

The Effect of Climate Change on Soil Organic Carbon over an Elevational Gradient

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Abstract

Climate change will increasingly impact ecosystem functioning due to shifts in species distributions as they seek their optimal climatic conditions. Plants rely on phenotypic plasticity of leaf traits to tolerate a change in their climate. Plant leaf traits also affect the carbon cycle of the local area, which may impact the carbon sequestration of the soils. For this project, I measured soil organic carbon over time using space-for-time substitution to study plant communities along an elevational gradient. I collected soil moisture, carbon, and efflux and, in addition, conducted a community survey of the plant species. Both soil carbon and soil moisture significantly increase across an elevational gradient. Additionally, soil carbon is best explained through a combination of soil moisture and biomaterial weight. As soil organic carbon is vulnerable to environmental changes, monitoring soil organic carbon is necessary to determine if there is a loss of carbon sequestration in the area, which can accelerate climate change.

Introduction

Although the direct effects of climate change have been thoroughly studied, there is a lesser-known impact on the carbon cycle of plants and soils that can result in feedback that enhances anthropogenic CO₂ in the atmosphere (Lashof et al, 1997). This feedback, however is especially likely in high-latitude and montane ecosystems where soils are carbon rich (Schlesinger, 1997; Whittaker, 1975) and vegetation is sensitive to climatic variables (Li et al, 2019; Bjorkman et al, 2018), such as snowmelt date and length of growing season (Goulden et al, 1998). Climate change in this area is additionally heightened due to snow cover feedback (Nicoletta et al, 2007; Groisman et al, 1994). With increasing temperatures, organisms shift upwards in alpine ecosystems as they seek the climate envelope they are accustomed to (Gómez et al, 2015), however, this movement causes the organisms at the top of mountains to face extinction with nowhere to go (Dullinger et al, 2012).

As terrestrial plants take up around 25% of anthropogenic atmospheric carbon (Riebeek, 2011) and the majority of terrestrial carbon is stored in the soil (Griscom et al, 2017; Crowther et al, 2016), assessing the soil carbon cycle is necessary to prevent the positive carbon-climate feedback. Recent studies have found that evaluating soil carbon cycling, both above- and below-ground processes, is an effective monitor to the ecosystem's health (Happonen et al, 2022; Sørensen et al, 2019). Soil organic carbon stores are vulnerable to environmental changes (Happonen et al, 2022; Prager et al, 2021). Previous research has found that under elevated CO₂ environments, the ecosystem showed decreased carbon sequestration (Jasoni et al, 2005). More specifically, another study found a 33% loss in subsoil carbon in five years of experimental warming (Soong et al, 2021). Even under conservative assumptions of soil carbon's response to warming, within a year, climate change would drive 55 (+/- 50) petagrams of carbon from the upper soil to the atmosphere by 2050, which translates to 12-17% of the expected anthropogenic emissions (Crowther et al, 2016).

Root activities, like rhizodeposits and root litter, contribute to soil organic carbon formation and decomposition and have been found to vary among plant species (Huang et al,

2021). As the base of every food web, plant communities can serve as an applicable predictor of ecosystem functions on a global scale (Wookey et al, 2009). Previous research has found that alpine plants rely on phenotypic plasticity of various leaf traits, such as area, thickness, dry matter content, and nutrients, to better tolerate experimental warming and cooling climate conditions (Henn et al, 2018). These changes in plant functional traits affect the carbon cycle as the rate of plant productivity is correlated (Hsu et al, 2018; Wright et al, 2004). While abiotic conditions also affect soil organic carbon, previous studies found that these effects occur only indirectly through traits of plant diversity (Prager et al, 2021). A shift in species composition was found to reduce carbon inputs to soil carbon both in the short and long term by reducing the decomposability of leaf litter (Saleska et al, 2002). In fact, a resampling of 121 sites in Crested Butte, Colorado, representing four different plant communities, 65 years after the initial study had significant changes in species richness, diversity, relative abundance, and the distribution matches with patterns expected of a warmer, drier climate (Zorio et al, 2018). As plants adjust to their new climate, its differences in productivity and root respiration could affect the amount of carbon stored in the soil.

Soil organic carbon compositions can be similar across sites with different landscape positions or vastly different between sites of similar vegetation types due to slightly different temperature and hydrologic conditions that affect the soil microbiota (Hsu et al, 2018). Microbial diversity along an elevational gradient decreases from lowest to highest elevations, while plants peak in richness and diversity at mid-elevations (Bryant et al, 2008). Though this study does not explore the specific taxon of soil microbiota, its influence is assumed through environmental factors such as soil temperature, moisture and seasonality which have been known to influence microbial soil organic carbon composition (Hsu et al, 2018). Reduction in soil moisture that has been found to accompany experimental warming was found to influence soil respiration in elevated temperatures (Carey et al, 2016). Meanwhile, lower average soil temperatures can result in slower microbial decomposition, thus leading to a larger amount of unoxidized carbon compounds in the soil (Hsu et al, 2018). Even examining varying depths of soil, research has found differences in plant inputs, microbial communities, and climate, which all contribute to soil organic carbon (Soong et al, 2021). Since subsoils contain roughly half of the global soil organic carbon (Jobbágy and Jackson, 2000), our study will collect soil cores rather than sampling surface soils for more accurate findings.

This study investigated how soil organic carbon changes across time in the face of climate change. Space-for-time substitution has been used in several studies to monitor long-term effects in a short-term period by assuming that spatial and temporal variation are equivalent (Pickett, 1989). Thus, by comparing soil carbon across an elevation gradient, assumptions can be made about the change in rate of carbon sequestration. With this research, we intend to answer the following questions: (1) How does soil carbon vary across elevation? (2) Has soil carbon changed over time with increased temperatures? Soil carbon should increase with elevation (Soong et al, 2021; Hsu et al, 2018; Crowther et al, 2016; Saleska et al, 2002), thus the rate of carbon sequestration can be said to decrease in the face of a warming climate. This research will

provide insight on the global carbon cycling of the local soil and spark further investigation into terrestrial carbon sequestration worldwide to prevent accelerating global warming.

