# The influence of silvicultural treatments and coarse woody material on forest soil carbon storage and sequestration

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# THE INFLUENCE OF SILVICULTURAL TREATMENTS AND COARSE WOODY MATERIAL ON FOREST SOIL CARBON STORAGE AND SEQUESTRATION

A Thesis Presented

by

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# ABSTRACT

Coarse woody material (CWM) plays a role in nutrient and chemical cycling in forest soils by creating a substantial reservoir of organic carbon and nutrients. However, there are a lack of studies looking at the long-term biogeochemical impacts of removing or altering CWM as there are few forests that remain undisturbed. As climate change impacts further affect factors influencing CWM inputs (mortality) and decomposition (moisture and temperature), understanding the role of CWM in a managed forest is vital. The purpose of this research is to quantify the effect of CWM on the amount of soil carbon, and whether the impact of CWM varies with canopy gap size. Objectives include examining the impacts of (1) the relationship between canopy gap size and soil C, and (2) the proximity to the CWM on soil carbon, ammonium, and nitrate. Results of this research indicate greater concentrations of carbon underneath the CWM regardless of canopy openness and soil moisture conditions. Greater carbon concentration indicates CWM is a buffer and can provide stability in a changing climate. This research will provide more information about the largest terrestrial source of carbon and how carbon concentrations change depending on forest management practices.

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# COMPREHENSIVE LITERATURE REVIEW

In the past, coarse woody material (CWM) has been overlooked due to low nutrient concentration compared to other sources of litter like leaf litter. However, low nutrient content does not signify low input to soil carbon and nutrient pools (Wiebe et al., 2014). There is limited literature addressing the importance of researching biogeochemical cycles beneath CWM; however, these dynamics will play a key role in forest management as the climate changes.

The largest global pools of carbon include the atmosphere, the ocean, and terrestrial soil (NASA). Terrestrial soil can be managed for a changing climate. Twice as much carbon is stored in soil than what is stored in vegetation, and the carbon is stored in soil in the form of soil organic carbon (SOC). Forests have the capacity to store large amounts of carbon as carbon is stored in both vegetation and soils (Jevon et al., 2019). With projected increases in temperature and precipitation across the United States (National Climate Assessment), adapting forests for these changes will be vital. This current research explores carbon storage in this large carbon pool in the context of forests.

Canopy gaps created by natural disturbances and forest management strongly influence successional patterns and ecosystem processes, by influencing microclimate (soil moisture and temperature) and plant inputs (Nyamgeroh et al., 2018, Tafesse et al., 2025). Gaps are naturally formed when trees fall or die as a part of natural disturbances (Box 2022), or through harvest-induced disturbances associated with the production of forest products (Gray et al. 2002). Gaps create structural complexity, provide sites for the establishment of certain tree species (Jönsson et al., 2023), and increase the rate of development of late successional forest conditions (Gray et al. 2002). Different percent canopy openness will be utilized for this current research to evaluate the influence of different canopy gaps on biogeochemical dynamics. The succession stages of below story vegetation depending on percent canopy openness is seen in this research as well. Late succession species were present in low canopy openness and early succession species are present in high canopy openness conditions.

The importance of CWM in affecting biodiversity in forest ecosystems is well documented, including serving habitat for rodents and nesting birds (Gonzalez-Polo et al., 2013). Increased microbial activity along the log with altered soil dynamics and nutrient cycling creates "pedogenic hot spots" (Kim et al., 2017). The soils underneath CWM have a more stabilized structure and more organic matter than soils farther away from the log (Kim et al., 2017). Removal of CWM has negative effects on N availability in soil, C pool, and microbial communities (Kim et al., 2017). The conclusion that soils underneath CWM are areas of high activity compared to surrounding soils will be researched in the form of analyzing C and N concentrations.

In the past, CWM has been removed from forests as usual forest management practices (Spears and Lajtha, 2004) due to cutting and harvesting in a managed forest. This issue is not seen in "pristine" or unmanaged forests (Laiho and Prescott, 2004).

During deadwood decomposition, carbon is lost from CWM as carbon dioxide or gets back into the soil through leachates and decomposition, adding to current C stocks in the soil (Wojciech et al., 2019). Past research has shown C and N concentrations change as CWM decomposes (Wiebe et al., 2014, Wojciech et al., 2019). The immobilization of N in soils beneath CWM creates a nutrient sink and mineralization creates a nutrient source (Wiebe et al., 2014). Deadwood during initial stages of decomposition has little effect on soil properties (Wojciech et al., 2019). Well-decayed boles in classes four and five have higher total C and N concentrations compared to surrounding mineral soil (Hart 1999). Decay stage has been identified as one of the reasons for variability in chemical concentration underneath the CWM. Samples in a higher decay class released greater quantities of C, N, and other ions into surface soil horizons than those in younger decay stages (Wojciech et al., 2019). Additionally, concentrations of C, N, and other chemicals were greater underneath the CWM than in the bare soil (Wojciech et al., 2019). CWM creates a carbon reservoir called "recalcitrant carbon islands" due to its slow decomposition and persistence in the environment (Gonzalez-Polo et al., 2013). The CWM samples in this research are in the early decay stages, so the C and N concentrations observed may not be as high as they will be when the CWM is in the later decay stages.

Commonly used methods in the literature for relating to CWM included leaving logs out in the field site and making sure they are far away from other CWM samples and trees (Goldin and Hutchinson, 2013). All the CWM in the experiments were usually the same age and same species (Kim et al., 2017). Additionally, there were replicates of each condition being studied in the form of multiple logs being in the same condition and assumed to be experiencing similar abiotic factors (Wojciech et al., 2019). In this research, all the CWM were *Acer saccharum* species and there were three replicated for each of the four canopy openness treatments. The CWM samples were placed in their locations in 2017 and are all in decay stages I and II.

The impacts of CWM on soils varied depending on decay stage, gap creation, soil moisture, and soil temperature. Results found in *Perrault et al., 2020* included warmer soils in closed canopy conditions compared to open canopy conditions, and higher soil and wood temperatures in gap openings up to five and seven years after gap creation. Within canopy gaps, highly decomposed CWM increased C and phosphorus (P) enzyme activities, impacting organic matter turnover and soil nutrient cycling (Perrault et al., 2020). Similar results were found in *Hart 1999* with the soils beneath well-decayed CWM having greater concentrations of C and N than surrounding surface mineral soil (Hart 1999).

This current research will look at CWM in the lower decay stages in a wide range of canopy gap types. Thus, the concentration of chemicals may differ or there may not be a large difference in chemicals between soil underneath the CWM and surrounding surface mineral soils. However, canopy gap presence and characteristics will likely impact soil carbon and nutrient dynamics.

## Introduction

A warming planet will have impacts on soil and its ability to store carbon. Soil is the second largest natural carbon (C) sink behind oceans surpassing the atmosphere and all vegetation on earth (Paustein et al, 2016). The effects of climate change on the world's soil and how soil will change from being a C sink to a C source is under-researched (Trumbore and Czimczik, 2008). The effects of a warming planet on the world's soils are unknown in terms of how mineral soil will continue to hold organic C (Trumbore and Czimczik, 2008). It is unknown because small changes in organic matter are too small to be observed over a few years let alone modeled for the future (Trumbore and Czimczik, 2008). Our research will look into the concentration of C with certain forest management practices which will help inform what conditions store the most C currently.

