ABIOTIC AND BIOTIC MEDIATION OF GRAZING IMPACTS ON SOIL CARBON IN NORTHERN ARIZONA

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ABSTRACT

ABIOTIC AND BIOTIC MEDIATION OF GRAZING IMPACTS ON SOIL CARBON IN NORTHERN ARIZONA

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Soil, the largest terrestrial carbon reservoir, has the ability to sequester carbon, however numerous variables influence its storage potential. Livestock management practices, precipitation, plant species composition, and soil parent material may all influence the potential for carbon to be stored in the soil. There is little empirical evidence measuring these effects in arid and semi-arid environments which motivated this study to sample across the Diablo Trust in northern Arizona. Stratified random sites were selected based on the locations of fence-lines or grazing exclosures that have excluded livestock for at least 20 years. Soil samples were collected from grazed and adjacent ungrazed sides of the fences across five distinct soil series and along a precipitation gradient ranging from 230 mm – 623 mm at the surface (0-5 cm) and subsurface (20-25 cm). The sites were measured for soil texture, precipitation, plant community composition, root biomass, soil organic carbon, and soil inorganic carbon. Results from the general linear models and the structural equation model found that the abiotic factors of precipitation and soil texture were the main drivers in soil organic and inorganic carbon. Grazing did not have a significant direct effect on soil organic or inorganic carbon, although there were significantly more C_4 grasses under the grazed treatments. Surprisingly, roots, especially C_4 roots, had a greater effect on soil inorganic carbon than organic carbon. More research is needed to better understand the mechanisms driving this interaction, but could be crucial to understand if this drives more carbon to be released into the atmosphere in semi-arid and arid environments. Overall, the results from this study show that the abiotic factors of soil texture and precipitation were the main drivers in soil organic and inorganic carbon across this semi-arid rangeland. This may be explained through the theoretical framework provided by the state-and-transition model which incorporates both equilibrium and non-equilibrium models. Arid and semi-arid environments have more stochastic rainfall patterns compared to mesic environments, driving net primary production, which increases with timely precipitation. Along the continuum of the state-and-transition model, semi-arid rangelands fall more along the non-equilibrium systems. If the non-equilibrium model explains more of the ecological dynamics within system in this semi-arid rangeland, then predictable sequestration of carbon is complex through management and it may not be appropriate to include management practices within protocols in the voluntary carbon market. More research is needed to better understand grazing's impact on soil carbon storage across various precipitation gradients. The research from this study shows that grazing had a minimal impact on soil carbon storage across a landscape scale and that there are biotic interactions with inorganic carbon that can no longer be ignored.

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TABLE OF CONTENTS

Chapter One: Grazing and soil carbon: The untold story of inorganic carbon **Page**

Introduction 1
References 7
Table and Figure 9

Chapter Two: Abiotic and Biotic Mediation of Grazing Impacts on Soil Carbon in Northern Arizona

Introduction 13
Methods 21
Results 30
Discussion 33
Conclusion 37
References 39
Tables and Figures 43

Chapter Three: Policy Implication for Rangeland Management

Introduction 61
References 66

Appendix A: NRCS Soil Series Description 68
Appendix B: Supplementary Graphs 82
Appendix C: Supplementary Tables 89

LIST OF TABLES

Chapter One **Page**

Table 1: *A-priori* Hypothesized Mechanisms and Observed Patterns 10

Chapter Two

Table 1: State-and-Transition Model 44
Table 2: *A-priori* Hypothesized Mechanisms and Observed Patterns 46

Appendix C

S1: Texture PCA Results 84
S2: Vegetation nMDS Results 85
S3: Vegetation nMDS Results 85
S4: General Linear Models 89
S5: Results from Soil Organic Carbon General Linear Model 90
S6: Results from Soil Inorganic Carbon General Linear Model 91
S7: Results from Surface Soil Organic Carbon General Linear Model 92
S8: Results from Surface Soil Inorganic Carbon General Linear Model 93
S9: Results from Subsurface Soil Organic Carbon General Linear Model 94
S10: Results from Subsurface Soil Inorganic Carbon General Linear Model 95
S11: Results from C_4 Grass General Linear Model 96

LIST OF FIGURES

Chapter One **Page**

Figure 1: *A-priori* Structural Equation Model 9

Chapter Two

Figure 1: Grazing Allotments on Arizona Public Lands 43
Figure 2: *A-priori* Structural Equation Model 45
Figure 3: Map of the Diablo Trust 48
Figure 4: Texture Principal Component Analysis 49
Figure 5: nMDS for Vegetation Composition 50
Figure 6: Pearson Correlation 51
Figure 7: Soil Organic Carbon Linear Regression 52
Figure 8: Box-and-Whisker Plot for Soil Organic Carbon 53
Figure 9: Soil Inorganic Carbon Linear Regression 54
Figure 10: Box-and-Whisker Plot for Soil Inorganic Carbon 55
Figure 11: Soil Carbon Linear Regression 56
Figure 12: Surface Soil Carbon SEM 57
Figure 13: Subsurface Soil Carbon SEM 58
Figure 14: Carbon and Nitrogen Linear Regression 59

Appendix B

Figure S1: Surface Pearson Correlation 82
Figure S2: Subsurface Pearson Correlation 83
Figure S3: Scree plot from Texture PCA 84
Figure S4: Scree plot from Vegetation nMDS 85
Figure S5: Soil Bulk Density Linear Regression 86
Figure S6: Soil Organic Carbon as a function of Nitrogen 87
Figure S7: Soil Inorganic Carbon as a function of Nitrogen 88

CHAPTER 1:

Grazing and soil carbon: The untold story of inorganic carbon

By

Megan Marie Deane McKenna, Nancy Collins Johnson, Deborah Huntzinger, Thomas Sisk

Introduction

Are semi-arid rangelands carbon sources? A recent study by Svejcar et al., (2008) measured the carbon flux across eight rangelands throughout the United States and found that the rangelands in the southwest were, on average, carbon sources. While this study spans less than a decade, it draws attention to the fact that rangelands in more arid and semiarid environments may be carbon sources, and management that may enhance or diminish this effect should be evaluated. Additionally, because many of the rangelands within the US are in arid and semiarid environments, the volatilization and sequestration of soil inorganic carbon (SIC) is an important form of carbon to consider when evaluating whether a rangeland is a source or sink (Follett *et al.*, 2001).

Management that stimulates microbial activity or plant growth may impact the SIC pool in dryland systems (Denef *et al.*, 2008). Reeder et al (2004) propose that grazing could increase SIC through stimulating root exudation. Increased production of organic acids in root exudates may enhance the weathering of calcium-bearing minerals, releasing Ca^{2+} into the soil profile that binds with HCO_3^- deeper in the soil profile to precipitate $CaCO_3$ (Lal & Kimble, 2000). Few other studies evaluate grazing's impact on SIC. More empirical evidence is needed to better understand whether the interaction between grazing and SIC increases or decreases SIC in semiarid and arid rangelands.

Soil inorganic carbon, in the form of carbonates, is a principal feature of many arid and semi-arid rangelands (Monger & Martinez-Rios, 2001; Reeder *et al.*, 2004). In arid areas of Arizona and southern New Mexico, SIC exceeds soil organic carbon (SOC) by a factor of ten (Monger & Gallegos, 2000). Recent studies have argued that carbonate biominerals precipitated with the influence of biological processes represent a greater contribution to the $CaCO_3$ pool on

Earth than physiochemical $CaCO_3$ (Skinner, 2005; Bindschedler *et al.*, 2016). While sequestration rates for inorganic carbon are substantially lower compared to organic carbon sequestration rates, the carbon that is stored as inorganic carbon may have a longer residence time of 30,000-90,000 years (Lal, 2003), so it is important to understand management implications for SIC storage.

In addition to management effects on SIC, abiotic factors such as precipitation and soil parent material have a strong influence on SIC. Monger and Martinez-Rios (2001) explain that the precipitation of $CaCO_3$ can be the result of the weathering, dissolution, and illuviation of $CaCO_3$ from soil surface layers to subsoil layers because there isn't enough precipitation to flush the Ca^{2+} from the soil profile, and it reprecipitates deeper in the soil. Soil inorganic carbon greatly increases when the parent material is limestone, however soil carbonates that form in non-calcareous parent material have highlighted the importance of biogenic precipitation of carbonates through exogeneous sources of Ca^{2+} (e.g., rain or calcium silicates) as well as the biomineralization of Ca^{2+} from roots and microorganisms (Bretz & Horberg, 1949; Gile *et al.*, 1965).

Biomineralization is the process in which biological activity forms minerals that contain both mineral and organic components (Weiner & Dove, 2003; Bindschedler *et al.*, 2016). Roots, bacteria, and fungi play a role carbonate precipitation (Monger & Gallegos, 2000; Skinner, 2005; Burford *et al.*, 2007; Bindschedler *et al.*, 2016), through two mechanisms of biomineralization; biologically induced mineralization (BIM) (Dupraz *et al.*, 2008) and organomineralization (Reitner *et al.*, 2011; Bindschedler *et al.*, 2016). Biologically induced mineralization occurs when biological activity induces physiochemical changes that create an environment in which biominerals can nucleate and grow (Dupraz *et al.*, 2008), whereas organomineralization involves an organic matrix that influences the morphology and composition of crystals through the interactions of minerals and organic matter (Dupraz *et al.*, 2008).

In order for $CaCO_3$ to precipitate, there must be high concentrations of Ca^{2+} and a high pH (Monger & Martinez-Rios, 2001). Recent studies have shown evidence of BIM from roots and microbes through processes that can alter the alkalinity, pH, and calcium concentrations. Through exudation of low molecular weight organic acids (LMWOA) and respiration, fungi can decrease the pH of the surrounding environment, thus contributing to the precipitation of $CaCO_3$. In addition to decreasing the pH, there is evidence to show that fungi can alter calcium concentrations. In order for fungal apical growth, the apex must have a high calcium concentration. Through the regulation of Ca^{2+} both actively and passively, fungi maintain a high calcium concentration in the apex compared to the cytoplasm (Jackson & Heath, 1993).

There is still much to be understood regarding the direct and indirect effects of grazing on SIC. While it is clear that SIC is a key feature of arid and semiarid rangelands, little research has examined grazing's effect on SIC. Current literature evaluates grazing's mediating effect on soil organic carbon (SOC) (Mcsherry & Ritchie, 2013; Lu *et al.*, 2017; Zhou *et al.*, 2017; Abdalla *et al.*, 2018). From these recent meta-analyses, it is clear that abiotic factors such as precipitation and soil texture, and biotic factors such as plant composition and root biomass all mediate grazing's effect on SOC. These factors may also mediate grazing's effect on SIC, however those effects are less understood.

Most studies that evaluate grazing effects have been conducted at a pasture-scale, while few landscape-scale studies have been performed (Silver *et al.*, 2010; Hewins *et al.*, 2018). There is high spatial and temporal variation across rangelands (Booker *et al.*, 2013), and spatial heterogeneity must be accounted for when understanding SOC and SIC dynamics (Bird *et al.*, 2002). Additionally, there are few empirical studies that examine grazing effects across semiarid rangelands in the United States. Most grazing studies occur in temperate climates. More long-term studies in cold and hot regions are needed to assess grazing's effect on belowground C cycling on various spatial and temporal scales (Zhou *et al.*, 2017).

This study samples across 100,000 acres of semiarid grazed rangeland to measure the grazing effects on SOC and SIC across a landscape that includes a gradient of mean annual precipitation (280mm - 610mm) and five distinct soil series. By incorporating the spatial heterogeneity inherent in rangelands, this study examines how biotic and abiotic factors mediate the impacts of livestock grazing on SOC and SIC across a semi-arid landscape. We hypothesize that biotic factors such as net primary production, grazing, and plant composition will have a greater effect on SOC, while abiotic factors such as precipitation and texture will have a greater effect on SIC.

Research Questions

Environmental gradients across semiarid rangelands in Northern Arizona were sampled to answer the following questions:

(1) What are the main drivers of soil carbon storage?

(2) What is the effect of grazing management on soil carbon?

(3) Does soil carbon storage differ at the surface and 20 cm below the soil surface?

To address these research questions, multivariate analyses were performed using general linear modeling as well as structural equation modeling. Figure 1 illustrates the working *a-priori* model that was used to guide the experimental design. The *a-priori* model was developed from an extensive literature review, prior research, and general ecological knowledge of the system

(Grace and Bollen, 2008). Dashed boxes represent conceptual variables without an exact specification for how they would be represented in final statistical models. Arrows between variables illustrate a hypothesized mechanistic relationship (Table 1). As mentioned previously, abiotic and biotic factors mediate the impact of grazing on soil carbon storage and a structural equation model is able to measure direct and indirect effects of interacting variables to gain a broader understanding of the multiple interactions occurring across the rangeland.

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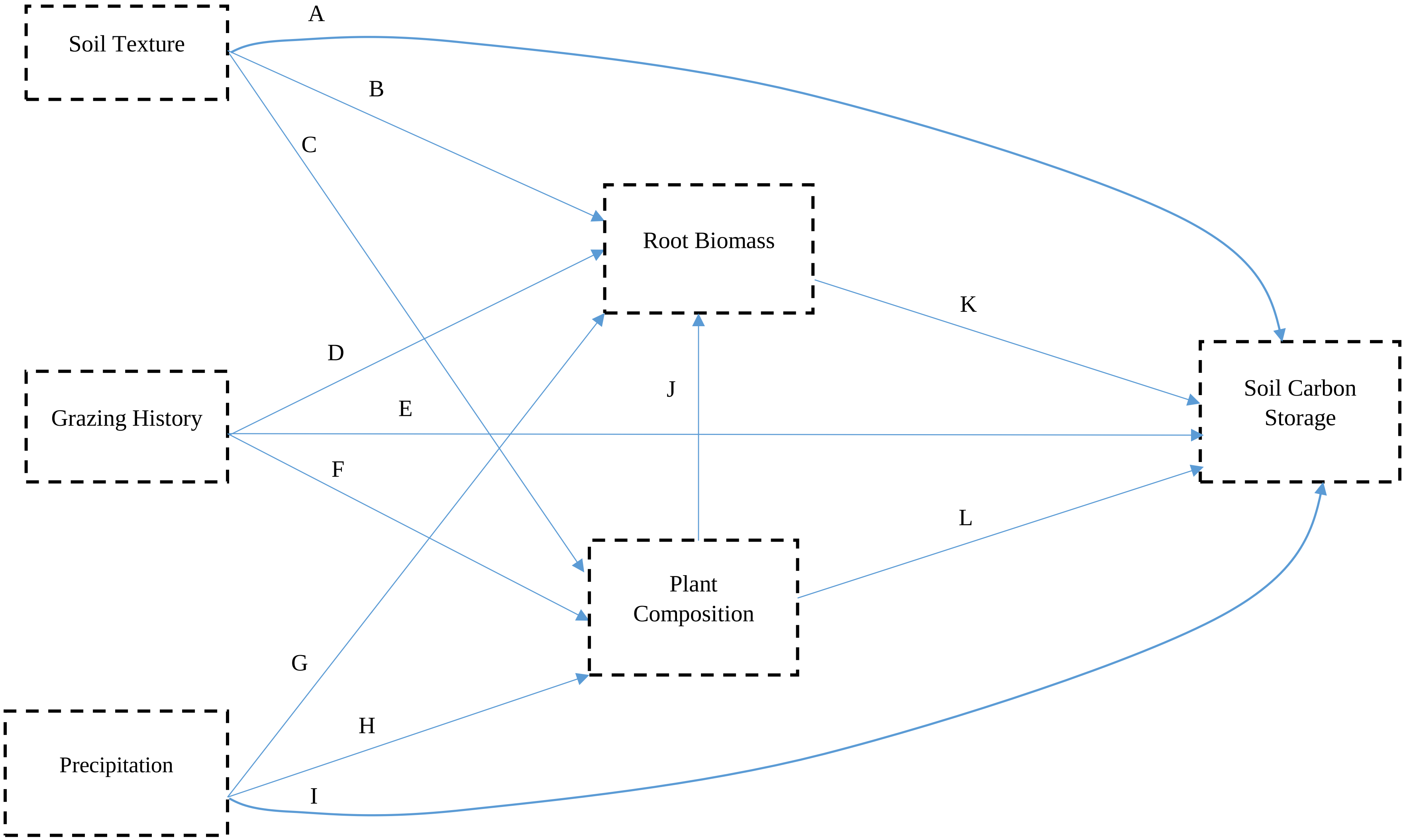

Figure 1. *A-priori* Structural Equation Model hypothesizing the influence of abiotic and biotic factors on soil carbon storage.

Pathway	**Alpha Code**	**Hypothesized Mechanism**	**Observed Pattern**
Texture → Soil Carbon Storage	A	Basalt derived clay-rich soil will have more SOC because clays form aggregates that protect soil carbon from microbial decomposition. Limestone derived sand-rich soil will have more SIC because of high CaCO$_3$ content of the parent material	Clay rich, wet areas had higher SOC and less SIC than sand-rich, dry areas in both the surface and subsurface.
Texture → Root Biomass	B	Fine textured soils have a higher water holding capacity and more roots than coarse textured soil	On the surface, root biomass was higher in clay-rich wet areas than sand-rich, dry areas. The relationship was opposite in the subsurface.
Texture → Plant Composition	C	Water holding capacity varies with soil texture and plant taxa vary in their water requirements	Higher cover of C4 grasses were observed in sand-rich dry areas than clay-rich wet areas
Grazing History →Root Biomass	D	Grazing will increase root biomass through die-back and regrowth	**Grazing had little influence on root biomass**
Grazing History → Soil Carbon Storage	E	Root die back and compensatory growth increases belowground organic matter	Grazing had a slight positive influence on SOC and SIC in the surface but not subsurface
Grazing History →Plant Composition	F	C$_4$ grasses will increase with grazing because they are generally more resilient to grazing pressure than C$_3$ grasses	Grazing increased the cover of C4 grasses
Precipitation → Root Biomass	G	Higher precipitation will generate higher net primary production and root biomass	See B
Precipitation → Plant Composition	H	Decreased precipitation will increase the abundance of drought tolerant plants such as C$_4$ grasses and shrubs	See C
Precipitation → Soil Carbon Storage	I	Increased precipitation will increase primary production and increase belowground carbon inputs (higher SOC), but it will increase leaching and result in lower SIC	See A

Plant Composition → Root Biomass	J	Plant taxa vary in their allocation to roots, the C_4 grass *B. gracilis* has a higher root:shoot ratio than other grasses	Root biomass was positively correlated with C4 grass cover
Root Biomass → Soil Carbon Storage	K	Increased root biomass will increase soil carbon storage	Surface root biomass had a weak positive correlation with SOC and a stronger negative correlation with SIC. **Subsurface root biomass has a weak negative correlation with both SOC and SIC**
Plant Composition → Soil Carbon Storage	L	*B. gracilis* increases fine root biomass and root turnover.	**On the surface, C_4 grass cover had a weak negative correlation with SOC and SIC; and, in the subsurface, a weak positive correlation with SOC and a negative correlation with SIC**

Table 1. Hypothesized pathways associated with the *a priori* model and hypothesized mechanisms for the influence of biotic and abiotic factors on soil carbon. Observed patters in bold font did not support the hypothesis.

CHAPTER 2:

Abiotic and Biotic Mediation of Grazing Impacts on Soil Carbon in Northern Arizona

By

Megan Marie Deane McKenna, Nancy Collins Johnson, Deborah Huntzinger, Thomas Sisk

Introduction

Human activities have increased the amount of atmospheric carbon dioxide (CO_2) from 280 ppm to 400 ppm over the last 270 years (IPCC 2014). As CO_2 levels rise, it is important to understand various atmospheric carbon mitigation strategies. Soils are the largest terrestrial carbon sink (Chapin *et al.* 2009) and land management practices that increase soil carbon have been proposed as strategies to mitigate atmospheric carbon levels (Lal *et al.* 2003).

Grazing has been proposed as a strategy to increase soil carbon storage on rangelands, however much uncertainty and disagreement remains regarding the impact of grazing on soil carbon storage across rangelands. Some studies have found that grazing increases soil organic carbon (SOC) storage through mechanisms such as increased plant production and belowground inputs (Johnson and Matchett 2001; Conant *et al.* 2003; Pineiro *et al.* 2010), increased root turnover (Derner *et al.* 2006), and a change in vegetation composition due to an increase in C_4 grasses (Reeder *et al.* 2004). In contrast, a number of studies have found grazing has negative effects on SOC due to removal of plant biomass (Zhou *et al.* 2017), decreased soil aggregate stability (Hamza and Anderson 2005; Steffens *et al.* 2008) and shifts in the microbial community (Eldridge *et al.* 2017). Other studies suggest that grazing is a only a minor factor in the regulation of soil carbon because abiotic factors such as precipitation and soil properties are the primary controllers of soil carbon storage (Briske *et al.* 2008; Paruelo *et al.* 2010; Ingram *et al.* 2008; Svejcar *et al.* 2008; Booker *et al.* 2013).

Meta-analyses

Recently, several meta-analyses have evaluated results from studies across the world to identify trends in the effects of grazing on soil carbon storage across varying climates, plant communities, and soil types (Mcsherry and Ritchie 2013; Lu *et al.* 2017; Zhou *et al.* 2017; Abdalla *et al.* 2018). All studies found that climatic variables, such as mean annual temperature and mean annual precipitation, were the main determinants in the grazing effect on soil carbon storage (Mcsherry and Ritchie 2013; Lu *et al.* 2017; Zhou *et al.* 2017; Abdalla *et al.* 2018). McSherry and Ritchie (2013) found that the interaction between precipitation and soil texture explained the most variation of the effect size of grazing on soil carbon storage. They were also able to uncouple precipitation and texture and found the greatest grazing effect in dry, clay-rich soils and in wet, sandy soils; reduced carbon storage was observed in clay-rich soils with higher precipitation. Abdalla et al., (2018) also found that abiotic factors determined if grazing intensity had a positive or negative effect on SOC, where all grazing intensities increased SOC storage in moist/warm regions, while only light grazing increased SOC storage in dry/warm conditions and moderate to high grazing intensities decreased SOC.

