ERDC/CRREL TR-23-18

Cold Regions Research and Engineering Laboratory

U.S. ARMY

US Army Corps of Engineers®

ERDC

Defense Resiliency Platform Against Extreme Cold Weather

Challenges and Limitations of Using Autonomous Instrumentation for Measuring In Situ Soil Respiration in a Subarctic Boreal Forest in Alaska, USA

Dragos A. Vas, Elizabeth J. Corriveau, Lindsay W. Gaimaro, and Robyn A. Barbato

December 2023

Distribution Statement A. Approved for public release: distribution is unlimited.

Defense Resiliency Platform Against Extreme
Cold Weather

ERDC/CRREL TR-23-18
November 2023

Challenges and Limitations of Using Autonomous Instrumentation for Measuring In Situ Soil Respiration in a Subarctic Boreal Forest in Alaska, USA

Dragos A. Vas, Elizabeth J. Corriveau, Lindsay W. Gaimaro, and Robyn A. Barbato

US Army Engineer Research and Development Center (ERDC)
Cold Regions Research and Engineering Laboratory (CRREL)
72 Lyme Road
Hanover, NH 03755-1290

Final Report

Distribution Statement A. Approved for public release: distribution is unlimited.

Prepared for Headquarters, US Army Corps of Engineers
Washington, DC 20314-1000

Under Program Element 0602144A, Project Number BN8

Abstract

Subarctic and Arctic environments are sensitive to warming temperatures due to climate change. As soils warm, soil microorganisms break down carbon and release greenhouse gases such as methane (CH_4) and carbon dioxide (CO_2). Recent studies examining CO_2 efflux note heterogeneity of microbial activity across the landscape. To better understand carbon dynamics, our team developed a predictive model, Dynamic Representation of Terrestrial Soil Predictions of Organisms' Response to the Environment (DRTSPORE), to estimate CO_2 efflux based on soil temperature and moisture estimates. The goal of this work was to acquire respiration rates from a boreal forest located near the town of Fairbanks, Alaska, and to provide in situ measurements for the future validation effort of the DRTSPORE model estimates of CO_2 efflux in cold climates. Results show that soil temperature and seasonal soil thaw depth had the greatest impact on soil respiration. However, the instrumentation deployed significantly altered the soil temperature, moisture, and seasonal thaw depth at the survey site and very likely the soil respiration rates. These findings are important to better understand the challenges and limitations associated with the in situ data collection used for carbon efflux modeling and for estimating soil microbial activity in cold environments.

Contents

Figures and Tables

Figures

Tables

Preface

This study was conducted for the US Army Corps of Engineers (USACE) under Program Element 0602144A, Project Number BN8. The technical monitor was Dr. Robert E. Davis, US Army Engineer Research and Development Center–Cold Regions Research and Engineering Laboratory (ERDC-CRREL).

The work was performed by the Terrestrial and Cryospheric Science Branch and the Biogeochemical Sciences Branch of the Research and Engineering Division, ERDC-CRREL. At the time of publication, Dr. John W. Weatherly and Mr. Nathan J. Lamie were branch chiefs, respectively; and Dr. John W. Weatherly was acting division chief. The deputy director of ERDC-CRREL was Dr. Ivan P. Beckman, and the director was Dr. Joseph L. Corriveau.

COL Christian Patterson was commander of ERDC, and Dr. David W. Pittman was the director.

1 Introduction

1.1 Background

Soil respiration is a critical process that occurs in all terrestrial ecosystems, and it plays a crucial role in the global carbon cycle. CO_2* is released from the soil into the atmosphere through microbial decomposition of organic matter. Several previous studies have shown that soil temperature and moisture affect soil microbial activity as measured through respiration (Wildung et al. 1975; Curiel et al. 2007; Moyano et al. 2013; Streit et al. 2014). Wang et al. (2010) found that soil moisture level can be a limiting factor in soil biogeochemical processes because low soil moisture levels can limit the diffusion of soluble nutrients (Manzoni et al., 2012). Conversely, saturated soil conditions can constrain oxygen availability (Kechavarzi et al., 2010), also limiting heterotrophic respiration rates.

The subarctic and Arctic regions are especially vulnerable to increased temperatures and is experiencing dramatic changes such as accelerated permafrost thaw, melting of ice features, and shifts in timing and accumulation of precipitation. Mean annual temperature is expected to reach a 5°C increase by 2100 in these regions (Lader et al. 2017), while a median global warming of 2.8°C is expected (IPCC 2023) highlighting the amplified warming of polar regions (Serreze et al. 2006). More than one third of the global carbon reserve is stored in northern peatlands (Gorham 1991) and when accounting for the 1,035 ± 150 Pg carbon stored in permafrost, the global soil carbon pool is increased by 50% (Schuur et al. 2015). Compared to temperate soils, high-latitude soil carbon stocks are especially vulnerable to a warming climate (Karhu et al. 2014). As the climate warms, this carbon stored in permafrost will become bioavailable creating a positive feedback loop where higher soil activity results in more warming, releasing even more carbon (Schuur et al. 2015; Guimond et al. 2021).

Long-term automated soil respirometer systems have proven to be an effective tool for quantifying in situ soil respiration, as they allow

---

* For a full list of the spelled-out forms of the chemical elements used in this document, please refer to *US Government Publishing Office Style Manual*, 31st ed. (Washington, DC: US Government Publishing Office, 2016), 265, https://www.govinfo.gov/content/pkg/GPO-STYLEMANUAL-2016/pdf/GPO-STYLEMANUAL-2016.pdf.

continuous, high-frequency measurements of CO_2 fluxes from the soil surface. Many studies have used automated respirometer systems of different makes and designs to successfully measure soil respiration under different environmental conditions (Suh et al. 2006), such as agricultural fields in eastern Italy (Delle Vedove et al. 2007), temperate oak forest in South Korea (Joo et al. 2012), and in a coniferous temperate forest in central Japan (Makita et al. 2018). Soil respiration consist of heterotrophic and autotrophic respiration. Heterotrophic respiration only encompasses the microbial decomposition of the soil organic matter, while autotrophic respiration comprises emissions from living roots and fungi (Epron 2010) and requires light to occur, a limiting factor in the arctic. The methods for measuring respiration using long-term automated respirometer system vary according to which component of the respiration, autotrophic, heterotrophic, or total, is being investigated.

Soil respiration can be measured using chamber or micrometeorological methods and the method depends on nature of observation required (Wagner-Riddle et al. 2006). Micrometeorological methods work well for long-term, continuous flux measurements and do not interfere with gas exchange processes, while chamber methods typically only cover small areas and can disturb the local environment (Wagner-Riddle et al. 2006). Two common micrometeorological methods are eddy covariance and the mass balance method. Eddy covariance towers observe the carbon exchange between ecosystem and atmosphere and measure the turbulent transport process between them (Liang and Wang 2020). They can directly measure the carbon flux in plant communities and the atmosphere, but use of these towers is limited by the hardware requirements. The mass balance method calculates flux from an area by calculating the difference in surface flux integrated over height between upwind and downwind positions (Wagner-Riddle et al. 2006). This method also can be difficult to deploy due to hardware constraints, often requiring multiple towers. Chamber-based methods can be easier to deploy in the field and work well for shorter-term studies (months and years versus the sometimes decades of the micrometeorological methods). The chamber methods involve either removing vegetation and installing soil collars to measure heterotrophic respiration using gas analyzers, or having static chambers sit on top of the vegetation and measuring both heterotrophic and autotrophic respiration. Common chamber-based methods use LI-COR technology (Elberling and Brandt 2003; Treat et al.

