

Exploring the impact of climate change on soil carbon storage in montane meadows

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Abstract

The excess of greenhouse gasses like carbon dioxide in the atmosphere urgently calls for a deeper understanding of existing natural mechanisms for carbon sequestration. Montane meadows act as a critical natural carbon sink, often having the capacity to store much more carbon in their soils than surrounding ecosystems. However, many factors associated with climate change can impact soil carbon storage processes, converting carbon sinks to carbon sources. This can be especially problematic in montane meadows because of their relatively high soil carbon content. This study uses experimental treatments to ask how soil carbon storage may be impacted by three factors associated with climate change: warming, shifts in plant community composition, and early snowmelt. I investigated these questions by measuring soil organic carbon (SOC), and by taking soil temperature and moisture data to understand the mediating influence of these factors on soil carbon storage. I found that although none of the treatments affected total SOC, warming and changes in plant community composition shifted the distribution of SOC along the soil horizon. SOC seemed to shift to shallower soil under these ecologically relevant treatments, which is worrying because carbon tends to be less stable in shallow soils compared to deep soils. Climate change may therefore be destabilizing carbon stores in a critical carbon sink.

Introduction

The release of greenhouse gasses like carbon dioxide into the atmosphere contributes to global warming, which can in turn accelerate this release of gasses and create a self-reinforcing feedback cycle (Nyberg and Hovenden 2020). Carbon sequestration and carbon storage through natural ecosystem functions can help absorb and contain some of this excess carbon, and most of this sequestered carbon ends up in soil carbon pools (Morra et al. 2023). Globally, the amount of carbon naturally stored in soil is double or even triple the combined amount of carbon in the atmosphere and in plants (Davidson et al. 2000; Canadell 2007; Jackson et al. 2017; Dignac et al. 2017; Hou et al. 2019; Nyberg and Hovenden 2020). Montane meadows have the capacity to store especially high amounts of carbon in their soils and are usually able to sequester more carbon than surrounding forests (Reed et al. 2021). This is because of their shallow water tables, which promote the growth of herbaceous plants with dense root mats that maintain high water saturation in the soil (Reed et al. 2021; Morra et al. 2023). Large carbon inputs from plants combined with this wetter environment allows montane meadows to contribute to carbon fluxes in mountainous areas disproportionately to their relative area (Reed et al. 2021; Morra et al. 2023). This can make them powerful carbon sinks; however, anthropogenic effects such as warming and shifts in watershed characteristics can quickly convert these meadows to carbon sources (Jackson et al. 2017; Reed et al. 2021). Ecosystems with the highest capacity for carbon

storage (i.e. montane meadows) are in danger of becoming huge carbon sources due to their large stocks of carbon (Reed et al. 2021). The release of greenhouse gasses from soils worldwide is thought to be even greater than fossil fuel emissions (Carey et al. 2016; Gerke 2022), emphasizing the need for further research on how climate change is impacting soil carbon cycling dynamics in montane meadows.

One factor associated with climate change that will likely impact soil carbon storage is warming temperatures. As phenological events shift earlier due to warming, ecosystem carbon gains could increase due to increased biomass production (Sistla et al. 2013; Ernakovich et al. 2014). However, changes in ecosystem carbon may differ from changes in soil carbon. Previous research suggests that these increases in biomass may have no impact on soil carbon (Jackson et al. 2017), and that warming may actually decrease soil carbon storage (Tate 1992; Kirschbaum 1995; Reed et al. 2021). This could be due to shifts in microbial/decomposer activity (Sistla et al. 2013; Jackson et al. 2017; Walker et al. 2018); many studies have shown that warming increases decomposition rates (Tate 1992; Jackson et al. 2017) and soil respiration rates (Carey et al. 2016; Nyberg and Hovenden 2020). However, fewer studies have looked into how changes to rates of soil respiration and decomposition impact the actual amount of carbon in the soil. Another way warming could impact soil carbon storage is by drying out the soil (Tate 1992; Saleska et al. 2002; Saleska et al. 2008), because drier soils are able to store less carbon than wetter soils (Tate 1992; Morra et al. 2023). These results suggest that warming may decrease soil carbon storage; however, studies that have looked into this question present conflicting results. Sistla et al. (2013) found that warming in an Alaskan tundra caused many ecosystem shifts but did not affect soil carbon stocks, yet Tate (1992) found that warming decreased carbon storage in New Zealand tussock grasslands. Similarly, Kirschbaum (1995) found that warming by one degree celsius decreased soil carbon stores by 3-10% depending on mean annual temperatures. The effect of warming on soil carbon storage therefore seems to be location-based (Carey et al. 2016).

Shifts in plant community composition due to climate change also could have an impact on soil carbon processes (Metcalf et al. 2011; Jackson et al. 2017). Plant species vary in their aboveground and belowground carbon allocation strategies (Metcalf et al. 2011; Jackson et al. 2017). This means that shifts in plant community composition could change the amount of carbon diverted into the soil as well as shifting decomposition by altering plant litter makeup, therefore altering soil organic matter inputs (Metcalf et al. 2011; Jackson et al. 2017; Zhou et al. 2019). For example, different plants have different amounts of the chemical suberin in their leaves, and suberin can be a determining factor in the stability of SOC (Lorenz and Lal 2005). Therefore changes in what plants dominate a montane meadow could change how much carbon the meadow is able to hold in its soils. Shifts in dominance will probably affect SOC also because dominant species have a powerful influence over soil carbon outputs (Metcalf et al. 2011). For example, dominant species removal can alter microbial community composition and nitrogen availability (Duan et al. 2022), both of which affect carbon cycling processes (Lavoie et al. 2011; Walker et al. 2018). Dominant species removal can also increase biomass in montane