In addition to climatic factors, McSherry and Ritchie (2013) found that the interaction between grazing intensity and the vegetation composition captured the second highest proportion of variance for SOC. These results suggest that increased grazing intensity increases SOC due to a shift in plant communities from C_3 dominated grasslands to C_4 dominated grasslands as grazing intensity increases. Abdalla et al. (2018) found similar results; C_4 dominated grasslands were found under higher grazing intensities and contributed to increased SOC. These results were not found in other meta-analyses. In the Tibetan plateau there are not C_4 grasses. Zhou et al. (2017) found that increased grazing intensity led to decreased SOC storage possibly due to decreased aboveground inputs removed by cattle. Lu et al. (2017) found that increased grazing intensity decreased SOC storage through the removal of palatable grasses and sedges that provided high-quality litter for decomposition belowground. Additionally, they concluded that moderate grazing increased plant diversity compared to low-intensity and high-intensity grazing (Lu et al., 2017).

Theoretical Framework for soil carbon storage across semi-arid rangelands

Theoretical models, such as the state-and-transition model, provide a framework to examine ecological dynamics across semi-arid and arid rangelands in order to better understand the effects of grazing management. State-and-transition models incorporate both equilibrium and non-equilibrium models along a continuum (Briske *et al.* 2003) (Table 1). Incorporating both models along a continuum provides a framework to evaluate abiotic and biotic factors within an ecosystem and determine where along the continuum the ecosystem falls. While equilibrium models stress the tight coupling of plant-herbivore systems and predict the degradation of rangelands to be largely attributed to excessive stocking rates (Derry and Boone 2010), non-equilibrium models attribute changes to rangeland ecology to stochastic abiotic factors such as drought that impact animal population rates (Vetter 2005; Derry and Boone 2010).

The state-and-transition model describes the dynamics of factors along a precipitation gradient (Vetter 2005; Booker *et al.* 2013). Arid and semi-arid environments have more stochastic rainfall patterns compared to mesic environments (Svejcar *et al.* 2008) and net primary production increases with timely precipitation (Schwinning and Sala 2004). Along the continuum of the state-and-transition model, semi-arid rangelands fall more along the non-equilibrium systems. However, that does not mean that all ecological dynamics are explained within the non-equilibrium model. If only the non-equilibrium model is considered, it negates the impact of management (Vetter 2005) and could suggest that stocking rates are irrelevant to ecological dynamics. Instead, it is important to recognize the biotic regulation that livestock provide can help maintain a steady state or cross a threshold and cross into another state.

Abiotic Factors

Precipitation

Precipitation has been found to have the largest influence on soil carbon in numerous studies (Derner and Schuman 2007; Hewins *et al.* 2018). Generally, net primary production is the primary source for SOC and increased precipitation increases aboveground net primary production that in turn increases inputs belowground (Burke *et al.* 1989). Derner and Schuman (2007) found that soil carbon storage from 0-30cm decreased under grazing treatments when precipitation was greater than 600mm due to increased microbial decomposition. Precipitation may also have an impact on the storage of soil inorganic carbon (SIC). For example, Monger and Martinez-Rios (2001) explain that the precipitation of $CaCO_3$ can be the result of the weathering, dissolution, and illuviation of $CaCO_3$ from soil surface layers to subsoil layers because there isn't enough precipitation to flush the Ca^{2+} from the soil profile, and it reprecipitates deeper in the soil.

Soil Texture

The clay content of soil is often positively correlated with SOC (Burke *et al.* 1989; Jobbágy and Jackson 2000). Clay-rich soils hold more organic carbon than sandy soils due to mineral sorption that decreases organic matter mineralization (von Lützow *et al.* 2006; Han *et al.* 2016), increased aggregate formation which protects SOC from microbial decomposition (Stockmann *et al.* 2013), and increased microbial biomass that excrete microbial metabolic products that bind clay particles (Han *et al.* 2016). In contrast, sandy soils have larger sized particles and do not form the same bonds with surfaces and metal ions that occur in clay-rich soils (von Lützow *et al.* 2006). As a result, there is less stabilization of organic matter on the surface of minerals and less protection for the SOC from microbial decomposition. In addition, soil texture will affect water availability to plants (Brady and Weil 2010). Clay-rich soils have a higher water holding capacity compared to sandy soils and this can affect root biomass and species distribution across a landscape.

Soil Inorganic Carbon

A principal feature of many arid and semi-arid rangelands is soil inorganic carbon (SIC) in the form of carbonates (Monger and Martinez-Rios 2001; Reeder *et al.* 2004). While sequestration rates for inorganic carbon (1 to 12 g $CaCO_3/m^2/yr$) (Gile et al., 1981; Gile et al., 1981; Schlesinger, 1985) are substantially lower compared to organic carbon sequestration rates (0.11 to 3.04 Mg C/ha/yr) (Conant et al., 2001), the carbon that is stored as inorganic carbon has a long residence time of 30,000-90,000 years (Lal 2003), so it is important to understand management implications for SIC storage. Reeder et al (2004) propose that grazing could increase SIC through stimulating root exudation. Increased production of organic acids in root exudates enhance the weathering of calcium-bearing minerals and release Ca^{2+} into the soil profile. Also, CO_2 from root respiration reacts with water to form HCO_3^- that combines with Ca^{2+} released from the weathering minerals. Water will move ions from plant root zones to the subsoil where a higher pH facilitates precipitation of $CaCO_3$ (Lal and Kimble 2000), thus increasing SIC storage.

Depth

Depth is an important factor to consider when evaluating carbon storage. Carbon that is deeper in the soil profile is most likely going to be older (Stockmann *et al.* 2013). This is due to a number of mechanisms. It has been proposed that SOC deeper in the soil profile has more protection from microbial decomposition due to mineral adsorption (Han *et al.* 2016) as well as a lack of a fresh carbon source that could provide microbes with energy needed to decompose recalcitrant SOC deeper in the soil profile (Jobbágy and Jackson 2000; Fontaine *et al.* 2007). Cellulose is a compound released by roots, and it provides microbes with energy used in decomposition (Fontaine *et al.* 2007). It has been proposed that root depth may determine the vertical distribution of SOC due to the release of exudates within the soil profile (Jobbágy and Jackson 2000).

Much research has been focused on understanding the stabilization mechanisms of SOC throughout the depth profile while less research has examined SIC. Arid and semi-arid climates are characterized by high concentrations of pedogenic SIC (Lal 2003), especially deeper within the soil profile (Denef *et al.* 2008). Within arid and semi-arid sites that have a limestone parent material, carbonates, also called caliche, stored within the soil profile because precipitation is low and CaCO3 deposits do not leach out of the bottom. Management that stimulates microbial activity or plant growth may impact the SIC pool in dryland systems (Denef *et al.* 2008). Through the process of biomineralization, bacteria and fungi have the ability to precipitate $CaCO_3$ in the presence of excess Ca^{2+} (Monger *et al.* 1991; Burford *et al.* 2007; Bindschedler *et al.* 2016).

Biotic Factors

Vegetation Composition

While soil texture and precipitation are important abiotic drivers of soil carbon storage, vegetation composition has also been recognized as an important biotic factor contributing to SOC and SIC in rangelands (Jobbágy and Jackson 2000; Reeder *et al.* 2004). Many studies have found that grazing increased the prevalence of C_4 grasses, such as *Bouteloua gracilis* (Frank *et al.* 1995; Conant *et al.* 2001; Reeder *et al.* 2004; Derner *et al.* 2006). This is due to selective grazing of C_3 grasses compared to C_4 resulting in an increased proportion of C_4 grasses (Hart

2001). Reeder et al., 2004 found that *B. gracilis*, a C_4 grass, increased SOC under different grazing treatments. One proposed mechanism is that, compared to other grasses, *B. gracilis* has a greater root-to-shoot ratio, allocating more biomass belowground, and thus increasing SOC. In addition, Dyer and Bokhari (1976) found that when *B. gracilis* is grazed, there is an increase in belowground respiration and root exudation. This allocation of resources belowground could lead to increased SOC storage within the rhizosphere.

Landscape-scale

Most studies that evaluate grazing effects have been conducted at a pasture-scale, while few landscape-scale studies have been performed (Silver *et al.* 2010; Hewins *et al.* 2018). There is high spatial and temporal variation across rangelands (Booker *et al.* 2013), and spatial heterogeneity must be accounted for when understanding SOC and SIC dynamics (Bird *et al.* 2002). Additionally, there are few empirical studies that examine grazing effects across semi-arid rangelands in the United States. Most grazing studies occur in temperate climates. More long-term studies in cold and hot regions are needed to assess grazing's effect on belowground C cycling on various spatial and temporal scales (Zhou *et al.* 2017).

My thesis research is an extension of a previous study (Roberts et al., 2016) that measured grazing effects on SOC in clay-rich soils at the pasture scale. My research expands the study area to 100,000 acres of semi-arid grazed rangeland to observe grazing effects on SOC and SIC across a landscape that includes a gradient of mean annual precipitation (280mm - 610mm) and five distinct soil series. By incorporating the spatial heterogeneity inherent in rangelands, this study examines how biotic and abiotic factors mediate the impacts of livestock grazing on SOC and SIC across a semi-arid landscape. We hypothesize that biotic factors such as net primary production, grazing, and plant composition will have a greater effect on SOC, while abiotic factors such as precipitation and texture will have a greater effect on SIC.

Research Questions

I studied environmental gradients in semi-arid rangelands in Northern Arizona to answer the following questions:

(1) What are the main drivers of soil carbon storage?

(2) What is the effect of grazing management on soil carbon?

(3) Does soil carbon storage differ at the surface and 20 cm below the soil surface?

To address these research questions, multivariate analyses were performed using general linear modeling as well as structural equation modeling. Figure 2 illustrates the working *a-priori* model that was used to guide the experimental design. The *a-priori* was developed from an extensive literature review, prior research, and general ecological knowledge of the system (Grace and Bollen, 2008). Dashed boxes represent conceptual variables without an exact specification for how they would be represented in final statistical models. Arrows between variables illustrate a hypothesized mechanistic relationship (Table 2). As mentioned previously, abiotic and biotic factors mediate the impact of grazing on soil carbon storage and a structural equation model is able to measure direct and indirect effects of interacting variables to gain a broader understanding of the multiple interactions occurring across the rangeland.

Methods

Study Area

The study area is located 35 miles southeast of Flagstaff, Arizona (34°55′50″ – 35°6′52″N, 111°26′33″ – 111°2′53″W). The sites are distributed across 100,000 acres within the Diablo Trust ranches that vary along a precipitation gradient (Figure 3). There are six distinct locations within the study area. Locations 1 and 2 were located from 2170 – 2200 m with annual precipitation of approximately 610 mm. Locations 3, 4, 5, and 6 were located from 1650 – 1850 m with annual precipitation of approximately 280 mm. Soils at locations 1 and 2 were classified as fine, mixed, superactive, mesic Pachic Arguistolls (Appendix A). Soil at location 3 was classified as Deama (Loamy-skeletal, carbonatic, mesic Lithic Calciustolls). Soils at locations 4 and 5 were classified as Winona (Loamy-skeletal, carbonatic, mesic Lithic Ustic Haplocalcids). Soil at site 6 was classified as Epikom (Loamy, mixed, superactive, mesic Lithic Haplocambids) Soil Series. All soils are classified as well-drained soils, the difference is their parent material; Deama soils are derived from limestone, Winona soils are derived from limestone and calcareous sandstone, and Epikom soils are derived from sandstone, mudstone, and shale.

Experimental Design

Stratified random sites were selected based on the locations of fence-lines or grazing exclosures that have been established for at least 20 years. The fence-line separated areas that had been excluded from grazing from areas that have experienced moderate grazing. Both ranches practice moderate planned grazing using a rotational pasture system. This means they aim for 40-60% utilization within each pasture. In addition to a grazing exclusion treatment, sites were also selected to capture the variation in soil texture as well as precipitation across the landscape. A total of 60 sites were proportionally distributed along 6 fence lines and randomly placed using values generated from randomizer.org. Sites were placed at least 100 m from each other to ensure spatial independence. This is the spacing that SoilGrids uses to map soils across the world. Cattle tend to run along fence-lines and higher levels of compaction often occur adjacent to fences. In order to reduce this "fence line effect," samples were placed at least 8 m away from the fence.

Bison Sites

Research prior to sampling, indicated bison grazing on Raymond Wildlife Area (sites 3 and 4) was minimal because there were only 20 head of bison across 14,000 acres. These sites were originally going to be used to compare exclusion from grazing (bison side) to grazing because the Deama Soil Series could be added to the soil variation. This was the only location within the Diablo Trust where the Deama Soil Series was found adjacent to a grazing exclosure. One of the goals of this research was to capture as much soil variation as possible, so this was a site that could add an additional variation by adding a soil series. Once sites were visited to collect samples, fresh tracks and manure indicated that bison had recently used the area. Sampling from this area was immediately stopped and the design was reconfigured to redistribute the remaining sites proportionally across the remaining fences. This conclusion was corroborated by bison tracking data. Samples were collected from a total of 9 sites. The interaction between bison sites x grazing history was evaluated using a general linear model. Grazing on the bison sites was not significantly different from other sites. As a result, all bison sites were included in the analysis.

Collection of Vegetation and Soil Samples

All samples were collected within a two week period in August of 2017. One vegetation sample and two soil samples were collected from the grazed and un-grazed sides of 60 randomly selected fence-line sites for a total of 120 vegetation samples and 240 soil samples. At each randomly assigned site, a 0.25 m^2 quadrat was thrown behind the back at least 8 m away from the fence line. All vegetation within the quadrat was clipped, sorted, identified to species and weighed. Final measurements grouped plant biomass into four functional groups: C_4 grass, C_3 grass, forbs, and shrubs.

Soil samples were collected directly beneath each vegetation sample at depths of 0 – 5 cm and 20 – 25 cm. Soils samples were collected using 88.72 mL bulk density metal cylinder (4.75 cm x 5.05 cm) using a technique developed in collaboration with Natural Resource Conservation Service to facilitate an accurate measurement of bulk density. The metal cylinder was placed in the middle of the vegetation quadrat. A wooden block was placed on top of the cylinder used to protect the cylinder as it was hammered into the soil. Once the cylinder was flush with the soil surface, a 27 – 30 cm hole was dug approximately 8 cm from the cylinder's edge so that a metal plate could be inserted below the cylinder such that the soil-filled cylinder could be extracted without losing the soil inside. Any soil that extended beyond the ends of the cylinder was removed using a sharp edge and the soil-filled cylinder was placed into an air-tight, labeled tin and transported to the laboratory to be weighed, oven dried at 105^{o}C for at least 48 hours and re-weighed to calculate soil moisture.

To collect subsurface soil samples, a place marker was positioned 20 cm below the surface sample. The soil above the marker was removed using a sharp narrow shovel and hand trowel. A flat surface was created to the side of the marker so the cylinder could be placed on top. A wooden block was placed on top of the cylinder and the cylinder was hammered until it was flush with the flat surface. The cylinder was extracted with a metal plate below, the excess soil was shaved from the ends, and the soil-filled cylinder was placed in a labeled air-tight tin and processed as describe above.

Bulk Density and Roots

Soil bulk density (volume/mass) was corrected by removing the volume and weight of rocks according to methods described by Throop et al., 2011. Soil samples were passed through sieves with 1 mm and 2 mm openings. Rocks were extracted, weighed, and their volume was measured using water displacement. Density of rocks was subtracted to calculate corrected soil bulk density (Throop et al., 2011). Roots were also removed from the sieves, dried and weighed.

$$BD = \left(\frac{M_s}{V_s}\right) - \left(\frac{M_r}{V_r}\right) \qquad \textit{Equation \#1}$$

Where BD is bulk density, M_s is mass of dried soil, V_s is the known volume from the cylinder that was used to collect soil samples, M_r is the mass of the rocks, and V_r is the volume of the rocks, measured using water displacement.

%C, %N, $\delta^{13}C$, and $\delta^{15}N$

All sieved samples were split using a soil microsplitter (Carpco Inc., model SS-16-3) and ground using a mortar and pestle that was cleaned with ethanol between each sample. Soil sub-samples that weighed 40 mg were placed in foil tins and sealed by rolling them into a ball. The samples were then analyzed for %C, %N, δ^{13}C, and δ^{15}N using the Elemental Analyzer (ECS 4010, Costech Analytical, Valencia, California, USA) coupled to a Delta V Advantage Stable Isotope Ratio Mass Spectrometer (Delta V, Thermo Scientific) via a Conflo IV (Finnigan, Bremen, Germany).

Soil Organic Matter and Soil Inorganic Carbon

All samples were analyzed for SOC and SIC following the protocol from the Sedimentary Records of Environmental Change Lab at Northern Arizona University. Soil samples were dried for at least 12 hours at 105°C prior to combustion. To measure soil organic matter (SOM), samples were burned at 550^{o}C for 5 hours and weighed. To measure SIC, the same samples were then placed back in the muffle furnace and burned at 950^{o}C for 5 hours. SOM was calculated using the following:

$$SOM = \left(\frac{DW_{105} - DW_{550}}{DW_{105}}\right) * 100 \qquad \textit{Equation \#2}$$

Where SOM represents soil organic matter (as a percentage), DW_{105} represents the dry weight of the sample before combustion, and DW_{550} is the dry weight of the sample after heating to 550^{o}C.

In the second step, soil inorganic carbon (SIC) was calculated using the following:

$$SIC = \left(\frac{DW_{550} - DW_{950}}{DW_{105}}\right) * 100 \qquad \textit{Equation \#3}$$

Where SIC represents soil inorganic carbon (as a percentage), DW_{550} is the dry weight of the sample after combustion of organic matter at 550^{o}C, DW_{950} represents the dry weight of the sample after heating to 950^{o}C, and DW_{105} is the initial dry weight.

Total carbon (g/m^2) was calculated using the following:

$$TC_{g/m^2} = \left(\frac{BD * C}{100}\right) * D * 10{,}000 \qquad \textit{Equation \#4}$$

Where BD is bulk density (g/cm^3), C is the %C calculated from the mass spectrometer, D is depth of 5 cm, and 10,000 is scaling from cm^2 to m^2.

Soil inorganic carbon (g/m^2) was calculated using the following:

$$\%SIC_{g/m^2} = \left(\frac{BD * SIC}{100}\right) * D * 10{,}000 \qquad \textit{Equation \#5}$$

Soil organic carbon (g/m^2) was calculated using the following:

$$\%SOC_{g/m^2} = \left(\frac{BD * SOM}{100}\right) * 0.58 * D * 10{,}000 \qquad \textit{Equation \#6}$$

Where 0.58 is a coefficient used to convert SOM to SOC (Lal 2004).

Texture

All sieved samples were split to ensure an equal distribution of particle size within the sample. Samples were prepared to remove all organics using the Northern Arizona University Sedimentary Records of Environmental Change Lab Protocol. Grain size was analyzed via laser diffraction using the LS-230 Beckman Coulter Particle Analyzer. Size classes corresponded to the following categories: clay, silt, very fine sand, fine sand, medium sand, coarse sand, and very coarse sand.

Climatic variables

Climatic variables were obtained from PRISM (PRISM Climate Group, Oregon State University, http://prism.oregonstate.edu, created 4 Feb 2004). PRISM provides free climate data for ecological modeling and GIS. Precipitation data are an average over the last 30 years. All other data were measured in the field.

Statistical Analysis Approaches

Texture

Differences among the texture was calculated using a Principal Components Analysis (PCA) and Bray-Curtis distances in PC-ORD (PC-ORD, Multivariate Analysis of Ecological Data, Version 5. MjM Software, Cleneden Beach, Oregon, U.S.A). Because texture was measured with a particle size analyzer, the results proportionally split the particles into three size classes. Using PCA as a data reduction tool, the texture was simplified as a single variable for the surface and subsurface within the structural equation model (McCune and Grace 2002). The distance between the points show how similar or dissimilar they are; the greater the distance, the more dissimilar (McCune and Grace 2002). The principal component values can be used as a variable within the structural equation model where positive values indicate the sample is high in sands and negative values indicate the sample is high in clays.

Vegetation Composition

Differences among the community were visualized using non-metric multidimensional scaling (nMDS) and Relative Sorenson distance in PC-ORD. The vegetation community was analyzed with nMDS because non-metric multidimensional scaling does not treat the absence of a species or functional group between sites as a similarity (Clarke, 1993), and thus is a better measurement for vegetation composition across a heterogeneous group of sites. In addition, nMDS allows for relativizations among sites (McCune and Grace 2002). The Relative Sorenson distance measure is mathematically equivalent to the Bray-Curtis distance, however, it is relativized among species to shift the emphasis to the proportions of species instead of absolute abundances (McCune and Grace 2002).

General linear models

To assess linearity, the relationships between SOC, SIC, texture, percent C_4 grasses, and roots were examined using a pairs plot. The strengths of the relationships were measured using Pearson correlation coefficients. A Pearson correlation plot was created in R using the corrplot package.

General linear models assume normally distributed response variables. All response variables were tested for normality. Surface SOC was normally distributed and did not require any transformation. Subsurface SOC, surface SIC, and subsurface SIC all had positive skews. Tukey transformations were performed on the surface and subsurface SOC and SIC (Tukey 1977). When the results from the variance tests of untransformed data offered the same interpretation, in terms of p-values and relative magnitude of test values, then results from untransformed data were presented.

For each response variable, a general linear model was constructed using fixed and random effects and run in JMP (JMP®, Version 13.0, SAS Institute Inc., Cary, NC 1989-2007). The fixed factors within the model were grazing history and depth and a two-way interaction between grazing history and depth. The random factor was defined as the pair of the samples taken on either side of the fence. By including the pair as a random factor, the model was able to account for the local variation that occurred between the pair. Because precipitation and texture were highly correlated in the models, within the general linear model, only texture was included because it was a measured variable while precipitation was a modeled variable from PRSIM.

Structural Equation Models

Structural equation models (SEM) were used to calculate the direct and indirect effects of abiotic and biotic factors on the surface and subsurface soil carbon, and also to test our hypothesized casual network of relationships among the factors (Grace 2006). While a multivariate linear regression can be used to calculate β values for both abiotic and biotic factors, it does not allow indirect path coefficients to be calculated which help to explain interactions among the factors. In this sense, a multivariate linear regression can provide exploratory results, but lacks the ability for confirmatory tests that evaluate multivariate hypotheses (Grace 2006). Similar to multivariate linear regressions, SEMs assume normally distributed residuals for the response variables and linear relationships. All residuals were tested for normality following the procedure for the multiple linear regression.

