a large concentration of sulfate was measured in soils derived from basalt. These results reflect greater quantities of amphibole in the basalt. Soils derived from granite have significantly lower concentrations of soluble salts anions compared to the basalt soils.

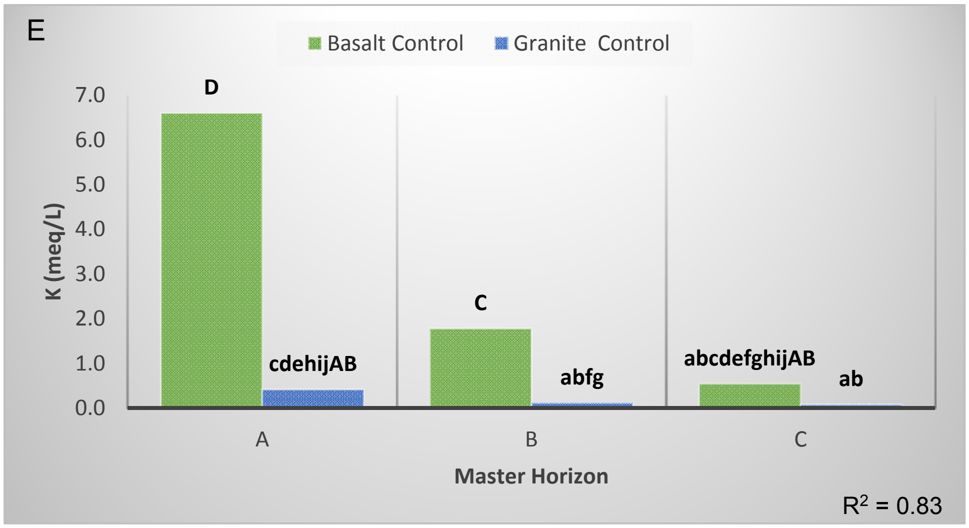
In addition, the accumulation of these water soluble salts will affect hydraulic properties of the surface horizons of soils by influencing the infiltration rates during precipitation events and evaporative losses (Young et al., 2004). Salts may be used as a proxy of the long term wetting front within the soil, suggesting the maximum depth of percolation approached the top of C horizon in basalt and the bottom of the profile in granite soils (Figure 2.6 B – G and Table 2.2 and 2.3).

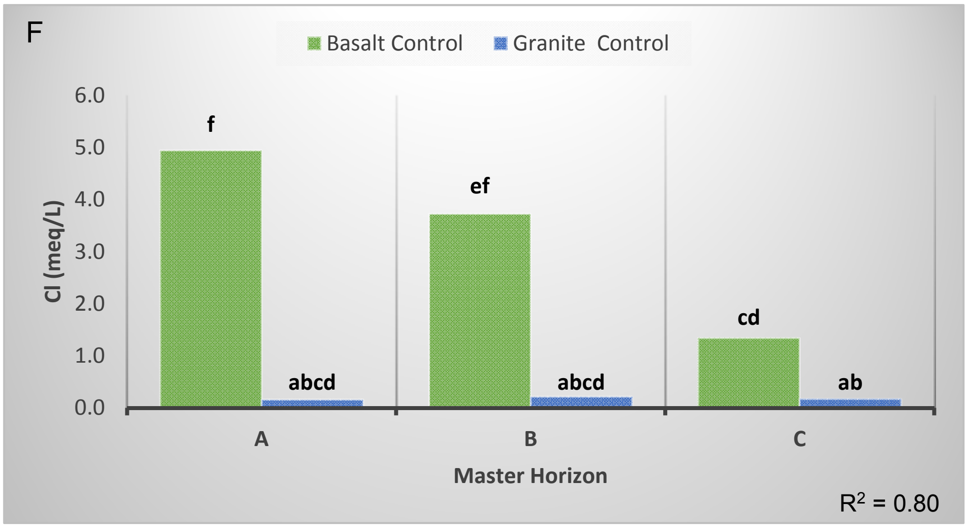
These data suggest that soils derived from basalt with finer texture have a marked decline in their depth of percolation is due to the accumulation of soluble salts. These results differ with the work of Phillips (1994), who showed that soluble salt profiles in desert soils are characterized by low concentrations near the soil surface, a peak in concentration a few meters below ground surface, and a decrease concentration below depth. Our results showed that the peak accumulations were within the top few centimeters of the surface horizons with the highest concentrations being sodium and sulfate salts. In contrast, soil derived from granite did not exhibit any peak accumulations and this due to chemical composition of granite and the coarser texture of the surface soil horizons. Therefore, salt distribution and content within soils profiles can provide an indication of long-term behavior of water movement and storage. Specifically, these salt profiles indicate there is a lack of precipitation to dissolve the salts and leach them out of the root zone, there are high evaporation rates that occur at the surface, and long-term impacts and shifts in the plant communities occur from decreased water uptake.

Cation Exchange Capacity (CEC) Figure 2.6 H, were statistically similar between basalt and granite soils, the average CEC for the A and B horizons for basalt were 16.6 meq/100g and 11.6 meq/100g in granite soils. The C horizon in granite soils was the most statistically dissimilar. These values further emphasize the low concentrations of clays as observed in Figure 2.5 C.


A
Basalt Control
Granite Control
pHw
bdef
abcdef
bf
abcdef
ac
abcdef
A
B
C
Master Horizon
$R^2 = 0.73$
B
Basalt Control
Granite Control
Ca (meq/L)
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
ab
ab
ab
ab
ab
ab
A
B
C
Master Horizon
$R^2 = 0.80$
C
Basalt Control
Granite Control
Mg (meq/L)
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
ab
ab
ab
ab
ab
ab
A
B
C
Master Horizon
$R^2 = 0.80$


D
Basalt Control
Granite Control
Na (meq/L)
20.0
18.0
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
j
ab
hij
abcdf
eg
abcd
A
B
C
Master Horizon
R² = 0.80


E
Basalt Control
Granite Control
K (meq/L)
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
D
cdehijAB
C
abfg
abcdefghijAB
ab
A
B
C
Master Horizon
R² = 0.83


F
Basalt Control
Granite Control
Cl (meq/L)
6.0
5.0
4.0
3.0
2.0
1.0
0.0
f
abcd
ef
abcd
cd
ab
A
B
C
Master Horizon
R² = 0.80

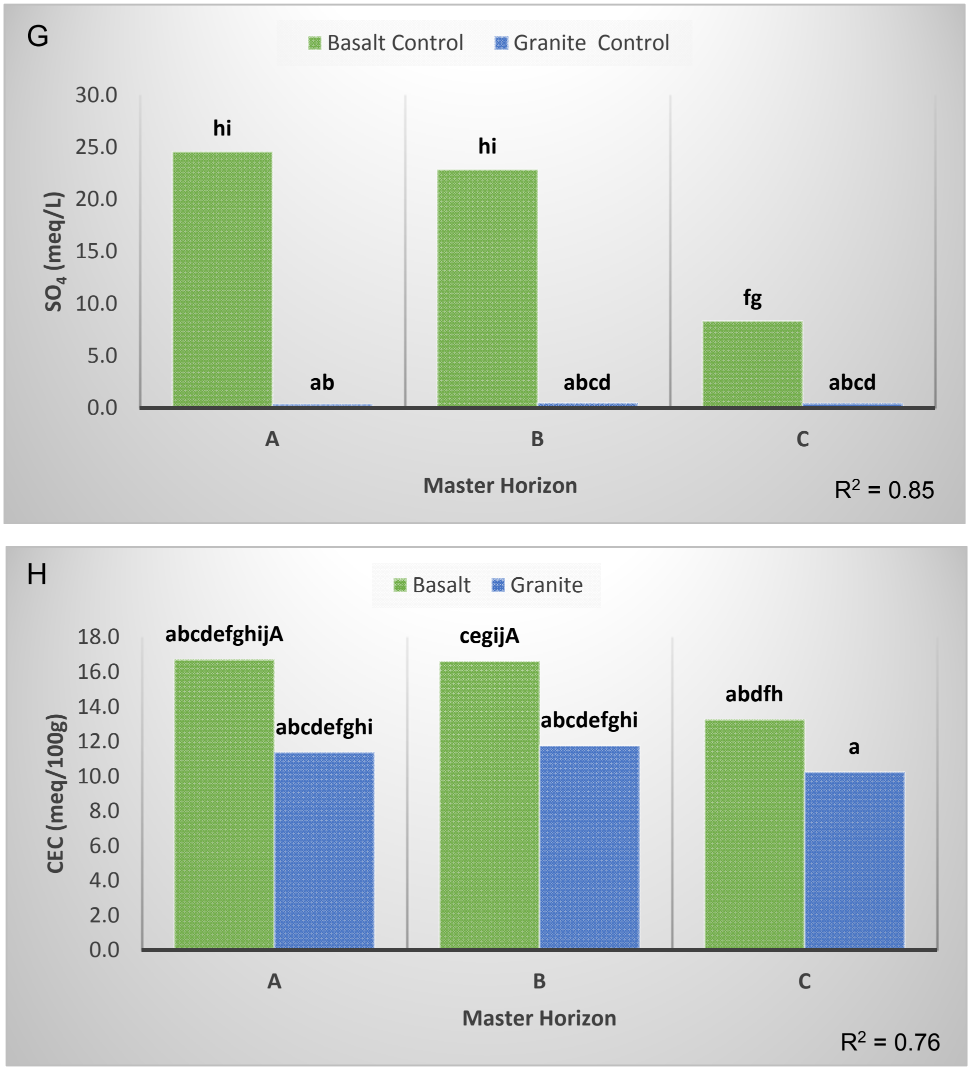


Figure 2.6 Comparing the chemical soil properties from soils derived from basalt and granite within each master horizon: (A) pHw, (B) Calcium (Ca), (C) Magnesium (Mg), (D) Sodium (Na), (E) Potassium (K), (F) Chloride (Cl), (G) Sulfate (SO_4) and (H) Cation Exchange Capacity (CEC). The interaction between of parent material and the master horizons in the linear model were significant $P \leq 0.05$. The lsmeans with different letters are significantly different (Tukey's).

Biogeochemical Properties

Soil organic carbon concentrations are statistically different between basalt and granite. Soils derived from basalt contain 23% more SOC than soils derived from granite but in both systems SOC was concentrated in the A horizon and share similar behaviors among the B and C horizons (Figure 2.7 A). Soil organic carbon is the lesser of the two pools of carbon in semi-arid environments, and is a critical component of soil quality as it affects many soil chemical, physical and biological properties. It is evident in this system that the water holding capacity and total water storage in the profile correspond has influenced the plant communities in the SLV which in turn has reduced the plant litter composition.

The SOC content is likely the result of the variability in vegetation density (higher density on basalt), hydrological properties and the likely the influence of texture on production and decomposition. The results show a higher concentrations of soil organic carbon in the soils derived from basalt, which are medium in texture and less susceptible to decomposition relative to the coarser grained counterpart.

However, a growing body of evidence has demonstrated that photodegradation, the breakdown of chemical compounds by solar radiation, plays a significant role in the decomposition of surface litter in arid ecosystems (Brandt et al., 2007). This abiotic process can account for up to 60% of litter mass loss in semi-arid systems which affects microbial decomposition from the changes in litter chemistry; increased leaching losses of dissolved organic matter from changes in litter solubility; and photochemical mineralization of the litter (Brandt et al., 2009). Further research is needed to fully determine the primary source of limited soil organic matter in this system.

The $CaCO_3$ concentrations in soils derived from basalt were higher when compared to soils derived from granite. The two parent materials are statistically different and have similarities among the horizons, specifically between the A horizon in basalt and the B horizon in granite (Figure 2.7 B).

These data indicate $CaCO_3$ accumulations more predominate in the A and B horizons of soils derived from basalt and greater accumulations is observed in the C horizon of soils formed from granite. The observed differences could be the result of the medium texture and more clay accumulation in the A and B horizons, resulting in less leaching to the C horizon. It could also be suggested there has been an additional accumulation of $CaCO_3$ from aeolian deposition. In contrast, soil derived from granite have coarse texture which allows for $CaCO_3$ to leach through the profile and accumulate predominately in the C horizon. Suggesting, that the $CaCO_3$ could be depositional and pedogenic in nature, however, further analytical analysis will need to be performed to confirm the origin.

The formation of carbonates is directly influenced by the carbonate bicarbonate equilibrium. Due to the low annual precipitation the rate of dissolution is limited and the advancement of $CaCO_3$ in the profile is also a proxy for the wetting front (Lal and Kimble 2000). The additional accumulations is being deposited in the soil pore space, which could lead to cementation, decrease in pore volume and decreased aeration in the lower part of the profile (Magaritz and Amiel 1981) as seen in the B horizon of the basalt soils. However, further analysis is need on the micromorphology characteristics.

The accumulation of $CaCO_3$ in the surface horizon of the granite control soils could also suggests there are additional external sources of carbonates entering the SLV. The prevailing wind direction is to the south east, which is transporting minerals and soil from the basaltic San Juan Mountains to the predominately granitic east side; this could be the primary source of the additional Ca.

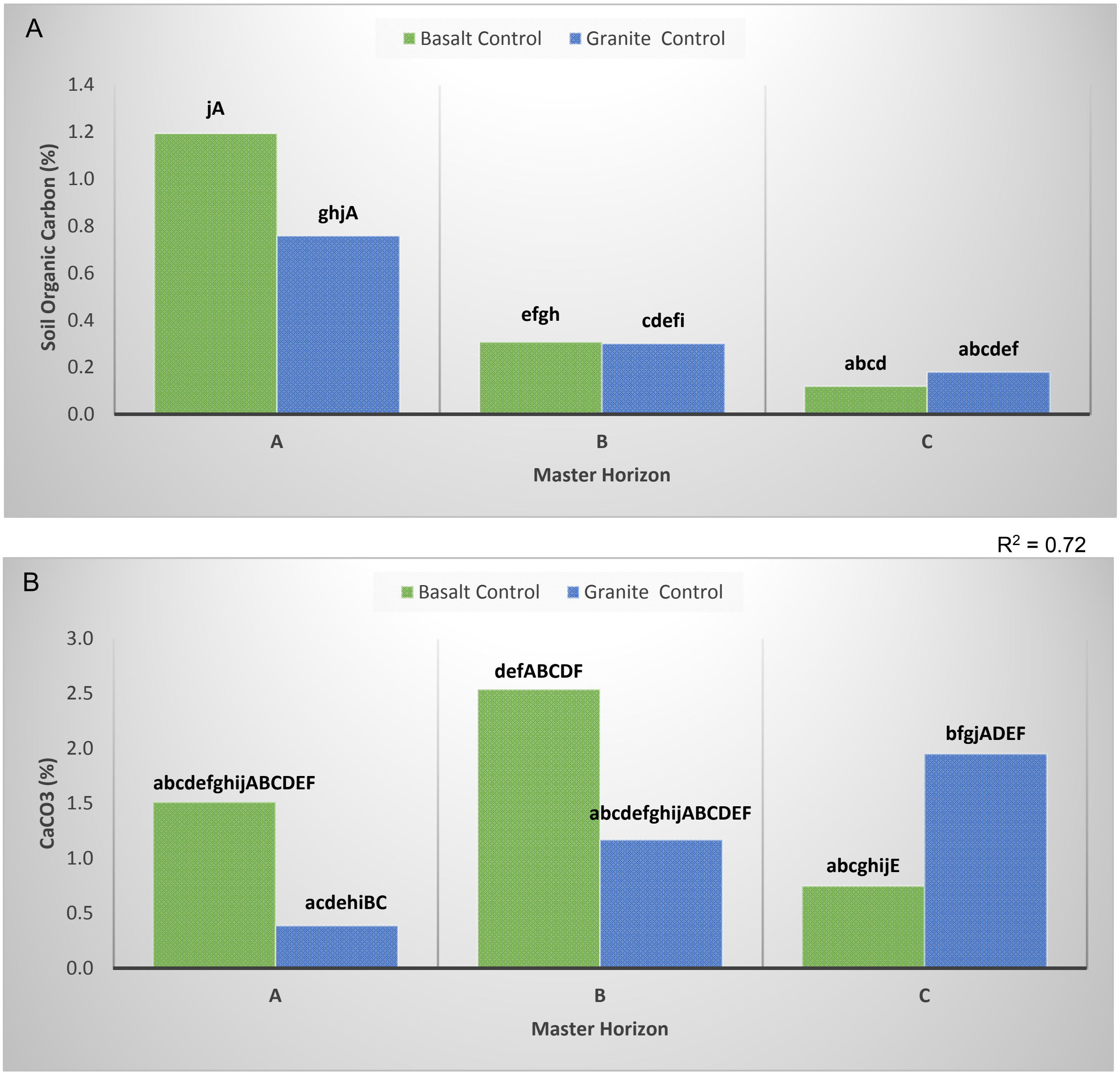


Figure 2.7 Comparing the biogeochemical soil properties from soils derived from basalt and granite within each master horizon: (A) Soil Organic Carbon % and (B) Calcium Carbonate ($CaCO_3$) %. The interaction between of parent material and the master horizons in the linear model were significant $P \leq 0.05$. The lsmeans with different letters are significantly different (Tukey's).

Soil Properties by Mass and Average

To further evaluate the soils that have formed from basalt and granite, we evaluated the clay content to a standard depth of 100 cm using the mass data method and by averaged the values of porosity, bulk density and bulk density ratio to 100 cm. These results were evaluated using an ANOVA to determine the statistical differences. The results compare the profiles of basalt vs. granite soils in further establishing them as bench mark soils by which their behavior patterns will be evaluated in chapter 3 as a function of long-term irrigation.

Physical Properties

The content of clay between basalt and granite was not statistically different (Figure 2.8). The similar clay content emphasizes that the chemical and physical weathering processes are slow due to the climatic conditions of the SLV. However, the CEC to the same depth were statistically different were basalt clays have a higher value (Figure 2.9). In addition, the results from porosity, bulk density and bulk density ratio in Figure 2.10 A-C were not statistically different between basalt and granite. In a study by Young et al. (2006) demonstrated the similarities in sand and clay content, soil development, and the general lack of swelling clays, the near-surface water balance characteristics and their associated response in water-limited ecosystems are similar. Our data suggests a similar relationship exists between the soils derived from basalt and granite in the surface horizons suggesting they share similar responses in the water balance characteristics and hydraulic properties (McDonald et al., 1996; Young et al., 2004) which is demonstrated by the porosity results in Figure 2.10 A. In addition, the percentage of sand (Figure 2.5 A) in both soils types and medium and coarse texture could be used to infer the behavior of that reflects the faster reduction in hydraulic conductivity due to enhanced soil drainage from the coarser soil texture. It has been demonstrated that younger soils have more sand and higher hydraulic behavior that can be associated with texture (Young et al., 2004). Therefore, texture traditionally has been used to infer soil hydraulic parameters, the difference in these results suggest that the water holding capacity and total water storage in the profiles is reflected in the plant community structure, which is primarily drought resistant plant. The observed plant communities were similar between basalt and granite soils in the SLV with only a few more plant species represented on the basalt soils.

The results from the bulk density ratio indicated that both parent material are closely related to that of the bulk density of their parent materials, basalt and granite (Chadwick et al., 1990). These results further accentuates the similarities in the profile development processes in the SLV and establishes the baseline by which we can observe changes due to irrigation practices in Chapter 3.

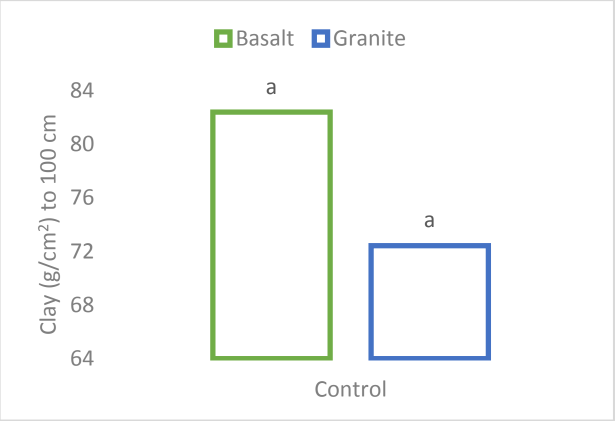


Figure 2.8: Mass data for clay (Clay faction x bulk density x depth) by parent material basalt and granite. Alpha = 0.05, P-value = 0.456

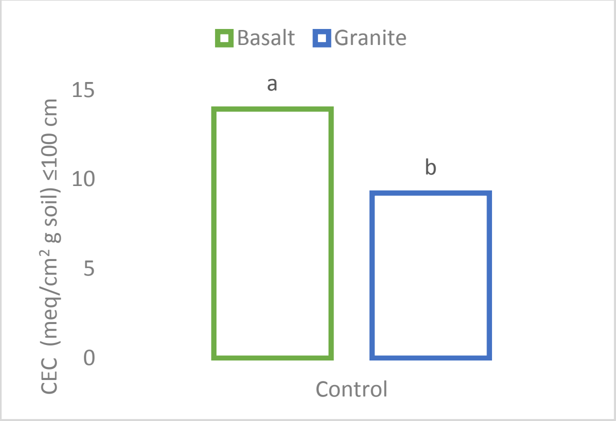


Figure 2.9: Cation Exchange Capacity - CEC (meq/100g) x the bulk density x the depth to 100 cm by parent material, basal and granite. Alpha = 0.05, P-value = 0.003**

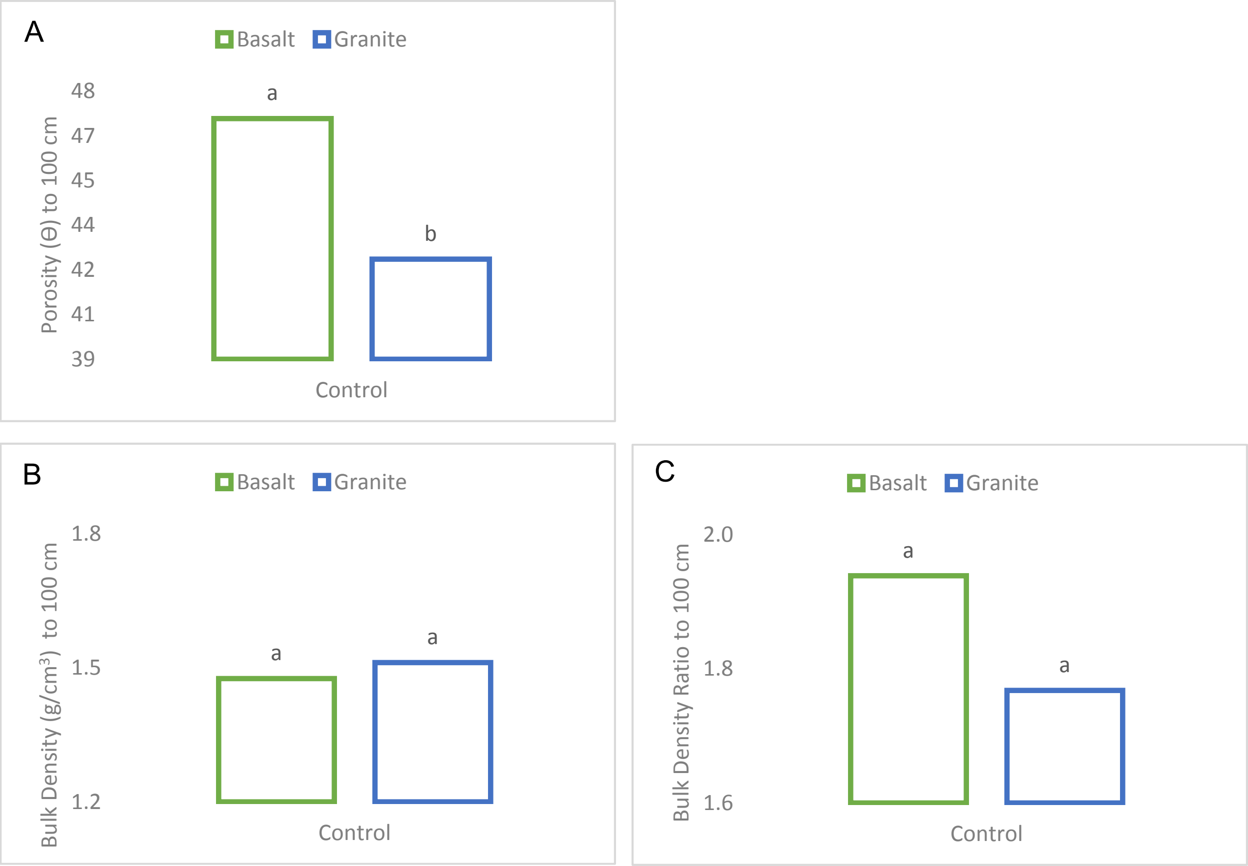


Figure 2.10: The values for porosity (1 - (P_b/P_p))*100 (A) P-value = 0.01**, Bulk Density (B) P-value = 0.425, and Bulk Density Ratio (P_p/P_b) (C) P-value = 0.385, basalt and granite controls. Alpha = 0.05

Biogeochemical Properties

The results from the ANOVA analysis for calcium carbonate show a statistical difference between basalt and granite with granite being of higher concentrations (Figure 2.11). Soil organic carbon also showed a statistical difference between the parent materials where basalt was higher in concentration (Figure 2.12).

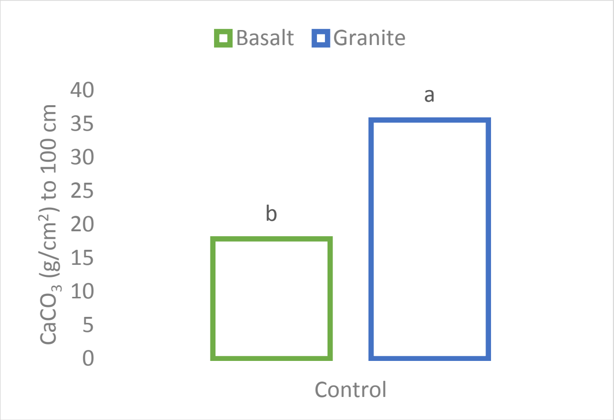


Figure 2.11: Mass data of $CaCO_3$ ($CaCO_3$ x bulk density x depth) to 100cm depth, basalt and granite controls. Alpha = 0.05, P-value = 0.166

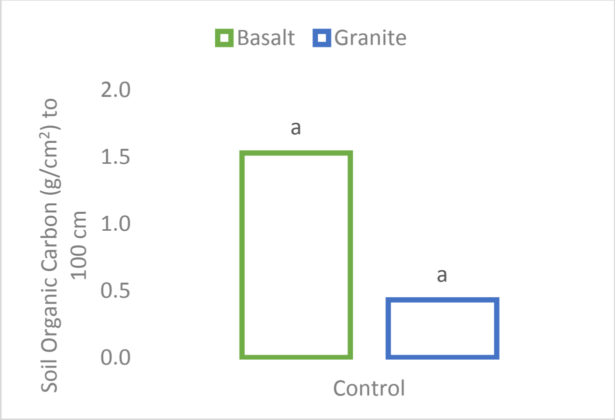


Figure 2.12: Mass data of Soil Organic Carbon (soil organic carbon x bulk density x depth) to 100cm depth, basalt and granite controls. Alpha = 0.05, P-value 0.107

Pedogenic Processes

Table 2.5 illustrates the general trends in pedogenic processes in both basalt and granite soils. Within the basalt soils sampled 100% of them had an active combination of three pedogenic processes, calcification, salinization, and alkalization. Only 66% of the granite modal pedons exhibited soil properties that classified them as with the process calcification. These results provide supporting classifications that distinguish them as benchmark soils.

Table 2.5: Pedogenic process by parent material, basalt and granite, number of samples in each control, number of pedons that exhibited the processes and the process type

Total Pedons Sampled	**Exhibited Processes**	**Processes**
14 - Basalt Control Pedons	10	Calcification Salinization Alkalization
9 - Granite Control Pedons	6	Calcification

Pre-cultivated Conditions of Soils

One of the challenges in working in cultivated regions is the establishment of "benchmarks" that can be used to assess the changes in soil properties resulting from cultivation practices. The use of uncultivated soils as ecological benchmarks provides an important first step in evaluating the influence of cultivation or other anthropogenic activities on soil. Benchmark soils, while being important soils in their own right, are also intended to serve as proxies for other similar soils. Their purpose is to focus data collection and the investigative effort on soils that have the greatest potential for extending collected data and resultant interpretations to other soils. This purpose is relevant both in making soil surveys and to soil scientists whose goal is to extend findings of their research to broader geographic settings.

In general, our results indicated that soils derived from basalt are statistically different and are 86% higher in their measurable electric conductivity (EC), 94% higher is their sodium adsorption ratio (SAR), and 85% higher in their exchangeable sodium percent (ESP) than soils derived from granite (Figure 2.13). The resulting soil classification for uncultured soils derived from basalt was a saline-sodic soil. Soils derived from granite in the uncultured condition were non-saline, non-sodic. The range of values are expressed as a 95% confidence interval in Table 2.7.

The classification suggests that hydrological conditions of these soils were quite different and the release of soluble salts via soil weathering processes were key drivers in ecosystem development. These results reiterate that soils derived from basalt, even in water-limited system, and are more vulnerable to the suite of chemical weathering processes than soils derived from granite.

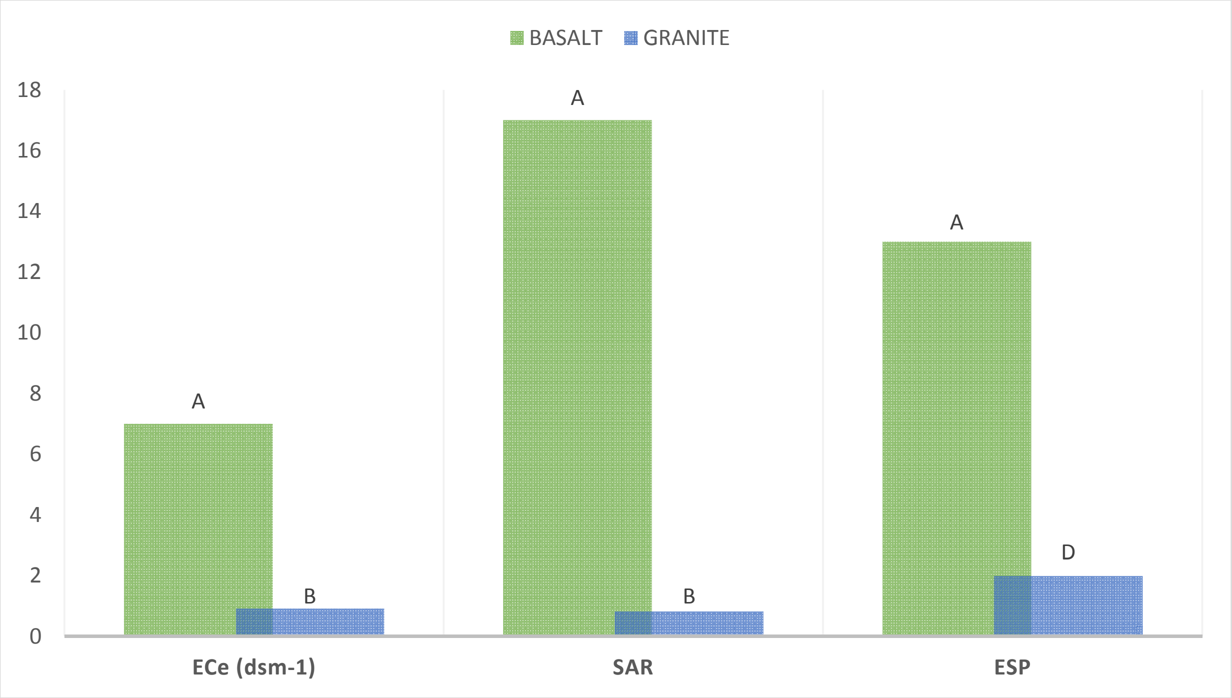


Figure 2.13: Comparison of the soil parameters for Electric Conductivity by extraction (ECe), Sodium Adsorption Ratio (SAR), and Exchangeable Sodium Percent (ESP) for soils derived from basalt and granite. The different letters are statistically different.

Table 2.6: Comparison of the parameters for Electric Conductivity extraction (ECe), Sodium Adsorption Ratio (SAR), and Exchangeable Sodium Percent (ESP) for soils derived from basalt and granite. The 95% confidence interval represents the predicted, low, and high expected values.

	Basalt			**Granite**		
	ECe	**SAR**	**ESP**	**ECe**	**SAR**	**ESP**
2.5%	5	9	7	1	0	1
Predicted	7	17	13	1	1	2
97.5%	10	30	23	2	2	5

Supporting Data

In further establishing the benchmark soils, I evaluated the difference between total mass of nitrogen to 100 cm and the average C:N to 100 cm for each parent material. Statistical nitrogen did not differ between basalt and granite and were at very low values, basalt 0.21 g/cm^2 and granite 0.11 g/cm^2 (Figure 2.13). The C:N ratio were statistically similar with basalt being slightly higher at 6.72 versus granite at 5.42 (Figure 2.14). The C:N ratio provide a means to evaluate the nutrient cycling responses from native to row crop and pasture irrigated agricultural in Chapter 3 and the microbial community composition in Chapter 4.

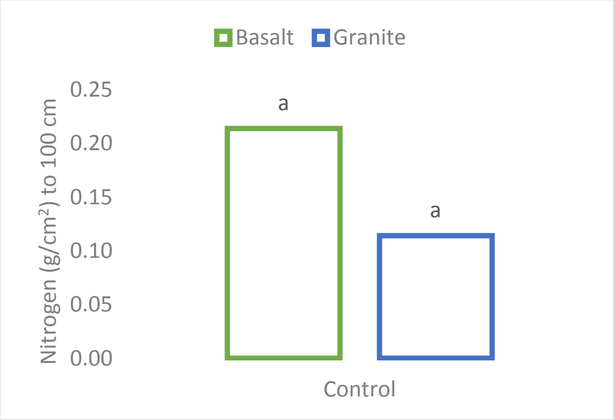


Figure 2.14: Mass data of total nitrogen (g/cm^2) (Nitrogen x bulk density x depth) to 100 cm, basalt and granite controls. Alpha = 0.05, P-value = 0.1412

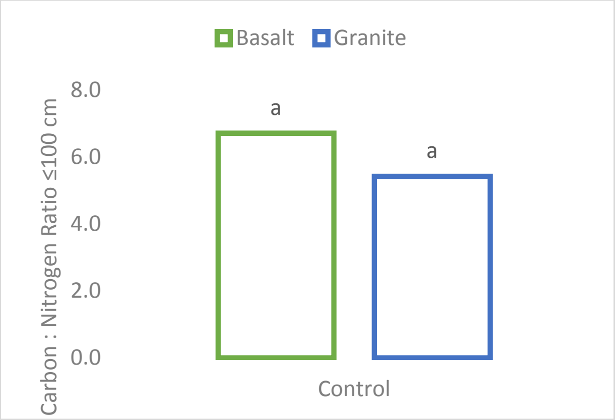


Figure 2.15: Carbon : Nitrogen Ratio to 100 cm, basalt and granite controls. Alpha = 0.05, P-value = 0.234

2.5 Summary and Conclusions

This study contrasts the physical, chemical, and biogeochemical properties of a geographically distributed collection of soils in the SLV of south central Colorado. Our objective was to evaluate the importance of parent material, (e.g., basalt vs granite), as soil forming factors and to establish their influences on soil properties in uncultured ecosystems of the SLV.

Our research results suggest that the distribution and patterns in soil conditions seen in the principal component analysis are a direct result of differences in the mineral composition of the parent material within water limited ecosystems. Soils derived from basalt were medium in texture, higher in nutrient concentrations and contained substantial amounts of Na and soluble salts in the profile. In contrast soils derived from granite parent materials were coarser in texture, have lower nutrient concentrations (relative to basalt) and do not possess properties reflecting the generation and retention of soluble salts during soil formation.

The intensity and duration of the weathering regime in this water limited systems were observed in the generation and concentration of clays. The soils derived from basalt have only a 10% increase in clay content to 100 cm over soils derived from granite, which were similar statically but differed in their cation exchange capacity. The results emphasize that the minerals contained within the basalt parent materials have smaller crystalline structure and have faster weathering rates which results a more clay development throughout the profile.

The similarities between the porosity and bulk density results emphasize that even though the parent materials are different in their structural compositions, their physical and chemical weathering processes are similar due to the climatic conditions of the SLV.

The classification of soils based on salinity further differentiate the soils by parent materials. These data revealed the soils derived from basalt are saline-sodic and soils derived from granite are non-saline non-sodic. These results provide further clarification that more soluble salts become available and/or retained during the weathering of basalt than granite. In addition, pedogenic processes were delineated between basalt and granite. The basalt soils had an active combination of three pedogenic processes, calcification, salinization, and alkalization. In contrast, the granite soils only exhibited calcification process.

In general, soils derived from basalt had higher concentration of all the soluble salts while soils derived from granite are considerably lower in all exchangeable ions with respect to basalt. In addition, calcium carbonate, soil organic carbon and nitrogen accumulations were only slightly higher in soils derived from basalt than granite, suggesting parent material is not the primary driver.

The findings present herein significantly represent soil property variability is driven mostly by the nature of the parent material when studying soils in semi-arid regions. These results are also significant for they provide the reference point for evaluating directional changes in soil properties as a function of anthropogenic pressures in arid and semi-arid regions, which are presented in the following chapters.

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CHAPTER 3

CHANGES IN SOIL PROPERTIES AS A FUNCTION OF IRRIGATED AGRICULTURE

3.1 Introduction

The increasing demands placed on cultivation to feed the swelling global population, along with the long-term over-utilization and cultivation in semi-arid regions has been the primary cause contributing to soil degradation globally. Soil degradation is defined as the decline in soil quality caused by improper use, usually for agriculture, pastoral, industrial or urban purposes. (Beinroth et al., 2007; UN 2010). In a report given by Dr. John Crawford (2012) at the University of Sydney, he stated that at the current rate of global soil degradation, we as a society have approximately 60 years of viable topsoil left for cultivation.

It has been reported extensively that irrigation plays an important role contributing to the degradation of soils (Pereira et al., 2012; Raiesi 2012; Steffen et al., 2007), especially in semi-arid region where evaporation exceeds precipitation for at least part of the year. Traditional cultivation in water-limited ecosystems alters the physical, chemical, and biogeochemical properties that reflect soil quality and functions. When perennial vegetation is replaced by annual row crops, the results are soil erosion, loss of soil nutrients, and reduction in stored soil organic carbon, which can lead to a decline in soil health and long-term productivity (Barrow 1991, Mayes 2014; Lal 2006). In addition, irrigation practices generally promote chemical degradation by increasing the concentration of soluble salt and alerting soil pH (Lal 2006). The increase in soluble salts drives saline (high salts content) and sodic conditions (high sodium content) and can be present in quantities sufficient to influence plant growth, particularly in poorly drained areas (Lal 2006). The degree to which these soils are altered varies due to the differences in the environmental conditioning variables, such as lithology (e.g., basalt and granite), geomorphology, water availability, and vegetation (Szabolc 1981).

One of the primary concerns is the rate at which soil is being lost. The loss is between 10 and 40 times the rate at which it can be naturally replenished, which reveals the severity of soil-related issues that we are faced with for the remainder of this century. There is a need to quickly regain a balance in the physical and biological processes that drive and maintain soil properties, (Amundson et al., 2015) especially in arid and semi-arid regions that occupy 44% of the global land area (UN 2010).

Currently, there is lack of quantitative information about key soil properties and their potential impact on soil degradation in arid and semi-arid regions. The San Luis Valley (SLV) of south central Colorado provides a case study of where the land in an arid climatic regime has been exploited for continuous and long term agricultural production. Anthropogenic activities in the San Luis Valley date back to the 1800's. In this early period of settlement and development, a mere 121,405 ha or 1% of the available land was used for agriculture and most of that land was adjacent to an accessible water source (Tomlin 1949). In 2010 the Colorado Decision Support System (Colorado Division of Water Resource 2014) reported that 789,471 ha is designated as agricultural land and 207,199 ha is designated for irrigated agriculture. This equates to 73% of the agricultural land is under irrigation management. The amount of land converted to agriculture increased 550% over the last 112 years. This increase in land use also shifted the distribution of crops to a narrower selection of wheat, barely, alfalfa, hay, and potatoes, which required a shift from a flood to a more modernized sprinkler irrigation. In addition, periodic episodes of low snow pack over the last 14 years have forced producers to incorporate more drought-tolerant crops.

The SLV is used as the system to intensively study the impact of irrigation on soil dynamics. The objectives of this study are to evaluate the influence of sprinkler and flood irrigation, as a function of parent material (basalt and granite) on key soil properties reflecting soil degradation in the San Luis Valley of south central Colorado.

3.2 Experimental Design

Study Area

The SLV is located in south central Colorado. The climate is arid and characterized by cold winters, moderate summers, abundant sunshine, and strong prevailing winds in the south to northeast direction. The valley is a high elevation desert with a base elevation is 2147 m. The mean annual precipitation is < 228 mm annually, and most of the valley receives 177 mm annually with the potential evapotranspiration exceeding 1016 mm (Emery 2013). The surrounding mountains, however, receive 762-1219 mm annually, which is the major source of water for the area (McNoldy and Doesken 2007). The SLV is flanked by the San Juan Mountains and the Sangre de Cristo Mountains on the west side and east side, respectively. These mountains range in elevations up to 2449 to 4372 m, creating a rain shadow effect, which reduces the amount of precipitation that reaches the valley floor. The average annual temperature is approximately 5°C, with extremes of -45°C and 32°C (Emery 2013).

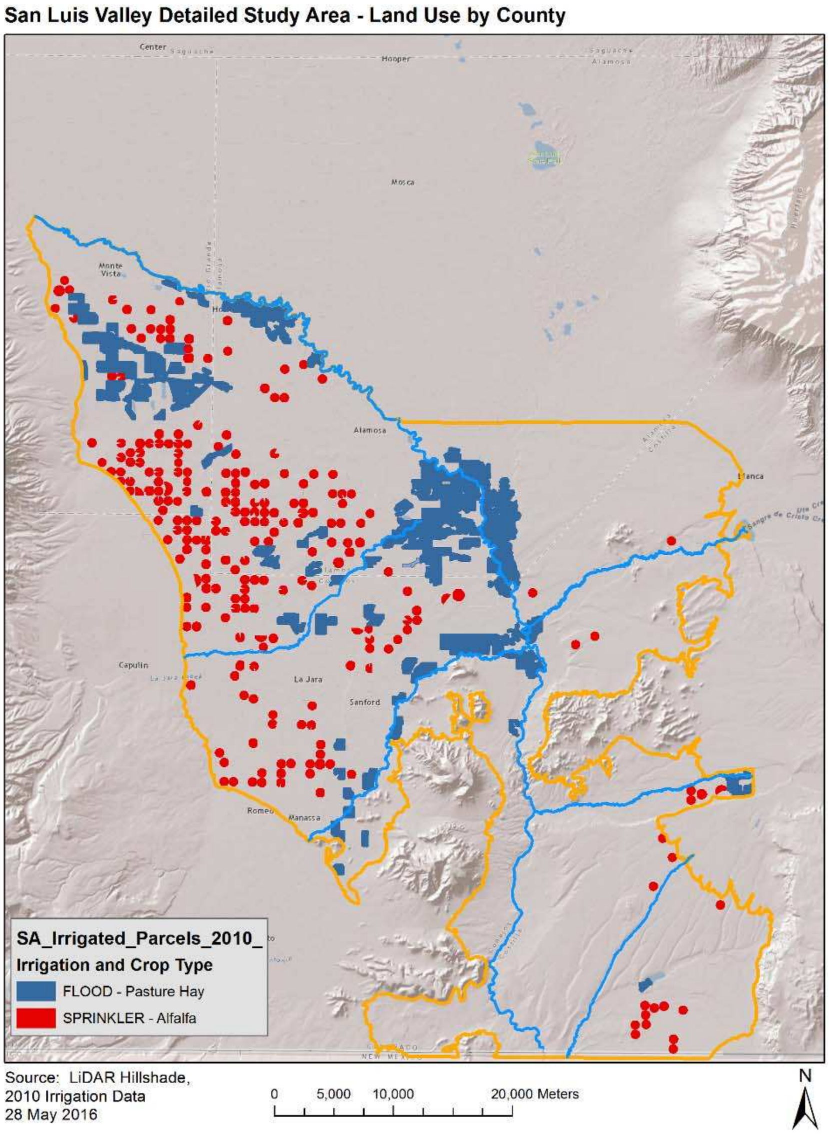
The San Juan Mountains are mafic and composed primarily of basaltic volcanic flows, tuffs and breccias and the Sangre de Cristo Mountains are felsic and composed primarily of granitic rocks. The valley is underlain by as much as 3657 meters of clay, silt, sand, and gravel derived from the surrounding mountain ranges, and interbedded volcanic flows and tuffs. The alluvial fan deposits that form the conduits between the bordering mountains and the valley floor are coarse and permeable near their tops and grade to fine grained, less permeable deposits toward the center of the valley floor (Emery 2013).