2007) and Picarro technology (Allan et al. 2014; Kelsey et al. 2016; Waldrop et al. 2021).

This report describes the deployment and the challenges associated with the long-term operation of a soil respirometer system and soil parameters instrumentation deployed in cold climates to measure heterotrophic soil respiration. Moreover, this study also provides a review of the data acquired with this instrumentation. These data will be used in future work to validate the Dynamic Representation of Terrestrial Soil Predictions of Organisms' Response to the Environment (DRTSPORE) estimates of CO_2 efflux in Fairbanks, Alaska. The model is based on empirical data collected from laboratory soil incubation studies using soils collected from various temperate and Arctic locations. Remotely sensed terrain data and weather models serve as inputs to the model to predict soil activity as a geospatial layer on a terrain map (Barbato et al. 2018).

1.2 Objectives

The objectives of this study were to provide in situ long-term measurements of heterotrophic soil respiration, soil temperature, and soil moisture at a site in the Engineer Research Development Center, Cold Regions Research and Engineering Laboratory's (ERDC-CRREL) Permafrost Tunnel Research Facility (PTRF) in Fairbanks, Alaska. The study site is situated in an undisturbed black spruce forest with moss and lichen ground cover overlaying ice-rich permafrost. Specifically, this study aims to achieve the following:

- Provide a method for successfully acquiring long-term in situ soil $C\text{-}CO_2$ efflux measurements in cold climates.
- Assess the effects of soil temperature, volumetric water content, and seasonal thaw depth on $C\text{-}CO_2$ efflux.
- Contribute to the future effort of validating the DRTSPORE model in cold climates by providing in situ soil respiration measurements for comparison with model outputs.

1.3 Approach

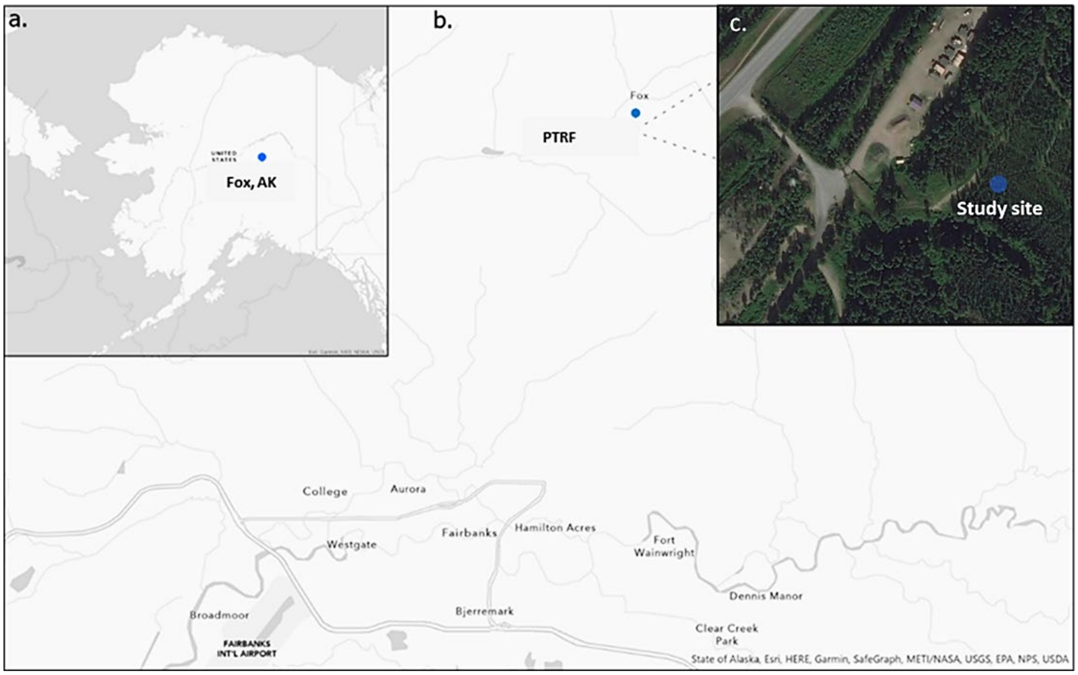
This study used a soil respirometer system, modified for cold climate operation, to collect long-term in situ $C\text{-}CO_2$ efflux (portion of carbon emitted) measurements from a boreal forest site located above the PTRF in Fox, Alaska. Soil temperature and moisture and seasonal thaw depth was measured from 20 May to 19 September 2022. These data will be used in future efforts to validate the DRTSPORE CO_2 efflux predictions for the study area, however; because of the significant impact that the instrumentation had on the local site, caution should be exercised when extrapolating the measurements to larger areas. We highlight the challenges of implementing these instruments in cold regions and conclude with recommendations for future efforts measuring soil respiration at similar sites.

2 Materials and Methods

2.1 Study Site

This study was conducted from August 2021 to September 2022 at a site located at the ERDC-CRREL's PTRF, approximately 13 km north of the town center of Fairbanks, Alaska (Figure 1).* The site is situated in an undisturbed black spruce forest (64.950611°N, 147.619929°W) with moss and lichen ground cover overlaying ice rich permafrost. The climate in this region is continental with a mean annual air temperature of −2.4°C, mean July temperatures of 16°C, and mean January temperature of −21.9°C; yearly extremes range from −51°C to 38°C (Jorgenson et al. 2020). Mean annual precipitation is 30.3 cm with 40%–45% falling as snow (Liston and Hiemstra 2011).

Figure 1. Geographical location of the study site in Fairbanks, Alaska. Map (*a*) of Alaska with a *blue pin* marking the study site. Zoomed-in map (*b*) of Fairbanks with a *blue pin* indicating the study site. Detailed view (*c*) of the study site with a *blue pin* marking the exact location. (Powered by Esri).



---

* For a full list of the spelled-out forms of the units of measure used in this document and their conversions, please refer to *US Government Publishing Office Style Manual*, 31st ed. (Washington, DC: US Government Publishing Office, 2016), 248–52 and 345–47, https://www.govinfo.gov/content/pkg/GPO-STYLEMANUAL-2016/pdf/GPO-STYLEMANUAL-2016.pdf.

2.2 Set-Up of Automated Efflux System for Long-Term Soil Respiration Monitoring

For long-term soil gas flux measurements, an off-the-shelf automated system (LI-COR Inc., Lincoln, Nebraska, USA) composed of four main components was deployed from August 2021 to September 2022; (1) a CO_2/H_2O gas analyzer and system control unit (LI-8100A), (2) a $CH_4/CO_2/H_2O$ trace gas analyzer (LI-7810), (3) a multiplexer (LI-8150), and (4) three opaque long-term chambers (8100-104) (Figure 2). The system employed a closed transient method for soil gas flux measurements and collected data every 30 min for a period of 120 s. For this method, a gas analyzer (e.g., LI-7810) is used to dynamically measure the soil fluxes accumulated within the chamber. During the measurement mode, sample air was drawn from the chamber to the gas analyzer and then sent back to the chamber. The rate increases of CH_4 and CO_2 concentrations was used to estimate soil gas flux.

