Precipitation Effects on Inter-Annual Variability of Rangeland Soil Carbon and Nitrogen

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ABSTRACT

Grasslands account for over 30% of global land cover and are predominantly managed for livestock production. Compost application has been proposed as a means to increase net primary productivity (NPP) and ecosystem carbon (C) and nitrogen (N) storage in soils. The goal of this study was to determine whether compost application on California rangelands leads to increased C and N sequestration through stimulation of plant activity. Since water is a limiting factor to growth in California rangelands, we used precipitation as an indicator of soil moisture to determine whether water availability is the primary driver of C and N content variability in Mediterranean grassland soils. Over five years, compost significantly increased both C and N concentration and content ($P<0.01$), but annual precipitation did not explain inter-annual variability. Compost plots averaged 1.5 Mg ha^{-1} yr^{-1} more than control plots in the 0-10 cm depth. When scaled to the 23 million ha of rangeland in California, we could sequester 34.5 million Mg C ha^{-1} yr^{-1} and offset 11% of California's annual CO_2 emissions with a one-time application of compost.

KEYWORDS

California annual grasslands, carbon sequestration, compost, soil moisture, nitrogen availability

INTRODUCTION

Sustainable land use plays an integral role in the future of environmental health because land-use practices significantly impact ecosystem functioning (Asner et al. 2004). Grasslands comprise over 30% of the Earth's land surface and are the most widely used land type for human activity (Hansen et al. 2000). Grasslands also store 28-37% of global terrestrial soil organic carbon (C) (Lal 2004). Rangeland ecosystems, the most common use of grasslands and critical contributors to global food production, are currently being degraded by poor management practices, such as overgrazing, that disregard long-term ecosystem functioning (Asner et al. 2004). Poor land management decreases soil C storage and alters physical soil properties that can in turn change soil moisture, microbial activity, nutrient retention, and many other processes that determine soil health (Cambarella and Elliott 1992, Stromberg and Griffin 1996). Decreased soil fertility, namely the lack of nitrogen (N), lowers plant productivity, resulting in decreased aboveground biomass for grazing animals (Jackson et al. 1988). Incorporating compost into rangelands can improve ecosystem function by preventing soil C and N depletion and increasing plant productivity (Harpole et al. 2007).

Compost application provides N, the limiting nutrient in grassland ecosystems, promoting net primary productivity (NPP) and increasing soil C and N pools (Harpole et al. 2007). N content has been shown to alter soil C cycling and ecosystem productivity, affecting not only plant growth but also the interactions between other key soil nutrients (Vitousek et al. 1997, Bobbink et al. 1998, Stevens et al. 2004). Increased NPP results in increased plant carbon dioxide comsumption through photosynthesis. Grassland plants allocate a high proportion of their biomass belowground in root systems, creating large amounts of C- and N-rich organic matter that can be decomposed by microbes and enter stable soil organic matter (SOM) pools (Jackson et al. 1996). Increasing N availability through compost addition promotes plant growth, but nutrient availability is not the only factor that determines growth rate in Mediterranean grassland systems (Harpole et al. 2007).

The lifecycle of annual grasslands is closely linked with wet and dry seasonal timing, making these ecosystems very responsive to changes in precipitation (Chou et al. 2008). Mean annual precipitation is a critical control of NPP and carbon dioxide (CO_2) uptake by plant activity (Knapp et al. 2002). Moisture availability also increases soil microbial activity, which significantly contributes to total ecosystem C cycling through heterotrophic respiration releasing CO_2 from the soil (Fierer and Schimel 2002). Drying-rewetting events can break down soil aggregates, exposing C stored within these aggregates to decomposition and loss (Fierer and Schimel 2002). Climate models predict future changes in annual precipitation in California ranging from – 30% to + 200%, proving the importance of researching impacts of precipitation on grassland ecosystem cycles (Hayhoe et al. 2004).