meadows (Vought et al. 2023 in prep), which would increase carbon inputs, suggesting that removal might increase SOC. This is also supported by the idea that dominant species removal can increase diversity (Gurevitch and Unnasch 1989), and higher diversity can promote SOC accumulation by decreasing C:N ratios and therefore increasing plant litter quality (Chen et al. 2018; Zhou et al. 2019). However, Duan et al. (2022) found that dominant species removal actually decreased biomass, which decreased SOC. This experiment was done in a farm, so perhaps the lower plant diversity in this setting hindered the ecosystem's ability to fill in the empty space created by removing the dominant species. This differential effect of removal on various ecological variables based on the study system indicates that the effect of removal on SOC might be location-dependent. A last factor that supports this idea is that the effect of removal on soil respiration sometimes varies by site and along elevation gradients (Dong et al. 2020). The effects of plant community composition shifts on soil carbon storage is therefore complex and needs further clarification.

A third ecological shift associated with climate change is earlier snowmelt timing. As temperatures warm, snowpack melts away sooner, which extends the dry period between snowmelt and monsoon rain and can contribute to longer, hotter summers (Angert et al. 2005; Knowles et al. 2018). Longer drought periods keep soils drier for longer periods of time and, as mentioned above, this has implications for soil carbon. Early snowmelt can lengthen the growing season, which in theory could increase plant productivity (Angert et al. 2005) and therefore increase soil carbon storage by adding carbon inputs; however, the benefits from a longer growing season seem to be canceled out by carbon losses during these hot dry periods (Angert et al. 2005). Trade-offs between the early and the late growing season under early snowmelt conditions appear to actually decrease the ability of important ecosystem carbon sinks like forests to sequester carbon (Knowles et al. 2018). Lastly, dissolved organic carbon (DOC) can be flushed out of soil during snowmelt (Hornberger et al. 1994; Brooks et al. 2010), suggesting that earlier/accelerated snowmelt could have an impact on soil carbon content. However, Conner et al. (2017) found that early snowmelt had no impact on DOC over three years of treatment compared to controls in aspen forests and subalpine meadows. I look into how these effects manifest in montane meadows.

This study aims to clarify the debated effects of warming, changes to plant community composition, and early snowmelt on soil carbon pools and fluxes. I will be specifically focusing on soil organic carbon (SOC), in conjunction with soil temperature and moisture. Measuring these variables in experimental plots will provide insight into how climate change is impacting soil carbon cycling, and will potentially allow me to make inferences about the mechanisms behind these impacts. I will ask three main questions. First, how does SOC differ between warmed plots and plots with ambient temperatures? Second, how does SOC differ between plots with removal of the dominant species and plots with no removal? And third, how does SOC differ between plots with early snowmelt and plots with unmanipulated snowmelt? I hypothesize that warming will decrease SOC because of accelerated microbial processes, altered plant community composition will increase SOC because these shifts may increase plant

biomass and diversity, and early snowmelt will decrease SOC because of longer drought periods. A sub-question is: What role do soil moisture and temperature play in these effects? My hypothesis is that soil moisture and temperature will often act as a mechanism for these effects on soil carbon storage.

Specific methodologies

I took data from two sites to answer these questions. For data on the impact of warming and plant community composition shifts on soil carbon processes, I took measurements at previously established Warming and (species) Removal in Mountains (WaRM) experimentation plots that were set up in 2013 at the Rocky Mountain Biological Laboratory in Gothic, Colorado (see Prager et al. 2022). I used the WaRM site in Almont (elevation: 2740 m, latitude: 38.992, longitude: -107.067). WaRM sites have eight sets of four 2mx2m plots (for a total of 32 plots). Each set of four has three experimental plots and one control plot. The first experimental treatment includes placing 1.5m diameter, 65cm tall hexagonal passive warming chambers with open tops over the plots, increasing air temperature by about two degrees celsius and soil temperature by about one degree celsius. The second experimental treatment includes removing the aboveground biomass of the dominant species (*Wyethia amplexicaulis*) in each plot. The third experimental treatment includes both of these treatments within the same plot to investigate interactive effects. Control plots are not manipulated. For data on the impact of earlier snowmelt on soil carbon processes, I took measurements at a previously established snowmelt manipulation site set up in 2022 (elevation: 2956 m, latitude: 38.963, longitude: -106.993). At this site, dark-colored tarps were placed on top of the snow on half (5 out of 10) of the 10mx10m plots, accelerating snowmelt by about 2 weeks.

Soil organic carbon

I collected one 3.5 diameter soil core 7.5 cm deep per plot at each of the two sites described above (WaRM in Almont and snowmelt manipulation). I sampled at roughly peak season. In the field, I divided each core in half to differentiate between the deeper mineral soil and the shallower humus layer, and put each sample into a plastic ziploc bag to be processed. To process a soil sample, I put it in a drying oven at 250 degrees celsius in an aluminum tin overnight to take out most of the moisture. I sifted it in a 2000 micron sifter, picked out the roots for three minutes using tweezers, and put it back into the drying oven. I then put 6 to 9 grams of the dried soil into a pre-weighed aluminum tin and took the mass of the soil. To burn off the soil organic carbon, I put the samples (about 20 at a time) into a 200 degree celsius muffle furnace and ran a pre-set program. The program brought the temperature up by 19 degrees celsius every minute until the temperature reached 430 degrees celsius, and then held the temperature at 430 for five minutes. I then took the samples out and put them back into the drying oven to cool for about an hour. I weighed the whole sample, then took out the soil and weighed the tin again. To calculate the soil organic carbon, I subtracted the post-burn soil weight from the pre-burn soil

weight and then divided that number by two under the assumption that about half of the matter that burned off was carbon as in Saleska et al. (2002).