Figure 2. Field site on 17 February 2022 (*left*). Field site on 2 June 2022 (*right*).

Four plots were identified in the PTRF field site located approximately 3 m apart in a square pattern. At each site, 50 × 50 cm area of vegetation (moss and lichen) and organic-rich soil (peat) was removed using a bread knife cleaned with 70% isopropanol (Figure 3). Vegetation was removed to collect respiration measurements from the mineral soil rather than vegetated soils. In three of the sites, soil collars made from thick-walled, 8 in. SDR 35 PVC pipe with an inside diameter of 21.34 cm and a height of 11.43 cm were inserted into the soil using a rubber mallet (see Figure 3) on 2 August 2021. Soil chambers were installed above the collars and secured with metal pins.

Figure 3. Image of vegetation removed from the chamber location with the soil collar visible (*left*) and chamber installed on the soil collar (*right*).

LI-8100 Automated Soil CO_2 Flux System Software Version 4.0.9 (LI-COR Inc., Lincoln, Nebraska, USA) was used to setup the soil respirometer system. The parameters required by the software to calculate the total system volume for flux calculation are the soil surface area inside the collar (cm^2), chamber offset (the distance between the soil surface and the upper edge of the chamber base plate), and extension tube volume (cm^3). Total system volume for chamber 1 was 5,846.4 cm^3, 6,132.4 cm^3 for chamber 2, and 6,005.3 cm^3 for chamber 3. Fifteen-meter cables connected three chambers to the LI-8150 multiplexer (LI-COR Inc., Lincoln, Nebraska, USA). The multiplexer contains a diaphragm pump that collects sample air from the chambers and distributes it to the sensor at a rate of 1.5 L/min–3 L/min in normal operating conditions.

Power to the instruments was provided by a 30 m long, 120 V, 15 A triple outlet extension cord. The extension cord was plugged into the local electric grid at the PTRF. The AC to DC (alternating to direct current) LI-COR 8150-700 power supply was used to power the LI-8100A and the LI-8150, and the AC to DC universal power adapter (LI-COR Inc., Lincoln, Nebraska, USA) compatible with 100 to 240 volts alternating current (VAC) powered the LI7810.

Data were collected using a laptop and Wi-Fi connection to the LI-8100A throughout the experiment. The data collected from the LI-8100A were .82z files and included all metadata and high-frequency data collected during chamber closure. The soil flux gas data were pre-processed for quality assurance/quality control (QA/QC) using the SoilFluxPro processing software (v5.2.0; LI-COR Inc., Lincoln, Nebraska, USA).

2.3 Measurement of Soil Parameters and Seasonal Thaw

Soil temperature and volumetric water content (VWC) were recorded every 15 minutes, from May 20th to September 23rd, 2022, using Onset HOBO 2x External Temperature Data Loggers (Onset, Bourne, Massachusett, USA) and Onset HOBO USB Micro Station Data Loggers (Onset, Bourne, Massachusett, USA) paired with EC5 Soil Moisture Smart Sensors (Onset, Bourne, Massachusett, USA). The temperature and VWC were measured at two depths (in the organic and mineral horizons) at each of the three 8100-104 long-term chambers (LI-COR Inc., Lincoln, Nebraska, USA) and at a site where the vegetation was left intact (vegetated site [VS] 1) (as shown in Table 1). VS1 site was located approximately 3 meters from the chamber 2 and 3 plots. Average temperature and moisture sensor depth was 19 cm at the organic and 31 cm at the mineral horizon.

Table 1. Long-term chambers and control sites soil temperature and volumetric water content (VWC) sensor placement.

Chamber	Vegetation (moss and lichen) Thickness (above surface soil) (cm)	Organic soil temperature and VWC sensor depth (cm)	Mineral soil temperature and VWC sensor depth (cm)
Chamber 1	12†	15	29
Chamber 2	20†	25	35
Chamber 3	15†	14	23
VS1	18	22	36

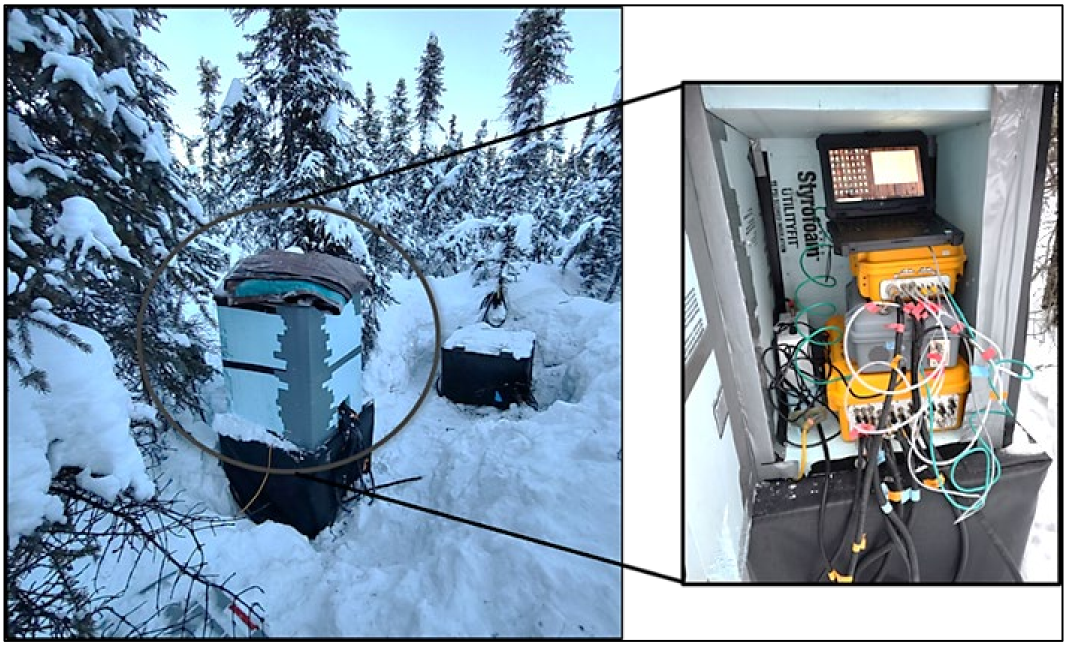
†Indicates the sites from which the vegetation was removed (bare sites).

Seasonal active layer thaw depth was measured at the three chamber sites, and at VS1 (where the vegetation was left undisturbed). These measurements were acquired every time a site visit was made ($n = 33$) from 23 May to 19 September 2022. Additional seasonal thaw measurements were made 20 cm to 30 cm from the chamber sites, where the ground vegetation was left intact ($n = 24$), starting 23 June to 19 September. The measurements were made by pushing a 1 cm diameter graduated metal rod (frost probe) downward into the ground to refusal to establish the distance between the ground surface vegetation and the top of the frozen soils (Shiklomanov et al. 2013).