Forests are increasingly being valued for their role in sequestering and storing C (Achat et al. 2015) as they store about 70% of the world's soil organic C (Getino-Álvarez et al. 2023). Although the emphasis of most strategies for increasing forest C storage focuses on aboveground plant biomass, forest soils represent the largest terrestrial C reservoir (Jobbagy and Jackson 2000, Georgiou et al. 2022). More C is held in soils than in forests and other vegetation (Achat et al. 2015, Jevon et al. 2019). Variations in how much C can be put into soil can be partially attributed to tree basal area, composition, biomass, productivity, and root production (Kreye et al. 2023). In general, soil C increases with forest productivity (Kreye et al. 2023), but soil C also depends on how quickly plant inputs to the soil are decomposed (Wojciech et al. 2019). Decomposition of soil C depend on factors such as nutrient availability, microbial composition, and climate (Wojciech et al. 2019).

Soil moisture impacts the ability of the soil to store C. Well-moistened soils with higher temperatures lead to increase microbial decomposition, increasing rates of C mineralization (Hao et al., 2025). In areas with rates of precipitation greater than rates of evapotranspiration, plant root abundance is favored allowing for greater inputs of soil organic C and mineral-stabilized organic matter (Heckman et al., 2023). This means more C is stored than is released, turning this area into a C sink (Heckman et al., 2023). This contrasts to dry soils with high temperatures where microbial activity decreases leading to greater emission of carbon dioxide ($CO_2$) into the atmosphere (Hao et al., 2025). While temperatures play a critical role in soils, soil moisture can have greater impacts as moisture dictates the activity of microbial decomposition directly relating to the C cycle (Hao et al., 2025). Soil moisture has a direct influence on processes related to plant photosynthesis and respiration, soil microbial activity, and organic matter decomposition (Hao et al., 2025). Soil moisture and microbial activity directly impact C sequestration in soils. In the optimal conditions, microorganisms decompose organic matter by stabilizing a portion with soil minerals, contributing to long-term C storage (Hao et al., 2025). Additionally, several microbes such as autotrophic bacteria and phototrophic protists fix $CO_2$ from the atmosphere into soil C, allowing some lands with high soil moisture to become important C sinks (Hao et al., 2025). With adequate soil moisture, all these processes can work as intended, allowing as much C sequestration as possible (Hao et al., 2025). When these processes get disturbed by issues such as extreme heating or extreme cooling for example, it becomes more difficult to sequester $CO_2$ (Hao et al., 2025).

Canopy gaps created by natural disturbances and forest management strongly influence successional patterns and ecosystem processes, by influencing microclimate (soil moisture and temperature) and plant inputs (Tafesse et al., 2025). Gaps are naturally formed when trees fall or die as a part of natural disturbances (Box 2022), or through harvest-induced disturbances associated with the production of forest products (Gray et al. 2002). Gaps create structural complexity, provide sites for the establishment of certain tree species (Jönsson et al., 2023), and increase the rate of development of late successional forest conditions (Gray et al. 2002). Small canopy gaps letting in little sunlight allow for the growth of shade-tolerant species while large canopy gaps filled with sunlight allow for the growth of less-tolerant, early succession or pioneer species (Gray et al. 2002). Gaps also influence forest and soil microclimate conditions (Gray et al. 2002). Large canopy gaps tend to have increased moisture and higher temperatures with greater decomposition and nutrient availability than small gaps or closed canopy conditions (Gray et al. 2002, Muscolo et al., 2014).

Forest gaps may also contain CWM, which includes fallen tree boles or branches and is a key component of temperature forest ecosystems due to their contribution to global C stocks (Perrault et al., 2020). They account for up to 73 Pg of carbon (C) or about 8% of the global C stocks (Perrault et al., 2020), and contribute <20% of nitrogen, phosphorous, potassium, C, and calcium – much less than other decaying litter (Laiho and Prescott 2004). Additionally, CWM accounts for 54% of accumulated organic matter on the forest floor including the forest floor and soil (Laiho and Prescott 2004). CWM plays a role in nutrient and chemical cycling in the soil by helping to create a substantial reservoir of organic C and nutrients (Kim et al. 2017, Spears et al., 2002). An additional way CWM impacts soil is through increasing soil moisture and creating a stable space against variations in climate beneath and around it (Gonzalez-Polo et al., 2023).

Soils under CWM have been found to have properties that differ from surrounding soils. For example, soils beneath CWM have high enzyme activity compared to surrounding soil lacking decaying wood on the surface (Gonzalez-Polo et al., 2023). Decomposition provides a process of getting bioavailable C and nutrients into mineral soil from CWM (Kim et al. 2017). Additionally, the decomposition of CWM changes the soil under and around it by altering the pH, the C:N ratio, and cation concentrations (Perreault et al., 2020). As a result, soil development and nutrient dynamics are different for soils under CWM versus surrounding soils under the organic horizon, with areas beneath CWM known as “pedogenic hot-spots” (Kim et al. 2017). Research has shown leaving CWM in forests increases microbial and enzymic activity and returns vital nutrients back into the soil to be used by living vegetation (Enrong et al., 2006, Jarron et al., 2021, Perreault et al., 2020). The dissolved organic C and the nitrogen (N) leaving the log create a substrate for saproxylic microbes and enzymes to live (Harmon et al., 1986, Perreault et al., 2020, van Galen et al., 2019).

CWM also plays a role in creating dissolved organic matter (DOM), which influences many soil processes such as humus formation, nutrient immobilization, podzolization, and dissolution of soil minerals (Spears et al., 2002). A component of DOM is organic acids which may increase the rate of soil weathering, changing soil pH, releasing cations from clays, and increasing the solubility of aluminum and iron ions in soil solutions (Spears et al., 2002). The characteristics and impacts of CWM vary with the wood species, forest type, forest disturbance levels, and ecological succession stage (Kim et al. 2017). However, there is a lack of studies looking at the long-term biogeochemical impacts of removing or altering CWD as there are few forests that remain undisturbed (Kim et al. 2017). However, as the forest adapts to a changing climate, understanding the role of decomposing wood in a managed forest is vital (Perreault et al., 2020).

Forests managed for wood production and disturbed forests will have less CWM than an unmanaged forest (Herrmann and Prescott, 2008, Magnússon et al., 2016, Perreault et al., 2020). Forests with the smallest amount of CWM are those where wood is constantly removed through harvesting, clear cutting, burning or salvage logging

(Harmon et al., 2020). Lower levels of CWM negatively impact soil quality and microbial function (Perrault et al. 2020). Changing forest management practices to retain more CWM will restore ecosystem functions related to C storage, nutrient cycling, and biodiversity of forest soils, although the magnitude and direction of effects can vary across biomes and soil types (Perrault et al. 2020).

The overall goals of this research were to determine the impact of CWM on the soils around it and the role canopy cover plays in the movement of C and N from and around CWM. My objectives included examining the relationships (1) between the size of the gap in the overstory tree canopy and the total soil C, and (2) between the proximity to CWM (beneath or away from CWM) and total soil C and ammonium ($NH_4^+$) and nitrate ($NO_3^-$) availability. This work will provide information on the impacts of CWM on soils and the ecosystem surrounding them, which are not well known. I expected to see an inverse correlation between canopy openness percentage and soil C concentration. The rate at which C is added to soil may increase or decrease depending on canopy conditions, which can impact other variables in the soil such as soil moisture and enzyme activity. The second objective was to examine how proximity to CWM and alters the concentrations of C, $NH_4^+$, and $NO_3^-$ found in the soil. I expected that total soil C would be higher near/under logs while $NH_4^+$ and $NO_3^-$ would be less available under logs (due to microbial immobilization) near/under CWM as opposed to being far away from CWM. Both objectives will show how forest management practices impact the C and nutrient cycling processes in forest ecosystems.

