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Effect of Climate Warming on Alpine Soil Decomposition in Western Norway

The Tea Bag Index and soil respiration along an altitudinal gradient

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Abstract

Litter decomposition in soils is a microbial process linked to soil respiration, affected by soil composition as well as environmental factors such as temperature and moisture. For alpine areas in particular, these stand to vary significantly with climate change. To characterize the impacts of these projected changes on the carbon fluxes and carbon cycling in the environment, this study uses turf transplants along an altitudinal gradient in Western Norway. Warming is simulated for alpine and sub-alpine soils. Because the soils differ in composition, this enables the quantification of the influence of soil composition on soil litter decomposition and respiration. Decomposition is quantified using the standard Tea Bag Index (TBI) where the mass loss of buried rooibos and green tea bags over an extended period is used to model the labile and recalcitrant fraction of litter in the soil. Respiration CO_2 fluxes are quantified from concentration measurements in an infrared gas analyzer (IRGA, LI-84A, LI-COR) across a prescribed period and bare soil area.

Results from this study show that simultaneous optimal soil moisture and temperature conditions maximize soil respiration and litter decomposition rates. These optimal ranges are 15-35% for soil moisture and the maximum measured 22 ºC for temperature. However, the impacts of the conditions individually are more complex: soil moisture is positively correlated with soil respiration, while the correlation with temperature is inconclusive. Decomposition rates and stabilization factors for the Liahovden, the alpine site, consistently exceed those for Joasete, the sub-alpine site, which contains less soil organic matter (SOM) and carbon. With warming, Joasete exhibits opposing behavior to that of Liahovden: reduced decomposition rates and litter stabilization. These findings suggest that the availability of nutrients due to soil moisture and the soil composition itself are the most important factors determining the carbon emissions and cycling in the soil. Nevertheless, under coupled optimal conditions (warmer climate with soil moisture at approximately 35%), there is a clear maximum in flux. The complexity of the interrelations of soil moisture and temperature for different soil types supports further research on the topic, with more replicates and soil moisture content variation plot by plot.

Preface

This additional thesis sprung out of my work as field intern with the Between the Fjords research group at the University of Bergen during the summer season of 2021. Having returned to the Netherlands with my mind still on the Nordic alpine grasslands, I embarked on this project which has affirmed my appreciation for soils and their complex behavior. In the past couple of months, I have learned so much not only in terms of concrete R and Python programming skills, but also about managing uncertainty, applying scientific thinking and the process of researching our interests, from start to finish.

I would like to thank Joseph for his eager collaboration and support on the project (and in supporting my beginner's learning in R), and thanks are due to Aud for her guidance and her inspiring standards of organization. I'm grateful to the THREE-D project on a whole for sharing cleaned data and including me in the broader research going on in the group. Last but not least, thanks to Bas for his enthusiasm, thoughtful questions and advice, making himself readily available to guide me along the way.

Much of this additional thesis has been written from Vancouver, Canada, so it goes without saying that I have appreciated the sound of rainfall accompanying my work, as well as breaks taken while walking in the forest with my family.

Emma Little
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1 Introduction

The decomposition of soil organic matter (SOM) and litter plays a vital role in carbon and nutrient cycling, with its rate generally understood to increase with temperature. It is a major driver of global carbon emissions and enables soil respiration. This process currently accounts for approximately 90 PgC per year—over nine times the annual contribution from fossil fuel combustion worldwide (Tiwari et al., 2021)(Quéré et al., 2018). With climate change, cold biomes stand to experience more extreme climate variability. As such, developing an understanding of the impact of warming on soil carbon stocks is crucial to assess the potential risk of positive feedbacks in CO_2 emissions or even possible buffering capabilities (Gavazov, 2010).

Temperature and moisture are two principal abiotic drivers of litter decomposition by soils, alongside pH, nutrient content and vegetation cover (Ivashchenko et al., 2021). Microbial activity is said to be reduced below 10 ºC or above 35 ºC, and soil dryness as well as oversaturation can threaten diffusion of nutrients and oxygen through the soil matrix. Moisture is purported to be optimal for soil decomposition activity near field capacity, which lies in the range of 15-35% for most soils (*Soil Water Storage Properties - Minnesota Stormwater Manual*, n.d.). Litter decomposition and recalcitrance have been quantified internationally using the so-called Tea Bag Index (TBI) burial experiment (Keuskamp et al., 2013). The TBI is a reference method to construct a decomposition curve from the measured mass loss of green and rooibos tea across a three-month period. It also enables the calculation of the decomposition rate constant k [day^{-1}] and the litter stabilization factor S [-], the latter of which is a good measure of recalcitrance, or carbon accumulation, within the soil (Keuskamp et al., 2013). While many studies have investigated the influence of temperature on SOM or litter decomposition to date, it remains a controversial topic (Moinet et al., 2020). Recently it has been postulated that the temperature sensitivity of SOM decomposition decreases with increased SOM stability, and that an immediate rise in decomposition rates with temperature can be slowed by reduced soil moisture, insufficient snow cover insulation, and shrub cover in the Alpine zone (Quéré et al., 2018)(Gavazov, 2010). Soil respiration and litter decomposition are both microbially-driven processes. Nevertheless, these findings suggest that there may be limitations to the upheld understanding that temperature is the most influential environmental condition on these processes. It could be that soil activity could be driven by more complex coupled interactions. In particular, rather than any one factor alone, Palmer et al. has recognized the need to examine the relationships between soil moisture, temperature and CO_2 flux for varied soil compositions (Palmer et al., 2019).