2.4 Modifications to an Automated Efflux System for Long-Term Soil Respiration Monitoring In Cold Climates

Operating scientific instrumentation in cold climates can be challenging mostly because of the extreme cold temperatures that are common from October to March. The soil respirometer system had an operating temperature range of –25°C to 45°C. To ensure that the instrumentation was at or above the minimum operating temperature, we custom-made an encloser (92 cm × 60 c × 60 cm) constructed with 5 cm thick Styrofoam (Figure 4). The temperature inside this custom-made insulated enclosure was monitored using an Onset HOBO UX100-003 temperature and relative humidity logger (Onset, Bourne, Massachusett, USA). The enclosure maintained an inside temperature above –20°C throughout the winter months, which was 5°C warmer than the minimum operating temperature of the instruments inside.

Figure 4. Outside view of a custom-made Styrofoam enclosure used to house LI-COR soil respirometer gas detectors at operating temperatures (*left*). Inside view of the Styrofoam container housing LI-8150, LI-8100A, and LI-7810 components (*right*).



We wrapped the cables and tubing connected to the 8100-104 long-term chambers to the soil respirometer system in 1.3 cm thick tubular pipe insulation foam to prevent/minimize clogging due to moisture freezing up inside the tubing.

Costco (Columbus, Indiana) folding tables with a surface of 91.4 cm × 91.4 cm were place over the 8100-104 long-term chambers in the winter months to prevent snow accumulating on the chambers (Figure 5). This was necessary as the chambers had to open and close freely to accurately measure soil respiration fluxes. Furthermore, M-D Building Products (Oklahoma City, Oklahoma) fiberglass screen mash was wrapped around the table from top to bottom to prevent snow from drifting on the 8100-104 long-term chambers. The tables were removed from over the chambers during the snow free months to minimize the changes to the environment at the plots.

Figure 5. The 8100-104 long-term chamber deployed during warmer months (*right*) and the 8100-104 long-term chamber deployed during winter months with setup modifications to protect from heavy snowfall (*left*).

3 Results and Discussion

3.1 Soil Temperature and Moisture

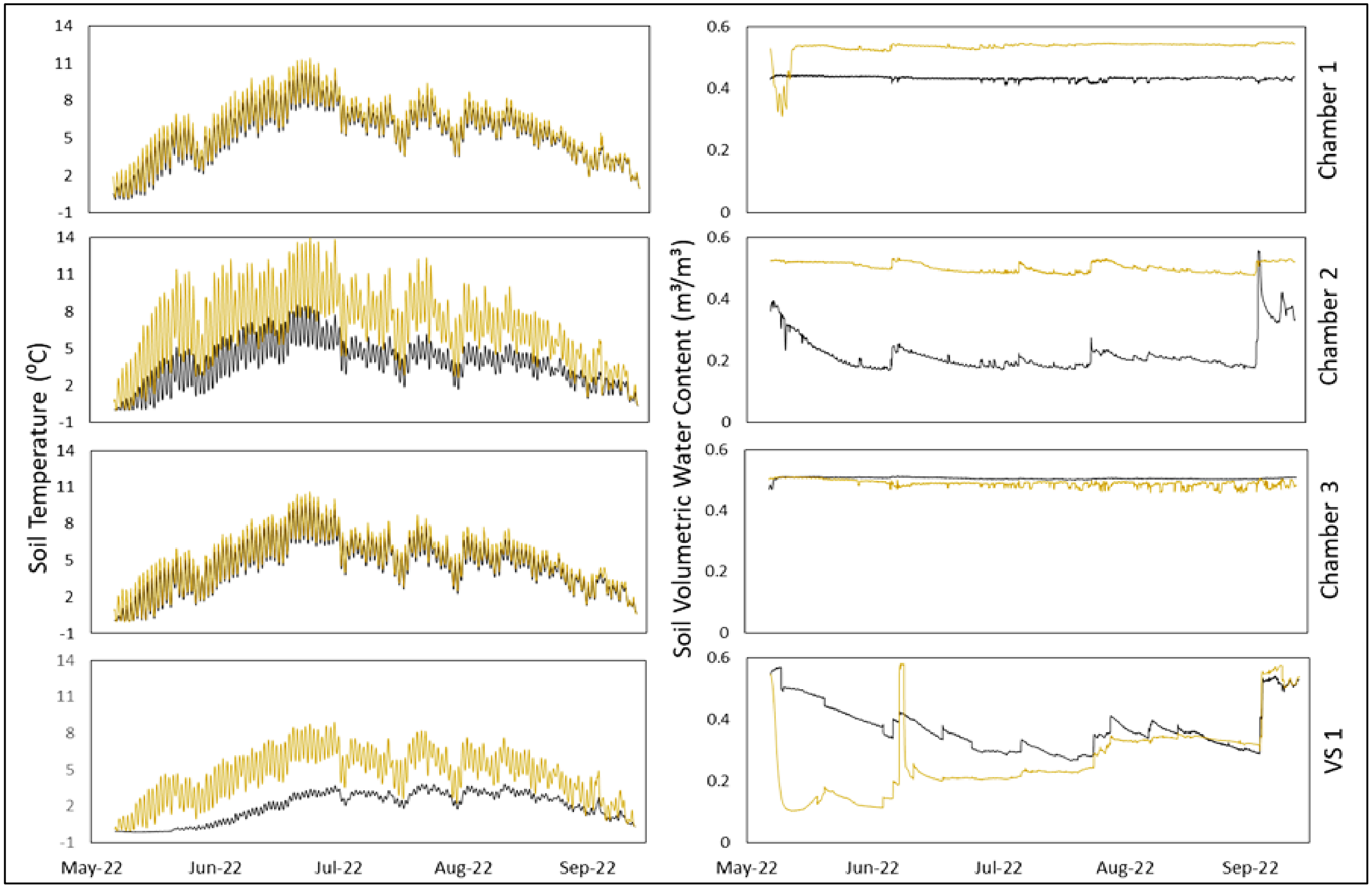
Soil temperature and moisture were measured from 20 May to 23 September 2022. The analysis presented in this report was performed on the data from the above date range. Note that the soil moisture probes are not reliable at temperatures less than 0°C. Overall, soil temperature ranged from –0.12°C to 13.98°C and soil moisture ranged from 0.11 m^3/m^3 to 0.58 m^3/m^3 (Figure 6).

The maximum organic soil temperature at all the chambers was recorded on 6 July and on 12 July at VS1 site while the minimum temperatures were recorded at or immediately after the sensors were deployed in late May 2022. Chamber 2 site had the highest, 13.98 °C, and the lowest, –0.03 °C, recorded organic soil temperatures. The maximum mineral soil temperature of 10.42 °C was recorded at chamber 2 on 7 July and –0.12°C for the minimum at VS1 on 25 May. VS1 1 site had the latest peek in the mineral soil temperature, from all the four sites, and it occurred on 2 August and the lowest maximum seasonal mineral soil temperature of 3.83°C.