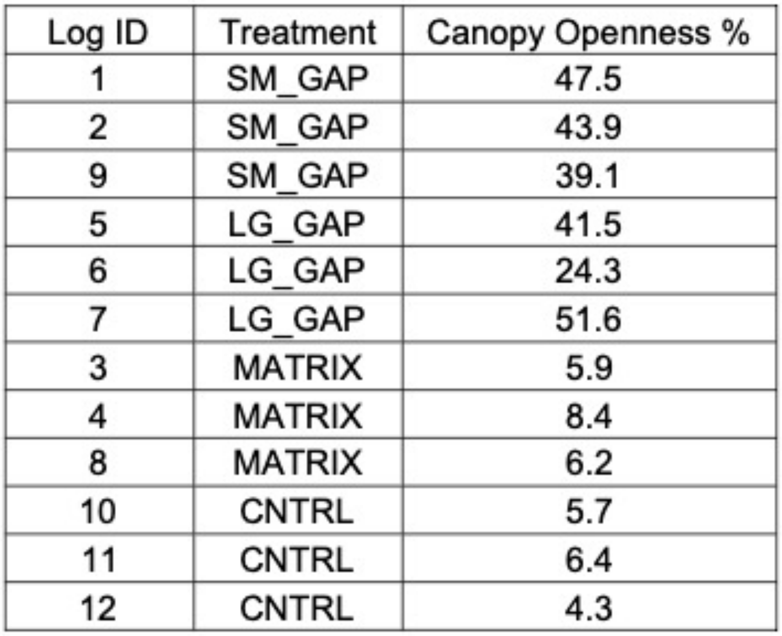
## Methodology

### *Site Description*

This experiment was located within a portion of the Dartmouth Second College Grant Adaptive Silviculture for Climate Change experiment in northern NH where there are twelve *Acer saccharum* logs were placed in locations with differing canopy openness percentages. The Second College Grant is a township that has been owned and managed by Dartmouth College since 1807. The forest is mature and relatively undisturbed. Main forest uses include forest management to support research activities and to produce wood for use by Dartmouth College and other entities.

The logs were harvested and placed in their locations in 2017 and as of 2024 were a mix of decay class 1 and 2. Logs were placed in four different levels of tree canopy classified as small gaps, thinned matrix, large gaps, and unmanaged control. The percentage of canopy openness for each level of tree canopy was 39.1- 47.5% for the small gap, 5.9 – 8.4% for the thinned matrix, 24.3 – 51.6% for the large gap, and 4.3 – 6.4% for the control gap. The percent canopy openness was measured when the logs were placed in 2017. Soils found at the research site includes Tunbridge-Berkshire-Lyman loamy sand and Peru fine sandy loam. Tunbridge-Berkshire-Lyman soils are found under logs 10, 11 and 12, and Peru fine sandy loam is found where the other lower elevation soils are located.

**Table 1.** Log numbers, their treatment category, and the percent canopy openness of their location.

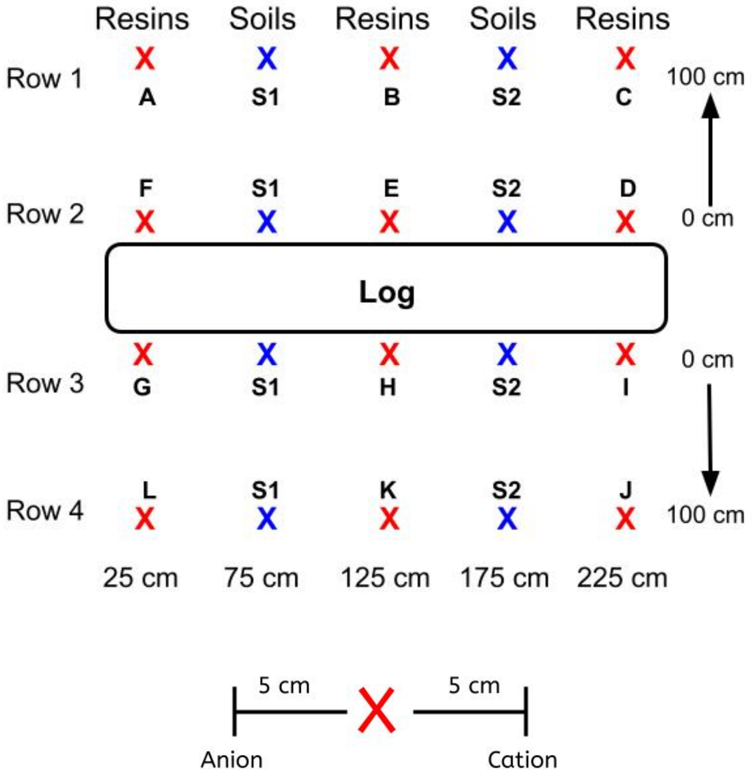


| Log ID | Treatment | Canopy Openness % |
|---|---|---|
| 1 | SM_GAP | 47.5 |
| 2 | SM_GAP | 43.9 |
| 9 | SM_GAP | 39.1 |
| 5 | LG_GAP | 41.5 |
| 6 | LG_GAP | 24.3 |
| 7 | LG_GAP | 51.6 |
| 3 | MATRIX | 5.9 |
| 4 | MATRIX | 8.4 |
| 8 | MATRIX | 6.2 |
| 10 | CNTRL | 5.7 |
| 11 | CNTRL | 6.4 |
| 12 | CNTRL | 4.3 |

*Resin Sticks*

To quantify soil $NH_4^+$ and $NO_3^-$ availability I used resin sticks constructed of cation-exchange resin membranes and anion-exchange resin membranes, which adsorb $NH4^+$ and $NO3^-$, respectively, from soil. They simulate plant roots and are a way of measuring the amount of available soil inorganic nitrogen that plant roots would be exposed to in situ (Rewcastle). I placed 288 resin sticks (144 of each type) so that there were 12 cations and 12 anions around each of the 12 logs. Resin sticks were in the field between mid-June and early mid-July of 2023.

**Figure 1.** Showing the log and where the resin sticks, and soil samples are in reference to it. Shows both distance from the log and distances along the log. Locations of the flags are represented by “X”.



For this experiment, four rows were placed around the log with rows one and two being upslope and rows three and four being downslope. Rows one and four were 100 cm from the log and rows two and three were located right against the log. Resin sticks (with three resin sticks per row) and soil samples were taken (two soil samples taken between where resin sticks were placed) in each of the four rows (Figure 1). A ruler was used to measure 5 cm away from the flag in both the left and right directions. The resin sticks were put in the soil in June 2023 and removed from the soil in the mid-July 2023. Both cations and anions strips were extracted using KCl and ultra-pure DI water. Resin stick extraction was completed in mid-to-late July with extracts kept frozen prior to analysis.

Concentrations of $NH_4^+$ and $NO_3^-$ in each extract was determined using colorimetric methods (Doane and Horwath 2003, Hood-Nowotny et al. 2010, Weatherburn 1967).