Methods

Study Sites

This research was conducted in field sites associated with Dr. Brian J. Enquist at the Rocky Mountain Biological Laboratory (RMBL) in Gothic, Colorado (30°57'N, 106°59'W, 2900 m elevation). RMBL was chosen based on its well-studied elevational gradient and previous research by Dr. Enquist on plant traits and communities across an elevational gradient. Six sites were chosen along the East River valley of RMBL. The sites ranged from sagebrush communities at the lowest elevation to subalpine meadows, and alpine plant communities at higher elevations. ArcGIS was used to map and analyze elevation of the six sites (Figure 1).

Field Methods

Each site was visited twice, once during the early season before flowers were in full bloom and once at peak vegetation biomass, except for the highest and lowest elevation sites. Due to the start date, the lowest site, Almont, was already at peak season. The highest site, Cinnamon, had snow blocking the road, which prevented access until later in the summer. Two soil cores of approximately 10 cm in length were collected outside, but near the boundary, of each of the five plots at each site. They were labeled A for upslope and B for downslope, so plot 1 would have two soil samples of 1A and 1B. The ten samples were stored in a cooler to retain the soil moisture until laboratory processing. The samples serve as independent data points due to the distance between and across the plots. A total of 100 samples were collected from all sites.

While at each site, soil efflux and a species abundance survey of each plot were conducted. Soil efflux was collected using a Licor 6400 Soil Chamber, where the soil temperature, carbon dioxide and water vapor flux were recorded and stored digitally. Temperature readings were used to predict microbe metabolism at each site. Carbon dioxide and water flux were analyzed with the soil carbon extracted from the samples to determine if a relationship exists.

For the species survey, each plot was gridded, then, moving grid by grid, the plants' abundance and nomenclature were noted down. Identification was based on a compiled field guide of abundant species found at the sites in previous years. A list of the five most abundant plants were noted for this project to analyze leaf traits and predict its effect on soil carbon measurements.

Soil Processing

Once back at the lab, the soil samples were crushed to break up any soil clumps. A representative sample of the core was weighed to ensure it is under 20 g, then placed in a tin. The remainder of the core was placed in a refrigerator as backup. The ten soil tin samples were then placed in a drying oven set at 105°C for 24-48 hours to remove moisture. Afterwards, the

samples were weighed again. Rocks and biomaterial were removed from the samples using a 2 mm sieve and measured independently before discarding. Biomaterial was picked out for a 5-minute period only for efficiency. The separated soil was then weighed again in its original tin, before being placed back into the drying oven for another hour to remove the moisture it may have accumulated during the process. Soil moisture was calculated by the difference between the wet soil and the dry soil, including for the weight of the rocks and biomaterial. The difference was then divided by the dry soil's weight. The soil samples were then ready for burning. Removing soil from the tins till only 6-9 g remain, the samples were placed on a preheated oven at 200°C. The oven ran on a program to combust the carbon in the soil by increasing the temperature by 19°C every minute till it reached 430°C. Once the samples were cool to the touch, their final weight was measured and recorded. Soil organic carbon is calculated as the difference between pre-burn and post-burn weight, divided by two.

Data Analysis

Soil carbon and soil moisture was tested for normality via a Shapiro-Wilk test, which indicated that these variables were not normally distributed. So, a Kruskal-Wallis (K-W) Test was used to determine if there was a trend between soil samples and sites, then a post-hoc paired Wilcoxon test was performed to compare the sites for statistical differences. Differences in soil carbon and soil moisture across the elevational gradient was done in this way. A K-W test was also used to determine if there was a difference between soil samples and slope. Finally, linear regression was used on soil carbon and other factors to determine the best model for predicting changes in carbon. Both single regressions and multiple regressions were done. RStudio was used to complete statistical analysis and illustrate figures (RStudio Team, 2022).

Results

Trends across an Elevational Gradient

Overall, soil carbon was significantly different across sites (K-W: $\chi^2 = 50.451$ DF = 5 , p-value < 0.001). Cinnamon, PBM, CBT, and Almont were found to be significantly different from each other and the other sites with Road and Pfeiler found to be similar to CBT and PBM (Figure 2). Splitting up the boxplots by slope revealed similar patterning and no significant difference was found between soil carbon and slope (Figure 3). Upslope (A) and downslope (B) cores appear similar to each other aside from the greater variation in CBT A and Cinnamon B samples.

Similarly, overall soil moisture was significantly different across sites (K-W: $\chi^2 = 42.85$ DF = 5 , p-value < 0.001). Again, Almont and Cinnamon were found to be significantly different, however, there was more overlap in the other sites (Figure 4). CBT and Almont had no significant difference, while Road, Pfeiler, and PBM were closely related to Almont and Cinnamon. When slope was introduced as a factor, there was again a similar pattern and no significant difference was found between soil moisture and slope (Figure 5). There was less variation between slopes as found in the soil carbon boxplots, but there were more outliers.

Predictor of Soil Carbon

A single linear regression of soil carbon on soil moisture found overall a significant relationship (L-R: DF = 98, p-value = 2.41×10^{-7} , $R^2 = 0.2315$). Further analyzing the model by sites, all except Almont showed a positive correlation in soil carbon and soil moisture (Figure 6). Separate linear regression tests by site showed only Road (L-R: DF = 18, p-value = 0.0324, $R^2 = 0.1871$), Pfeiler (L-R: DF = 18, p-value = 0.00029, $R^2 = 0.5008$), and PBM (L-R: DF = 18, p-value = 0.00212, $R^2 = 0.3842$) with significant relationships.

The multiple linear regression of soil carbon on soil moisture and elevation showed that only soil moisture was a significant predictor of carbon (ML-R: DF = 97, Elevation p-value = 0.982, Moisture p-value = 1×10^{-5} , overall p-value = 1.733×10^{-6} , $R^2 = 0.2236$) (Figure 7). The blue line shows the association between the predictor variable and soil carbon, while holding the other predictor constant. The points labeled are the 2 observations with the largest residuals and the 2 observations with the largest partial leverage. Another multiple linear regression of soil carbon on soil moisture and biomass weight demonstrated to be the best model as both predictors were significant effectors on soil carbon (ML-R: DF = 97, Biomass p-value = 3.06×10^{-10} , Moisture p-value = 5.80×10^{-5} , overall p-value = 3.877×10^{-15} , $R^2 = 0.4851$) (Figure 8).

Plant Abundance

Compiling the five most abundant species surveyed from all the sites revealed that CBT and Road had three species in common (Table 1). Almont and Pfeiler, also Cinnamon and Pfeiler, shared a single species. PBM had no species in common with the other sites.