The maximum VWC in the organic and mineral soils were measured at the VS1 site and they were 0.58 m^3/m^3 on 21 June and 0.55 m^3/m^3 on 22 May respectively. The minimum for the of VWC values 0.11 m^3/m^3 were recorded on 26 May at the VS1 site for the organic sediments and 0.17 m^3/m^3 at the chamber 2 site on 18 June for the mineral soil. The organic soil temperatures were consistently warmer than the mineral soil temperature at all the sites throughout the monitoring period with the few following exceptions: out of 12,072 recorded soil temperature values, higher mineral soils values were recorded 80 times at chamber 1, 26 times at chamber 2, 214 times at chamber 3, and 154 times at the VS1 1 site.

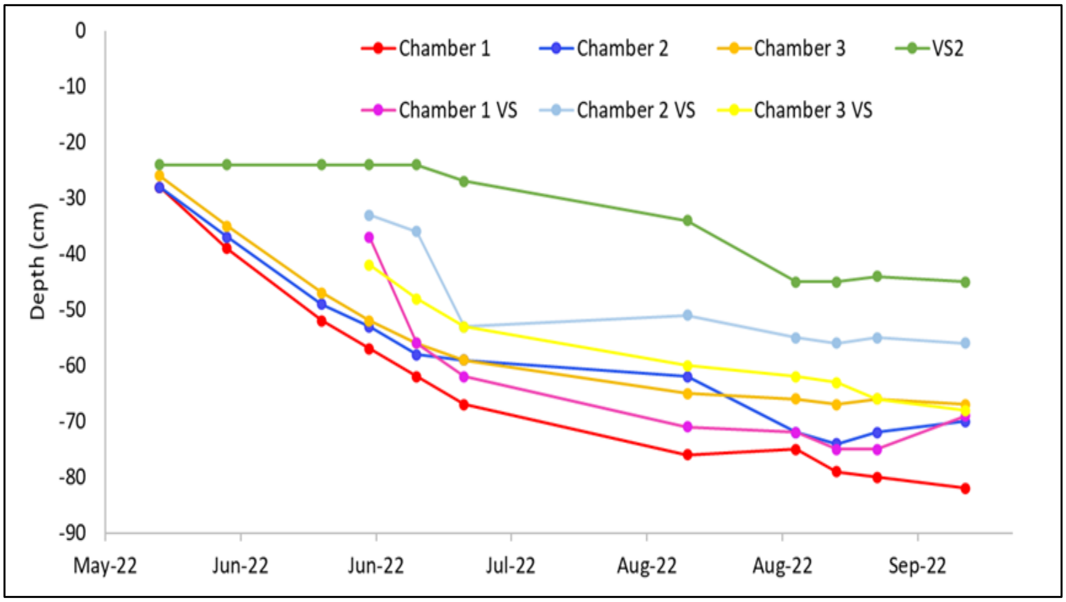
Chamber 1 and 2 sites predominantly had higher average VWC in the organic soils (0.53 m^3/m^3 and 0.5 m^3/m^3 respectively) while chamber 3 and the VS1 sites in the mineral soils (0.54 m^3/m^3 and 0.37 m^3/m^3 respectively) (Figure 6). The dryer and cooler mineral soils at chamber 2 are likely due to the deeper organic soil horizon and thicker vegetation layer as compared to chambers 1 and 3 (Table 1). Despite that the vegetation was removed from the chamber plots, the surrounding vegetation likely still affected the thermal regime at the plots.

Figure 6. Soil temperature and moisture data in the organic soils (*brown*) and mineral soils (*black*) from the three long-term chambers and the control site.



Seasonal active layer thaw depth Seasonal thaw depth was measured at two locations at the chamber sites; at the long-term chamber where the vegetation was removed and in the immediate vicinity (approximately 30 cm) of the chambers where the vegetation was left intact (VS) as well as at the VS1 site from 23 May to 19 September 2022, every time a site visit was made. The maximum seasonal soil thaw depth measured at all the sites were recorded in September 2022. Overall, the maximum seasonal thaw depth for all the bare sites (*n* = 3) was –73 ± 4.6 cm (standard error [SE]) and –61 ± 3.8 cm (SE) for the vegetated sites (*n* = 4). However, when only VS1 located approximately 3 m from the chamber sites was considered, the maximum thaw depth was much shallower: –49 cm (SE) (Figure 7). Seasonal thaw depth at the VS near the chambers were likely deeper than at the VS1 site due to the warmer soil temperatures near the chambers as compared to VS1 site (Figure 6). The average percentage increase in active layer depth between the bare and vegetated plots at each chamber plot was: 10.6% at chamber 1.25% at chamber 2, and 14.4% at chamber 3, highlighting the difference between vegetated and bare soil thermal regimes. The significantly higher increase in active layer depth between the bare and vegetated sites at the chamber 2 plot, as compared to chamber 1 and 3 plots, was likely due to the thicker vegetation layer present at chamber 2 (Table 1).

Figure 7. Seasonal thaw depth at the chamber (bare) and vegetated (VS) plots, and VS2 site from 23 May to 19 September 2022.



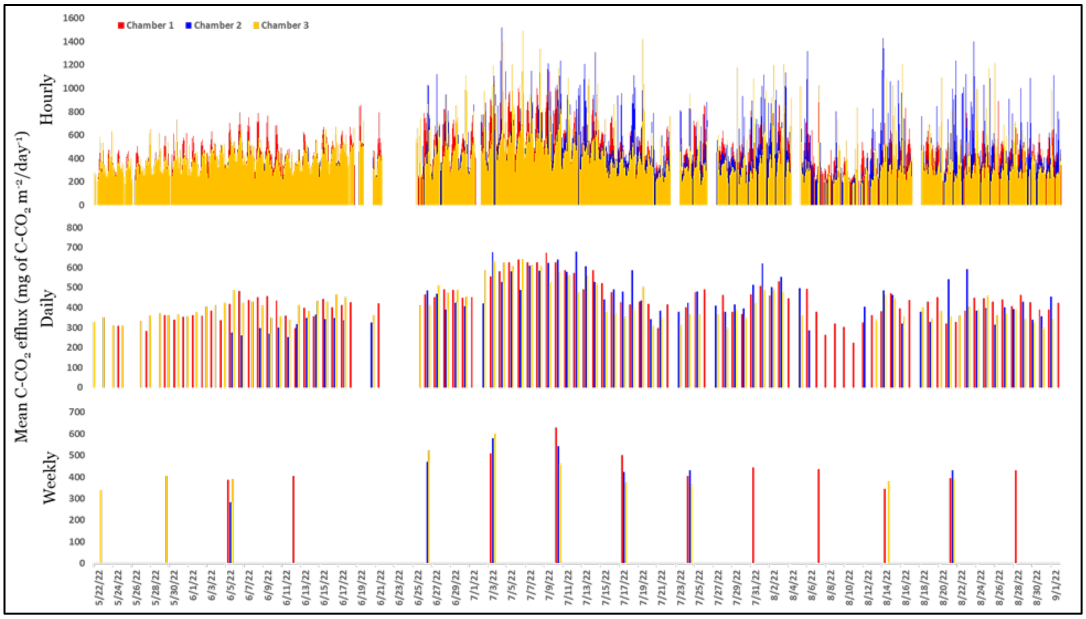
3.2 Soil Respiration Results from the Automated Efflux System

The soil respirometer system experienced severe malfunctions during the study period that resulted in the equipment having to be sent back to the manufacturer for repairs. During a typical gas measurement, the instrument provides a graph of the entire reading over the 120 s period, which should appear primarily linear with respect to slope as gas continues to build in the chamber after it is sealed. The R^2 value from these readings should reflect the linearity of these measurements and therefore this value should provide a metric for evaluating the quality of each gas measurement. Both the LI-870 and the LI-7810 provided data with R^2 values less than 0.5 for the majority of the study period (2 August 2021 to 23 September 2022). This could be because the soil temperatures were very cold and possibly reached the limit of detection during the winter months for these instruments. During the winter months, soil moisture is locked in frozen soil and the water in the pore space in unavailable to the microbes and therefore nutrient availability for microbial activity and heterotrophic respiration is limited. The LI-7810 CO_2 data showed an increase in the measurement R^2 value (0.5 or higher) once the soil temperature started to increase at the beginning of May 2022.