### *Soil Samples*

As for the resin sticks, soils were sampled in four rows with two soil samples taken per row. Mineral soil samples were collected from the top of the mineral soil surface, beneath the forest floor organic layers (0 to 10 cm). Samples were first collected in mid-November 2023 but were resampled in June 2024 to accommodate for shortcomings found in the soils previously collected, which were highly saturated due to record rainfall over the summer. Once dried, it was seen that several of the samples were mainly roots and leaf litter. While these are important parts of soil, there was not enough mineral soil in the samples to accurately measure soil C content.

Gravimetric soil moisture was determined by drying soil samples at 60 degrees Celsius for 48 hours. Soil C and N content were determined by combustion (UNICUBE instrument) on homogenized and ground soil samples. Soil temperature and soil moisture were measured in field using the Acclima 315L sensor for temperature and TEROS-21 sensor for moisture. Both sensors were placed 10 cm beneath the organic layer of soil. The TEROS-21 measures matric potential which refers to the pressure adhering water to soil particles on ceramic discs of known pore size (Lutz et al.). Measurements were taken at each sensor located at each of the twelve logs every hour of every day for four years. The data collected over four years was averaged to calculate average soil moisture and temperature for each log location.

### *Statistical Analysis*

Both one-way and two-way ANOVAs were done in Microsoft Excel to get a brief overview of statistical significance between the different treatment groups depending on soil C concentration. The concentrations for all the samples collected in both June and November were averaged by row number and space number. Along with an ANOVA analysis in excel, multiple two-way ANOVA analyses were completed in R showing the interactions between soil moisture, soil temperature, canopy gap percentage, and C concentration. Significance between the variables was determined using F values.

A Percent C Model was created combining factors affecting the amount of C stored such as soil moisture, soil temperature, percent canopy openness, the percent of C found in the sample, and the percent of nitrogen found in the sample. This model considered all these variables to more accurately predict which log is sequestering the most C beneath it. Additionally, models were constructed to determine which variables best explained percent of C stored and percent canopy openness.

Soil C data were analyzed using a linear mixed model that included sampling location nested within log and sampling date (June or November) as random effects and variance structures for soil moisture (varConstPower) and position (near or away from log; varIdent). Soil $NH_4^+$ and $NO_3^-$ availability (determined via resin strips) were analyzed using linear mixed models that included sampling location nested within log as a random effect and, for $NO_3^-$ only, a variance structure for soil moisture (varConstPower). Soil C, $NH_4^+$, and $NO_3^-$ data were log transformed to meet homogeneity of variance and normality assumptions. Model fixed effects for all analyses included position, percent canopy openness, soil temperature, and soil moisture. The model for soil C also included the sampling date (June or November) and models for $NH_4^+$ and $NO_3^-$ also included mean soil C (averaged across June and November samplings).

In the soil C model, we found that soil C was significantly different between samplings (P=0.04). However, the mean and range of the data were very similar between samplings, so we did not consider sampling date in further analyses (June mean = 12.4%, range = 3.0-43.6%; November mean = 14.2%, range = 2.0-45.0%).

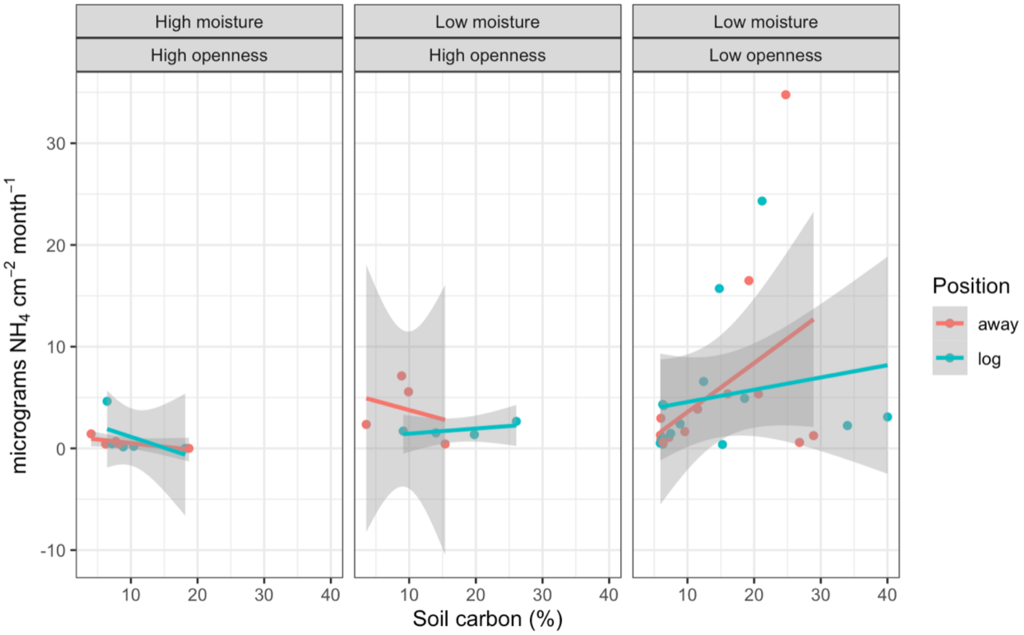
All linear mixed effects models were fit using the nlme package in R Studio (R Core Team 2024; RStudio Team 2020; Pinheiro et al., 2023). We calculated marginal and conditional R2 values using the piecewiseSEM package in R (Lefcheck, 2016). Marginal R2 describes the proportion of variance explained by fixed factors alone (i.e., manure application season, tillage, CC, date, and interactions), while conditional R2 describes the proportion of variance explained by fixed and random factors (fixed factors plus plot; Nakagawa and Schielzeth, 2013). Treatment significance was assessed using F tests.

## Results

### *Ammonium*

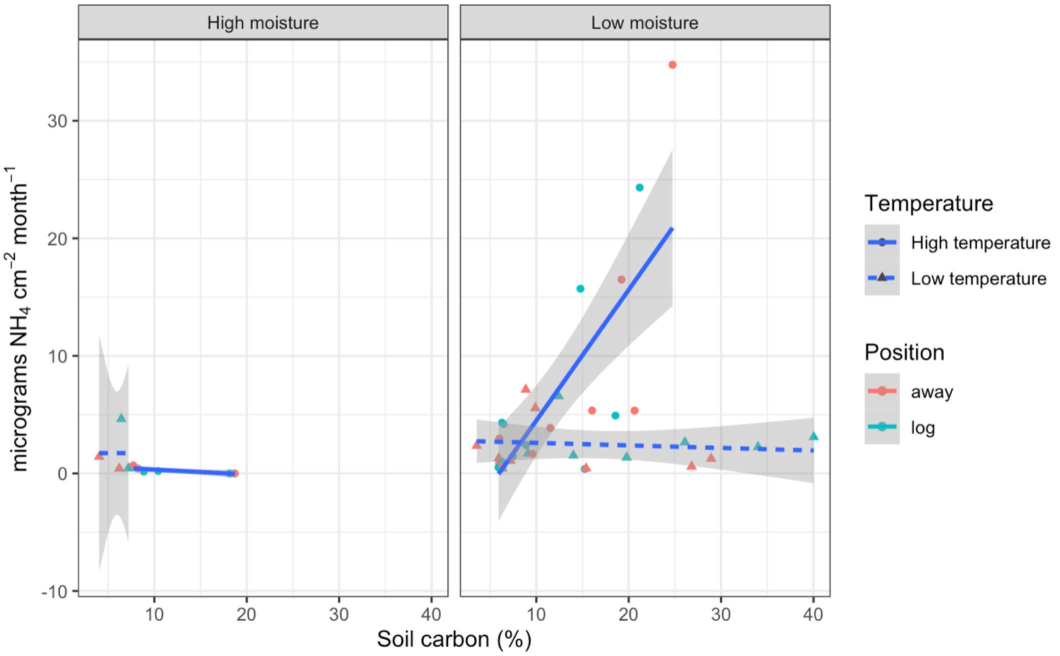
There were significant correlations between $NH_4^+$ concentration, soil C, sample position, and moisture/canopy openness conditions. Concentration of $NH_4^+$ was highest in areas of low moisture and low openness with concentrations greatest away from the log. There was a more rapid increase in concentration as the soil C concentration increased in low moisture and low openness conditions with the most dramatic increase seen in samples being taken away from the log. The concentration of $NH_4^+$ changed by about 12 micrograms with a change in soil C concentration of 24% for samples taken away from the log. This pattern differs in the low moisture/high openness and high moisture/high openness conditions (Figure 2).