A good model fit indicates that the model has the ability to reproduce the data. For SEMs, it is recommended to use multiple tests for fit because each test has its own strengths and weaknesses (Grace 2006). χ^2, p-values, root mean square error of approximation (RMSEA), and Joreskög's goodness of fit index (GFI) were used assess model fit. High p-values for the χ^2, RMSEA values close to zero and GFI values close to 1 indicate good fit.

The final SEM differs from the *a priori* model because after running the *a priori,* depth was found to be a large driver in explaining the variance in soil carbon and was added to the model. Instead of representing an exogenous variable, depth was incorporated into two response variables, creating surface and subsurface organic and inorganic carbon. Additionally, precipitation and soil texture were found to be highly correlated and could not be included as separate exogenous variables. Instead, they were combined into a composite variable that represented abiotic factors. Composite variables represent the combined effects of two conceptually similar variables (Grace, 2006), in this case, precipitation and soil texture are represented as abiotic factors. Finally, plant composition was represented by looking at the proportion of C_4 grasses present at each site because after running a nMDS on the vegetation community, it was found that C_4 grasses capture 56% of the variation of the first axis.

Results

Soil texture

Principal Components Analysis performed on the surface and subsurface soil texture for three size classes; sand, silt, and clay showed that Axis 1 captured 93% of the variation (Table S1) and the scree plot showed a significant drop in stress from one to two axes, but minimal decrease between axis 2 and 3 (Figure S3). Clay and silt were on the opposite side from sands showing that the points on the left side of the graph are high in fine particle sizes and the points on the right are high in sand particles (Figure 4).

Vegetation

Non-metric multidimensional scaling performed on four plant functional groups; C4 grasses, C3 grasses, Shrubs, and Forbs, showed that Axis 2 captured 54% of the variation (Figure 5). The scree plot showed a significant drop in stress from one to two axes, but minimal decrease between axes 2 through 4 (Figure S4). The scree plot's final stress for a 2-dimensional solution was 12.10491. Values below 20 generally indicate a stable solution (Grace and McCune 2002). The results from this nMDS Ordination showed that C_4 grasses accounted for 53% of the variance in the dissimilarity of the vegetation composition (Table S3). As a result, C_4 grasses were used as the endogenous variable within the SEM.

Pearson Correlation

A Pearson correlation matrix quantitatively verifies the correlations between all measured variables. Variables were separated by depth. All relationships were significant except for certain relationships with surface and subsurface roots. Positive significant relationships are represented with blue and negative significant relationships are represented in red. Stronger relationships are represented with darker colors.

Soil Organic Carbon

Soil texture (F = 188.6915, p-value <0.001), depth (F= 8.5985, p-value = 0.0038), and the interaction between depth and texture (F = 34.0782, p-value <0.001) were significant predictors of SOC (Appendix, Table xx). Grazing history did not have a significant effect on SOC (F = 0.8551, p-value = 0.3565). The significant interaction between depth and texture is shown in Figure 7.

Because depth, texture, and the interaction between depth and texture were significant, the surface and subsurface data were analyzed separately. The significant predictors for surface SOC were texture (F = 195.7720, p-value < 0.0001), C4 grasses (F = 6.4289, p-value = 0.0128) and Surface Roots (F= 4.9044, p-value = 0.0295). When subsurface data was analyzed, the significant predictors of SOC were subsurface texture (F = 88.8755, p-value < 0.001), subsurface roots (F = 4.1587, p-value = 0.0443), and the bison sites (F = 9.9815, p-value = 0.0025). Because the interaction between bison site and grazing was not significant, the bison sites remained in the model.

Soil Inorganic Carbon

Soil depth (F = 50.2967, p-value <0.001), texture (F= 34.7129, p-value < 0.001), and the interaction between depth and texture (F = 63.9769, p-value < 0.001) were significant predictors of SIC (Appendix, Table xx). Grazing history did not have a significant effect on SIC (F = 0.0005, p-value = 0.9818). The significant interaction between depth and texture is shown in Figure 9.

Inorganic carbon was analyzed on the surface and subsurface. When a general model was run for surface inorganic carbon, the only significant effect in the model was texture (F = 42.3726, p-value <0.001). The only significant effect in subsurface SIC was subsurface texture (F = 99.22, p-value < 0.001).

Structural Equation Models

A number of the *a-priori* hypotheses Table 2 were supported in the surface SEM, with 85% of the variation in SOC and 55% of the variation in SIC explained (Figure 12). Abiotic factors captured in the composite of precipitation and surface soil texture were the main drivers for organic carbon (0.90) and inorganic carbon (-0.81). Grazing history had a small effect on SOC (0.06) and SIC (0.05). Grazing history also increased the percent of C_4 grasses (0.17). C_4 grasses have a strong relationship with the surface roots (0.30), however they only capture 7% of the variation in surface roots. Contrary to the *a-priori* hypothesis, the percent of C_4 grasses within the vegetation community were not strongly related to SOC (-0.05) but displayed a stronger negative relationship with SIC (-0.13).

The subsurface SEM captured 77% of the variation in SOC and 77% percent of the variation in SIC (Figure 13). The abiotic composite created from precipitation and soil texture was the main factor for SOC (0.83) and SIC (-0.94). Grazing history had no effect on organic or inorganic carbon. Percent C_4 grasses only captured 4% of the variation of subsurface roots (0.05). There was little relationship between C_4 grasses and subsurface SOC (0.06) and SIC (-0.08).

Carbon and nitrogen

There was a strong relationship between carbon and nitrogen on clay-rich soils ($R^2 = 0.61266$, $p<0.001$) and a weaker relationship on sandy soils ($R^2 = 0.37832$, $p<0.001$) (Figure 14).

Discussion

What are the main drivers of soil carbon storage?

Abiotic factors, such as precipitation and texture, were the strongest predictors of organic and inorganic carbon. Within this study, it was not possible to uncouple these factors, and as such it is not possible to determine if precipitation or texture was a bigger driver across the rangeland. The abiotic factors were not able to be uncoupled because despite extensive searching, it was not possible to find dry clay-rich sites or wet sandy sites with grazing exclosures. Even though precipitation and soil texture weren't able to be uncoupled, the evidence shows that abiotic factors were the largest drivers of SOC and SIC across the rangeland. There is evidence to show that more SOC occurred in the wetter/clay-rich soils compared to the drier/sandy soils. The data showed a different slope between soil carbon and nitrogen in the clay-rich soils compared to the sandy soils (Figure 14), this difference could arise from more extreme water limitation in the sandy sites compared to the clay-rich sites, or possibly higher microbial biomass in clay-rich soils (Han *et al.* 2016).

It was hypothesized that roots and plant composition would contribute to organic storage. While roots and C_4 grasses had small effects on SOC, their effects on SIC were not expected. The general linear model showed that roots had a significant effect (Appendix C) on surface SIC, and the structural equation model showed evidence of direct effects from roots and C_4 grasses on surface SIC and significant effects on subsurface SIC. Reeder et al (2004) found an increase in inorganic carbon under heavy grazing and attributed that increase to an increased proportion of *B.gracilis*, a C_4 grass. Their evidence suggested that because *B.gracilis* has a greater root:shoot ratio, there were increased root exudates under areas with increase *B.gracilis*. The acids from the root exudates weathered sources of Ca^{2+}, and new Ca^{2+} were released into the soil solution of the root zone. In this study, C_4 grasses and roots decreased the surface and subsurface SIC. While the mechanism for the negative relationship is unclear, two possible mechanisms include that the SIC could have been reprecipitated lower within the soil profile or the SIC could have been weathered and volatilized to the atmosphere.

What is the effect of grazing management on soil carbon?

Grazing management did not have a significant direct effect on soil carbon storage. Roberts et al., (2016) found that grazing increased SOC with increasing grazing intensity. Their study was conducted on clay-rich soils similar to the clay-rich soils measured in this study. In their results, there was a significant difference in SOC between the exclosed plots and the plots grazed with a high intensity. The authors found that SOC measurements from the moderate grazing always fell in between the ungrazed and high-intensity plots. The results from Roberts et al., (2016) provide context for the findings of this study. Figure 8 shows there was a slight increase in SOC storage on the surface of clay-rich soils. While this increase is not significant, it does follow a similar trend in the results from Roberts et al., 2016.

The results from this study contribute empirical evidence regarding the interaction between precipitation and texture. McSherry and Ritchie (2013) found that above 600 mm of precipitation on clay-rich soils, the grazing effect decreased SOC storage. This study did not find evidence for that interaction. The clay-rich soils had an average mean annual rainfall of 610 mm, slightly above the cut-off determined by McSherry and Ritchie. The grazing effect did not decrease SOC on the clay-rich soils.

Grazing history did not have a significant effect on SIC, however the structural equation model shows evidence that grazing had an indirect effect on SIC through its significant effect on plant composition. As hypothesized in the *a-priori*, grazing history had a significant effect on the proportion of C_4 grasses (supplemental information). Previous studies show that C_4 grasses such as *B.gracilis* have a greater root:shoot ratio. As mentioned above, root exudates are acidic and may contribute to the weathering of Ca^{2+} sources such as limestone, impacting SIC.

Contrary to the *a-priori* hypothesis, grazing did not have a significant effect on root turnover. This may be due to the timing of sample collection. Roberts et al (2016) found significant root death 10 days after grazing, however when samples were taken 2 months later, there was no difference between roots in the grazed and ungrazed treatments. This shows that in order to measure root turnover, samples would need to be taken immediately after grazing. The samples in this study were not taken immediately after grazing occurred, so it was not possible to accurately capture any grazing effect on root turnover.

Does soil carbon storage differ at the surface and 20 cm below the soil surface?

Soil carbon storage on the surface and subsurface varied between the clay-rich soils and the sandy soils. There was more SOC on the surface of clay-rich soil and the subsurface of sandy soil (Figure 11). This may be due to the depth of the roots for each of the soil textures. Vertical distribution of SOC has been connected with root depth (Jobbágy and Jackson 2000). Roots in clay-rich soils tend to lie closer to the surface because it is difficult to penetrate deeper through clay due to aggregation and small pore size. Roots in sandy soils tend to penetrate deeper to access water that resides deeper in the soil. The results from this study possibly suggest that the vertical distribution of SOC was associated with root depth.

There was also a difference in surface and subsurface SIC storage between clay-rich and sandy soils. While there was little detectable SIC in the clay-rich soils, sandy soils contained significant amounts of SIC, especially in the subsurface. Most likely, this is due to the caliche layer that resides in limestone derived soils. This finding highlights an important feature of semi-arid rangelands with sedimentary parent material containing $CaCO_{3+}$: more carbon is stored as inorganic carbon compared to organic carbon. Results from this study also suggest that grazing may indirectly influence SIC storage through roots and the increased proportion of C_4 grasses. The *a-priori* model hypothesized that texture would impact the water holding capacity and effect the plant and root composition. The evidence from this study confirms that there was a greater proportion of C_4 grasses in sandy soils where water availability is low and a greater root:shoot ratio is needed in order to access water.

State-and-Transition Model

The state-and-transition model integrates aspects of equilibrium and non-equilibrium models (Briske *et al.* 2003, 2005; Vetter 2005) and provides a theoretical framework to explain the results from this study. Abiotic factors such as precipitation and soil texture were the main drivers in determining the variation in soil organic and inorganic carbon on the surface and subsurface. This supports the non-equilibrium model within the continuum in the state-and-transition model, stating that the ecological dynamics of arid and semi-arid rangelands are driven by the stochasticity of precipitation (Briske *et al.* 2003; Booker *et al.* 2013). While abiotic factors were the main drivers in explaining the variation in soil organic and inorganic carbon across a semi-arid rangeland, it is important to recognize that this study examined the effects of moderate grazing and did not sample the extremes. It is possible that if plots had been continually grazed without consideration for timing or stocking rate, there could have been a significant negative grazing effect. Therefore, this study cannot evaluate grazing effects under high-intensity grazing.

Diablo Trust ranchers carefully consider the timing and stocking rate when they graze their cattle. For example, they try not to graze the same pasture during the same season year after year. Instead, they alter when a pasture is grazed to minimize that grazing effect on the vegetation during the growing season. Due to their management decisions, the ranchers maintain a steady state of mixed-grass shrub land and reduces the risk of crossing a threshold into another state. By maintaining a steady-state of mixed grass shrubland, the equilibrium component of the state-and-transition model is incorporated.

It is important to consider the non-equilibrium and equilibrium aspects of the study when interpreting the results because if only the non-equilibrium aspects are considered, there may be a disregard for management and its influences across the range. If management is not recognized as contributing to the current steady-state, there is a possibility for degradation. Similarly, if only the equilibrium aspects are considered, then the stochasticity of rainfall may not be included in management decisions regarding timing and stocking rate, and possibly resulting in detrimental effects.

Final conclusions

In this semi-arid rangeland, abiotic factors were the main drivers of soil carbon. On both the surface and subsurface, there was an unexpected negative relationship between plant roots, vegetation composition and SIC. Further study is required to understand the mechanisms driving the unexpected decrease in SIC with increasing cover by C_4 grasses and root biomass. This is especially important because SIC accounted for 3 times the amount of carbon compared to SOC. These results are for a landscapes-scale study that spanned precipitation and soil texture gradients. This study did not sample the extremes of grazing utilization and these results should not be extrapolated to other grazing studies because grazing effects are highly contextualized across precipitation levels, soil textures, plant community compositions, and grazing intensities. It is important to recognize the biotic influences that result from grazing management decisions who consider timing and stocking rate. Using the state-and-transition model as a framework to understand the ecological dynamics across various rangelands can provide land managers and policymakers a better understanding of how grazing will impact soil carbon storage across a gradient of precipitation and soil textures.

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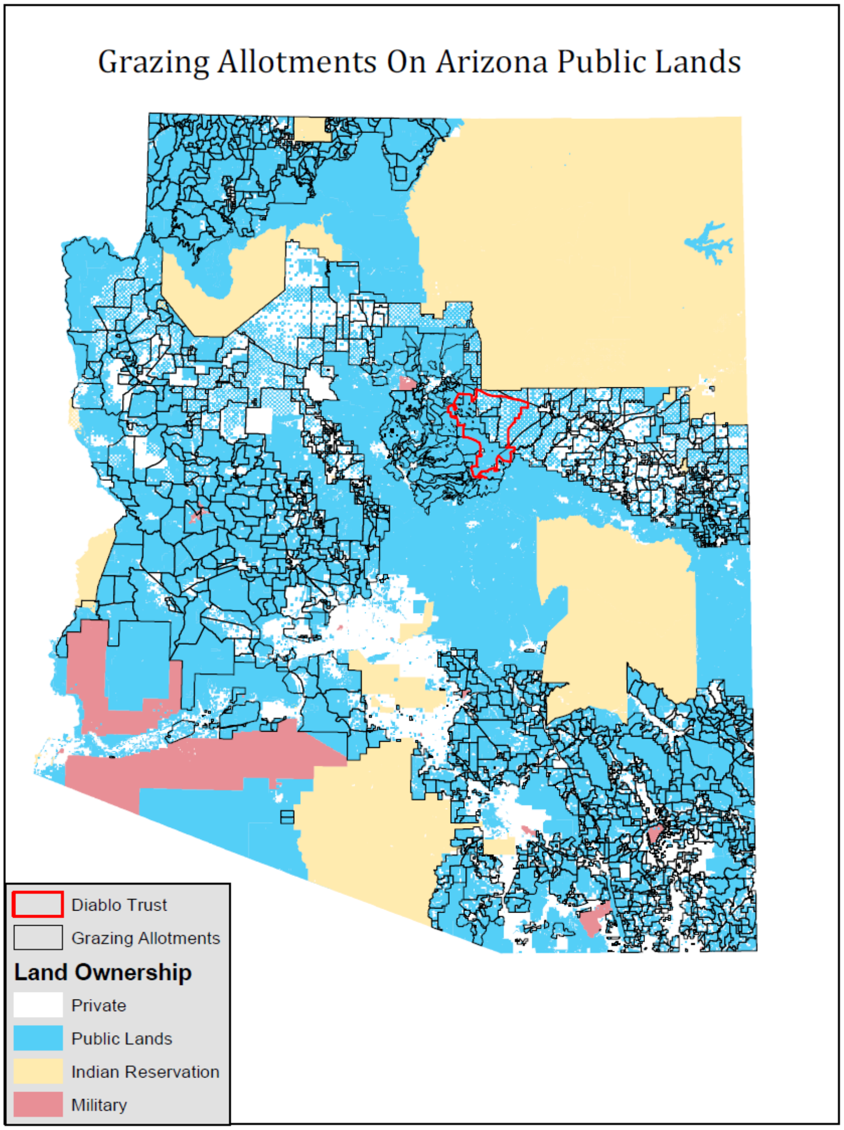
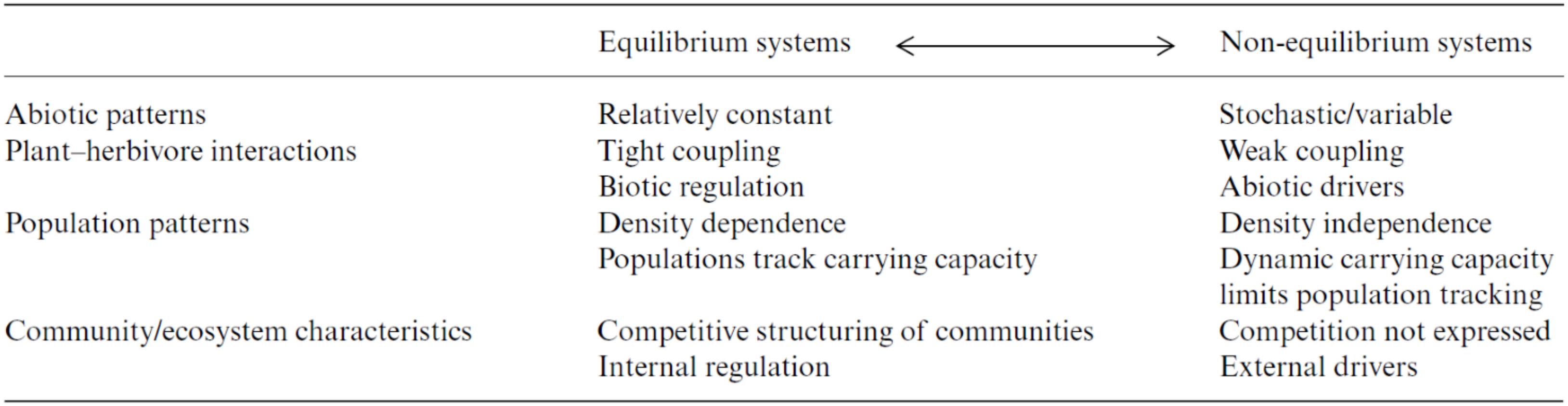


Figure 1. Map of grazing allotments on public lands of Arizona, which comprise 74% of all public lands.



	Equilibrium systems	⟷	Non-equilibrium systems
Abiotic patterns	Relatively constant		Stochastic/variable
Plant–herbivore interactions	Tight coupling		Weak coupling
	Biotic regulation		Abiotic drivers
Population patterns	Density dependence		Density independence
	Populations track carrying capacity		Dynamic carrying capacity limits population tracking
Community/ecosystem characteristics	Competitive structuring of communities		Competition not expressed
	Internal regulation		External drivers

Table 1. Attributes of equilibrium and non-equilibrium systems are based on how a system is internally regulated and responds to abiotic factors such as precipitation. Reproduced from Briske et al (2003).