Identification and location of field sites

Field sites were selected on the basis of the state factor model (Jenny 1994), in which the variability of relief, climate and time were minimized and parent material differences were assessed as the independent variable conditioning soil properties. Field sites were restricted to the south central part of the SLV where the geographic feature of the Rio Grande River and HWY 160 was used as the division between the east and west sides, and the north and south side of the SLV, respectively. To control for relief an elevation gradient constrained the study area to the valley floor, between 2147 – 2351 m, and slope to less than 2%. A combination of geospatial analyses including a Geographical Information System (GIS) was used along with interviews and field observations to identify prospective locations where cultivation practices had not occurred (for control sites) in the last 84 years on the soil parent material of interest. Areas of interest were refined by intersecting the 2010 common land units, 2011 LiDAR 10m hill shade, slope and elevation, NDVI vegetation data, Colorado Geological Survey and United States Geological Survey geology maps, and ESRI™ base map imagery. These analyses isolated the areas within the SLV where both parent material-land use combinations could be found consistent with our project goals. The entire study area is approximately 2.14 km^2 (1.26 km^2 on the west .87 km^2 on the east) (Figure 3.1).

Figure 3.1: The San Luis Valley as outlined by the LiDAR foot print and the study area as outlined in orange. The study area is 2.14 km^2 - 1.26 km^2 on the west .87 km^2 on the east, with respect to the Rio Grande River.

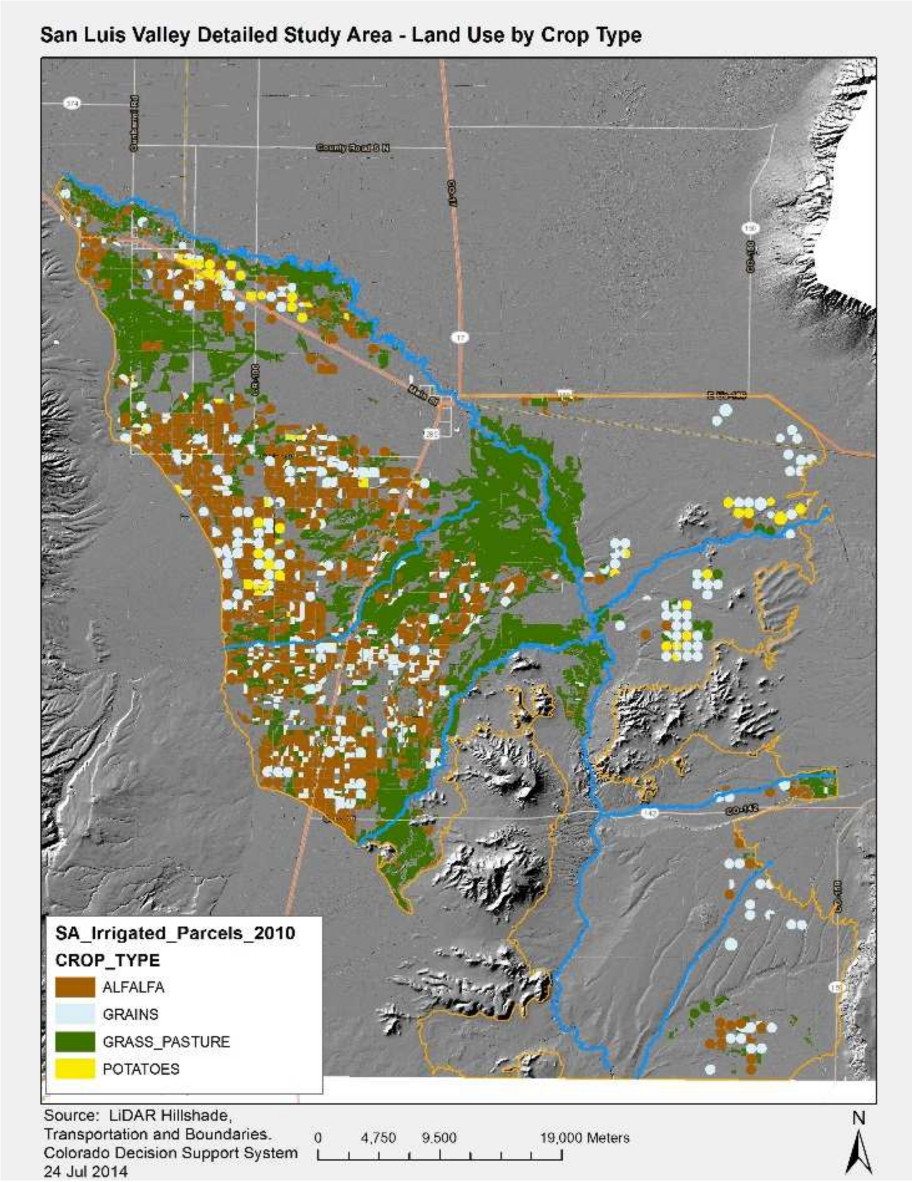
Soils derived from basalt (mafic) were located in Rio Grande County, Alamosa County, and Conejos County, CO, west of the Rio Grande River. Soil derived from granite (felsic) were located in Costilla County, CO east of the Rio Grande River. Both soils derived from basalt and granite has the same three major land uses - sprinkler and flood irrigation treatments and controls (non-cultivated sites). Figure 3.2 depicts the distribution of the land by sprinkler and flood parcels and crop type within the study area.



Source: LiDAR Hillshade,
2010 Irrigation Data
28 May 2016

Figure 3.2: The distribution of land use and cropping systems as of 2010 by county within the SLV study area as outlined in orange.

The dominant crops for each treatment are: alfalfa for basalt and granite sprinkler treatment, pasture hay grasses for basalt and alfalfa for granite flood treatment. The dominant vegetation for the majority of the control sites was Greasewood (*Sarcobatus vermiculatus*), greene's rabbitbrush (*Chrysothamnus greenei*), salt grass (*Distichlis spicata* (L.), and blue gramma (*Bouteloua gracilis*) (Dixon 2012). Figure 3.3 depicts the current distribution of cropping systems within the study area.



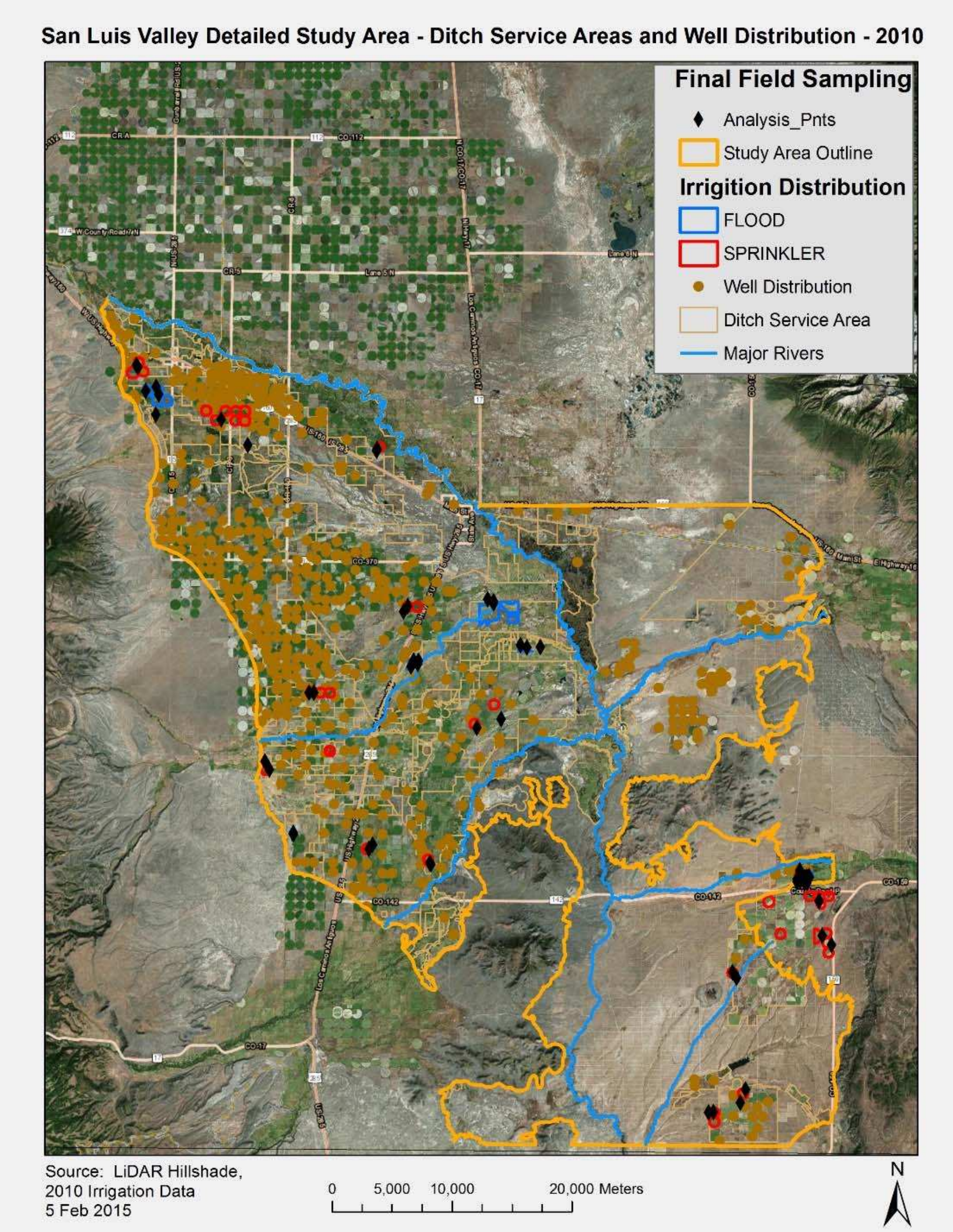
Source: LiDAR Hillshade, Transportation and Boundaries. Colorado Decision Support System 24 Jul 2014

Figure 3.3: Distribution of cropping systems as of 2010 within the SLV study area as outlined in orange.

Within the study area surface and subsurface water is the primary source for irrigation. Most irrigation began in the late 1800's by means of surface water flood irrigation from the Alamosa, Conejos, and Rio Grande Rivers, and the Trinchera and Culebra Creeks. From the late 1800's until the late 1960's, most flood irrigation was slowly replaced by center pivot sprinkler irrigation and new well were drilled providing water from the confided and unconfined aquifers, however, flood irrigation is still part of the valley agricultural landscape. The Colorado Division of Agriculture water quality database 26-year average for pH is 7.57, sodium 38.02 ppt and EC 462.27 µs/cm, these values are comparable to that of rain water (Appendices 9 - 12). The average amount of water applied with sprinkler and flood irrigation ranges from 153 - 1226 mm typically from April through July. The change in the amount of available water occurred from 2004 until 2010 when the seasonal supply of irrigation water started to decline due to decreased snow pack in the San Juan and Sangre de Cristo Mountains. By 2010, most flooded fields entered drought conditions.

In the mid 1960's until 2014, sprinkler irrigation delivered between 304 – 914 mm of water to alfalfa during the growing season from April through Oct. From 2004 through 2014, during the low snow pack years, the amount of sprinkler water delivered did not change. Figure 3.4 shows the distribution of wells and ditches on the west and east side of the Rio Grande River as of 2010. The wells provide additional water to support crops past the initial surface water allocation.

Further water restriction came in the 1980's when the Colorado Division of Water placed a cap on the installation of wells due to the large amount of water being extracted from the aquifers without adequate recharge. In 2014, the Colorado Division of Water Region 3, declared the confined and unconfined aquifers had declined by 1 million acre feet water.



Source: LiDAR Hillshade,
2010 Irrigation Data
5 Feb 2015

Figure 3.4: Distribution of the ditches and wells as of 2010 with the study area as outline in orange.

A total of 14 control and 20 treatment pedons were sampled from soils derived from basalt and 9 control and 14 treatment pedons were sampled from soils derived from granite (Table 3.2). Figure 3.5 illustrates the locations and distribution of the sampled soils by the treatment type (control, sprinkler, and flood), and by parent material (basalt west of the Rio Grande River and granite east of the Rio Grande River).

Table 3.1: The sampling design for the control, sprinkler and flood treatments pedons and the number of pedons sampled by parent material

Number of Pedons Sampled	Parent Material	Treatments
10	Basalt	Sprinkler
10	Basalt	Flood
14	Basalt	Control
7	Granite	Sprinkler
7	Granite	Flood
9	Granite	Control

Total number of samples used for analysis was 284 horizons from 57 pedons

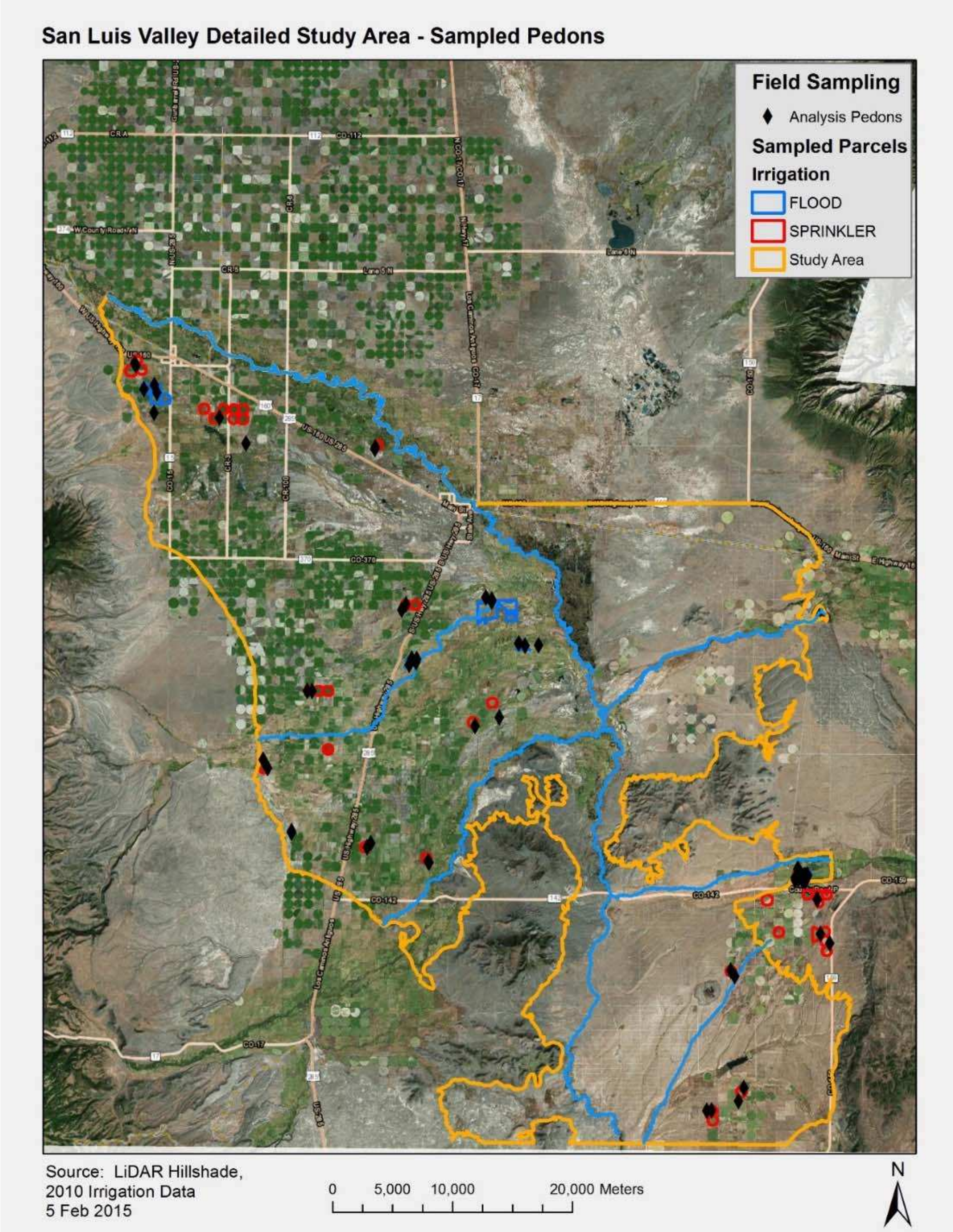


Figure 3.5: The distribution of the available treatment sites and the pedons selected for analysis within the SLV study area as outlined in orange.

Physical, chemical and biogeochemical soil properties were measured and evaluated at 57 sites across the three major land uses – control (non-cultivated), sprinkler and flood irrigation (cultivated), on two different parent materials – basalt and granite (Table 3.2).

Table 3.2: The type soil analysis performed by category - physical, chemical and biogeochemical for the soils derived from basalt and granite.

Physical	**Chemical**	**Biogeochemical**
Sand *	pH *	Calcium Carbonate *ǂ
Silt *	Electric Conductivity (ECe) *	Soil Organic Carbon *ǂ
Clay* ǂ	Sodium Adsorption Ratio (SAR) *	Total Carbon ł
Soil Bulk Density *ǂ	Exchangeable Sodium Percent (ESP) *	Total Nitrogen ǂ
Soil Bulk Density Ratio ǂ	Exchangeable Base Cations and Anions *	C:N ratio ǂ
	Cation Exchange Capacity *ǂ	

* Linear mixed effect model analysis
ǂ ANOVA mass data or average analysis

3.3 Methods

Field Methods

Soil samples were collected from each pedon using a hand auger to depths reaching parent material, which varied by site from 33 to 165 cm. Soils were described morphologically and sampled by genetic horizon in accordance with the NRCS Field Book for Describing and Sampling Soils, version 3.0 (Schoeneberger et al., 2012). The native plant community composition of the valley during the time soils were collected included sagebrush, greasewood, rubber rabbit brush, Greene’s rabbit brush, grassland, and shrub-steppe communities (Dixon 2012). Sampling of research sites occurred between Aug – Nov 2014.

Soil analysis

All soil samples were air-dried and sieved to < 2mm. Soil particle size distribution analysis was performed using the modified 2-hour hydrometer method (Gee and Bauder 1986). Bulk density was estimated by as outlined in Rawls (1983). Soil pH paste and Electric

Conductivity (EC) for saline sodic soil, measured using the saturated paste method, using an Oaklon™ pH 2700 meter YSI Model 35 Conductance Meter (Handbook 60, method 2). Cation Exchange Capacity (CEC) was measured using the displacement (pH 8.2) method, NRCS, Soil Survey Investigation Report No. 42. Version 4.0. Method 4B4b (modified). The CEC ionic concentration was analyzed using the Inductive Coupled Plasma Optical Emission Spectrometer (ICP-OES) Perkin Elmer Optima 7300 DV. Exchangeable Cations and Exchangeable Sodium Percent (ESP) was measure using Handbook 60, method 18 and 20b and the ionic concentration was analyzed using the ICP-OES Perkin Elmer Optima 7300 DV. Sodium Adsorption ratio (SAR) was measured using the Handbook 60, method 2. The SAR ionic concentration was analyzed using the ICP-OES Perkin Elmer Optima 7300 DV. Anion concentrations were measured using the saturated paste method, Handbook 60, method 2. Anion concentration were analyzed with the Ion Chromatography System, Thermo Scientific Dionex ICS-1100. Carbonate and Bicarbonate was measured using the Titration with Acid Handbook 60, method 12. Total carbon (C) and nitrogen (N) were determined on finely ground soil, and then analyzed with a LECO-TruSpec ® CN628 Elemental Combustion Analyzer (St Joseph, MI, USA).

Total calcium carbonate content was determined by measuring the CO_2 released using the Inorganic Carbon Analysis by Modified Pressure-Calcimeter Method (Sherrod et al., 2002). Each sample was finely ground and passed through 200-um sieve. Samples were transferred to a Wheaton serum bottle, in which a 2-ml (.50 dram) auto sampler vial was inserted containing 2-ml of the acid reagent of 6 M HCl acid containing 3% by weight of $FeCl_2*4H_2O$. HCL evolved CO_2 during a 2 to 24-hour period at which time, the pressure inside was measured using the pressure transducers and voltage meter. Measured values were converted to concentration of inorganic carbon using a calibration curve generated from known concentration of $CaCO_3$ standards. Percent Soil Organic Carbon (SOC) was determined by taking the difference of the results found from each carbon analysis (total C – inorganic C = organic C).

Particle density of granite 2.65 g/cm^3 (Crawford 2013) and particle density of basalt 2.79 g/cm^3 (Hyndman and Dury 1977).

Statistical Analyses

The sampling design represents data collected and summarized in groups; 34 pedons representing the two treatments (i.e., sprinkler and flood irrigation) and 23 control pedons, on two parent materials (e.g., basalt and granite). Principle component analyses were performed on 263 observations with the prcomp procedure within R 3.2.3 (R Core Team 2015). The inherit ANOVA aov method in R was used to evaluate results from the mass balance data and to evaluate the R^2 values of the parameters entered into the linear model. To evaluate the statistical significance of the liner mixed-effects model, the lsmeans from lsmeans-package was used, the parameter was a confidence level of 0.95, p value adjustment used the tukey method for comparing a family of 18 estimates and the significance level used was alpha = 0.05 (Lenth 2016) and the MuMIn (Barton 2016).

The soil properties were analyzed using a linear mixed-effect model within R 3.2.3. The linear mixed-effect model describes the relationship between a response variable and independent variables. Tests were conducted on the log-transformed data to satisfy the assumption of normality, yielding a total of 263 observations. The linear mixed effects model used the lme4 package (Bates et al., 2015), and MASS package (Venables et al., 2002); 0.95 confidence intervals for analyzing mixed effect regression models were determined using the merTools package (Knowles and Frederick 2016). Parent and parcel grouping describes how the treatment and control pedons were grouped together for analysis were considered random variables and the soil properties were fixed. The linear mixed effect model analyzed the response variable with the interaction of the parent material, sprinkler, flood and control as treatments. Significance was determined at $P \leq 0.05$.

3.4 Results and Discussion

Changes in Soil Morphological Properties

Soil morphology provides the frame work to examine soil properties as a reflection of the soils internal genetic characteristics, function and resiliency, present and past processes, and conditions of formation (Mitchell et al., 2005). The main soil morphological properties that correlate with climate are typically organic matter content, clay content, color, and presence or absence of calcium carbonate and other soluble salts (Birkeland 1999). Altering the climate has been shown to have various effects on soils properties and process, such as changing the amount the chemical and physical properties of the soil.

The most distinctive morphological characteristics that have been altered due to irrigation, between soils derived from basalt and granite, were profile development and soil depth (Table 3.3 and 3.4). In general, both the basalt and granite control profiles have shallow A horizon, well-defined argillic horizon (Bt) with accumulation of calcium carbonate, and clear C horizons boundaries. Basalt pedons however, were developed to depths (140 cm) twice that of granite pedons (70 cm) and an appreciable accumulation of soluble salts that were not present in the granite soils.

The morphological data for the irrigated basalt soils relative to basalt control pedons are shown in Table 3.3. The textures from these soil range from sandy loam to sandy clay loam. Relative to the basalt control, basalt soils with sprinkler and flood irrigation have less sodium and soluble salt concentrations, less clay accumulated in the top 46 cm of the pedon, and accumulations of calcium carbonate occurred deeper in the profile (>23 cm).

The morphological data for the irrigated granites soils relative to granite control are shown in Table 3.4. Relative to the granite control pedon, granite soils with sprinkler treatment showed minimal accumulations of clay and thicker accumulation of calcium carbonate. Soils from flood treatments were weakly developed and calcium carbonate was no longer present.

These morphological changes occurred in both basalt and granite sprinkler irrigated soils; a thick plow layers and less clay relative to their control counterparts. In addition, these profiles have a lost their clear boundaries designation in the C horizons, and have significantly reduced soluble salts. Similar results are seen with flood irrigation, the notable exceptions were the presence of an organic layer, the removal of the soluble salts, reduced accumulations of calcium carbonate, a mixed C horizon, and an increase in profile depth to 145 cm for basalt and 115 for granite.

Similar studies that have been conducted in semi-arid regions have shown with respected to native dryland soils vs. irrigation, all concluded that irrigation caused no significant changes in physical properties such as texture, bulk density, aggregate stability, or hydraulic conductivity (Hussein et al., 1992; Bordovsky et al., 1999; Lueking and Schepers 1985; William 2001). These results are similar in with respect to the basalt and granite controls, the directional change in texture, bulk density, aggregate stability, and hydraulic conductivity was minimal for both soil types.

Table 3.3: Morphological characteristic from soils derived from basalt, the abbreviations are defined as basalt sprinkler (BS), basalt control (BC), basalt flood (BF). Environmental variables: elevation, slope %; soil profile characteristic: horizonation, depth in centimeters, texture, and Munsell color.

Location	**Elevation (m)**	**Slope %**	**Horizon**	**Depth (cm)**	**Texture**	**Munsell* Moist Color**
BS-1	2308	1.3	Ap	0-33	SCL	10YR 5/3
			Bk1	33-76	SCL	10YR 7/3
			Bk2	76-94	SCL	10YR 7/3
			Bw1	94-122	SCL	7.5YR 6/4
			Bw2	122-132	SCL	7.5YR 5/4
			BC	132-145	SL	7.5YR 5/3
BC-1	2305	0.54	Anz	0-5	SL	10YR 3/2
			Btkz	5-46	SCL	10YR 2/1
			Bkz	46-81	SL	10YR 3/1
			BC	81-112	LS	7.5YR 3/1
			Ck	112-132	SL	7.5YR 4/2
BS-6	2291	.86	Ap1	0-3	SL	7.5YR 3/2
			Ap2	3-23	SL	7.5YR 3/2
			Bkn1	23-41	SL	7.5YR 4/2
			Bkn2	41-71	SL	10YR 5/4
			Bn	71-155	SL	10YR 5/4
BC-6	2290	0.18	A	0–3	SL	10YR 3/2
			Btkz	3-25	SL	7.5YR 4/4
			Bt1	25-56	SL	7.5YR 4/4
			Bt2	56-69	SL	10YR 5/3
			BC	69-99	SL	10YR 4/3
			C1	99-130	SL	10YR 3/3
			C2	130-142	SL	
BF-1	2320	0.55	Oi	0-5		
			A	5-56	SCL	10YR 4/3
			Bk1	56-61	SCL	10YR 5/2
			Bk2	61-76	SCL	10YR 6/3
			BC	76-119	SCL	7.5YR 7/4
			2BC	119-135	SCL	10R 6/4
BC-11	2324	0.56	Anz	0-3	SCL	7.5YR 3/3
			BAnz	3-18	SCL	7.5YR 4/3
			Btknz	18-51	SCL	7.5YR 6/4
			Bk	51-102	SCL	7.5YR 7/4
			BCK1	102-127	SCL	7.5YR 6/4
			BCK2	127-147	SCL	7.5YR 5/4

*Munsell soil colors standards value Hue/Chroma – Texture abbreviations; SCL – Sandy Clay Loam, SL – Sandy Loam, LS – Loamy Sand

Table 3.4: Morphological characteristic from soils derived from granite, the abbreviations are defined as granite sprinkler (GS), granite control (GC), granite flood (GF). Environmental variables: elevation, slope %; soil profile characteristic: horizonation, depth in centimeters,texture Munsell color.

Location	**Elevation (m)**	**Slope %**	**Horizon**	**Depth (cm)**	**Texture**	**Munsell* Moist Color**
GS-3	2361	1.48	Ap	0-30	SL	7.5YR 4/4
			Bk1	30-43	SL	7.5YR 4/4
			Bk2	43-58	SL	7.5YR 6/4
			BCk	58-102	SCL	7.5YR 6/4
GC-3	2362	0.55	A	0-8	SL	7.5YR 4/4
			AB	8-28	SL	7.5YR 4/4
			Btk	28-61	SCL	7.5YR 7/2
			Bk	61-69	SCL	7.5YR 7/2
			BCK	69-94	SCL	7.5YR 7/3
GS-7	2294	0.74	Ap	0-28	SL	7.5YR 3/4
			Btk1	28-64	SCL	7.5YR5/4
			Btk2	64-114	SC	7.5YR 6/4
			Bk	114-130	SCL	7.5YR 6/4
			BCk1	130-140	SCL	7.5YR 6/4
			BCk2	140-150	SCL	7.5YR 6/4
GC-7	2292	0.41	A	0-3	SL	7.5YR 3/3
			Bw	3-23	SL	7.5YR 4/3
			Btk	23-38	SCL	7.5YR 6/3
			BCK	38-46	SCL	7.5YR 6/4
			2Btk	46-56	SCL	7.5YR 7/3
GF-6	2341	1.30	A	0-3	L	10YR 3/2
			AB	3-30	SCL	10YR 3/2
			Bw	30-64	SL	10YR 4/3
			BC	64-89	SL	10YR 4/3
GC-9	2338	0.95	A	0-5	SL	7.5YR 4/3
			AB	5-23	SL	7.5YR 3/2
			Bw	23-46	SL	7.5YR 4/4
			Bk	46-58	SL	7.5YR 5/4
			CBK	58-60	SL	

*Munsell soil colors standards value (Hue/Chroma), texture abbreviations: SCL – Sandy Clay Loam, SL – Sandy Loam, LS – Loamy Sand, L - Loam, SC – Sandy Clay

Soil degradation is defined as a decline in soil quality caused by improper use usually from agriculture practices. Soil quality is a measure of the conditions of soil relative to the requirements of one or more biotic species and or to any human need or purpose (Verheye 2008). To address the broader issue of soil degradation the expectation is the soil properties from the three groups (physical, chemical and biogeochemical) which are outlined in Table 3.2 will be the bases of the statistical analysis in determining the changes in soil quality as direct function of agriculture.

Statistical Analyses

Principal component analysis (PCoA) differentiates the soil derived from basalt and granite and master horizons (A, B, C) and explains the variability among the soil properties. These linear combinations were uncorrelated to reduce variance inflation. The 11 uncorrelated properties that were selected from the 22 measured include: physical properties – sand, clay; chemical properties – pH, calcium (Ca^{+2}), magnesium (Mg^{+2}), sodium (Na^{+}), potassium (K^{+}), chloride (Cl^{-}) and sulfate (SO_4^{-2}), and biogeochemical properties of calcium carbonate ($CaCO_3$) and soil organic carbon (OC).

The soil properties clustered by parent material, treatment (sprinkler and flood) and master horizons (A, B, and C), mostly among granite sprinkler, granite flood, and basalt sprinkler, and within the B and C horizons (Figure 3.6). PCoA axis 1 explained 37% and PCoA axis 2 explained 20%, for a total of 57% of the variability in these data explained. Large, positive coefficients indicated the dominate soil properties are located on the positive side of PCoA axes. Large, negative coefficients indicate the dominant soil properties are located on the negative side of the PCoA axis.

The soil properties with the positive eigenvector coefficient for PCoA 1 in Figure 3.6, is sand and calcium carbonate. In contrast, the soil properties with negative eigenvector coefficients for PCoA 1, and more associated with properties to the left of PCoA 1, includ clay, pH, soil organic carbon, calcium, magnesium, sodium, potassium, chloride, and sulfate (Appendices 4).

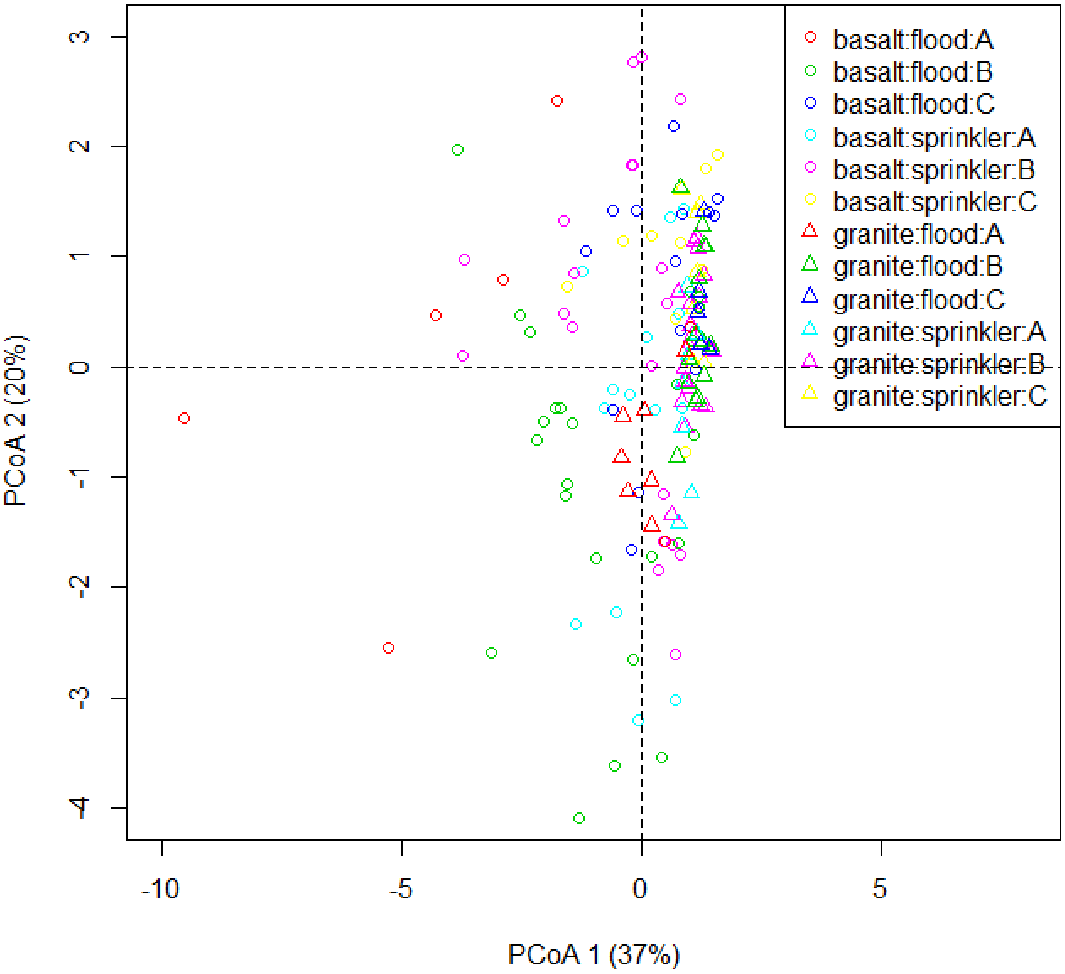


Figure 3.6: The distribution of the principal components analysis by parent material (basalt and granite), treatments, sprinkler and flood, and master horizon (A, B, C). The percent variance explained by each principal component (PCoA) is shown in parentheses.

Principal component analysis variations for sprinkler irrigation

Principal component analysis differentiates the variability in the soil properties as a function of treatment and parent material. Properties derived from basalt and subjected to sprinkler irrigation (Figure 3.7), PCoA 1 explained 33% and PCoA 2 explained 23%, for a total of 56% of the variability of these data explained. Soil properties with the most positive eigenvectors coefficients for PCoA 1 is sand, pH, calcium carbonate, calcium, magnesium, sodium, potassium, chloride, and sulfate. In contrast, the soil properties with a negative eigenvector coefficient for PCoA 1 is clay and soil organic carbon (Appendices 5).

Soil properties derived from granite and subjected to sprinkler irrigation (Figure 3.8), PCoA 1 explained 26% and PCoA 2 explained 21%, for a total of 47% of the variability of these data explained. Soil properties with the most positive eigenvectors coefficients for PCoA 1 is sand and soil organic carbon. In contrast, the soil properties with a negative eigenvector coefficient for PCoA 1 is clay, pH, calcium carbonate, calcium, magnesium, sodium, potassium, chloride, and sulfate (Appendices 6). The 11 selected soil properties only capture, on average 51% of the variability between the two soil types subjected to sprinkler irrigation.

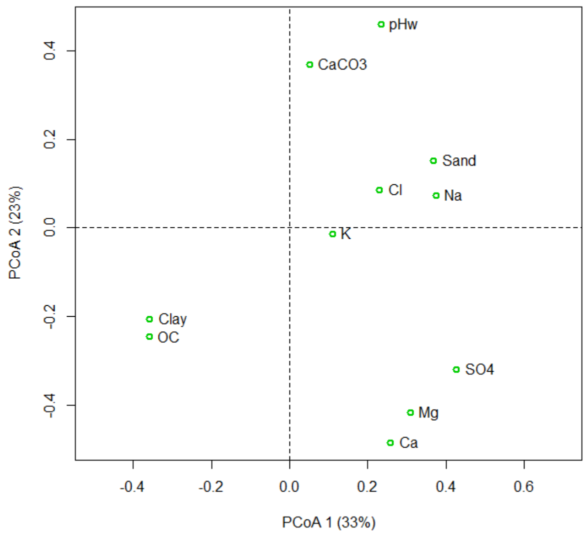


Figure 3.7: Distribution of the basalt soil properties effected by sprinkler irrigation. The percent variance explained by each principal component (PCoA) is shown in parentheses.

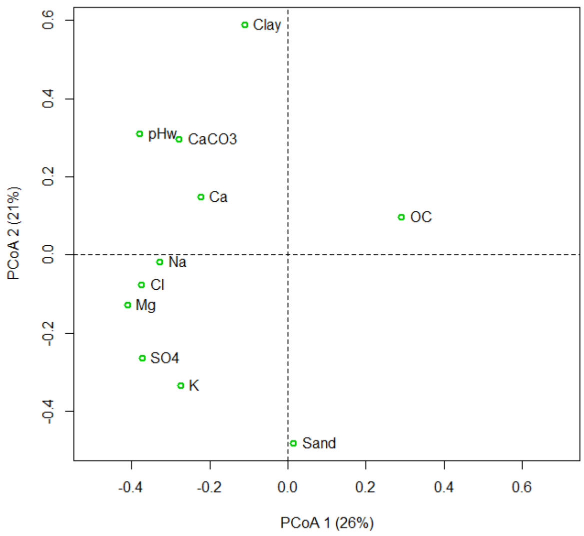


Figure 3.8: Distribution of the granite soil properties effected by sprinkler irrigation. The percent variance explained by each principal component (PCoA) is shown in parentheses.

Principal component analysis variations for flood irrigation

Principal component analysis differentiates the variability in the soil properties as a function of parent material and treatment. Properties derived from basalt and subjected to flood irrigation (Figure 3.9), PCoA 1 explained 41% and PCoA 2 explained 23%, for a total of 64% of the variability of these data explained. Soil properties with the most positive eigenvectors coefficients for PCoA 1 is clay, pH, calcium carbonate, soil organic carbon, calcium, magnesium, sodium, potassium, chloride, and sulfate. In contrast, the soil property with a negative eigenvector coefficient for PCoA 1 is sand (Appendices 7).

Properties derived from granite and subjected to flood irrigation Figure 3.10, PCoA 1 explained 34% and PCoA 2 explained 23%, for a total of 57% of the variability of these data explained. Soil properties with the most positive eigenvectors coefficients for PCoA 1 is clay, pH, soil organic carbon, calcium, magnesium, sodium, potassium, and sulfate. In contrast, the soil properties with a negative eigenvector coefficient for PCoA 1 is sand, calcium carbonate, and chloride (Appendices 8). The 11 selected soil properties only capture, on average 61% of the variance between the two soil types.

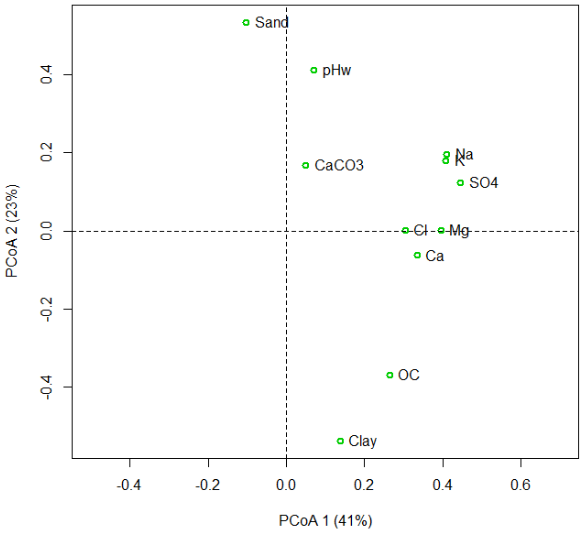


Figure 3.9: Distribution of the granite soil properties effected by flood irrigation. The percent variance explained by each principal component (PCoA) is shown in parentheses.

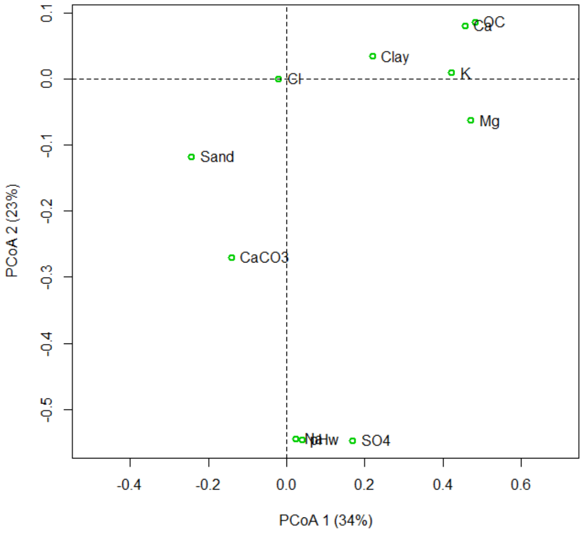


Figure 3.10: Distribution of the basalt soil properties effected by flood irrigation. The percent variance explained by each principal component (PCoA) is shown in parentheses.

Model analysis

This study was set up to analysis the soil properties that were derived from basalt and granites and how these soil properties are influenced by sprinkler and flood agriculture irrigation practices. The analysis accounts for the interactions between parent materials, treatments, and horizons and their combinations, which equates to six categories. In addition, these six categories are examined among 17 soil properties. The initial interpretation of these interactions using an ANOVA analysis (Table 3.5), which reveals that parent material is the most influential interactions, followed by treatment and parent material with horizon and treatment, and the interaction of horizon with treatment and horizon with parent material were the least influential interactions. The 17 soil properties are represented as response variables and their significance among the six categories are exposed. The strongest responses variables with parent materials were calcium, magnesium, sodium, and sulfate. The second responses were sand, silt and chloride. The statistical significance were represented by number of asterisks *** with the responses variables and could be used as the soil properties that indicate the health or degradation of the soils.

Further examining the influence of treatment pH, chloride, calcium carbonate and potassium was effected. However, parent material with treatment indicated that effects were primarily with clay, sodium, potassium, and sulfate, which indicates that not all soils are equal in their response to treatments. In addition, this initial examination reveals that horizonation primarily effected the physical properties (sand, silt, clay, bulk density) and soil organic carbon. The secondary effects of horizons were with cation exchange capacity, calcium and magnesium but the interactions of horizon with parent material and treatment were not statistically significant.

Table 3.5: Model analysis using ANOVA and R2 values to assess the interactions between parent material, treatments and horizons. Response variables are the soil properties used in the model.