In a field study conducted by R. Ryals and W. Silver in 2008, one of three experimental blocks contained almost double the level of C and N as the other two blocks, in both control and compost amended plots. After closer examination, they found that this block contained a natural spring, therefore increasing soil moisture and water availability. This discrepancy demonstrates that soil moisture is a significant factor in annual grassland soil C and N storage. Three years after compost application, plots treated with compost increased 25-70% in net ecosystem C storage ($P < 0.001$) compared to control plots (excluding the block placed above the spring), showing the potential for compost application to increase C storage in an ecosystem regulated by soil moisture availability (Ryals and Silver 2013).

The goal of this study is to determine the role of precipitation, and therefore soil moisture, in rangeland C sequestration. I hypothesized that precipitation is the primary driver of inter-annual variability in soil C and N storage in annual grasslands because seasonal rainfall drives the processes that regulate C and N cycling, such as NPP and heterotrophic respiration. I predicted that soil C and N in control plots would be more sensitive to variations in precipitation than compost-treated plots because organic matter amendments increase soil moisture retention. The null hypothesis was that there was no correlation between precipitation and soil C and N levels.

METHODS

Climate and precipitation data

I obtained climate data from the Marin Municipal Water District to determine the daily rainfall and temperature for the duration of the study. I collected data on mean annual precipitation and monthly precipitation. One water year was defined as September 1 to August 31.

Study System

The study site was a privately owned, grazed, coastal grassland in Nicasio, CA (38.06° N, 122.71° W). California grasslands are mainly populated by nonnative grass and forb species such as *Avena barbata*, *Bromus hordeaceus*, *Lolium multiflorum*, *Erodium* spp., *Trifolium* spp. (Bartolome et al. 2007). The climate is Mediterranean, characterized by cool, wet winters and warm, dry summers. The growing season occurs during the rainy season, starting in early fall and ending in late spring. Mean annual precipitation is 950 mm/yr (38-year mean) and temperatures range from approximately 6° C to 20° C, with an average of 14.7° C. Soils are classified as Mollisols, the typical soil type found under North American grassland (Beaudette and O'Geen 2009). The site has been grazed since 1900, with a break from 2000-2005.

Experimental Design

Soil characteristics were measured in 3 compost treatment and 3 control plots sampled from October 2008 to June 2013. The field experiment was started in October 2008 by R. Ryals and W. Silver (Ryals and Silver 2013). Lab assistants took samples and processed them. The original study ended in 2011, but the Silver lab continued to collect and process data using the same methods.

Field plan and block design

Three blocks (Block 5, 6, 7) were established, each of which contained 2 plots (one treatment and one control) that were 25 x 60 m with buffers no smaller than 5 m in between. To control for landscape heterogeneity in vegetation and soil, blocks were placed in different microwatersheds. In December 2008, treatment plots received about 1.3cm layer of composted organic green waste from Feather River Organics (Marysville, California, USA). The compost had a carbon concentration of 20.57%, a nitrogen concentration of 1.87%, and a C:N ratio of 11. The surface layer application added 7.0 Mg ha^{-1} of dry compost matter, corresponding to 1.42 Mg C ha^{-1} and 0.129 Mg N ha^{-1} using the above concentrations.

Cattle were rotated through for up to four weeks in the fall and spring using a typical regional pattern, resulting in about 130 Mg ha^{-1} of residual dry matter. Cattle were able to graze the entire block, rather than being restricted to certain plots. There were barbed wire and electric fences in the area around the study site to deter wildlife from entering and grazing on the plots, but they did not completely restrict access.

Data Collection

Carbon measurement technique

At the end of each growing season (May or June), we took nine samples per plot, arranged in a 3x3 pattern for a total of 108 samples. We collected soils using a 7 cm-diameter corer to 10 cm depth. Large roots and identifiable compost pieces were taken out by hand. Soil was ground using a ball grinder, SPEX Sample Prep Mixer Mill 8000D (Metuchen, New Jersey, USA) and C and N concentration were measured with a Carlo Erba Elantech elemental analyzer. This analyzer incinerates the soil samples and measures C and N in gas form that results from the combustion. C and N concentration was measured in g C/g soil. Measurements were rock corrected by sieving the soil through a 2-mm screen, measuring rock mass, and subtracting it from the initial mass. Bulk density was measured in g soil/m^3. Concentrations were converted to content using the bulk density measurements: $\frac{g\ soil}{m^3}\ (bulk\ density) \times \frac{g\ C}{g\ soil}\ (concentration) \times m\ (depth) = \frac{g\ C}{m^2} (content)$. Final data was reported in units of Mg C ha^{-1}.