This study aims to characterize the impact of climate warming on soil decomposition activity along an altitudinal gradient in Western Norway. This will be investigated using the Tea Bag Index (TBI) method and bare soil carbon flux measurements in ambient (control) and warmed transplanted (treatment) turfs. We will compare the control plots with transplant treatments, as the latter effectively mimics the effect of climate change, impacting both temperature and moisture. It is hypothesized that with average soil temperatures ranging between 10-35ºC , with a soil moisture content between 15-35%, and for the most SOM-rich soils, the rate of decomposition will be the highest.

2 Materials and Methods

2.1 Study Area

The altitudinal gradient consists of a semi-natural grassland with calcareous soil in Western Norway, as reported by Halbritter et al. in unpublished project materials (Halbritter et al., 2022). Along this gradient, experiments are run at three locations with climates as described in Table 1.

Table 1: Soil properties per location (Halbritter et al., 2022)

Location	Elevation [m]	Mean Annual Temperature [°C]	Mean Annual Precipitation [mm/yr]
Alpine (Liahovden)	1290	0.68	2660
Sub-Alpine (Joasete)	920	2.36	1787
Boreal (Vikesland)	469	4.39	1871

2.1.1 Treatments

Along the altitudinal gradient, two sites are studied: Liahovden and Joasete. These sites were set up in 2019 with 80 50x50cm plots and 16 bare soil respiration collars. Key soil characteristics for the upper 5 cm layer of these sites are summarized in Table 2, drawn from unpublished results by Halbritter et al, measured in 2019 (Halbritter et al., 2022).

Table 2: Soil characteristics by site

Site	pH [-]	SOM Fraction [-]	C Fraction [-]
Alpine (Liahovden)	5.16 ± 0.05	0.62 ± 0.06	0.276 ± 0.032
Sub-Alpine (Joasete)	4.50 ± 0.11	0.27 ± 0.05	0.129 ± 0.009

Warming has been applied as a treatment to the sites by transplanting 40 local turfs including soil and plant communities to lower elevations, as shown in Figure 1, with the mass transplant conducted in 2020. The effect of warming may be assessed by comparing the ambient (control) plots to the warming (transplanted) turfs. This study took part within the THREE-D project, in which plots were also subject to nitrogen deposition and grazing. Nitrogen deposition has been simulated by the addition of the pelletized fertilizer (YaraBela OPTI-NS 27-0-0 (4S) with varied loadings: 0, 0.5, 1, 5, 10, 50, 100, 150 kg N ha^{-1} yr^{-1}, and grazing by periodic clippings of vegetation manually with scissors (Halbritter et al., 2022) For the context of this study, when assessing soil respiration, the only treatment investigated is warming as the soil respiration collars are free of vegetation and assumed not to be nitrogen-limited.

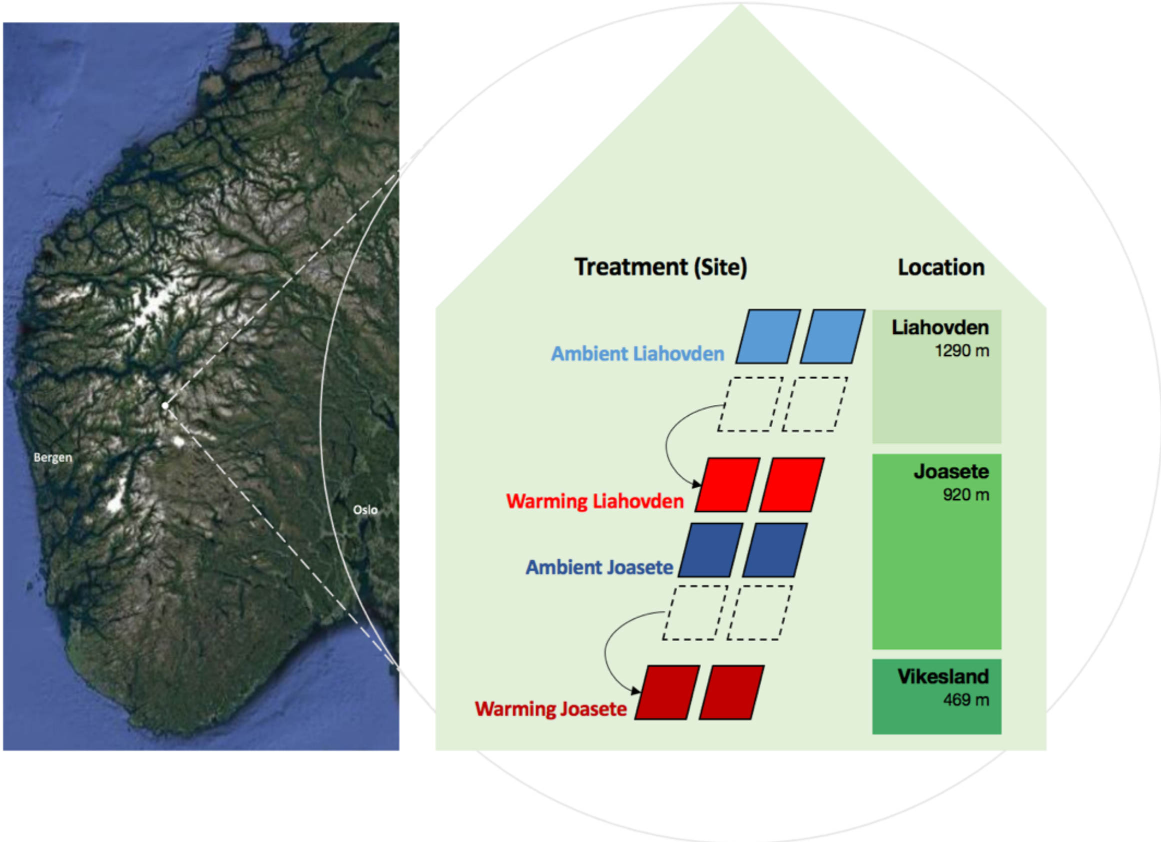

Figure 1: Location of study area (left); and definition of treatment, site and location along the altitudinal gradient (right)