			Categories				
Response variable	**Parent Material**	**Treatment**	**Horizon**	**Parent x Treatment**	**Treatment x Horizon**	**Parent x Horizon**	**Model R2**
pHw	5 .	1 ***	3 *	5 *	6 .	2 *	0.202
Electric Conductivity Extraction (ECe)	1 ***	2 ***	3 ***	4 ***	6 .	5 *	0.498
Sodium Adsorption Ratio (SAR)	1 ***	3 ***	4 **	2 ***	6 *	5 *	0.459
Exchangeable Sodium Percent (ESP)	1 ***	3 **	6	2 ***	5	4 .	0.274
Cation Exchange Capacity (CEC)	1 ***	4 **	2 ***	3 ***	6	5	0.305
Soil Bulk Density (SBD)	4	2	1 ***	6	3	5	0.312
Sand	2 ***	4 *	1 ***	3 **	5	6	0.225
Silt	2 ***	6	1 ***	3	4	5	0.988
Clay	4*	6 .	1 ***	2 ***	5 .	3 *	0.347
Calcium	1 ***	3	2 *	4	5	6	0.161
Magnesium	1 ***	3	2 *	4	5	6	0.182
Sodium	1 ***	3 ***	4 **	2 ***	6 *	5 *	0.473
Potassium	3 ***	2 ***	4 ***	2 ***	5 **	6 *	0.464
Chloride	2 ***	1 ***	4 **	3 ***	6	5 *	0.427
Sulfate	1 ***	6	4 .	2 ***	5	3 *	0.545
Calcium Carbonate	5	1 ***	3 **	4 *	6	2 **	0.196
Soil Organic Carbon	4 *	3 *	1 ***	5	6	2 *	0.377
Ranking order of Statistically Signficance	1	4	3	2	5	5	

Linear Model Analysis for Directional Changes in Soil Properties

The initial examination of the data using the ANOVA exposed the soil properties that could provide indicators of soil health/degradation and revealed that the interactions of parent material and treatment were statistically significant (Table 3.5). These interactions were further examined using a linear mixed effect model, which statistically evaluated the interactions and produced results that estimate the state of this system in terms of the parent materials and input fluxes as a function of treatment. The control soils were used as the benchmark soils, which are outlined in Chapter 2, and the sprinkler and flood irrigated soils represent the directional change in the model. The results from my study showed clear evidence that directional changes are occurring under irrigation practices and differ between the soil properties derived from basalt and granite. The statistical significances and the magnitude of change were evaluated relative to the basalt and granite controls and the treatment soils (sprinkler and flood), and the master horizons (A, B, and C).

Changes in Physical Properties

The clay percent concentration in the A horizon of basalt soils with sprinkler treatment was 23%, 5% higher than the control at 22%. The clay percent in flood irrigated soils was 31%, which was 41% higher with respect to the control soils at 22%. The clay percent in the B horizon with sprinkler was 23%, which is 4% less than the control at 24%. The clay percent was 28% with the flood treatment, 17% higher than the control clay. In the C horizon, sprinkler treatment changed the clay percent to 15%, 7% higher than the control at 14%. The flood treatment changed the clay percent to 12%, a 13% decrease from the control at 14% (Figure 3.11).

The clay percent concentration in the A horizon of granite soils with sprinkler treatment was 22%, 29% higher than the control at 17%. The clay percent with flood irrigation was 21%, 24% higher than the control. The clay percent in the B horizon with sprinkler was 24%, 14% higher than the control at 21%, and clay percent in the flooded soils was also 21%, the same as the control. In the C horizon, sprinkler treatment changed the clay percent to 20%, 25% higher than the control at 16%. The flood treatment changed the clay percent to 12%, a 25% decrease from the control at 16% (Figure 3.11).

The overall clay accumulation within the profile in basalt soil with sprinkler was 2% higher than the control and 20% higher with flood with respect to the control. In contrast, the clay accumulation in granite soils was 22% higher with sprinkler with respect to the control and only 1% higher with flood to the control (Figure 3.11).

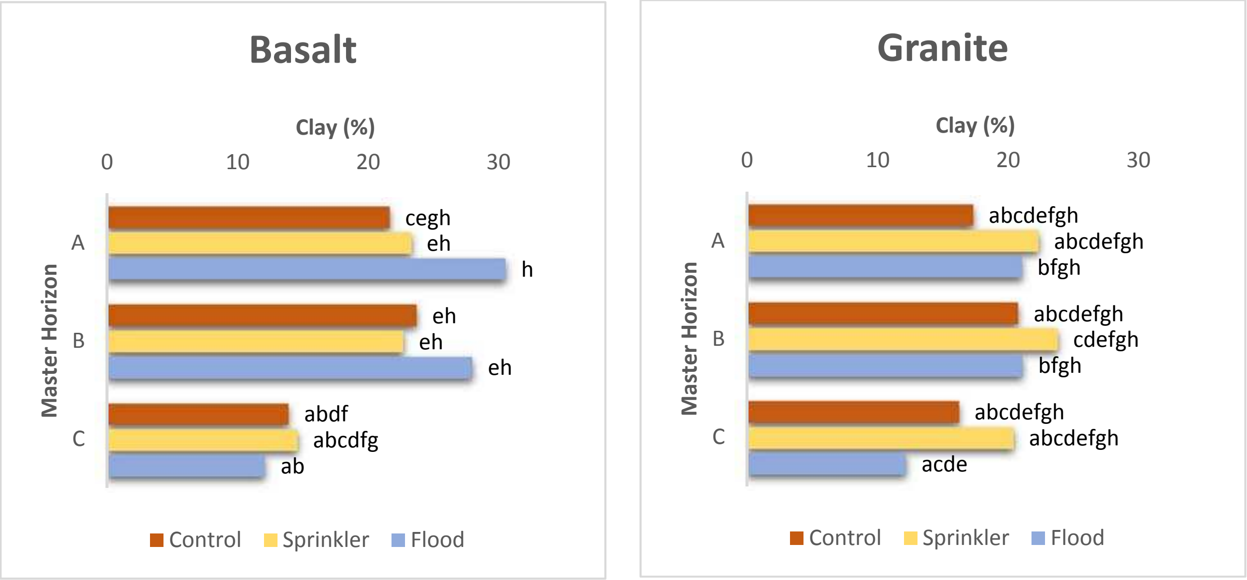


Figure 3.11: Clay content (weight %) by master horizons for basalt and granite parent materials, and by treatment (control, sprinkler, and flood). R^2 = 0.70 and lsmeans with different letters are significantly different (Tukey's).

Cation Exchange Capacity (CEC) in Figure 3.12 were statistically different among the basalt and granite controls. The statistical variation within the master horizons of basalt was primarily caused by the treatment effect of sprinkler and more predominantly with the flood treatment in the A and B horizons. The C horizon was statistically similar among the treatments.

Granite CEC's for sprinkler treatment were statistically the same among the master horizons and were closely associated with the controls in the A and B horizons. Flood treatment was statistically the same in the A and B horizons and had a slight variation in the C horizon and were also closely associated with the controls. The C horizon in the granite control was the distinctly different horizon observed between basalt and granite.

The range of CEC values for all treatment types were between 10 and 21 meq/100g, which is indicative of 1:1 kaolinite clays.

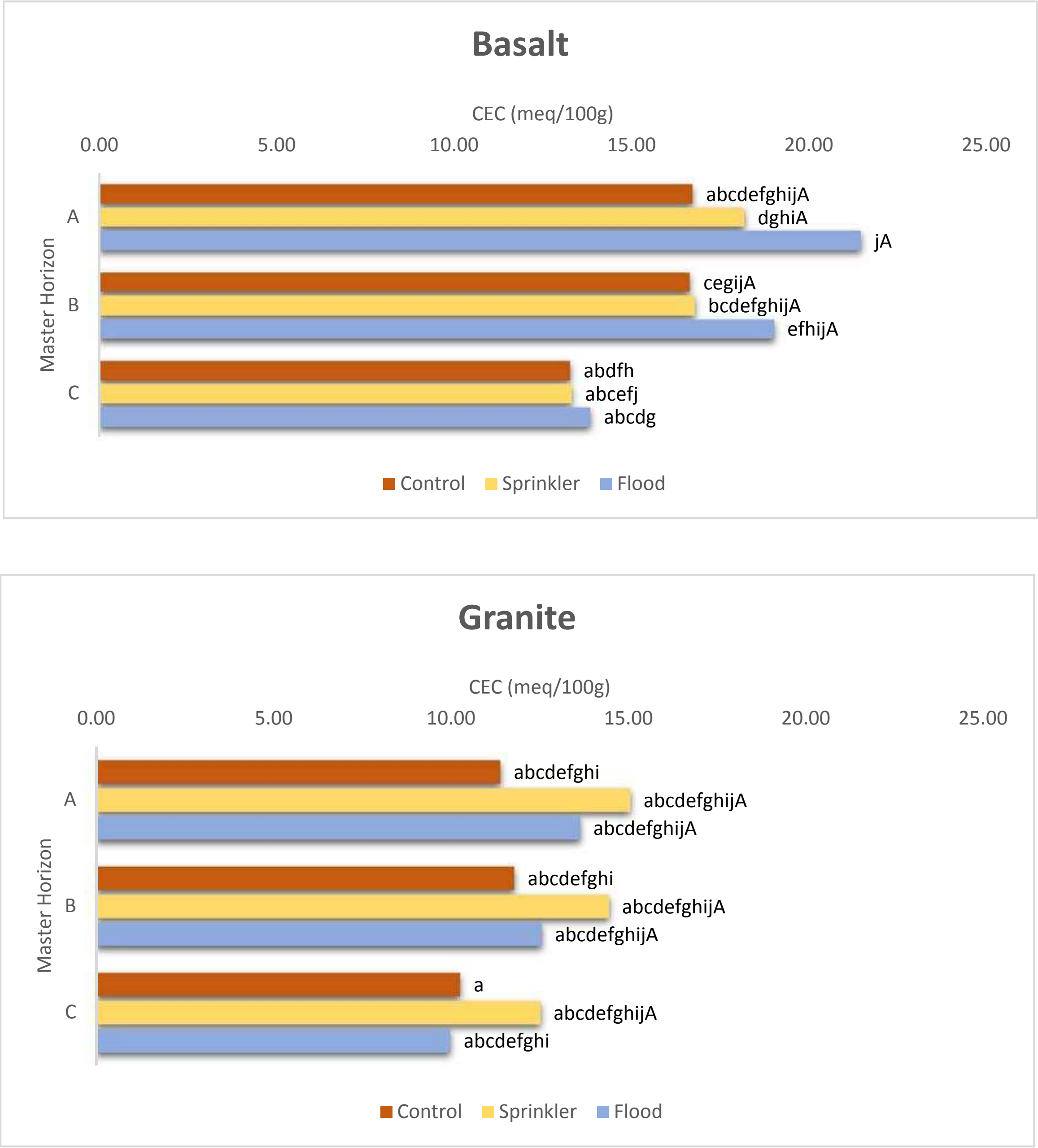


Figure 3.12: Cation Exchange Capacity (CEC) (meq/100g) by master horizons for basalt and granite parent materials, and by treatment (control, sprinkler, and flood). R^2 = 0.76 and lsmeans with different letters are significantly different (Tukey's).

Additional analysis compared basalt and granite profiles to a standard depth of 100 cm. The clay mass data calculated the clay fraction times the bulk density times the depth from each horizon (g clay/g soil * g soil/vol soil * soil depth), summed for the profile, and analyzed with an ANOVA. The mass data for clay in Figure 3.13 reveals an accumulation in clay from sprinkler and flood treatment in basalt soils. In contrast granite had an accumulation in clay from sprinkler irrigation and a decrease from flood irrigation.

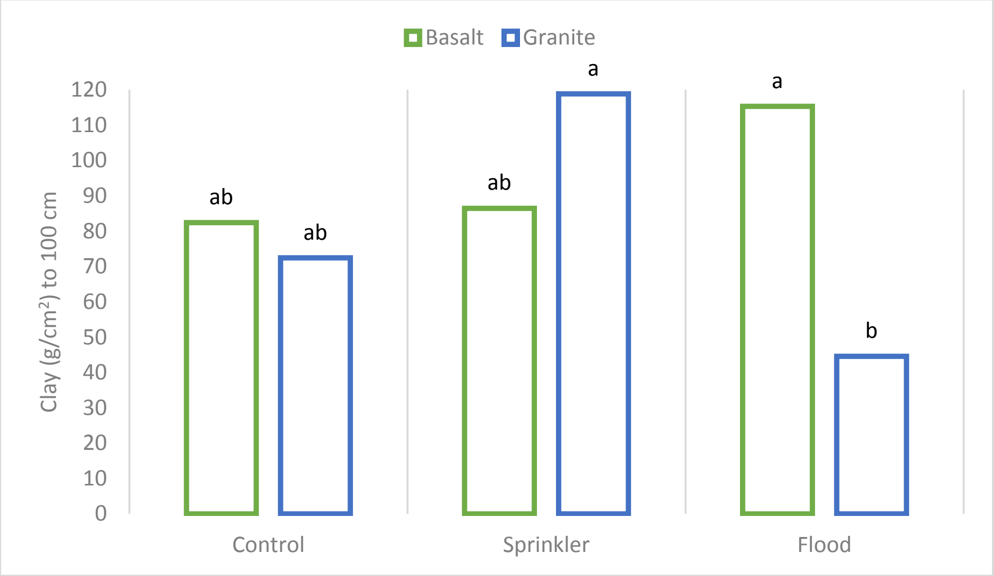


Figure 3.13: Mass data for clay for basalt and granite parent materials, and by treatment (control, sprinkler, and flood). ANOVA alpha = 0.05, p value = 0.001. The different letters are significantly different.

The mass data for cation exchange capacity (CEC) was statistically different within the control soils (Figure 3.14). The CEC mass data calculated the CEC (meq/100g) times the bulk density (g soil/cm^3) times the depth from each horizon (cm) to 100 cm and analyzed with an ANOVA. The treatments shared similarities between the two parent materials with the sprinkler treatment and were statistically differed between the parent materials with the flood treatment. However, the CEC values remained at or below 20 meq/100g. These results reinforce that the weathering of feldspars and biotite has not produced detectable 2:1 clays. The clay classification was kaolinite a 1:1 clay.

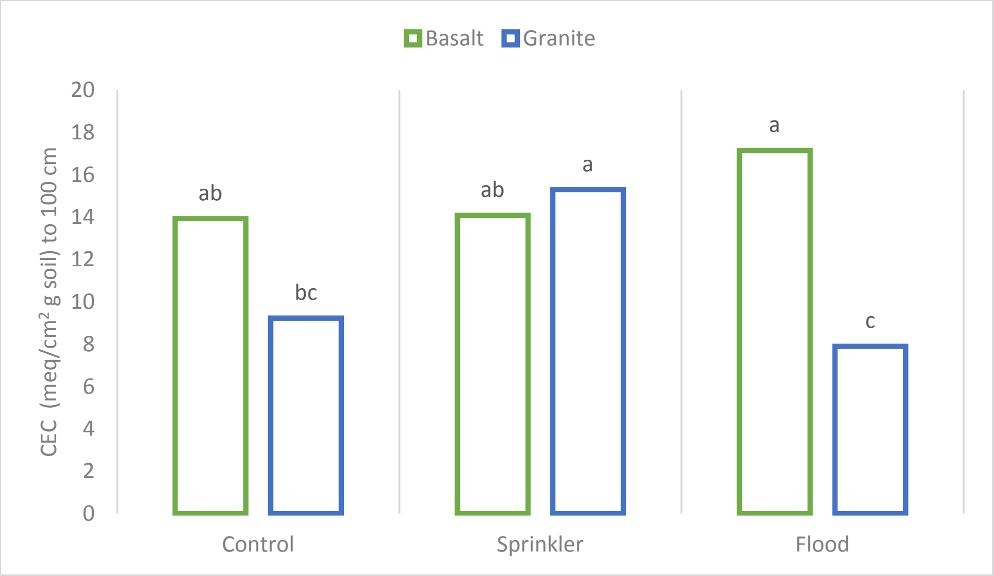


Figure 3.14. Mass data for Cation Exchange Capacity (CEC) for basalt and granite parent materials, and by treatment (control, sprinkler, and flood). ANOVA alpha = 0.05, p value = 1.81E-05***. The different letters are significantly different.

The analysis of clay enrichment assessed the treatment effects on clay accumulations. The analysis was performed on the differences between the control soils and the treatment soils from the clay mass data represented in Figure 3.13 using an ANOVA. Figure 3.15 shows the limited accumulation among the treatment groups, sprinkler on granite soils had the most accumulation. Flood treatment reveals a similar response on basalt soils and reinforced the limited accumulation on granite soils. Statistically the treatments for basalt soils were the same and the granite soils differed, but share similarities with basalt soils.

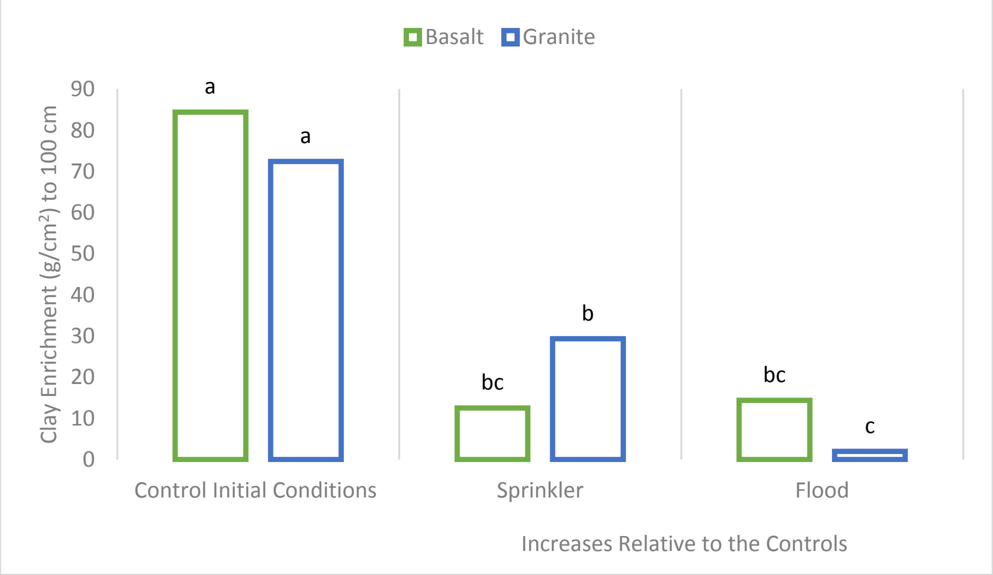


Figure 3.15: Clay enrichment for basalt and granite parent materials, and by treatment (control, sprinkler, and flood). ANOVA alpha = 0.87, p value = 0.2. The different letters are significantly different.

Further analysis was performed to evaluate the mass of soil per area to the top of the C horizon that accumulated a function of irrigation. Figure 3.16 shows the controls were statistically different between the parent materials (basalt and granite). An accumulation of soil occurred within the basalt sprinkler and flood treatments, and for granite sprinkler; they were statistically similar. In contrast an observed reduction in soil occurred within granite flooded soils. The result was not statistically different from the granite control, which indicated similarities between the initial conditions and treatment affects.

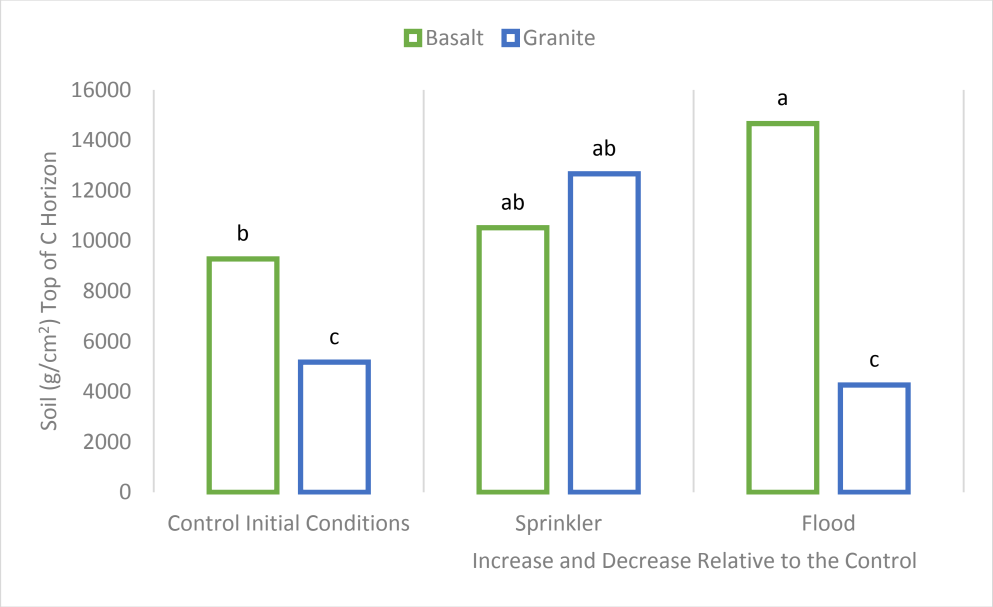


Figure 3.16: Mass of soil per area to the top of C horizon for basalt and granite parent materials, and by treatment (control, sprinkler, and flood) to the top of the C horizon. ANOVA alpha = 0.65 p value = 0.005**. The different letters are significantly different.

The bulk density values for basalt and granite soils were statistically similar. There was some variations in values of basalt soils in the control, bulk density was 6% less than the bulk density in granite soils. The bulk density in the A horizon of basalt soil with sprinkler treatment was 5% more and statistically similar to the control. The changes in bulk density in the B and C was negligible and shared statistical similarities with the basalt controls (Figure 3.17). The general trend was increased values in bulk density in the B and C horizons of the basalt control and treated soils.

The bulk density in the A horizon of granite soil was 4% more with sprinkler and 7% less with flood. Bulk density in the B and C horizons showed negligible changes (Figure 3.17).

The total change in bulk density in soils derived from basalt was a 7% with sprinkler and a 1% with flood. Total bulk density changes in soils derived from granite was 3% with sprinkler and 9% less with flood.

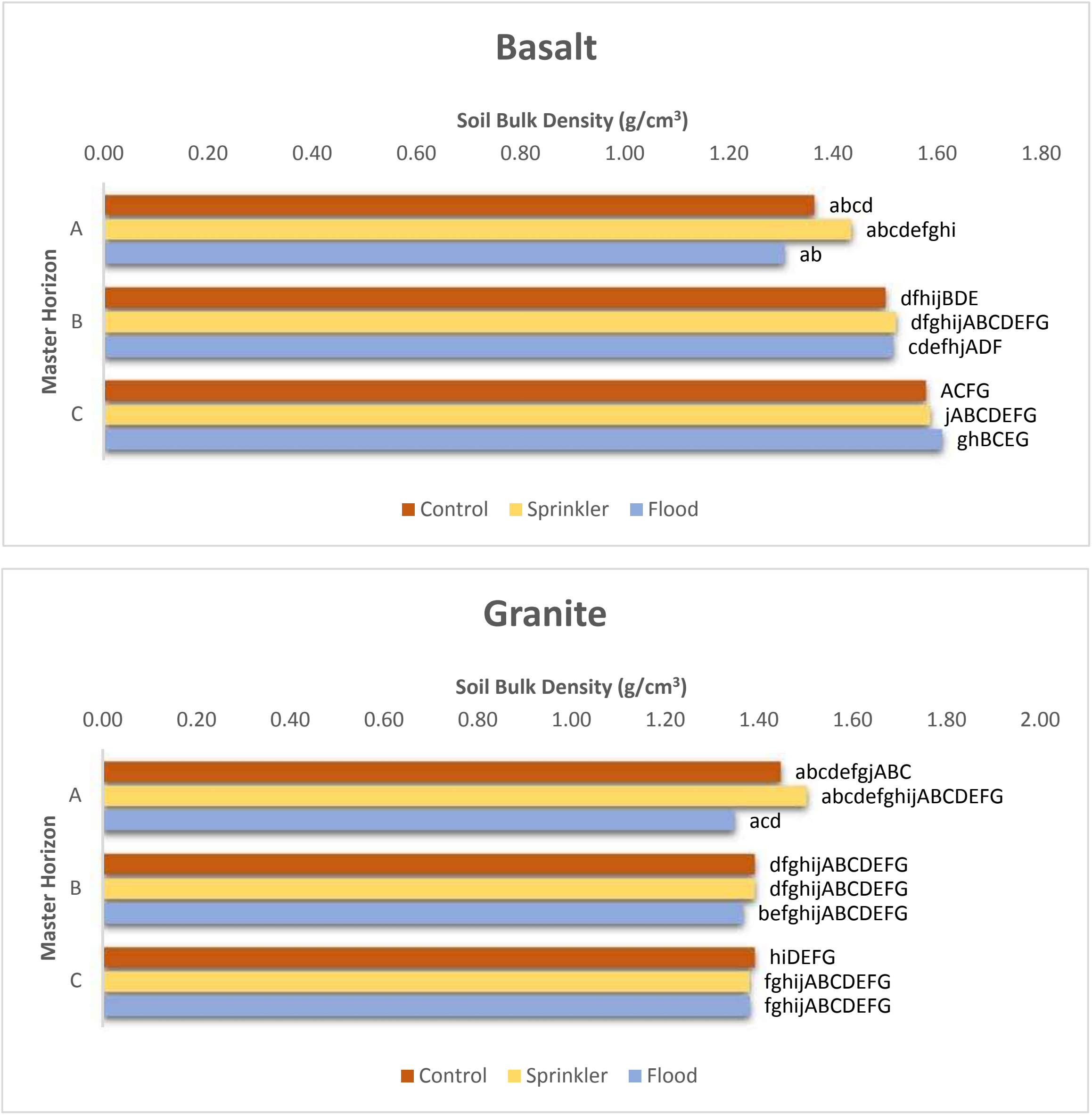


Figure 3.17: Soil Bulk Density by master horizons for basalt and granite parent materials, and by treatment (control, sprinkler, and flood). $R^2 = 0.71$ and lsmeans with different letters are significantly different (Tukey's).

The results for the average bulk density to a 100 cm depth showed that basalt was unaffected by the treatments and granite sprinkler was statistically different from granite control but shared similarities with basalt sprinkler and flood and granite flood (Figure 3.18).

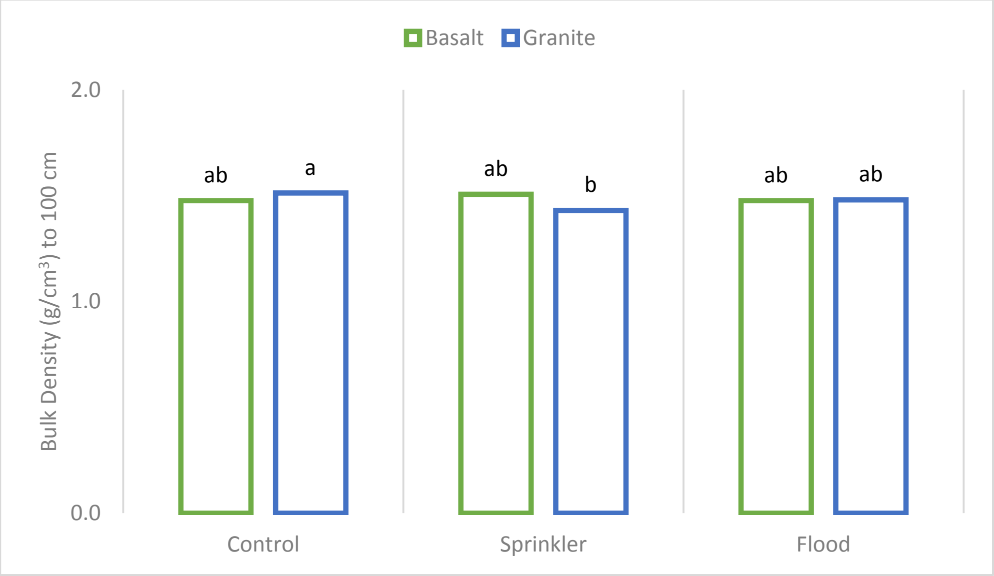


Figure 3.18: Bulk density for basalt and granite parent materials, and by treatment (control, sprinkler, and flood). ANOVA alpha = 0.68 p value = 0.722. The different letters are significantly different.

Bulk density ratio describes the residual enrichment of the less mobile elements caused by dissolution of minerals, leaching of the more soluble constituents, and consequently increases the porosity; the ratio is the bulk density of parent material divided by the bulk density of soil (Chadwick et al., 1990). Figure 3.19 shows a similar pattern of behavior between the controls and treatments. The majority of the ratio were 1.8 with the one exception of basalt sprinkler has a ratio of 1.5. These values can be related to porosity (Figure 3.21) where basalt sprinkler had an increase in porosity compared to granite sprinkler and flood treated soils.

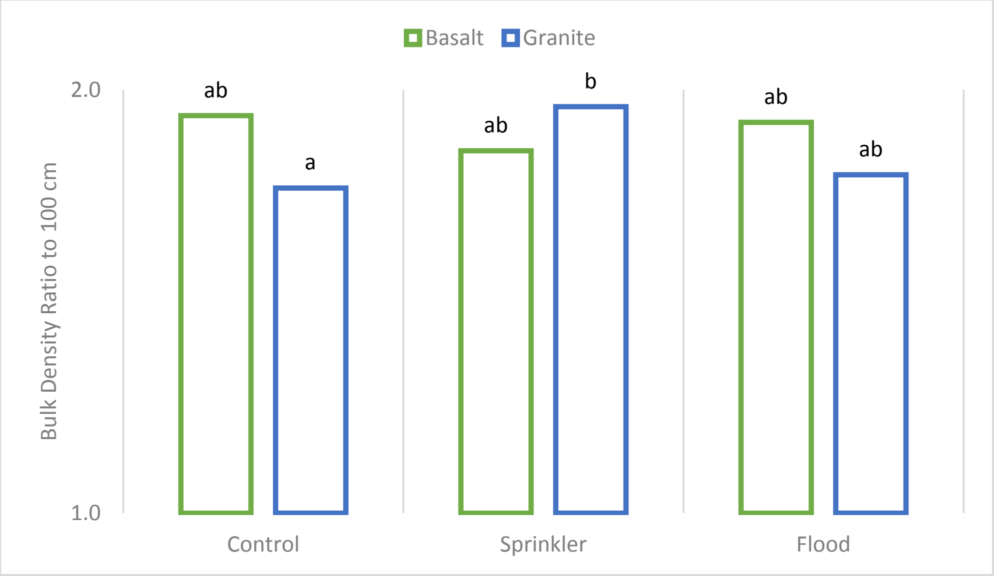


Figure 3.19: Average Bulk density ratio for basalt and granite parent materials, and by treatment (control, sprinkler, and flood). ANOVA alpha = 0.5 p value = 0.345. The different letters are significantly different.

The porosity, (1 - (P_b/P_p)) * 100, for each profile reveals that sprinkler irrigation was not statistically different from the basalt and granite controls. Basalt flood irrigation was statistically different from the controls and differed from granite flood irrigation. Granite control, sprinkler and flood were not statistically different (Figure 3.20). The porosity ranged from 42 and 50 percent for the basalt and granite controls and treatments, which reflects that the change in constituents that affect infiltration, ground water movement, and storage were negligible.

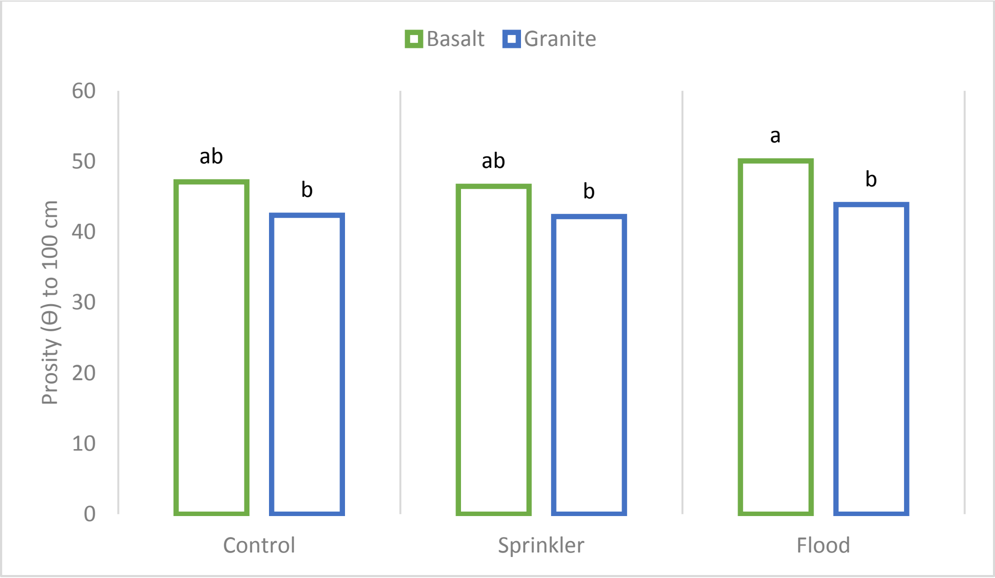


Figure 3.20: Porosity for basalt and granite parent materials, and by treatment (control, sprinkler, and flood). ANOVA alpha = 0.05 p value = 0.0002***. The different letters are significantly different.

Land use effect on physical properties

A study that evaluated the long-term irrigation effects (10 - 230 yrs.) in desert soils in Saudi Arabia found significant increases in clay illuviation in the soil profiles with increasing years of irrigation (Heakal and Al-Awajy 1989). Wierzchos et al. (1997) studied a pair of irrigated (100 yrs.) and non-irrigated pedons in northeast Spain, reporting changes in pore size and distribution with irrigation. The non-irrigated pedon had greater macrospores volume and uniform pore-size distribution, whereas the irrigated pedon predominately contained very small pores. Presley et al. (2004) showed that irrigation can affect the particle size distributions and translocation of clay through the soil profile by increasing mineral weathering. However, these studies did report that irrigation impacted physical properties but did not clarify the origin of their parent materials.

My data reflects similarities with these studies with regard to porosity, clay illuviation and bulk density. A change in clay accumulation in soils derived from basalt with sprinkler irrigation was seen in the surface horizon, suggesting the amount of water coupled with the finer-textured soils and pore space does not facilitate the process of illuviation in the same way as flood irrigation. In contrast, the surface and subsurface horizons with flood irrigation contained more clay, suggesting the difference is partially due to clay deposition and secondary weathering processes. Flood irrigation seems to stimulate the mineral weathering and promote clay movement throughout the profile more than sprinkler.

The clay accumulation in granite soils was greater with sprinkler irrigation compared to basalt sprinkler-irrigated soils. The clay accumulation with flood irrigation on basalt soils was similar to the sprinkler irrigations, however, flood irrigation on granite soils was negligible compared to the accumulation results on basalt soils. This suggests that clay is being leached from granite soil profiles due to the relationship between the coarser texture, pore-size distribution, and porosity. The effects of leaching were also evident in the mass of soil per area data, where granite-flooded soils showed a decline in the amount of soil within the profile. In addition, it is plausible there has been an increase in the chemical weathering (e.g. hydrolysis) within the granite minerals, allowing for secondary mineral weathering to occur and subsequently an accumulation of clay above the C horizon.

The disparity in the clay content between basalt and granite can also be a result of the mineral composition of biotite, which contributes to the increased production of clay in the granite irrigation soils. However, texture is one of the drivers in clay accumulation and basalt soil are finer in texture and technically should weather faster, therefore clay accumulation should be greater in basalt then granite soils. Therefore, further analysis is need to determine the types of clay that are present in this system to determine the observed disproportion in the clay content.

Aside from irrigation, other cultural practices and their effects could have impacted the same properties. Irrigated soils received more nitrogen fertilizer (almost exclusively in anhydrous ammonia form) than the control sites. It is plausible that the combined effects of increased soil acidity from fertilization as well as increased precipitation from irrigation have intermingled to enhance the conditions for more intense mineral weathering (Presley et al., 2004).

The bulk density of soil depends on the composition and the structural conditions, which vary with soil textures and is also influenced by soil aggregates. Bulk density influences the strength of the soils, plant growth, water infiltration, and drainage (Erbach 1987). Sandy soils tend to have higher bulk density than clay soils and typically volcanic soils have low bulk densities due to high concentrations of organic matter and clay (Lal 2006). The bulk density values in soils derived from basalt and granite are consistent with the high concentrations of sand; the bulk density values for basalt soils by classification should be higher.

The study revealed that basalt soils are classified as medium texture and granite soils are classified as coarse texture, therefore, their behaviors are similar. The bulk density of surface horizons of basalt and granite soils was greatest with sprinkler irrigation and least with flood irrigation. The results also indicate a predominant directional change among clay and soil organic carbon throughout the profile, which influences bulk density depending on the concentrations of one or both. Typically, the cause of the structural change is a function of tillage, but in these sites the flood soils are no-till and the sprinkler soils are tilled approximately every seven years. The results showed that the bulk density increased in basalt soils but decreased in granite soils. Typically, the changes in bulk density are due to the subsurface layers having reduced organic matter, and root penetration compared to surface layers and therefore, contain less pore space. In addition, the arrangement of the size and shape of the soil aggregates influences the inter-aggregate porosity (Lebron et al., 2002), which also helps explain the differences between basalt and granite soils. These coupled relationships explain the minimal directional change seen in bulk density in the treatment soils with respect to the control soils.

In addition, the basalt soils with flood irrigation showed lower bulk densities with smaller amounts of soil organic carbon and more clay. In contrast, granite soils with flood irrigation showed a lower bulk density with more clay and soil organic carbon. Additional correlations within these responses include the treatment types and crop management practices for harvesting, which influence the residual concentration of organic matter left on the soil surface. These practices create a coupling effect that contributes to the fluctuation in the bulk density in the surface and subsurface horizons in soils derived from basalt and granite.

Soil Chemical Properties

The pH in basalt soil have statistical similarities with granite soil but differed through the master horizons. The pH in the granite soil controls were statistically the same in the master horizons. Comparing the parent materials, pH in the basalt control was 6% more than the pH in the granite control. The pH values in basalt soils became statistically more similar in the A horizon and then became the same in the B and C horizons for both sprinkler and flood treatments. In addition, the pH in all three horizons reduced with both treatments (Figure 3.21).

The pH in the A horizon of granite soil was statistically different in the sprinkler treatment but was the same in the flood. The pH in the B horizon was statistically the same. The pH with sprinkler treatment in the C horizon was statistically different and increased by 4% from the control pH value (Figure 3.21).

The pH values in the soils derived from basalt reduced by 11% with sprinkler treatment and 12% with flood treatment. Total pH values in the soils derived from granite increased by 1% with sprinkler and reduced by 4% with flood treatments. The pH values remained in the neutral to alkaline range in the controls and treatments.

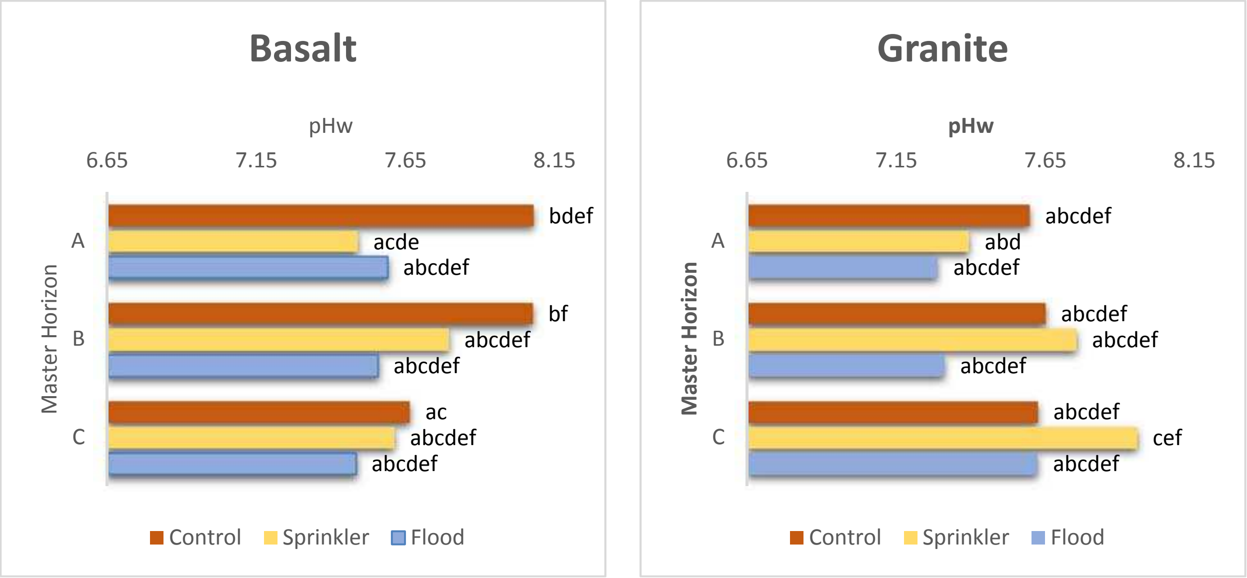


Figure 3.21: pH (saturated paste) by master horizons for basalt and granite parent materials, and by treatment. $R^2 = 0.73$ and lsmeans with different letters are significantly different (Tukey's).

Calcium in soils derived from basalt and soils derived from granite are statistically the same. The major difference was the basalt control soils had an initial concentration that was 65% more than in the granite control soils. Calcium in the A horizon of basalt sprinkler was 26% more and 6% less with flood with respect to the control. In the B horizon calcium was 7% less with sprinkler and 40% less with flood compared to the control. In the C horizon calcium was 18% more with sprinkler and 37% less with flood compared to the control, however, the treatment effects were not statistically different from the controls (Figure 3.22).

Calcium in the A horizon of granite soil had 16% more with sprinkler and 46% more with flood compared to the control. In the B horizon calcium was 14% less with sprinkler and 6% less with flood compared to the control. In the C horizon calcium was 9% more with sprinkler and 1% less with flood compared to the control. The treated soils were statistically the same as the control soils (Figure 3.22).

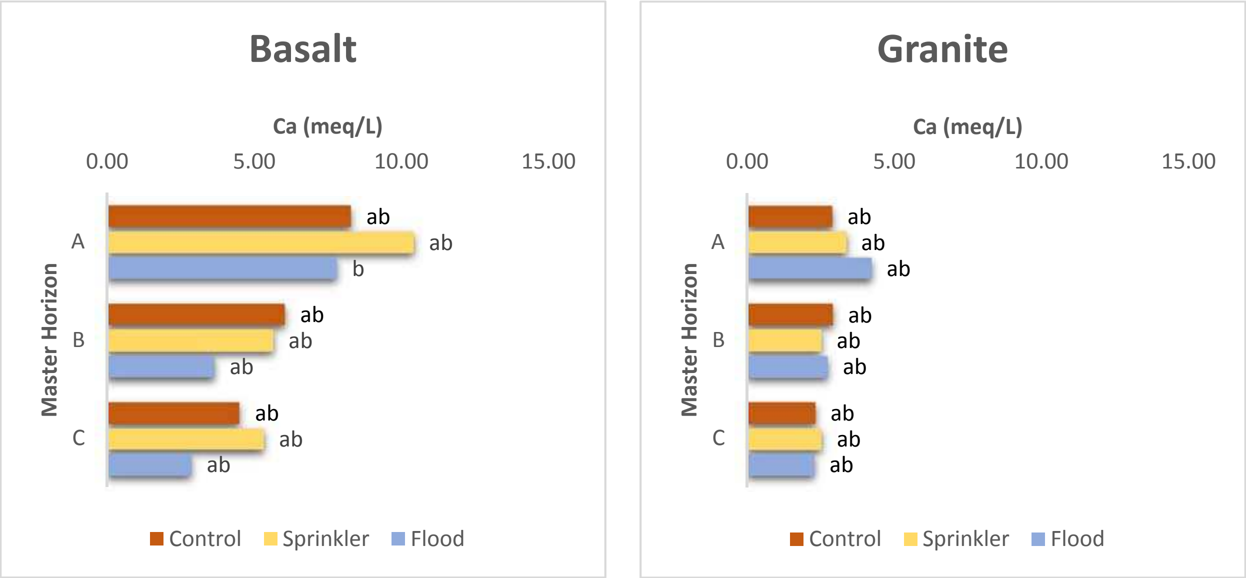


Figure 3.22: Ca concentration by master horizons for basalt and granite parent materials, and by treatment. R^2 = 0.80 and lsmeans with different letters are significantly different (Tukey's).

Magnesium in soils derived from basalt and soils derived from granite were statistically the same. The major difference is in the initial concentrations, soil derived from basalt had 78% more in the control than soil derived from granite. Magnesium in the A horizon of basalt soil was 24% less with sprinkler and 12% less with flood treatment compared to the control. Magnesium in the B horizon was 36% less with sprinkler and 56% less with flood compared to the control. Magnesium in the C horizon was 10% less with sprinkler and 53% less with flood compared to the control. Statistically the flood treatment showed variability throughout the profile, but shared similarities with the control and sprinkler treatments (Figure 3.23).

Magnesium in the A horizon of granite soil had 4% more with sprinkler and 129 % more with flood compared to the control. Magnesium in the B horizon had 13% less with sprinkler and 16% more with flood compared to the control. Magnesium in the C horizon had 23% more with sprinkler and flood compared to the control. The treated soils and the control soils were not statistically different (Figure 3.23).