Soil temperature and moisture

I downloaded soil temperature and moisture data from TMS probes in each plot, which have logged soil temperature and moisture every fifteen minutes since the establishment of the plots (Wild et al. 2019).

Statistical analysis

I analyzed my data in R version 4.3.1 using ANOVA and a post-hoc Tukey test to see if there was an interaction between treatment and depth. I determined significance with a p value of 0.05.

Results

I found a significant interaction between warming, removal, and depth using an ANOVA test ($F=4.985$, $p=0.0296$). There was no significant difference in soil organic carbon (SOC) between the warming, removal, warming and removal, and control treatments (Figure 1), but I did find a significant difference between SOC in deep and shallow soil in WaRM plots overall; shallower soil contained more SOC than deep soil (Figure 1). This difference between deep and shallow soil was significant only in the removal ($p=0.0289$) and the warm plots ($p=0.0178$), not in the control ($p=0.9866$) and combined warming and removal plots ($p=0.7840$) (Figure 1). Also, SOC in shallow soil in removal plots was significantly higher than SOC in deep soil in warming plots as well ($p=0.0012$; Figure 1).

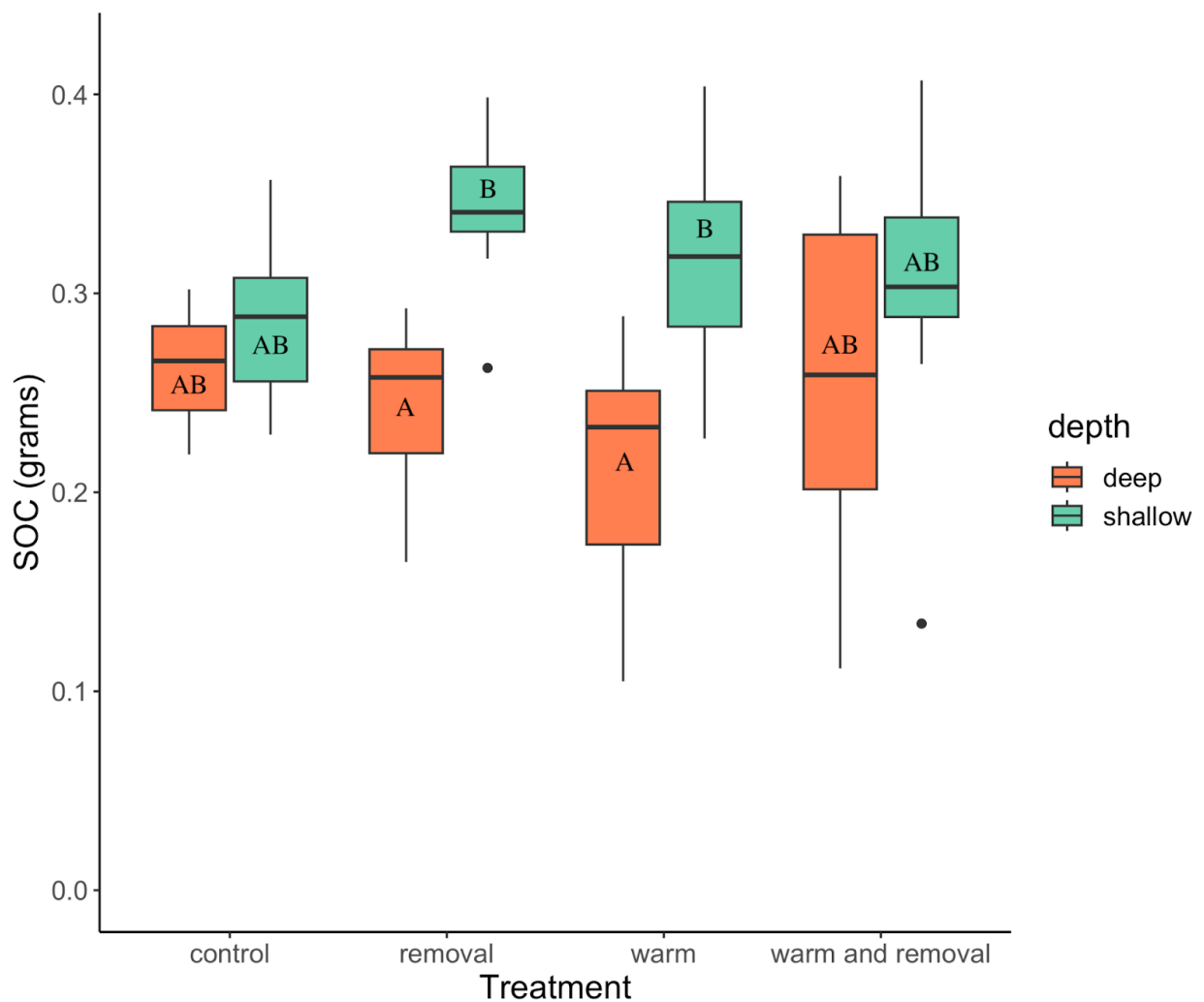


Figure 1: SOC vs treatment in Almont WaRM plots Letters represent differences in significance; if two boxplots share a letter they are not significantly different from each other.

I found no significant difference between SOC in early snowmelt plots compared to control plots ($F=0.856$, $p=0.368$; Figure 2). I also found no significant difference between SOC in deep and shallow soil in the early snowmelt plots ($F=2.972$, $p=0.103$; Figure 2).