Statistical Analysis

To analyze treatment effects on soil organic C and N, I used a one-way analysis of variance (ANOVA) of a randomized block design using R 3.1.2 (Berkeley, California). This test compared soil C and N in treatment and control plots, accounting for the difference in variability between plots. To analyze individual block trends, I made simple linear models with year and treatment as variables. I used multiple linear regressions to analyze the correlation between annual precipitation and ecosystem C and N storage. I performed a Shapiro-Wilks normality test to determine whether my data were normally distributed. Statistical significance was defined as $P < 0.10$ and correlation was measured using adjusted R^2 values.

RESULTS

Inter-annual variability in precipitation

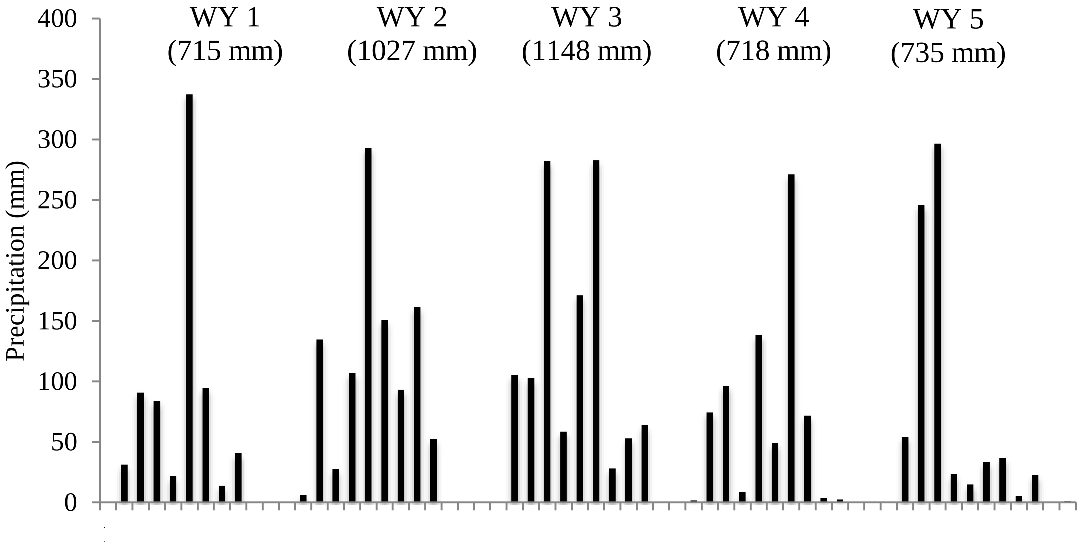


Figure 1: Precipitation totals by month for the duration of the study, starting in September 2008 and ending in August 2013.

Precipitation averaged 868.63 mm per water year during the study period, with a range of 715.26-1148.33 mm (SD = 204.61). The bulk of annual precipitation occurred during December-March, but WY 2 had an unusually dry beginning of the year and an extended wet season (Figure 1).

During the months of highest rainfall, there is a high variation between years (SD = 114-127) (Figure 1). In the dry season (June-August), there was no rainfall except in two outlier months in 2009 and 2013. In November, month 3, there was a significant early rainfall during WY 4 and a very low rainfall during WY 2.