The total change in magnesium in the soil derived from basalt was 70% and 121% less with sprinkler and flood. Total change in magnesium in soil derived from granite was 12% and 167% more with sprinkler and flood.

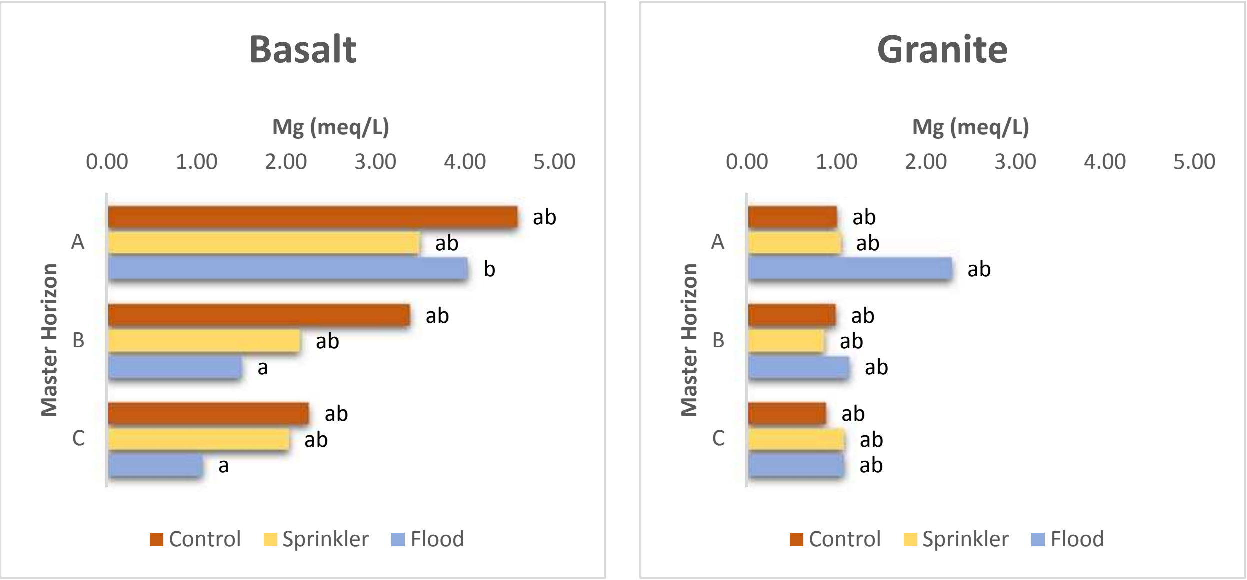


Figure 3.23: Mg concentration by master horizons for basalt and granite parent materials, and by treatment. $R^2 = 0.80$ and lsmeans with different letters are significantly different (Tukey's).

Sodium in soils derived from basalt were statistically different from the soils derived from granite in the control. The concentration was 99% more in the basalt control than the granite control. In the A horizon of basalt sprinkler soils, sodium was 91% less in concentration and statistically different with respect to the control. Sodium in the flood treatment was 65% less than the control. Sprinkler and flood treatments in the B horizon shared statistical similarities and the concentrations were 82% and 83% less respectively when compared to the control. Sodium in the C horizon was also statistically similar between sprinkler and flood treatments, they were 69% and 70% less in concentration with respect to the control (Figure 3.24).

Sodium in granite soil was statistically similar throughout the profile. In the A horizon of the sprinkler and flood treatments sodium increased in concentration by 8% and 105% respectively compared to the control. In the B horizon sprinkler and flooded soils were statistically the same, the concentrations decreased by 116% with sprinkler and 1% with flood compared to the control. In the C horizon sodium increased by 267% with sprinkler and 75% with flood and they were statistically similar (Figure 3.24).

The total change in sodium in the soil derived from basalt was 241% and 219% less with sprinkler and flood. Total sodium change in soil derived from granite was 391% and 179% more with sprinkler and flood. In addition, basalt and granite soils shared statistical similarities with both treatments.

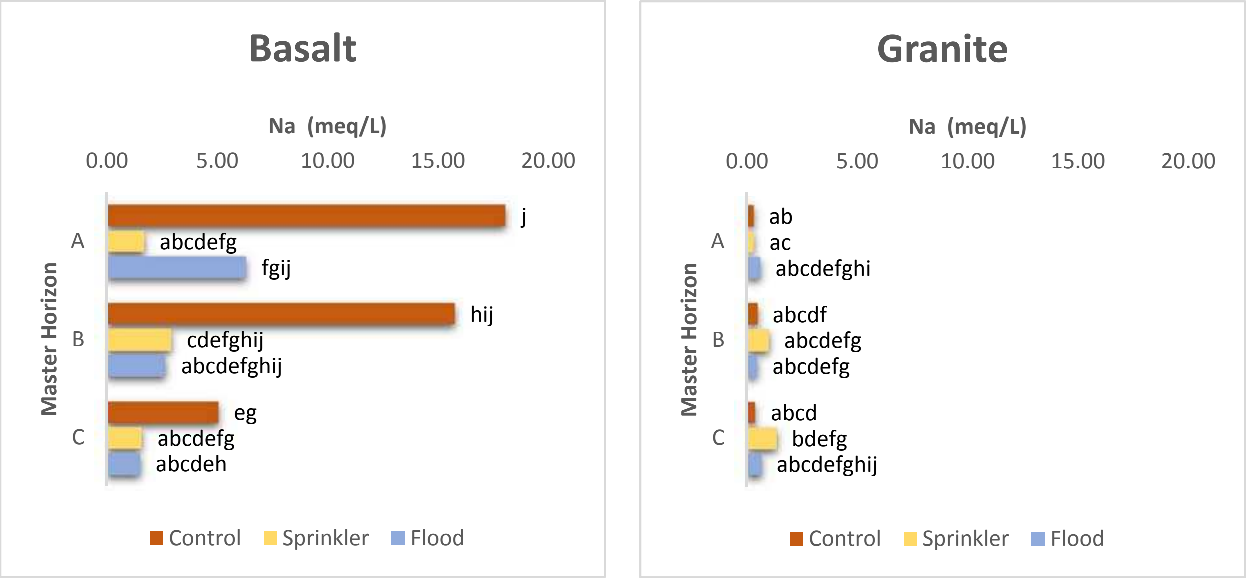


Figure 3.24: Na concentration by master horizons for basalt and granite parent materials, and by treatment. R^2 = 0.80 and lsmeans with different letters are significantly different (Tukey's).

The sodium adsorption ratio (SAR) is directly influenced by the proportional change to the sodium concentration relative to calcium and magnesium. The SAR in basalt soils were statistically different and had a 97% higher initial values than the SAR's in granite soils. In the A horizon of basalt soil the SAR's were statistically similar with sprinkler and flood treatments. In the sprinkler soil SAR was 90% less and 66% less in the flooded soils with respect to the control. In the B horizon sprinkler and flood treatments SAR's were also statistically similar, 78% and 79% less. In the C horizon the SAR results were statistically similar, 68% and 63% less with sprinkler and flood (Figure 3.25).

In the granite control soils the SAR values for the A horizon was statistically similar throughout, while the B and C horizons were statistically the same. The flood treatment was statistically same in the A and B horizons and only differed slightly in the C horizon. The SAR values for sprinkler treatment was to some extent statistically different in the A horizon and similar in the B and C horizons. Overall, the SAR values in the A horizon was 3% less with sprinkler and 47% more with flood compared to the control. The SAR value in B horizon was 123% more with sprinkler and 8% less with flood compared to the control. The SAR value in the C horizon had 227% and 29% more with sprinkler and flood compared to the control (Figure 3.25).

The total change in SAR in the soil derived from basalt was and 237% and 209% less with sprinkler and flood. The total SAR change in soil derived from granite was 351% and 98% more with sprinkler and flood. Overall, sprinkler and flood treatments on both parent materials shared statistical characteristics.

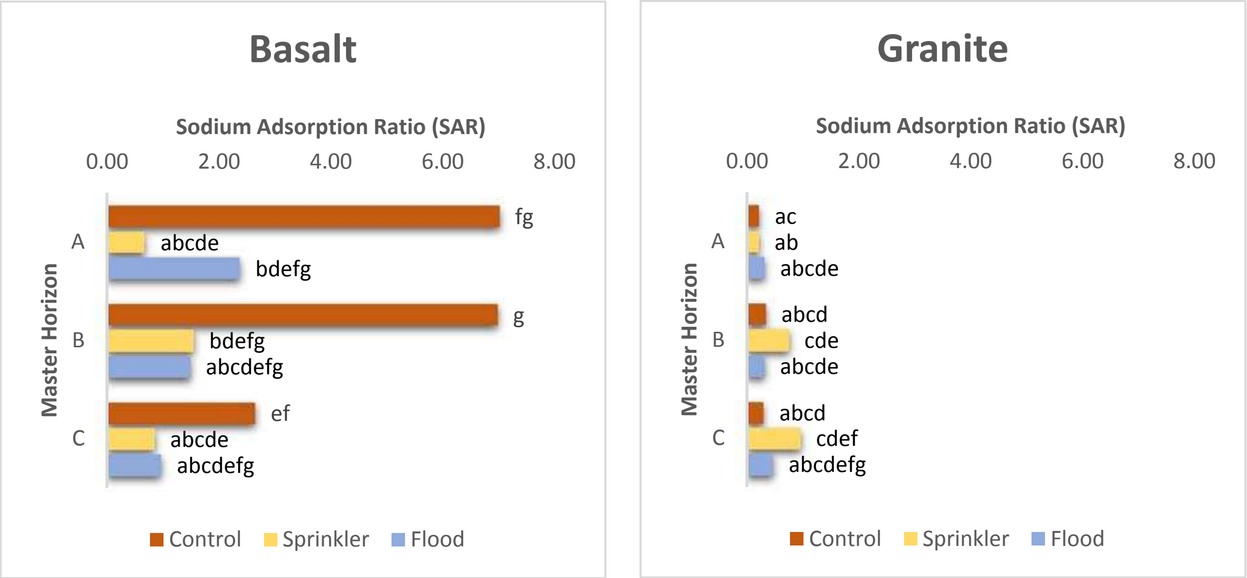


Figure 3.25: Sodium Adsorption Ratio (SAR) by master horizons for basalt and granite parent materials, and by treatment. R^2 = 0.74 and lsmeans with different letters are significantly different (Tukey's).

The exchangeable sodium percent (ESP) are directly influenced by the sodium concentrations, see Figure 3.24. The ESP values in soils derived from basalt were statistically different primarily in the A horizon and were the same in the B and C horizons. The ESP value were also statistically different from the granite soils, primarily in the A horizon and shared similarities in the B and C horizons. The ESP values were 91% more in the basalt control than granite control (Figure 3.26).

Sprinkler irrigation decreased the ESP in the entire profile of the basalt and granite soils. The A horizons were statistically different while the B and C horizons were similar to their controls. Flood irrigation also decreased the ESP values in both basalt and granite and were similar statistically to both the controls and sprinkler soils in the B and C horizons. In addition, both basalt and granite had the same magnitude of changes throughout the profile with sprinkler and flood (Figure 3.26). Total change was 163% and 102% less with sprinkler and flood.

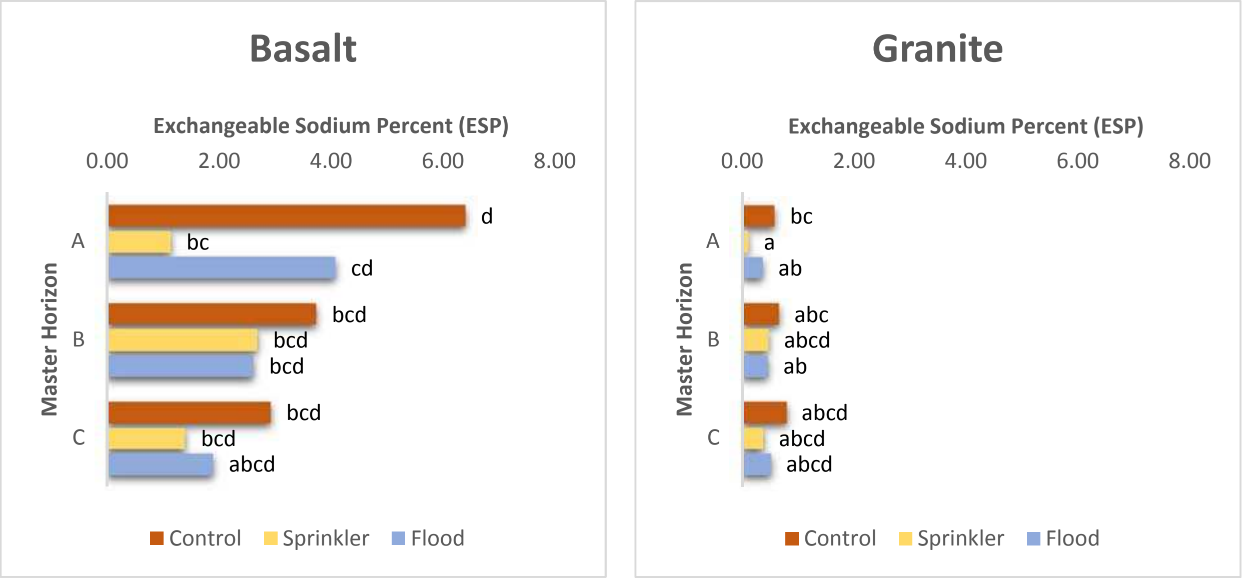


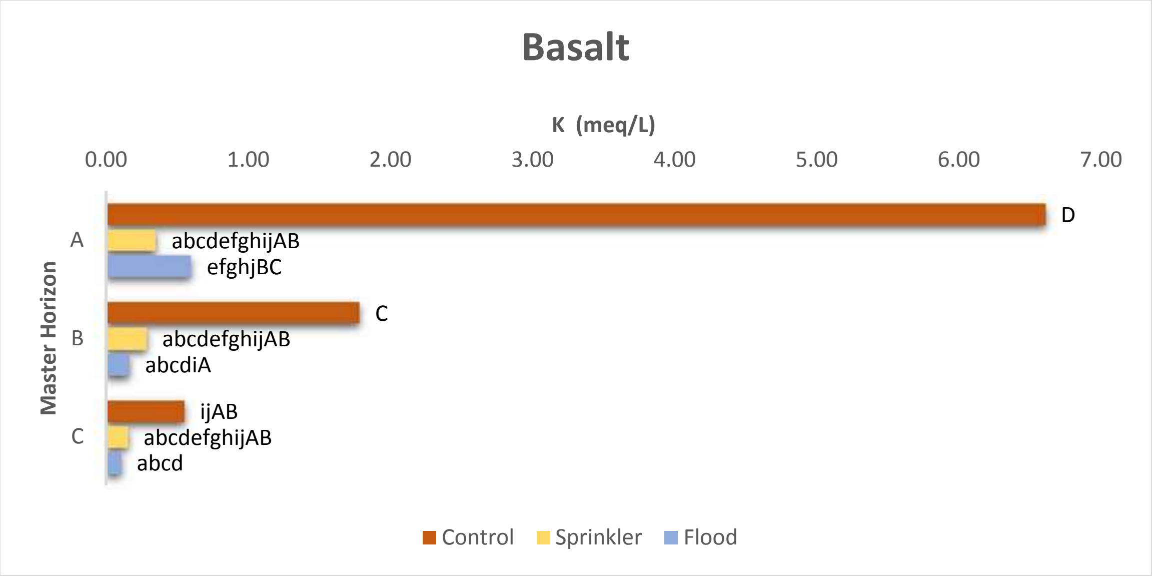
Figure 3.26: Exchangeable Sodium Percent (ESP) by master horizons for basalt and granite parent materials, and by treatment. $R^2 = 0.72$ and lsmeans with different letters are significantly different (Tukey's).

Potassium in soil derived from basalt was 94% more in the control than soil derived from granite. Potassium in the A horizon of basalt soil was 95% and 91% less with sprinkler and flood compared to the control. Potassium in the B horizon was 84% and 91% less with sprinkler and flood compared to the control. Potassium in the C horizon was 72% and 81% less with sprinkler and flood compared to the control (Figure 3.27).

Potassium in the A horizon of granite soil was 71% less with sprinkler and 2% more with flood compared to the control. Potassium in the B horizon was 20% less with sprinkler and no change with flood compared to the control. Potassium in the C horizon was 33% more with sprinkler and 53% more with flood compared to the control (Figure 3.27).

The initial potassium concentrations were higher in basalt soil than granite (Figure 3.27). The controls were statistically different between basalt and granite and the master horizons. Throughout the basalt profile, sprinkler irrigated soils were statistically the same and they were also the same as the A and C horizons of granite sprinkler soils. Flood irrigation in basalt soils had more statistical variation throughout the profile. Flooded granite soils had more variation in the A and B horizons and were statistically the same as sprinkler soils in the C horizon.

The total change in potassium in the soil derived from basalt was 251% and 263% less with sprinkler and flood. Total potassium change in soil derived from granite was 34% less with sprinkler and 122% more with flood.



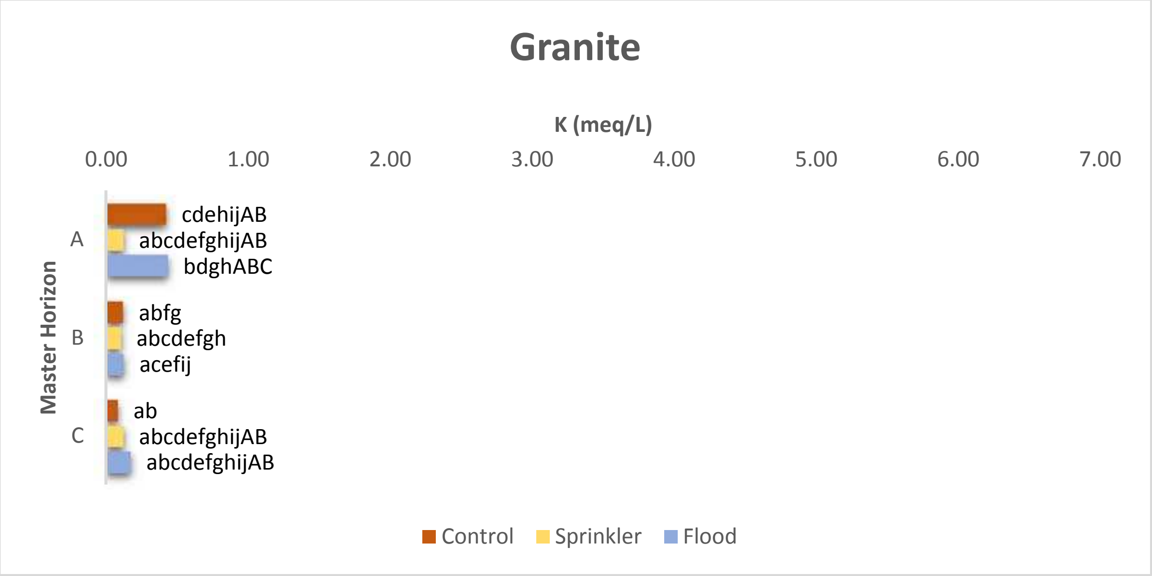


Figure 3.27: K concentration by master horizons for basalt and granite parent materials, and by treatment. R^2 = 0.83 and lsmeans with different letters are significantly different (Tukey's).

The electric conductivity (EC) values is the product of all exchangeable bases (Ca, Mg, Na, and K). The magnitude of change was influenced by the change in exchangeable sodium (Figure 3.24). The EC in soil derived from basalt was 89% more in the control than soil derived from granite. The controls were statistically different between basalt and granite. The A and B horizons of basalt control were similar statistically while the C horizon differed. Basalt sprinkler soil was statistically similar throughout the profile. The EC values, with respect to the controls, in the A horizon of basalt soil was 66% less, the B horizon was 58% less, and the C horizon was 36% less. Basalt flood irrigation was statistically different in the A horizon and was similar in the B and C horizons. The EC values were also less throughout the profile with respect to the control, the A horizon was 56% less, the B horizon was 74% less, and the C horizon was 60% less compared to controls (Figure 3.28).

The EC values for the granite control soil was statistically similar throughout the master horizon with the C horizon being statistically different. Granite sprinkler irrigation was statistically similar throughout the profile the EC values were 21% less in the A horizon, 3% less in the B horizon, and 50% more in the C horizon. Granite flood irrigation was statistically similar throughout the master horizons. Flooded soil had more statistically similarities to sprinkler soil in the B and C horizons. The EC values were 45% more in the A horizon, 15% less in the B horizon, and 34% more in the C horizon compared to the controls (Figure 3.28).

The total change in EC in the soil derived from basalt was 160% and 191% less with sprinkler and flood irrigation. Total EC change in soil derived from granite was 26% and 64% more with sprinkler and flood irrigation.

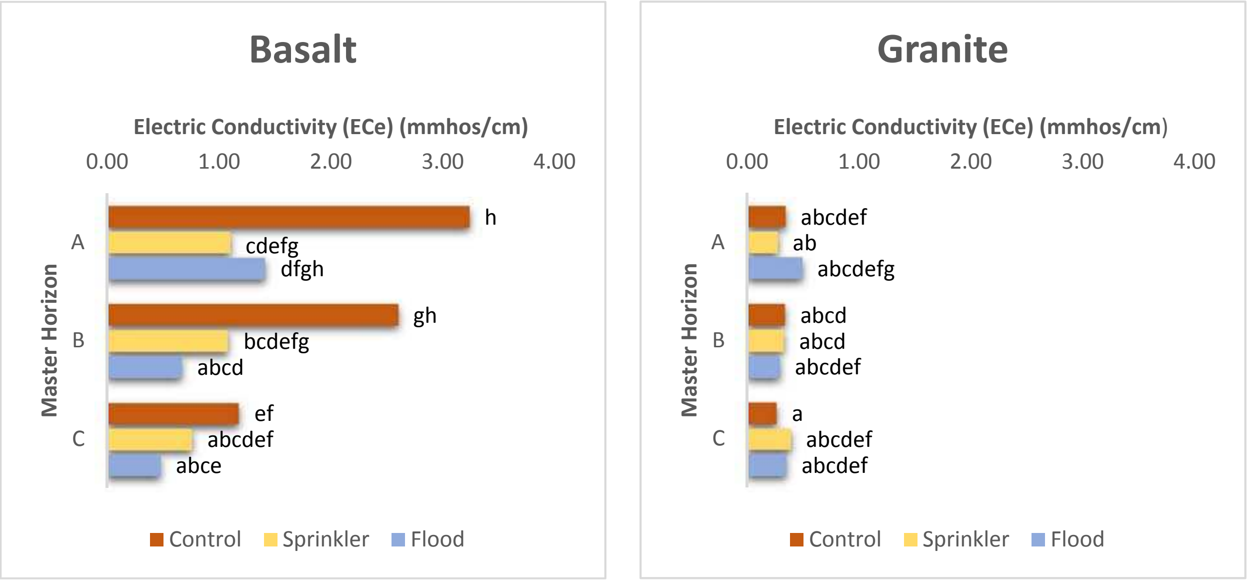


Figure 3.28: Electric Conductivity extracted (ECe) by master horizons for basalt and granite parent materials, and by treatment. R^2 = 0.82 and lsmeans with different letters are significantly different (Tukey's).

The initial concentration of chloride in soil derived from basalt was 97% more in the control than soil derived from granite which resulted in the basalt control being statistically different from the granite control. Basalt control master horizons were also statistically different while granite control master horizons were statistically the same in the A and B horizons.

Sprinkler irrigation in the basalt soil changed the chloride concentration. The A horizon was 93% less, the B horizon was 92% less, and the C horizon was 87% less compared to the controls; statistically the A and B horizons were the same. Flood irrigation also changed the chloride concentration, 81% less in the A horizon, 91% less in the B horizon, and 98% less in the C horizon compared to the controls (Figure 3.29).

Sprinkler irrigation in the granite soil changed the chloride concentrations; 31% less in the A horizon, 20% less in the B horizon, and 32% more in the C horizon compared to the controls; statistically the A horizon shared similarities with the B and C horizons, while the B and C horizons were the same. Flood irrigation also changed the chloride concentrations; 95% more in the A horizon, 7% more in the B horizon, and 76% less in the C horizon compared to the controls; statistically the master horizons were similar (Figure 3.29).

The total change in chloride in the soil derived from basalt was 273% and 270% less with sprinkler and flood. Total chloride changes in soil derived from granite was 19% less under sprinkler and 12% more with flood.

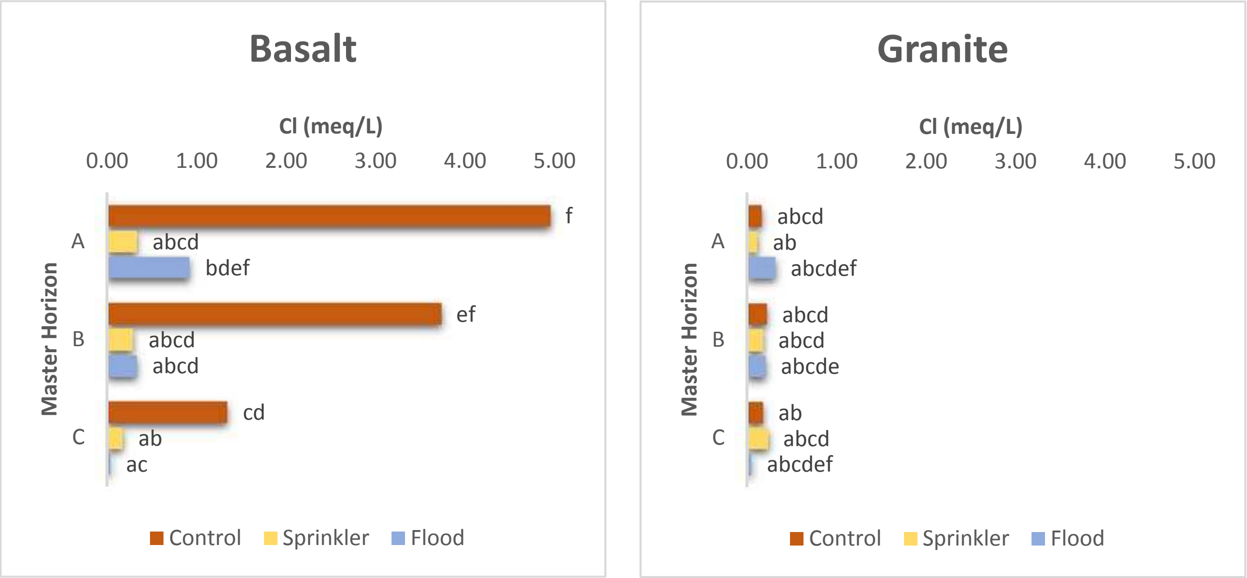


Figure 3.29: Cl concentration by master horizons for basalt and granite parent materials, and by treatment. R^2 = 0.78 and lsmeans with different letters are significantly different (Tukey's).

The initial concentration of sulfate in soil derived from basalt was 99% more in the control than soil derived from granite. Statistically basalt control differed from granite control. Sprinkler irrigation in basalt soil changed the sulfate concentrations; 77% less in the A horizon, 64% less in the B horizon, and 26% less in the C horizon compared to the controls. Statistically basalt sprinkler soils were the same in the master horizons. Flood irrigation in basalt soils also changed the sulfate concentrations; 50 % less in the A horizon, 76% less in the B horizon, and 62% less in the C horizon compared to the controls; statistically the flooded soil differed from the master horizons and shared similarities with the sprinkler soil (Figure 3.30).

The sulfate concentrations were also changed in the granite soil with sprinkler and flood irrigation. Sulfate in sprinkler irrigation in granite soil was 50% more in the A horizon, 138% more in the B horizon, and 390% in the C horizon compared to the controls; statistically the horizons shared similarities, but the A and C horizons were the most different. Sulfate in flood granite soil was 100% more in the A horizon, 2% less in the B horizon, and 52% more in the C horizon compared to the controls; statistically the horizons were the same (Figure 3.30).

The total change in sulfate in the soil derived from basalt was 168% and 188% less with sprinkler and flood. Total sulfate change in soil derived from granite was 579% and 150% more with sprinkler and flood.

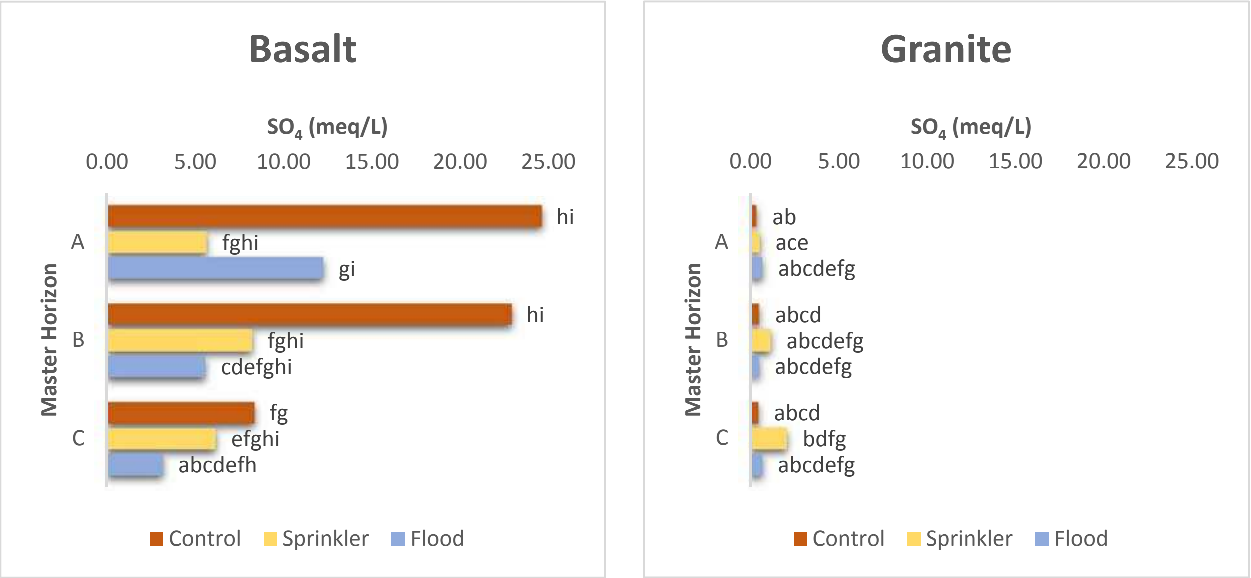


Figure 3.30: SO_4 concentration by master horizons for basalt and granite parent materials, and by treatment. $R^2 = 0.85$ and lsmeans with different letters are significantly different (Tukey's).

Land use effects on soil chemical properties

In arid regions the soil reactions are more alkaline because rainfall does not leach the calcium and other basic materials out of the soil. Within my study area the pH range was the neutral to alkaline within the controls, which also corresponded with the calcium concentrations in both basalt and granite control soils. The pH ranges responded similarly with both sprinkler and flood irrigation regardless of parent materials. This suggests that the minimal change in pH is correlated to the quality of the irrigation water (Appendices 9 - 12) and the water is not directly influencing a change observed in this chemical property. However, sprinkler irrigation created more calcium and flood irrigation created less calcium in soils derived from basalt and the resulting pH range remained neutral (7.48 to 7.79). In contrast, sprinkler and flood irrigation created more calcium in soils derived from granite and the pH range also remained neutral (7.29 – 7.96). This suggests that the amount of calcium delivered through both irrigation practices could be similar, but the retention of calcium can be related to texture, clay content, and amount of irrigation water applied.

The results show a significant difference in the concentrations of the following ions in the control soils of basalt than granite; calcium 65%, magnesium 78%, sodium 99%, potassium 94%, chloride 97%, and sulfate 99%. The data also reflects a general trend of greater concentration of these ion in the A and B horizons and lower accumulations in the C horizon for both soil types. The treatment effects of sprinkler and flood irrigation for basalt soils resulted in lower concentrations of these ions and granite soils had higher concentrations of these ions. The treatment effects, in general, reduced the distinction between the master horizons.

The magnitude of change for calcium was smaller in comparison to the previously mentioned ions. Calcium cumulatively was at a higher concentration with sprinkler irrigation in soils derived from basalt and granite, but was less in basalt flooded soils and more in granite flooded soils. The source calcium at these higher levels may have been due to $CaSO_4.2H_20$, $CaCO_3$, or Ca-silicate dissolution (Amundson and Lund 1985). In addition dissolution and as point of reference, Ca and Na are released in relative proportions to their abundance in the plagioclase feldspars (Garrels 1967), our data represents a Ca:Na ratio of 11:19 for basalt and 3:0.54 for granite. Due to the complex geology of the valley, the above is one possible scenario for the calcium and sodium sources. However, analysis of elemental the composition of these soils would be needed to confirm the source of the elevated sodium concentrations found in the basalt controls. However, the above scenario is a plausible explanation for the calcium and sodium concentrations measured in the granite controls.

The impact of irrigation was more apparent in the change in concentrations of sodium, potassium, chloride, and sulfate in soils derived from basalt. The cumulative reduction of sodium with sprinkler was 84% and 73% under flood. Also, the sodium adsorption ratio and exchangeable sodium percent declined with respect to the change in sodium. The removal of these soluble salts is also reflected in the EC values with both treatments with respect to their controls. The opposite effect in sodium concentration were measured in the granite treatment soils; cumulatively, sodium increased 59% with sprinkler and 139% with flood irrigation. This suggest sodium increases probably occurred as a result of Na-silicate dissolution (Garrels 1967).

The cumulative change in potassium concentrations in basalt soils was a reduction of 251% with sprinkler and 236% with flood. In contrast, soils derived from granite had a 34% reduction with sprinkler and an increase of 122% with flood. The cumulative changes in the chloride concentrations were significant, 273% with sprinkler and 270% with flood for basalt soils. Granite soils had a 19% reduction with sprinkler and an increase of 12% with flood. The cumulative change in sulfate was a reduction of 167% with sprinkler and 188% with flood in basalt soils and a significant increase of 579% with sprinkler and 150% with flood in granite soils. These values emphasize the inequality in the nutrient concentrations inherited in the soils from basalt and granite. It further accentuates the impact of irrigation on the removal and addition of these nutrients with the profile through the leaching and weathering processes.

Consequently, it is difficult to determine exactly when the maximum leaching occurred, since each site in the study has been subject to irritation for an average of 84 years. Amundson and Lund in 1985, determined that a maximum of 5 years of leaching reduced the sodium, potassium, chloride, and sulfate concentration by at least an order of magnitude, compared with the native sites in San Joaquin Valley of California. They also suggested this change could be indicative of the attainment of a steady-state condition between the solution and solid phases in the soils.

They used chloride as the reference ion due to the fact that chloride is assumed to be a conservative ion in soil solution and the chemical concentration in a saturated extract is more enriched relative to the irrigation water concentrations of chloride. Therefore, it can be assumed that mineral dissolution or ion exchange has occurred (Amundson and Lund 1985). The findings in the San Luis Valley are comparable to those found in the San Joaquin Valley. For the basalt controls, sodium, potassium, magnesium, calcium, and sulfate, all increased relative to chloride, and where steady-state conditions could be established, based on the EC values. These finding were also observed in the granite control soils where the concentrations are lower, but remain higher than chloride and proportional increased under irrigation treatments.

The increase in sulfate, which showed a higher concentration in basalt then granite soils, could be the result of $CaSO_4.2H_2O$ dissolution (Amundson and Lund 1985). In addition, the concentrations of potassium in the results appeared to be controlled by a solid phase. According to Amundson and Lund (1985), the largest source of potassium in the soil is due to the partially weathered biotite. The result revealed that the basalt controls have a higher concentration of potassium than the granite controls; therefore, it can be surmised that basalt biotite is more accessible during the weathering process than granite biotite.

The analysis also exposed a trend in the directional change for sulfate and sodium in the B and C horizons of sprinkler irrigated granite soils with respect to the controls. The magnitude of change for sulfate and sodium seems dramatic especially, in the granite soil, due to the small range, the increased levels were less than 2.0 meq/L for both ions.

With respect to sodium, the increase affected the sodium adsorption ratio and electric conductivity and had no effect on the exchangeable sodium percent. This suggests that the increases are not due to management practices but could be an accumulation over time through the water source. The irrigation water, for both basalt and granite soil is either surface or subsurface in origin. One theory of the source of this of sulfate and sodium ions could be from the subsurface water, which is filtered through relic volcanic formations. However, further analysis is needed to verify the source of the sulfate and sodium ions.

In addition, both the basalt and granite soils are dominated by sand particles therefore, porosity and permeability are important factors controlling water and solute movement (Lal 2006), and also affects bulk density. The porosity for basalt (44%) and granite (47%) are relatively the same, which is reflected in the reduced concentrations of soluble salts in the irrigated basalt soils. However, there was an increase in soluble salts for granite soils but the change in concentration was not reflected in the bulk density values for either soil type. This suggests the pore size in both soils is large enough to accommodate the solute movement without measureable changes in bulk density.

Biogeochemical properties

The percentage of soil organic carbon in soil derived from basalt was 36% more in the control than soil derived from granite. Statistically, basalt controls differed from granite controls primarily in the A horizon; the B and C horizons were statistically similar regardless of parent material. Sprinkler irrigation changed the soil organic carbon percent in the A horizon of basalt soil by 17% less with sprinkler and 8% less with flood irrigation compared to the controls. Soil organic carbon in the B horizon had a similar response 41% less with sprinkler and 21% less with flood compared to the controls and they were statistically similar. Soil organic carbon in the

C horizon also had a similar response 42% less with sprinkler and 32% less with flood compared to the controls and they were statistically similar (Figure 3.31).

The percent of soil organic carbon in in the A horizon of granite soil changed primarily with flood irrigation 121% more and sprinkler was 9% less compared to the controls. Statistically, flood differed from both the control and sprinkler treatment. Soil organic carbon in the B horizon was also influenced by flood irrigation with 47% more than the control, and was statistically differed from both the sprinkler and control treatments. The same occurred in the C horizon were soil organic carbon was 62% more with flood and 40% less with sprinkler and the C horizon had the same statistically trend as the A and B horizons (Figure 3.31).

The total change in soil organic carbon in basalt soil was 97% with sprinkler and 61% less with flood. Total change in soil organic carbon in granite soil was 87% less with sprinkler and 272% more with flood.

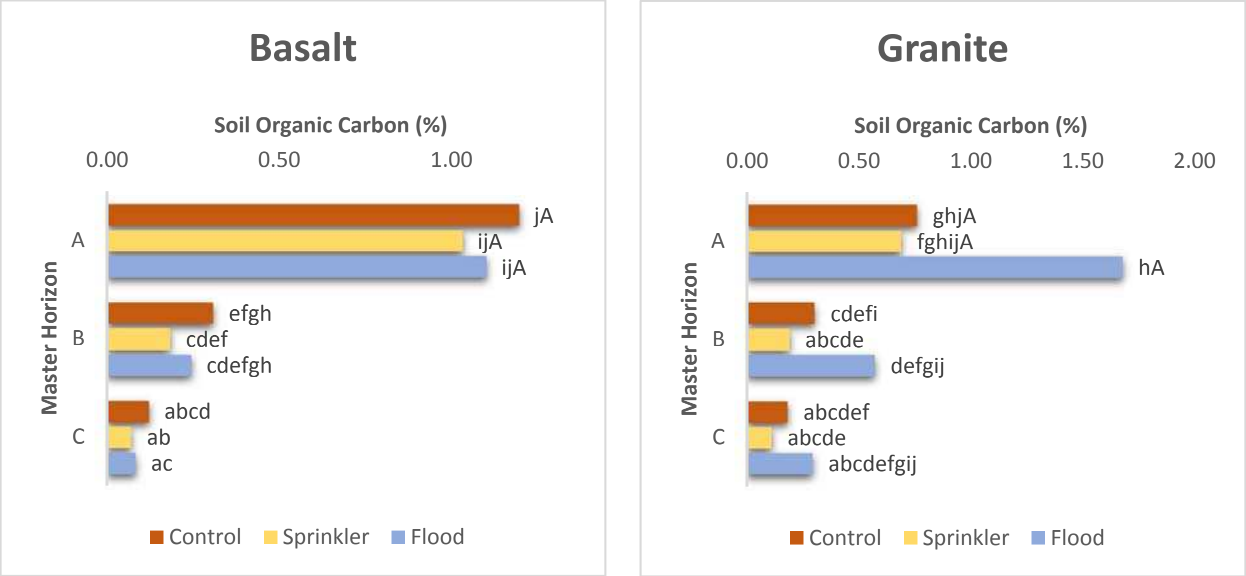


Figure 3.31: Soil Organic Carbon percent by master horizons for basalt and granite parent materials, and by treatment. R^2 = 0.72 and lsmeans with different letters are significantly different (Tukey's).

The mass data for soil organic carbon in Figure 3.32 statistically shows a difference between the control for basalt and granite. The results showed that treatments were statistically the same regardless of parent material. The calculation for mass data used soil organic carbon percent times the bulk density times the depth from each horizon, summed for the profile and analyzed with an ANOVA.

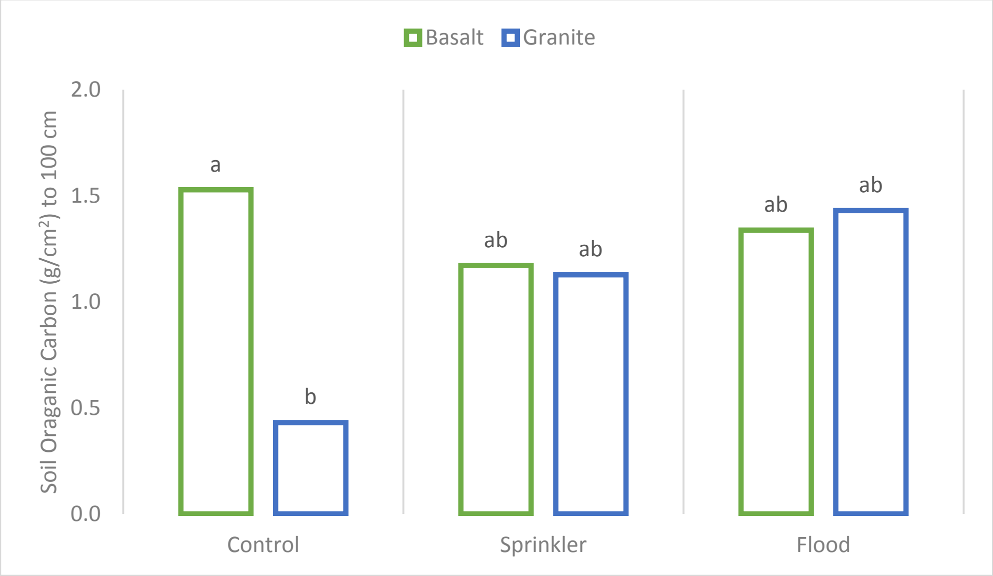
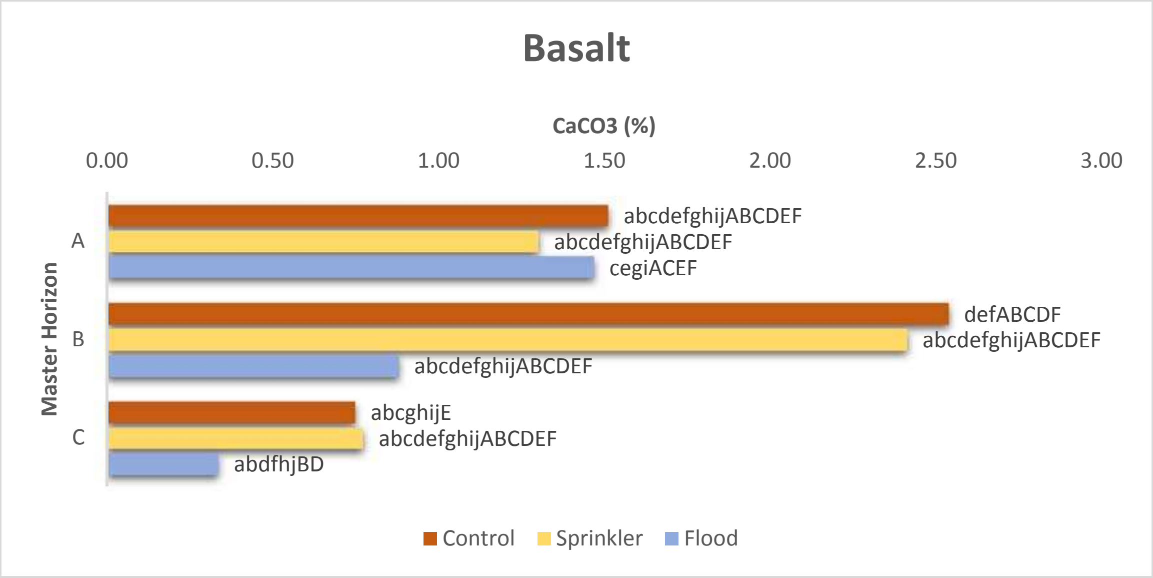


Figure 3.32: Mass data for soil organic carbon for basalt and granite parent materials, and by treatment (control, sprinkler, and flood). ANOVA alpha = 0.4 p value = 0.268. The different letters are significantly different.