Discussion

After investigating how soil organic carbon can change due to climate change, it was found that soil carbon does increase with elevation. Since greater elevation represents past, colder climates, the results of this study suggest that soil carbon will decrease with warming temperatures, supporting previous studies (Soong et al, 2021; Hsu et al, 2018; Crowther et al, 2016; Saleska et al, 2002). There was an increase in soil carbon (Figure 2) and soil moisture (Figure 4) between the lowest elevation, Almont, and highest elevation site, Cinnamon, that were significantly different. The mid-elevation sites had some similarities to each other, which may be due to the relative proximity in the sites (Figure 1). PBM-Pfeiler and Road-CBT pairs are close to each other distance-wise and elevation and may have had similar vegetation and microbe diversity that contributed to similar soil carbon and moisture. Analysis of the most abundant species showed that CBT and Road share three of five plants (Table 1). Despite Cinnamon and PBM being close in distance and elevation, Cinnamon's soil samples were collected after a day of heavy rain which may have influenced the results. Considering the correlation between soil carbon and soil moisture (Figure 6), this seems likely.

Nearly 50% of the variation in soil carbon values can be explained by a combination of soil moisture and biomaterial weight (Figure 8). Soil temperature and moisture have been known to influence microbial activity, and by extension soil carbon, (Hsu et al, 2018), so that

relationship is supported by previous studies. Wetter soil could benefit the surrounding vegetation by providing a necessary resource for continued productivity (Huang et al, 2021) and could possibly hinder microbial respiration through colder soil temperatures (Hsu et al, 2018). As for biomaterial weight, with only a 5-minute limitation on removing all roots and leaves from the sample, there may have been an increase in soil carbon due to the remaining carbon-containing biomaterial. Samples with a greater biomaterial weight may suggest that those sites contain species with dense root systems, which could affect the soil carbon (Huang et al, 2021). The traits of the plants in the plots may have also influenced the thickness of the roots (Wright et al, 2004), which could affect how easily they were able to be removed from the collected soil samples. Elevation itself did not have a large effect on soil carbon (Figure 7), potentially due to the fact that soil carbon is affected by the abiotic conditions associated with elevation (i.e. temperature and soil moisture). If soil temperature from the soil efflux data could be incorporated, which can substitute for the elevation variable, it could serve as another predictor of soil carbon.

These findings can be further improved by including the soil efflux and community composition data. As mentioned above, including soil temperature as a predictor of soil carbon could improve the model. Additionally, examining the relationship between carbon dioxide flux and measured soil carbon may provide more information on the intricacies of the alpine community carbon cycle. Similarly for water flux and measured soil moisture, examining this relationship may finally demonstrate the elevation's influence on the carbon cycle. As for the community composition data, analyzing the specific leaf traits and hypothetically dictating its role in soil carbon would add the biotic influences of the carbon cycle. It may also serve as an easier indicator of changes in soil carbon by monitoring species distribution and shifts (Zorio et al, 2018; Saleska et al, 2002). Expanding this short-term study to a long-term study by observing soil carbon trends of previous years could strengthen the relationships found between soil carbon, moisture, and biomaterial weight, and may possibly shed light on the true trend of soil carbon across time. To potentially streamline this process, it may be more efficient to forgo collecting soil cores at early and peak seasons. Several Wilcox tests were done to compare the averages in soil carbon across seasons and it was determined that there is no significant difference (Figure 9). Rather than revisiting the same sites twice in one summer, more sites that could increase the elevational gradient could be added. Overall, this research is only the beginning to deducing the carbon cycle in the world's most vulnerable ecosystems. Further investigations should be done to delve into this cycle, for if we can piece together the various influences on soil carbon in alpine communities, we could make management decisions worldwide that can mitigate the acceleration of global warming.