2.2 Tea Bag Index Decomposition

The Tea Bag Index is a standardized reference method used to quantify soil decomposition rates and carbon cycling, developed Keuskamp et al. (Keuskamp et al., 2013). In the time since its conception, it has been applied internationally in citizen science and academic research projects, using readily accessible and inexpensive Lipton tea as a standard litter. The mass loss of green tea (*Camellia sinensis*, EAN: 87 22700 05552 5) and rooibos tea (*Aspalathus linearis*, EAN: 87 22700 18843 8) across a defined decomposition period is enables the calculation of two decomposition parameters which may be used to fit a two-phased decay curve (Keuskamp et al., 2013). In the calculation of the decay curve, green tea is used to estimate the readily degrading labile fraction of litter in the soil and rooibos the slowly degrading recalcitrant fraction.

In this study, the individual green and rooibos tea bags were weighed, then implanted in all 80 plots at an 8 cm depth pending available soil, and were incubated over 3-4 months (June - September 2021). The tea bag recovery took place in two field campaigns, so one cohort of tea bags experienced 94-97 days of decomposition, while another experienced 112-119 days. At the end of the decomposition period, the unearthed teabags were dried and weighed according to the protocol from the Tea Bag Index project, and the decomposition was measured using the mass loss across the incubation period (*Stepwise Protocol – Teatime4Science*, n.d.). The protocol differed only in the drying process, in which Keuskamp recommends conditions of max. 70 °C for 48 hours—in this case the tea bags were kept at 65 °C for only 24 hours.

For consistency, out of the total 80 plots, this study analyzes only the tea bag results from the 16 plots equipped with soil collars. These plots, each with one green and one rooibos tea bag buried, correspond to the plots in which soil respiration was measured.

2.3 Respiration

The soil respiration fluxes were measured using a closed loop chamber system, installed on a bare soil collars in the plots (see left, Figure 2). In this system, the air-tight plastic chambers were connected to an infrared gas analyser (IRGA, LI-84A, LI-COR) throughout a 3-minute measurement period, in which CO_2 concentration was measured in parts per million (ppm) every second. As the chambers were airtight, the slope of the measured CO_2 concentration against time can be used to calculate the CO_2 flux from the soil.

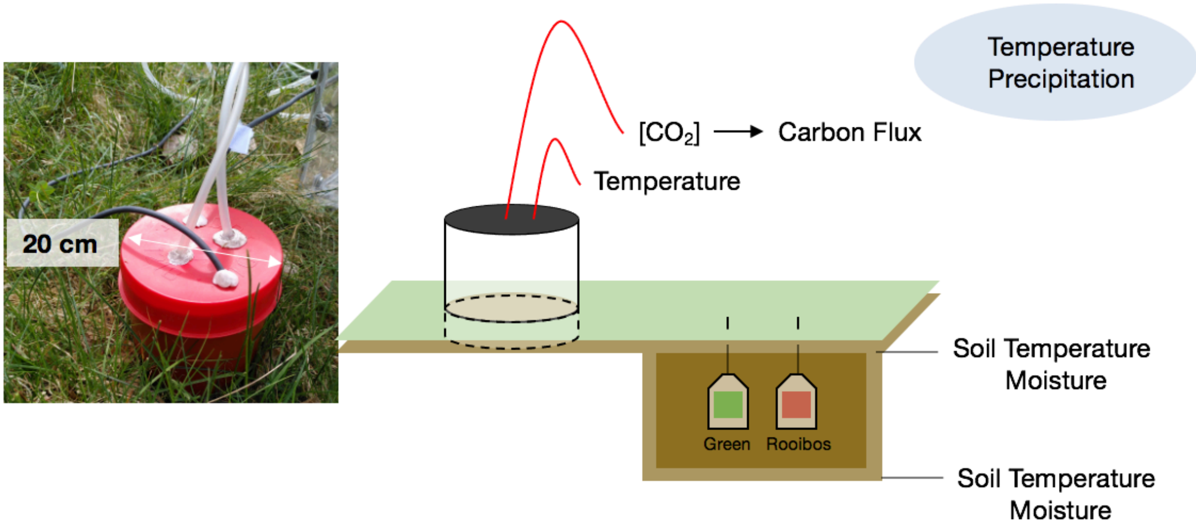

Figure 2: Experimental setup for soil decomposition, summarizing key parameters measured. Soil collar visualized on the left (photo credit: Joseph Gaudard).

The chambers were installed in November 2020, adjacent to the decomposition experiments as shown in Figure 2 (right), extending approximately 13 cm above the surface. The soil bounded by the chambers was kept bare through periodic vegetation clearings that took place during field campaigns. Across the entire decomposition period, four field campaigns took place.

2.4 Environmental Conditions

Temperature was measured continuously (15 minute intervals) at 15 cm elevation, at the surface and 5 cm below the surface. Soil moisture was measured within the top 5 cm layer using a Delta-T Devices (Cambridge, England), SM300 Moisture Sensor by taking four dispersed replicate measurements per plot during each field campaign. In tandem with the CO_2 measurements, soil and air temperature within the chambers were logged every 10 seconds.