The percent of calcium carbonate in basalt control soil was 64% more than in the granite control soil and statistically the controls differed between parent materials. The percent of calcium carbonate changed in the irrigated basalt soils, in the A horizon the change was 14% less with sprinkler and 3% less with flood and statistically sprinkler was the same and flood differed from the control. Calcium carbonate in the B horizon was 5% less with sprinkler and 65% less with flood and statistically sprinkler and the control were similar with flooding being different. Calcium carbonate in the C horizon had 3% more with sprinkler and 55% less with flood and statistically differed from the control (Figure 3.33).

The percent of calcium carbonate in the A horizon of granite soil was 3% more with sprinkler and 29% less with flood. Statistically sprinkler was slightly different from the control and flood differed from both the control and sprinkler. Calcium carbonate in the B horizon was 20% more with sprinkler and 17% less with flood and statistically there were no difference. Calcium carbonate in the C horizon was 30% more with sprinkler and 67% less with flood and statistically there were variations among the treatments compared to the control. Overall, flooded soils were statistically the same throughout the profile (Figure 3.33).

The total change in calcium carbonate in the basalt soil was 16% and 123% less with sprinkler and flood. Total calcium carbonate change in granite soil was 59% more with sprinkler and 172% less with flood.



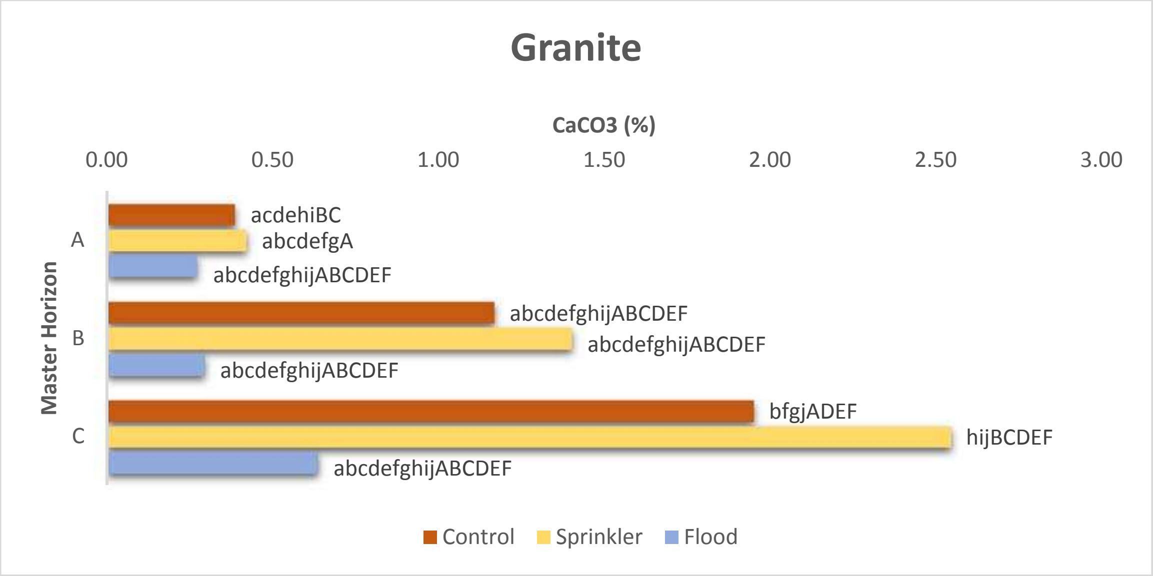


Figure 3.33: $CaCO_3$ percent by master horizons for basalt and granite parent materials, and by treatment. $R^2 = 0.73$ and lsmeans with different letters are significantly different (Tukey's).

The mass balance results for calcium carbonate show that the control and sprinkler basalt soils are the same and flood treatment differed slightly. In contrast, granite soil differed more among the three treatments but shared similarities between the control and sprinkler treatments. The calculation for the mass of calcium carbonate used calcium carbonate percent times the bulk density times the depth from each horizon, summed for the profile and analyzed with an ANOVA. (Figure 3.34).

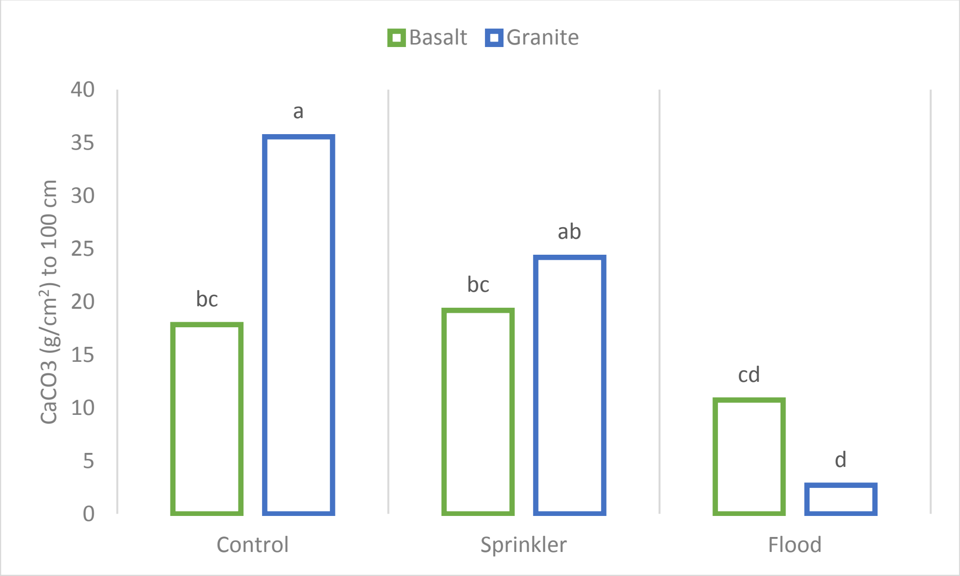


Figure 3.34: Mass data for calcium carbonate for basalt and granite parent materials, and by treatment (control, sprinkler, and flood). ANOVA alpha = 0.55 p value = 0.105. The different letters are significantly different.

To further evaluate the dynamics in these soil profiles, I looked at the mass data of nitrogen by treatment in Figure 3.36. The calculation used the total nitrogen percent times the bulk density times the depth from each horizon, summed for the profile and analyzed with an ANOVA. Nitrogen follows the same trend in the control and sprinkler as soil organic carbon (Figure 3.32), however differs with flood treatment specifically with basalt. In addition, the carbon to nitrogen ratio in Figure 3.36 shows that basalt control, flood, and granite flood are statistically the same and granite control, sprinkler, and basalt sprinkler are the same.

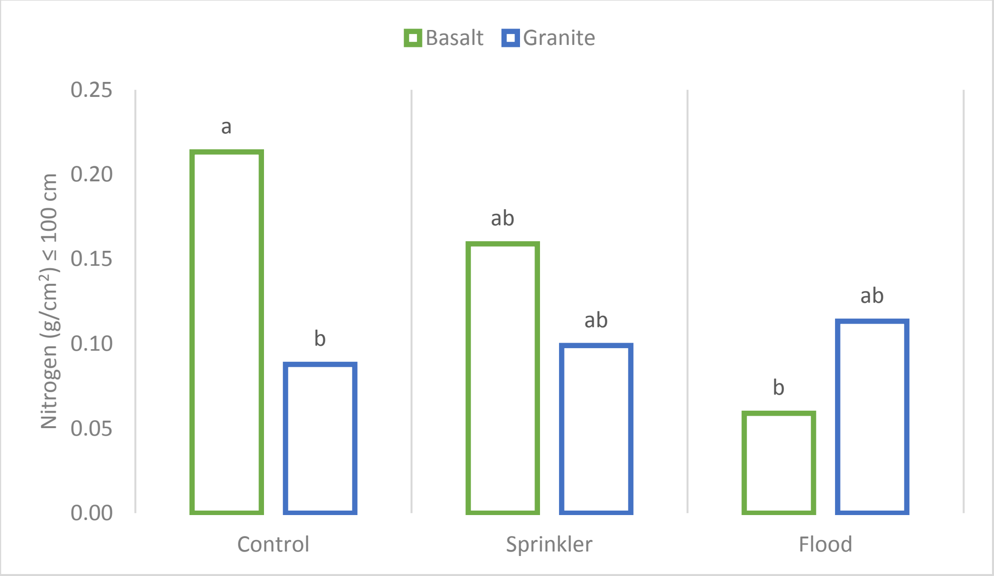


Figure 3.35: Mass data for nitrogen for basalt and granite parent material, and by treatment (control, sprinkler, and flood). ANOVA alpha = 0.88 p value = 0.62. The different letters are significantly different.

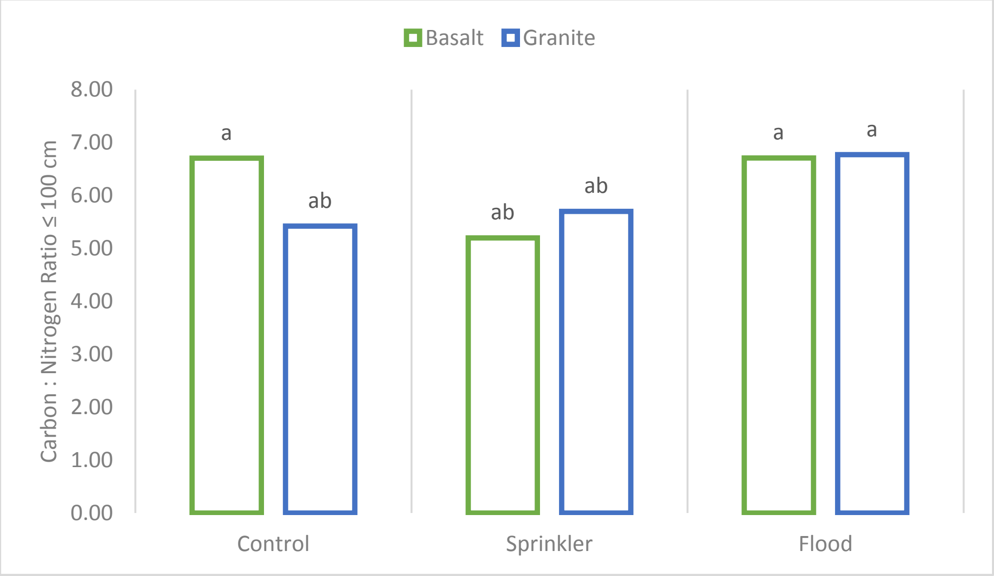


Figure 3.36: Carbon : Nitrogen ratio for basalt and granite parent material, and by treatment (control, sprinkler, and flood). ANOVA alpha = 0.44 p value = 0.20. The different letters are significantly different.

Land use effects on biogeochemical properties

It is well known that soil organic carbon is a critical component of soil quality as it affects many soil chemical, physical, and biological properties. Cultivation has reduced the amount of available soil organic carbon by approximately half in the last two centuries and it is generally accepted that this loss has been a major factor leading to the decline in soil quality and function (Kirby et al., 2013). Soil organic carbon is the lesser of the two pools of carbon in semi-arid regions where plant productivity is low. Soil texture and mineralogy are thought to be especially important for maintaining soil organic carbon stocks (Mayes et al., 2014). Soil with higher clay and silt concentrations tend to have higher soil organic carbon due to increased surface area (Six et al., 2002; Mayes et al., 2014).

The soils formed on basalt have textures that range from medium to fine, a slightly higher clay content, and more initial soil organic carbon in the controls than soil derived from granite. Statistically the change in the percent of soil organic carbon for the entire profile was the same with sprinkler and flood irrigation regardless of the parent material. The results of the linear model showed most of the variation occurred in the A horizon with sprinkler and flood irrigation, the B and C horizons responded similarly and both parent materials showed more of a benefit from flood irrigation especially in coarser-texture granite soils, which facilitates the accumulation of soil organic carbon with depth.

The overall differences between the cultivation practices on basalt soil is noticeable, suggesting less residual plant material is left after harvesting on sprinkler than flood sites. It also infers that there are other driving factors reducing the soil organic carbon stocks such as higher soil moisture content, microbial activity and respiration, and ultraviolet volatilization of soil organic carbon (Mayes et al., 2014; Brandt et al., 2007 and 2009; Burke et al., 1989). However, there is no direct, or obvious correlation between the chemical, physical, and biogeochemical properties that would account for the increase in soil organic carbon in the flooded granite soil. One theory could be the addition of soil organic carbon through management practices, but due to availability and cost, this is unlikely. Our results show, where arable lands and cultivation practices intersect, soil organic carbons stocks differ with irrigation practices and management types, but there is no clear evidence how these difference may affect soil productivity, health, quality, and function (Mayes et al., 2014; Burke et al., 1998). In addition, the total nitrogen results show a reduction in basalt soil from sprinkler irrigation and a slight increase in granite soil. However, the carbon to nitrogen ratio were statistically the same among the treatments and regardless of parent material. Therefore, the results show no clear evidence of the effects of irrigation on productivity and function, but does reflect how low the concentrations are within this system when the control soils are compared to the treatment soils.

The initial concentration of calcium carbonate between parent materials differed, basalt was higher versus lower in granite. However, the results of this study indicate pedogenesis is not the only process intrinsic to the accumulation of carbonates in the San Luis Valley, CO. The formation of carbonates is directly influenced by the carbonate bicarbonate equilibrium, specifically the process of dissolution and precipitation from irrigation practices. The accumulation of soil inorganic carbon (SIC) observed in the irrigated agriculture, indicates a detectable change in carbonate concentrations. The observed changes in the upper profile are caused by a coupling effect of one or more processes. A study by Lal and Kimble (2000) demonstrated that homogenization of the upper horizons during cultivation resulted in the changes in carbonate distribution throughout the profile. Cultivation affects the partial pressure of CO_2 due to soil organic carbon decomposition and root respiration, which leads to formation of HCO_3^- reacting with the increased amount of applied H_20. The percolation of H_2O down the profile transports the Ca^{+2} and HCO_3^- into the subsoil horizons.

The equations of Arkley (1963) and Jenny in (1941) both predicted an increase in the depth at which secondary carbonates are encountered with increased precipitation, or in this study, irrigations. Their model predicted that carbonates will accumulate at the maximum depth of leaching. Thus, the irrigation practices used in this study differ in the depth of the wetting front. The accumulation calcium carbonate occurred primarily in the A and B horizons of the basalt soil. This suggests that pedogenic processes are secondary to the processes of deposition and subsequent dissolution of calcium bearing minerals (Brahney et al., 2013) followed by the primary processes of transfer and translocation within the soil profile. Statistically the mass data confirms the processes in the A and B horizons are the same and the difference occurred in the C horizon.

The granite soil showed an opposite trend with the primary zones of accumulations in the B and C horizons primarily with sprinkler irrigation. These results suggest these soils are older in terms of their soil development and calcification processes. These results corresponded with differenced in irrigation type and texture, confirming that the distribution of carbonates in the soil profile is in fact regulated by the amount of available water, leaching, texture, and the concentration of carbon dioxide in soil air (Lapenis et al., 2008).

The summer temperatures support higher microbial activity and increased root respiration triggering carbonate dissolution and the saturation of soil water with carbonate and bicarbonate ions. This generates high biological activity in the rooting zone near the soil surface increasing evapotranspiration, which stimulates the upward capillary movement of water. As the soil solution moves upward, the dissolved carbon dioxide escapes into the atmosphere precipitating carbonates (Lapenis et al., 2008). This is demonstrated in the irrigated sites where changes in carbonate concentrations are different from their non-irrigated comparison sites. However, precipitation of carbonates deeper in the profile release CO_2 back into the atmosphere, whereas carbonates remaining in solution in groundwater and rivers represent a net sink for atmospheric CO_2 (Lapenis et al., 2008).

The addition of inorganic carbon to the system through the formation of secondary carbonates is dependent on the addition of biomass, crop residue return, and external sources of calcium. The chemistry of the irrigation applied is likely different than the natural rainfall, although the chemistry of both water sources were not analyzed in this study. It could be suggested that their chemical properties are similar due to low variability between the control and treatment. Thus, the full impact of intensive irrigation agriculture on the SOC and SIC pools is not completely known; however, the addition of organic matter to the soil releases CO_2 that sets in motion the processes of dissolution and precipitation of carbonates (Lal and Kimble 2000).

Soil Property Distribution

In this study, I found clear evidence that soil properties within the control soils diverged with respect to parent material using the principal component analysis and the same properties in cultivated irrigation soils (sprinkler and flood) converged. These results indicate the parent material is the primary factor and treatment with parent material is the secondary driving factor in this system (Table 3.5). These results were also validated by the clustering of certain soil properties within the same treatments (sprinkler and flood). The clustered soil properties derived from basalt with sprinkler irrigation were clay and soil organic carbon, sand and sodium, and calcium and magnesium. The properties that clustered with flood irrigation were sodium and potassium, calcium and chloride, and magnesium and sulfate. The basalt control clusters were chloride and sulfate, sodium and potassium, calcium carbonate and soil organic carbon, and calcium and clay Figure 3.37.

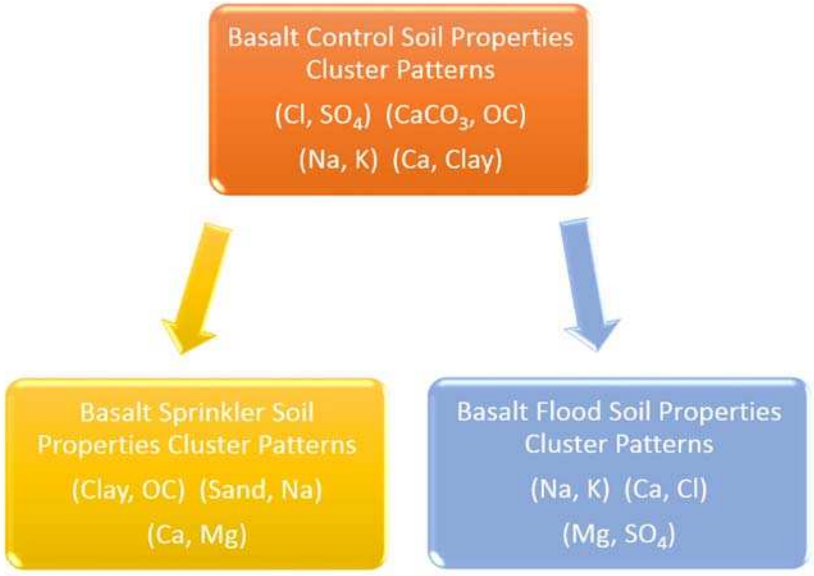


Figure 3.37: Principal component analysis clustering groups from soil derived from basalt, control and treatments (sprinkler and flood).

In contrast, the soil properties derived from granite with sprinkler irrigation clusters were sodium, chloride and magnesium, potassium and sulfate, and pH and calcium carbonate. The properties that clustered with flood irrigation were soil organic carbon and calcium, and sodium and pH. The granite control clusters were pH, clay, and calcium carbonate, sand and potassium, and magnesium, sodium, chloride, and calcium Figure 3.38.

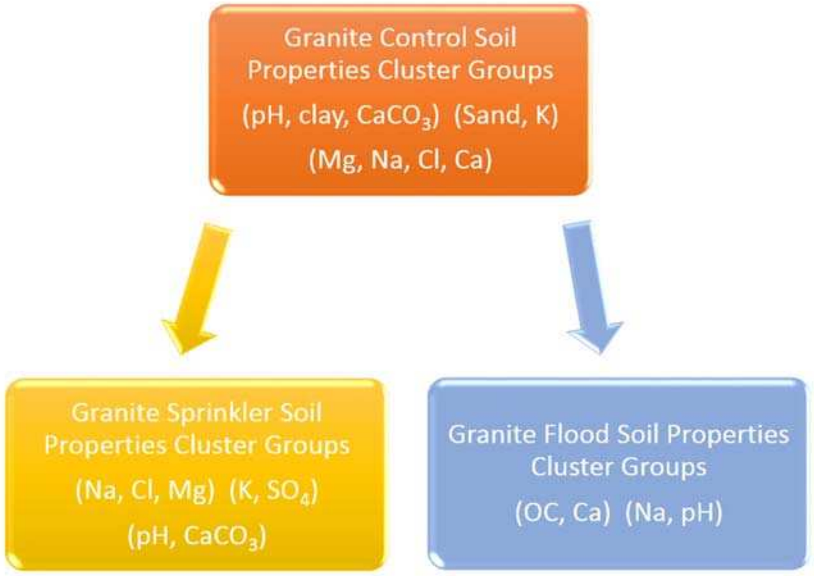


Figure 3.38: Principal component analysis clustering groups from soil derived from granite, control and treatments (sprinkler and flood).

These patterns differ among the basalt and granite controls suggesting certain properties group together based on similar behavioral patterns and change relative to each other when influenced by specific treatments. This also suggests the other properties (i.e., sand) respond independently. The results partially correspond to the linear model results where by clay and organic matter are coupled due to their lower concentrations, and the ion concentrations are proportionally lowered with respect to chloride. However, further analysis is required to understand their coupling responses.

Saline Sodic and Non-Saline Sodic

The water quality data gathered by Colorado Department of Agriculture and extracted from the ground water database from 1989 to 2015 for the irrigation water for Alamosa, Conejos, Costilla, and Rio Grande counties is represented in appendices 9-12. An excerpt of the mean data values for pH, sodium and specific conductance is listed in Table 3.6. The water data is well below the recommend EPA limit of 20 mg/L for sodium concentrations and does not represent a hazard for row crop production.

Table 3.6: Water quality data excerpt from Colorado Department of Agriculture data from the San Luis Valley by county (Alamosa, Conejos, Costilla, and Rio Grande) for pH, sodium and specific conductance.

Properties	**Alamosa**	**Conejos**	**Costilla**	**Rio Grande**
pH	7.85	7.45	7.5	7.51
Sodium (ppt)	92.55	10.32	35.6	13.62
Specific Conductance (µs/cm)	788.56	242.55	541.56	278.27

A study by Buol et al. (1997) demonstrated that salt accumulation can occur through irrigation of crops with water that is only slightly saline (around 0.07S m^{-1}). The results indicate directional change in the classification of these soils as a direct result of the chemical changes that have occurred from irrigation practices, and suggests these changes are a function of the water quality. In addition, it is speculated that the increase in sodium levels in granite soils (Costilla County) is due to accumulation of salt over time, due to the low levels present in the irrigation water, but it is plausible that over 84 years of irrigations could increase the concentrations of this ion at depth.

The change in the sodium concentrations with respect to the controls in each soil system were also reflected in the EC, SAR, and ESP soil values. The soil classes were adopted from Lal (2006) in Table 3.7, which provided the parameters for the re-classification. The basalt control pedons were classified as saline-sodic soils. The basalt soils irrigated by sprinkler and flood shifted to non-saline non-sodic soils (Figure 3.39).

In contrast, the granite control pedons were non-saline, non-sodic soils and remained in the same classification with sprinkler and flood treatments (Figure 3.40). Neither change is indicative of soil degradation but reflects an improvement in soil quality based on agriculture practices and the quality of the irrigation water.

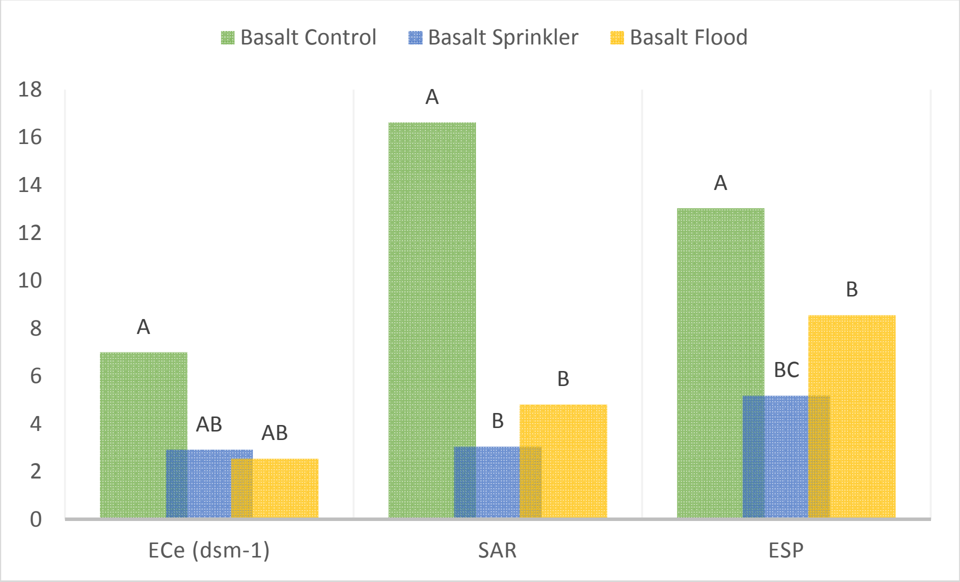


Figure 3.39: Comparison of the soil parameters for Electric Conductivity by extraction (ECe), Sodium Adsorption Ratio (SAR), and Exchangeable Sodium Percent (ESP) for soils derived from basalt and granite and by treatment. The different letters are statistically different.

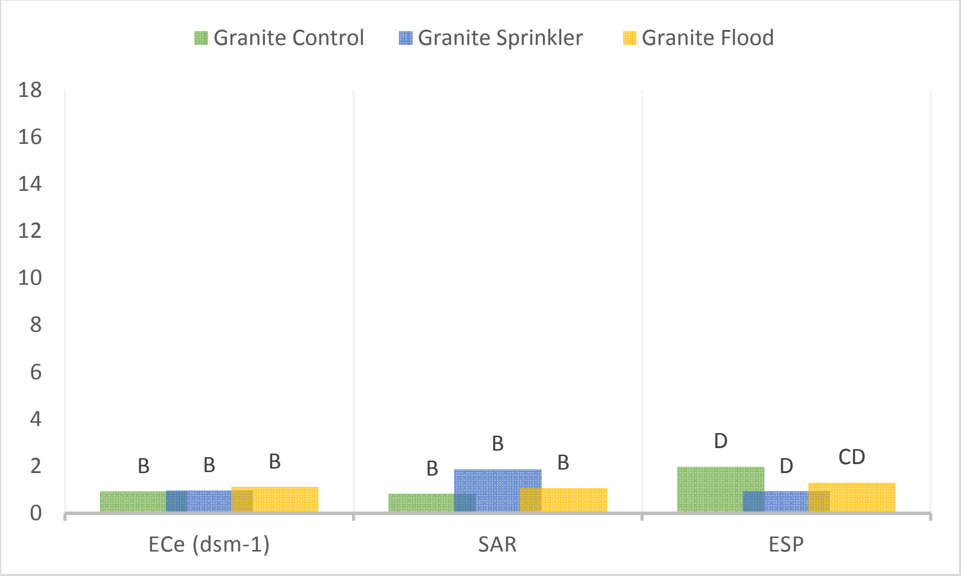


Figure 3.40: Comparison of the soil parameters for Electric Conductivity by extraction (ECe), Sodium Adsorption Ratio (SAR), and Exchangeable Sodium Percent (ESP) for soils derived from granite and granite and by treatment. The different letters are statistically different.

Table 3.7: Soil classification, Electric Conductivity extraction (ECe), Sodium Adsorption (SAR), and Exchangeable Sodium Percent (ESP) (Lal 2006)

Soil Classes	**ECe dSm^{-1}**	**SAR**	**ESP**
Non-saline Non-sodic	<4	<13	<15
Saline	>4	<13	<15
Saline-Sodic	>4	>13	>15
Sodic	<4	>13	>15

Change in pedogenic processes

The general trends in pedogenic processes in both basalt and granite control soils and their directional changes as a function of irrigation are outlined in Table 3.8. Within the basalt control soils, 100% had an active combination of three pedogenic processes: calcification, salinization, and alkalization. Sprinkler irrigation chemically reduced the occurrence of calcification to 40% and only 10% retained the soil properties of the alkalization processes. The process of salinization was no longer detectable in the sampled soils in either sprinkler of flood irrigation. In contrast, flood irrigation results were similar for calcification and alkalization, except 10% retained salinization soil properties.

Only 66% of the granite control pedons exhibited soil properties that classified them as having undergone the process of calcification. Sprinkler and flood irrigation chemically reduced the occurrence of calcification to 28%. No other pedogenic processes were revealed.

Table 3.8: Pedogenic process as outlined by Simonson (1959) for soils derived from, basalt and granite, the number of soils sampled in each treatment types (control, sprinkler and flood), number of pedons that exhibited the processes and the processes type.

Total Pedons Sampled	**Pedons Exhibited Processes**	**Processes Type**
14 - Basalt control Pedons	14	Calcification Salinization Alkalization
10 - Basalt Sprinkler Pedons	4	Calcification
	1	Alkalization
10 - Basalt Flood Pedon	4	Calcification
	1	Alkalization
	1	Salinization
9 - Granite Modal Pedons	6	Calcification
7 - Granite Sprinkler Pedons	2	Calcification
7 - Granite Flood Pedons	2	Calcification

*57 Pedons sampled

3.5 Summary and Conclusions

The objective of this study was to evaluate the influence of sprinkler and flood irrigation, as a function of parent material (basalt and granite) on key soil properties critical to assessing soil degradation. The principal component and the directional change analysis exposed clear differences among the physical, chemical, and biogeochemical properties as a function of parent material. Principal component analysis indicates sand as the dominant physical property. The remaining soil properties (clay, pH, calcium, magnesium, sodium, potassium, chloride, sulfate, soil organic carbon, and calcium carbonate) diverged under sprinkler and flood irrigation and showed differences between basalt and granite. The linear model analysis revealed that clay, soil organic matter, and bulk density are coupled and have similar behavioral patterns and change relative to each other when influenced by sprinkler and flood irrigation.

The directional change from the basalt native soils to the irrigated basalt soils was represented primarily as a reduction in the concentrations among pH, magnesium, sodium, potassium, sulfate, chloride, and soil organic matter. The directional changes from the native to the irrigated granite soils were more variable and occurred among bulk density, pH, calcium, magnesium, sodium, potassium, chloride, sulfate, and calcium carbonate.

The clay enrichment data shows limited accumulations as a result of irrigation practices but the overall change in the amount of soil within the profile increased with sprinkler irrigation on both basalt and granite. Flooded basalt soils had a small increase over sprinkler irrigation, while granite soils had a decrease, suggesting the mass of soil per area is affected by the parent material and irrigation practices.

The mass data for soil organic carbon, nitrogen and the carbon to nitrogen ratio indicates that agriculture practices have improved the concentrations of soil organic carbon but have not made a dramatic difference in the nitrogen levels. Even though nitrogen is a part of the amendments applied to these crops, the accumulation of nitrogen is limited due to texture, the high percent of sand, and the amount of irrigation water applied. These factors contribute to increased nitrogen depletion, which result in the carbon to nitrogen ratio for the controls and treatments being statistically similar.

These findings are significant because they represent diversification in soil properties as a function of parent material and a directional change as a result of agricultural practices. The results demonstrate that calcium, magnesium, sodium, and potassium in soils derived from basalts are proportionally less as a result of cultivated irrigation, due plant uptake, leaching, or loss of residual input. However, there is no evidence these soils are in a state of nutrient imbalance, but rather their soil properties are changing in a definite direction as a function of the land use and time. As an example, the increase in sodium with sprinkler irrigation within granite soil, the amount was not enough to create saline conditions in those cultivated sites. However, it is unclear, in this particular system, the threshold of ion concentrations that would need to be surpassed to exhibit a significant loss in the soils productivity, quality, and function (Barrows 1991, Mayes 2014, and Lal 2006).

Therefore, in addressing the question of degradation, the results provide a solid foundation for the case of resiliency instead of degradation. Irrigated agriculture in the SLV has created an example of how irrigation in a semi-arid region has improved soil conditions relative to the native soils. This was evident in the changes to the sodium, SAR and EC relationships, where the decrease in sodium is due to leaching of salts through predominantly well -drained sandy soils with excellent water quality. The other example is the increase in soil organic matter with flood irrigation in the no till pasture hay grass site, again improving the soil quality and resiliency.

Furthermore, the results highlight the importance in evaluating the physical, chemical, and biogeochemical properties collectively in determining their assemblage as a function of the underlying substrates. These results provide the physical and chemical parameters by which the key indicators can be selected, which are texture, clay content, percent of soil organic matter, sodium, sulfate and chloride ions. These indicators demonstrate that irrigation practices in the San Luis Valley have improved the soil health and show how resilient these agroecosystems are to cultivation when compared to the native soil conditions. This information also provides a new outlook on irrigation in semi-arid regions when the water quality does not contribute to salinity or sodic conditions and the quantity improves the conditions of the soils within row crop production. This information can also be used to construct a matrix from these key indicators to evaluate the impacts of climate change, agricultural practices, and land use change in other semi-arid regions that are being impacted by population growth.

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CHAPTER 4

THE INFLUENCE OF LAND USE ON MICROBIAL BIODIVERSITY OF SOILS WITHIN THE SAN LUIS VALLEY OF COLORADO

4.1 Introduction

Soils contain living biota as well as mineral material and organic matter. They are the manifestation of the combined effects of additions to the ground surface, transformations within the soils, vertical transfers within the soil, and removals from the soil, and it is the interface at which all the environmental components interact, both influencing and responding to external variables (Birkland 1974; Ellis and Mellor 1995). In arid and semi-arid regions, the conditions of soil formations are driven by the mineral composition of the parent material and the intensity and duration of the weathering regime. As a consequence, sand and silt fractions tend to be composed mainly of inherited primary minerals, while clay fractions are dominated by secondary minerals, either formed *in-situ* or transported from other environments (Karathanasis 2007). It is within this complex matrix that the diversity of organisms interacts with one another and with the various plants and animals in the ecosystem forming a complex web of biological activity. The biological composition of soil is dominated by bacteria and fungi that contribute a wide range of essential services to the sustainable function of all ecosystems (FAO 2016).

Soil microorganisms are essential for maintaining terrestrial ecosystems due to their involvement in regulating nutrient cycling and organic matter dynamics. Microbial communities are key indictors in evaluating soil quality and functions because they react to small changes in the soil environment (Jia et al., 2010; Marinari et al., 2006). These qualities have attracted many researches to gauge degradation processes by making use of relevant parameters in soil microbial community composition (Jia et al., 2010).

Long-term agriculture in semi-arid regions contributes to soil degradation globally (Raiesi 2012), which ultimately impacts the soils' ability to provide the services necessary to maintain human civilizations (Steffen et al., 2007). It has been shown that microorganisms drive biogeochemical cycles within soils, and that traditional agricultural practices generally produce significantly poorer soil quality relative to the quality of native or uncultured soils, due to destruction of soil structure and loss of organic matter, leading to modifications in the physical, chemical, and biogeochemical properties, including lower organic C and N contents (Jia et al., 2010; Barrows 1991). This occurs when perennial vegetation are replaced by annual row crops; the results are soil erosion, loss of soil nutrients, and reduction in stored carbon; which can lead to a decrease in soil quality and threatens the continued productivity of the soil and decreased resilience (Barrow 1991; Mayes 2014; Lal 2006;).

Soil microbial communities are affected by soil characteristics, plant species, environmental conditions, and crop-management strategies (Marschner et al., 2001). These combined effects have caused considerable interest in characterizing microbial community composition globally (Zhou 2011). This is reflected in the body of research that has focused on the effects of soil type, texture, organic matter, temperature, moisture, pH, and specific nutrient elements of nitrogen, phosphorus, and potassium on microbial communities (Zhou 2011; Stromberger et al., 2007; Kocyigit 2009; Marinari et al., 2006; Jia et al., 2010; Carmen et al., 2010; Anderson and Domsch 1989). This research also includes the relationships between microbial community composition with chemical and biogeochemical properties as a function of increased salinity or alkalinity in agricultural lands (Pankhurst et al., 2001).

Soils inherit their chemical composition from the parent material from which they are derived. This is especially important in drier regions where parent material has a greater influence on soils properties in the initial stages of soil development (Birkland 1974; Verheye 2008). As a result, the suite of inherited soil properties ultimately determines how soils will respond to land use changes.

A number of approaches have been used to characterize the effects of different agricultural practices on the composition of microbial communities. These approaches include fatty acid analysis, extracellular enzyme assay, and a variety of techniques for analyzing extracted nucleic acids. With each approach the goal is to obtain an impartial “snapshot” of the whole community composition. Despite the fact that each approach has its own limitations, these methods have been used extensively as tools to examine the organization and dynamics of microbial communities in relation to other natural constituents (Pankhurst et al., 2001).

It is well known that microbial communities are key indictors in evaluating soil quality and functions because they react to small changes in the soil environment, specifically changes within the physical, chemical, and biogeochemical cycles. Cultivation has altered the native vegetation which influences the microbial community composition. It has been documented that the reduction of soil organic matter has been directly linked to cultivation, which effects precipitation and modifies soil texture. Honeycutt (1986) demonstrated significant increases in soil organic matter losses with increased precipitation, suggesting higher decomposition and erosion rates. Tiessen et al. (1982), Schimel et al. (1985a), and Burke et al. (1989) documented organic matter losses to be highest in medium textured soils. In addition, decreased carbon and nitrogen contents in arable soils are attributed to a decrease of available substrate to tillage and removal of plant residues (Ananyeva et al., 2008). The effective changes in organic carbon also influences soil pH. Typically, soil pH range is inherited from the mineral composition of parent material. In semi-arid regions the pH range is neutral or alkaline due to less intense weathering and leaching, and the buffering effects of the carbonates. However, conversion of native vegetation to row crops can change the pH after a few years. These changes are caused by the removal of soil minerals when crops are harvested, changes in clay content, erosion of the surface layer, and the effects of nitrogen and sulfur fertilizer, which result in soil acidification (NRCS 2014).

Cultivation also affects the soil temperature through the process of evaporative cooling during the summer months (Williams 2007); changes in soil moisture due to the wetting and drying cycles can create periods of anaerobic conditions and affects gas diffusion and alter soil texture, which results in the loss of aggregate stability and decrease water holding capacity (Raiesi 2012). Our objectives were to distinguish microbial community composition by parent material and treatment, and to identify the key soil properties (physical, chemical, and biogeochemical) that reflect the changes in microbial community composition and soil degradation.

Our study employed the ester-linked fatty acid methyl ester (EL-FAMEs) method to detect differences between the microbial communities on two different parent materials, basalt and granite, within three treatments, control or native site, irrigated agriculture sprinkler and flood. The long-term agricultural practices in the San Luis Valley (SLV), in south central Colorado, provided the opportunity for improving our understanding of these interactions. Our objectives were to distinguish microbial community composition by parent material and land use, and to identify the key soil properties (physical, chemical, and biogeochemical) that reflect the changes in microbial community composition that may influence soil degradation.

4.2 Experimental Design

Study Area

The SLV is located in the South Central part of Colorado. The climate is arid and characterized by cold winters, moderate summers, abundant sunshine, and strong prevailing winds in the south to northeast direction. The valley is a high elevation desert; the base elevation is 2147 m. The Sangre de Cristo mountain range flanks the east side of the valley and the San Juan Mountains on the west. These mountains range in elevations of up to 2449 to 4372 m, creating a rain shadow effect, which reduces the amount of precipitation that reaches the valley floor. The 30-year climate normal from 1971-2000 indicates the mean annual precipitation is < 228 mm annually, and most of the valley receives 177 mm annually and the potential evapotranspiration exceeds 1016 mm (Emery et al., 2013). The surrounding mountains, however, receive 762-1219 mm annually, which is the major source of water for the area (McNoldy and Doesken, 2007). The average annual temperature is approximately 5°C, with extremes of -45°C and 32°C (Emery et al., 2013).

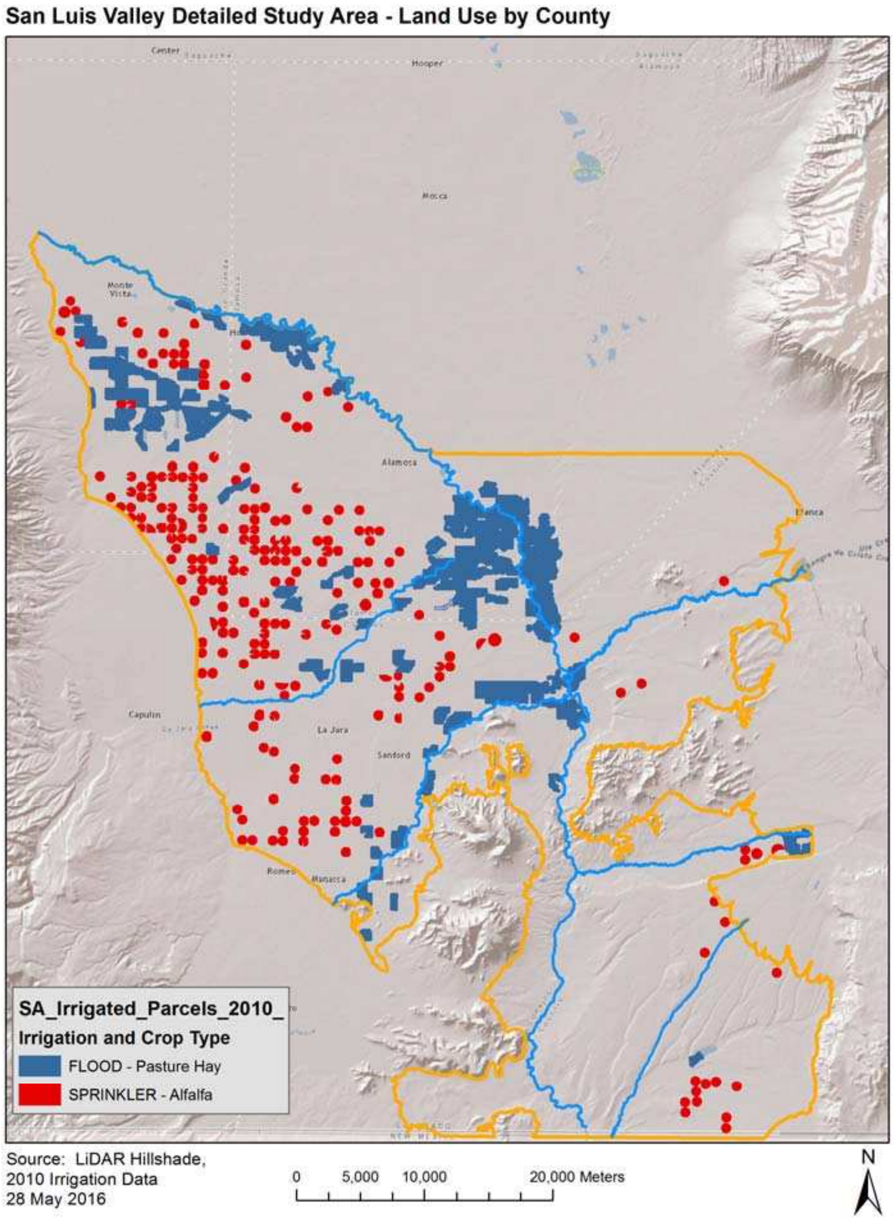
The geological setting of the SLV consists mainly of mafic (e.g. basalt) and intermediate igneous rocks (e.g. granite). The San Juan Mountains consist mainly of volcanic flows, tuffs and breccias, which contain relative low amounts of silicon, sodium aluminum, potassium and relatively high amounts of iron, magnesium and calcium (Emery, 2013). The Sangre de Cristo Mountains are composed of felsic rocks (e.g. granite) and igneous, metamorphic, and sedimentary rocks contain relatively high amounts of silicon, sodium aluminum, potassium and relatively low amounts of iron, magnesium and calcium. The valley is underlain by as much as 3657 meters of clay, silt, sand, gravel, and interbedded volcanic flows and tuffs. The alluvial deposits are coarse and permeable near the bordering mountains and grade to fine grained, less permeable deposits toward the center of the valley (Emery, 2013). Therefore, the crystalline structure of the basalt and granite dictates the limitations of the weathering process and the subsequent development of the soil profile.