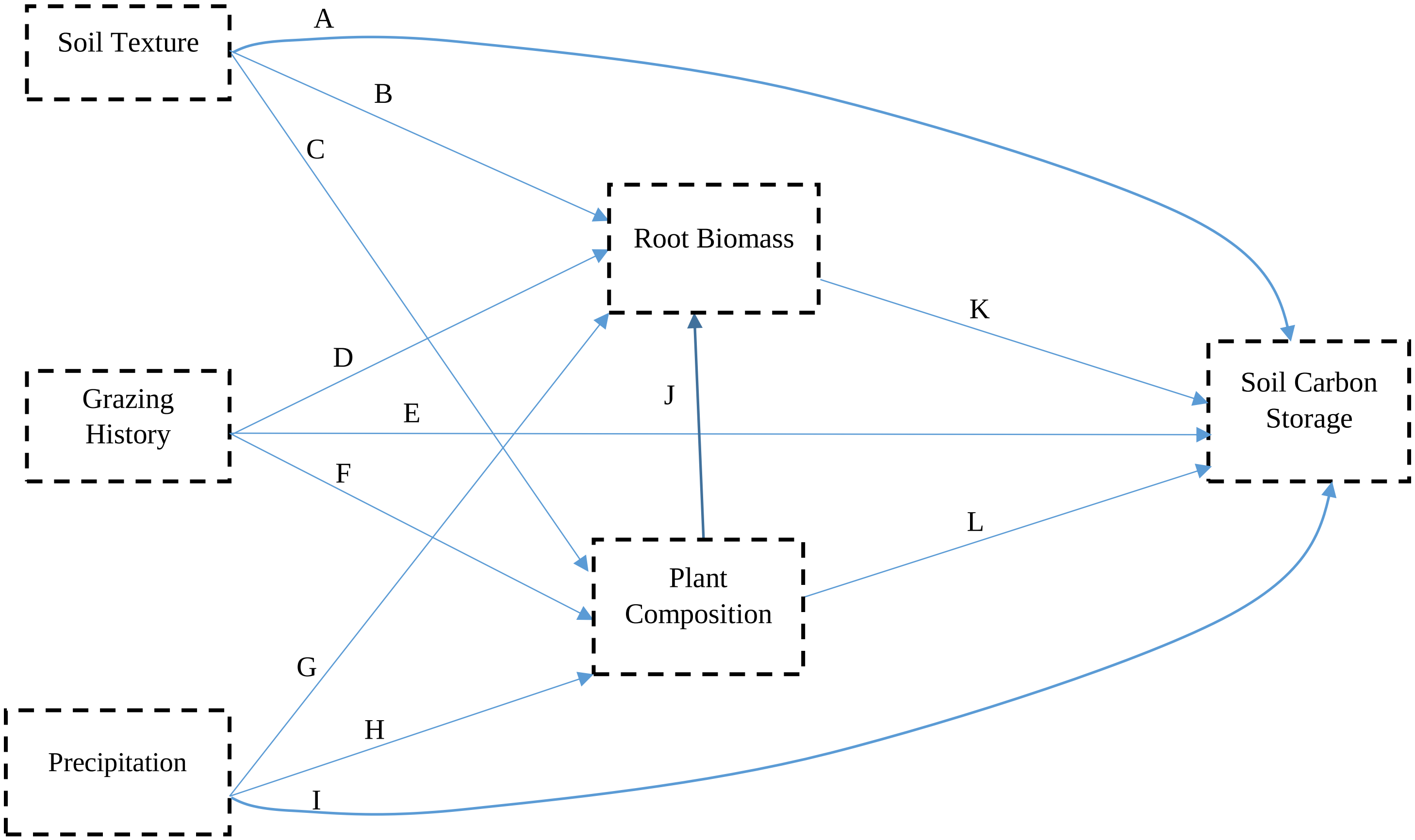
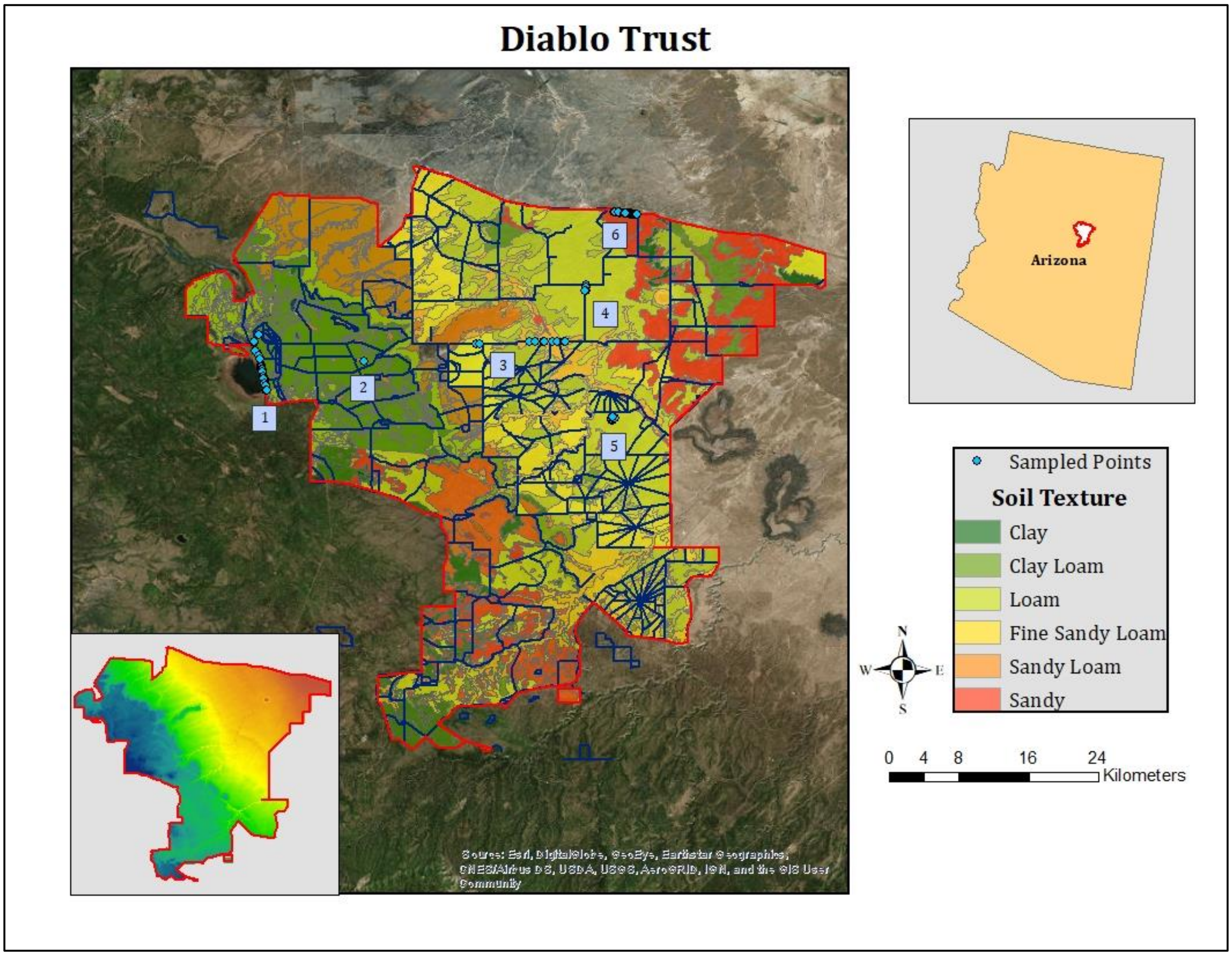


Figure 2. *A-priori* Structural Equation Model hypothesizing the influence of abiotic and biotic factors on soil carbon storage.

Pathway	**Alpha Code**	**Hypothesized Mechanism**	**Observed Pattern**
Texture → Soil Carbon Storage	A	Basalt derived clay-rich soil will have more SOC because clays form aggregates that protect soil carbon from microbial decomposition. Limestone derived sand-rich soil will have more SIC because of high $CaCO_3$ content of the parent material	Clay rich, wet areas had higher SOC and less SIC than sand-rich, dry areas in both the surface and subsurface.
Texture → Root Biomass	B	Fine textured soils have a higher water holding capacity and more roots than coarse textured soil	On the surface, root biomass was higher in clay-rich wet areas than sand-rich, dry areas. The relationship was opposite in the subsurface.
Texture → Plant Composition	C	Water holding capacity varies with soil texture and plant taxa vary in their water requirements	Higher cover of C4 grasses were observed in sand-rich dry areas than clay-rich wet areas
Grazing History →Root Biomass	D	Grazing will increase root biomass through die-back and regrowth	**Grazing had little influence on root biomass**
Grazing History → Soil Carbon Storage	E	Root die back and compensatory growth increases belowground organic matter	Grazing had a slight positive influence on SOC and SIC in the surface but not subsurface
Grazing History →Plant Composition	F	C_4 grasses will increase with grazing because they are generally more resilient to grazing pressure than C_3 grasses	Grazing increased the cover of C4 grasses
Precipitation → Root Biomass	G	Higher precipitation will generate higher net primary production and root biomass	See B
Precipitation → Plant Composition	H	Decreased precipitation will increase the abundance of drought tolerant plants such as C_4 grasses and shrubs	See C

Precipitation → *Soil Carbon Storage*	I	Increased precipitation will increase primary production and increase belowground carbon inputs (higher SOC), but it will increase leaching and result in lower SIC	See A
Plant Composition → *Root Biomass*	J	Plant taxa vary in their allocation to roots, the C_4 grass *B. gracilis* has a higher root:shoot ratio than other grasses	Root biomass was positively correlated with C4 grass cover
Root Biomass → *Soil Carbon Storage*	K	Increased root biomass will increase soil carbon storage	Surface root biomass had a weak positive correlation with SOC and a stronger negative correlation with SIC. **Subsurface root biomass has a weak negative correlation with both SOC and SIC**
Plant Composition → *Soil Carbon Storage*	L	*B. gracilis* increases fine root biomass and root turnover.	**On the surface, C_4 grass cover had a weak negative correlation with SOC and SIC; and, in the subsurface, a weak positive correlation with SOC and a negative correlation with SIC**

Table 2. Hypothesized pathways associated with the *a priori* model and hypothesized mechanisms for the influence of biotic and abiotic factors on soil carbon. Observed patters in bold font did not support the hypothesis.



Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Figure 3. Map of sampled sites across the Diablo Trust. The map in the bottom right is a map of the precipitation gradient, higher precipitation values are represented in blue and lower precipitation values are represented in red.

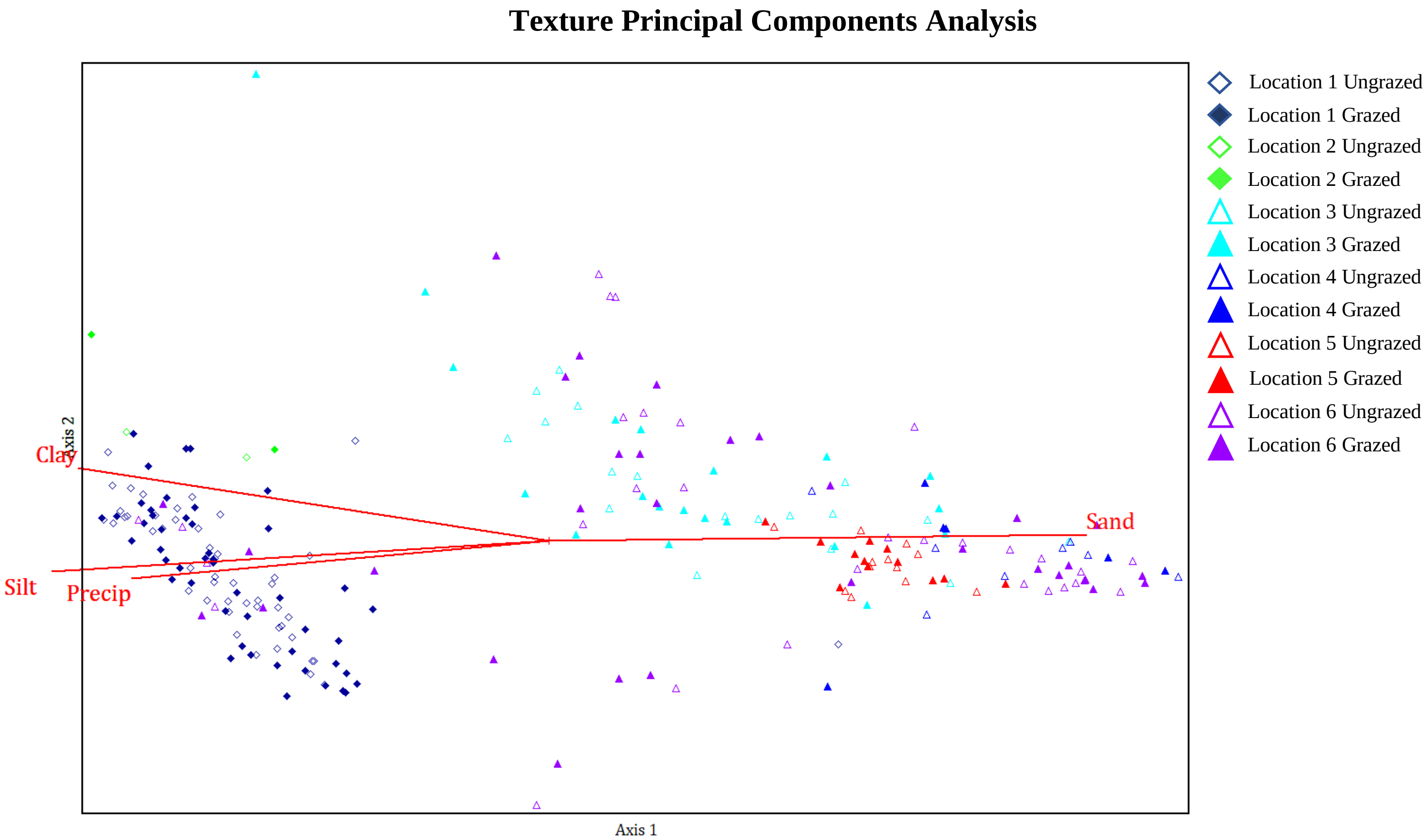


Figure 4. A two-dimensional PCA of sampled texture across six distinct site locations. Distance between sample units approximate dissimilarity in particle size class. Sites with a higher percentage of clay and silt particles are on the left side of the graph and sites with a higher percentage of sand particles are on the right side of the graph.

nMDS for Vegetation Composition

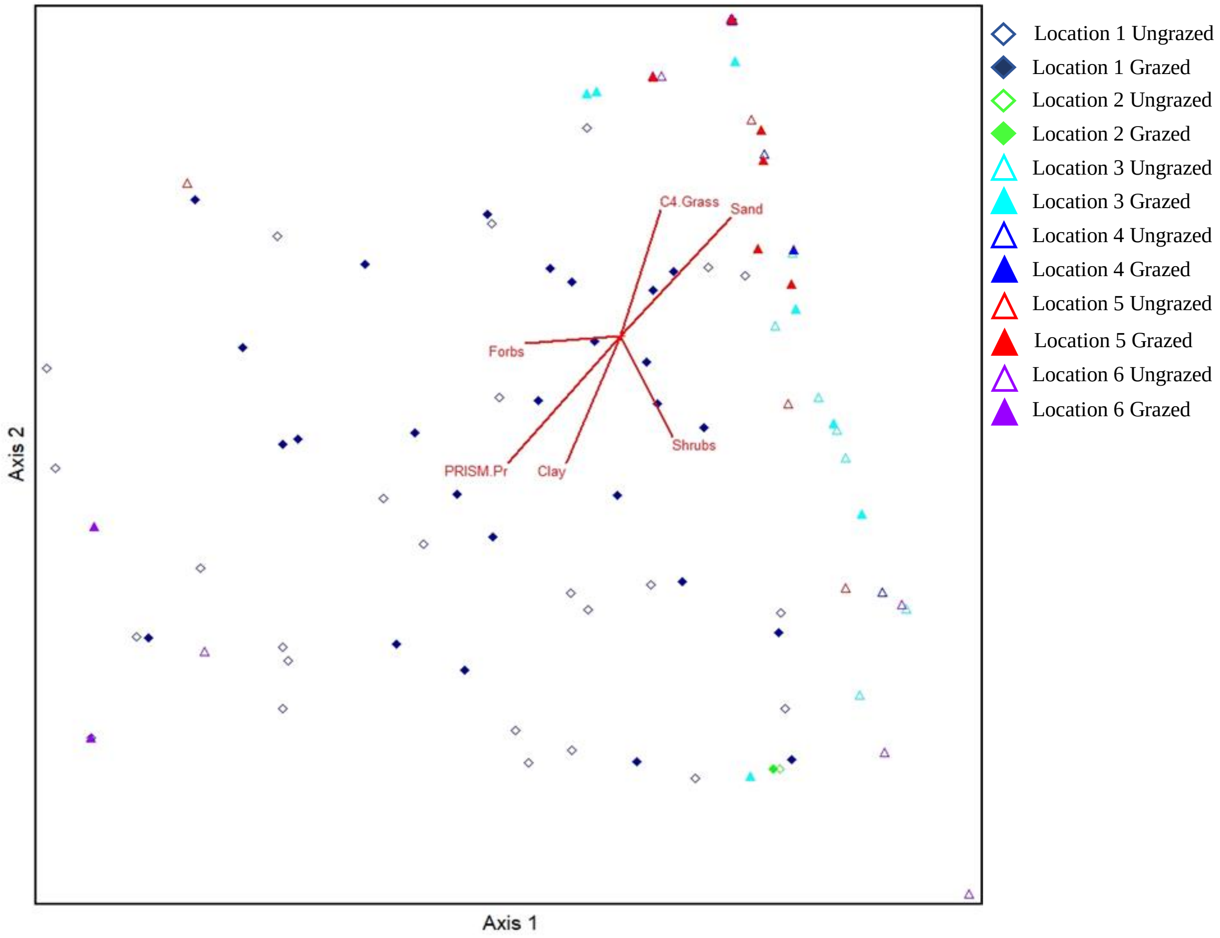
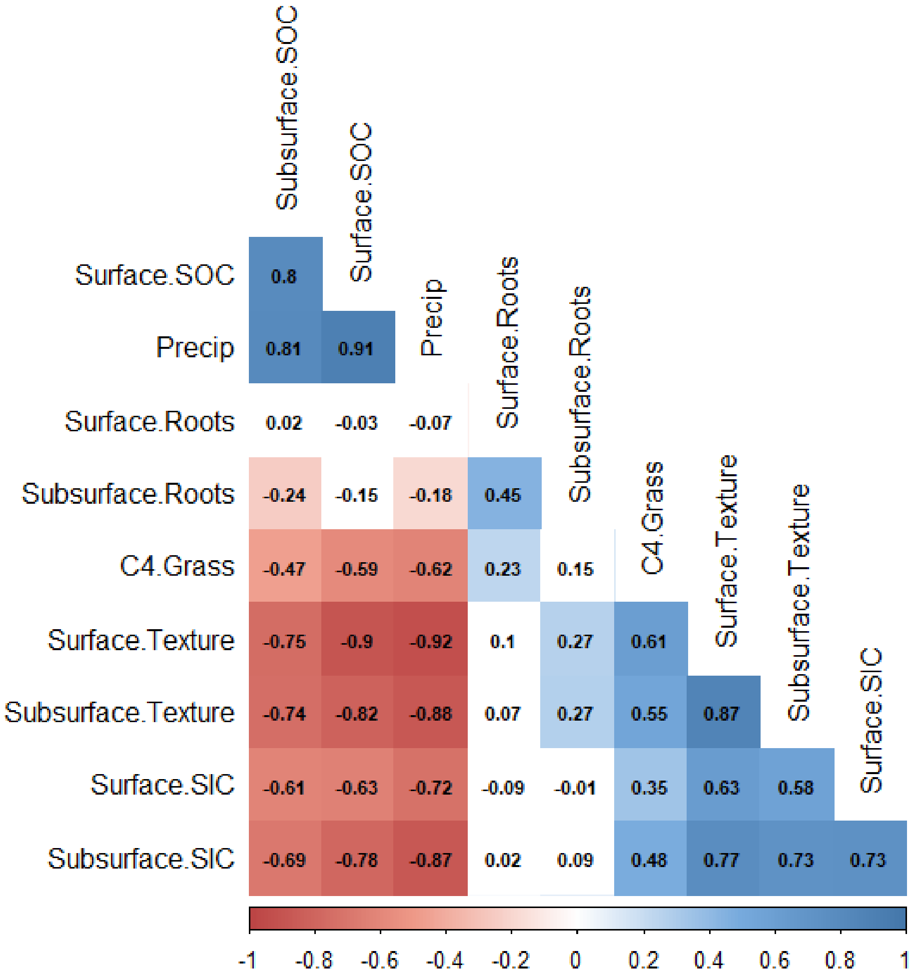


Figure 5. nMDS ordination for the functional groups of the vegetation community. The proportional abundance of C_4 grasses, C_3 grasses, Forbs, and Shrubs were ordinated within the non-metric multidimensional space. C_4 grasses accounted for 53% of the variance in the dissimilarity for axis 2.



	Subsurface.SOC	Surface.SOC	Precip	Surface.Roots	Subsurface.Roots	C4.Grass	Surface.Texture	Subsurface.Texture	Surface.SIC
Surface.SOC	0.8								
Precip	0.81	0.91							
Surface.Roots	0.02	-0.03	-0.07						
Subsurface.Roots	-0.24	-0.15	-0.18	0.45					
C4.Grass	-0.47	-0.59	-0.62	0.23	0.15				
Surface.Texture	-0.75	-0.9	-0.92	0.1	0.27	0.61			
Subsurface.Texture	-0.74	-0.82	-0.88	0.07	0.27	0.55	0.87		
Surface.SIC	-0.61	-0.63	-0.72	-0.09	-0.01	0.35	0.63	0.58	
Subsurface.SIC	-0.69	-0.78	-0.87	0.02	0.09	0.48	0.77	0.73	0.73

Figure 6. Pearson correlation table showing the relationship between surface and subsurface variables. Positive significant correlations are marked and blue and positive negative correlations are marked in read. Significant values have p-value < 0.05

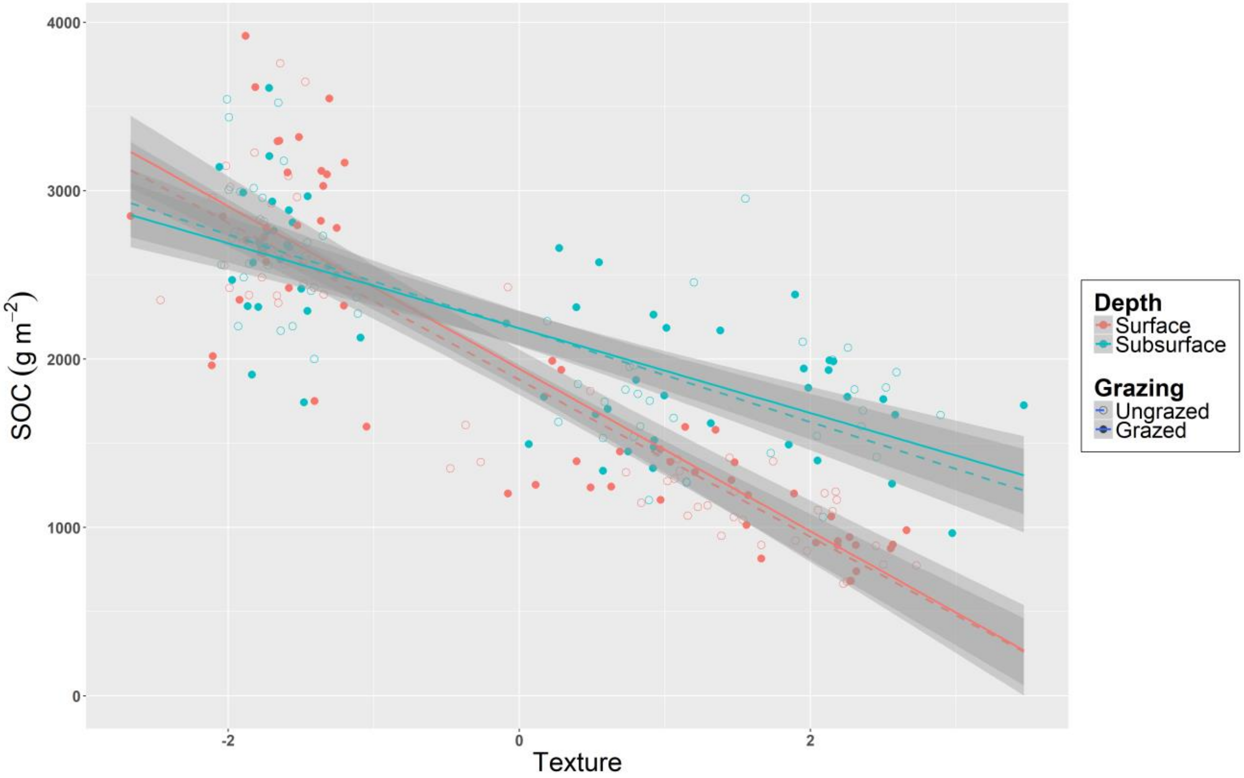


Figure 7. Linear regression illustrating the significant interaction between texture and depth on soil organic carbon. There was no significant difference in soil organic carbon under the two grazing treatments.