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Tables and Figures

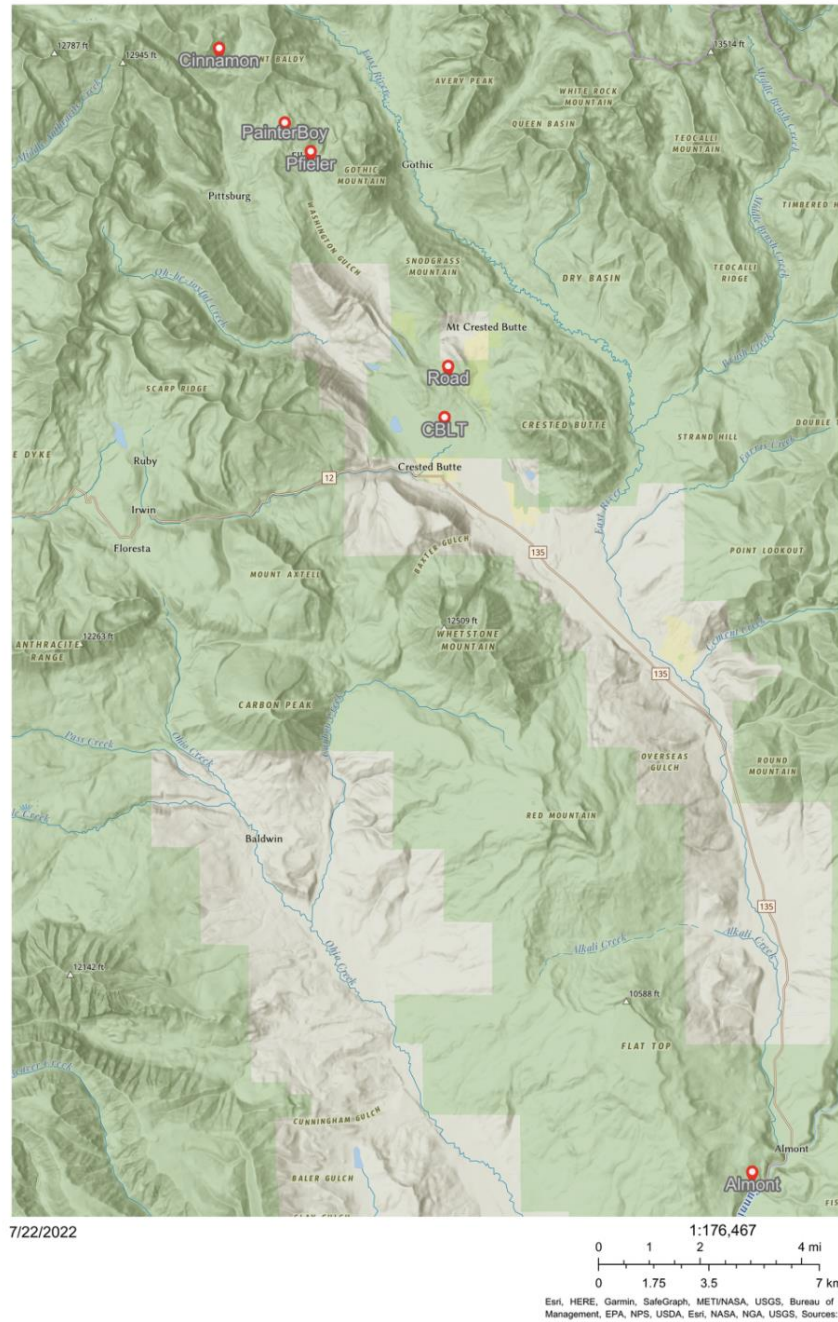


Figure 1: Map of study sites: Almont (38.6545, -106.8609, 2,475 m in elevation), CBLT (Crested Butte Landtrust; 38.8818, -106.9803, 2,700 m in elevation), Road (38.8972, -106.9787, 2,815 m in elevation), Pfeiler (38.9610, -107.0313, 3,173 m in elevation), PBM (Painter Boy Mine; 38.9697, -107.0412, 3,374 m in elevation), Cinnamon (38.9916, -107.0664, 3,459 m in elevation).

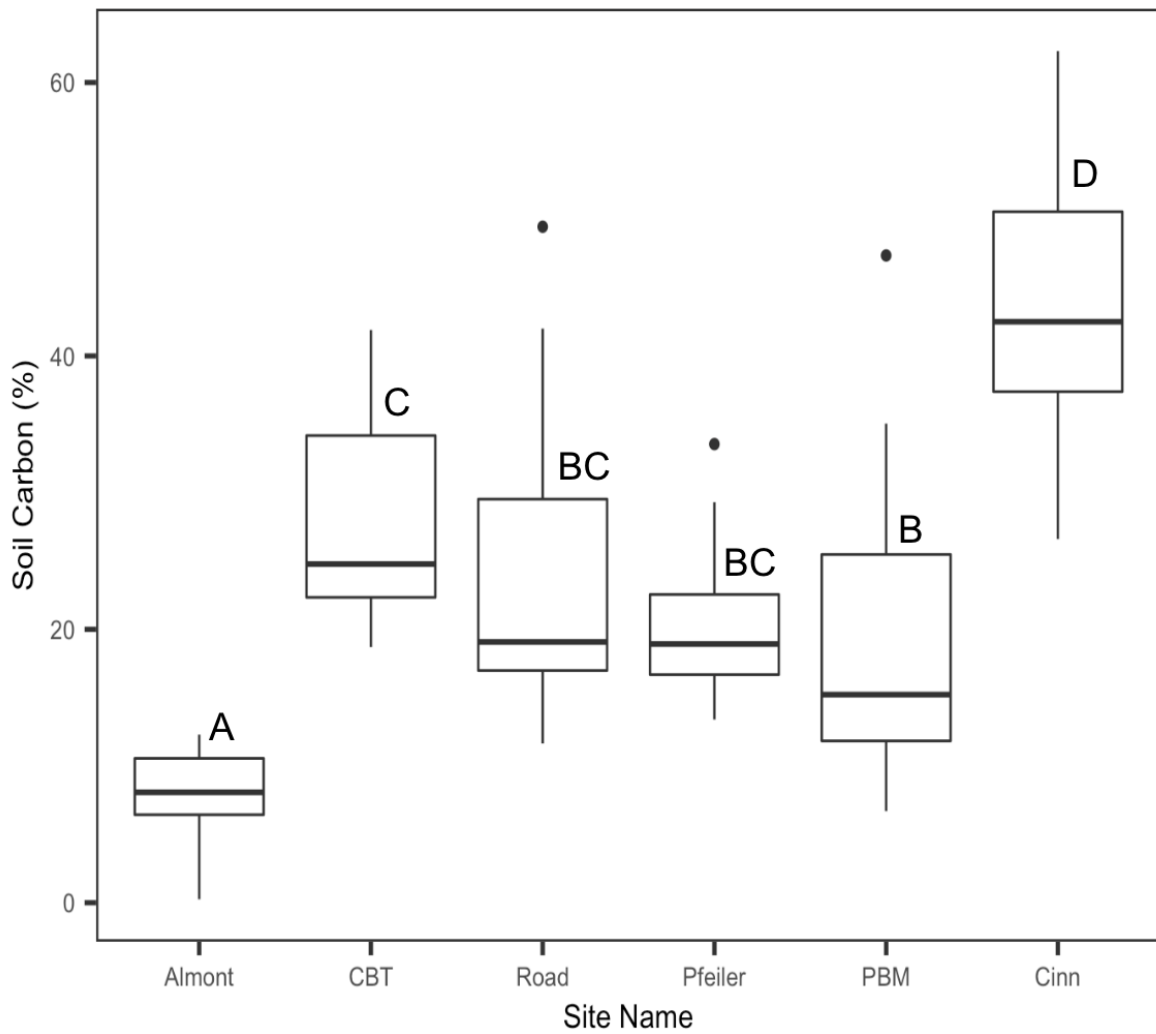


Figure 2: Distribution of soil carbon across an elevational gradient. The overall trend showed a significant increase in carbon across all sites (K-W: $\chi^2 = 50.451$ DF = 5 , p-value < 0.001). Individually, Almont and Cinnamon are significantly different from each other and the other sites. Meanwhile, Road and Pfeiler share similarities with CBT and PBM, which are individually significantly different from each other.