Identification and location of field sites

Our experimental design utilized the state factor approach (Jenny 1994), and we focused on examining parent material and land use (e.g. soil forming factor Humans) as the key conditioning variables affecting soil properties in the SLV, and minimized differences in other variables (e.g. climate, relief, time) across the study area to locate field sites. A Geographic Information Systems (GIS) was used to identify prospective locations where 1) cultivation practices had not occurred (control sites), 2) sprinkler irrigation sites, and 3) flood irrigation sites on the soil parent materials of interest, and a combination of geospatial analyses, interviews with land owners and managers and our own field observations to select sites. Areas of interest were located by intersecting the 2010 common land units, 2011 LiDAR 10m hill shade, slope and elevation, NDVI vegetation data, Colorado Geological Survey and USGS geology maps, and ESRI™ base map imagery. We restricted prospective areas for field sites to the southern central part of the San Luis Valley which encompasses Alamosa, Rio Grande, Conejos, and Costilla counties. To control for relief an elevation gradient constrained study area to the valley floor, between 2147 – 2351 m, and slope to less than 2%. These analyses isolated the portions of the valley where both parent material-land use combinations could be located (Figure 4.1).

Figure 4.1: The San Luis Valley as outlined by the LiDAR foot print and the study area as outlined in orange. The study area is 2.14 km^2 - 1.26 km^2 on the west .87 km^2 on the east, with respect to the Rio Grande River.

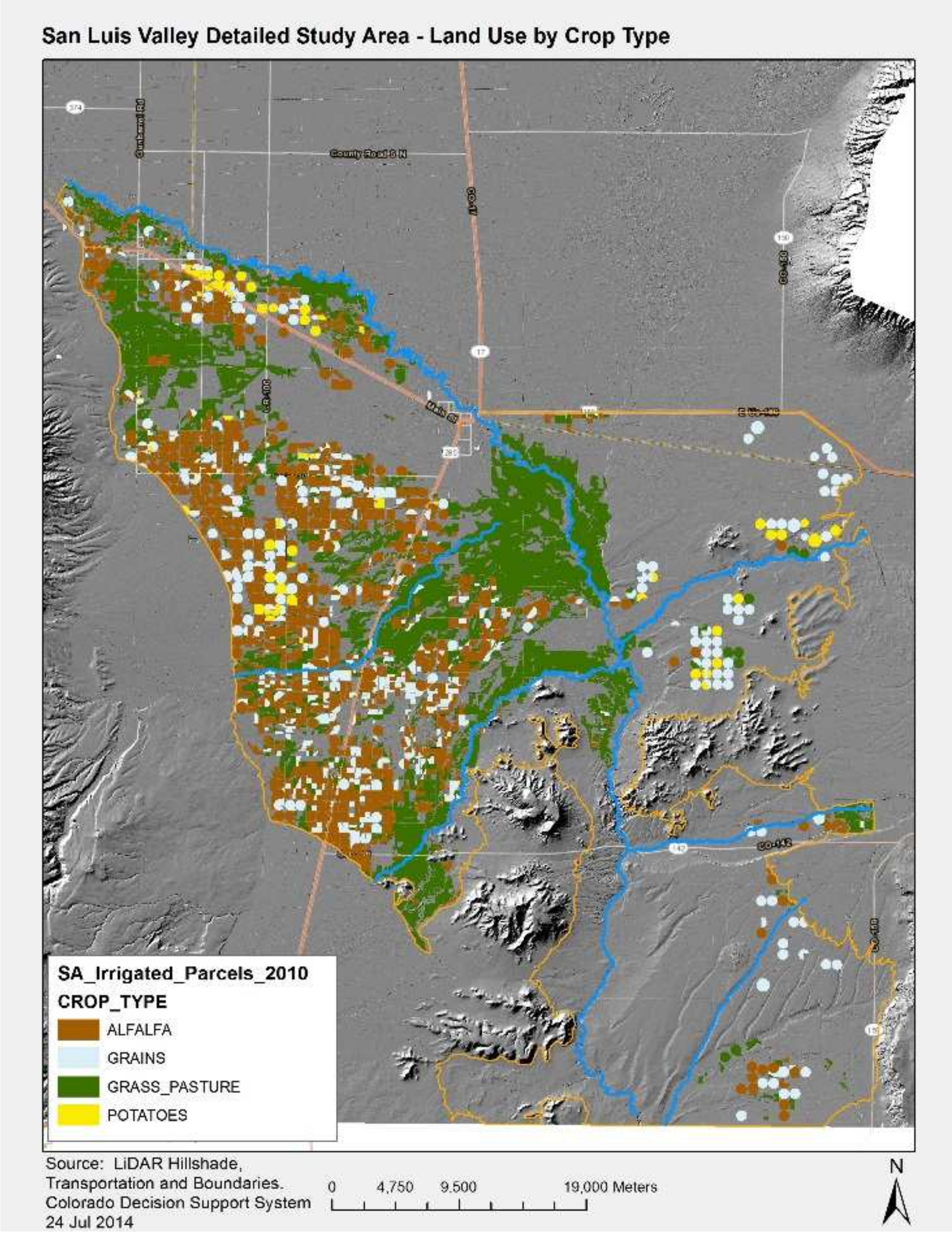
Soils derived from basalt were located in Rio Grande County, Alamosa County, and Conejos County, CO, west of the Rio Grande River. Soil derived from granite were located in Costilla County, CO east of the Rio Grande River. Soil derived from basalt and granite have the same three major land uses - sprinkler and flood irrigation treatments and controls (non-cultivated sites). Figure 4.2 depicts the distribution of the sprinkler and flood parcels by crop type within the study area.



Source: LiDAR Hillshade,
2010 Irrigation Data
28 May 2016

Figure 4.2: The distribution of land use and cropping systems as of 2010 by county within the study area as outlined in orange.

The dominate crops for each treatment are: alfalfa for basalt and granite sprinkler treatment, pasture hay grasses for basalt flood treatment; alfalfa for granite flood treatment. Figure 4.3 depicts the distribution of crops within the study area.



San Luis Valley Detailed Study Area - Land Use by Crop Type

Source: LiDAR Hillshade, Transportation and Boundaries. Colorado Decision Support System
24 Jul 2014

Figure 4.3: Distribution of cropping systems as of 2010 within the SLV study area as outlined in orange.

The dominate vegetation for the majority of the basalt controls was Greasewood (*Sarcobatus vermiculatus*), greene's rabbitbrush (*Chrysothamnus greenei*), salt grass (*Distichlis spicata* (L.), and blue gramma (*Bouteloua gracilis*) (Dixon 2012). Site observation indicated mature vegetation with no pervious recorded evidence of agriculture practices and confirmed by the land owners. The dominate vegetation for the majority of the granite controls were Greasewood (*Sarcobatus vermiculatus*) and salt grass (*Distichlis spicata* (L.) (Dixon 2012). Site observation indicated mature vegetation with no pervious recorded evidence of agriculture practices and confirmed by the land owners.

Within the study area the primary source for irrigation water is surface and subsurface. Most irrigation began in the late 1800's by means of flood irrigation from surface water from the Alamosa, Conejos, and Rio Grande Rivers, and the Trinchera and Culebra Creeks. The amount of additional water applied during the growing season under flood irrigation ranges from 153-1226 mm typically from 1 April to 31 July. Center pivot irrigation comprises the majority of the irrigation practice since its implementation in the mid 1960's, delivering between 304 – 914 mm of additional water during the 6 month growing season.

Soil samples for microbial analysis were selected from areas that were directly influenced by agricultural practices, as well as control sites with no known history of cultivation. Due to accessibility, 14 control and 20 treatment sites were sampled from soils derived from basalt, and 9 control and 14 treatment sites were sampled from soils derived from granite (Table 4.1). Figure 4.4 illustrates the locations and distribution of the sampled soils by the treatment type (control, sprinkler, and flood), and by parent material (basalt west of the Rio Grande River and granite east of the Rio Grande River).

Table 4.1: The sampling design for the number of microbial samples by parent material and treatment.

Number of Microbial Samples	Parent Material	Treatment
14	Basalt	Control
10	Basalt	Sprinkler
10	Basalt	Flood
9	Granite	Control
7	Granite	Sprinkler
7	Granite	Flood

57 microbial samples were used for analysis

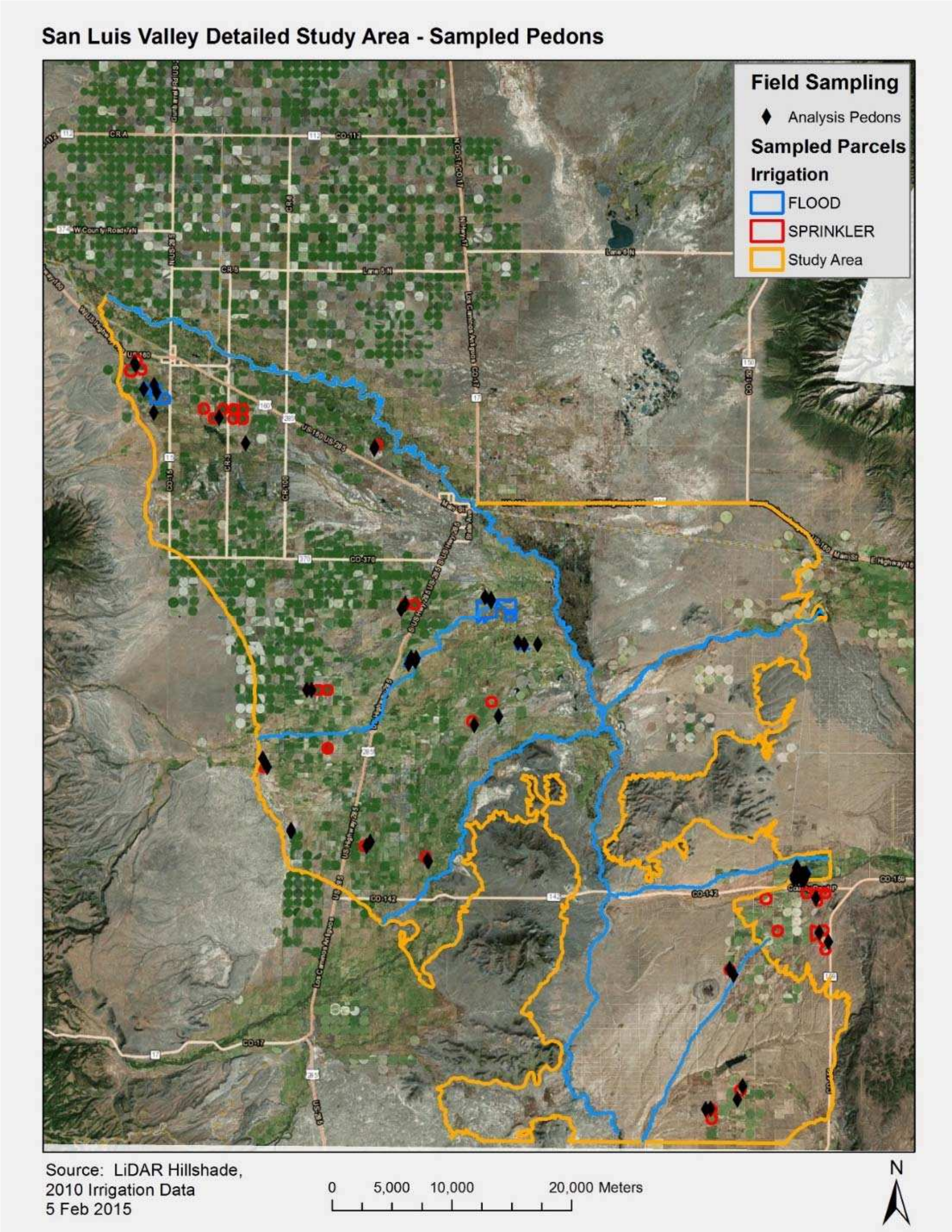


Figure 4.4: The distribution of the available treatment sites and the pedons selected for analysis within the SLV study area as outlined in orange.

4.3 Methods

Field Methods

Soil samples were collected from 0-15 cm depth using a balling spade on each treatment type, control, sprinkler, and flood from each parent material (basalt and granite) and soil characteristics were taken from the A and B horizons where applicable and averaged. Each soil sample was placed in a cooler on ice and transported to a freezer for storage. The plant community composition of the valley during the time the controls were collected included sagebrush, greasewood, rubber rabbit brush, Greene's rabbit brush, grassland, and shrub-steppe communities (Dixon 2012). The dominant crop type was alfalfa in the sprinkler treatments, with one exception treatment was in a barely rotation, and the crop was pasture hay grasses for basalt flood treatments and alfalfa for granite flood treatments. Sampling of research sites occurred between Aug – Nov 2014.

Soil Microbial analysis

Microbial community structure was characterized by the extraction and analysis of ester-linked fatty acid methyl ester (EL-FAMEs) from soil, as described by Schutter and Dick (2000). In brief, 5 g soil were extracted with 0.2 M KOH during a 37°C, hour-long incubation with periodic mixing, followed by addition of 1.0 M acetic acid to neutralize the pH of the tube contents. EL-FAMEs were portioned into an organic phase by addition of hexane, which was removed from the aqueous phase after centrifugation at 480 x g for 20 min at 4°C. An internal standard (32 nmols C19:0) was added to each EL-FAME sample before the hexane solvent was evaporated off with nitrogen. EL-FAMEs were re-suspended in hexane and samples were analyzed by using the Agilent 5973N Mass Selective Detector Interface to a 6890 gas chromatograph with a 7683 automatic liquid sampler by the Colorado State University Central Instrument Facility. The samples peaks were identified using the FAME37 and BAME from Sigma-Aldrich and the mass spectral matching with NIST library. Biomarkers of specific functional groups were assigned according to Schutter and Dick (2000). Bacterial markers were the sum of *i*14:0, *i*15:0, *a*15:0, *i*16:0, 16:1ω7c, *i*17:0, *a*17:0, 17:0 cy, and 19:0 cy. The EL-FAMEs 18:2ω6,9c and 18:1ω9 were used as the indicators for fungi, and 16:1ω5c for arbuscular mycorrhizal (AM) fungi. The ratio between 17:0 cy and its metabolic precursor 16:1ω7c and 19:0 cy and its metabolic precursor 18:1ω7c were used as stress indicators (Stromberger et al., 2007).

Statistical Analyses

The total number of samples collected from soils derived from basalt and granite encompassed 34 samples from the two treatments (sprinkler and flood) and 23 samples from the control soils. Soil EL-FAME data were normalized to mol% and analyzed by principal components analysis (PCA) with variance-covariance matrix using PC-ORD statistical package (MjM Software, Gleneden Beach, OR, 1999). Multi-response permutation procedure (MRPP) was used to compared community structure by parent material (basalt and granite) and by treatment (control, sprinkler, and flood), with a significance of $P \leq 0.05$, using PC-ORD statistical package.

Principal component analysis (PCA) was used to evaluate the variance of the microbial responses; biomass, fungi:bacteria ratio, stress 1 (17:0 cy : 16:1 ω7c), stress 2 (19:0 cy : 18:1 ω7c), and AM Fungi (16:1ω5c) constrained by parent material (basalt and granite), treatment (control, sprinkler, and flood), and soil properties within the three groups (physical, chemical, and biogeochemical) using R (R Core Team 2015).

Analysis of variance (ANOVA) test were performed on the untransformed microbial responses data: biomass (sum of bacterial and fungal EL-FAMEs), fungi:bacteria ratio, stress 1 (17:0 cy : 16:1 ω7c), stress 2 (19:0 cy : 18:1 ω7c), and AM Fungi (16:1ω5c) with parent material (basalt and granite) and treatment (control, sprinkler, and flood) using R aov and TukeyHSD procedure (R Core Team 2015) when ANOVA showed a significance of $P \leq 0.05$.

Pearson correlation coefficients were calculated among the following responses; biomass, fungi:bacteria ratio, stress 1 (17:0 cy : 16:1 ω7c), stress 2 (19:0 cy : 18:1 ω7c), and

AM Fungi (16:1ω5c) with parent material (basalt and granite) and treatment (control, sprinkler, and flood) using the cor.test package (R Core Team 2015).

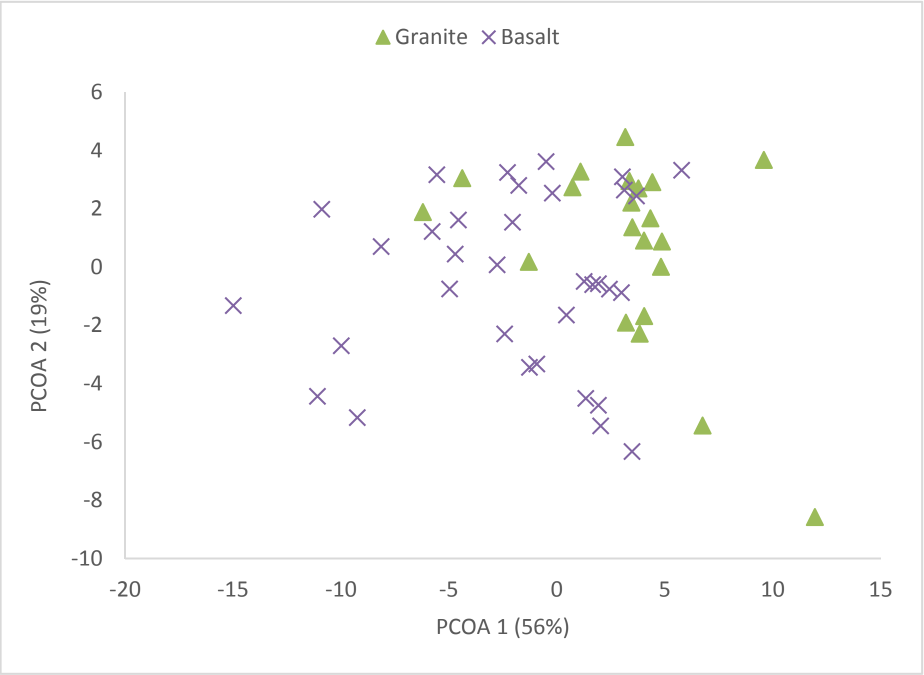
A linear model was determined to described the microbial responses; biomass, fungi:bacteria ratio, stress 1 (17:0 cy : 16:1 ω7c), stress 2 (19:0 cy : 18:1 ω7c), and AM Fungi (16:1ω5c) with parent material (basalt and granite) and treatment (control, sprinkler, and flood) using the foreign package (R Core Team 2015) and the multcomp package (Toreston et al., 2008). The 95% confidence intervals were calculated using the aforementioned packages.

4.4 Results

Principal Component Analysis EL-FAME Data

Principal component analysis was used to explain the variation in the data set containing 24 EL-FAMEs as influenced by parent material (basalt and granite) and treatment (control, sprinkler, and flood). The microbial communities clustered by parent material (Figure 4.5A) as well as by treatment (Figure 4.5B). PCoA 1 explained 56% and PCoA 2 explained 19%, for a total of 75% of the variation of these data were explained Table 4.2 presetn eigenvector coeficients of EL-FAMEs. Large, positive coefficients indicate EL-FAMEs that are enriched with microbial communities located on the positive side of PCoA axis. Large, negative coefficients indicate EL-FAMEs that are enriched with microbial communities found on the negative side of the PCoA axis (Figures 4.5 A and B).

A)



B)

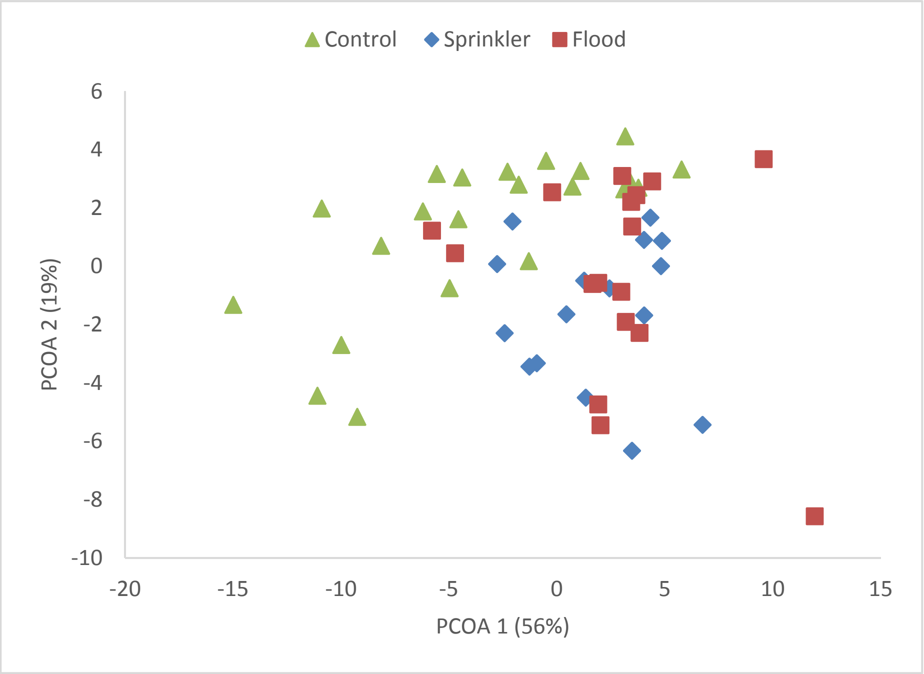


Figure 4.5: Principal components analysis of microbial community EL-FAMEs from soils (0-15 cm depth) on (A) basalt and granite parent material and (B) treatment, modal, sprinkler, and flood. The percent variance explained by each principal component analysis (PCoA) is shown in parentheses.

Ester-linked FAMEs with most positive eigenvectors coefficients for PCoA 1 in Figure 4.5 A and B were 16:0, 16:1ω5c, 18:0, 14:0 (Table 4.2). In contrast, EL-FAMEs with negative eigenvector coefficients for PCoA 1, and thus more associated with communities to the left of PCoA 1, included iso-C15, iso-C16, 10Me-C16, anteiso-C15:0, anteiso-C17:0, 16:1ω7c, 18:1ω9c, iso-C17m, and 19:0cy (Table 4.2).

Table 4.2: Microbial EL-FAMEs with the greatest eigenvector coefficients for principal component (PCoA) axes 1 and 2 as shown in Figure 4.5.

El-FAME	**PCoA 1**	**PCoA 2**
iso-C15:0	-1.0419	0.0728
iso-C16:0	-0.6955	0.6519
10Me-C16:0	-0.6671	0.3697
anteiso-C15:0	-0.5193	0.1128
anteiso-C17:0	-0.4407	0.2183
C16:1ω7	-0.403	0.137
C18:1ω9	-0.4028	-0.0288
iso-C17:0	-0.393	-0.0288
cy-C19:0	-0.3681	-0.0125
C18:1ω7	-0.1734	-0.4143
cis-C17:0	-0.1571	0.0816
10Me-C18	-0.1367	0.066
10Me-C17	-0.1338	0.1575
iso-C14:0	-0.1212	-0.0109
cy-C17:0	-0.1207	0.0406
C17:0	-0.0567	0.0628
C12:0	-0.0374	0.0751
C13:0	-0.0235	0.0131
C18:2ω6,9	-0.0053	-0.2708
C15:0	0.038	0.0823
C14:0	0.1618	0.6388
C18:0	0.2816	0.3891
C16:1ω5	0.4273	-2.7865
C16:0	4.9887	0.3834

Multi-Response Permutation Procedure (MRPP)

Multi-Response Permutation Procedure (MRPP) defined the groups based on the categorical conditioning variables of parent material and treatment. The results were based on the Sorensen distance measure, and pair wise comparisons were made on the untransformed data set. The MRPP results for parent material (basalt and granite n=55) were significant ($P < 0.05$; A=0.055); meaning that microbial communities structure differed based on parent material. Similarly, microbial community structure differed according to treatment (control, sprinkler, and flood) ($P<0.05$; A=0.096).

Physical, chemical, and biogeochemical soil properties associated with the microbial samples

The soil properties derived from basalt and granite where grouped into three categories physical, chemical, and biogeochemical and three treatment type's control, sprinkler and flood irrigation. Soil characteristics are described in Table 4.3.

The pH ranged from neutral to alkaline in both parent materials, and soil subject to irrigation was also in the neutral to alkaline range (7.3 to 8.3). The concentrations for calcium, magnesium, sodium, potassium, sulfate, chloride, calcium carbonate, and organic carbon were greater in the basalt control soils and lower under basalt sprinkler and flood treatments. In contrast, the same soil properties in the granite control soils were of much lower concentration than the basalt, and varied by treatment type. Lower concentrations were measured in the granite sprinkler treatment for calcium, magnesium, potassium, and calcium carbonate, and greater concentrations were measured in sodium, chloride, and organic carbon. Granite soils subjected to flood had greater values in all of the ion concentrations (Table 4.3).

Table 4.3: Physical and chemical properties by average and standard deviation, that vary by parent material and treatment. Physical property Sand (%). Chemical properties pHw, cations and anion by meq/L - calcium (Ca), magnesium (Mg), sodium (Na), potassium (K), sulfate (SO_4), and chloride (Cl). Biogeochemical properties percent calcium carbonate (CaCO3) and percent organic carbon (OC).

Parent Material &Treatment		**Sand %**	**pHw**	**Ca (meq/L)**	**Mg (meq/L)**	**Na (meq/L)**	**K (meq/L)**	**Cl (meq/L)**	**SO_4 (meq/L)**	**$CaCO_3$ %**	**OC %**
Control For Basalt Sprinkler	Avg	53.0	8.3	19.6	13.1	215.8	30.0	108.4	232.7	8.4	1.1
	StDev	15.6	0.7	27.4	22.7	376.2	66.2	231.1	317.9	8.3	1.0
Basalt Sprinkler	Avg	59.4	7.5	11.6	3.3	3.1	0.6	0.3	10.0	3.8	1.0
	StDev	17.0	0.3	9.1	1.5	4.7	0.5	0.2	12.3	3.6	0.4
Granite Control for Sprinkler	Avg	65.5	7.5	3.6	1.2	0.4	0.4	0.1	0.6	2.2	0.6
	StDev	7.2	0.6	0.6	0.5	0.4	0.3	0.0	1.0	3.2	0.3
Granite Sprinkler	Avg	61.7	7.5	3.5	1.1	0.7	0.1	0.2	0.6	1.9	0.7
	StDev	7.7	0.4	1.0	0.3	0.2	0.0	0.1	0.2	2.5	0.2
Basalt Control for Flood	Avg	58.0	8.1	32.3	45.5	127.0	18.2	37.1	208.4	5.1	5.7
	StDev	5.0	0.4	4.1	52.2	90.5	18.2	63.0	165.7	3.5	4.8
Basalt Flood	Avg	44.2	7.5	18.0	8.8	23.9	1.3	4.4	60.6	4.6	3.8
	StDev	21.3	0.8	13.1	7.0	33.6	2.3	7.8	57.8	4.5	3.9
Granite Control for flood	Avg	68.0	7.4	2.5	1.0	0.3	0.2	0.2	0.3	0.2	0.7
	StDev	0.0	0.3	0.6	0.2	0.1	0.0	0.0	0.0	0.1	0.0
Granite Flood	Avge	67.7	7.3	5.3	3.0	1.4	0.6	0.5	0.7	0.4	1.6
	StDev	9.4	0.3	2.4	0.5	2.6	0.4	0.6	0.5	0.4	0.6

Principal Component Analysis - Microbial Response with Parent Material, Treatment, and Soil Properties

The principal components analysis (PCoA) was performed on the microbial responses as a function of parent material, treatment, and soil properties (Figure 4.6). This figure displays the clustering pattern of the microbial communities. The same analysis was performed to show the relationships and correlations of factors that influenced the microbial community structure patterns (Figure 4.7). PCoA 1 explained 30% and PCoA 2 explained 24%, for a total of 54% of the variation in these data explained. Large, positive coefficients indicated the dominate variable are located on the positive side of PCoA axes. Large, negative coefficients indicate the dominant variable are located on the negative side of the PCoA axis.

The variables with the positive eigenvector coefficients for PCoA 1 in Figure 4.6 and 4.7, were biomass, fungi:bacteria ratio, stress 1 ratio (17:0 cy and its precursor 16:1ω7c), AM fungi (16:1ω5c), and sand. In contrast, the variables with negative eigenvector coefficients for PCoA 1, and more associated to the left of PCoA 1, were stress 2 1(9:0 cy : 18:1ω7c), pHw, calcium carbonate, organic carbon, calcium, magnesium, sodium, potassium, chloride, and sulfate (Table 4.4).

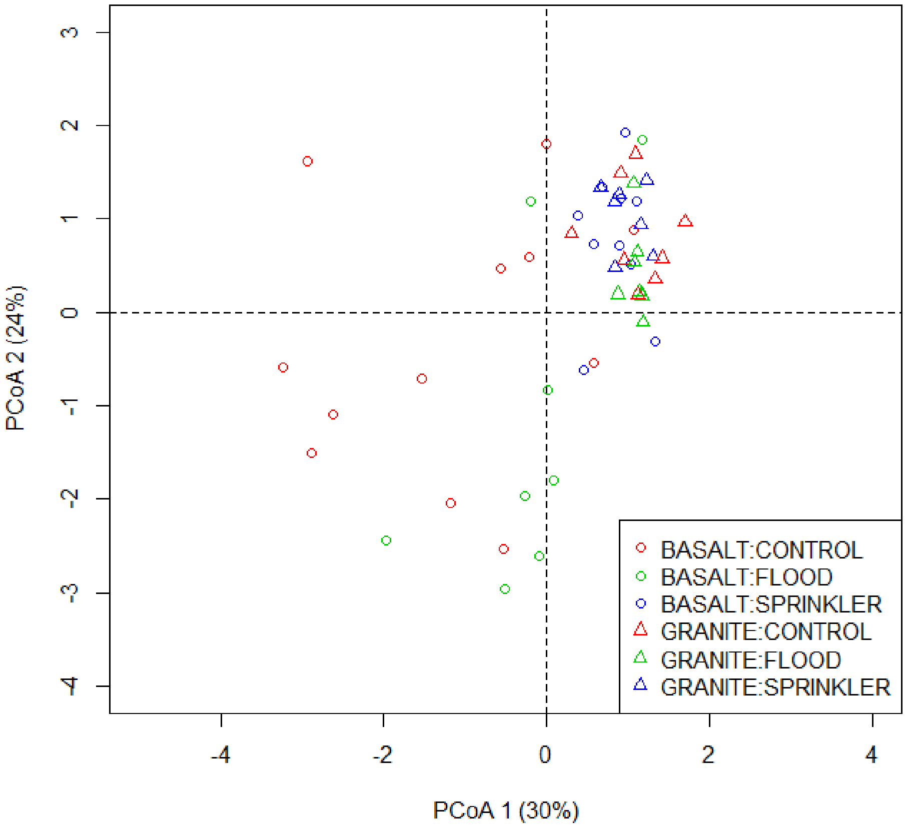


Figure 4.6: Principal components analysis of microbial community responses (biomass, Fungi:Bacteria ratio, stress 1 ratio (17:0 cy : 16:1ω7c), stress 2 ratio (19:0 cy : 18:1ω7c), and Arbuscular Mycorrhizal (AM) Fungi 16:1ω5c; as function of parent material, basalt and granite, and treatment, control, sprinkler, and flood. The percent variance explained by each principal component (PCoA) is shown in parentheses.

These data also revealed clustering of certain soil properties within the treatments and parent materials (basalt and granite). The soil properties that clustered were calcium and magnesium, and sodium, potassium, and chloride (Figure 4.7 and Table 4.4).

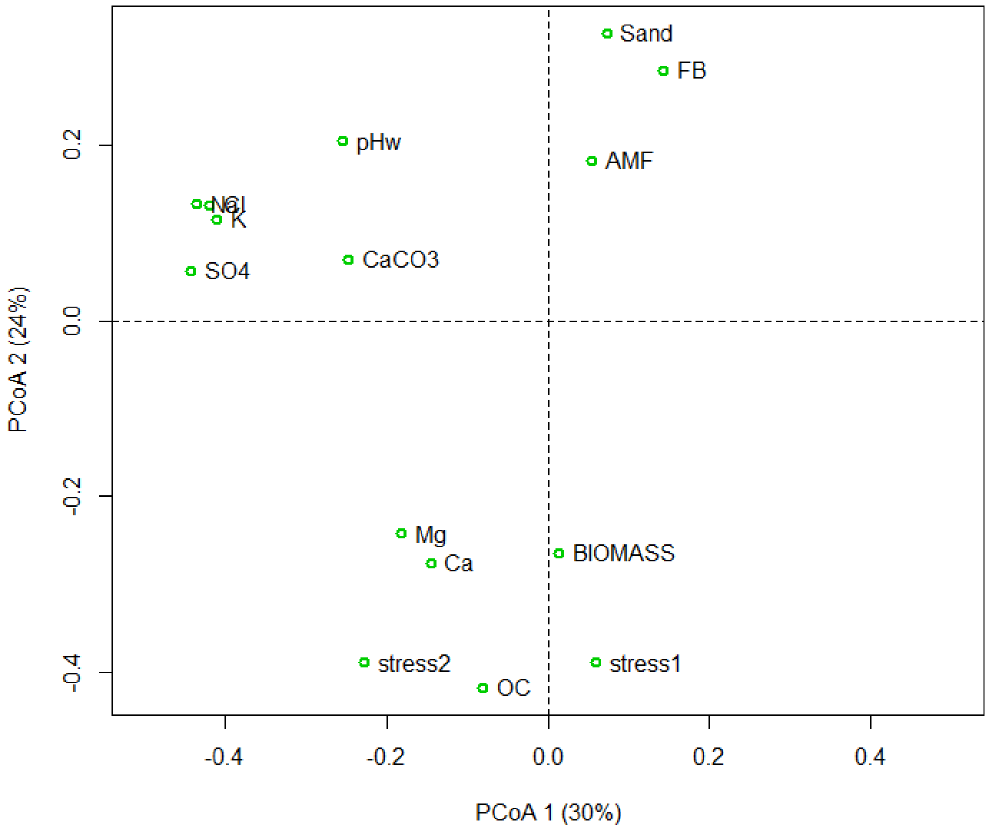


Figure 4.7: Principal components analysis of microbial community responses as a function of soil properties. Microbial community responses labels are Biomass, Fungi:Bacteria ratio (F:B), stress1 ratio (17:0 cy : 16:1ω7c), stress2 ratio (19:0 cy : 18:1ω7c), and Arbuscular Mycorrhizal (AM) Fungi 16:1ω5c. Soil properties physical – sand; chemical – pHw, calcium (Ca), magnesium (Mg), sodium (Na), potassium (K), sulfate (SO4), and chloride (Cl); biogeochemical – calcium carbonate (CaCO3) and organic carbon (OC). The percent variance explained by each principal component (PCoA) is shown in parentheses.

Table 4.4: Microbial responses variables, biomass, fungi-to-bacteria, stress 1, stress 2, arbuscular mycorrhizal (AM) fungi with the soil properties variables pHw, calcium carbonate (CaCO3), organic carbon (OC), calcium (Ca), magnesium (Mg), sodium (Na), potassium (K), chloride (Cl), and sulfate (SO4). The greatest eigenvector coefficients for principal component (PCoA) axes 1 and 2 as shown in Figure 4.8

Microbial and Soil Properties	**PCoA 1**	**PCoA 2**
Biomass	0.01	-0.26
Fungi:Bacteria	0.14	0.28
Stress1 (17:0cy: 16:1ω7c)	0.06	-0.39
Stress2 (19:0cy: 18:1ω7c)	-0.23	-0.39
AM Fungi (16:1ω5c)	0.05	0.18
Sand	0.07	0.33
pHw	-0.25	0.20
Calcium Carbonate ($CaCO_3$)	-0.25	0.07
Soil Organic Carbon (OC)	-0.08	-0.42
Calcium (Ca)	-0.15	-0.28
Magnesium (Mg)	-0.18	-0.24
Sodium (Na)	-0.43	0.13
Potassium (K)	-0.41	0.12
Chloride (Cl)	-0.42	0.13
Sulfate (SO_4)	-0.44	0.06

Analysis of Variance (ANVOA)

The analysis of variance test was performed to assess the statistical difference within the individual microbial responses, as a factor of parent material and irrigation treatments ($P < 0.05$). The interaction effect of parent material and irrigation treatment was statistically significant.

Microbial Total Biomass

The total microbial biomass EL-FAMEs was determined in each parent material (basalt and granite) and treatment (control, sprinkler, and flood) and evaluated based on the concentration of total EL-FAMEs (nmol g^{-1} soil). The total microbial biomass was significantly higher in is soils derived from basalt and subjected to flood irrigation (Figure 4.8).

The mean biomass in soils derived from basalt within the control was 862 nmols g^{-1} soil, and in soils derived from granite the mean biomass was 588 nmols g^{-1} soil, which equates to a

32% greater biomass concentration in the soil derived from basalt than granite. The treatment influences on biomass in soils derived from basalt were seen as a reduction of 18% (729 nmols g^{-1} soil) under sprinkler irrigation and an increase of 71% (1472 nmols g^{-1} soil) under flood irrigation. The same treatments in soils derived from granite also showed a 4% (567 nmols g^{-1} soil) reduction under sprinkler irrigation and a 35% (911 nmols g^{-1} soil) increase under flood irrigation. The result indicate the primary difference observed were between parent materials and the secondary effect was the directional change under treatment type, however there was limited variation between granite control and granite sprinkler.

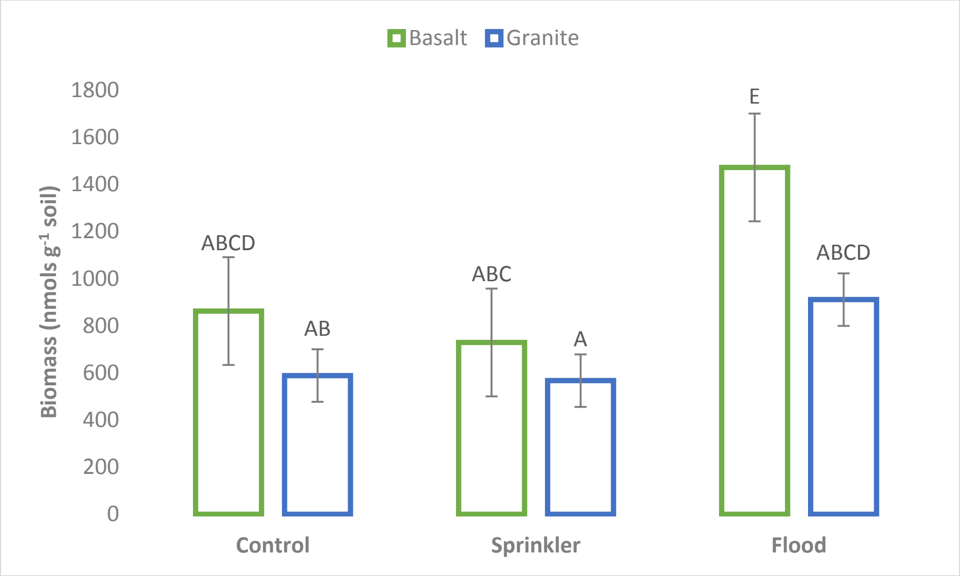


Figure 4.8: The effects of parent material and irrigation treatments on microbial biomass, as measured by total EL-FAME concentrations in nmols g^{-1} soil. Comparisons were made on the basis of analysis of variance (ANOVA) n=57 microbial samples extracted from soils (0-15 cm). Bars represent the standard error. Bars labeled with different letters are significantly different (*P* < 0.05).

Fungi:Bacteria Ratio

The ratio of fungal EL-FAMEs to bacterial EL-FAMEs was determined in each parent material (basalt and granite) and treatment (control, sprinkler, and flood) Figure 4.9. The results were not statistical different between parent material and treatment.

The mean ratio in the control basalt soils was 0.17 and 0.22 for the control granite soils, which equates to a 26% higher ratio in soil derived from granite than basalt. The treatment influences on the fungi-to-bacterial ratio in soils derived from basalt was a 28% increase (0.22) under sprinkler irrigations and a 16% reduction (0.15) under flood irrigation. The same treatments on soils derived from granite showed a reduction of 23% (0.17) under sprinkler and flood irrigation. The result indicate the primary difference observed were between parent materials and the secondary effect was the directional change under treatment type, however there was limited variation between both parent materials and treatment types, the ratio was proportionally the same among all groups.

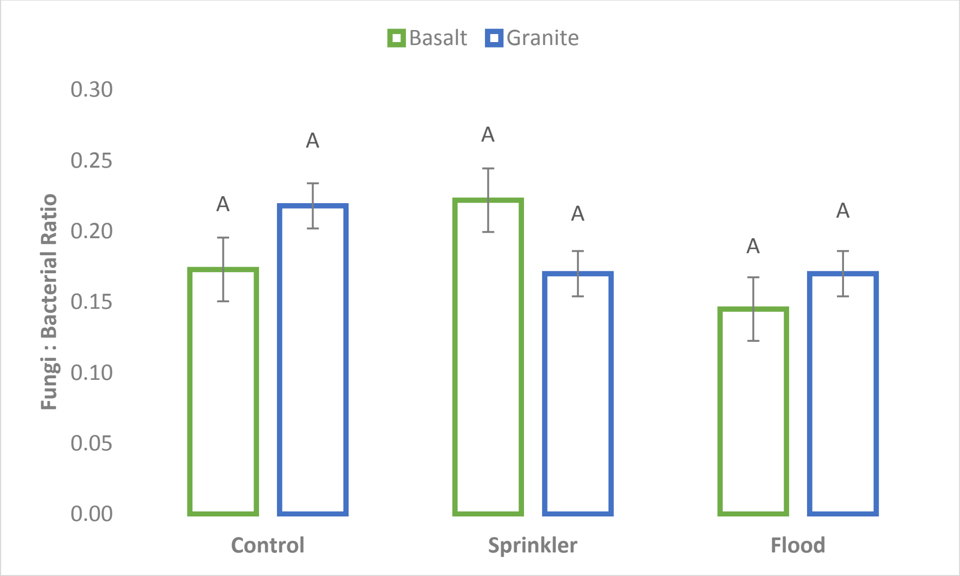


Figure 4.9: The effects of parent material and irrigation treatments of the fungal-to-bacteria ratio EL-FAME biomarkers. Comparisons were made on the basis of analysis of variance (ANOVA) n=57 microbial samples extracted from soils (0-15 cm). Bars represent the standard error. There were no significant differences among means.

Stress 1 Ratio (17:0 cy : 16:1 ω7c)

The ratio of EL-FAMEs 17:0 cy to its precursor 16:1ω7c, an indicator of stress among Gram-negative bacteria, was determined in each parent material (basalt and granite) and treatment (control, sprinkler, and flood) Figure 4.10. The interaction of parent material and irrigation treatment was statistically significant. The stress ratio of 17:0 cy-to-16:1ω7c was significantly higher in flooded soil from basalt parent material than in any other soil.

The mean ratio in the control basalt soils was 0.23 and 0.26 for in the control granite soil, which equates to a 13% higher stress ratio in soil derived from granite than basalt. The treatment influences on the stress 1 ratio in soils derived from basalt showed a 15% reduction (0.20) under sprinkler irrigations and a 74% increase (0.40) under flood irrigation. The same treatments on soils derived from granite showed a reduction of 36% (0.17) under sprinkler and a 6% (0.24) reduction under flood irrigation. The result indicates similarities difference between parent materials and the treatment types. The only significant directional change was under flood irrigation within basalt soils; however, there were similar variation between granite control and granite flood.