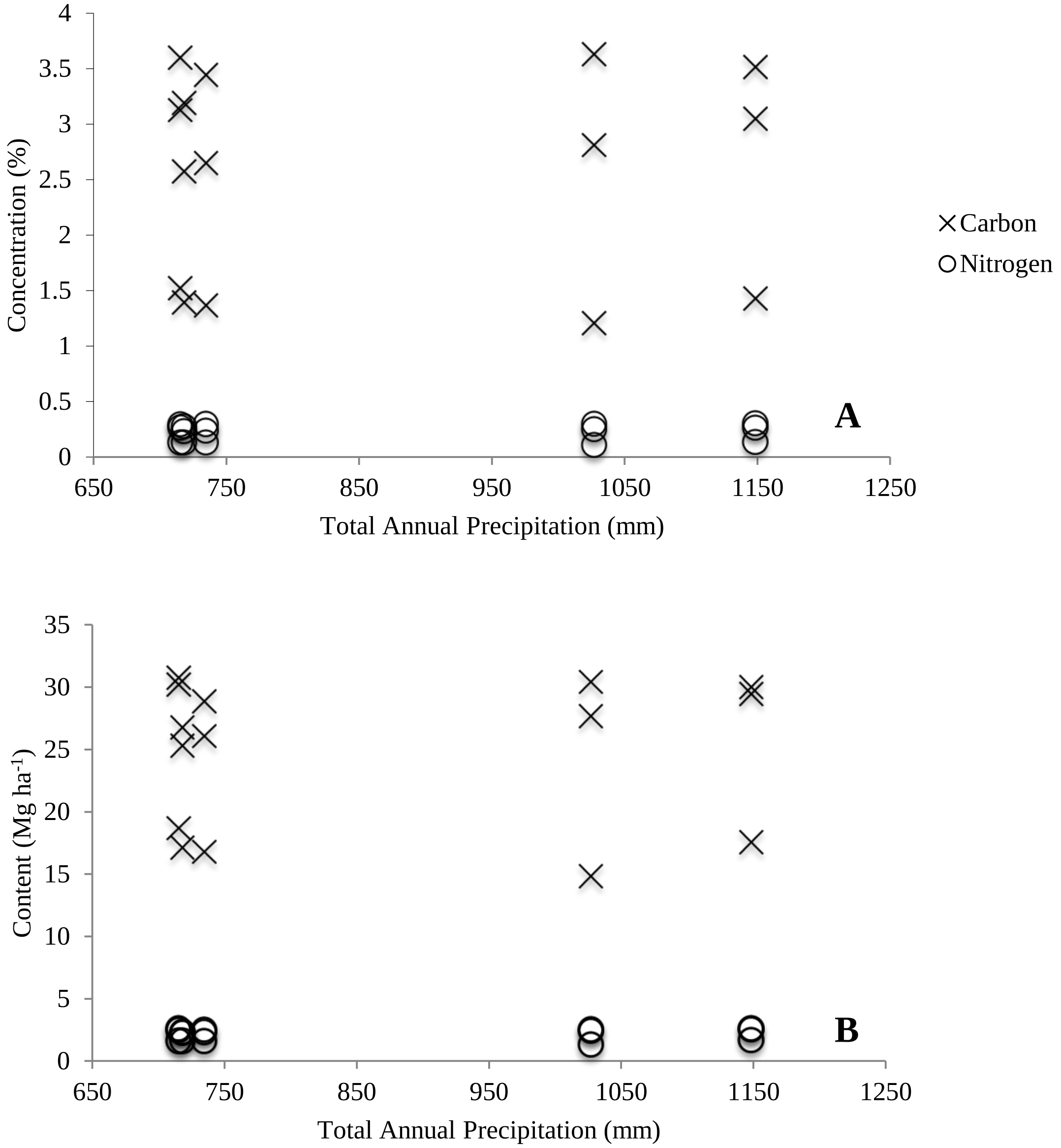


Figure 2: All four variables plotted by total annual precipitation to visualize C and N trends dependent on rainfall. (A) C and N concentration per block per year. (B) C and N content per block per year.

Randomized Block Design

Treatment was significantly higher for N concentration (P=0.004), N content (P=0.03), C concentration (P=0.02), and C content (P=0.05). Year was not a significant factor for N concentration or N content, but was significant (P=0.03) for both C concentration and C content (Figure 3).