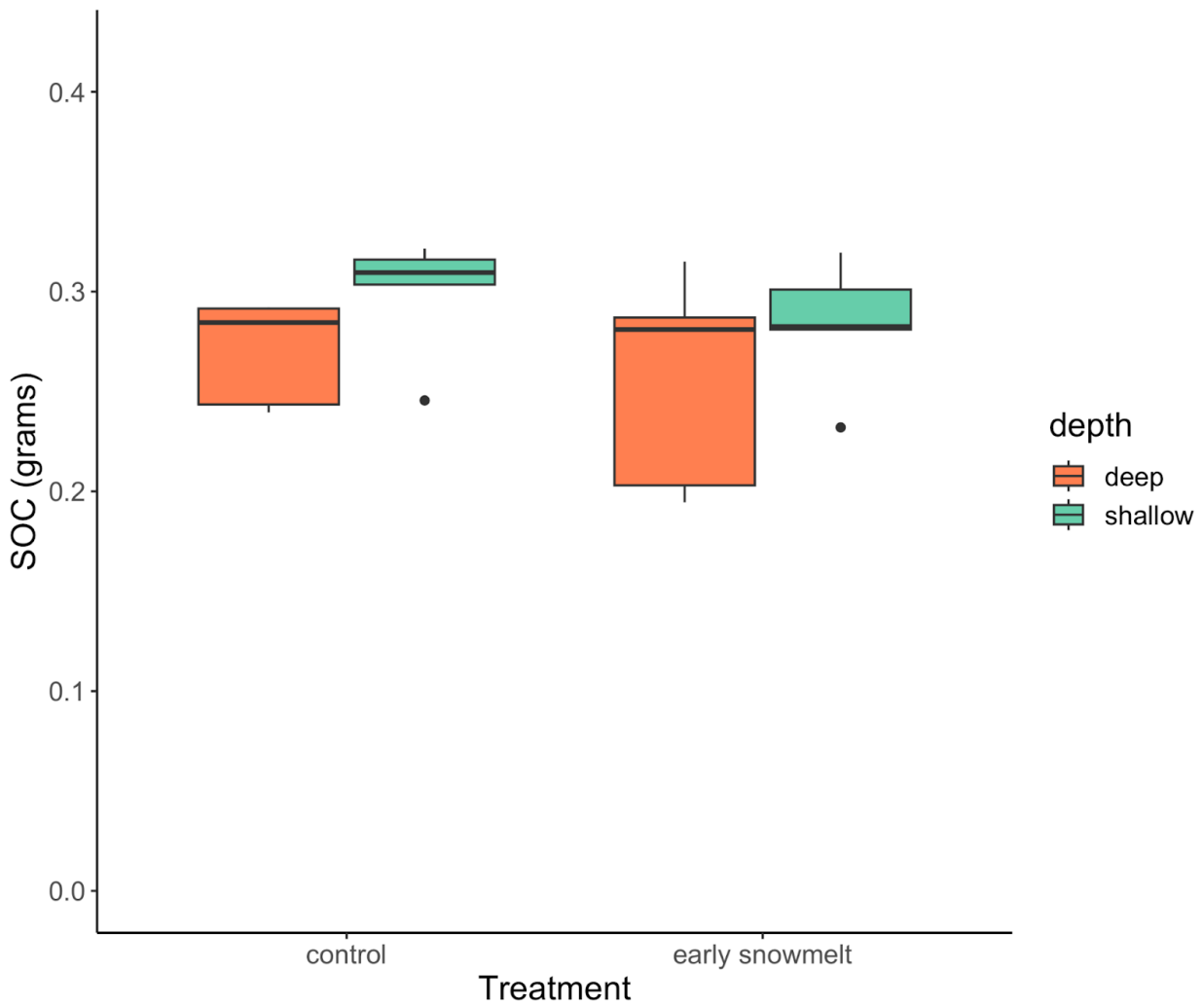


Figure 2: SOC vs treatment in snowmelt manipulation plots.

Discussion

I found no effect of warming, dominant species removal, warming and dominant species removal, or early snowmelt on soil organic carbon (Figures 1 and 2).

Warming

Eight years of warming had no effect on SOC (Figure 1). There are a couple potential reasons for this. One is that the warming chambers brought air temperature up by about 2 degrees celsius but soil temperature up by only about 1 degree celsius, so the direct impact of the treatment may have manifested aboveground more than belowground. Warming can sometimes increase aboveground plant biomass (Sistla et al. 2013), although we did not see this effect overall in our plots (Vought et al. 2023 in prep). In fact, there was an overall decrease in biomass in our warming plots (Vought et al. 2023 in prep). The dominant species in our plots (*Wyethia*) did respond very positively with warming, however, and warming can sometimes increase the thickness of leaves, height of plants, and the mass per area of each leaf (Kovenock and Swann 2018). These changes in plant traits may not have shown up in the Vought et al. in prep (2023) biomass measurements because they used allometric equations to estimate biomass. This means that instead of clipping biomass inside of sensitive long-term plots, they calculated the ratio between percent cover and biomass by clipping nearby plots, and then applied this ratio to the percent cover of the WaRM plots to estimate their biomass (Vought et al. 2023 in prep). Percent cover ignores traits like leaf thickness, plant height, and leaf mass per area. The aboveground effect of the warming treatment could have therefore increased carbon inputs into the soil even though warming did not appear to increase overall biomass in the estimates I'm looking at. I expected SOC to decrease with warming due to accelerated microbial processes (Tate 1992; Sistla et al. 2013; Jackson et al. 2017; Walker et al. 2018), and it's possible that this did occur as an effect of warming. However, these SOC decreases may have been offset by simultaneous increases in carbon inputs as described above. As mentioned above, the treatment's effect on aboveground factors like plant production was higher (2 degrees celsius versus 1 degree celsius) than its effect on belowground factors like microbial processes, so the treatment's effect was potentially greater for SOC inputs than SOC outputs. This could have led to a possible underestimation of warming's depleting effect on SOC stores.