2.5 Calculations

2.5.1 Decomposition

Litter decomposition is understood to follow an exponential decay function that we will use here. Considering both the decomposition of labile and recalcitrant material, this may be expressed through the following equation for the remaining mass fraction of tea at a point in time t (W(t), unitless) (Keuskamp et al., 2013).

$$W(t) = a_i e^{-k_1 t} + (1 - a_i) e^{-k_2 t} \qquad 1$$

In this equation, a_i represents the readily decomposable (labile) fraction of litter. k_1 [day^{-1}] represents the decomposition rate constant of this labile fraction and k_2 [day^{-1}] the decomposition rate constant of the recalcitrant fraction of litter. In the early stages of decomposition the labile fraction decays rapidly.

On a very long timescale, following the decay of the labile fraction, litter mass loss is determined by k_2. The timescale experienced in the TBI decomposition experiments is sufficiently short that we can assume that the decomposition of the recalcitrant fraction is negligible, so $e^{-k_2 t}$ simplifies to 1.

The final expression for litter decomposition is shown in Equation 2, in which a_i refers to the readily decomposable fraction of the teas (a_r: rooibos, a_g: green). The litter decomposition rate for both types of tea is k, which is estimated from the total mass loss of the slow-degrading rooibos tea across the burial experiment.

$$W(t) = a_i e^{-kt} + (1 - a_i) \tag{2}$$

In order to estimate the readily decomposable fraction of rooibos tea (a_r), the stabilization factor S must be calculated at a late stage in decomposition. S provides an indication of the carbon accumulation in the soil and depends upon environmental conditions (Berg & Meentemeyer, 2002). Therefore it is assumed to be consistent across tea varieties, an assumption which has been supported by research findings (Keuskamp et al., 2013). With faster decomposition, green tea is used to calculate S according to Equation 3, equivalent to the difference between the chemically hydrolysable fraction and the actual degraded fraction of green tea (a_g). S therefore represents the stable, recalcitrant portion of degradable material in the soil.

$$S = 1 - \frac{a_g}{H_g} \tag{3}$$

With the stabilization factor calculated, the readily decomposable fraction of rooibos tea is determined according to Equation 4 so it may be entered into the main decay equation (2). The values used for H_g and H_r, the chemically hydrolyzeable fractions of tea, are 0.842 and 0.552, respectively (Keuskamp et al., 2013).

$$a_r = H_r (1 - S) \tag{4}$$

2.5.2 Respiration

Soil respiration may be represented accurately by measuring the CO_2 emissions from soil (Hanson et al., 2003). This provides a measure of the response of soil biological activity to varying environmental conditions, which may be compared to the results of the TBI burial experiment. Soil respiration provides a more detailed insight into the dynamics of the soil activity across the summer season, as it relies upon measurements from four field campaigns rather than one mass loss measurement like in the TBI.

The equation for CO_2 flux across the soil surface is determined from the mass-balance derived change in concentration in the chamber over time (Kroon & Hensen, n.d.). This expression is shown in Equation 5. V_T refers to the total volume of the chamber and the connecting tubes (in m^3), and A is the surface area of soil bounded by the chamber in m^2. Flux is typically measured in this application in $mmol/m^2/h$. Detailed dimensions and the full dataset may be accessed by running the Python script in the GitHub repository linked in Supplementary Information.

$$F_{CO_2} = \frac{dc_{CO_2}}{dt} \frac{V_T}{A} \tag{5}$$

The dc_{CO2}/dt term (in mmol $CO_2/m^3/h$) is calculated from the linear slope of the CO_2 concentration over time (m, in ppm/s) which is estimated by the best fit of gas analyzer measurements over the measurement period. In this best fit, the first and last 30 seconds of measurements are removed from the field data where outliers and inconsistency typically arise.

In order to use m to calculate dc_{CO2}/dt we must recognize that the slope in ppm/s is equivalent to the volume ratio of CO_2 to total gas in the chamber-tubing system. The molar concentration of total gas in the chamber (c_{gas}, in μmol/L) may be calculated by the ideal gas law, as shown in Equation 6.

P refers to the atmospheric pressure in atm, V to the volume of the above-ground portion of the soil collar plus the tubing inner volume (m^3), R is the gas constant (8.21 m^3 atm μmol^{-1} K^{-1}) and T the ambient temperature (K) in the flux chamber during measurement. The pressure is assumed to be in equilibrium with the atmosphere, at 1 atm.

$$c_{gas,\,T}=\frac{n_{gas,T}}{V_T}=\frac{PV_T}{RT}\cdot\frac{1}{V_T}=\frac{P}{RT} \qquad 6$$

Assuming that the change in CO_2 concentration is sufficiently low relative to the gas in the chamber-tubing system, dc_{CO2}/dt is estimated by the product of the slope m multiplied by the total gas concentration (in mmol/L). This is shown in Equation 7, in which the last term is a unit adjustment to make dc_{CO2}/dt suitable for the final flux expression in the units mmol/m^2/h (Equation 8).

$$\frac{dc_{CO_2}}{dt}=m\cdot c_{gas,T}=m\cdot\frac{P}{RT}\cdot\left(\frac{3600\ s/h}{1000\ \mu mol/mmol}\right) \qquad 7$$

$$F=m\cdot\frac{PV_T}{RT\cdot A} \qquad 8$$

Respiration (CO_2 flux) was compared directly to temperature by plotting. In order to compare the respiration to site-averaged soil moisture, the ambient and warmed fluxes were fixed for temperature, using soil temperature fixed at 15ºC. Likewise, to compare the flux to temperature, the fluxes were fixed at a soil moisture content of 30%. Further detail on the temperature and moisture correction applied may be found in the GitHub repository in Supplementary Information.