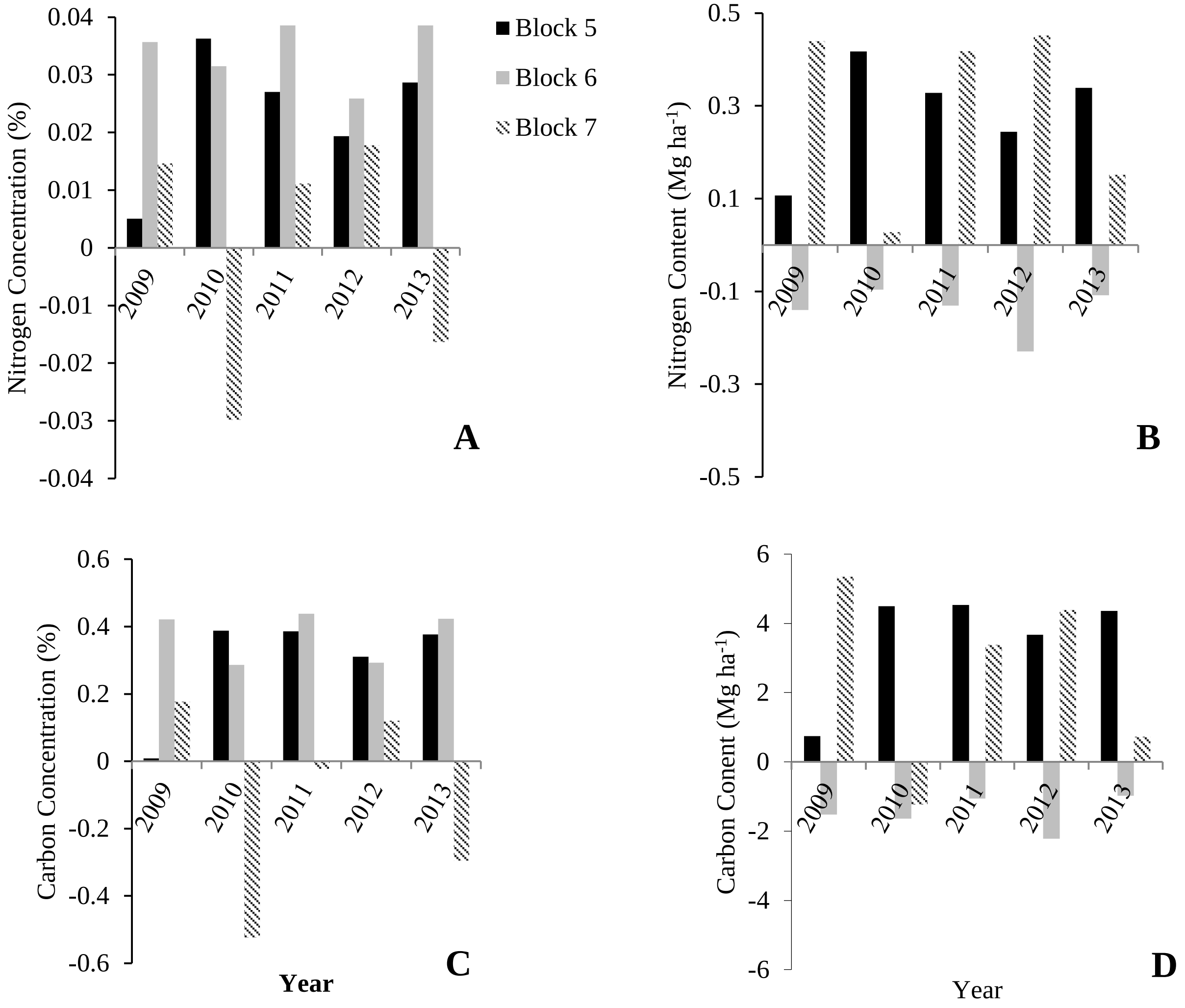


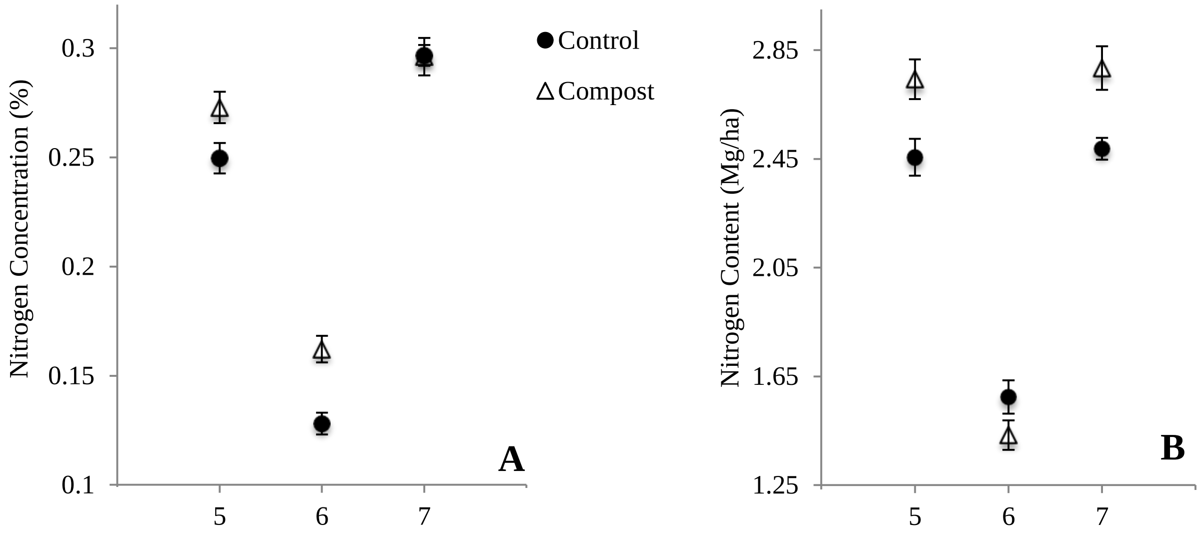
Figure 3: 5-year trends of the four variables shown by block. (A) Nitrogen concentration by block by year. (B) Nitrogen content by block by year. (C) Carbon concentration by block by year. (D) Carbon content by block by year. All graphs are differences between treatment and control plots so any values above the x-axis represent positive effects of compost application. We can see that there are varying trends between years and blocks for all the variables and a general positive trend.

Nitrogen Concentration and Content

Block 6 had significantly lower N concentration than both Block 5 and Block 7 (P=0.002) (Figure 4). Block-dependent analysis showed that N concentration in the treatment plots were significantly higher than control plots in Block 5 (P=0.04) and Block 6 (P=0.008), but not significantly higher in Block 7. For N content, Block 5 and Block 6 were significantly different ($P<0.005$), but Block 5 and Block 7 were not significantly different (Figure 4). N content in the treatment plots were significantly higher than the control plots in Block 5 ($P=0.02$) and Block 7 ($P=0.02$), but not in Block 6. Neither N concentration nor content were significantly affected by year. There was no significant effect of precipitation on N concentration ($P=0.75$, $R^2 = -0.03$), or N content ($P=0.71$, $R^2=-0.03$) (Figure 2).

Carbon Concentration and Content

C concentration in Block 6 was significantly lower than both Block 5 ($P<0.0005$) and Block 7 ($P<0.005$) (Figure 4). Block 5 and Block 7 did not have significantly different results between the treatment and control ($P=0.06$ and 0.44, respectively), but treatment significantly increased C concentration in Block 6 ($P=0.01$). C content was significantly higher in Block 5 and 7 than in Block 6 ($P<0.0005$), but not significantly different between Block 5 and Block 7 (Figure 4). Block 5 showed the only significant increase in C content with treatment ($P=0.03$). Year was not a significant factor for C concentration or content. There was no significant effect of precipitation on C concentration ($P=0.83$, $R^2=-0.03$) or C content ($P=0.81$, $R^2=-0.03$) (Figure 2).