**Figure 2.** The correlation between ammonium and soil carbon percentage differs depending on moisture and canopy openness conditions.



Adding temperature as a variable indicated that in low moisture conditions the concentration of $NH_4^+$ and soil C dramatically increased in high temperature and low moisture conditions. This contrasts to high moisture conditions where the concentration of $NH_4^+$ does not change regardless of the temperature and soil C concentrations (Figure 3).

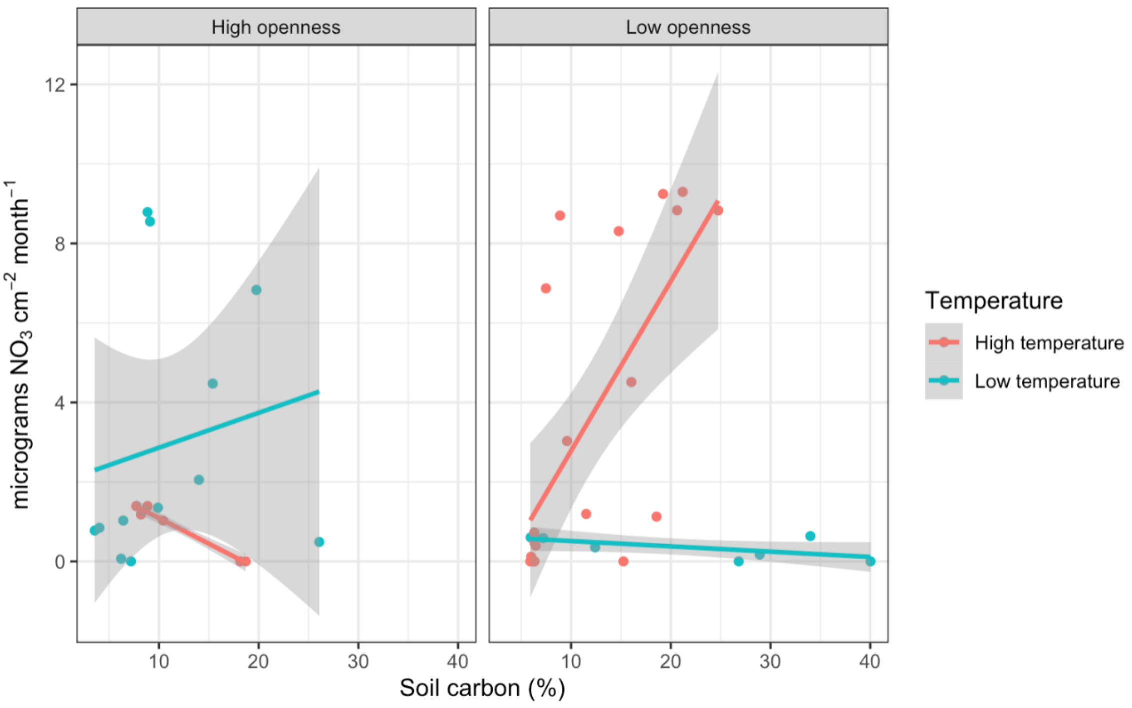
**Figure 3.** Ammonium and soil carbon has different correlations depending on moisture, temperature, and where the sample was collected.



*Nitrate*

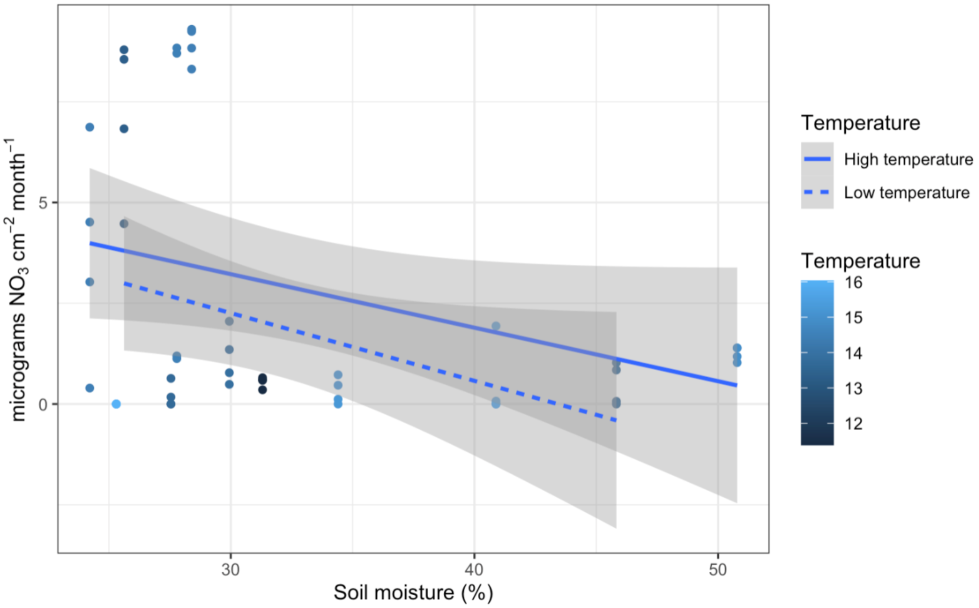
In areas with high openness and low temperature, $NO_3^-$ concentration increased with the soil C concentration. This contrasts to high openness and high temperature conditions where the concentration of soil nitrate decreased with increasing soil C concentration. Under low openness conditions with high temperature, there was a sharp increase in $NO_3^-$ concentration as soil C concentration increased. There is a strong positive correlation between high temperature, low openness, $NO_3^-$ and soil C with an increase in $NO_3^-$ concentration of about 7.5 micrograms and an increase in soil C of 9%. This contrasts to high temperature and high openness conditions where the concentration of $NO_3^-$ decreases by about 1.7 micrograms with an increase in soil C concentration of about 12% (Figure 4).

**Figure 4.** The correlation between nitrate and soil carbon depends on high or low openness and high or low temperature.



When looking at a correlation between $NO_3^-$ concentration, soil moisture percentage, and temperature, the concentration of $NO_3^-$ decreases in both high and low temperature conditions. The high temperature condition has the greatest concentration of $NO_3^-$ compared to low temperature conditions regardless of soil moisture percentage. The highest concentration of $NO_3^-$ in the high temperature condition is about 4 micrograms with a soil moisture of just less than 25%. The concentration of $NO_3^-$ decreases to slightly less than 1 with a soil moisture greater than 50% (Figure 5).