2.5.3 Statistics

Relationships between measured environmental conditions, decomposition parameters and respiration were evaluated using Pearson correlation coefficients (r), which assumes a linear correlation. By this metric, positive values of r demonstrate positive correlation, with a stronger association the closer r is to 1. Negative values of r demonstrate negative correlation with increasing strength approaching -1. Within the range near 0 the correlation is weak or non-existent. In order to compare the measurements and calculated parameters, average soil temperature across the summer period was paired with the plots by destination site. A similar strategy was used for average soil moisture, albeit using discrete measurements across the four summer campaigns. In the case of soil respiration, the average carbon flux across the four summer campaigns were averaged by treatment. The decomposition parameters k and S were paired with the respiration measurements by plot ID.

3 Results

3.1 Tea Bag Decomposition

Based on the single-measurement bulk mass loss measured across the field season, the TBI exponential decay fit for litter decomposition (Equation 2) is shown in Figure 3 for rooibos and green tea. A logarithmic plot could alternatively be made to estimate constants in this exponential relation. As expected in the TBI method, from the measured mass loss of green tea we see that it is faster to degrade.

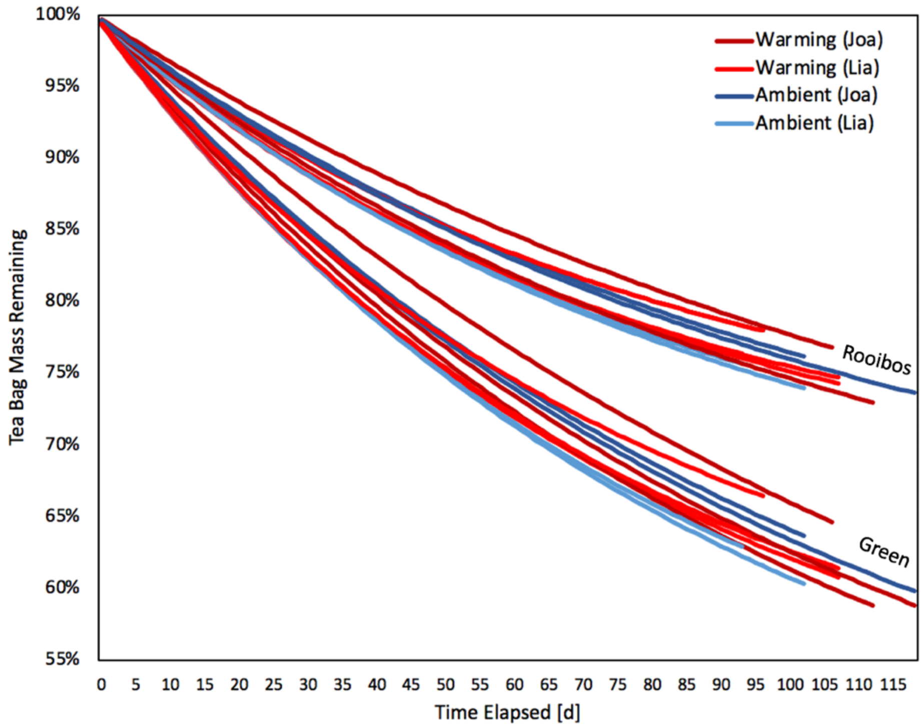

Figure 3: Relative tea bag decomposition over time according to the TBI decay fit

The link between the decomposition rate and the stabilization factor is visualized in Figure 4.

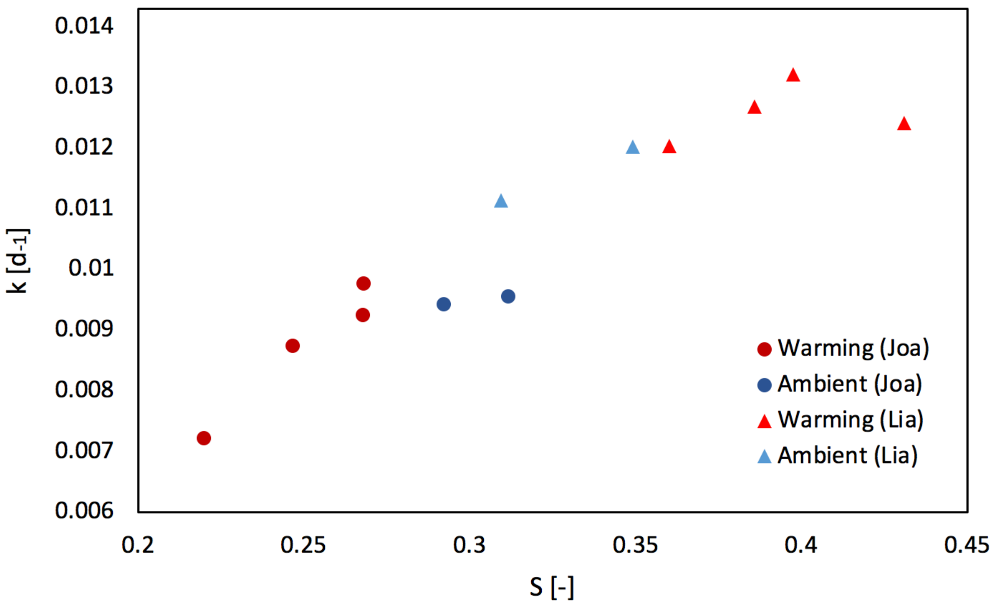

Figure 4: Comparison between data inferred decomposition rate k [d^{-1}] and stabilization factor S along the altitudinal gradient, as calculated through the TBI

3.2 Soil Respiration

The soil respiration as measured during the four field campaigns are shown in Figure 5. The expected increase in flux with warming is adhered to in campaigns 2 and 3, during the mid-summer period.