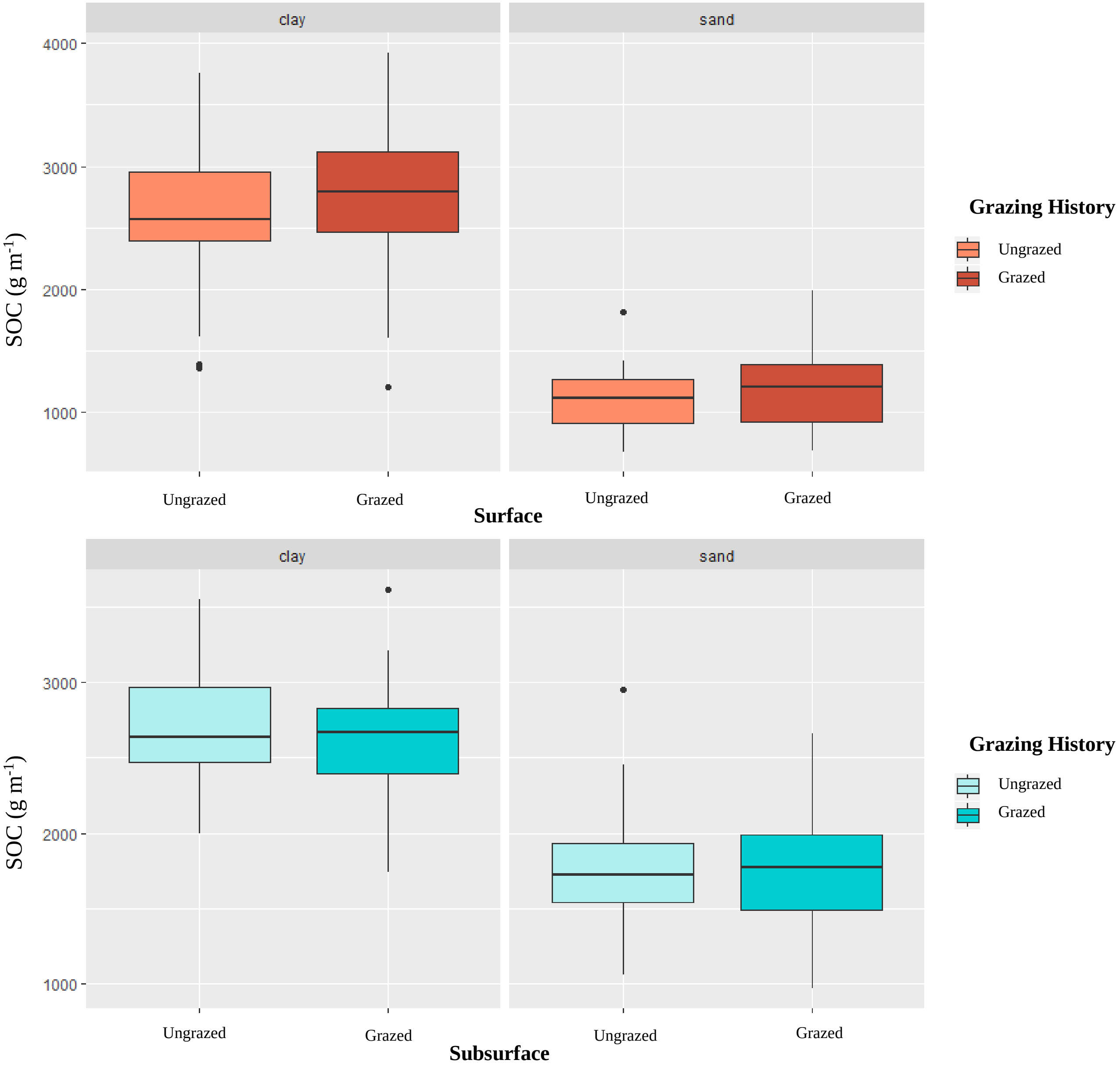


Figure 8. Surface and subsurface soil organic carbon on clay-rich and sandy soils under different grazing histories. There were no significant difference between the grazing treatments on either soil texture.

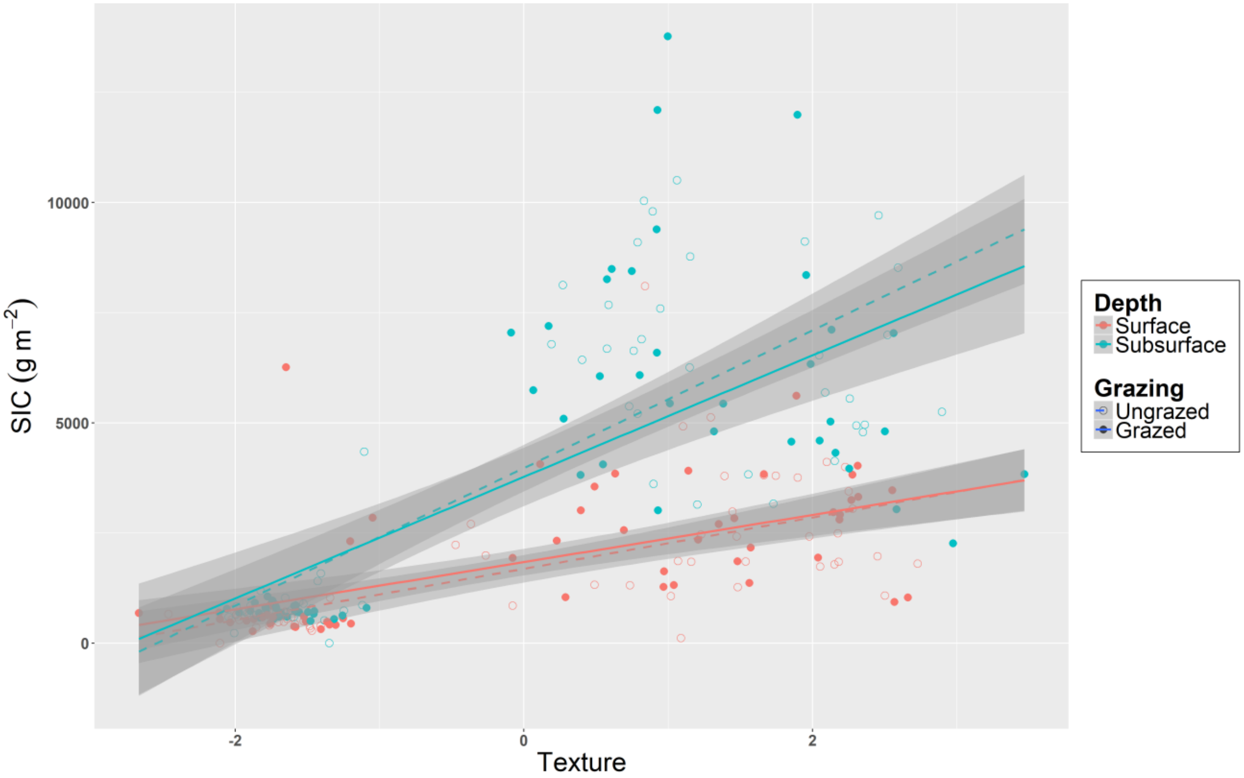


Figure 9. Linear regression illustrating the significant interaction between texture and depth on soil inorganic carbon. There was no significant difference in soil organic carbon under the two grazing treatments.

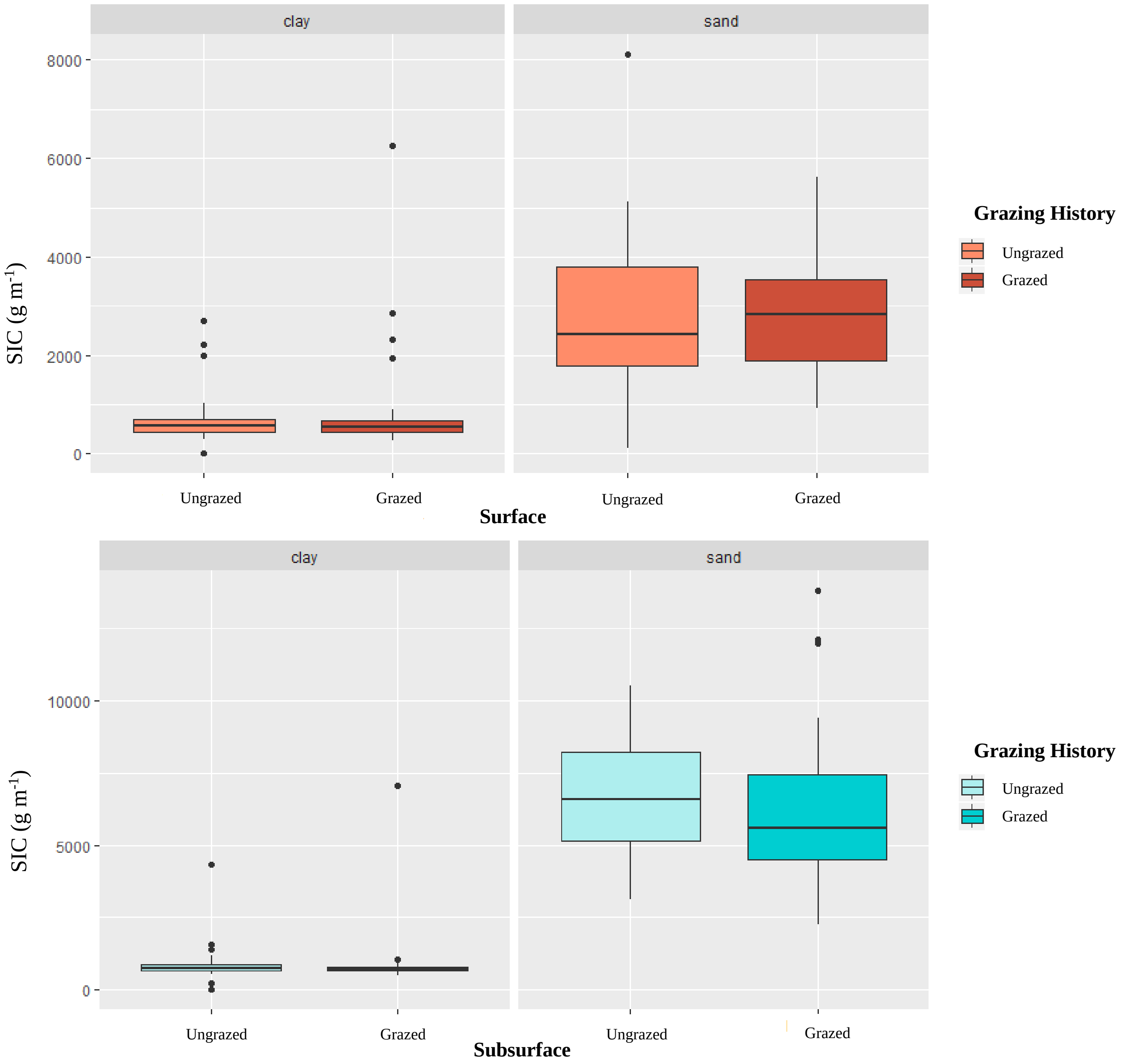


Figure 10. Surface and subsurface soil organic carbon on clay-rich and sandy soils under different grazing histories. There were no significant difference between the grazing treatments on either soil texture.

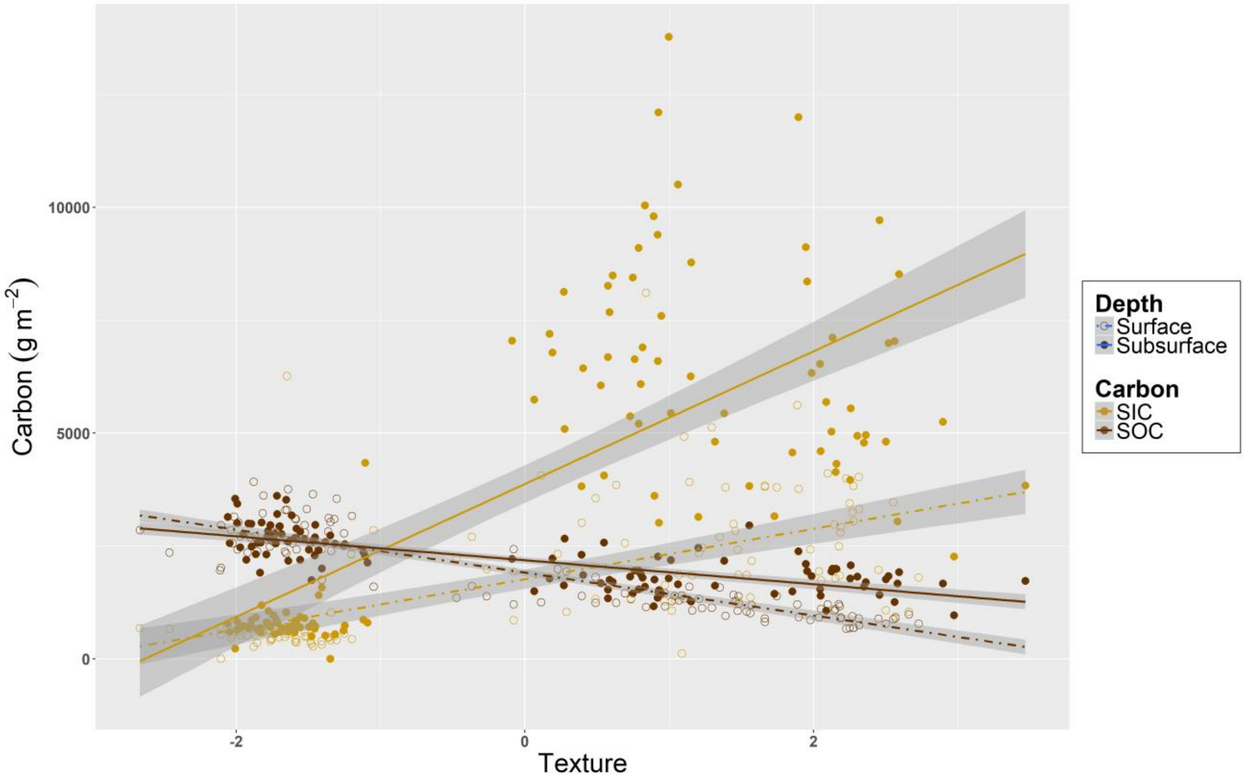


Figure 11. Linear regression of soil carbon across soil texture. Soil carbon is differentiated between soil organic carbon (SOC) and soil inorganic carbon (SIC). Soil texture, depth, and the interaction between soil texture and depth were all significant in the general linear model.

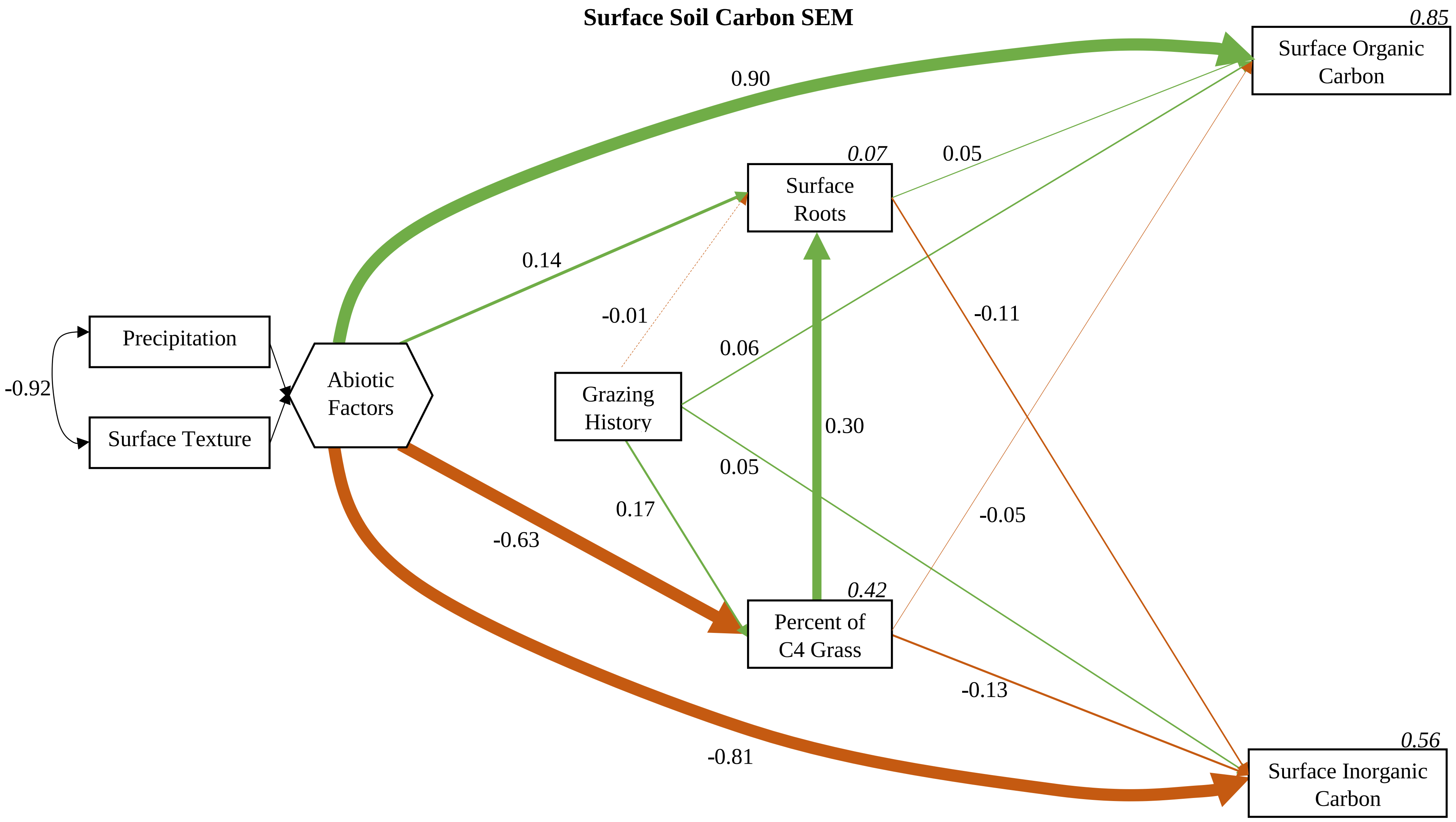


Figure 12. Surface structural equation model of the abiotic and biotic contributions to organic and inorganic carbon in semi-arid rangelands. Values associated with arrows (and line widths) correspond to the path strength. Positive partial path coefficients are represented in green and negative partial path coefficients are represented in red. Rectangles represent measured variables and the hexagon represents a composite effect. The italic numbers above the variables represent the proportion of variation explained through the paths. Model fit $\chi^2 = 0.803$, $P = 0.849$, $\chi^2/\text{df} = 0.268$, GFI = 0.998, and RMSEA = 0.