A total of 28,656 soil CO_2 and CH_4 efflux observations were obtained during the period when the LI-7810 trace gas analyzer was operational from January to September 2022. Due to instrument issues such as the LI-7810 trace gas analyzer optical bench failure and poor CO_2 efflux measurement R^2 values (0.5 or less), only 40% of the CO_2 and 10% of the CH_4 efflux data was used for the statistical analysis. The benefit of having both the LI-8100 and LI-7810 instruments deployed was the ability to interchange results. For example, the LI-8100 instrument had a long-term H_20 sensor failure that was not initially detected, which led to all the CO_2 efflux data acquired with this instrument being discarded.

Figure 8 shows the hourly, daily, and weekly average C-CO_2 efflux from the three chambers from 20 May to 1 September. No averages were calculated when 20% or more of the data were missing. Chamber 2 had the highest mean hourly (1,523.1 mg of C-CO_2 m^{-2}/day^{-1}) and daily (679.7 mg of C-CO_2 m^{-2}/day^{-1}) and chamber 1 the highest weekly (629.8 mg of C-CO_2 m^{-2}/day^{-1}) CO_2 efflux. The average CO_2 efflux from all three chambers was 423.8 mg of C-CO_2 m^{-2}/day^{-1}.

Figure 8. Hourly, daily, and weekly mean C-CO2 efflux colored by chamber showing that chamber 2 had the highest mean hourly and daily fluxes and chamber 3 had the highest weekly flux.



Overall, there were cumulatively 4,882 g of C-CO$_2$ m^{-2} and 1.2 g of C-CH$_4$ m^{-2} from all the chamber plots combined. Chamber 1 had the highest cumulative C-CO$_2$ efflux of 1,816 g of C-CO$_2$ m^{-2}, followed by chamber 3, 1,704 g of C-CO$_2$ m^{-2}, and chamber 2 with 1,362 g of C-CO$_2$ m^{-2} . Chamber 2 had the highest cumulative C-CH$_4$ efflux of 0.91 g of C-CH$_4$ m^{-2} followed by chamber 1 with 0.21 g of C-CH$_4$ m^{-2}, and lastly chamber 3 with 0.13 g of C-CH$_4$ m^{-2}. The difference in the cumulative CO$_2$ efflux between the three chambers should not be used as an indicator as the actual overall CO$_2$ efflux from these plots because of the varying number of data points at each chamber: chamber 1 (n = 4366), chamber 2 (n = 3330), and chamber 3 (n = 4270).

Soil temperature is a key driver of soil respiration, however, the relationship between soil temperature and soil respiration is not always straightforward and can be influenced by factors such as soil moisture, nutrient availability, and the composition of the underlying microbial community (Curiel et al. 2007; Moyano et al. 2013; Barbato et al. 2015). One factor that can also affect the relationship between soil temperature and soil respiration is the lag time between changes in soil temperature and changes in soil respiration. Lag time refers to the delay between a change in the environmental conditions and the response of the ecosystem. Several studies have shown that there can be a lag time of hours to days and weeks between changes in soil temperature and changes in soil respiration (Kuzyakov and Gavrichkova 2010; Carey et al. 2016).

Our initial regression analysis of the C-CO_2 efflux with soil temperature and VWC relationship revealed a low to moderate correlation with R^2 values ranging from 0.16 to 0.36. Due to the poor correlation, we performed a regression analysis between the C-CO_2 efflux data and the 2, 4, 6, 8, and 12 hr interval lag time soil temperature data. The relationship at chamber 1 site increased slightly when the C-CO_2 efflux was correlated to a soil temperature lag time of 2 and 4 hr. The R^2 values increased from 0.36 to 0.45 when correlated to a 2 hr mineral horizon soil temperature lag time and from 0.32 to 0.45 for the 4 hr organic horizon soil temperature lag time. There was a decline in the R^2 values when the C-CO_2 efflux was correlated to any of the 2 to 12 hr interval lag timed soil temperature data at the chambers 2 and 3 sites (Table 2). The poor correlation between C-CO_2 efflux data and the 2, 4, 6, 8, and 12 hr interval lag time soil temperature and VWC data indicated a possible longer lag time between the changes in soil temperature and VWC and the change in C-CO_2 efflux.

Table 2. Linear regression analysis (R^2) of soil CO_2 efflux versus soil temperature lag time of 0, 2, 4, 6, 8, and 12 hr, respectively.

Chamber	Soil Layer	0 hr	2 hr	4 hr	6 hr	8 hr	10 hr	12 hr
Chamber 1	Organic	0.36	0.45	0.44	0.34	0.21	0.12	0.06
	Mineral	0.32	0.40	0.39	0.33	0.23	0.14	0.08
Chamber 2	Organic	0.16	0.11	0.08	0.06	0.05	0.06	0.07
	Mineral	0.21	0.18	0.14	0.11	0.10	0.11	0.12
Chamber 3	Organic	0.16	0.11	0.06	0.03	0.02	0.03	0.06
	Mineral	0.17	0.12	0.08	0.05	0.03	0.33	0.05

The C-CO_2 efflux and soil temperature correlation significantly increased at all the chamber plots when the linear regression analysis was conducted on the daily and weekly averaged data. Chambers 1 and 2 weekly averages of the mineral and organic soil temperatures best correlated to the C-CO_2 efflux with R^2 values of 0.65 to 0.85, while at chamber 3 site daily averages had a better correlation to the C-CO_2 efflux with R^2 values of 0.39 for the organic and 0.36 for the mineral soil daily average temperatures (Table 3).

Table 3. Linear regression analysis (R^2) of average hourly, daily, and weekly soil CO_2 efflux (C-CO_2 m^{-2}/day^{-1}) versus soil temperature (°C).

	Hourly		Daily		Weekly	
Chamber	Organic	Mineral	Organic	Mineral	Organic	Mineral
Chamber 1	0.36	0.32	0.51	0.48	0.67	0.65
Chamber 2	0.16	0.21	0.59	0.64	0.78	0.85
Chamber 3	0.16	0.17	0.39	0.36	0.31	0.29

A similar regression analysis was conducted to investigate the relationship between the hourly, daily, and weekly averaged C-CO_2 efflux and VWC values. Only chamber 2 site had a low to moderate correlation with R^2 values for the daily averages ranging from 0.37 (mineral) to 0.49 (organic) and 0.48 (mineral) to 0.6 (organic) for the weekly averaged values (Table 4).