It's also possible that warming's effect was not visible in my results because when warming reduces SOC, decomposing microbes are constrained by this depletion of resources, so carbon processing by these microbes decelerates and SOC can build back up again (Walker et al. 2018). This can create an up and down cycle of SOC every few years (Walker et al. 2018), and I could have sampled during one of the peaks. Another reason I may not have seen an effect of warming is that microbial decomposition of carbon can also be constrained by many other environmental factors (Lavoie et al. 2011; Walker et al. 2018). For example, decomposition rates can be limited by how much nitrogen there is in the soil (Lavoie et al. 2011). This means that the apparent stability of SOC in response to temperature shifts may have been a temporary phenomenon, as the microbes may not have had enough available nitrogen to be able to decompose the carbon and subsequently release it from the soil. If conditions had been different and nitrogen inputs had increased, for example, then decomposing microbes may have been able to become active and eventually overtake the carbon buildup (Lavoie et al. 2011). This is

especially relevant in the warming treatments because nitrogen acts as a limiting factor for decomposition only under certain conditions, and one of those is high temperatures (Lavoie et al. 2011). I may have seen no effect of warming because microbes in warming plots were limited by low nitrogen availability while the microbes in controls were not limited by nitrogen availability. Therefore carbon outputs in warming plots could have been slowed compared to controls, and this would have balanced out potential SOC losses due to warming.

Although there was no difference between the amount of SOC in warming and control plots, warming did have a significant effect on where along the soil horizon this SOC was stored. SOC seemed to shift shallower (Figure 1). This could be because the loss of carbon in shallow soil due to warming was overridden by increased litter deposits, and losses in deep soil occurred if only on a small scale. Sistla et al. (2013) found a similar result that warming changed the distribution of carbon in the soil without changing total carbon storage. Their results directly contradict mine, however; they found that warming homogenized SOC across deep and shallow soil, and I found that warming stratified SOC. This could be due to the difference in our study ecosystems; they were studying a moist acidic tussock (MAT) Alaskan tundra ecosystem which usually has a pH of less than 5 (Walker et al. 2003), while I was looking at a relatively dry site with a pH of about 6.21 (Prager et al. 2022). SOC storage can vary based on moisture and pH (Chen et al. 2018). High pH and drier conditions can both limit soil carbon buildup (Tate 1992; Chen et al. 2018; Morra et al. 2023), so maybe the higher pH and dryness of my study site made it so that carbon stores were relatively small to begin with. This would heighten the impact of potential increased carbon inputs due to warming. Also, warming in a MAT tundra increases thaw depths, which was what they thought caused the homogenization of SOC (Sistla et al. 2013); perhaps thaw depth as a determining factor for SOC stratification is a less significant factor in montane meadows than in tundra ecosystems.

Plant community composition

Similar to warming, dominant species removal did not have a significant effect on overall SOC (Figure 1). Removal increased overall plant biomass (Vought et al. 2023 in prep), so perhaps this treatment increased carbon inputs and balanced out predicted SOC losses associated with removal (Duan et al. 2022).

Also similar to warming, removal did significantly affect the distribution of SOC along the soil horizon (Figure 1). Shallow carbon stores were greater than deep carbon stores in removal plots whereas shallow and deep SOC were not statistically different in control plots (Figure 1). This could be due to the shift in plant community composition; when *Wyethia* was removed there was much more *Erigeron spp.*, which has a shallower root system. Roots are a major mechanism by which carbon is translocated into the soil from the air, so there is likely a lot of carbon input where there are a lot of roots (Kuzyakov and Domanski 2000). Deeper and thicker root systems like *Wyethia* often have a stabilizing effect on SOC (Lorenz and Lal 2005). The removal of plants with deeper root systems and the influx of plants with shallow root systems therefore could lead to less carbon being deposited in deep soil and more carbon being deposited in shallow soil, which could explain the shift of SOC to shallower soil. (Although in the removal plots *Wyethia* roots were not pulled up, cutting off all of their aboveground biomass likely limited their growth significantly.) This is an especially relevant result because over the

past 65 years there has been an increase in *Erigeron spp.* (despite an overall decrease in forbs) as well as an increase in the dominance of grass species in montane meadows around my study area (Zorio et al. 2018). Grasses are sometimes less discriminatory than forbs (Smedley 1991) and in some climate change models they are predicted to have a competitive advantage in montane meadows (Zorio et al. 2018). This could represent a shift toward shallow root systems in this ecosystem in this area, as forbs tend to have deeper root systems than graminoids (Zhang et al. 2020). This study demonstrates one potential effect of relevant climate-altered plant community composition.

Warming and removal

Warming and removal treatments when combined in one single treatment did not have an effect on SOC (Figure 1). The fact that both warming and removal stratified SOC in the soil yet when the treatments were mixed there was no effect on SOC distribution suggests that there may be an interactive effect of the two treatments. When removal plots were warmed, the biomass stayed the same as the control instead of increasing as it did under ambient temperatures (Vought et al. 2023 in prep). Since *Wyethia* was removed, it was not positively responding to warming either. This could help to explain the lack of result on SOC. The interactive effect of warming and removal therefore remains unclear and warrants further research.