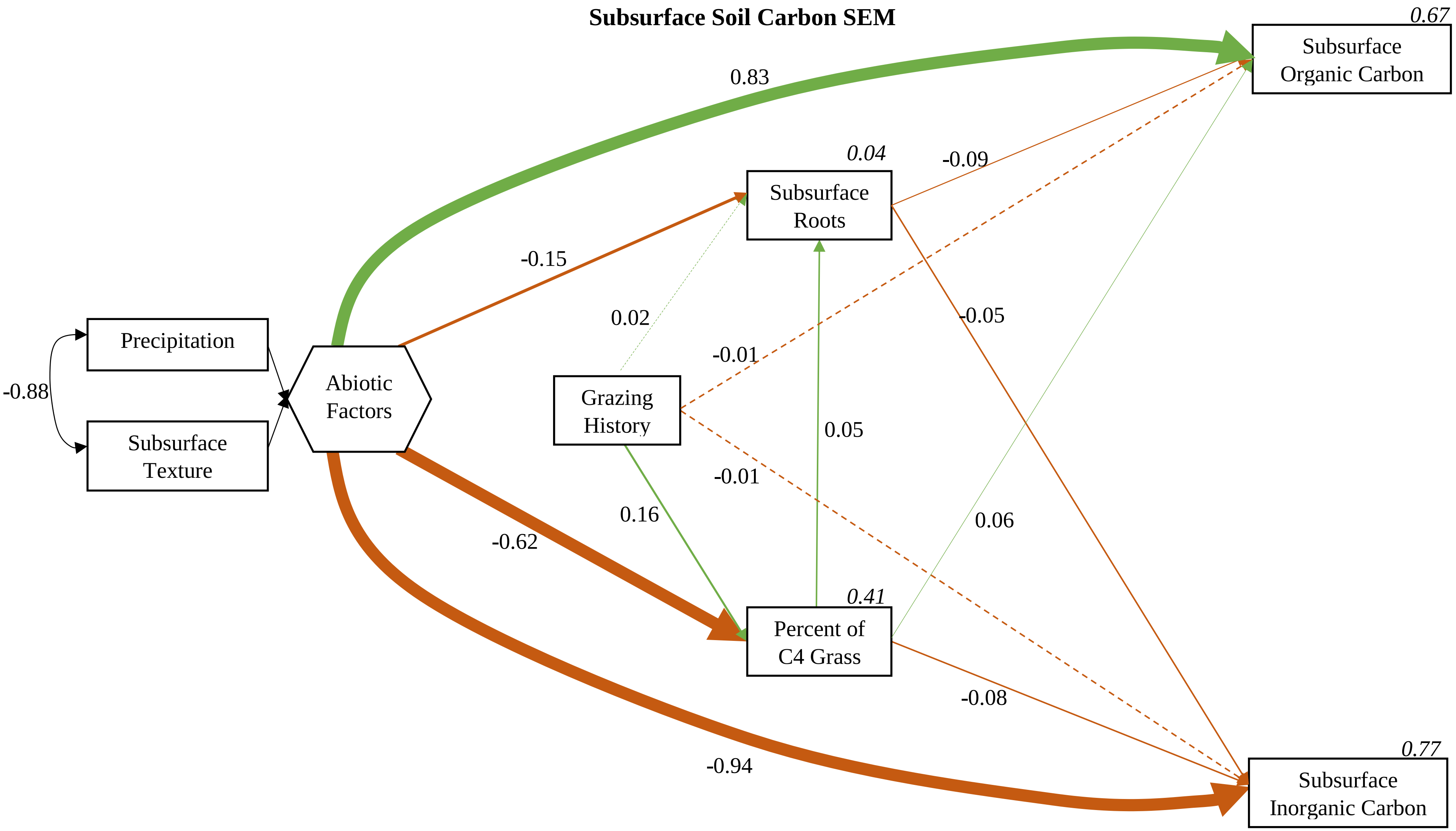


Figure 13. Subsurface structural equation model of the abiotic and biotic contributions to organic and inorganic carbon in semi-arid rangelands. Values associated with arrows (and line widths) correspond to the path strength. Positive partial path coefficients are represented in green and negative partial path coefficients are represented in red. Rectangles represent measured variables and the hexagon represents a composite effect. The italic numbers above the variables represent the proportion of variation explained through the paths. Model fit $\chi^2 = 7.076$, $P = 0.132$, $\chi^2/df = 1.769$, GFI = 0.984, and RMSEA = 0.080

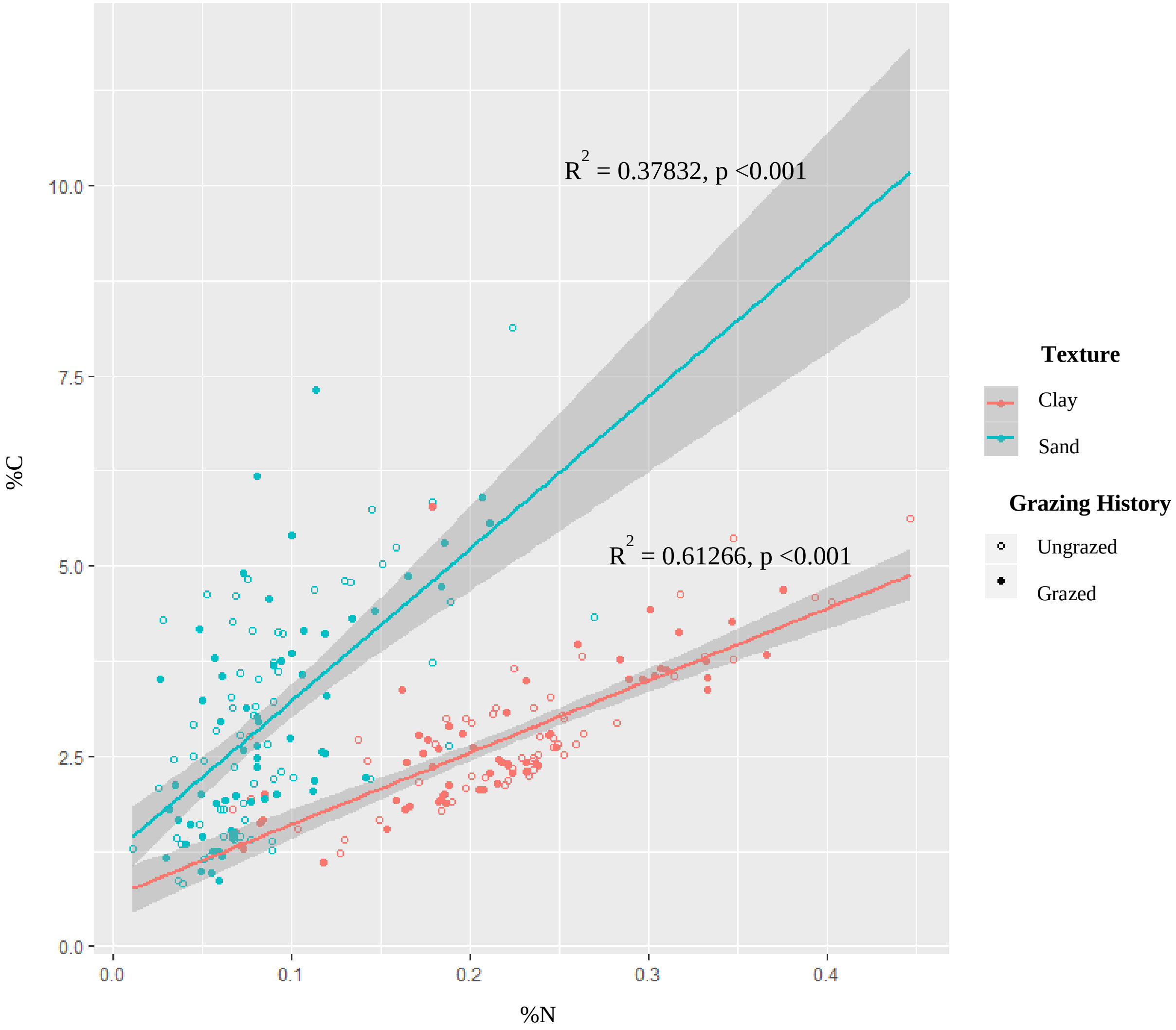


Figure 14. Relationship between carbon and nitrogen across clay-rich and sandy soils under grazed and ungrazed treatments. Clay-rich soils had significantly lower C:N values compared to sandy soils.

CHAPTER 3:

Policy implications for rangeland management

By

Megan Marie Deane McKenna, Nancy Collins Johnson, Deborah Huntzinger, Thomas Sisk

Introduction

Human activities have increased the amount of atmospheric carbon dioxide (CO_2) from 280 ppm to 400 ppm over the last 270 years (IPCC 2014). As CO_2 levels rise, it is important to understand various atmospheric carbon mitigation strategies. Soils are the largest terrestrial carbon sink (Chapin *et al.* 2009) and land management practices that increase soil carbon have been proposed as strategies to mitigate atmospheric carbon levels (Lal *et al.* 2003).

Rangelands comprise 31% of US lands (Follett *et al.* 2001; Havstad *et al.* 2007). Through the widespread adoption of Recommended Management Practices on grazed lands, such as grazing management and growing improved pasture species (Conant *et al.* 2001), it is estimated that grazing lands contribute to 15% of the U.S. soil carbon storage potential (Lal *et al.* 2003). Because rangelands may help mitigate CO_2 emissions, policies should be directed towards avoiding rangeland conversion and encouraging management practices that maximize soil carbon storage. The following chapter will review these proposed policies and make recommendations for policy applications within the context of a state-and-transition model.

California's voluntary offset market and the Agricultural Conservation Easement Program (ACEP) are two economic policies that support rangeland conservation as well as management practices that improve rangeland health. For the purpose of this chapter, ACEP will be discussed in terms of the Conservation Reserve Program (CRP) because there have been more economic analyses of CRP and both programs are run by the USDA to support land conservation.

Cap-and-Trade

In 2006, Assembly Bill 32 was signed by Gov. Schwarzenegger. AB32 targeted the 6 "Kyoto" gases; CO_2, CH_4, N_2O, SF_6, CFCs, and PFCs. While there has been much attention focused on the carbon cap set by the bill, it is important to recognize that AB32 is a suite of actions targeted at reducing emissions such as enforcing low carbon fuel standards, increasing energy efficiency, and supporting cleaner vehicles. Under AB32, entities that emit more than 25,000 tCO_2e annually are regulated to emit below a cap that decreases with each year. This means approximately 350 companies within the industrial, electrical and transportation sectors are regulated. Placing a cap on these companies, accounts for nearly 85% of the state's total greenhouse gas emissions (Center for Climate and Energy Solutions, 2014).

Companies are allowed to use compliance-grade offset credits (8% limit) in order to meet their cap. Compliance offset credits provide economic efficiencies by reducing emissions faster, incentivizing new technologies, and obtaining reductions within unregulated sectors. There are two offset markets; compliance and voluntary markets. Voluntary offsets support companies who want to incorporate climate reductions within their mission or practices. The voluntary market offers an opportunity for businesses to financially support practices that contribute to emissions reductions. There are three Offset Project Registries that issue offset compliance and voluntary credits using approved technical protocols.

The American Carbon Registry has three protocols approved for the voluntary market that are related to rangelands: "Avoided Conversion of Grasslands and Shrublands to Crop Production," "Compost Additions to Grazed Grasslands," and "Grazing Land and Livestock Management." Climate Action Reserve has one protocol approved for the voluntary market, "Grassland Project." Through the implementation of these protocols, native ecosystems are maintained, rangeland is prevented from being converted to cropland, and soil organic carbon content is increased through the input of compost.

While these protocols have been approved, there have been few transactions for these credits. A large barrier to entering the voluntary market is that credits need to prove to be additional, permanent, and credible in order to be allocated. Additional means that the emissions would not be reduced without the use of the protocol. Permanent is defined as emissions being permanently removed from the atmosphere. Ensuring additionality, permanence, and credibility is expensive, and has been argued to be unrealistic within certain ecological contexts (Booker *et al.* 2013). This will be discussed further within a theoretical framework later in this chapter.

Conservation Reserve Program

The Conservation Reserve Program provides numerous ecosystem benefits by paying farmers to retire environmentally sensitive land. While the ecosystem benefits are great, farmers are not renewing their contracts with CRP because the economic incentive from CRP is less than crop prices (Chen and Khanna, 2014). In addition, currently there are 24.3 million acres currently enrolled in the program, down from the peak of 37 million acres in 2007 (FSA, 2015), and less legislative support for CRP has reduced the total cap to support 24 million acres nationally.

State-and-Transition Model

Both the CRP and voluntary markets have the potential to offer valuable ecosystem services when broadly implemented however it is important to discern when each program should be considered. The state-and-transition model provides an ecological context to evaluate if/when to use the described policies.

Rangeland ecology has evolved over the last thirty years to incorporate a state-and-transition model to explain ecological dynamics, human management, and herbivore influence (Briske *et al.* 2003, 2005). The state-and-transition model incorporates a continuum from equilibrium to non-equilibrium models that can provide context to rangeland management decisions and their ability to influence ecological dynamics across a rangeland system (Vetter

2005). While equilibrium models stress the tight coupling of plant-herbivore systems and predict the degradation of rangelands to be largely attributed to excessive stocking rates (Derry and Boone 2010), non-equilibrium models attribute changes to rangeland ecology to stochastic abiotic factors such as drought that impact animal population rates (Vetter 2005; Derry and Boone 2010).

Because the state-and-transition model describes the dynamics of factors along a precipitation gradient (Vetter 2005; Booker *et al.* 2013), it can provide a framework for policymakers when considering which rangeland policies to implement across the United States. Booker et al (2013) argues that rangelands that are more defined by non-equilibrium systems (ie arid and semi-arid rangelands) should not be considered for a protocol within the voluntary market that focus on management practices because the stochasticity of abiotic factors make it impossible for ranchers to ensure additionality and permanence. Within these rangelands, policies should be focused on avoided conversion so that the rangeland is not developed or converted to crop. By preventing this conversion, rangelands will provide ecological services such as nutrient cycling and habitat. Appropriate policy options that currently exist include ACEP, the Avoided Grassland Conversion protocol from the American Carbon Registry, and the Grassland Project protocol from the Climate Action Reserve.

It may be appropriate to incorporate a cap-and-trade protocol within more mesic environments, however more research is still needed regarding the impact of management practices and their ability to sequester carbon. The state-and-transition model highlights that there are more opportunities for management in mesic environments because herbivores provide biotic regulation through grazing and abiotic factors such as precipitation are relatively constant (Briske *et al.* 2003; Vetter 2005). While some studies have found that grazing has the ability to increase soil organic carbon (Conant *et al.* 2003; Derner *et al.* 2006; Pineiro *et al.* 2010; Teague *et al.* 2011), there is still much unknown about how long that carbon is stored belowground.

Conclusion

Using the state-and-transition model can provide a theoretical framework for policymakers when making decisions about policy options for rangelands. While this framework can aid in initial guidance for policymakers, it is important to recognize that grazing impacts vary drastically based on precipitation, soil parent material, plant composition, and grazing intensity. No policy should be enacted without prior research of the specific area.

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APPENDIX A

SOIL SERIES DESCRIPTIONS

Sites 1 and 2 Soil Series Description

Natural Resources Conservation Service
MLRA Soil Survey Office
1615 S Plaza Way
Flagstaff, AZ 86001
(928) 214-0450

United States Department of Agriculture

Date: 6/25/2015

Subject: TSS – Technical Soil Service, Flagstaff MLRA SSO

To: NAU School of Earth Sciences and Environmental Sustainability

Purpose: Soil investigation for grazed and ungrazed plots on private land, Flying M Ranch.

Participants: James Harrigan, Jennifer Puttere, Aradhana Roberts

Location: Flying M Ranch near Mile Marker 324 on Lake Mary Rd, Flagstaff, AZ; Z12 0460148E 3871915N. Elevation is 2125m (6971 ft). Major vegetation is representative of proposed LRU 35.9. Ponderosa pine, Utah juniper, Alligator juniper, oneseed juniper, blue grama, western wheatgrass and squirreltail. There is no ESD written for this site. This site occurs on a private allotment within National Forest land.

Background and Status: The location of the site has only been mapped by US Forest Service in the Terrestrial Ecosystems Survey of the Coconino National Forest where it is described as Vertic Argiborolls.

Activities: Hand-dug soil pits were observed and described. Vegetation lines were used to characterize plant species composition.

Observations and Decisions: Three auger holes were observed within the site. At each site soils were fine and very deep at all locations. The soil and the landform across the field where the research area is located appears to be uniform.

Recommendations: The soil description is provided as a reference for NAU staff.

Author: Jennifer Puttere

Attachments: Soil Description and two maps

Summary:

Three key species are being observed for this project:

Artemisia spp. (Mugwort)

Pascopyrum smithii (Western wheatgrass)

Bouteloua gracilis (Blue grama)

Artemisia spp.

Pascopyron spp.

Table 1. Species observed on this site

Common Name	Scientific Name	Percent Occurrence
Squirreltail	*Elymus elymoides* subsp. *Elymoides*	15
Western wheatgrass	*Pascopyrum smithii*	25
Cheatgrass	*Bromus tectorum*	5
Musk thistle	*Carduus* spp.	2
Sweetclover	*Melilotus* spp.	10
Western salsify	*Tragopogon dubius*	2
Annual forbs	Annual forbs	15
Doubting mariposa lily	*Calochortus ambiguus*	TR
Fleabane daisy	*Erigeron* spp.	TR
Buckwheat	*Eriogonum* spp.	5
Geranium	*Geranium* spp.	TR
Locoweed	*Oxytropis* spp.	2
Utah juniper	*Juniperus osteosperma*	2
Artemisia	*Artemisia* spp.	15
Skunkbush sumac	*Rhus trilobata*	2

The second observed site had blue grama, and has been ungrazed for 18 years.

Table 2. Observed Soil Pit Description

Depth cm	Horizon	Color moist	Texture	Structure	pH	Effervescence	Clay %
0-5	A	7.5YR 2.5/3	L	2MGR	7.2	VS	26
5-15	ABt	7.5 YR 2.5/3	C	3MABK	7.2	VS	45
15-37	Bt	7.5YR 3/3	C	2FSBK	8.0	VS	42
37-70	Btk1	7.5YR 3/3	C	N/A	8.0	ST	40
70-107	Btk2	7.5YR 4/3	C	N/A	8.0	ST	40
107-125	Btk3	7.5YR 3/3	C	N/A	8.0	VE	40

Production: 249 lb/acre

Bare ground: 76%

Canopy cover: 72%

Basal Cover: 24%

Other ground cover: None

Other observations:

This site, when viewed as a landscape, appears to have good vegetative cover (Top photo). However, when viewed closely, there are large patches of bare ground along with hoof damage from grazing (Lower photo).

Soil Description; June 23, 2015

Taxonomic Classification: Fine, mixed, superactive, mesic Pachic Argiustolls

Location

Geographic Coordinate System (Latitude-Longitude):
34° 59' 20.8'' north, 111° 26' 12.0'' west

A—0 to 2 inches (0 to 5 cm); loam, very dark brown (7.5YR 2.5/3), moist; 26 percent clay; moderate medium granular structure; moderately sticky and moderately plastic; common fine and very fine roots throughout; 5 percent gravel; very slightly effervescent; neutral, pH 7.2; clear smooth boundary.

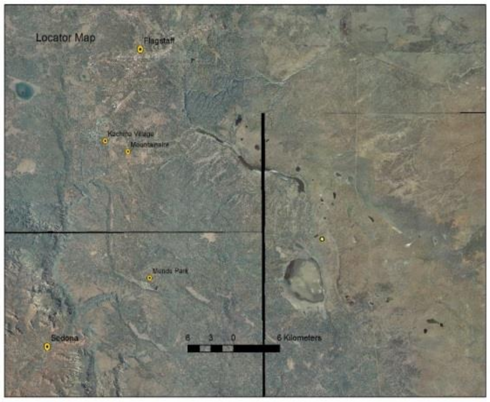
ABt—2 to 6 inches (5 to 15 cm); clay, very dark brown (7.5YR 2.5/3), moist; 45 percent clay; strong medium angular blocky structure; very sticky and very plastic; common medium, fine, and very fine roots throughout; prominent clay films, 0 percent gravel; very slightly effervescent; neutral, pH 7.2; clear smooth boundary.

Bt—6 to 15 inches (15 to 37 cm); clay, dark brown (7.5YR 3/3), moist; 42 percent clay; moderate medium subangular blocky structure; very sticky and very plastic; few very fine roots throughout; prominent clay films and pressure faces, 1 percent gravel; very slightly effervescent; moderately alkaline, pH 8.0; gradual smooth boundary.

Btk1—15 to 28 inches (37 to 70 cm); clay, dark brown (7.5YR 3/3), moist; 40 percent clay; moderate fine subangular blocky structure; very sticky and very plastic; few very fine roots throughout; medium spherical carbonate masses in matrix, prominent pressure faces, 0 percent gravel; strongly effervescent; moderately alkaline, pH 8.0; gradual smooth boundary.

Btk2—28 to 42 inches (70 to 107 cm); clay, brown (7.5YR 4/3), moist; 40 percent clay; moderate fine subangular blocky structure; very sticky and very plastic; coarse spherical carbonate masses in matrix, 0 percent gravel; strongly effervescent; moderately alkaline, pH 8.0; gradual smooth boundary.

Btk3—42 to 49 inches (107 to 125 cm); clay, dark brown (7.5YR 3/3), moist; 40 percent clay; moderate fine subangular blocky structure; very sticky and very plastic; coarse spherical carbonate masses in matrix, prominent pressure faces, 0 percent gravel; violently effervescent; moderately alkaline, pH 8.0.



Site 3 Soil Series Description

LOCATION DEAMA NM+AZ

Established Series
Rev. REN-DGS-RLB
11/2014

DEAMA SERIES

The Deama series consists of shallow and very shallow, well drained soils with moderately slow permeability above very slowly permeable limestone bedrock. They formed in colluvium mainly from limestone. Deama soils are on hills, ridges, plateaus, or mesas. Slope ranges from 0 to 90 percent. Mean annual precipitation is about 15 inches and mean annual air temperature is about 52 degrees F.

TAXONOMIC CLASS: Loamy-skeletal, carbonatic, mesic Lithic Calciustolls

TYPICAL PEDON: Deama very stony loam, rangeland. (Colors are for dry soil unless otherwise noted.)

A--0 to 4 inches; dark grayish brown (10YR 4/2) very stony loam, very dark grayish brown (10YR 3/2) moist; weak fine granular structure; slightly hard, friable, slightly sticky and slightly plastic; many fine roots; 15 percent angular limestone pebbles, 15 percent cobbles, 15 percent stones; slightly effervescent; moderately alkaline; gradual wavy boundary. (1 to 7 inches thick)

Bk1--4 to 8 inches; dark grayish brown (10YR 4/2) very stony loam, very dark grayish brown (10YR 3/2) moist; weak fine subangular blocky structure; slightly hard, friable, slightly sticky and slightly plastic; common fine roots; 20 percent angular limestone and hard caliche pebbles; 10 percent cobbles, 10 percent stones; discontinuous hard calcium carbonate coatings on rock fragments; violently effervescent; moderately alkaline; clear wavy boundary.

Bk2--8 to 13 inches; brown (10YR 4/3) very stony loam, dark brown (10YR 3/3) moist; weak fine subangular blocky structure; slightly hard, friable, slightly sticky and slightly plastic; common fine roots; common fine pores; 25 percent angular limestone and caliche pebbles, 15 percent cobbles, 20 percent stones; many moderately thick hard calcium carbonate coatings on rock fragments, most numerous on the bottom side; violently effervescent; moderately alkaline; clear abrupt boundary. (Combined thickness of the Bk horizon is 6 to 13 inches)

R--13 to 18 inches; limestone bedrock; upper surface coated with hard calcium carbonate about 1/8 inch thick.

TYPE LOCATION: Otero County, New Mexico; approximately 1.1 mile northwest of Red Lake-Augustine Tank road; near the center of the northwest quarter, sec. 4, T. 13S., R. 16E. Latitude 33 degrees 13 minutes 3.89 seconds north and longitude 105 degrees 22 minutes 48.07 seconds west. UTM 464587E and 3675300N.

RANGE IN CHARACTERISTICS:

Soil Moisture: An ustic moisture regime bordering on aridic. Intermittently moist in some part of the soil moisture control section November through March and July through September. The soil is driest during May and June.