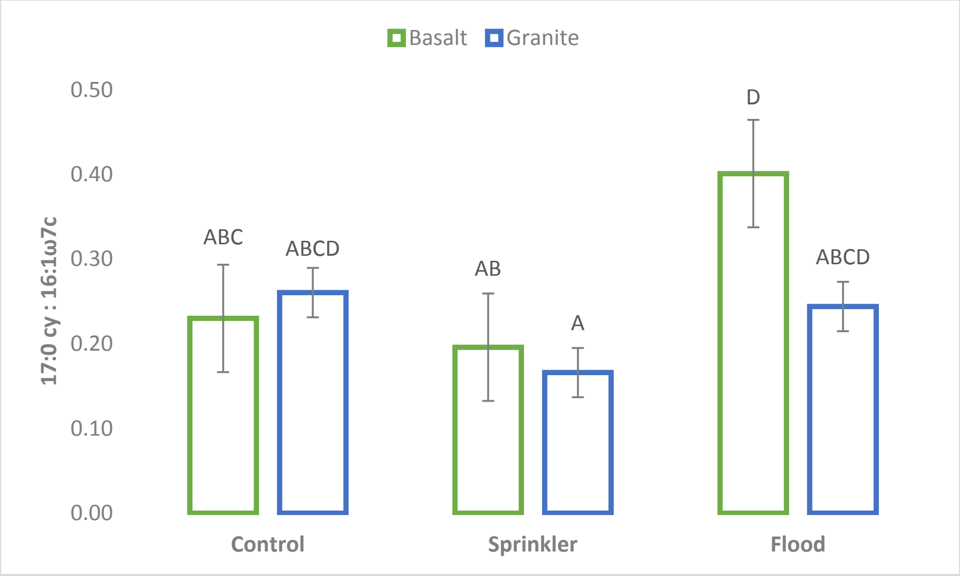


Figure 4.10: The effects of parent material and irrigation treatments on the ratio 17:0 cy to its precursor 16:1ω7c. Comparisons were made on the basis of analysis of variance (ANOVA) n=57 microbial samples extracted from soils (0-15 cm). Bars represent the standard error. Bars labeled with different letters are significantly different (*P* < 0.05).

Stress 2 Ratio (19:0 cy : 18:1 ω7c)

The ratio of EL-FAMEs 19:0 cy to its precursor 18:1ω7c, an indicator of stress among Gram-negative bacteria, was determined in each parent material (basalt and granite) and treatment (control, sprinkler, and flood) Figure 4.11. The interaction of parent material and irrigation treatment was statistically significant. The stress ratio of 19:0 cy-to-18:1ω7c was significantly higher in flooded soil from basalt parent material than in any other soil.

The mean ratio in the control basalt soils was 0.43 and 0.11 for the control granite soil, which equates to a 300% higher stress ratio in soil derived from basalt than granite. The treatment influences on the stress 2 ratio in soils derived from basalt showed a 64% reduction (0.15) under sprinkler irrigations and a 23% increase (0.53) under flood irrigation. The same treatments on soils derived from granite showed a reduction of 33% (0.07) under sprinkler and a 28% (0.14) increase under flood irrigation. The result indicate the primary difference observed were between parent materials and the secondary effect was the directional change under treatment type, especially between basalt control and basalt sprinkler. In contrast, basalt control and flood were similar. All of the treatments under granite had similar responses.

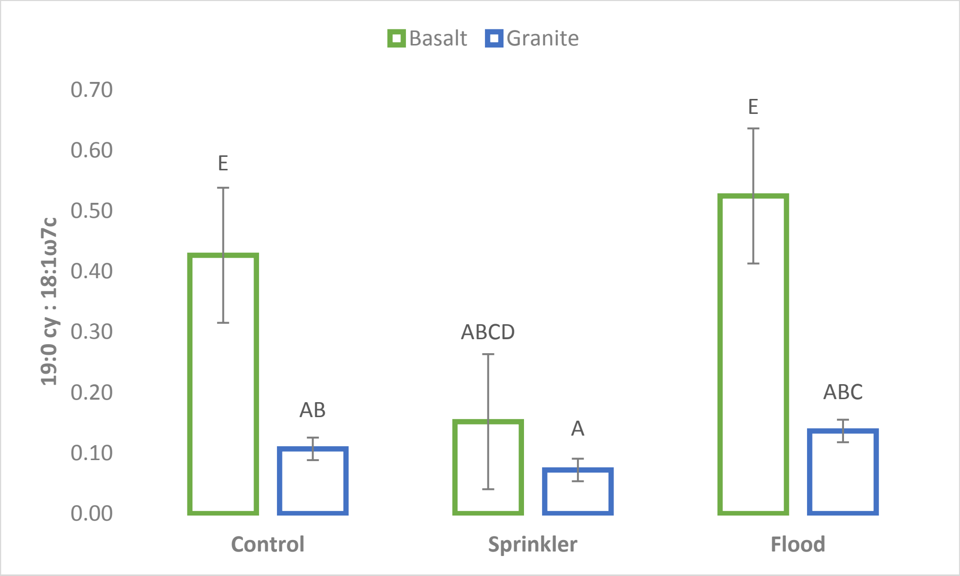


Figure 4.11: The effects of parent material and irrigation treatments of the ratio 19:0 cy to its precursor 18:1ω7c. Comparisons were made on the basis of analysis of variance (ANOVA) n=57 microbial samples extracted from soils (0-15 cm). Bars represent the standard error. Bars labeled with different letters are significantly different ($P < 0.05$).

Arbuscular Mycorrhizal Fungus (16:1ω5c)

The Arbuscular Mycorrhizal (AM) Fungus biomarker 16:1ω5c (nmols g^{-1} of dry) was determined in each parent material (basalt and granite) and treatment (control, sprinkler, and flood) Figure 4.12. The total microbial biomass was significantly higher in is soils derived from basalt and granite and subjected to sprinkler and flood irrigation.

The mean AM Fungi in the control soils derived from basalt was 0.12 nmols g^{-1} dry soil and 0.07 nmols g^{-1} of dry soil in granite, which equates to a 38% greater AM Fungi concentration in the soil derived from basalt than granite. The treatment influences on AM Fungi in soils derived from basalt were seen as an increase of 97% (0.24 nmols g^{-1} of dry soil) under sprinkler irrigation and 34% (0.16 nmols g^{-1} dry soil) under flood irrigation. The same treatments in soils derived from granite also showed a 160% (0.19 nmols g^{-1} dry soil) increase under sprinkler irrigation and a 200% (0.22 nmols g^{-1} dry soil) increase under flood irrigation.

The result indicate the primary difference observed were among treatment types and parent material was a secondary response. The directional change was primarily under irrigation practices.

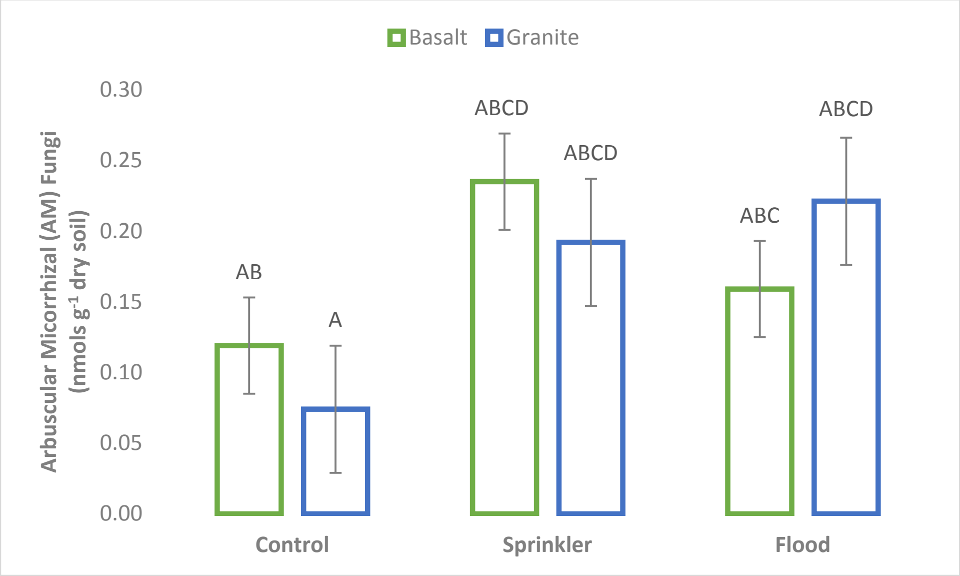


Figure 4.12: The effects of parent material and irrigation treatments of Arbuscular Mycorrhizal (AM) Fungi 16:1ω5c nmols g^{-1} dry soil. Comparisons were made on the basis of analysis of variance (ANOVA) n=57 microbial samples extracted from soils (0-15 cm). Bars represent the standard error. Bars labeled with different letters are significantly different ($P > 0.05$).

Microbial Responses as a function of Parent Material, Treatment, and Soil Properties

Correlation Analysis

The Pearson's correlation analyse was performed to assess the strength of a linear relationship between the microbial responses (total biomass, fungi-to-bacteria ratio, two stress responses ratios among Gram-negative bacteria, and arbuscular mycorrhizal fungi) and the soil properties (% sand; pH; extractable Ca, Mg, Na, K, SO_4, Cl in milliequivalents/liter (meq/L), %

$CaCO_3$, and % soil organic C) as a factor of parent material (basalt and granite) and treatment (control, sprinkler, and flood) ($P < 0.05$).

Linear Model Soil Properties

To further analyze the relationship between microbial responses and the same soil properties from Chapter 3, the linear model was used to evaluate the interactions of parent material (basalt and granite) and treatments (control, sprinkler and flood) with the five microbial communities (total biomass, bacteria to fungi, stress ratio's and the AM Fungi). The linear model assessed the sensitivity of the microbial communities to changes in the soil properties from their current steady state conditions for soils derived from basalt and granite and subjected to sprinkler and flood treatments. The input data values were taken from EL-FAME analysis and the soil analysis; the model provided a predicted response for each microbial EL-FAME community to an increase in the soil properties by one unit of measurement (e.g. 1 percent or 1 meq/L), within each combination of parent material and treatment. The predicted values are either positive or negative and used to assess the behavior of the five microbial communities: total biomass, fungi-to-bacteria ratio, two stress responses ratios among Gram-negative bacteria, and arbuscular mycorrhizal fungi.

The data consist of 23 controls (14 basalt and 9 granite) and 34 treatments (17 sprinkler and 17 flood) in all six categories (basalt control, basalt sprinkler, basalt flood, granite control, granite sprinkler, and granite flood) and 10 soil properties (% sand; pH; extractable Ca, Mg, Na, K, SO_4, Cl in milliequivalents/liter (meq/L), % $CaCO_3$, and % soil organic C).

Total Biomass

The correlation of biomass to each soil properties was determined for each parent material (basalt and granite) and treatment (control, sprinkler, and flood) Table 4.5 and Table 4.6. The correlations that were statistically significant are highlighted in red in each table.

The correlations coefficients between biomass and soils properties within the basalt control were sulfate as negatively correlated and organic carbon as positively correlated. The positively correlated coefficients with basalt flood were calcium, magnesium, chloride, and sulfate (Table 4.5).

The positive correlation coefficients between biomass and soil properties with in granite control were magnesium, sodium, chloride, and sulfate. The negatively correlated coefficients within granite sprinkler were magnesium and organic carbon. The positive correlated coefficient within granite flood was organic carbon (Table 4.6).

The correlations seem to differ primarily between the parent materials with treatment types as the secondary response. The biomass correlations shift depend on treatment type relative to the control, often to different soil properties. Basalt flood treatment has more correlations where sprinkler had no correlations. Granite control had more correlations and shifted to less under both sprinkler and flood.

Table 4.5: Correlation analysis for total Biomass for each soil property physical – sand; chemical – pHw, calcium (Ca), magnesium (Mg), sodium (Na), potassium (K), sulfate (SO_4), and chloride (Cl); biogeochemical – calcium carbonate (CaCO3) % and organic carbon (OC) % and combination of parent material (basalt) and treatment (control, sprinkler, and flood). Pearson's correlation coefficient *($P<.05$).*

Total Biomass	**Basalt Control**		**Basalt Sprinkler**		**Basalt Flood**	
Soil Properties	**Pearson**	***P value***	**Pearson**	***P value***	**Pearson**	***P value***
Sand	-0.89	0.76	-0.15	0.68	0.42	0.23
pHw	-0.39	0.16	-0.01	0.97	0.35	0.32
Calcium (Ca)	0.27	0.35	-0.31	0.23	0.64	0.04
Magnesium (Mg)	0.15	0.61	-0.18	0.49	0.66	0.04
Sodium (Na)	-0.43	0.12	0.19	0.48	0.54	0.11
Potassium (K)	-0.29	0.31	0.01	0.98	0.47	0.17
Chloride (Cl)	-0.38	0.19	0.27	0.30	0.61	0.06
Sulfate (SO_4)	-0.47	0.09	-0.23	0.37	0.65	0.04
Calcium Carbonate ($CaCO_3$) %	-0.36	0.21	-0.10	0.70	0.23	0.53
Soil Organic Carbon (OC) %	0.49	0.07	0.04	0.89	-0.14	0.69

Table 4.6: Correlation analysis for total Biomass for each soil property physical – sand; chemical pHw, calcium (Ca), magnesium (Mg), sodium (Na), potassium (K), sulfate (SO_4), and chloride (Cl); biogeochemical – calcium carbonate (CaCO3) % and organic carbon (OC) % and combination of parent material (granite) and treatment (control, sprinkler, and flood). Pearson's correlation coefficient *(P<.05).*

Total Biomass	**Granite Control**		**Granite Sprinkler**		**Granite Flood**	
Soil Properties	**Pearson**	***P value***	**Pearson**	***P value***	**Pearson**	***P value***
Sand	-0.48	0.23	-0.03	0.96	0.42	0.35
pHw	-0.12	0.78	-0.16	0.72	0.27	0.56
Calcium (Ca)	0.23	0.58	-0.33	0.47	0.66	0.11
Magnesium (Mg)	0.87	0.01	-0.91	0.00	0.28	0.55
Sodium (Na)	0.74	0.03	-0.44	0.31	0.24	0.61
Potassium (K)	-0.10	0.81	-0.59	0.16	0.52	0.23
Chloride (Cl)	0.68	0.06	0.00	0.99	-0.66	0.11
Sulfate (SO_4)	0.77	0.03	0.06	0.91	0.33	0.47
Calcium Carbonate ($CaCO_3$) %	-0.35	0.39	-0.23	0.62	0.14	0.76
Soil Organic Carbon (OC) %	-0.32	0.45	-0.73	0.06	0.69	0.09

The linear model predicts how sensitive biomass (nmols g^{-1} soil) is to increases among the soil properties within the six groups (Figure 4.13). Changes in biomass +/- 500 nmols g^{-1} soils will be described. Biomass in granite control soils showed a negative response with organic carbon and a positive response with magnesium, sodium, and chloride. Biomass in granite sprinkler had a negative response with organic carbon, magnesium, sodium, and potassium. In soils derived from basalt, biomass responses to changes in soil properties was well below the 500 nmols g^{-1} soils description threshold, indicating limited sensitivity levels.

The primary influence in biomass sensitive was between the parent materials, more sensitive to changes in soils properties derived from granite, and limited sensitive to changes in soil properties derived from basalt.

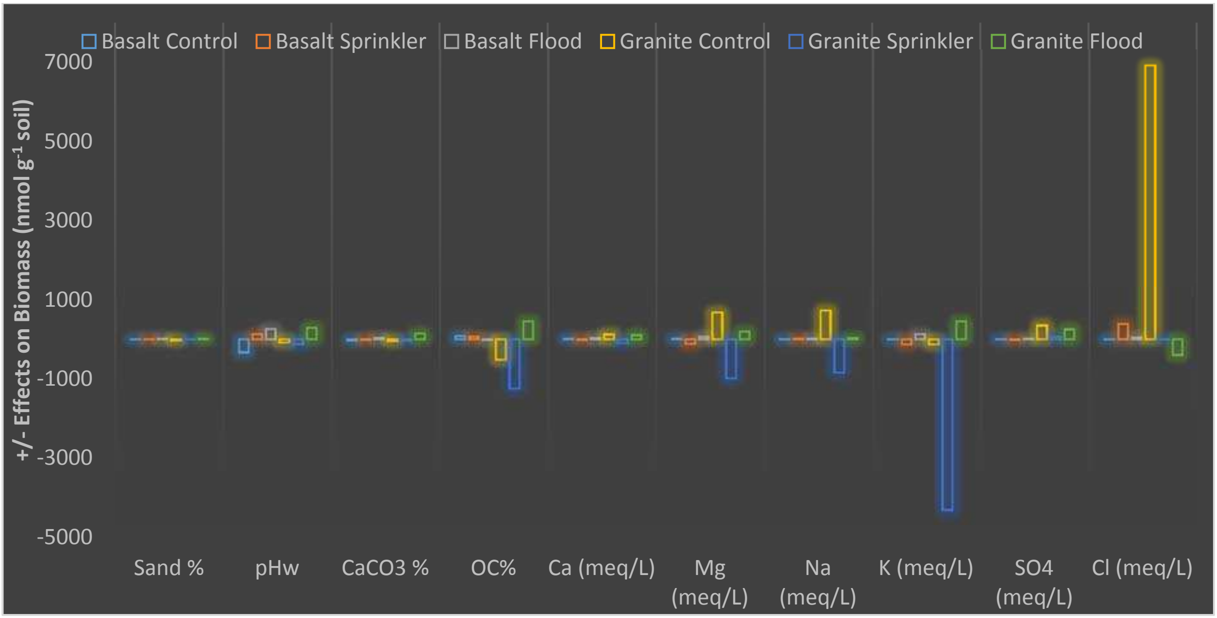


Figure 4.13: The linear model results for biomass sensitivity when influenced by changes in the physical – sand; chemical – pHw, calcium (Ca), magnesium (Mg), sodium (Na), potassium (K), sulfate (SO_4), and chloride (Cl); biogeochemical – calcium carbonate (CaCO3) % and organic carbon (OC) % soil properties and their distribution among the six parent material x treatment combinations; basalt control, basalt sprinkler, basalt flood, granite control, granite sprinkler, and granite flood. Predictions were made within the 95% confidence interval.

Fungi:Bacteria Ratio

The correlation with the fungi-to-bacteria ratio for each soil properties was determined in each parent material (basalt and granite) and treatment (control, sprinkler, and flood) Table 4.7 and Table 4.8. The correlations that were statistically significant are highlighted in red in each table.

The correlations coefficients between the fungi-to-bacteria ratio and soils properties within the basalt sprinkler was, positively correlated with sodium. The positively correlated coefficients with basalt flood was sand (Table 4.7).

The negatively correlation coefficients between fungi-to-bacteria ratio and soil properties within granite sprinkler were magnesium and sodium. The positively correlated coefficients within granite flood were calcium, magnesium, and organic carbon and negatively correlated with chloride (Table 4.8).

The correlations seem be similar primarily between the parent materials with treatment types as the secondary response. The fungi-to-bacteria correlations shift depend on treatment type relative to the control, often to different soil properties. Basalt control resulted in no correlations with the fungi-to-bacteria ratio however, one correlation occurred within basalt sprinkler and basalt flood. Granite control resulted in no correlations, and increased in correlations under sprinkler and flood.

Table 4.7: Correlation analysis for the fungi to bacteria ratio for each soil property physical – sand; chemical – pHw, calcium (Ca), magnesium (Mg), sodium (Na), potassium (K), sulfate (SO_4), and chloride (Cl); biogeochemical – calcium carbonate (CaCO3) % and organic carbon (OC) % and combination of parent material (basalt) and treatment (control, sprinkler, and flood). Pearson's correlation coefficient *($P<0.05$).*

Fungi:Bacteria Ratio	**Basalt Control**		**Basalt Sprinkler**		**Basalt Flood**	
Soil Properties	**Pearson**	***P value***	**Pearson**	***P value***	**Pearson**	***P value***
Sand	-0.16	0.58	0.28	0.44	0.64	0.05
pHw	-0.21	0.47	0.12	0.64	0.55	0.10
Calcium (Ca)	-0.10	0.74	0.00	0.99	-0.37	0.29
Magnesium (Mg)	-0.05	0.10	0.08	0.76	-0.30	0.40
Sodium (Na)	-0.23	0.43	0.77	0.00	0.02	0.95
Potassium (K)	-0.19	0.51	0.39	0.12	-0.10	0.79
Chloride (Cl)	-0.16	0.60	0.19	0.47	-0.02	0.94
Sulfate (SO_4)	-0.35	0.22	0.27	0.29	-0.20	0.59
Calcium Carbonate ($CaCO_3$) %	0.12	0.68	0.04	0.89	0.41	0.23
Soil Organic Carbon (OC) %	-0.35	0.22	0.02	0.94	-0.44	0.20

Table 4.8: Correlation analysis for the fungi to bacteria ratio for each soil property physical – sand; chemical – pHw, calcium (Ca), magnesium (Mg), sodium (Na), potassium (K), sulfate (SO_4), and chloride (Cl); biogeochemical – calcium carbonate (CaCO3) % and organic carbon (OC) % and combination of parent material (granite) and treatment (control, sprinkler, and flood). Pearson's correlation coefficient *($P<0.05$).*

Fungi:Bacteria Ratio	**Granite Control**		**Granite Sprinkler**		**Granite Flood**	
Soil Properties	**Pearson**	***P value***	**Pearson**	***P value***	**Pearson**	***P value***
Sand	0.26	0.53	0.32	0.49	0.14	0.77
pHw	-0.38	0.35	-0.24	0.61	0.66	0.10
Calcium (Ca)	0.19	0.65	-0.24	0.60	0.78	0.04
Magnesium (Mg)	0.09	0.83	-0.87	0.01	0.79	0.03
Sodium (Na)	-0.08	0.86	-0.76	0.05	0.43	0.34
Potassium (K)	0.30	0.46	-0.52	0.23	0.52	0.23
Chloride (Cl)	0.30	0.47	0.13	0.79	-0.70	0.08
Sulfate (SO_4)	-0.11	0.80	0.28	0.54	0.65	0.11
Calcium Carbonate ($CaCO_3$) %	-0.21	0.62	-0.11	0.81	0.47	0.28
Soil Organic Carbon (OC) %	0.44	0.27	-0.57	0.18	0.87	0.01

The linear model predicted how sensitive the fungi-to-bacteria ratio is to increases among the soil properties within the six groups (Figure 4.14). Changes to the fungi-to-bacteria ratio above +/- 0.10 will be described. Fungi-to-bacteria in granite control soils showed a positive response with organic carbon and chloride. Granite sprinkler negative responses were magnesium, sodium, and potassium. Granite flood had a positive response to pH, organic carbon, calcium carbonate, magnesium, potassium, and sulfate and a negative response to chloride.

The primary influence in fungi to bacteria sensitive was between the parent materials, more sensitive in changes in soils properties derived from granite, and limited sensitive to changes in soil properties derived from basalt.

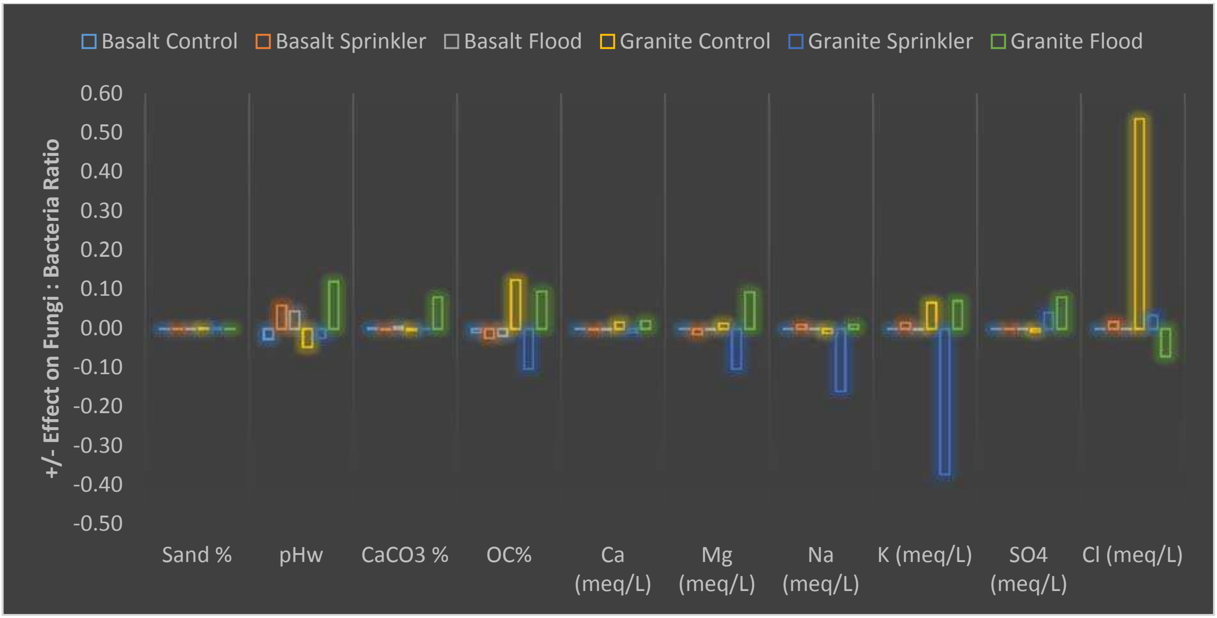


Figure 4.14: The linear model results for the fungi to bacteria ratio sensitivity when influenced by changes in the physical – sand; chemical – pHw, calcium (Ca), magnesium (Mg), sodium (Na), potassium (K), sulfate (SO_4), and chloride (Cl); biogeochemical – calcium carbonate (CaCO3) % and organic carbon (OC) % soil properties and their distribution among the six parent material x treatment combinations; basalt control, basalt sprinkler, basalt flood, granite control, granite sprinkler, and granite flood. Predictions were made within the 95% confidence interval.

Stress Ratio 1 (17:0 cy : 16:1 ω7c)

The correlation with 17:0 cy to its precursor 16:1ω7c, an indicator of stress among Gram-negative bacteria, ratio to each soil properties was determined in each parent material (basalt and granite) and treatment (control, sprinkler, and flood) Table 4.9 and Table 4.10. The correlations that are statistically significant are highlighted in red in each table.

The correlations coefficients between 17:0 cy to its precursor 16:1ω7c and soils properties within the basalt control were negatively correlated with sodium, potassium, chloride, and sulfate. The negative correlated coefficients with basalt sprinkler was sand and the postive coefficient was organic carbon. The negative coefficients with basalt flood were pH and calcium carbonate (Table 4.9).

The negatively correlation coefficient between 17:0 cy to its precursor 16:1ω7c and soil properties within granite control was calcium. The positively correlated coefficient within granite sprinkler was pH. The negatively correlated coefficients within granite flood were calcium and a positive response with chloride and organic carbon (Table 4.10).

The correlations seem be similar primarily between the parent materials and treatment types as the secondary response. The 17:0 cy to its precursor 16:1ω7c correlations shift depend on treatment type relative to the control, often to different soil properties. Basalt control had more correlations and the number of correlations reduced under basalt sprinkler and basalt flood. Granite control, granite sprinkler each had one correlations as granite flood increased in correlations.

Table 4.9: Correlation analysis for the 17:0 cy : 16:1 ω7c Stress Ratio 1 for each soil property physical – sand; chemical – pHw, calcium (Ca), magnesium (Mg), sodium (Na), potassium (K), sulfate (SO_4), and chloride (Cl); biogeochemical – calcium carbonate (CaCO3) % and organic carbon (OC) % and combination of parent material (basalt) and treatment (control, sprinkler, and flood). Pearson's correlation coefficient *($P<0.05$).*

Stress Ratio 1 (17:0 cy : 16:1 ω7c)	**Basalt Control**		**Basalt Sprinkler**		**Basalt Flood**	
Soil Properties	**Pearson**	***P value***	**Pearson**	***P value***	**Pearson**	***P value***
Sand	-0.16	0.58	-0.76	0.01	-0.53	0.12
pHw	-0.36	0.20	0.04	0.87	-0.82	0.00
Calcium (Ca)	-0.02	0.94	-0.03	0.92	0.18	0.62
Magnesium (Mg)	0.20	0.50	-0.22	0.40	-0.02	0.96
Sodium (Na)	-0.63	0.02	0.01	0.98	-0.30	0.40
Potassium (K)	-0.60	0.02	0.21	0.42	-0.20	0.59
Chloride (Cl)	-0.65	0.01	0.26	0.30	0.07	0.84
Sulfate (SO_4)	-0.58	0.03	-0.31	0.22	-0.13	0.72
Calcium Carbonate ($CaCO_3$) %	-0.47	0.09	0.29	0.26	-0.70	0.03
Soil Organic Carbon (OC) %	0.45	0.11	0.63	0.01	0.44	0.20

Table 4.10: Correlation analysis for the 17:0 cy : 16:1 ω7c Stress Ratio 1 for each soil property physical – sand; chemical – pHw, calcium (Ca), magnesium (Mg), sodium (Na), potassium (K), sulfate (SO_4), and chloride (Cl); biogeochemical – calcium carbonate (CaCO3) % and organic carbon (OC) % and combination of parent material (granite) and treatment (control, sprinkler, and flood). Pearson's correlation coefficient *($P<0.05$).*

Stress Ratio 1 **(17:0 cy : 16:1 ω7c)**	**Granite Control**		**Granite Sprinkler**		**Granite Flood**	
Soil Properties	**Pearson**	***P value***	**Pearson**	***P value***	**Pearson**	***P value***
Sand	0.23	0.58	-0.12	0.79	0.13	0.78
pHw	-0.28	0.49	0.72	0.07	-0.26	0.57
Calcium (Ca)	-0.75	0.03	0.57	0.18	-0.83	0.02
Magnesium (Mg)	-0.27	0.52	0.67	0.10	-0.36	0.43
Sodium (Na)	-0.27	0.51	0.67	0.10	0.03	0.95
Potassium (K)	-0.16	0.70	0.22	0.64	-0.64	0.12
Chloride (Cl)	0.49	0.22	0.14	0.76	0.99	0.00
Sulfate (SO_4)	-0.26	0.53	-0.42	0.35	-0.24	0.61
Calcium Carbonate ($CaCO_3$) %	-0.17	0.69	0.46	0.30	-0.16	0.73
Soil Organic Carbon (OC) %	0.25	0.55	-0.07	0.87	-0.89	0.01

The linear model predicted how sensitive the 17:0 cy to its precursor 16:1ω7c ratio is to increases among the soil properties within the six groups (Figure 4.15). Changes in 17:0 cy to its precursor 16:1ω7c above +/- 0.10 will be described. 17:0 cy to its precursor 16:1ω7c within basalt sprinkler has a positive response with organic carbon. Basalt flood had a negative response with pH. In soils derived from granite, within the control 17:0 cy to its precursor 16:1ω7c responses positively to organic carbon and chloride, and negatively to calcium. Granite sprinkler positively responses were magnesium, sodium, and potassium. Granite flood had a negative response with organic carbon and potassium, and a positive response with chloride (Figure 4.15).

The primary influence in 17:0 cy to its precursor 16:1ω7c sensitive was between the parent materials, more sensitive in changes in soils properties derived from granite, and limited sensitive to changes in soil properties derived from basalt.

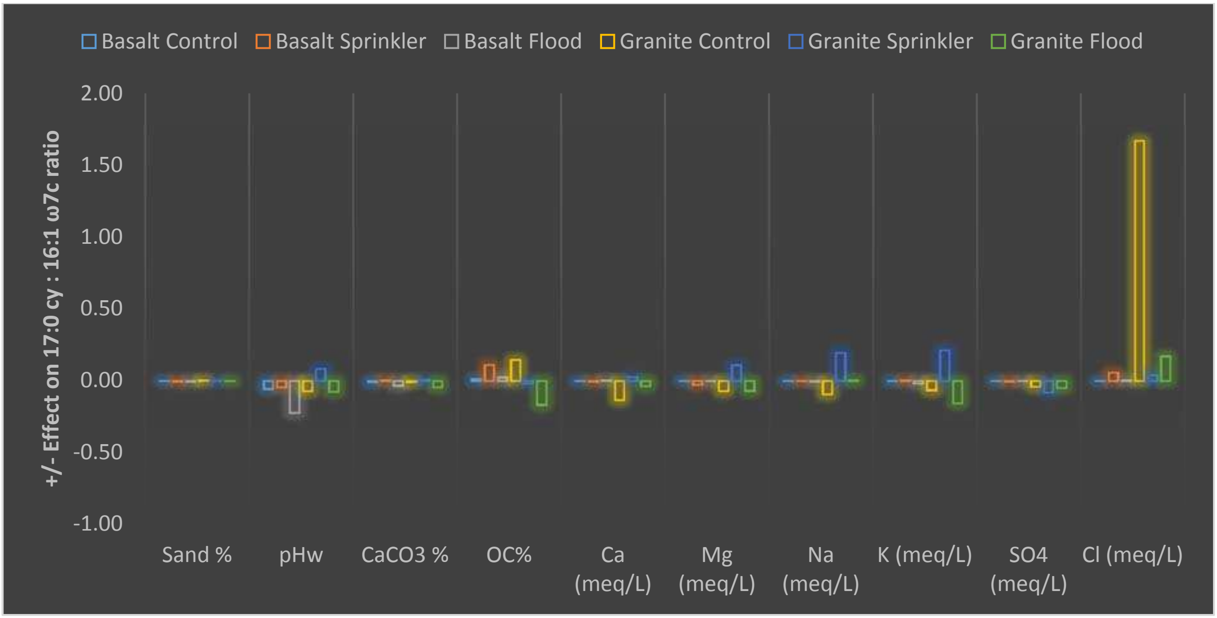


Figure 4.15: The linear model results for the 17:0 cy : 16:1 ω7c Stress Ratio 1 sensitivity when influenced by changes in the physical – sand; chemical – pHw, calcium (Ca), magnesium (Mg), sodium (Na), potassium (K), sulfate (SO_4), and chloride (Cl); biogeochemical – calcium carbonate (CaCO3) % and organic carbon (OC) % soil properties and their distribution among the six parent material x treatment combinations; basalt control, basalt sprinkler, basalt flood, granite control, granite sprinkler, and granite flood. Predictions were made within the 95% confidence interval.

Stress Ratio 2 (19:0 cy : 18:1 ω7c)

The correlation with 19:0 cy to its precursor 18:1ω7c, an indicator of stress among Gram-negative bacteria, ratio to each soil properties was determined in each parent material (basalt and granite) and treatment (control, sprinkler, and flood) Table 4.11 and Table 4.12. The correlations that are statistically significant are highlighted in red in each table.

The correlations coefficients between 19:0 cy to its precursor 18:1ω7c and soils properties within the basalt control positively correlated with organic carbon. The positively correlated coefficient with basalt sprinkler were calcium, magnesium, sodium, and sulfate. The negative coefficient with in basalt flood was pH. (Table 4.11).

The negatively correlation coefficients between 19:0 cy to its precursor 18:1ω7c and soil properties with in granite sprinkler was sand. The negatively correlated coefficients within granite flood were calcium and potassium and positively correlated with chloride and organic carbon (Table 4.12).

The correlations seem be similar primarily between the parent materials. The secondary response is from treatment types. The 19:0 cy to its precursor 18:1ω7c correlations shift depend on treatment type relative to the control, often to different soil properties. Basalt control had one correlation and the number of correlations increased under basalt sprinkler and remained the same with one in basalt flood. Granite control had no correlations and increased to one in granite sprinkler and four in granite flood.

Table 4.11: Correlation analysis for the 19:0 cy : 18:1 ω7c Stress Ratio 2 for each soil property physical – sand; chemical pHw, calcium (Ca), magnesium (Mg), sodium (Na), potassium (K), sulfate (SO_4), and chloride (Cl); biogeochemical – calcium carbonate (CaCO3) % and organic carbon (OC) % and combination of parent material (basalt) and treatment (control, sprinkler, and flood). Pearson's correlation coefficient *($P<0.05$).*

Stress Ratio 2 (19:0 cy : 18:1 ω7c)	**Basalt Control**		**Basalt Sprinkler**		**Basalt Flood**	
Soil Properties	**Pearson**	***P value***	**Pearson**	***P value***	**Pearson**	***P value***
Sand	-0.19	0.52	0.42	0.23	-0.44	0.19
pHw	-0.10	0.73	0.08	0.77	-0.62	0.06
Calcium (Ca)	0.18	0.53	0.64	0.01	0.16	0.66
Magnesium (Mg)	0.42	0.14	0.62	0.01	0.13	0.73
Sodium (Na)	0.17	0.56	0.51	0.04	0.06	0.86
Potassium (K)	0.37	0.19	0.38	0.13	0.15	0.67
Chloride (Cl)	0.24	0.41	0.28	0.27	-0.06	0.87
Sulfate (SO_4)	0.25	0.38	0.74	0.00	0.17	0.64
Calcium Carbonate ($CaCO_3$) %	-0.11	0.71	0.20	0.45	-0.43	0.22
Soil Organic Carbon (OC) %	0.50	0.07	0.07	0.80	0.45	0.20

Table 4.12: Correlation analysis for the 19:0 cy : 18:1 ω7c Stress Ratio 2 for each soil property physical – sand; chemical – pHw, calcium (Ca), magnesium (Mg), sodium (Na), potassium (K), sulfate (SO_4), and chloride (Cl); biogeochemical – calcium carbonate (CaCO3) % and organic carbon (OC) % and combination of parent material (granite) and treatment (control, sprinkler, and flood). Pearson's correlation coefficient *($P<0.05$).*

Stress Ratio 2 **(19:0 cy : 18:1 ω7c)**	**Granite Control**		**Granite Sprinkler**		**Granite Flood**	
Soil Properties	**Pearson**	***P value***	**Pearson**	***P value***	**Pearson**	***P value***
Sand	0.02	0.96	-0.69	0.09	-0.43	0.34
pHw	-0.22	0.61	-0.08	0.86	0.00	0.99
Calcium (Ca)	-0.09	0.84	-0.39	0.39	-0.74	0.06
Magnesium (Mg)	-0.08	0.85	0.02	0.96	-0.17	0.72
Sodium (Na)	-0.28	0.50	0.24	0.60	0.03	0.95
Potassium (K)	0.14	0.75	0.20	0.67	-0.74	0.06
Chloride (Cl)	-0.02	0.96	0.21	0.65	0.78	0.04
Sulfate (SO_4)	-0.15	0.72	-0.04	0.94	-0.16	0.73
Calcium Carbonate ($CaCO_3$) %	0.52	0.19	0.07	0.87	0.09	0.85
Soil Organic Carbon (OC) %	0.29	0.49	-0.20	0.66	-0.71	0.07

The linear model predicted how sensitive 19:0 cy to its precursor 18:1ω7c ratio is to increases among the soil properties within the six groups (Figure 4.16). Changes in 19:0 cy to its precursor 18:1ω7c above +/- 0.03 will be described. 19:0 cy to its precursor 18:1ω7c had a response within all six groups to changes in organic carbon. The positive response was within basalt control, basalt flood, and granite control and negative responses were within basalt sprinkler, granite sprinkler, and granite flood. Basalt flood had a strong negative response within pH. Granite sprinkler has positive responses with sodium, potassium, and chloride. Granite flood has a negative response with potassium and a positive response with chloride (Figure 4.16).

The primary influence in 19:0 cy to its precursor 18:1ω7c sensitive was between the parent materials, more sensitive in changes in soils properties derived from granite, and limited sensitivity to changes in soil properties derived from basalt.

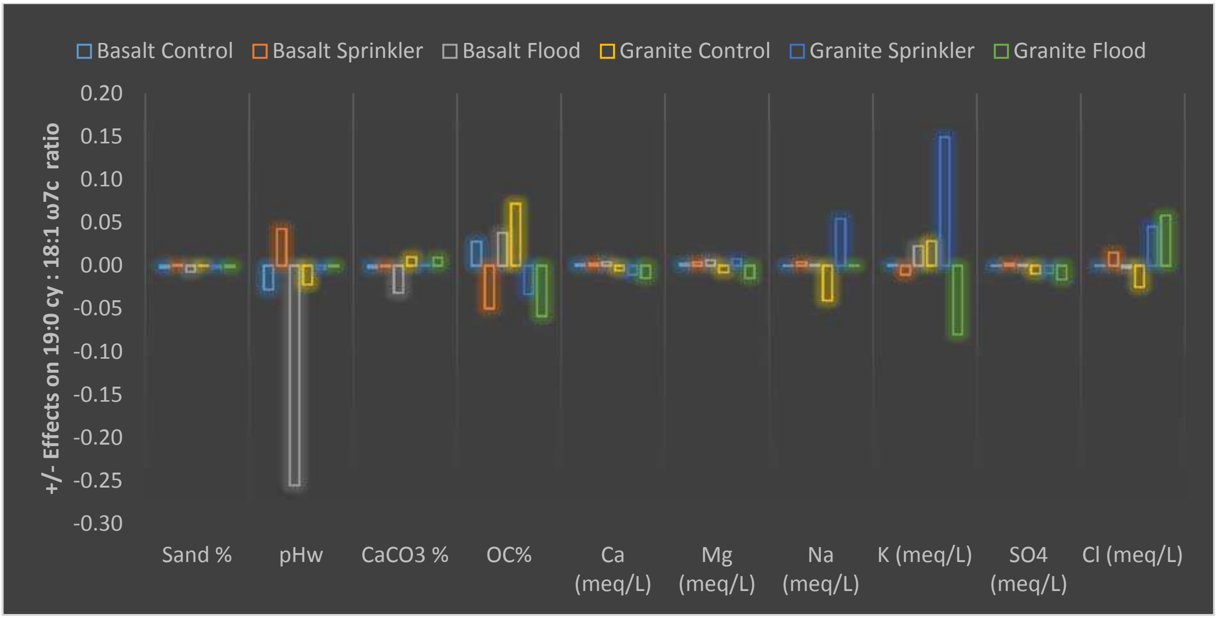


Figure 4.16: The linear model results for the 19:0 cy : 18:1 ω7c Stress Ratio 1 sensitivity when influenced by changes in the physical – sand; chemical – pHw, calcium (Ca), magnesium (Mg), sodium (Na), potassium (K), sulfate (SO_4), and chloride (Cl); biogeochemical – calcium carbonate (CaCO3) % and organic carbon (OC) % soil properties and their distribution among the six parent material x treatment combinations; basalt control, basalt sprinkler, basalt flood, granite control, granite sprinkler, and granite flood. Predictions were made within the 95% confidence interval.

Arbuscular Mycorrhizal (AM) Fungi (16:1ω5c)

The correlation with the Arbuscular Mycorrhizal (AM) fungi 16:1ω5c to each soil properties was determined in each parent material (basalt and granite) and treatment (control, sprinkler, and flood) Table 4.13 and Table 4.14. The correlations that are statistically significant are highlighted in red in each table.

The correlations coefficients between the AM fungi (16:1ω5c) and soils properties within the basalt control was negatively correlated with calcium. The negative correlation was organic carbon within basalt flood (Table 4.13).

The positive correlation coefficients between AM fungi (16:1ω5c) and soil properties within granite flood were pH, sodium, sulfate, and calcium carbonate (Table 4.14).

The correlations seem be similar between the parent materials, and treatment types are the secondary response. The correlations shift dependent on treatment type relative to the control, often to different soil properties. Basalt soils had very few correlations among the three treatments and granite flood had the most correlations.

Table 4.13: Correlation analysis for the Arbuscular Mycorrhizal (AM) Fungi (16:1 ω5c) for each soil property physical – sand; chemical – pHw, calcium (Ca), magnesium (Mg), sodium (Na), potassium (K), sulfate (SO_4), and chloride (Cl); biogeochemical – calcium carbonate (CaCO3) % and organic carbon (OC) % and combination of parent material (basalt) and treatment (control, sprinkler, and flood). Pearson's correlation coefficient *($P<0.05$).*

Arbuscular Mycorrhizal (AM) Fungi (16:1ω5c)	**Basalt Control**		**Basalt Sprinkler**		**Basalt Flood**	
Soil Properties	**Pearson**	***P value***	**Pearson**	***P value***	**Pearson**	***P value***
Sand	0.07	0.82	0.35	0.33	0.52	0.12
pHw	0.17	0.55	0.42	0.10	0.06	0.86
Calcium (Ca)	-0.58	0.03	-0.10	0.70	-0.07	0.85
Magnesium (Mg)	-0.37	0.19	0.41	0.10	-0.12	0.73
Sodium (Na)	0.23	0.44	0.06	0.81	-0.21	0.57
Potassium (K)	0.29	0.32	0.29	0.26	-0.11	0.76
Chloride (Cl)	0.27	0.36	-0.01	0.96	0.32	0.37
Sulfate (SO_4)	0.12	0.68	-0.08	0.75	-0.16	-0.15
Calcium Carbonate ($CaCO_3$) %	0.03	0.91	0.30	0.24	-0.15	0.67
Soil Organic Carbon (OC) %	-0.38	0.18	-0.16	0.55	-0.62	0.06

Table 4.14: Correlation analysis for the Arbuscular Mycorrhizal (AM) Fungi (16:1 ω5c) for each soil property physical – sand; chemical – pHw, calcium (Ca), magnesium (Mg), sodium (Na), potassium (K), sulfate (SO_4), and chloride (Cl); biogeochemical – calcium carbonate (CaCO3) % and organic carbon (OC) % and combination of parent material (granite) and treatment (control, sprinkler, and flood). Pearson's correlation coefficient *($P<0.05$).*

Arbuscular Mycorrhizal (AM) Fungi (16:1ω5c)	**Granite Control**		**Granite Sprinkler**		**Granite Flood**	
Soil Properties	**Pearson**	***P value***	**Pearson**	***P value***	**Pearson**	***P value***
Sand	0.12	0.77	-0.11	0.81	-0.06	0.89
pHw	0.06	0.90	0.39	0.38	0.77	0.04
Calcium (Ca)	-0.30	0.47	0.55	0.20	-0.52	0.24
Magnesium (Mg)	-0.12	0.78	0.43	0.34	0.22	0.63
Sodium (Na)	0.04	0.93	0.48	0.27	0.88	0.01
Potassium (K)	-0.10	0.81	-0.16	0.73	-0.05	0.92
Chloride (Cl)	0.48	0.23	-0.10	0.83	0.31	0.50
Sulfate (SO_4)	-0.11	0.80	-0.66	0.10	0.73	0.06
Calcium Carbonate ($CaCO_3$) %	-0.18	0.67	0.29	0.53	0.85	0.01
Soil Organic Carbon (OC) %	0.14	0.74	-0.23	0.62	0.05	0.92

The linear model predicted how sensitive AM Fungi (16:1ω5c) (nmols g^{-1} dry soil) biomarkers is to increases among the soil properties within the six groups (Figure 4.17). Changes in AM Fungi above +/- 0.10 will be described. AM Fungi 16:1ω5c has a positive response to pH within basalt sprinkler. Granite control has a positive response within chloride. Granite sprinkler has positive responses with pH, magnesium, and sodium, and a negative response with organic carbon, potassium, and sulfate. Granite flood had a positive response with pH, calcium carbonate, sulfate, and chloride (Figure 4.17).