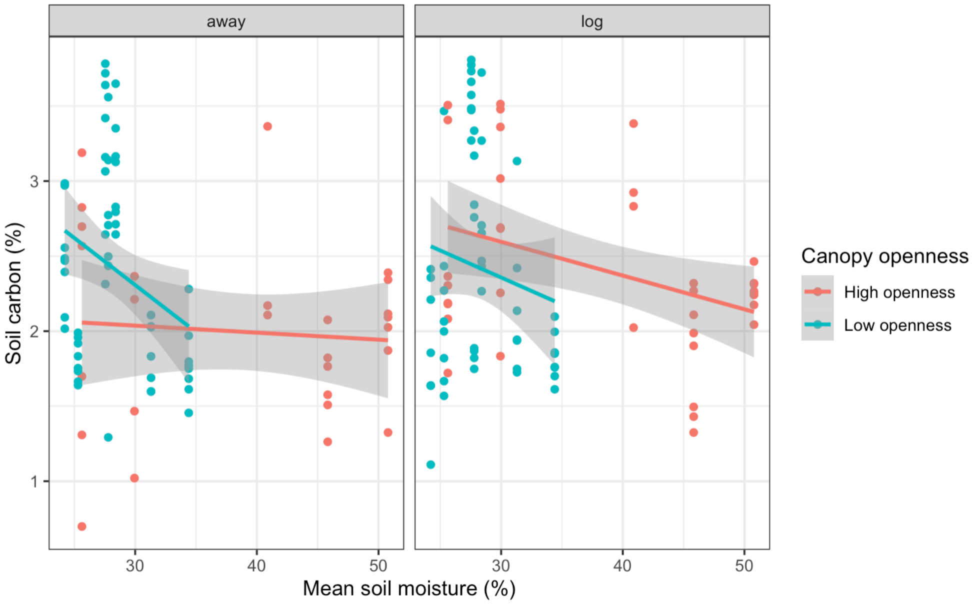
**Figure 5.** Nitrate and soil moisture have a negative correlation for both high and low temperature conditions.



*Carbon*

The canopy openness condition leading to the greatest amount of C sequestered depended upon location relative to the log. In low canopy openness conditions, soils away from the log had the greatest C concentration, but in high canopy openness conditions soils at the log held the most C. Soil moisture was always higher underneath the log compared to the surrounding soil for logs located in areas with high canopy openness conditions. This is most pronounced when the soil moisture is closer to 25% rather than higher soil moistures. With a low canopy openness, there was no difference in soil moisture when comparing surrounding soil to soil underneath the log. Additionally, more C is stored underneath the log compared to surrounding soil in high canopy openness conditions percentages. The concentration of C changed marginally when looking at the log or surrounding soil when there was low canopy openness. In high canopy openness conditions, the concentration of C stayed the same across all soil moisture percentages when looking away from the CWM. For both canopy conditions, the concentration of C decreased when soil moisture increased, indicating an inverse relationship between C concentration and moisture in soil. Soils underneath the log had a more consistent relationship with C concentration and moisture than surrounding soils regardless of canopy openness amount (Figure 6).

**Figure 6.** The correlation between soil carbon and mean soil temperature varies depending on if the soil was sampled against the log or away, and if there was a high or low canopy openness.



C concentration decreased as the canopy openness percentage and soil moisture increased. The greatest C was stored when the canopy openness percentage was below 10% and when soil moisture was below 35%. The C percentage decreased about 6%, the canopy openness percentage increased 45% and the soil moisture increased by about 25% (Figure 7). Concentration of C decreased as the canopy openness percentage increased, particularly for samples taken away from the log (Figure 8). The concentration of C slightly decreased as the canopy gap increased with the samples taken at the log, but the decrease is far less pronounced than for soils collected away from the log (Figure 8).

**Figure 7.** Graph comparing the percentage of carbon to the percentage of canopy openness with a line of best fit. Points represent percentage of soil moisture shown by a blue gradient as seen to the right of the graph.

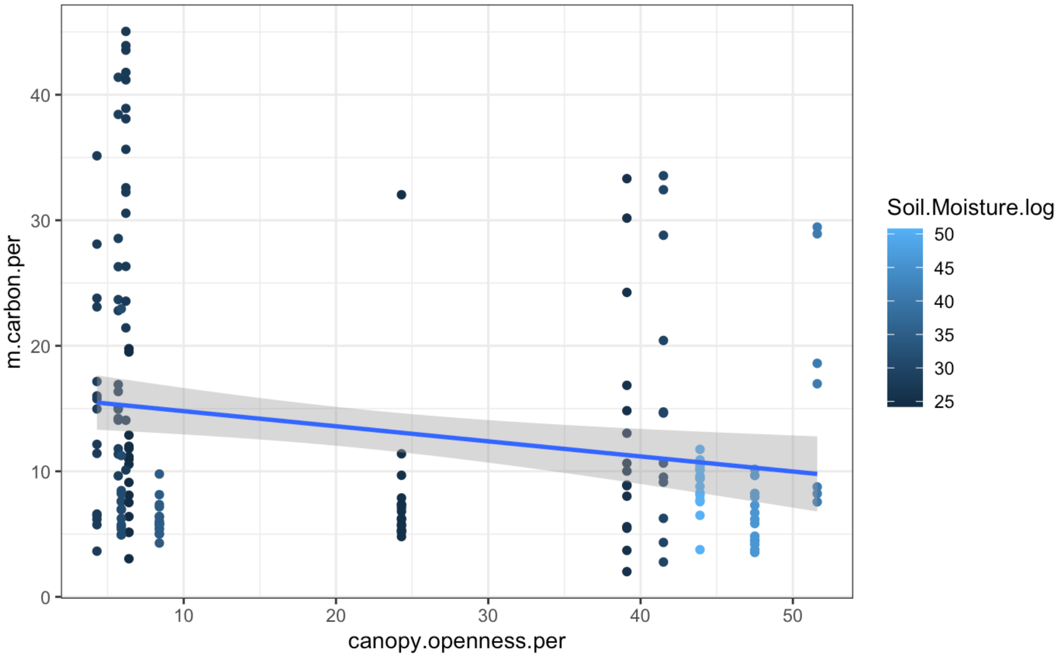
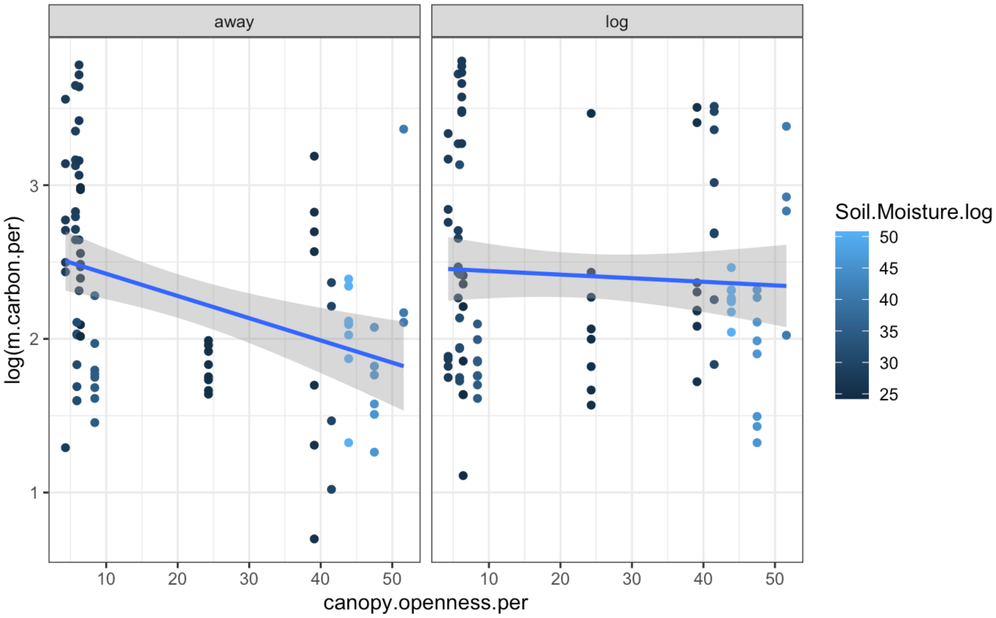


**Figure 8.** Graph showing the concentration of carbon depending on location of soil sample taken being away from or next to the log. Compares carbon concentration to canopy openness percentage with percentage of soil moisture being indicated by the shade of the blue dot seen in the legend on the right of the graph.