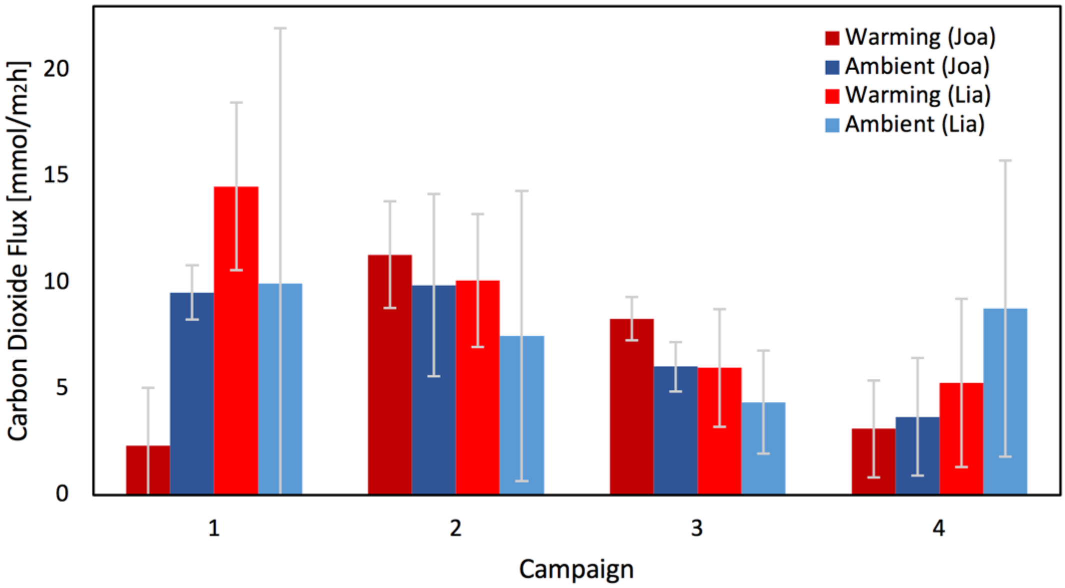

Figure 5: Soil respiration by treatment and site across the summer season

The effect of temperature and moisture on soil respiration is compared in Figure 7, in which CO_2 flux refers to the raw flux (not fixed for temperature or moisture) as calculated from the bare soil measurements.

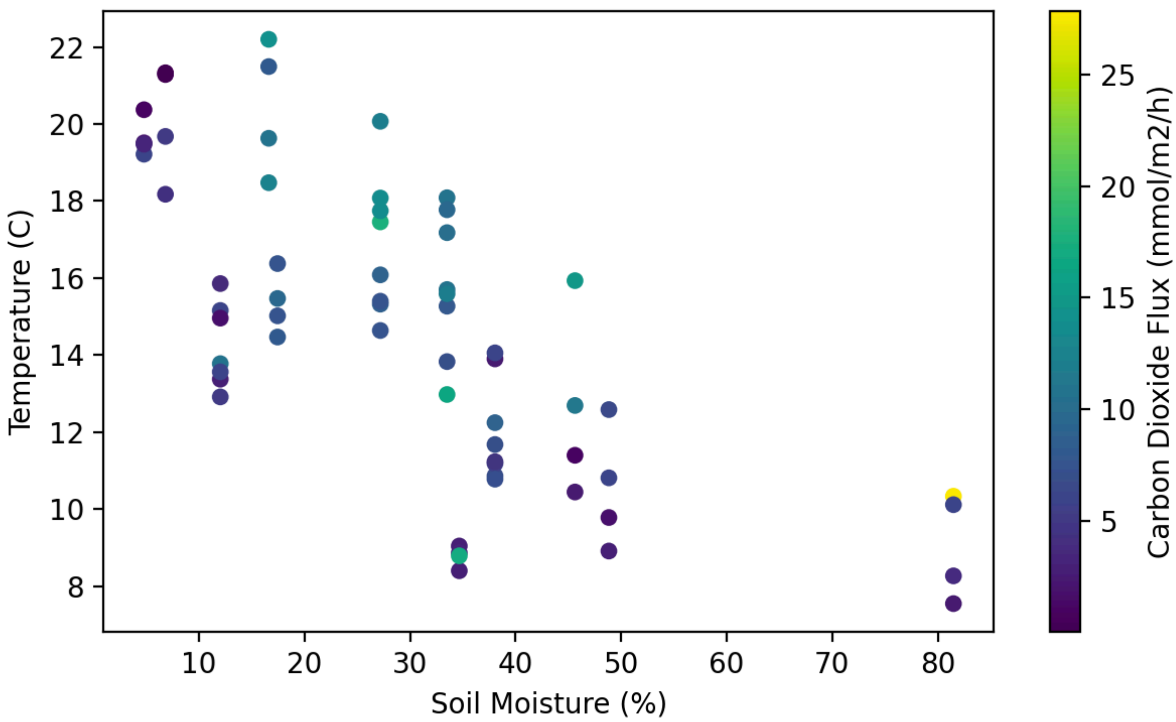

Figure 6: Respiration (CO_2 flux) variation with soil moisture and temperature

Figure 7 shows the calculated fluxes fixed for temperature at 15 °C (top) and for moisture at 30% (bottom). The fluxes are organized by site, which differ in soil composition, with Joasete on the left and Liahovden on the right. In this figure, matching plots are paired by their ambient or warming treatments, with the linear slope calculated to quantify the strength of the respiration response to the specific environmental condition for which it is fixed. This method is used to investigate the effect of temperature and moisture individually. The impact of the time of year may also be inferred, as the campaigns across the summer season are identified (1, 2, 3, 4). The measurements from campaign 1 on Liahovden appears to be an outlier subjected to snowmelt dynamics, with near-saturated soil and a high flux. As it relates to moisture, we see the existence of an optimal window for respiration: most of the slopes stabilize near zero when around the defined range (15-35%). If they cross the boundary of the range, we see the highest respiration rates take place within the range, regardless of ambient or warmed. On average we see a positive respiration response demonstrated by positive ambient-warmed slopes for soil moisture on both sites across the summer season. Late in the summer (in campaigns 3 and 4) this response is stronger. For temperature, Joasete experiences an average positive respiration response across the summer season, while Liahovden negative. The response is more strongly positive in the late season but still remains uncharacteristically mostly negative on Liahovden.