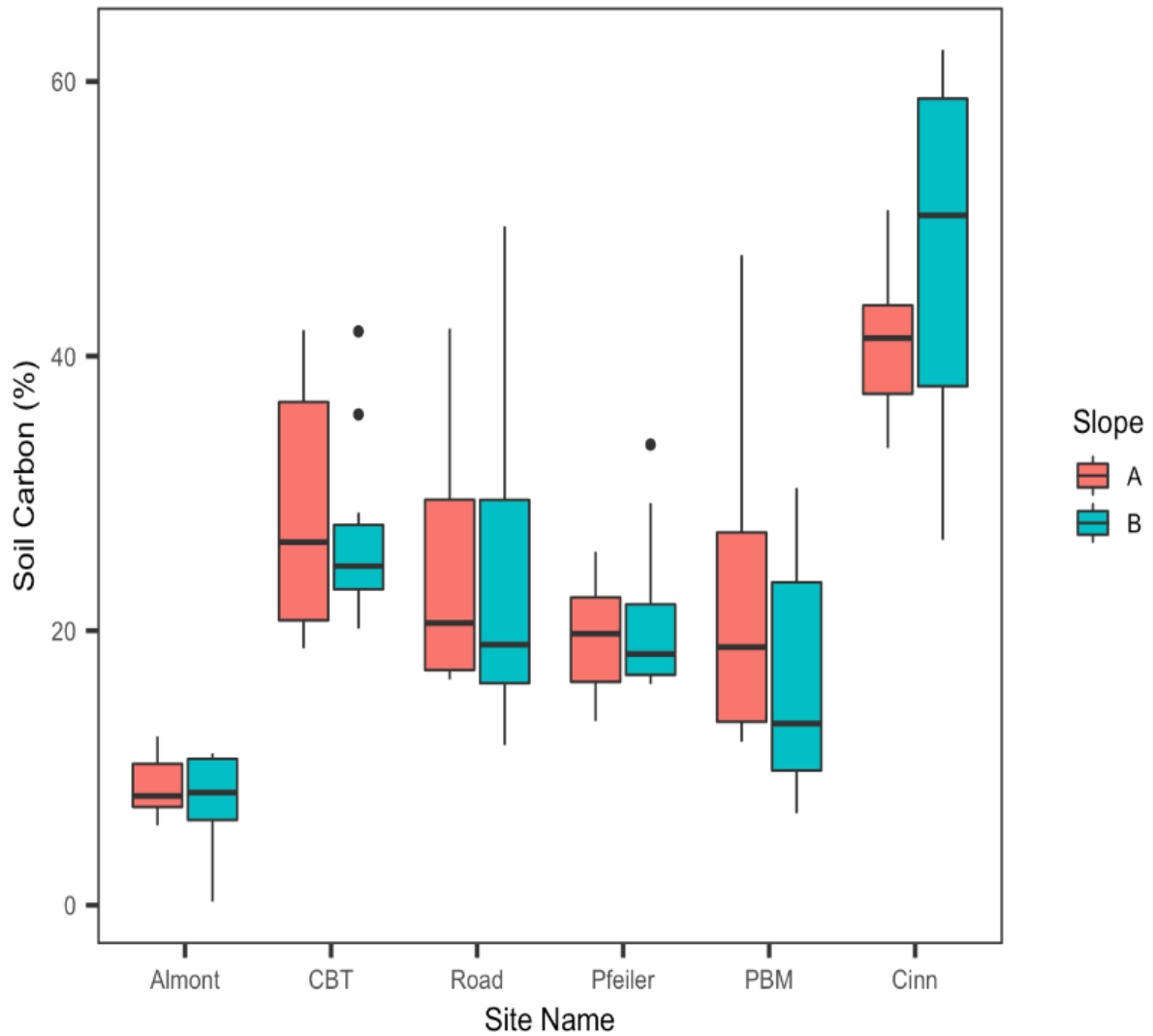


Figure 3: Distribution of soil carbon across an elevational gradient separated by slope at which soil samples were collected, with A as upslope and B as downslope. There is no significant difference between soil carbon and slope (p-value >0.5).