In our study, we observed that C-CO_2 efflux and soil temperature were most correlated when the regression analysis was run on the daily and weekly averages which agrees with the previous findings from Kuzyakov and Gavrichkova (2010) and Carey et al. (2016).

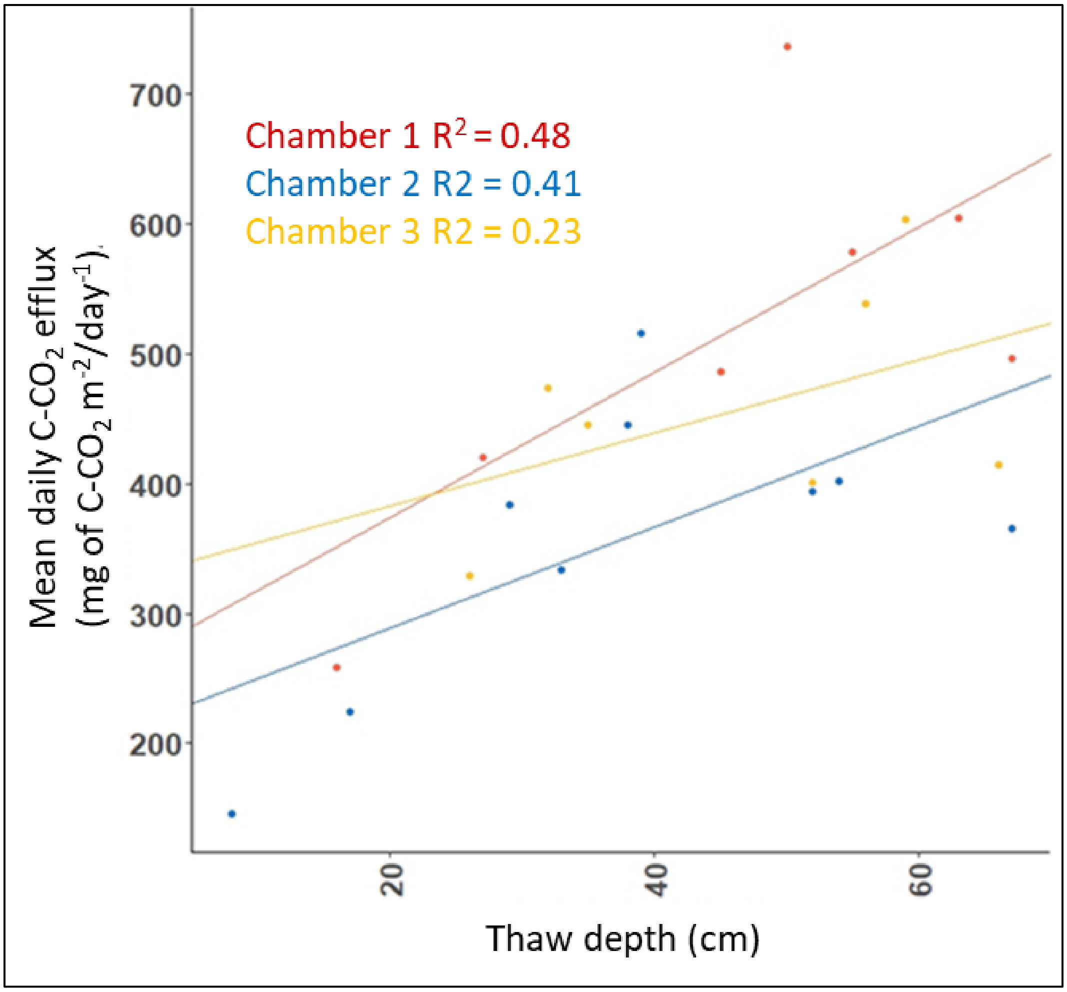
Table 4. Linear regression analysis (R^2) of average hourly, daily, and weekly soil CO_2 efflux (C-CO_2 m^{-2}/day^{-1}) versus soil VWC (m^3/m^3).

	Hourly		Daily		Weekly	
Chamber	Organic	Mineral	Organic	Mineral	Organic	Mineral
Chamber 1	0	0.01	0.04	0.04	0.09	0.08
Chamber 2	0.15	0.09	0.49	0.37	0.60	0.48
Chamber 3	0	0	0.03	0	0.02	0

Seasonal thaw depth is another factor found to contribute to soil respiration rates. In areas where thaw depth is shallow, microbial activity may be limited to the upper layers of soil, leading to lower overall respiration rates. Scott-Denton et al. (2003) found that spatial variation in soil respiration was positively correlated to the organic horizon depth, which is related to the thaw depth.

A linear regression between seasonal thaw depth and CO_2 efflux was conducted to determine if these relationships between the two parameters existed at our site (Figure 9). There was a low to moderate positive correlation between weekly seasonal thaw depth measurements and weekly C-CO_2 efflux averages 1 had the greatest thaw depth (–28 cm to 82 cm) as well as the highest average respiration rate (432 mg of C-CO_2 m^{-2}/day^{-1}).

Figure 9. Linear regression analysis was used to assess the correlation between thaw depth and mean daily soil efflux between 19 May 2022 and 31 August 2022. Results show soil CO_2 efflux tends to increase with thaw depth.



In our study, there was a significant difference in thaw depth between the bare sites and the ones where the vegetation was left intact; maximum seasonal thaw depth was shallowest at the control sites, and it was approximately half of that measured at the chamber 1 site (Figure 7). Vegetation cover can have a significant effect on permafrost thaw and mitigating its impact on the environment and the underlying soils. Vegetation cover can prevent permafrost thaw in several ways: it provides shade and insulation which reduces the amount of solar radiation reaching the soil, it absorbs and stores water, and it stabilizes the surface soils and prevents erosion (Kanevskiy et al. 2017; Turetsky et al. 2010; Heijmans et al. 2022).

One of the most significant challenges of deploying and long-term operation of scientific instrumentation in cold climates is dealing with the harsh weather conditions such as extreme cold temperatures and snow accumulation over the instrumentation. To overcome these challenges, we modified our soil respirometer system setup (as described in Section 2). Modifications such as building a custom-made enclosure to maintain the required minimum operating temperature, covering the chambers to prevent snow accumulation, and insulating the tubing to prevent and minimize clogging due to moisture freezing up inside ensured that the instruments' operating requirements were met. One drawback of these modifications was their impact on the environment where the instruments were deployed. Snow provides an effective thermal insulation when the snow depth exceeds 10 cm (Zhao et al. 2018); the maximum annual average snowpack depth measured at this site was 87 cm on 7 April 2022. The lack of snow cover very likely changed the thermal regime at the chamber sites as compared to the snow-covered soundings which could have led to reduced soil respiration as compared to the undisturbed surrounding soils.