Snowmelt

Early snowmelt did not impact total SOC (Figure 2). One important limitation of this result is that there were very few replicates in the snowmelt manipulation experimental design (only 10 plots total, with 5 of each treatment). This could have made it harder to see trends. Also, these experimental plots have only been established for one year, and SOC might take longer than that to build up or become depleted. However, my result that snowmelt timing did not affect SOC is consistent with what Conner et al. (2017) found after three years of treatment and with 36 experimental plots. It could be that an even longer-term study is needed to see the effects of early snowmelt on SOC and to understand the influences of temperature and moisture on these effects. It's also possible that early snowmelt does not have a large impact on SOC; as seen in S4, the early snowmelt treatment only had an effect on soil temperature for a couple weeks before the treatment and control plots began to look fairly similar. Conner et al. (2015) found that early snowmelt did not significantly impact soil moisture either, but I found that there was an effect of the treatment on soil moisture throughout the season (S3). This effect was especially pronounced during the abnormally long drought period between mid June and early August that we experienced this year. The difference between my result and the Conner et al. (2017) result could indicate that drought potentially has an impact on snowmelt timing's effect on soil moisture. I took my soil samples during an especially dry season where the volumetric moisture content for most of the summer was far below 35%, which is very dry for montane meadow soils (Surfleet et al. 2019). The drought therefore possibly exacerbated soil dessication in early snowmelt plots, limiting the soil's ability to hold onto moisture through dry stretches. This potential effect of drought on soil moisture's response to snowmelt timing is especially relevant during an era of climate change; maybe early snowmelt will have more and more of an effect on soil moisture as droughts become more and more intense and frequent (Strzepek et al. 2010). This intuitively

would affect SOC because of the mediating influence of moisture on soil's carbon storage capacity (Tate 1992; Morra et al. 2023). Therefore it is possible that I would see the effects of early snowmelt if I continued studying these plots for many more years. It's also possible that I saw no effect on SOC despite this shift in soil moisture because the combined effects of soil temperature and moisture are more significant than the effect of just one factor or the other, and temperature remained fairly similar throughout most the season between treatment and control plots.

Early snowmelt also did not affect the distribution of SOC across the soil horizon compared to control treatments (Figure 2). This could be due to the fact that I sampled SOC based on depth instead of based on soil horizon, and in the snowmelt plots the shallow soil seemed to be from the same soil horizon as the deep soil. I judged this tactically and visually; the shallow soil had pretty much the same texture, color, and dryness as the deep soil. Deeper sampling into another horizon could have provided more insightful results. The small sample size might have made it harder to see trends as well. Early snowmelt could also expose soils to more frequent or dramatic freeze/thaw cycles because it removes the soil's insulating layer during a time of year when temperature fluctuations are dramatic (Sang-Eun et al. 2011). This causes cryoturbation, which can have a homogenizing effect on soils (Sistla et al. 2008). The soil cores I collected seemed to be fairly homogenous in both treatment and control plots, however. This could also be due to the fact that the early snowmelt soil was only exposed to outside air temperatures for a few weeks more than the control soil and a freeze/thaw cycle may not have occurred during this timeframe. It's possible that I would see this effect during years with more frequent freeze/thaw cycles or in a year where a freeze/thaw cycle occurred during the period between the early snowmelt treatment and control treatment.

Future directions

This study looked at soil carbon in experimental plots that were treated in various ecologically relevant ways to see how climate change may be altering carbon cycling processes in montane meadows. Interestingly, many of my results had to do with soil depth and the location of SOC across soil horizons even though my methods were not aimed at these questions. It's therefore possible that my methods led to misleading results regarding depth; for example, I did not account for the impact of depth on the thermal stability of SOC (Hou et al. 2019). I calculated SOC by how much mass burned off during a preset program in the muffle furnace (see methods). However, deeper soils sometimes lose less mass than shallow soils when burned, and the temperature at which deep soils lose mass is higher than for shallow soils (Hou et al. 2019). My methods may have led to inaccurate results because I did not account for this differential response of deep and shallow soils to burning. A study with methods aimed at answering questions about depth could provide clearer results for other reasons as well. For example, measurements could include deeper soil samples as in Lorenz and Lal (2005) and Hicks Pries et al. (2017), and a division of soil based on soil horizon rather than depth for a more accurate view into SOC movement through soil.

More generally, future research in this area could focus on other parts of the carbon cycle, such as soil respiration, decomposition, or carbon fixation, to get an even better understanding of how these complex processes are shifting due to climate change. (I took a few soil respiration

measurements, but due to technical difficulties I could not use these data; see S5). Another direction could include questions about the role of elevation in these effects. It could also be interesting to examine C:N ratios rather than just carbon in the soil, as nitrogen and its concentration relative to carbon can be important determining factors in carbon source/sink dynamics (Zhou et al. 2019; Liu et al. 2020; Duan et al. 2022). The interactive effect I saw of warming and dominant species removal on the location of SOC in the soil also warrants further research, as the mechanism behind this interaction is unclear and these two environmental effects may occur together in natural ecosystems.

Conclusions

My most notable conclusion is that warming and removal as independent treatments do not affect total SOC, but do affect where it is along the soil horizon. The apparent shift of SOC from deeper to shallower soil in this study due to environmentally relevant experimental treatments (removal of a dominant forb and warming) is worrying because of the instability of shallow SOC relative to deep SOC (Lorenz and Lal 2005; Hicks Pries et al. 2017; Hou et al. 2019). Shallower SOC tends to be less chemically recalcitrant and therefore more easily processed by microbes and subsequently released into the atmosphere, while deeper SOC is more mineral-protected so it has longer turnover rates and may be less responsive to warming than surface level SOC (Lorenz and Lal 2005; Hicks Pries et al. 2017; Hou et al. 2019). More specifically, shallow soil can be less thermally stable than deep soil (Hou et al. 2019), which brings up concerns regarding warming global temperatures as the temperature sensitivity of soil organic materials could determine whether soils will release or hold onto carbon and therefore accelerate or mitigate climate changes (Davidson et al. 2000). Although the factors associated with climate change that I studied are not directly affecting the amount of carbon stored in soils in montane meadows, they may be destabilizing soil carbon stores in this critical ecosystem.