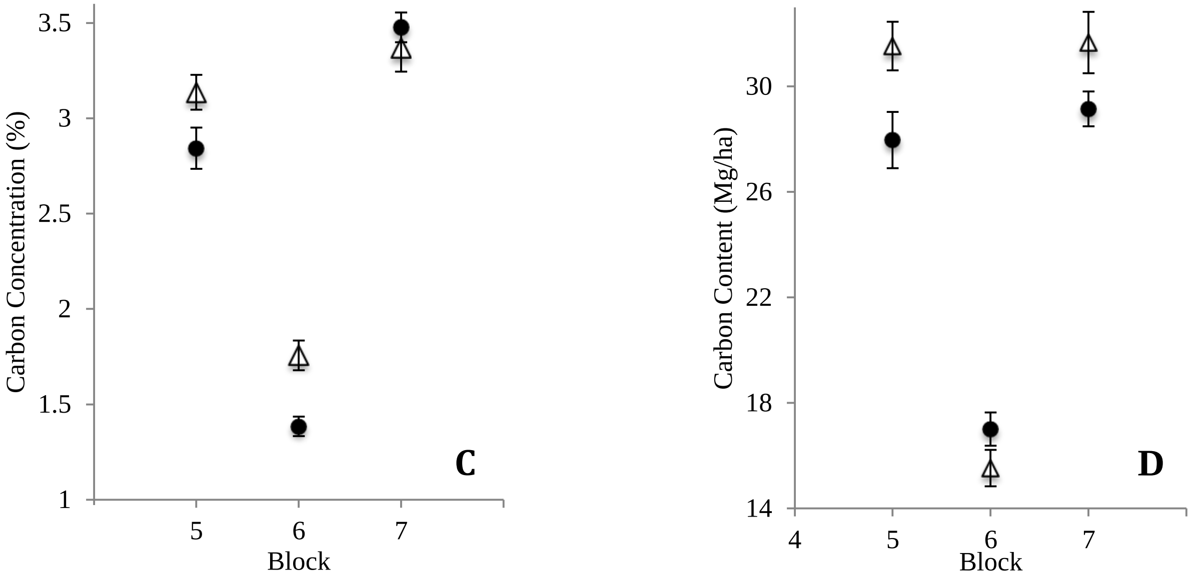


Figure 4: 5-year means and standard errors for the four variables by treatment by block. (A) Nitrogen concentration. (B) Nitrogen content. (C) Carbon concentration. (D) Carbon content. The significant differences between blocks and trend of Block 6 containing lower values than both Block 5 and Block 7 can clearly be seen.

DISCUSSION

Influence of precipitation

I expected that the wide range of annual precipitation (715-1148 mm) would affect C and N dynamics due to fact that water is a limiting factor for plant growth and microbial activity in Mediterranean grasslands, but precipitation was not a significant explanatory variable in this study (Harpole et al. 2007). Precipitation is an important predictor for annual NPP, a major pathway in C cycling, but might have less influence on the numerous other processes and factors at work (Nippert et al. 2009).

We used mean annual rainfall to predict C content variance, but we did not factor in the timing of rainfall, which is an important driver of C cycling (Lal et al. 2004, Chou et al. 2008). In increasingly erratic patterns of rainfall, less variability of C content can be explained by soil water content (Harper et al. 2005). This suggests that other factors, such as substrate availability or microbial stress, could play a larger role in C cycling with fewer, larger rainfalls. Around 700 mm of rainfall, we saw C content range from 14 - 35 Mg ha^{-1}. This range of values supports the idea that other factors increase in influence when rainfall events are further apart.

Extended dry periods also lead to large CO_2 losses during early rainfalls in the wet season. During long dry periods, labile SOM and dead microbial mass builds up, creating lots of substrate for microbial growth. When a rainfall event occurs, microbial activity is stimulated and this carbon leaves the system as CO_2 from heterotrophic respiration (Austin et al. 2004). There was one significantly large, early rainfall event during November 2012 that potentially led to a loss of C in the last year of data.

Compost effects on C and N storage

Compost plots had significantly higher C concentration, C content, N concentration, and N content compared to the control plots for the five years of the study (Figure 3). While some C and N increase is a result of direct addition from compost, we removed all visible root and compost matter and therefore measured only C and N that was fully broken down or added by plant activity. We saw an increase in NPP for all compost plots, which suggests C and N increased primarily due to higher rates of plant growth (Ryals and Silver 2013).

The positive impacts of compost addition lasted for all 5 years of our study (Figure 3). Although there was some variability between years, almost every block in all years showed positive increases in C and N concentration. Several studies show that rangeland soil C loss can be significant, so increases in our system lead us to believe that management with compost application has the potential to reverse these trends of C loss (Bellamy et al. 2005, Schipper et al. 2007, Chou et al. 2008).