The primary influence in arbuscular mycorrhizal fungi 16:1ω5c sensitivity was between the parent materials, more sensitive in changes in soils properties derived from granite, and limited sensitivity to changes in soil properties derived from basalt.

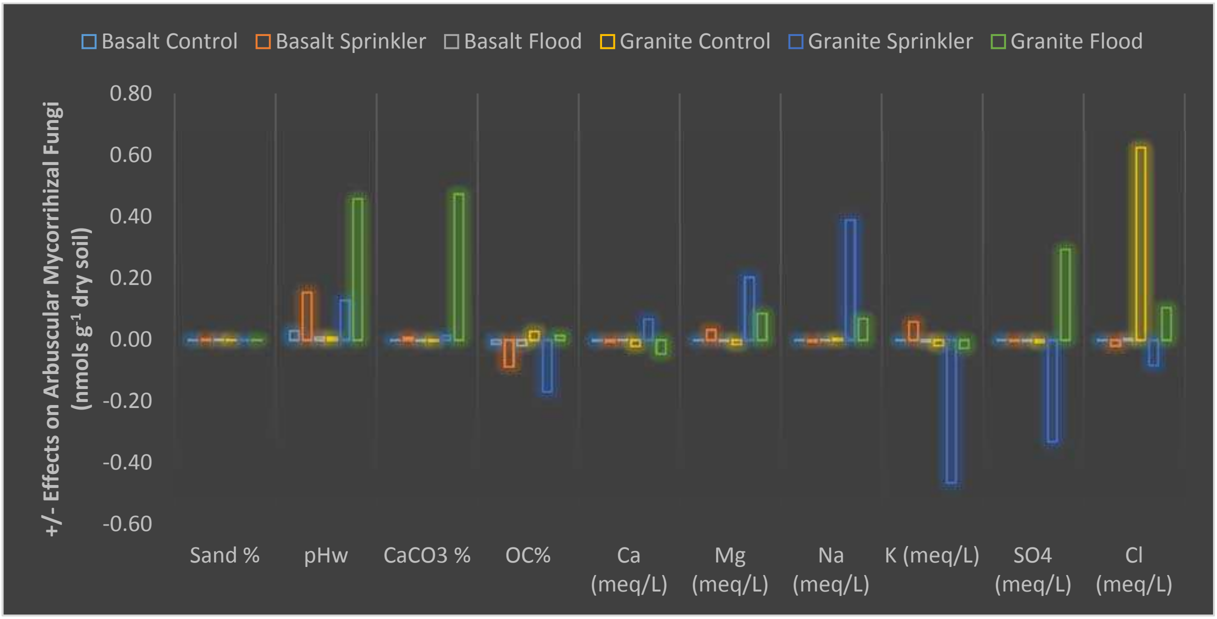


Figure 4.17: The linear model results for the Arbuscular Mycorrhizal (AM) Fungi 16:1ω5c (nmols g^{-1} dry soil) sensitivity when influenced by changes in the physical – sand; chemical – pHw, calcium (Ca), magnesium (Mg), sodium (Na), potassium (K), sulfate (SO_4), and chloride (Cl); biogeochemical – calcium carbonate (CaCO3) % and organic carbon (OC) % soil properties and their distribution among the six parent material x treatment combinations; basalt control, basalt sprinkler, basalt flood, granite control, granite sprinkler, and granite flood. Predictions were made within the 95% confidence interval.

4.5 Discussion

Microbial Community Composition

In this study, we found clear evidence that EL-FAME community composition differed between soil derived from basalt and granite. Microbial communities also clustered into distinct groups based on irrigation treatment. According to analysis of variance tests, microbial EL-FAME responses (biomass, stress ratios, and arbuscular mycorrhizal fungi) were significantly affected by the interaction between parent material and irrigation treatment. The analysis of variance (ANOVA) results were further evaluated for microbial community similarities and differences among the parent material x irrigation treatment groups.

Analysis of Variance (ANOVA)

Microbial biomass did not vary significantly between basalt control and sprinkler, or among granite control, sprinkler, and flood. Biomass difference were primarily in basalt flood soil, where biomass was 101% greater in the basalt flood soil compared to the other treatment groups. Contributing factors for the differences in the basalt flood group were an increase in clay and reduced sand content in the upper 15 cm. The amount of water applied during the growing season was approximately 1017 mm and under irrigation for an average of 84 years; management is no-till pasture hay grass fields, which promotes microbial community growth and activity due to lack of physical disturbance (Stromberger et al., 2007; Peterson et al., 2002; Peterson et al., 1998; Follett et al., 1989).

The fungi-to-bacteria ratio revealed limited variability among the six groups, which indicates the proportion of each microbial population (bacteria and fungi) were similar. An interesting result came from the basalt flood ratio which was the lowest among the six groups even though it had the highest biomass concentration, indicating that biomass, fungi, and bacteria are not directly correlated.

Typically, fungi and bacteria differ in their response to changes in agriculture management practices; fungi are more tolerant to lower water potentials in soil than bacteria

(Griffin 1972) although such a relationship is not always observed (Williams 2007). However, the results in this study suggests the management and irrigation practices in the San Luis Valley have similar effects on these two microbial populations. The pasture hay grass fields are no-tilled and subjected to flood irrigation. The alfalfa fields are subjected to sprinkler irrigation and mostly no-till, but approximately every seven years the alfalfa fields are tilled. Overall, there is evidence that the two management practices did not differentially affect proportions of bacteria and fungi, as demonstrated by the narrow range of variability between fungi-to-bacteria ratio.

Within the microbial community structure, we measured two different EL-FAME stress ratios. Stress 1 is the ratio of 17:0 cy to its precursor 16:1ω7c and stress 2 is the ratio of 19:0 cy to its precursor 18:1ω7c. These ratios are proposed indicators of bacterial stress as accumulation of cyclopropyl fatty acids were observed in response to various stresses, including organic carbon and oxygen depletion, low pH, and desiccation (Stromberger et al., 2007). This study found indications that stress is also related to parent material and treatment types.

Stress 1 responses were similar among five groups, basalt control and sprinkler, granite control, sprinkler, and flood. These five groups were statistically similar in their pH (7.5 to 8.3), texture, and the amount of irrigation water received. Other studies have indicated that Gram-negative bacteria are thought to be more sensitive to dramatic changes in water potential (Williams 2007). The basalt flood group was dissimilar in its stress response, however, the primary difference of this group is texture (greater clay and lower sand content) and a no significant change in pH (7.5). It could be suggested that the soils derived from basalt due to their soil physical properties have a higher water holding capacity. In addition, the basalt flood group receives 1073 mm of additional water, experiences greater frequencies of anaerobic conditions throughout the growing season; this combination of variables may have contributed to the higher stress response observed (Mentzer et al., 2006).

Stress 2 response was greatest in basalt control and flooded soils, suggesting it is even more sensitive to the flooded and dryer conditions (Williams et al., 2007). It can be inferred that basalt control soils experienced stress from limited water (<177 mm annual), reduced water holding capacity because of its low clay content (23%) and higher sand content (52%). In contrast, basalt flood has a higher clay content (30%) lower sand content (38%) However, granite control soils, which has similar soil properties, granite control clay content (19%) and sand content (65%) and granite flood clay content (21%) and sand content (62%), did not have the same response, suggesting an inherent difference between the parent materials.

In comparison, granite control, sprinkler, and flood, and basalt sprinkler had stress 2 levels between .07 and .14, which is a 585% reduction in stress levels from the basalt sprinkler and flood groups. The argument could then be made that other soil processes may be influencing the stress levels. These processes are salinization, alkalization, and calcification and were present in 100% of basalt control soils sampled and the same processes occurred in only 15% of the basalt flooded soils. Overall, the implications of increased stress, even at modest, “tolerable” levels may have substantial influences on ecosystems functioning. Such as stressed imposed shifts in the allocation of C and N which microbes must meet to survive and remain active (Schimel et al., 2007). Therefore, the differences between stress 1 and 2 reflects the different life strategy of these microbes in the same environment.

The fatty acid maker 16:1ω5c is a major lipid component of arbuscular mycorrhizal (AM) fungi (Graham et al., 1995) and has been used as a biomarker for AM fungi in soils (Stromberger et al., 2007). The presence of AM fungi is expected to be more abundant in soils under native grasses due to the greater root biomass of plants that are hosts to AM fungi, and lack of physical disturbance (Larkin 2003). However, in this study, cultivated sites had the largest accumulation of AM fungi; basalt sprinkler and flood, and granite sprinkler and flood. Historically, these groups have been in cultivation on average for 84 years and they have yielded substantial more below ground biomass and very little, to no disturbance from management practices.

Overall, the control soils had a 129% lower concentrations of AM fungal biomass, compared to irrigated soils. Between the two control soils, the control soil derived from basalt had a 38% higher AM fungal biomass than granite control soils. The plant composition basalt and granite were comparable; basalt plant community's composition was Greasewood (*Sarcobatus vermiculatus*), greene's rabbitbrush (*Chrysothamnus greenei*), salt grass (*Distichlis spicata* (L.), and blue gramma (*Bouteloua gracilis*). The granite plant community's composition was less diverse with only Greasewood (*Sarcobatus vermiculatus*) and salt grass (*Distichlis spicata* (L.) (Dixon 2012). The greater diversity of plant species growing in basalt control soil may explain the greater amount of AM fungi; studies have shown positive correlations between AM fungal biomass and plant community diversity (Stromberger et al., 2007). Alternatively, the increase in AM fungi in the basalt soils could be attributed to the soil physical properties, with granite-derived soil having a courser texture and lower water-holding capacity than basalt-derived soil. In addition to the physical aspects of the soil, soil derived from basalt has greater concentrations of nutrients available to microbial communities than soils derived from granite. This aspect alone could be the simple explanation for the measured difference in AM fungi composition.

Correlations between Microbial community composition and soil properties

The microbial communities and soil properties were analyzed using principal component analysis which showed evidence that correlations exist among certain soil properties and microbial communities. Soil properties that show a pattern of clustering together are sodium, chloride and potassium, and magnesium and calcium. Interestingly, sand and the fungi-to-bacteria ratio associated with each other. This suggests that high concentrations of sand have proportionally the same amount of fungi and bacteria.

Further analysis using the Pearson's correlation coefficient found evidence that the majority of microbial community compositions and their soil properties were similar between the two parent materials and irrigation treatment effects were secondary relative to the controls.

The soil chemical and biogeochemical properties that associated more frequently with microbial communities were organic carbon, calcium, magnesium, sodium, and chloride. Flood treatment, regardless of parent material, has the most coefficients between the microbial communities and soil properties.

Microbial community sensitivity to change in soil properties

Soil microbial community composition depends on a large number of physical, chemical, and biogeochemical soil properties, and its characterization requires the selection of indicators most sensitive to environmental changes (Elliott 1994; Larkin 2003). It is not useful to pick individual microbial or soil properties because they vary both seasonally and spatially. The proper approach is defining key soil properties holistically (Marinari et al., 2006). The collective approach defines key physical, chemical, and biogeochemical soil properties, which predicts changes in microbial communities within specific parent material and treatments types.

The correlation analysis provided the current steady state conditions between microbial communities and soil properties derived from basalt and granite. Using a liner model we predicted the sensitivity of microbial communities to changes in soil properties to further evaluate differences between parent materials (basalt and granite) and treatment types (control, sprinkler, and flood). The results were evaluated with the correlation coefficients for similarities and differences.

Microbial community biomass in soils derived from granite, in the control treatment showed a positive response to changes in concentrations of magnesium, sodium, and chloride; organic carbon had a negative response; the coefficients were magnesium, sodium, chloride, and sulfate. Granite soils subjected to sprinkler irrigation responded negatively with the addition of magnesium, sodium, potassium, organic carbon; potassium resulted in the highest negative response. Correlation coefficients for granite sprinkler were magnesium and organic carbon. Negative responses to increases in organic carbon were unexpected, due to the fact that organic carbon is a primary indicator of microbial and soil quality. Therefore, the response suggests that the one percent increase from the mean of 0.59% is not enough to produce a positive response and it also infers that plant residual material is being removed through management practices. The only group positively affected by organic carbon was granite flood, which has a mean of 1.56%. This suggests that the accumulated amount of organic carbon in the system can sustain a marginal increase or decrease without changing the biomass response. These results show the properties that have significant correlation coefficients may not be sensitive to change and vice versa. The primary influence in biomass sensitive was granite parent material, which inherently has low nutrient content.

The sensitive responses for the fungi-to-bacteria ratio in granite control showed a positive response to organic carbon and chloride; there were no coefficient for this group. Chloride had the biggest impact and shifted the community a fungal community in the granite control soils. Granite sprinkler has a negative response to magnesium, sodium, and potassium; magnesium and sodium were the coefficients. These ions collectively shifted granite sprinkler towards a bacteria community. Granite flood has a positive response from pH, organic carbon, calcium carbonate, magnesium, potassium, and sulfate and a negative response from chloride; calcium, magnesium, chloride, and organic carbon were the coefficients. These properties shifted towards a fungal community. Basalt sprinkler and flood showed a positive response to changes in pH in conjunction with granite flood. The increase in pH could be in part due to the change in the partial pressure of carbon dioxide, and due to the presence of sulfates, iron and manganese in the form of hydroxides and carbonates especially within the flooded soils (Mitchell 2005; Karathanasis 2007). The concentrations of iron and manganese in soils derived from basalt averaged <.007 ppm for manganese, and < 0.18 ppm for iron; however, the availability of sulfate is > 900 ppm. In contrast, iron, manganese, and sulfate concentrations in soils derived from granite were; iron <1.43 ppm, manganese <0.00, and sulfate 358 ppm. These values are significantly different from basalt soils. These observable shifts in the fungi-to-bacteria ratio could be linked to the available chemical elements within each parent material.

The suite of response for fungi-to-bacteria were dominated by changes in soils properties derived from granite, and reflected limited sensitive to changes in soil properties derived from basalt. These results reinforce the deficiencies of the available nutrients in the granite parent material, the potential benefits from irrigations management practices on granite soil. The results emphasis the sensitivity of fungi to changes in organic carbon, soil texture, especially those that have limited water-holding capacity and high infiltration rates, pH, and most of the major cations and ions.

We evaluated the responses of two stress indicators, 17:0 cy to its precursor 16:1ω7c and 19:0 cy to its precursor 18:1ω7c. Even though these indicators are specific to Gram-negative bacteria, the two ratios responded independently of each other under the same conditions. The sensitive responses for the 17:0 cy to its precursor 16:1ω7c are either increase stress from a positive response or decrease in stress from a negative response. Granite control showed a positive response to chloride and organic carbon and a negative response to pH, calcium and sodium; calcium was the coefficient. Granite sprinkler had positive responses from pH, magnesium, sodium, and potassium; pH was the only coefficient. Granite flood has a positive response from chloride and negative responses from pH, organic carbon, magnesium, and potassium; calcium, chloride, and organic carbon were the coefficients. Basalt sprinkler had a negative response to pH and positive response with organic carbon, which was a coefficient together with sand. Basalt flood had a negative response with pH; pH and calcium carbonate were the coefficients.

Among the five groups influenced by an increase in pH reduced the stress 1 ratio in the basalt flood group, which had the highest response. The reason for the possible increase in pH was caused by the reactions with iron, manganese, and sulfates in the basalt soils. The stress increased only in granite sprinkler from an increased in pH, suggesting there is also iron, manganese, and sulfate hydroxides and carbonates present and the soils potentially become flooded under sprinkler irrigation at certain points during the growing season. Collectively, the all of the cations and anions, with the exception of sulfate either increased stress or decreased stress dependent on treatment type in soils derived from granite; granite control and flood had reduced stress and granite sprinkler had increased stress. Surprisingly, an increase in chloride in the granite control soils increased the stress level passed the ratio of one, indicating the change in this soil anion is detrimental to Gram-negative bacteria without a counter balance cation, possible phosphorous, which was not measured in this study. The increase of chloride also increased the stress level in granite flood but remained within the range of variability. Lastly, a predicted increase in organic carbon for basalt sprinkler and granite control did not reduce the stress levels, which suggests there is a threshold by which organic carbon needs to exceed before a positive response can be observed. For example, the initial organic carbon content for granite control was 0.6%, a one-unit increase of 0.6% is only 0.006%, this infinitesimal amount of additional organic carbon is not enough to reduce the stress level.

Stress ratio 2, 19:0 cy to its precursor 18:1ω7c, the sensitivity that were positive responses for granite control were potassium and organic carbon and the negative response was chloride; there were no correlations coefficients for this group. Granite sprinkler had positive responses from chloride, sodium, and potassium and negative response from organic carbon; sand was the only coefficient. Granite flood had a positive response from chloride and a negative response from organic carbon, magnesium, and potassium; calcium, potassium, chloride, and organic carbon were the coefficients. Basalt control had a positive response from organic carbon and a negative response to pH; organic carbon was the only coefficient. Basalt sprinkler had a positive response with pH and a negative response with organic carbon; calcium, magnesium, and sodium were the coefficients. Basalt flood had a negative response with pH and calcium carbonate and a positive response with organic carbon and potassium; pH was the only coefficient.

Sensitivity responses among the ions for stress 2 was limited to magnesium, sodium, potassium, and chloride. Organic carbon reduced stress in granite sprinkler, granite flood, and basalt sprinkler and increased stress in basalt control, basalt flood, and granite control. The result within basalt flood was not expected due to the fact the crop is pasture hay grasses, with a mean organic carbon level of 3.8%, which is harvested but not tilled. Natural turnover of grass should provide residual material to promote organic carbon input. This result suggest that organic matter could be removed by water erosion or there is another driver that is reducing the availability of organic carbon, not only in this group but within the valley.

The suite of responses for both stress ratios were dominated by the sensitive in changes in soils properties derived from granite, and reflected limited sensitive to changes in soil properties derived from basalt. The differences were seen stress 2 from pH, which effected all three treatment types in basalt soils, which was the only significant change observed in basalt soils. In addition, changes to organic carbon seem to ubiquitous to parent material type and treatment. The general trend was similar between the stress ratios for granite soils, which continues to reinforce the deficiencies in the nutrients availability in the granite parent material.

The fatty acid maker of 16:1ω5c is a major lipid component of arbuscular mycorrhizal (AM) fungi and this biomarker has been identified as being sensitive to a variety of stresses and soil disturbances. Their characteristic function is nutrient uptake and soil aggregations (Sylvia et al., 2005). AM Fungi sensitivities that were positive responses for basalt control was pH; the correlations coefficients were calcium. Basalt sprinkler has a positive response from pH and a negative response with organic carbon; there were no correlations coefficients for this group. Granite sprinkler had a positive response from pH, magnesium, and sodium and a negative response to potassium, sulfate, and organic carbon; there were no correlations coefficients for this group. Granite flood had a positive response from pH, calcium carbonate, sulfate, and chloride; pH, sodium, sulfate, and calcium carbonate were the correlations coefficients for this group.

The sensitivity analysis revealed increases in calcium carbonate have a positive influence on AM fungi in the granite flood group, calcium carbonate was also a correlation coefficient. In a study by Navazio et al. (2008) found that free calcium increased intracellular communication in establishing the symbiosis functions of AM fungi. This suggests the processes of calcium carbonate dissolution, which liberates calcium and bicarbonate into the soils derived from granite, and are inherently deficient, is beneficial to AM Fungi.

The sensitivity modeled indicated a 1% increase in organic carbon in the granite and basalt sprinkler groups will not have a positive impact the amount of AM fungi. This response warrants further analysis to identify the organic carbon threshold by which a positive change in the quantity of AM fungi can be observed.

The suite of responses for AM fungi were dominated by the sensitivity in changes to the soils properties derived from granite, and reflected limited sensitive to changes in soil properties derived from basalt. The interesting exception was the increase in pH within basalt control and sprinkler groups had a positive response on AM fungi. Within granite soils, calcium was the only ion that did not response to the model.

4.6 Conclusion

The objective of this study was to distinguish microbial community composition as a function of parent material and land use, to identify key soil properties that will predict changes in microbial community composition, and evaluate the influences on soil degradation. These objects were supported by the results of this study. Principal component analysis of EL-FAME's indicated the microbial communities differed for soils derived from basalt and granite parent material. The microbial communities further diverged by irrigated treatment types, control, sprinkler, and flood. The principal component analysis revealed that soils derived from granite shared constituents among the three treatment types and responded similarly. In contrast, soil derived from basalt shared constituents between the control and sprinkler treatments, which responded similarly, but flood treatment remained separated and responded independently. The ANOVA analysis for all five microbial community composition as a function of parent material and treatment revealed that microbial biomass and community structure did not vary significantly between the parent materials and treatments, the exception was flooded soil derived from basalt. The fungi and bacteria community composition was proportional the same between all treatment types and parent materials. The ratios of two stress indicators (17:0 cy to its precursor 16:1ω7c and 19:0 cy to its precursor 18:1ω7c) responded similarly in granite soils but varied in their stress ratios in basalt soils. Analysis of AM fungal communities, using the biomarker 16:1ω5c, indicated higher relative amounts in the irrigation treatments in both parent materials.

The study revealed correlations between microbial communities and soil properties. The correlated properties were primarily pH, magnesium, sodium, potassium, chloride, and organic carbon. The correlations were similarly distributed between basalt and granite, but differed primarily under flood irrigation. The model further revealed the sensitivity of the microbial communities to changes in the soils properties based on parent material and treatment. Microbial communities inhabiting soils derived from granite where more sensitive to changes in pH, magnesium, sodium, potassium, chloride, and organic carbon from both sprinkler and flood irrigation than microbial communities inhabiting soils derived from basalt, which were sensitive primarily to changes in pH and organic carbon under both irrigation practices. However, the responses were negligible compared to granite soils. The model further exposed soil properties that did not have a direct correlation coefficient within the current environment but had a positive or negative impact on microbial communities.

Our findings are important because they represent soil microbial community constraints as a function of parent material under the same climatic conditions, and agricultural practices. It highlights the importance in evaluating the physical, chemical, and biogeochemical soil properties holistically in determining key properties that collectively impact microbial community structure. Our results indicate that soils derived from basalt are more resistant to changes than soils derived from granite and that the same land use cannot be assumed to contain the same concentrations of chemical and biogeochemical properties. This study improves the knowledge about long-term agriculture practice in semi-arid region. The results also improve our capability to model environmental responses as management practices escalate in response to global pressure to increase agriculture production.

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CHAPTER 5

SUMMARY AND CONCLUSIONS

5.1 Summary and Conclusion

The research took place in the San Luis Valley (SLV), a semi-arid high elevation desert in south central Colorado. The SLV is an important agricultural region with a 150-year history of irrigated cultivation. The natural geological formation of the SLV encompasses basalt and granite parent materials geographically divided by the Rio Grande River, which provided a unique environment for the benchmark model (Chapter 2). The long-term irrigation practices provided the condition variables that influenced the directional change in soil properties (Chapter 3) and the microbial community composition (Chapter 4).

The primary objective of this work was to elucidate the impacts of irrigated cultivation in a semi-arid region as a function of parent material diversification (basalt and granite) by evaluating degradation in terms of the directional change in the physical, chemical, and biogeochemical soil properties and microbial community composition. Specifically, the primary objective allowed evaluation of the unique soil properties that distinctly separate soils derived from basalt and granite. These properties became the benchmark model for evaluating the impact of irrigated agriculture. These physical, chemical, and biogeochemical soil properties were assessed for their resiliency or susceptibility to continued anthropogenic pressures from land use change. The expectation was that the basalt benchmark soils would be rich in nutrients and have approximately 35 - 40% clay content, while granite soils would be in the medium range for nutrient content with approximately 40 to 45% clay. We found that the basalt soils do have high nutrient concentrations but only 20% clay, whereas granite soils have very low nutrient concentrations and 18% clay. The dominant particle in this system was sand, 57% for basalt soils and 66% for granite soils. The implications of a sandy medium changes the water storage dynamics, the retention of nutrients, and accumulation of soils organic carbon and nitrogen. In addition, the climatic conditions of cold winters and moderate summers had slowed the clay weathering process in both parent material environments.

A second objective of this research evaluated the magnitude and directional change of these benchmark soils as a function of long-term (84 years) irrigated cultivation (sprinkler and flood) in a semi-arid ecosystem. The goal was to select a set of physical, chemical, and biogeochemical properties that would quantify the dynamic behavioral differences between basalt and granite lithologies. The subset provides a group of uncorrelated properties for evaluating the impacts of irrigation practices and develops a matrix for determining the resiliency and health of the current system. The results indicated that water quality, clay, soil bulk density, soil organic carbon, sodium, sulfate and chloride were the key indicators in this irrigated agroecosystem. Typically in irrigated agricultural regions, the water quality is a contributing factor to the accumulation of soluble salts, primarily sodium. An increased level of sodium causes dispersion of clays, toxicity to plants through osmotic stress, and increased evaporation from the soil surface. However, this was not found in the San Luis Valley. The native basalt soils had elevated accumulations of sodium while the irrigated sites had significantly reduced levels, which suggest that to the irrigated water quality is comparable to that of rain water. The implication of exceptional water quality in a medium of sand is that reduced levels of all soluble salts and reduced plant stress creates a uniquely “sustainable” agroecosystem within a water-limited system.

The third objective of this research distinguished microbial community composition as a function of parent material and treatment, and assessed key soil properties that influenced microbial community composition. The expectations was that microbial communities would differ between treatment types, which would be influenced by pH, soil organic matter, and sodium concentrations. The results indicated that microbial communities inhabiting soils derived from granite were more sensitive to changes in pH, magnesium, sodium, potassium, chloride, and organic carbon from both sprinkler and flood irrigation than microbial communities inhabiting soils derived from basalt, which were sensitive primarily to changes in pH and organic carbon under both irrigation practices. The microbial analysis showed that stress indicators (17:0 cy to its precursor 16:1ω7c and 19:0 cy to its precursor 18:1ω7c) responded similarly in granite soils but varied in their stress ratios in basalt soils. Analysis of AM fungal communities, using the biomarker 16:1ω5c, indicated higher relative amounts in the irrigation treatments in both parent materials. The soil properties with the most influence on microbial community composition were pH, magnesium, sodium, potassium, chloride, and organic carbon. Knowledge of these key soil properties provides a means to evaluate the sensitivity of the microbial community structures and behavioral responses to the impacts of agricultural land use changes in semi-arid regions.

The main conclusions are agroecosystems are more resilient to land use impacts when the planting medium is primarily composed of the sand size fraction, water quality is comparable to rain water, and microbial community composition flourishes among row crops with extensive root systems that are in a no-till management regime. Also, semi-arid regions in which the climatic conditions range from cold to moderate temperatures, foster slow weathering of the substrate by retaining higher percentages of sand and slow the development of clays. These areas benefit from an increased application of water which flushes the soil profiles of excess soluble salts. Furthermore, soil properties of basalt and granite are divergent when observed in their native environments, but become convergent as a function of irrigated agriculture practices.

APPENDIX

Appendices 1: Soil properties from 23 control pedons derived from basalt and granite with the greatest eigenvector coefficients for principal component (PCoA) axes 1 and 2 shown in Figure 2.5 A and B.

Soil Properties	PCoA1	PCoA2
Sand	0.19	-0.50
Clay	-0.14	0.51
pHw	-0.24	-0.16
Calcium Carbonate (CaCO3)	-0.04	0.28
Organic Carbon (OC)	-0.13	0.28
Calcium (Ca)	-0.22	0.38
Magnesium (Mg)	-0.27	0.19
Sodium (Na)	-0.44	-0.23
Potassium (K)	-0.41	-0.21
Chloride (Cl)	-0.44	-0.15
Sulfate (SO4)	-0.44	-0.12

Appendices 2: Soil properties from 14 control pedons derived from basalt with the greatest eigenvector coefficients for principal component (PCoA) axes 1 and 2 shown in Figure 2.6.

Soil Properties Basalt	PCoA 1	PCoA 2
Sand	-0.16	0.47
Clay	0.16	-0.47
pHw	0.24	0.22
Calcium Carbonate (CaCO3)	0.11	-0.27
Organic Carbon (OC)	0.12	-0.31
Calcium (Ca)	0.17	-0.42
Magnesium (Mg)	0.24	-0.21
Sodium (Na)	0.45	0.22
Potassium (K)	0.42	0.19
Chloride (Cl)	0.45	0.12
Sulfate (SO4)	0.45	0.12

Appendices 3: Soil properties from 9 control pedons derived from granite with the greatest eigenvector coefficients for principal component (PCoA) axes 1 and 2 shown in Figure 2.7

Soil Properties Granite	**PCoA 1**	**PCoA 2**
Sand	0.17	0.34
Clay	-0.20	-0.41
pHw	-0.17	-0.32
Calcium Carbonate (CaCO3)	-0.17	-0.49
Organic Carbon (OC)	0.21	0.30
Calcium (Ca)	-0.40	0.20
Magnesium (Mg)	-0.40	0.23
Sodium (Na)	-0.42	0.16
Potassium (K)	0.13	0.31
Chloride (Cl)	-0.42	0.18
Sulfate (SO4)	-0.39	0.19

Appendices 4: Soil properties from 34 treatment pedons derived from basalt and granite with the greatest eigenvector coefficients for principal component (PCoA) axes 1 and 2 shown in Figure 3.6.

Soil Properties	**PCoA1**	**PCoA2**
Sand	0.12	0.55
Clay	-0.14	-0.52
pHw	-0.01	0.42
Calcium Carbonate (CaCO3)	0.02	0.21
Organic Carbon (OC)	-0.14	-0.34
Calcium (Ca)	-0.37	-0.07
Magnesium (Mg)	-0.41	0.00
Sodium (Na)	-0.42	0.21
Potassium (K)	-0.40	0.16
Chloride (Cl)	-0.31	0.03
Sulfate (SO4)	-0.46	0.11

Appendices 5: Soil properties from 10 sprinkler treatment pedons derived from basalt with the greatest eigenvector coefficients for principal component (PCoA) axes 1 and 2 shown in Figure 3.7.

Soil Properties	**PCoA1**	**PCoA2**
Sand	0.37	0.15
Clay	-0.36	-0.21
pHw	0.23	0.46
Calcium Carbonate (CaCO3)	0.05	0.37
Organic Carbon (OC)	-0.36	-0.25
Calcium (Ca)	0.26	-0.49
Magnesium (Mg)	0.31	-0.42
Sodium (Na)	0.37	0.07
Potassium (K)	0.11	-0.01
Chloride (Cl)	0.23	0.09
Sulfate (SO4)	0.43	-0.32

Appendices 6: Soil properties from 7 sprinkler treatment pedons derived from granite with the greatest eigenvector coefficients for principal component (PCoA) axes 1 and 2 shown in Figure 3.8.

Soil Properties	**PCoA1**	**PCoA2**
Sand	0.01	-0.48
Clay	-0.11	0.59
pHw	-0.38	0.31
Calcium Carbonate (CaCO3)	-0.28	0.30
Organic Carbon (OC)	0.29	0.10
Calcium (Ca)	-0.22	0.15
Magnesium (Mg)	-0.41	-0.13
Sodium (Na)	-0.33	-0.02
Potassium (K)	-0.27	-0.33
Chloride (Cl)	-0.37	-0.08
Sulfate (SO4)	-0.37	-0.26

Appendices 7: Soil properties from 10 flood treatment pedons derived from basalt with the greatest eigenvector coefficients for principal component (PCoA) axes 1 and 2 shown in Figure 3.9.

Soil Properties	**PCoA1**	**PCoA2**
Sand	-0.10	0.53
Clay	0.14	-0.54
pHw	0.07	0.41
Calcium Carbonate (CaCO3)	0.05	0.17
Organic Carbon (OC)	0.26	-0.37
Calcium (Ca)	0.33	-0.06
Magnesium (Mg)	0.40	0.00
Sodium (Na)	0.41	0.20
Potassium (K)	0.41	0.18
Chloride (Cl)	0.30	0.00
Sulfate (SO4)	0.45	0.12

Appendices 8: Soil properties from 7 flood treatment pedons derived from granite with the greatest eigenvector coefficients for principal component (PCoA) axes 1 and 2 shown in Figure 3.10.

Soil Properties	**PCoA1**	**PCoA2**
Sand	-0.24	-0.12
Clay	0.22	0.03
pHw	0.04	-0.55
Calcium Carbonate (CaCO3)	-0.14	-0.27
Organic Carbon (OC)	0.48	0.09
Calcium (Ca)	0.46	0.08
Magnesium (Mg)	0.47	-0.06
Sodium (Na)	0.02	-0.54
Potassium (K)	0.42	0.01
Chloride (Cl)	-0.02	0.00
Sulfate (SO4)	0.17	-0.55

Appendices 9: Water quality data for Alamosa County from 1989 to 2015, Parameters, Units, N (number of wells), Mean, Max. Colorado Department of Agriculture, ground water database.

ALAMOSA **Parameter Name**	**Units**	**N**	**Mean**	**Min**	**Max**
Alkalinity (CaCO3)	mg/L	27	187.4	74	549
Aluminum	mg/L	2	0.25	0.2	0.3
Barium	mg/L	20	0.07	0	0.16
Bicarbonate	mg/L	27	228.6	90	669.6
Boron	mg/L	26	0.2	0	1.01
Bromide	mg/L	5	0.31	0.1	0.9
Calcium	mg/L	27	84.43	8.8	567.5
Chloride	mg/L	33	49.26	2	301.6
Chromium	mg/L	15	0.02	0	0.1
Copper	mg/L	4	0.02	0	0.03
Dissolved Orthophosphate	mg/L	5	0.15	0.1	0.22
Fluoride	mg/L	6	0.27	0.2	0.53
Hardness (CaCO3)	mg/L	27	276.2	29	1745
Iron	mg/L	26	0.11	0	0.95
Lead	mg/L	3	0.09	0.1	0.11
Magnesium	mg/L	27	15.94	1.8	80.1
Manganese	mg/L	20	0.38	0	3.11
Molybdenum	mg/L	7	0.02	0	0.05
Nickel	mg/L	2	0.02	0	0.03
Potassium	mg/L	26	8.52	0.9	43
Sodium	mg/L	27		15	418.3
Specific Conductance (Lab)	µs/cm	27	788.6	247	2950
Sulfate	mg/L	33	219.1	2.7	1814.2
Total Dissolved Phosphorus	mg/L	20	0.27	0.1	1.4
Total Dissolved Solids (Lab)	mg/L	27	730.3	214	3360
Zinc	mg/L	22	0.02	0	0.08
pH (Lab)		27	7.66	7.2	8.4
Nitrate as Nitrogen	mg/L	43	5.69	0.2	37
DO (% Sat) FlowCell		6	24.45	1.8	47.6
DO (mg/L) FlowCell		43	2.18	0.2	6.5
Oxidation-Reduction Potential (Field)	mV	12	86.35	13	150.8
Salinity (Field)	ppt	11	0.34	0.1	0.92
Specific Conductance (Field)	µs/cm	15	587.6	1	1799
Total Dissolved Solids (Field)	g/L	15	103.7	0.1	699
Water Temperature (Surface)	°C	43	11.86	8.8	15.1
pH (Field)		15	7.24	6.7	7.83

Appendices 10: Water quality data for Conejos County from 1989 to 2015, Parameters, Units, N (number of wells), Mean, Max. Colorado Department of Agriculture, ground water database.

CONEJOS

Parameter Name	**Units**	**N**	**Mean**	**Min**	**Max**
Alkalinity (CaCO3)	mg/L	11	84.73	46	160
Aluminum	mg/L	1	0.1	0.1	0.1
Barium	mg/L	2	0.01	0	0.02
Bicarbonate	mg/L	11	103.3	56	195.4
Boron	mg/L	7	0.04	0	0.07
Bromide	mg/L	1	0.05	0.1	0.05
Cadmium	mg/L	1	0.01	0	0.01
Calcium	mg/L	11	39.58	18	89.2
Chloride	mg/L	20	9.08	1	45.7
Chromium	mg/L	8	0.02	0	0.03
Copper	mg/L	2	0.03	0	0.03
Dissolved Orthophosphate	mg/L	7	0.28	0.1	0.63
Fluoride	mg/L	9	0.24	0.1	0.43
Hardness (CaCO3)	mg/L	11	132.2	63	286
Iron	mg/L	2	0.14	0	0.24
Lead	mg/L	4	0.08	0.1	0.15
Magnesium	mg/L	11	8.06	3.2	15.5
Manganese	mg/L	3	0.16	0.1	0.34
Molybdenum	mg/L	5	0.01	0	0.02
Potassium	mg/L	10	3.98	2.2	6.7
Sodium	mg/L	11	10.32	3.2	33.9
Specific Conductance (Lab)	µs/cm	11	242.6	130	515
Sulfate	mg/L	20	40.02	2	172
Total Dissolved Phosphorus	mg/L	8	0.19	0.1	0.4
Total Dissolved Solids (Lab)	mg/L	11	242.1	119	535
Zinc	mg/L	8	0.03	0	0.05
pH (Lab)		11	7.26	6.5	8.1
Nitrate as Nitrogen	mg/L	41	1.24	0.1	6.14
DO (% Sat) FlowCell		9	41.62	2.1	82.8
DO (mg/L) FlowCell		37	4.33	0.2	9.17
Oxidation-Reduction Potential (Field)	mV	23	86.43	2.5	217.8
Salinity (Field)	ppt	18	0.13	0.1	0.22
Specific Conductance (Field)	µs/cm	29	286.7	134	515
Total Dissolved Solids (Field)	g/L	29	77.22	0.1	335
Water Temperature (Surface)	°C	40	10.6	8.5	14.35
pH (Field)		28	7.11	6.1	8.39

Appendices 11: Water quality data for Costilla County from 1989 to 2015, Parameters, Units, N (number of wells), Mean, Max. Colorado Department of Agriculture, ground water database.

COSTILLA **Parameter Name**	**Units**	**N**	**Mean**	**Min**	**Max**
Alkalinity (CaCO3)	mg/L	9	142.3	80	226
Aluminum	mg/L	1	0.1	0.1	0.1
Barium	mg/L	2	0.03	0	0.03
Bicarbonate	mg/L	9	173.8	98	275.9
Boron	mg/L	8	0.17	0.1	0.55
Bromide	mg/L	1	0.07	0.1	0.07
Cadmium	mg/L	1	0.01	0	0.01
Calcium	mg/L	9	74.86	33	293.2
Chloride	mg/L	11	28.42	2	105.8
Chromium	mg/L	8	0.02	0	0.02
Copper	mg/L	6	0.05	0	0.17
Dissolved Orthophosphate	mg/L	1	0.06	0.1	0.06
Fluoride	mg/L	2	0.37	0.2	0.57
Hardness (CaCO3)	mg/L	9	241.3	106	892
Iron	mg/L	9	0.08	0	0.38
Lead	mg/L	3	0.18	0.1	0.26
Magnesium	mg/L	9	13.26	5.7	39
Manganese	mg/L	3	0.04	0	0.07
Nickel	mg/L	4	0.01	0	0.02
Potassium	mg/L	8	5.85	1.6	29.4
Sodium	mg/L	9	35.6	6	168.6
Specific Conductance (Lab)	mg/L	9	541.6	194	2140
Sulfate	μs/cm	11	116.1	12	939.8
Total Dissolved Phosphorus	mg/L	2	0.1	0.1	0.1
Total Dissolved Solids (Lab)	mg/L	9	488.4	211	1865
Zinc	mg/L	9	0.03	0	0.07
pH (Lab)		9	7.41	7	7.8
Nitrate as Nitrogen	mg/L	#	2.25	0.3	8.3
DO (% Sat) FlowCell		2	32.6	10	54.9
DO (mg/L) FlowCell		15	4.43	0.2	9.2
Oxidation-Reduction Potential (Field)	mV	4	78.5	20	117.4
Salinity (Field)	ppt	4	0.15	0.1	0.19
Specific Conductance (Field)	μs/cm	6	305.7	226	386
Total Dissolved Solids (Field)	g/L	6	66.3	0.2	248
Water Temperature (Surface)	°C	15	11.73	8.8	14.7
pH (Field)		6	6.72	6.4	7.18

Appendices 12: Water quality data for Rio Grande County from 1989 to 2015, Parameters, Units, N (number of wells), Mean, Max. Colorado Department of Agriculture, ground water database.

RIO GRANDE

Parameter Name	**Units**	**N**	**Mean**	**Min**	**Max**
Alkalinity (CaCO3)	mg/L	26	102	22.8	239
Aluminum	mg/L	3	0.17	0.1	0.3
Barium	mg/L	25	0.06	0.01	0.18
Bicarbonate	mg/L	26	124.37	27.8	291.3
Boron	mg/L	22	0.03	0.01	0.12
Bromide	mg/L	3	0.08	0.06	0.1
Cadmium	mg/L	1	0.01	0.01	0.01
Calcium	mg/L	26	38.37	5.4	124.2
Chloride	mg/L	37	9.16	1	52.9
Chromium	mg/L	9	0.02	0.01	0.04
Copper	mg/L	7	0.01	0.01	0.03
Dissolved Orthophosphate	mg/L	11	0.28	0.12	0.55
Fluoride	mg/L	11	0.21	0.14	0.34
Hardness (CaCO3)	mg/L	26	119.45	14.3	387
Iron	mg/L	17	0.03	0.01	0.06
Lead	mg/L	2	0.13	0.07	0.19
Magnesium	mg/L	26	5.74	0.2	18.7
Manganese	mg/L	7	0.03	0.01	0.08
Molybdenum	mg/L	2	0.03	0.03	0.03
Nickel	mg/L	2	0.17	0.01	0.33
Potassium	mg/L	26	3.49	0.2	6.9
Sodium	mg/L	26	13.62	2.9	34.9
Specific Conductance (Lab)	µs/cm	26	278.27	57	895
Sulfate	mg/L	37	22.99	1.9	121.2
Total Dissolved Phosphorus	mg/L	19	0.12	0.01	0.3
Total Dissolved Solids (Lab)	mg/L	26	243.85	45	736
Zinc	mg/L	19	0.03	0.01	0.11
pH (Lab)		26	7.46	7	8.1
Nitrate as Nitrogen	mg/L	56	4.31	0.23	22
DO (% Sat) FlowCell		11	36.53	1.9	83.2
DO (mg/L) FlowCell		51	4.43	0.22	9.84
Oxidation-Reduction Potential (Field)	mV	26	97.08	6.2	227.4
Salinity (Field)	ppt	23	0.13	0.05	0.29
Specific Conductance (Field)	µs/cm	33	274.24	116	599
Total Dissolved Solids (Field)	g/L	33	59.76	0.08	383
Water Temperature (Surface)	°C	60	11.85	9.24	16.1
pH (Field)		33	7.14	6.24	8.32