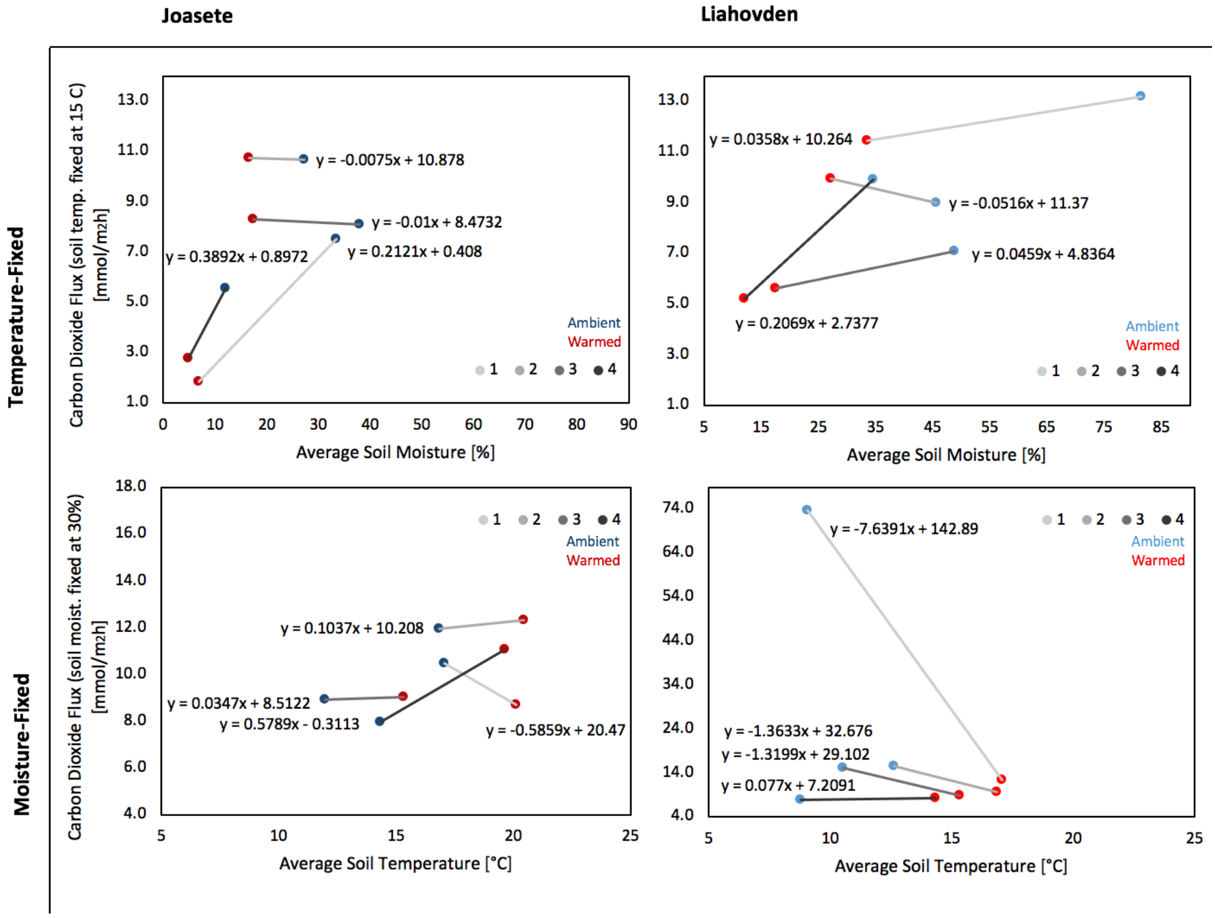

Figure 7: Soil respiration for ambient-warmed treatments across the four campaigns. Sub-alpine Joasete (left); Alpine Liahovden (right).

3.3 Statistical Analyses

The correlation coefficients for the respiration by treatment (site) are shown in Table 3. The warming sub-alpine site and the ambient alpine site plots have an uncharacteristic negative correlation with temperature. Furthermore, the negative correlation is contradictory, as for one site it is present for the warming treatment and for the other the ambient. Moisture is found to be positively correlated on all sites, nearly perfectly so for the warmed treatment of Joasete. These findings suggest that while complex interrelations are likely present as the correlations are only moderate, the link between increases in moisture and soil respiration is more statistically significant than for temperature and soil respiration.

Table 3: Correlation coefficient (r) for soil respiration and environmental factors, divided by site.

Site	Treatment	Temperature r [-]	Moisture r [-]
Joasete	Warming	-0.21	0.92
	Ambient	0.73	0.55
Liahovden	Warming	0.82	0.40
	Ambient	-0.45	0.41

The correlation coefficients for the TBI decomposition constants are shown in Table 4. Temperature is negatively correlated for both k and S which would infer that they are inversely related—an uncharacteristic finding as the rate of decomposition should increase with temperature according to the law of Arrhenius. For moisture k and S are moderately positively correlated which does not provide information on the existence of an optimal window, meaning instead that there is a medium correlation between increases in moisture and decomposition rates. Respiration is near perfectly correlated with k and S which supports the experimental design in using the TBI burial experiment as a reference measurement for respiration.