Variability between blocks

There were differences in trends shown by the three blocks. Soil C and N contents and concentrations in Block 6 were always significantly lower than Block 5 and Block 7, showing the spatial heterogeneity of the soil conditions across the study site (Figure 4). Blocks were places in separate microwatersheds on the site to help account for this expected heterogeneity, but this significant difference between blocks shows that block placement potentially affected the concentration and content levels measured in this study.

Block 5 was on difficult terrain, therefore making it hard to spread compost there. As a result, this layer of compost was not as evenly applied as the other blocks. The compost-amended plot in Block 5 did not show a significant increase of C or N in the first year, but then increased and remained higher than its control counterpart for the remainder of the study. Both other blocks had an immediate response of C and N to amendment, so this lag effect in Block 5 could be due to the inconsistent compost application.

We saw net increases in soil C and N with compost additions in almost all blocks regardless of initial concentration values, showing that blocks that contained higher C and N levels were still positively affected by compost addition. Gulde et al. 2007 saw increases in soil organic carbon with manure application up to 120 Mg ha^{-1} yr^{-1}, so our one-time compost application of 7 Mg ha^{-1} is far below the potential soil carbon saturation capacity of these rangeland soils.

Likely effects of bulk density

Block 5 and Block 7 were not significantly different in C and N concentration, but were significantly different in C and N content. A disparity in bulk density accounts for this difference when converting from concentration to content, showing that bulk density significantly differed between these two blocks. Bulk density also had a strong effect in Block 6, seen in the difference between concentration and content (Figure 4). For both C and N, concentration is significantly higher in treatment plots but content is lower. This shows that bulk density was consistently lower in compost plots, likely due to the incorporation of compost into the top 10 cm soil layer. Compost has a much lower bulk density than soil, therefore leading compost plots to have lower bulk densities and lower conversions from concentration to content (Van Ginkel et al. 1999).

Limitations and Future Directions

Soil moisture is the true driver of all plant, microbial, and chemical activity (Harpole et al. 2007). For this study, we used annual precipitation as an indicator of soil moisture, but these two factors are not the same. Temperature, timing of rainfall, plot slope, and soil type are some of many potential confounding factors that could decouple precipitation and soil moisture (Austin et al. 2004). Soil moisture measurements were taken by the lab, but were not included in this study due to its small scale. Future studies of larger scales and intensity should include soil moisture measurements in their analyses to create a more accurate correlation between C, N, and soil moisture levels.

All concentration to content calculations were based off one bulk density measurement taken in 2010 in each plot. Bulk density was an important factor between blocks and was likely impacted by compost amendment. Annual measurements of bulk density for all blocks would increase precision of content calculations and show if the effects of compost application on bulk density measurements change over time.

Broader Implications

The results of this study are only based on the top 10 cm of soil, but C and N concentration and content were increased by compost additions down to 100 cm (Ryals and Silver 2013). 27-77 % of soil C is found below 20 cm, so this analysis represents only a small fraction of the total potential of the system to store C and N (Harrison et al. 2011). Increased soil N concentration can help increase future soil quality because nitrogen availability has a major influence on SOM formation (Paustian et al. 1992). Increases in NPP due to higher N availability are beneficial because they influence C and N dynamics in soil, but also provide higher amounts of forage for cattle when grazing.

Using commercially available compost or plant and manure waste diverts these products from waste management techniques that lead to high off-gassing of harmful greenhouse gases. The benefits of atmospheric CO_2 sequestration in rangeland soils from compost addition are only part of the total greenhouse gas emission reduction and retention potential of this management practice (DeLonge et al. 2013). The lack of influence of precipitation on our system shows that even during periods of varying water availability, grasslands amended with compost will continue to store C and N for at least five years after the compost application. Compost plot C increased by an average of 1.5 Mg ha^{-1} yr^{-1} over all 5 years. If we scale this up to the 23 million ha of rangeland in California, we would sequester 34.5 million Mg C ha^{-1} yr-1 and offset 11% of California’s annual CO_2 emissions (Air Resources Board).

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