## Discussion

### *Immobilized Nitrogen*

The process of N immobilization occurs simultaneously with N mineralization but can be favored when the C/N ratio of the decomposed organic matter exceeds 30 (Hagemann et al, 2016). During N immobilization, microbes assimilate inorganic N for protein synthesis (Hagemann et al, 2016). The inorganic N can include $NH_4^+$ and $NO_3^-$, and $NH_4^+$ can be converted into $NO_3^-$. The amount of plant residue and organic matter in the soil can impact whether more mineralization or immobilization occurs. In the timeline of CWM decomposition, an increase in the overall N pool increases at the beginning with microbes utilizing all the new N, and then N release takes place towards the end. The increase in N stock in CWM during decomposition occurs due to the microbial immobilization of N. Nitrogen losses from CWM can occur in the form of dissolved organic N (DON), $NO3^-$, and $NH4^+$ (Bantle et al. 2014). The concentration of N changes in the CWM as it decomposes with new CWM being low in N and as it decomposes the quantity of N increases. As the concentration of N increases, microbial colonization increases allowing for biological N fixation to occur (Benoist et al. 2022, Foster and Lang, 1982). This is likely to N becoming free as the breakdown of CWM occurs.

When looking at $NO3^-$ and C, there is a strong correlation between the two in high temperature/low openness conditions. Our research suggests N in the form of $NO3^-$ can become immobilized in high temperature/low canopy openness environments. The greatest concentration of $NO3^-$ by far was seen in these conditions compared to high and low temperature/low openness and low temperature/low openness. The reason for this increase in the overall N pool may be microbes taking advantage of all the free N from the CWM and turning it into inorganic N, creating a large pool of $NO3^-$. This process outlined by *Bantle et al., 2014* would suggest that large amounts of $NO3^-$ are immobilized due to microbial activity (Figure 4). The pattern of high temperature/low openness discontinues when comparing $NO3^-$ and soil moisture at high and low temperatures. The concentration of $NO3^-$ is consistently greater at high temperatures than low temperatures regardless of soil moisture percentage. There is a negative correlation between $NO3^-$ concentration and soil moisture percentage (Figure 5).

### *C/N Dynamics and CWM*

The ability of soils to provide N for plant uptake relies on C availability, and the ability of C to remain in soils relies on N availability (Holz and Augustin 2021). CWM begins as a N sink due to initial high C/N ratios and then as it becomes more decayed becomes a net N source (Metzger et al., 2008). In *Metzger et al 2008,* higher rates of nitrification and net mineralization were found in bare soil as opposed to underneath CWM. The reasons for this could be microbes in the bare soil were C limited, meaning the assimilation of $NO3^-$ was reduced resulting in the accumulation of $NO3^-$ in the soil. A second reason for this could be abiotic conditions such as temperature and soil moisture impacting the turnover of the microbial community and contributed to increased N mineralization rates (Metzger et al., 2008).

In this research, there does not appear to be a consistent correlation between soil C concentration and the concentration of $NH_4^+$ in the soil across different moisture and openness conditions. The greatest difference in concentrations at the log and away from it were seen in low moisture/openness conditions. The soil away from the log displayed a stronger correlation between $NH_4^+$ in the soil and soil C concentration (Figure 2). The reason for this may be similar to what *Metzger et al 2008* suggested that N may be mineralized away from the CWM at a higher rate due to abiotic factors. The abiotic factors that may be present in this research include temperature and moisture which is seen compared in Figure 3 when looking at the correlation between $NH_4^+$ and soil C. In low moisture/high temperature conditions, there is a high correlation between an increase in $NH_4^+$ and soil C (Figure 3).

### *Carbon/Soil Moisture/Temperature Dynamics*

Globally, soil organic C (SOC) stocks are positively correlated with mean annual precipitation and negatively correlated with mean annual temperature. Results from *Das et al., 2019* show the wettest soils had the highest SOC and organic material (OM) levels (Das et al., 2019). This means on average more C is stored when precipitation is greater, and less C is stored with higher temperatures.

When looking at the relationship between C and soil moisture in the present study, there was a negative correlation between an increase in soil C and an increase in soil moisture seen across varying conditions. Analysis from *Green et al., 2019* mentions a decrease in soil C storage as soils gradually dry in response to climate change (Green et al., 2019). Our research suggests too much moisture can have the same effect. The greatest concentration of C was seen in soils with a moisture concentration of less than 30%. The conditions measured include high and low canopy openness away from and underneath the log. The greatest amount of C was stored in high openness conditions underneath the log (Figure 6). Background literature and this research suggests high soil moisture can lead to either high or low carbon sequestration. For example, carbon is stored in high concentrations in wetlands and peatlands because there is limited oxygen which slows the rate of decomposition (Hao et al., 2025). This contrasts to a northern hardwood forest where oxygen is abundant, and increased moisture decreases carbon sequestration.

This pattern was supported by our analyses, which showed significant differences between soil moisture, soil temperature, soil C, and canopy openness percentage. Reasons for this trend could be increased plant diversity in early succession conditions promoted by the large canopy gap, as past work (Hou et al., 2024, Lange et al., 2015, Liu et al., 2018, and Yang et al., 2017*)* suggests the formation of canopy gaps increase long-term soil C storage by promoting plant diversity. Soil C storage is linked to inputs by plant roots which can include root exudates emitting C. Higher quantities of C will be exchanged in the soil in areas with greater plant diversity compared to areas with lower plant diversity (Lange et al., 2015). There may be more plants and a greater diversity of plants within large canopy gaps which may play a role in greater soil C storage (Figure 6).

Another reason for this may be increased microbial activity underneath the log, also known as “pedogenic hot spots” (Kim et al., 2017). Increased microbial activity would mean accelerated breakdown of the CWM, freeing organic C into the soil to be mixed into humus or SOC. The relationship between soil C changed when directly comparing soil C and canopy openness percentage while accounting for soil moisture. In particular, there was a negative correlation between soil C concentration and canopy openness (Figure 7). These correlations become clearer when separating the samples collected underneath the log and samples collected away from the log. There is a strong inverse correlation between C and canopy openness for soil samples collected away from the log. There is a slight inverse correlation between C concentration and canopy openness for samples collected underneath the log. The concentration of C underneath the logs is greater for samples collected underneath the log in high canopy openness conditions compared to samples collected away from the log (Figure 8). This trend suggests soil conditions underneath the CWM may stay more stable as the climate changes creating a physical buffer compared to surrounding soils.