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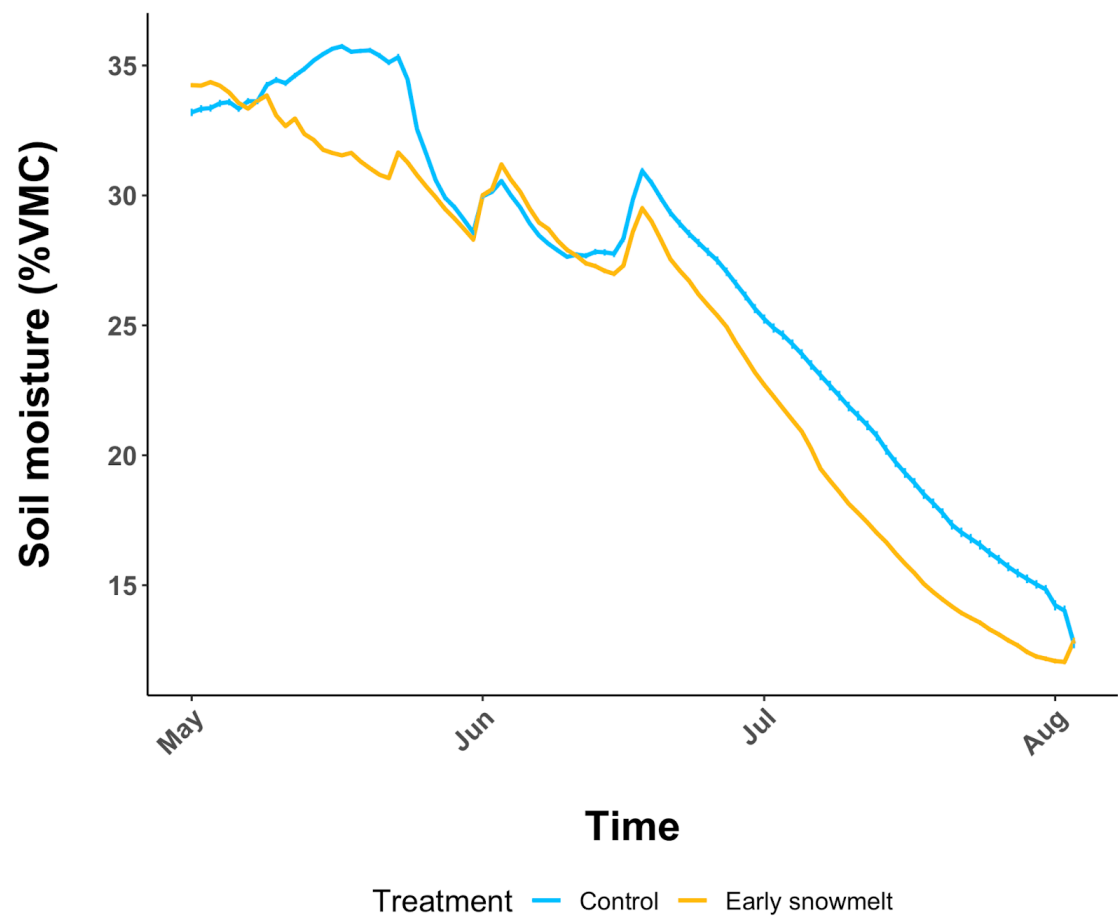
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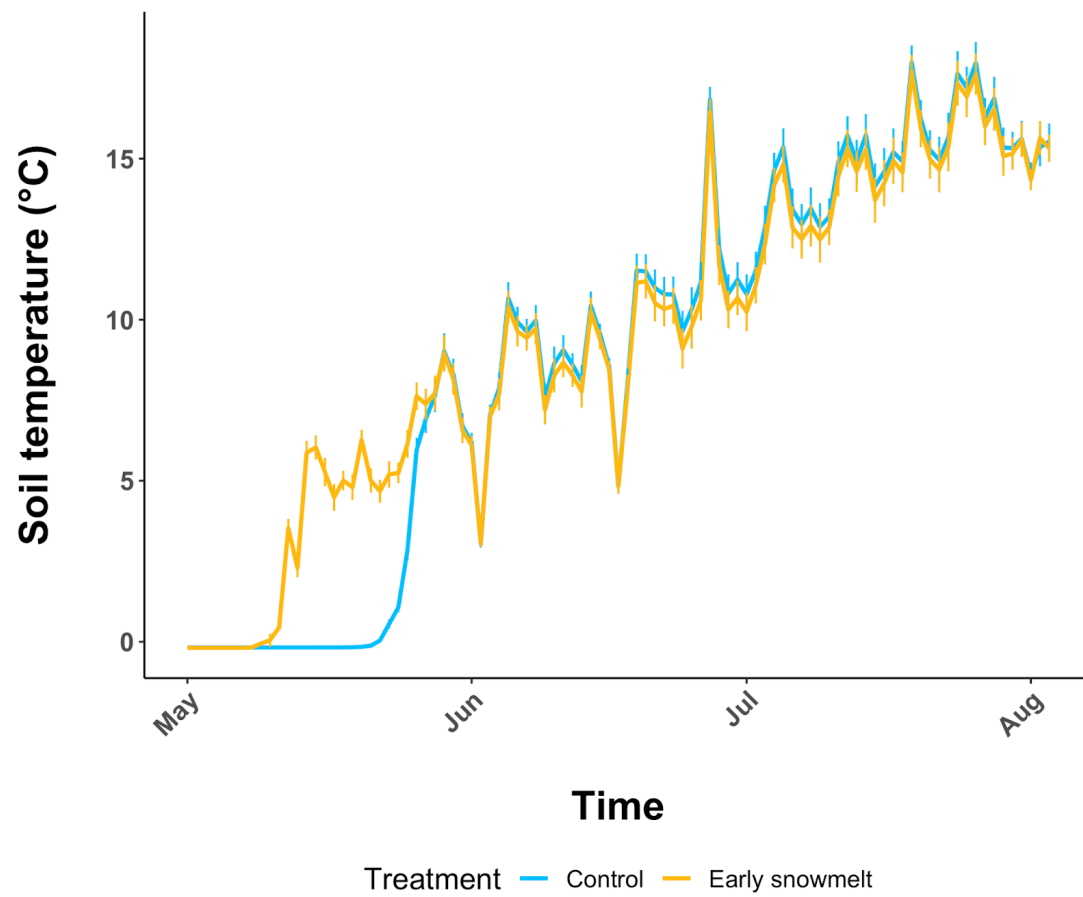
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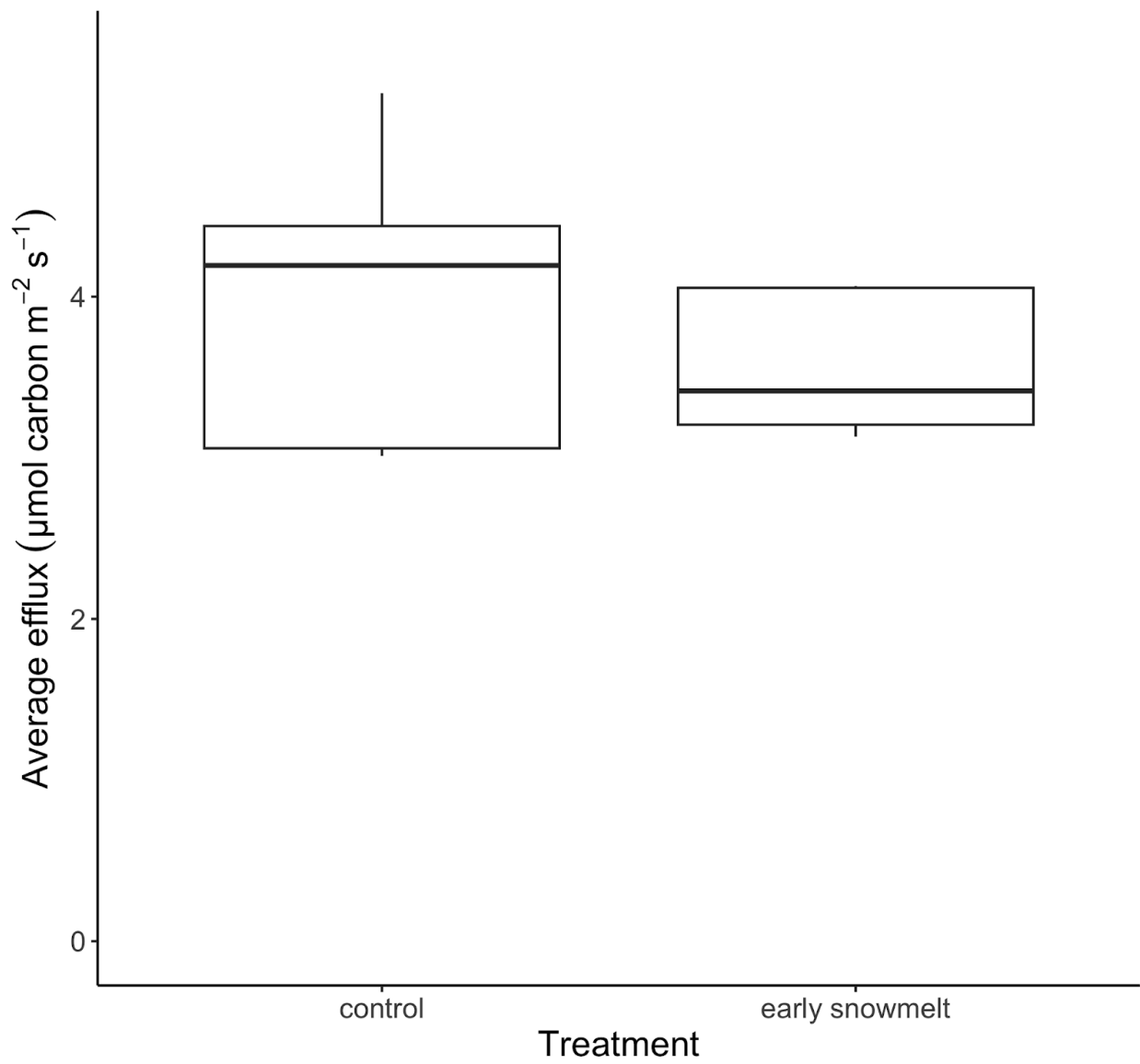
Appendix



S3: Soil moisture (percent volumetric moisture content) over time in snowmelt manipulation experiment



S4: Soil temperature over time in snowmelt manipulation experiment



S5: average efflux vs treatment in snowmelt manipulation plots. I found no significant difference in soil respiration between early snowmelt and control plots ($p=0.404$).