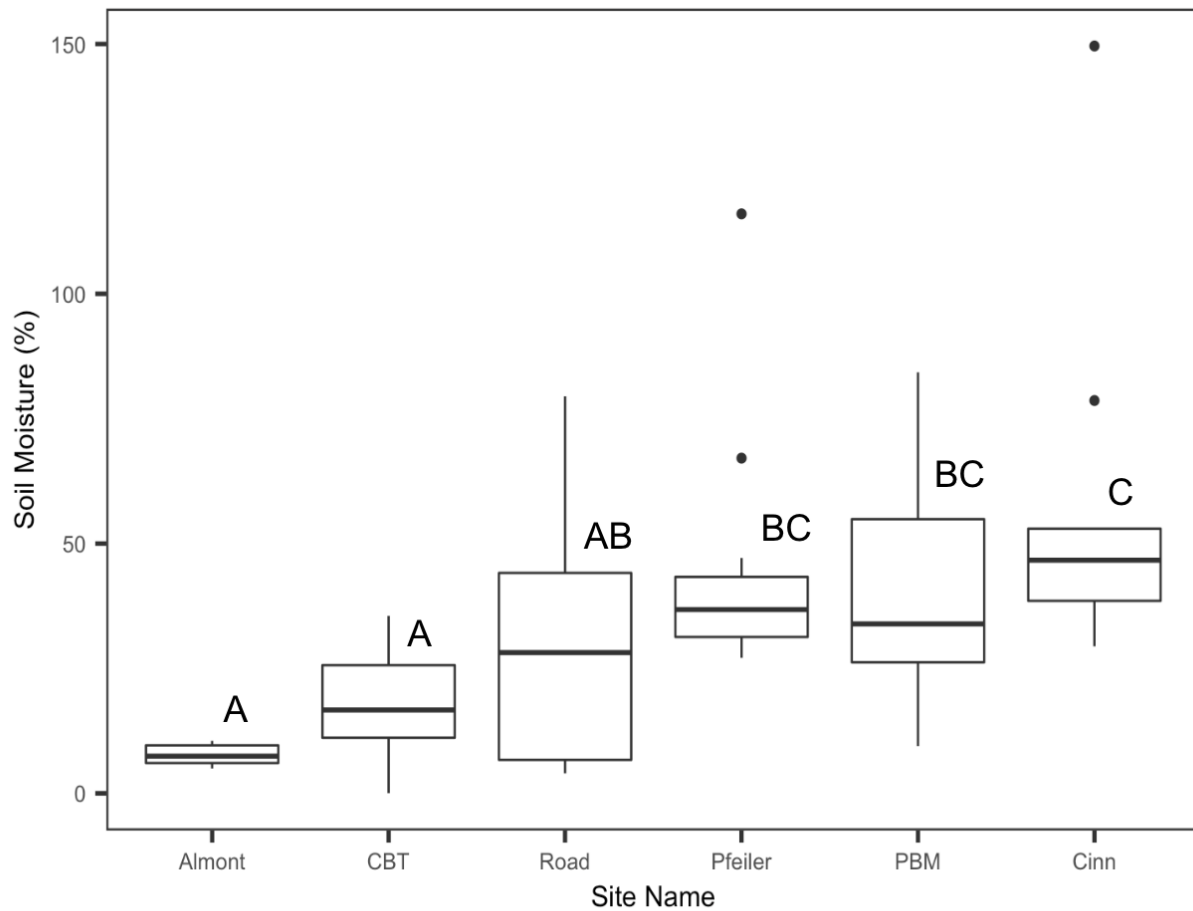


Figure 4: Distribution of soil moisture across an elevational gradient. The overall trend showed a significant increase in carbon across all sites (K-W: $\chi^2 = 42.85$ DF = 5 , p-value < 0.001). Individually, Almont and Cinnamon are, again, significantly different from each other and the other sites. CBT, however, is not significantly different from Almont. Road, Pfeiler, and PBM all share similarities with Almont and Cinnamon.

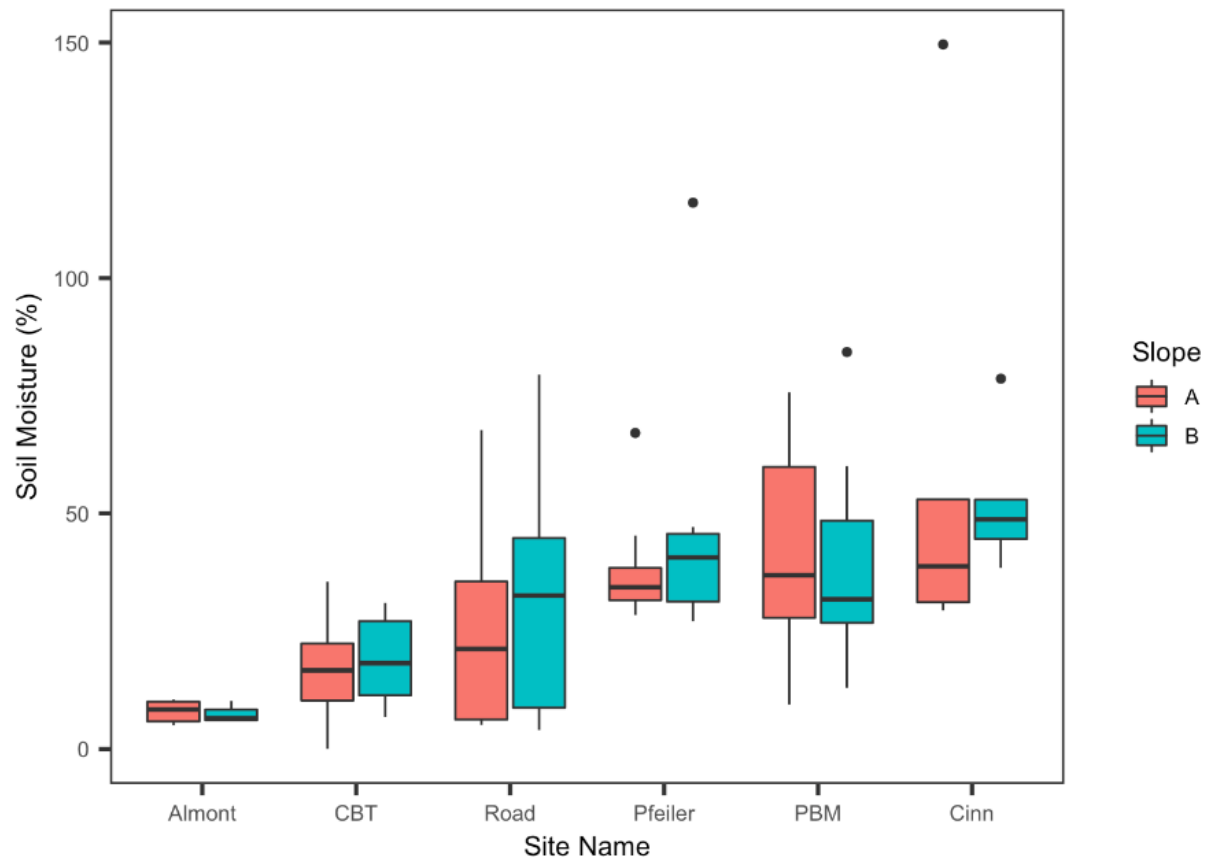


Figure 5: Distribution of soil moisture across an elevational gradient separated by slope at which soil samples were collected, with A as upslope and B as downslope. There is no significant difference between soil moisture and slope (p-value >0.5).