Mean Annual Soil Temperature: 47 to 59 degrees F.
Depth to bedrock: 7 to 20 inches
Reaction: Slightly to strongly alkaline
Rock fragments: 35 to 85 percent in the particle-size control section
Clay content: 18 to 35 percent in the particle-size control section
Calcium carbonate equivalent: 40 to 60 percent in the particle-size control section

A horizon
Hue: 5YR, 7.5YR, 10YR
Value: 2 to 6 dry, 1 to 4 moist
Chroma: 2 or 3, dry or moist
Texture: fine sandy loam, sandy loam, loam, silt loam, clay loam
Rock fragments: 15 to 85 percent

Bk horizon
Hue: 5YR, 7.5YR, 10YR
Value: 4 to 8 dry, 2 to 7 moist
Chroma: 2 to 4, dry or moist
Texture: sandy loam, loam, sandy clay, clay loam

COMPETING SERIES: This is the Legate(NM) series. Similar soils are the Ector, Lozier,Oro Grande, Rudd, and Tortugas series. Legate soils average less than 18 percent clay in the particle size control section. Ector soils have a thermic temperature regime. Lozier soils do not have a mollic epipedon. Oro Grande and Rudd soils have less than 40 percent carbonates in the control section.
Tortugas soils do not have a calcic horizon.

GEOGRAPHIC SETTING: The Deama soils are on hills, ridges, mesas, or plateaus. Slopes range from 0 to 90 percent. The soils formed in colluvium derived mainly from limestone. Mean annual precipitation ranges from 12 to 18 inches and mean annual temperature ranges from 45 to 58 degrees F. Frost-free season ranges from 110 to 180 days and elevation ranges from 4,500 to

8,660 feet

GEOGRAPHICALLY ASSOCIATED SOILS: These are the Asparas, Cale, Darvey,Harvey, Jarita, Kerrick, Pena, and Shanta soils and the competing Lozier soils.
Asparas, Darvey, and Harvey soils: more than 40 inches deep.
Jarita soils: deeper than 20 inches to bedrock and have an argillic horizon.
Kerrick soils: have a petrocalcic horizon.
Pena soils: do not have a lithic contact within 20 inches of the surface.
Shanta and Cale soils: have less than 35 percent rock fragments.

DRAINAGE AND PERMEABILITY: Well drained. Permeability of the soil material is moderately slow above a very slowly permeable bedrock. Runoff is high on slopes less than 1 percent and very high on slopes greater than 1 percent.

USE AND VEGETATION: These soils are used primarily for livestock grazing. Principal vegetation is blue grama, black grama, hairy grama, sideoats grama, bluestem spp, oak bush, pinyon, alligator juniper, and oneseed juniper.

DISTRIBUTION AND EXTENT: Foothills adjoining mountainous areas of south-central New Mexico and northern Arizona. The series is moderately extensive. MLRA 42.

MLRA SOIL SURVEY REGIONAL OFFICE (MO) RESPONSIBLE: Phoenix, Arizona

SERIES ESTABLISHED: Valencia County (East Valencia Area), New Mexico, 1970.

REMARKS: Diagnostic horizons and features recognized in this pedon are:

Mollic epipedon - 0 to 8 inches. (A and Bk1 horizon).
Calcic horizon - 4 to 13 inches. (Bk horizons).
Lithic contact - The R contact at 13 inches.

Classified according to Soil Taxonomy Second Edition, 1999; Keys to Soil Taxonomy, Twelfth Edition, 2014.

Revised for the correlation of White Sands Missile Range, New Mexico; October, 2014, NMS

National Cooperative Soil Survey
U.S.A.

Sites 4 and 5 Soil Series Description

LOCATION WINONA AZ+NM UT

Established Series
Rev. DRT/RLB
10/2011

WINONA SERIES

The Winona series consists of very shallow and shallow, well drained soils that formed in eolian deposits over alluvium from limestone and calcareous sandstone. Winona soils are on plateaus and hills and have slopes of 0 to 70 percent. The mean annual precipitation is about 11 inches and the mean annual air temperature is about 52 degrees F.

TAXONOMIC CLASS: Loamy-skeletal, carbonatic, mesic Lithic Ustic Haplocalcids

TYPICAL PEDON: Winona extremely gravelly loam - rangeland. (Colors are for dry soil unless otherwise noted.)

A--0 to 2 inches; brown (7.5YR 5/3) extremely gravelly loam, brown (7.5YR 4/3) moist; weak fine granular structure; soft, very friable, nonsticky and slightly plastic; many very fine roots; common very fine irregular pores; 60 percent gravel, 20 percent cobble and 5 percent stones; violently effervescent, 32 percent calcium carbonate equivalent; moderately alkaline (pH 7.9); clear wavy boundary. (1 to 4 inches thick)

Bw--2 to 10 inches; brown (7.5YR 5/3) extremely gravelly loam, brown (7.5YR 4/3) moist; weak medium subangular blocky structure; slightly hard, friable, slightly sticky and slightly plastic; many very fine roots; common very fine tubular pores; 55 percent gravel and 10 percent cobble; violently effervescent, 37 percent calcium carbonate equivalent; moderately alkaline (pH 7.9); abrupt wavy boundary. (6 to 10 inches thick)

Bk--10 to 17 inches; very pale brown (10YR 7/3) extremely gravelly loam, brown (10YR 5/3) moist; weak medium subangular blocky structure; slightly hard, friable, slightly sticky and slightly plastic; many very fine roots; common very fine tubular pores; 50 percent gravel and 10 percent cobble; many coarse soft calcium carbonate masses and thin coatings on rock fragments; violently effervescent, 54 percent calcium carbonate equivalent; moderately alkaline (pH 8.0); abrupt wavy boundary. (1 to 8 inches thick)

2R--17 inches; fractured limestone; discontinuous calcium carbonate coatings.

TYPE LOCATION: Coconino County, Arizona; 1900 feet north and 2200 feet east of the southwest corner of section 15. T. 32 N., R. 4 W.

RANGE IN CHARACTERISTICS:

Soil moisture - Intermittently moist in some part of the soil moisture control section during July-September and December-February. Driest during May and June. Ustic aridic soil moisture regime.

Soil Temperature - 48 to 56 degrees F.

Rock fragments - 35 to 70 percent limestone and chert gravel, channers, cobble and flagstones

Depth to bedrock - 6 to 20 inches

Calcium carbonate - 40 to 60 percent calcium carbonate equivalent

A horizon
Hue: 5YR, 7.5YR, 10YR
Value: 4 to 6 dry, 3 or 4 moist
Chroma: 2 to 4 dry
Reaction: slightly or moderately alkaline

Bk horizon
Hue: 5YR, 7.5YR, 10YR
Value: 5 to 7 dry, 3 to 6 moist
Chroma: 2 to 4, dry or moist
Texture: loam, sandy loam, very fine sandy loam, fine sandy loam, silt loam, clay loam (15 to 30 percent clay)
Calcium carbonate: segregated and as coatings on rock fragments
Bw horizon is not present in all pedons.

COMPETING SERIES: Competing series are the Scrapy (NV), Splimo (UT) and Yaki (UT) series.
Scrapy soils have a calcic horizon at 1 to 3 inches below the surface.
Splimo soils have mean annual soil temperature of 47 to 51 degrees and a calcic horizon at 5 to 10 inches deep.
Yaki soils do not have Bw horizon and the profile is dominated by cobbles.

GEOGRAPHIC SETTING: Winona soils are on plateaus and hills. Slopes are dominantly 2 to 15 percent, but range from 0 to 70 percent. These soils formed in eolian deposits over alluvium from limestone and calcareous sandstone. Elevations range from 4700 to 7100 feet. The climate is semiarid with a mean annual precipitation of 8 to 14 inches occurring as summer thunderstorms and gentle winter rain and snow. The mean annual air temperature ranges from 46 to 54 degrees F. The mean temperature for July is 71 degrees F. and for December is 31 degrees F. The frost-free period ranges from 120 to 180 days.

GEOGRAPHICALLY ASSOCIATED SOILS: These are Boysag, Tovar, and Tusayan soils. Boysag and Tovar soils have argillic horizons. Tusayan soils are 20 to 40 inches deep over bedrock.

DRAINAGE AND PERMEABILITY: Well drained; slow to rapid runoff; moderate permeability.

USE AND VEGETATION: These soils are used for livestock grazing and wildlife habitat. Vegetation is blue grama, black grama, needleandthread, galleta, sand and spike dropseed, hairy grama, muttongrass, bottlebrush, squirreltail, alkali sacaton, winterfat, bigelow sage, fourwing saltbush, cliffrose, juniper and pinyon pine.

DISTRIBUTION AND EXTENT: Northern Arizona and west central New Mexico. MLRAs 35, 36, 38

MLRA SOIL SURVEY REGIONAL OFFICE (MO) RESPONSIBLE: Phoenix, Arizona.

SERIES ESTABLISHED: Coconino County, (Long Valley Area), Arizona; 1971.

REMARKS: Diagnostic horizons and features recognized in this pedon are:

Ochric epipedon - The zone from 0 to 2 inches (A horizon)

Calcic horizon - The zone from 10 to 17 inches (Bk horizon)

Lithic contact - The boundary at 17 inches (2R horizon)

Classified according to Soil Taxonomy Second Edition, 1999; Keys to Soil Taxonomy Eleventh Edition, 2010

The type location is moved to a site with carbonatic mineralogy. The original site averaged 29 percent calcium carbonate equivalent. New Mexico has correlated and published Winona as carbonatic or the mineralogy would be reclassified as mixed.

Update and revisions for the correlation of Little Colorado River Area (AZ707), Sept. 2011, CEM

Site 6 Soil Series Description

LOCATION EPIKOM AZ

Established Series
Rev. DRT/RLB
10/2011

EPIKOM SERIES

The Epikom series consists of shallow, well drained soils that formed in alluvium from sandstone, mudstone and shale. Epikom soils are on plateaus and mesas and have slopes of 0 to 25 percent. The mean annual precipitation is about 8 inches and the mean annual air temperature is about 51 degrees F.

TAXONOMIC CLASS: Loamy, mixed, superactive, mesic Lithic Haplocambids

TYPICAL PEDON: Epikom fine sandy loam - rangeland. (Colors are for dry soil unless otherwise noted.)

A--0 to 3 inches; reddish brown (5YR 5/4) fine sandy loam, reddish brown (5YR 4/4) moist; weak thin platy structure; slightly hard, very friable, slightly sticky and slightly plastic; few fine roots; common fine vesicular and many irregular pores; violently effervescent; moderately alkaline (pH 8.0); abrupt smooth boundary. (3 to 5 inches thick)

Bw--3 to 15 inches; reddish yellow (5YR 6/6) gravelly loam, yellowish red (5YR 5/6) moist; weak fine and medium subangular blocky structure; slightly hard, friable, slightly sticky and plastic; common fine and medium roots; few irregular and tubular pores; 20 percent gravel; violently effervescent; moderately alkaline (pH 8.2); abrupt wavy boundary. (7 to 15 inches thick)

2R--15 inches; interbedded sandstone and shale; common calcium carbonate coatings in joints.

TYPE LOCATION: Coconino County, Arizona; about 48 miles east and 18 miles south of Flagstaff; 600 feet west of the center of section 32, T. 18 N., R. 14 E.

RANGE IN CHARACTERISTICS:

Soil Moisture: Intermittently moist in some part of the soil moisture control section during July-September and December-February. Driest during May and June. Typic aridic soil moisture regime.

Soil Temperature: 51 to 59 degrees F.

Depth to bedrock: 10 to 20 inches

Clay content: Averages less than 18 percent in the control section

Rock Fragments: Averages less than 35 percent in the control section; can range to 60 percent in any one horizon.

A horizon
Hue: 2.5YR, 5YR, 7.5YR
Value: 4 to 7 dry, 3 to 5 moist
Chroma: 2 to 6, dry or moist
Reaction: Slightly to strongly alkaline

B horizon
Hue: 2.5YR, 5YR, 7.5YR
Value: 4 to 7 dry, 3 to 6 moist
Chroma: 2 to 6, dry or moist
Texture: Sandy loam, loam, fine sandy loam
Reaction: Slightly to strongly alkaline
Calcium carbonate: Less than 15 percent calcium carbonate equivalent as disseminated or coatings on rock fragments.

COMPETING SERIES: These are the Leanto(UT) and Lyeflat (OR) series. Leanto soils have hue yellower than 5YR and are moist in the moisture control section for longer periods due to a higher rainfall component. Lyeflat soils have 10YR or 2.5Y hues and SAR that range from 13 to 30 percent.

GEOGRAPHIC SETTING: Epikom soils are on plateaus and mesas and have slopes of 0 to 25 percent. These soils formed in alluvium from sandstone, mudstone and shale. Elevations range from 4,220 to 7,000 feet. The mean annual precipitation ranges from 6 to 10 inches. The mean annual air temperature is 49 to 57 degrees F. The frost-free period is 130 to 180 days.

GEOGRAPHICALLY ASSOCIATED SOILS: These are the Boysag, Navajo,Purgatory, and Tours soils. Boysag soils have argillic horizons. Navajo and Tours soils are very deep. Tours soils are also fine-silty. Purgatory soils have bedrock at depths of 20 to 40 inches.

DRAINAGE AND PERMEABILITY: Well drained; slow to moderate runoff; moderate or moderately rapid permeability.

USE AND VEGETATION: Epikom soils are used for livestock grazing and wildlife habitat.

The present vegetation is black grama, blue grama, galleta, alkali sacaton and fourwing saltbush.

DISTRIBUTION AND EXTENT: Northern Arizona. This series is extensive. MLRA 35.

MLRA SOIL SURVEY REGIONAL OFFICE (MO) RESPONSIBLE: Phoenix, Arizona

SERIES ESTABLISHED: Coconino County Area, Arizona, Central Part; 1980.

REMARKS: Diagnostic horizons and features recognized in this pedon are:

Ochric epipedon - The zone from 0 to 3 inches (A horizon)

Cambic horizon - The zone from 3 to 15 inches (Bw horizon)

Lithic contact - The boundary at 15 inches (2R horizon)

Classified according to Soil Taxonomy Second Edition, 1999; Keys to Soil Taxonomy, Eleventh Edition, 2010

Update and revisions for the correlation of Little Colorado River Area (AZ707), Sept. 2011, CEM

National Cooperative Soil Survey
U.S.A.

APPENDIX B:

SUPPLEMENTARY GRAPHS

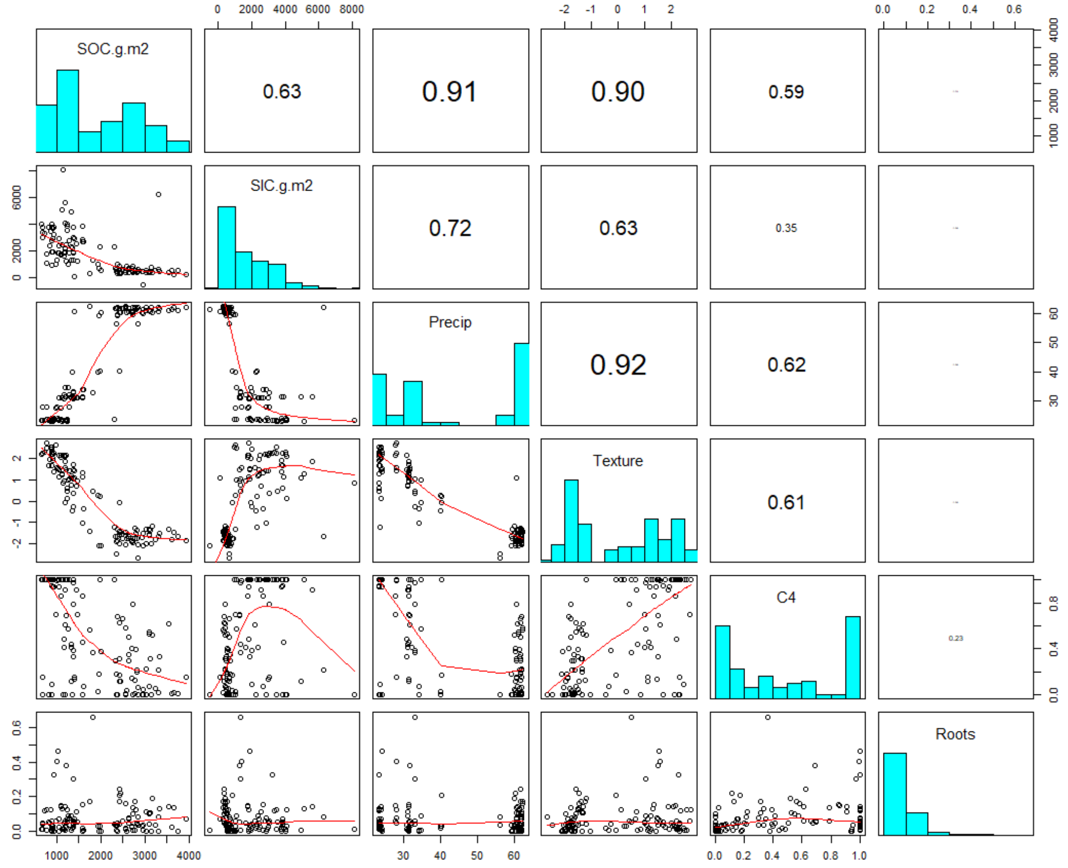


Figure S1. A pairs plots examining the Pearson correlation coefficients for all variables on the surface. Significance is displayed by the proportional size of the path values written in the upper right half of the figure. The only coefficients that weren't significant were the relationships involving the roots.

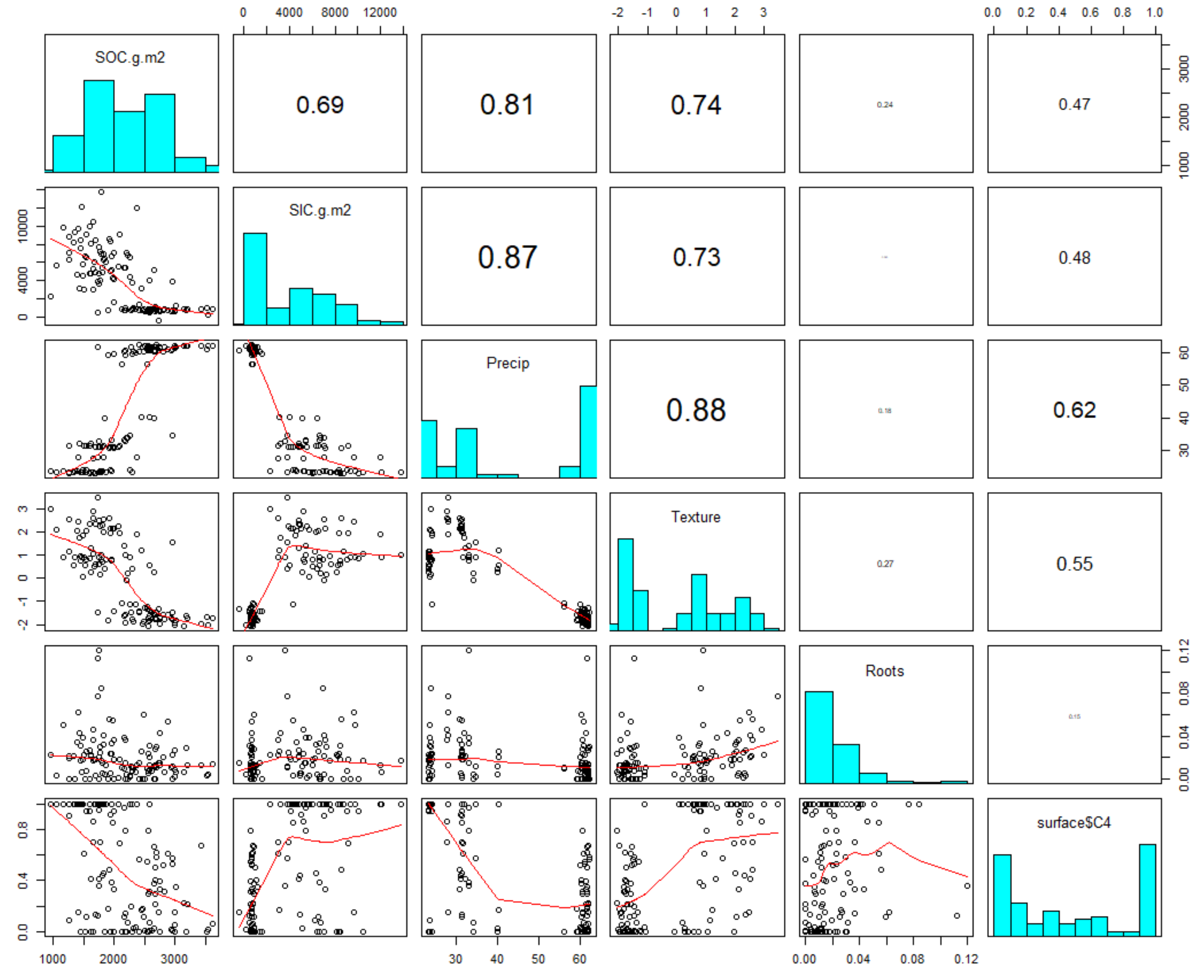


Figure S2. A pairs plots examining the Pearson correlation coefficients for all variables on the subsurface. Significance is displayed by the proportional size of the path values written in the upper right half of the figure. The only coefficients that weren't significant were the relationships involving the roots.