In this research, the CWM is in decay classes I and II, meaning it did not have as much impact on soils as more decomposed CWM in later decay classes. As mentioned in *Wojciech et al, 2019*, wood at the highest decomposition stages released more ions into surface soil horizons compared to CWM at lower decay classes. The composition of chemicals of the organic residue in the soil depends greatly on decay class (Wojciech et al, 2019). The CWM in this research did not emit as many chemicals into the soil as it could if the logs were more decomposed. When the CWM reaches decay classes IV and V, there will be greater chemical concentrations present.

### *Conclusions*

With the rising concentration of CO2 in the atmosphere, the topic of C sinks and storage has turned to terrestrial sources of C sequestration. Soil organic matter (SOM) holds C in the form of mostly decomposed biomass. This pool of C held in the O horizon of the soil can exceed aboveground terrestrial biomass C pools (Vejre et al., 2003).

This research shows the concentration of N is highest in low openness/low moisture/high temperature conditions. The highest concentration of C can be found in low openness/low moisture conditions as a whole, but when sampled underneath the CWM, canopy openness becomes less of a concern as C can be stored in every canopy openness condition as opposed to bare soil. Low canopy openness conditions are overall better for C and N abundance.

These results have farther reached effects than forest soils and forest management. C storage and sequestration will be vital as forests change with the planet warming. While there isn’t a big difference with low canopy openness, there is a difference in high canopy openness conditions which can be applicable to situations taking place in forests around the world. High canopy openness conditions may be prevalent in managed forests and these forests make up a lot of space around the world. While the management of CWM may seem insignificant, any C stored will have a small impact on keeping it out of the atmosphere.

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## Conflict of Interest Statement

The authors declare no conflict of interest.

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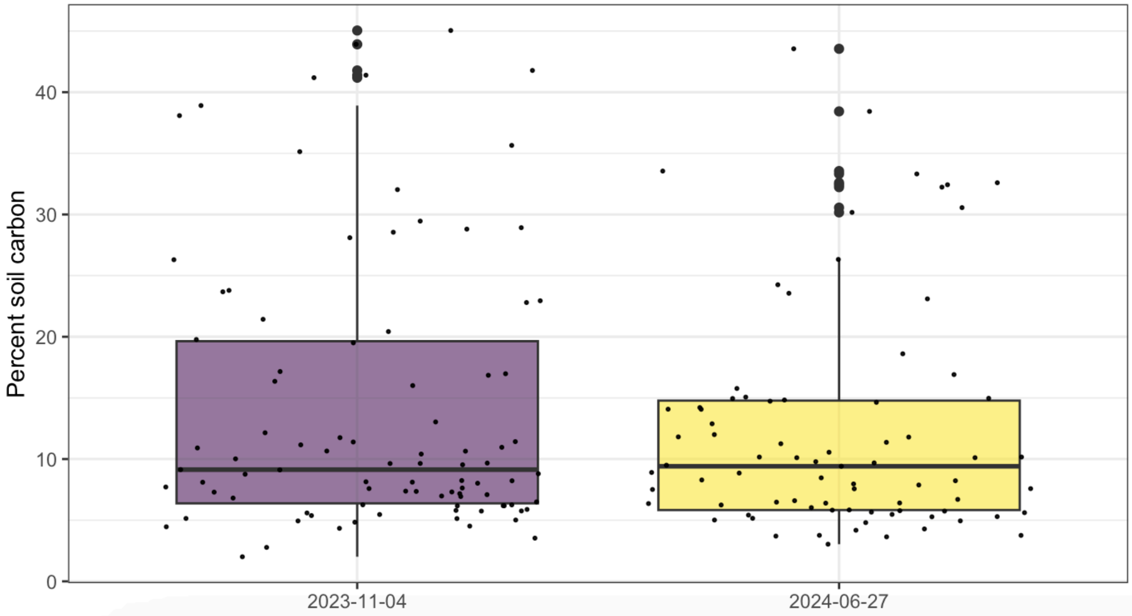
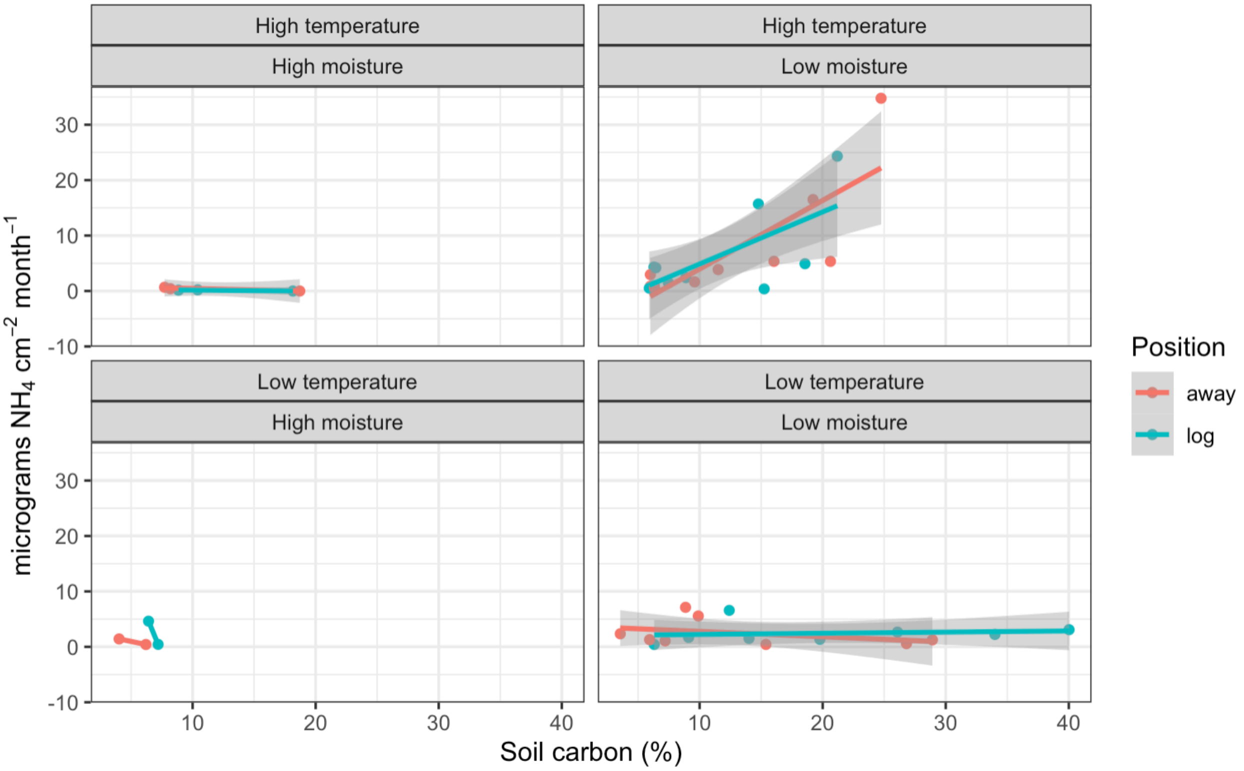
## Appendix


Percent soil carbon
0
10
20
30
40
2023-11-04
2024-06-27


High temperature
High moisture
High temperature
Low moisture
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High moisture
Low temperature
Low moisture
micrograms NH$_4$ cm$^{-2}$ month$^{-1}$
-10
0
10
20
30
Soil carbon (%)
10
20
30
40
Position
away
log