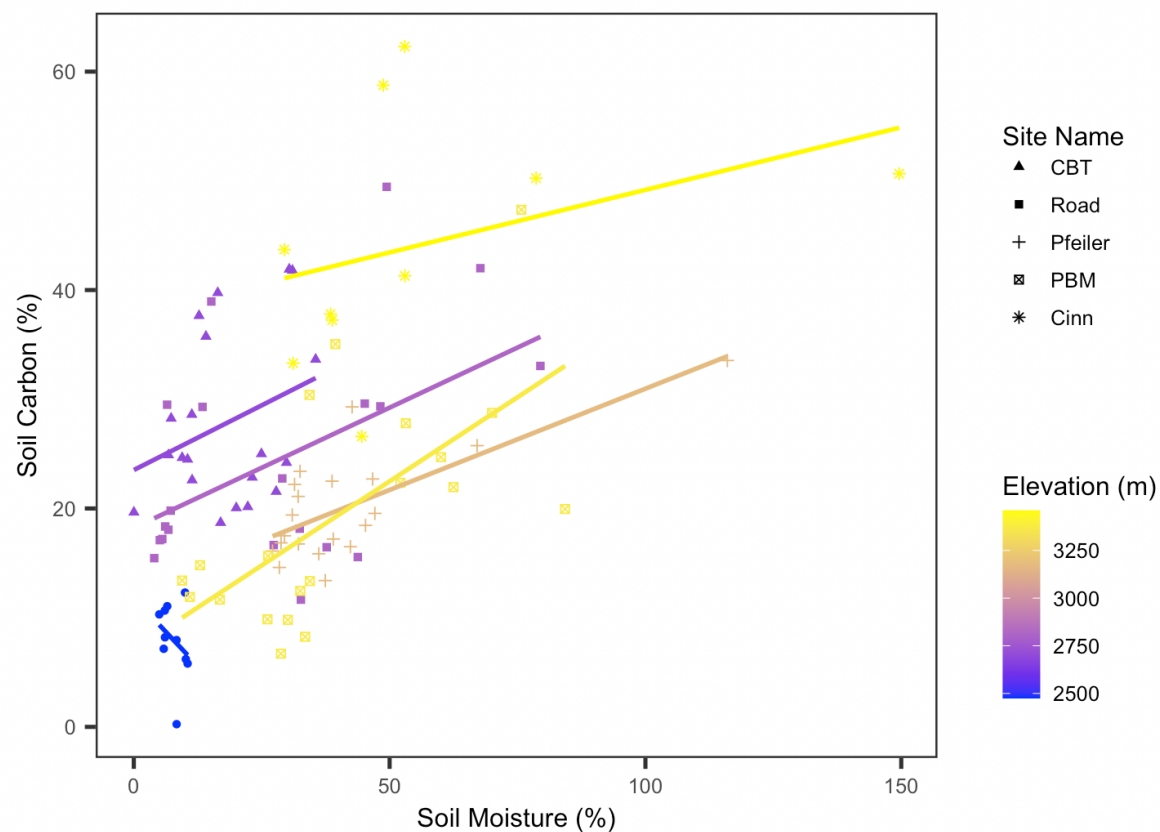


Figure 6: Single linear regression of soil carbon on soil moisture. Overall, there was a significant relationship between the two variables ($DF = 98$, $p\text{-value} = 2.41e-07$, $R^2 = 0.2315$). Individually, by site, only Road ($DF = 18$, $p\text{-value} = 0.0324$, $R^2 = 0.1871$), Pfeiler ($DF = 18$, $p\text{-value} = 0.00029$, $R^2 = 0.5008$), and PBM ($DF = 18$, $p\text{-value} = 0.00212$, $R^2 = 0.3842$) had significant relationships.

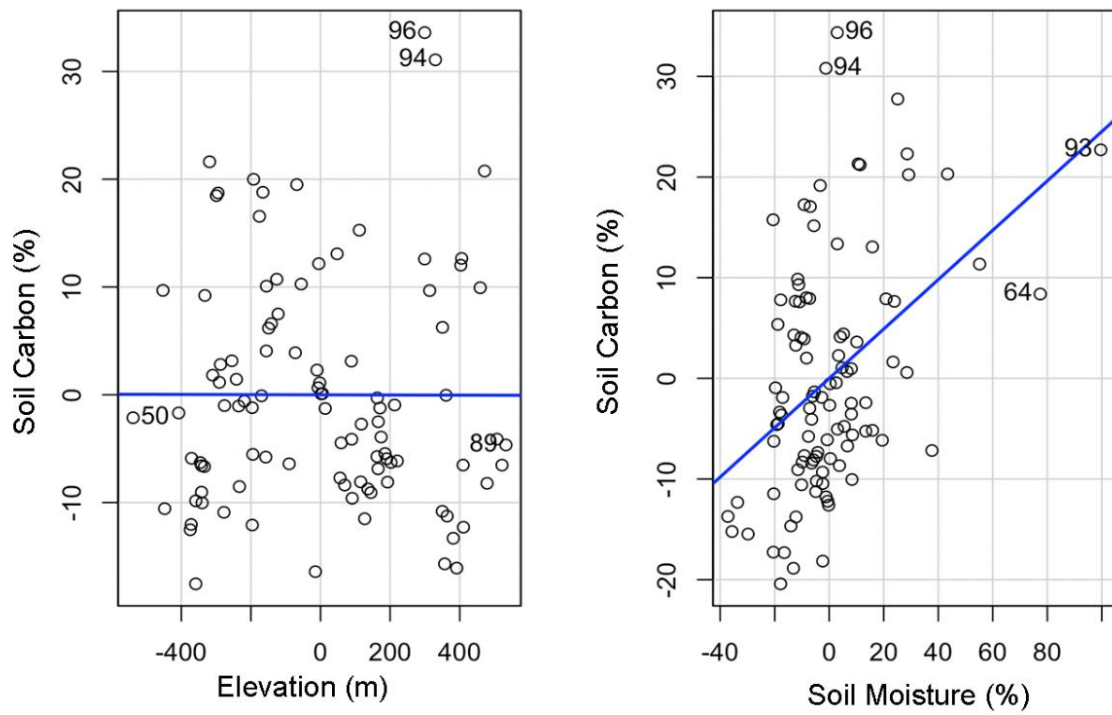


Figure 7: Multiple linear regression of soil carbon on soil moisture and elevation. There was a significant relationship only between soil carbon and soil moisture ($p\text{-value} = 1\text{e-}05$). Overall, there is a significant relationship between the three variables ($DF = 97$, $p\text{-value} = 1.733\text{e-}06$, $R^2 = 0.2236$).