Table 4: Correlation coefficient (r) for decomposition, environmental factors and soil respiration

Parameters	Temperature r [-]	Moisture r [-]	Respiration r [-]
k	-0.60	0.57	0.90
S	-0.53	0.48	0.94

4 Discussion

The utilization of the Tea Bag Index to link the decomposition rate and the stabilization factor, as plotted in Figure 4, provides valuable insight into the soil activity along the altitudinal gradient. For Liahovden, the alpine site, warming induces increased decomposition rates as well as increased litter stabilization (carbon accumulation within the soil). For Joasete, the sub-alpine site, however, warming leads to lower decomposition rates and lower litter stabilization for the most part as well. These results indicate the existence of an optimal window for decomposition in terms of both environmental conditions and soil properties. Especially, the importance of the SOM and/or carbon content in the soil may be inferred from this figure. Liahovden (ambient and warming treatments) demonstrates consistently higher decomposition rates than Joasete although it experiences approximately 2 ºC lower temperatures on average. Soil from the alpine site has a significantly higher fraction of SOM and carbon (see Table 1), likely driven by the prolonged frost and more frequent freeze-thaw cycles relative to the sub-alpine site, enhancing both carbon storage and solubility (Song et al., 2017). Furthermore, the thinner total soil layer at Liahovden is likely to promote interactions with the calcareous ($CaCO_3$-rich) bedrock, driving the increased pH at this site. On a whole, the results in the k-S plot show better litter decomposition in Liahovden than Joasete. Here, warming does not universally increase soil decomposition, which is contrary to the findings of Azizi-Rad in a recent study (Azizi-Rad et al., 2022).

The respiration measurements across the campaigns in Figure 5 suggest that the most active period for soil microbial activity is early to mid-summer, likely due to the increase in temperatures paired with increased soil moisture. Campaign 4 experienced the lowest average moisture, while 3 experienced lowest temperatures on average. Furthermore, the figure shows that the absolute range in respiration is broader for warmed (transplanted) plots than for ambient plots. However, with the assumption that the soils are not nitrogen-limited, these findings remain based on just four replicate measurements, for which soil moisture can vary significantly across the site. In particular, the observational spread in the data for ambient Liahovden and atypical ambient-warmed respiration behavior (with a strong negative A-W slope) is likely due to the extended period of snowmelt and freeze-thaw cycles saturating some regions of the soil.

The soil respiration results presented in Figure 6 are in support of the hypothesis. CO_2 flux appears to be maximized when both soil moisture is around 30% and when soil temperatures are highest (around 22 ºC). For flux fixed with individual environmental effects, the highest average soil respiration occurs within the whole 15-35% soil moisture range, and the dynamics for temperature are not so clear. Warming Joasete induces, on average, increased respiration rates, with positive-slopes for ambient-warming treatments as shown in Figure 7. Alpine warmed plots have on average positive ambient-warmed slopes that exceed the sub-alpine average slopes, suggesting that the sensitivity to climate warming is stronger for more carbon-rich soils. The alpine site experiences higher overall fluxes as well, consistent with the findings of the TBI analysis. Upon fixing flux for soil moisture, the ambient alpine plots are associated with much higher respiration rates than warmed plots. This contrasts the results for raw flux which show increased flux with increased temperature.

These contrasting findings could be due to soil moisture discrepancies across the site as the average soil moisture used has significant standard deviations (up to ±23%). This indicates limitation of using of site-averaged moisture, as intra-site variability is large. In this instance, the site-wide average was necessary due to the positioning of the bare soil flux chambers being either adjacent or in separate areas from the plots to which they are labelled.

5 Conclusion

Results from this study show that simultaneous optimal soil moisture and temperature conditions maximize soil respiration and litter decomposition rates. These environmental conditions correspond to a warmer climate in which there is sufficient (but not too much) moisture, with approximately 30% saturated open pore space—a balance that is unlikely to be consistently maintained in a warming climate. Global average temperatures will increase by 1.5 °C or more in the near-term with 50% likelihood, even under low-emissions scenarios (Pörtner et al., 2022). In terms of precipitation, more extreme rainfall events are expected, and the frequency and duration of drought periods are predicted to increase. According to the findings of this study, the resultant impacts upon soil activity and CO_2 emissions are difficult to predict. Extreme moisture conditions, either very wet or dry, may cause uncharacteristic behaviour. Nevertheless, in general the activity of the soil appears to be reduced beyond the identified optimal moisture window, which is a promising conclusion regarding the future contribution of soils to global greenhouse gas emissions.

In terms of individual environmental conditions, soil moisture appears to be the most influential, governing nutrient transport and gas diffusion through the soil. Temperature alone does not seem to influence CO_2 flux with a discernible trend, and in the instances where just one or neither of the conditions is optimal, SOM and carbon content have a distinguishable impact, in which higher carbon and organic matter appear to drive higher fluxes. The complexity of the interrelations analyzed here should be subject to further research by studying moisture plot by plot and adding more replicates to solidify these findings. In particular, the influence of SOM and carbon content variation should be further investigated to decouple the relationship between these two factors and soil respiration in a warming climate.

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7 Supplementary Information (SI)

Detailed Python scripts may be found on Emma Little's GitHub repository (see link below), originally forked from Joseph Gaudard (forked from Aud Halbritter).

https://github.com/solomelittle/Three-D/tree/soilrespiration2021/Python

Data cleaning and processing was all done in Python, as well as the plotting of Figure 6. The plotting of Figures 3,4,5 and 7 were done in Excel.