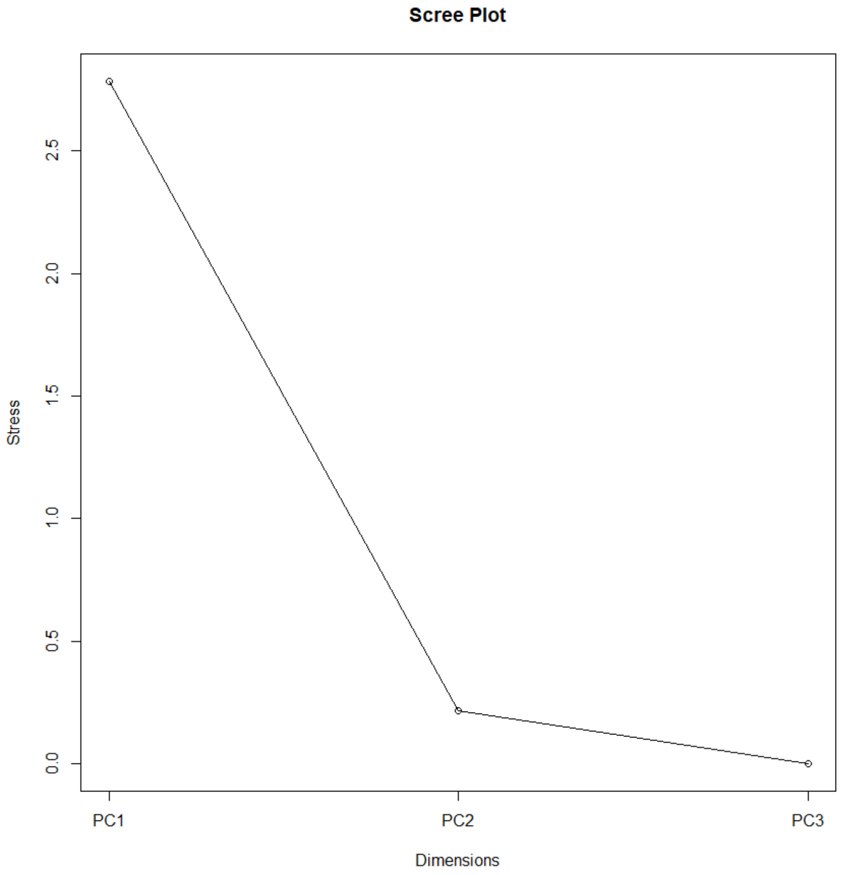


Figure S3. A scree plot from the texture PCA displaying stress as a function of the number of principal components. "Stress" is inversely related to how well the data fit.

	PC1	**PC2**	**PC3**
Standard Deviation	1.673	0.44844	0.001996
Proportion of Variance	0.933	0.06703	0

Table S1. Proportion of the variance captured from each axis within the texture PCA

Scree Plot for Vegetation nMDS Ordination

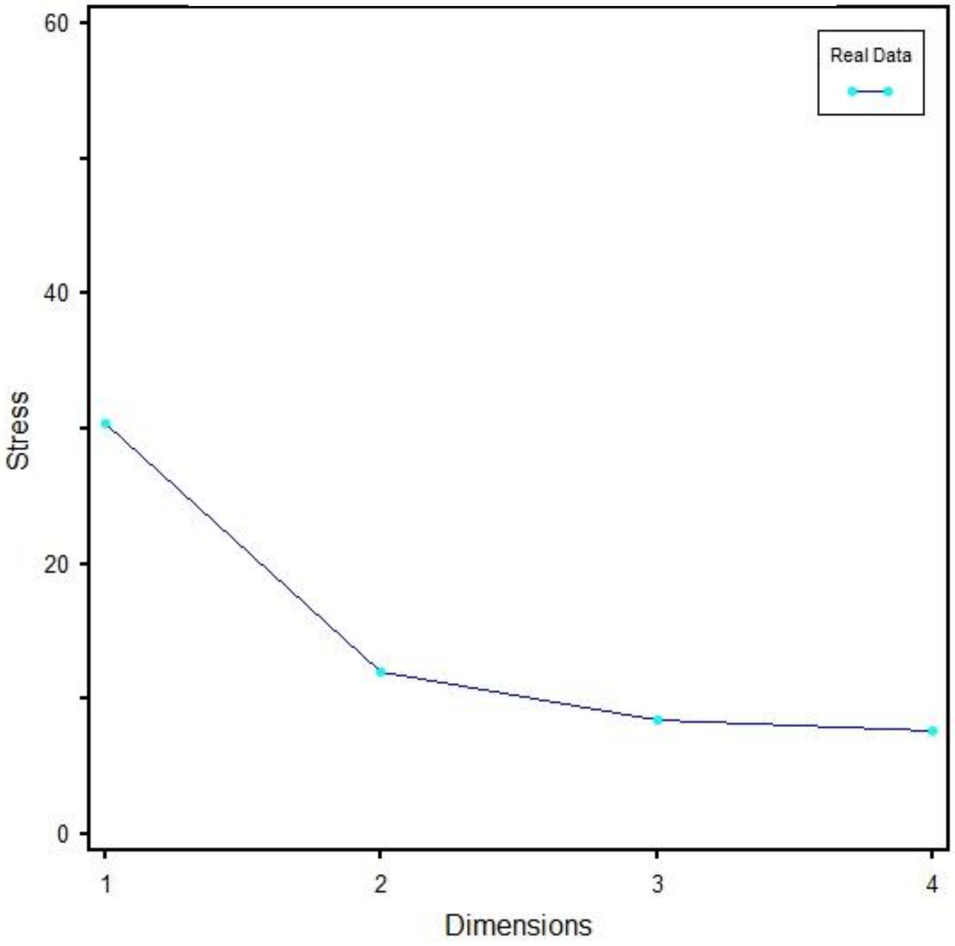


Figure S4. A scree plot from the vegetation nMDS displaying stress as a function of the number of axes. “Stress” is inversely related to how well the data fit.

Axis	Increment	Cumulative
1	0.379	0.379
2	0.540	0.920

Table S2. Proportion of variance captured by axes 1 and 2 from the nMDS>

	C4 Grasses	C3 Grasses	Shrubs	Forbs
MDS1	0.294	-0.385	0.337	-0.453
MDS2	0.533	-0.266	-0.477	0.018

Table S3. Proportion of the variance captured by each variable for axes 1 and 2 from the nMDS.

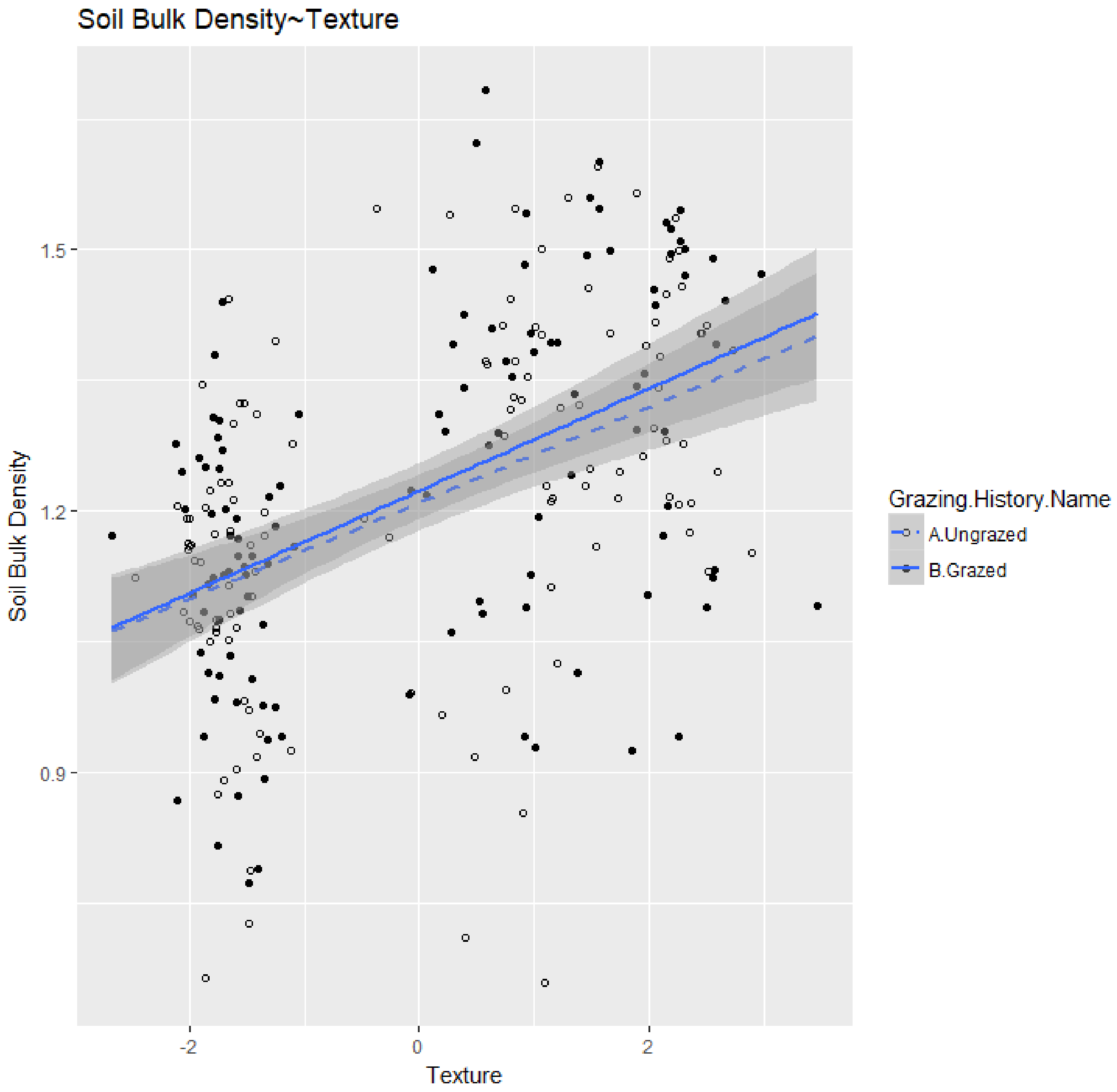


Figure S5. A linear regression of soil bulk density across a span of textures. Bulk density increased in the more sandy, dry soils

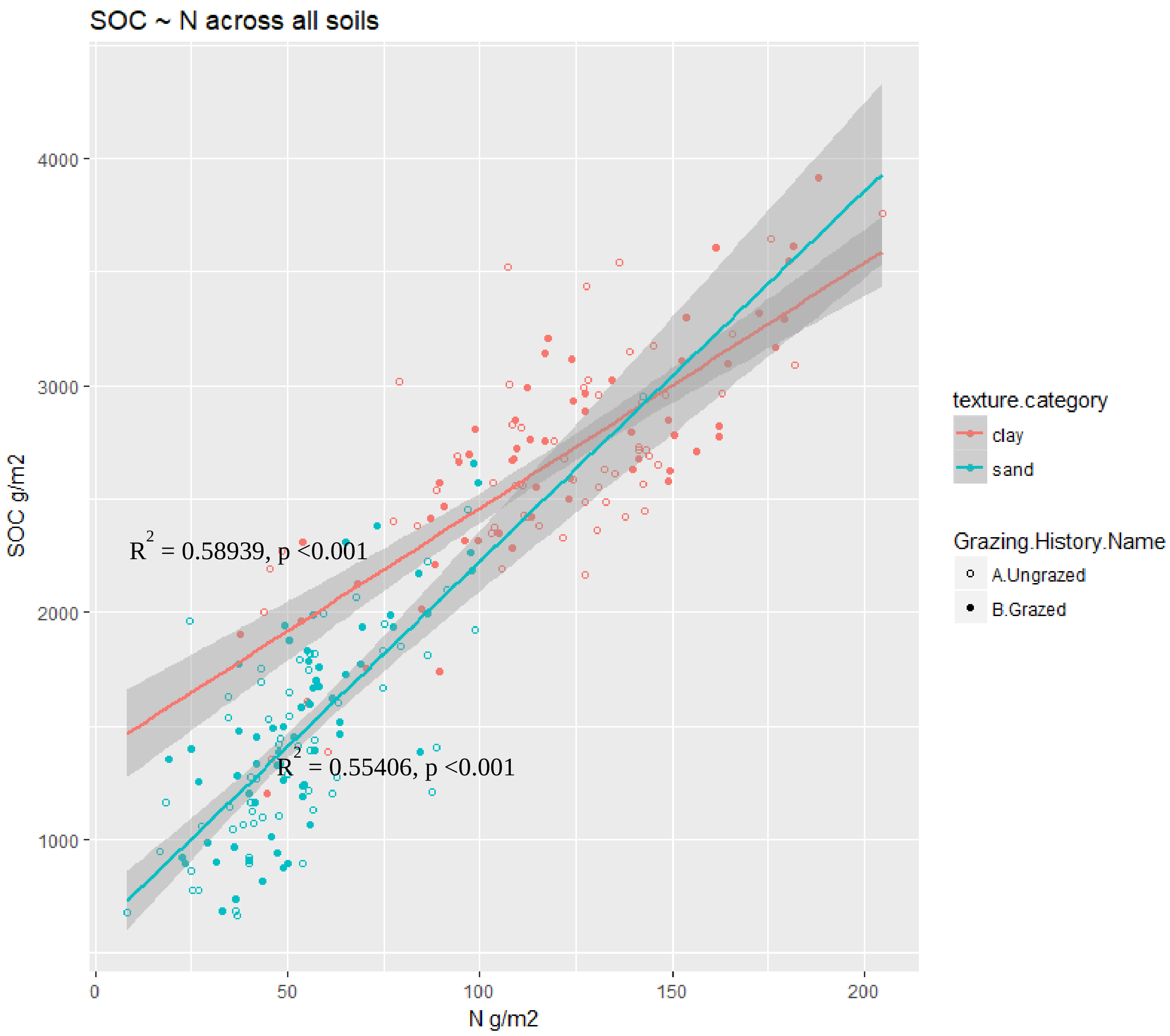


Figure S6. A linear regression evaluating the relationship between nitrogen and soil organic carbon. The slopes were significantly different from each other. The clay-rich, wetter sites had a higher R2 value compared to the sandy, dry sites.

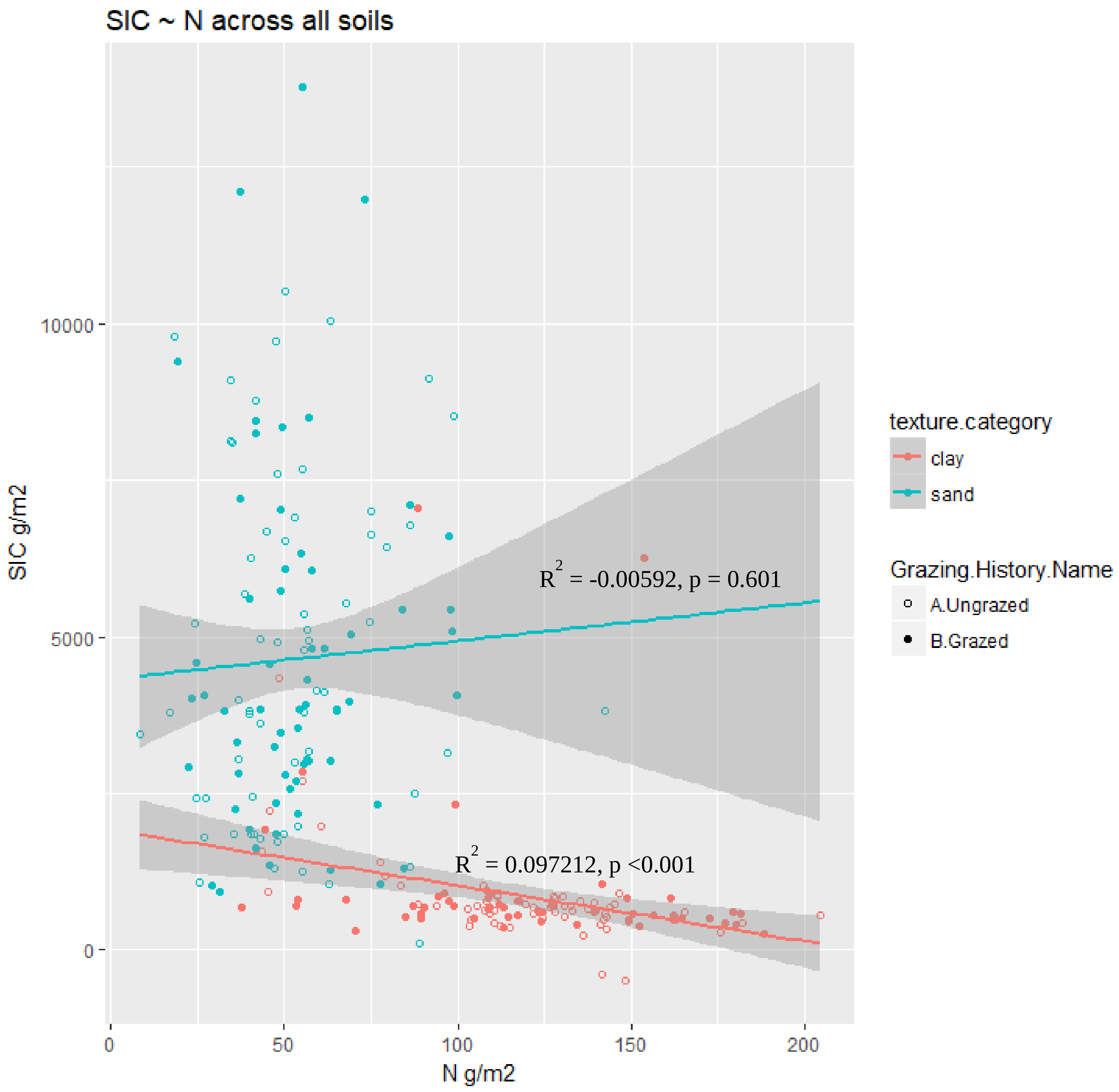


Figure S7. A linear regression evaluating the relationship between nitrogen and soil organic carbon. The slopes were significantly different from each other. The clay-rich, wetter sites had a higher R^2 value compared to the sandy, dry sites.

APPENDIX C:

SUPPLEMENTARY TABLES

SOC GLM	SOC ~ Texture + C4 Grasses + Roots + Grazing History + Depth + Grazing History*Depth + Depth*Texture + Grazing History * Texture
SIC GLM	SIC ~ Texture + C4 Grasses + Roots + Grazing History + Depth + Grazing History*Depth + Depth*Texture + Grazing History * Texture

Table S4. Table of the general linear models run for SOC and SIC. Depth, texture, and the interaction between depth and texture were all significant.

Source	N	F Ratio	Prob > F
Grazing.History	120	0.8551	0.3565
Depth	120	8.5985	0.0038*
Bufflo.Site	120	0.0058	0.9395
Texture	120	188.6915	<.0001*
Cleaned Root Weight (g)	120	1.0513	0.3065
%C4 Grass	120	3.8623	0.0508
Bufflo.Site*Grazing.History.Name	120	0.0022	0.9631
Grazing.History*Depth	120	1.3783	0.2421
Texture*Depth	120	34.0782	<.0001*
Grazing.History*Texture	120	0.0000	0.9953

Table S5. F-ratios from general linear model of soil organic carbon. Significant effects and interactions are indicated

Source	**Nparm**	**DF**	**DFDen**	**F Ratio**	**Prob > F**
Grazing.History	1	1	143.9	0.0005	0.9818
Depth	1	1	161.7	50.2967	<.0001*
Bufflo.Site	1	1	39.8	0.1524	0.6983
Texture	1	1	130.3	34.7129	<.0001*
Cleaned Root Weight (g)	1	1	167.6	1.5389	0.2165
%C4 Grass	1	1	170.7	0.0051	0.9433
Grazing.History*Depth	1	1	143.8	0.8242	0.3655
Texture*Depth	1	1	154.4	63.9769	<.0001*
Grazing.History*Texture	1	1	145.9	0.9216	0.3386
Bufflo.Site*Grazing.History	1	1	143.9	0.0356	0.8506

Table S6. F-ratios from general linear model of soil inorganic carbon. Significant effects and interactions are indicated..

Source	Nparm	DF	DFDen	F Ratio	Prob > F
C4Grass	1	1	95.7	6.4289	0.0128*
Grazing.History	1	1	57.31	1.6509	0.2040
Buffalo.Sites*Grazing.History	1	1	56.06	0.0949	0.7592
Buffalo.Sites	1	1	59.6	3.6071	0.0624
Surface.Texture	1	1	104	195.7720	<.0001*
Surface.Roots	1	1	84.5	4.9044	0.0295*

Table S7. F-ratios from general linear model of surface soil organic carbon. Significant effects and interactions are indicated

Source	Nparm	DF	DFDen	F Ratio	Prob > F
C4Grass	1	1	107.4	0.0412	0.8395
Grazing.History	1	1	54.24	0.4189	0.5202
Buffalo.Sites*Grazing.History	1	1	52.78	0.0421	0.8383
Buffalo.Sites	1	1	56	1.7168	0.1955
Surface.Texture	1	1	96.95	42.3726	<.0001*
Surface.Roots	1	1	96.21	3.8499	0.0526

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Grazing.History	1	1	1048365	0.7637	0.3840
C4.Grass	1	1	96514	0.0703	0.7914
Surface.Roots	1	1	5669400	4.1301	0.0444*
Surface.Texture	1	1	72454952	52.7829	<.0001*

Table S8. F-ratios from general linear model of surface soil inorganic carbon. Significant effects and interactions are indicated. The first model is the first run. Buffalo sites were removed from the second model because the effects were not significant.

Source	Nparm	DF	DFDen	F Ratio	Prob > F
Subsurface.Texture	1	1	98.94	88.8755	<.0001*
Grazing.History	1	1	57.99	0.0122	0.9124
Subsurface.Roots	1	1	91.41	4.1587	0.0443*
C4.Grass	1	1	94.38	0.0034	0.9536
Buffalo.Sites	1	1	63.06	9.8915	0.0025*
Buffalo.Sites*Grazing.History	1	1	58.08	0.0005	0.9819

Table S9. F-ratios from general linear model of subsurface soil organic carbon. Significant effects and interactions are indicated

Source	Nparm	DF	DFDen	F Ratio	Prob > F
Subsurface.Texture	1	1	99.22	44.5744	<.0001*
Grazing.History	1	1	55.58	1.2160	0.2749
Subsurface.Roots	1	1	86.49	2.9370	0.0902
C4.Grass	1	1	89.78	2.7872	0.0985
Buffalo.Sites	1	1	60.94	0.1934	0.6617
Buffalo.Sites*Grazing.History	1	1	55.72	0.2457	0.6221

Table S10. F-ratios from general linear model of subsurface soil inorganic carbon. Significant effects and interactions are indicated.

Source	Nparm	DF	DFDen	F Ratio	Prob > F
Grazing.History	1	1	57.73	6.5103	0.0134*
Surface.Texture	1	1	66.68	65.9242	<.0001*
Surface.Texture*Grazing.History	1	1	64.29	0.0123	0.9120

Table S11. F-ratios from general linear model for C_4 grasses. Significant effects and interactions are indicated