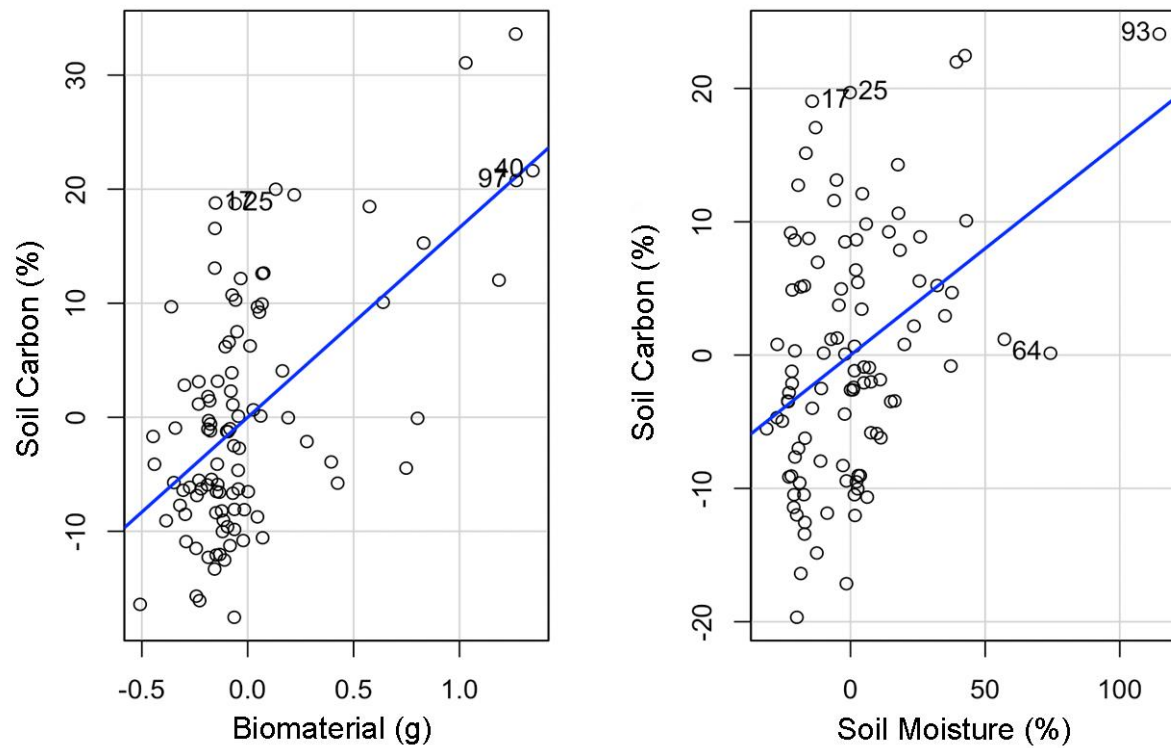


Figure 8: Multiple linear regression of soil carbon on soil moisture and removed biomaterial weight. There was a significant relationship between both soil moisture ($p\text{-value} = 5.80\text{e-}05$) and biomaterial weight ($p\text{-value} = 3.06\text{e-}10$). Overall, there is a significant relationship between the three variables ($DF = 97$, $p\text{-value} = 3.877\text{e-}15$, $R^2 = 0.4851$).

Table 1: The five most abundant species at each site. Bolded taxons are those shared between two or more sites.

Site Name	Almont	CBT	Road	Pfeiler	PBM	Cinnamon
Top 5 Most Abundant	Achnatherum pinetorum	Collomia linearis	Valeriana occidentalis	Ligusticum porteri	Veratrum tenuipetalum	Ligusticum porteri
	Artemisia tridentata	Poa pratensis	Collomia linearis	Heliomeris multiflora	Descurainia californica	Senecio crassulus
	Castilleja chromosa	Geum triflorum	Poa pratensis	Viola nuttallii	Thlaspi arvense	Vaccinium floribundum
	Erigeron eatonii	Bromus inermis	Gayophytum ramosissimum	Potentilla gracilis	Polygonum douglasii	Draba aurea
	-Penstemon caespitosus -Crepis occidentalis	Equisetum laevigatum	Bromus inermis	Erigeron eatonii	Erythronium grandiflorum	Achillea millefolium

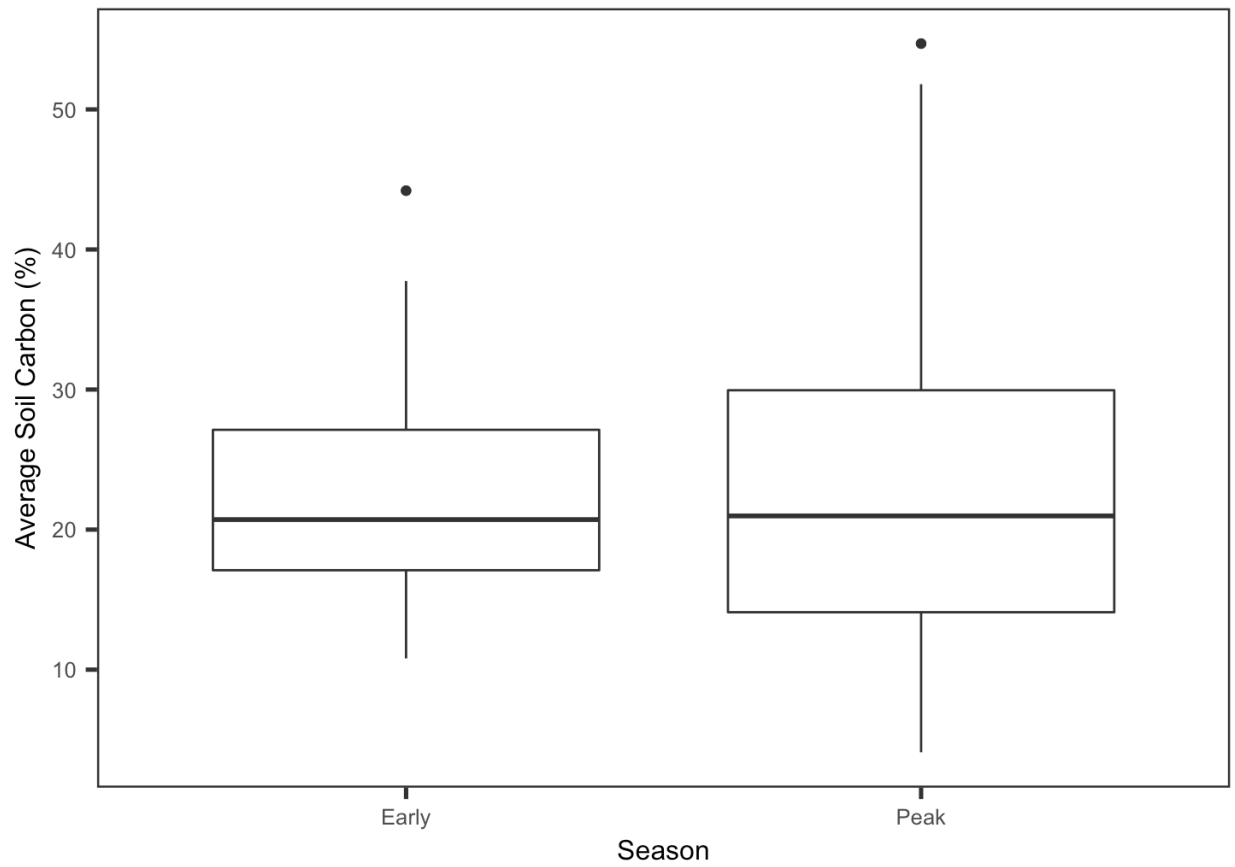


Figure 9: Distribution of soil carbon across seasons: early season and peak vegetation biomass. There is no significant difference in carbon between seasons.