Our study focused on measuring heterotrophic soil respiration which required the removal of the vegetation layer at the chamber site. This disturbance significantly impacted the soil temperature, soil moisture, and seasonal thaw depth at the chamber sites. A one-way ANOVA analysis revealed that the soil temperature, at both the organic and mineral horizons, between the bare and vegetated sites, to be significantly different as demonstrated by high F values from 1,047.89 (organic) to 2,067.89 (mineral) and extremely low p-values from 4.09E-212 (organic) to 0.0 (mineral). Similar results were observed for the VWC data one-way ANOVA analysis where the F values were 12,931.5 (organic) and 7,721.05 (mineral) and p-values were 0 for both the organic and mineral horizons between the bare and vegetated sites. Both organic and mineral horizon soil temperatures were consistently warmer and had a more pronounced diurnal variation at the bare sites as compared to the vegetated sites (Figure 6). By removing the vegetation, the soil underneath was exposed to the atmosphere which likely led to higher organic and mineral soil temperatures and an increase in the organic soil water content.

There were several studies that focused on soil respiration rates in Arctic and subarctic regions, as they are an important component of the global carbon cycle. In an early study conducted near the town of Fairbanks, Alaska, by Schlentner and Clive (1985) from 1 May to 30 September in 1980 and 1981, soda lime was used to measure soil respiration. The measurements were made by first drying and then weighing the soda lime before and after field deployment and the CO_2 absorption was determent gravimetrically using a balance. There results found that both soil temperature and moisture can affect soil respiration. In a more recent study, Watts et al. (2021), investigated the soil respiration fluxes from tundra and boreal ecosystems in Alaska and Northwest Canada. Automated long-term chambers and eddy covariance towers were used to measure soil respiration from September 2016 to August 2017. Their research showed that soil temperature was an important driver of soil respiration with 58% of the regional soil respiration is occurring in the summer months, 27% in the shoulder seasons, and only 15% in the winter months. Moreover, their results show that soil respiration significantly impacted the carbon uptake from high latitude permafrost regions in Alaska and Canada. Similar to their finding, our research revealed that temperature had the strongest correlation to soil respiration with the highest respiration rates recorded in July. Rodenhizer et al. (2022) investigated the effect of abrupt permafrost thaw on C efflux at a tussock tundra site in Alaska from 1 May 2017 to 30 April 2020. The CO_2 efflux was measured using eddy covariance towers. Their findings show that with abrupt increased in thaw there was an increased in CO_2 release from soil to the atmosphere. Comparable to their findings, our research also revealed that increased thaw depth positively affects soil respiration.

These studies have found that soil respiration rates in cold regions vary depending on factors such as soil temperature and moisture, permafrost thaw, and vegetation cover. However, the main takeaway from these and other recent studies that focused on cold regions soil respiration and its contribution to the global carbon budget is that as temperatures warm, soil respiration rates will increase due to increased microbial activity and decomposition of newly available organic matter from previously frozen soils.

4 Conclusions and Recommendations

Measuring soil temperature, soil moisture, and soil respiration is crucial in changing climates, especially in cold climates where the balance of carbon stored in the soil is becoming increasingly important to the global carbon budget. As soil temperatures in cold regions increase, microbial activity will also likely increase in the soil, which can have a significant impact on the amount of carbon released from these soils into the atmosphere. By measuring in situ soil respiration, researchers can estimate the amount of carbon that is being released from the soil and use this information to develop more accurate carbon emissions predictive models. However, some considerations should be considered when using the in situ acquired data for modeling. Deploying instrumentation in the field can change the local environmental conditions and the organisms within it. This is especially true in Arctic and subarctic environments as they are very sensitive to change. In our research, we significantly altered the local environment by first removing the vegetation from the chamber sites, and second, by preventing the snow from accumulating over the sites. These changes, even though necessary for in situ heterotrophic soil respiration measurements and long-term automated instrument operation, significantly altered the soil thermal regime of the sites and most likely the measured soil respiration rates. Researchers should consider these in situ data limitations when performing model validations and regional CO_2 efflux estimations. We recommend avoiding using the chamber method for in situ heterotrophic soil respiration measurements in cold climates where vegetation plays an important role in the soil temperature regime. A less intrusive method and instrumentation needs to be developed if more accurate in situ heterotrophic soil respiration rates are desired.

Bibliography

Allan, J., J. Ronholm, N. C. S. Mykytczuk, C. W. Greer, T. C. Onstott, and L. G. Whyte. 2014. "Methanogen Community Composition and Rates of Methane Consumption in Canadian High Arctic Permafrost Soils: Methane Consumption by Arctic Permafrost Methanogens." *Environmental Microbiology Reports* 6 (2): 136–144. https://doi.org/10.1111/1758-2229.12139.

Barbato, R. A., K. L. Foley, and C. M. Reynolds. 2015. *Soil Temperature and Moisture Effects on Soil Respiration and Microbial Community Abundance*. ERDC/CRREL TR-15-6. Hanover, NH: ERDC-CRREL. http://hdl.handle.net/11681/5549.

Barbato, R. A., L. Waldrup, K. Messan, R. Jones, S. J. Doherty, K. Foley, C. Felt, M. Morgan, and Y. Han. 2018. *Dynamic Representation of Terrestrial Soil Predictions of Organisms' Response to the Environment*. ERDC/CRREL TR-18-15. Hanover, NH: ERDC-CRREL. http://dx.doi.org/10.21079/11681/29349.

Carey, J. C., J. Tang, P. H. Templer, K. D. Kroeger, T. W. Crowther, A. J. Burton, J. S. Dukes et al. 2016. "Temperature Response of Soil Respiration Largely Unaltered with Experimental Warming." *Proceedings of the National Academy of Sciences* 113 (48): 13797–13802. https://doi.org/10.1073/pnas.1605365113.

Curiel Yuste, J., D. D. Baldocchi, A. Gershenson, A. Goldstein, L. Misson, and S. Wong. 2007. "Microbial Soil Respiration and Its Dependency on Carbon Inputs, Soil Temperature and Moisture." *Global Change Biology* 13 (9): 2018–2035. https://doi.org/10.1111/j.1365-2486.2007.01415.x.

Delle Vedove, G., G. Alberti, M. Zuliani, A. Peressotti. 2007. "Automated Monitoring of Soil Respiration: An Improved Automatic Chamber System." *Italian Journal of Agronomy* 2 (4): 377–382. http://dx.doi.org/10.4081/ija.2007.377.

Elberling, B., and K. K. Brandt. 2003. "Uncoupling of Microbial CO2 Production and Release in Frozen Soil and Its Implications for Field Studies of Arctic C Cycling." *Soil Biology and Biochemistry* 35 (2): 263–272. https://doi.org/10.1016/S0038-0717(02)00258-4.

Epron, D. 2010. "Chapter 8—Separating Autotrophic and Heterotrophic Components of Soil Respiration: Lessons Learned from Trenching and Related Root-Exclusion Experiments." In *Soil Carbon Dynamics: An Integrated Methodology*, ed. W. L. Kutsch, M. Bahn, and A. Heinemeyer. Cambridge, UK: Cambridge University Press, 157–168. https://doi.org/10.1017/CBO9780511711794.009.

Gorham, E. 1991. "Northern Peatlands: Role in the Carbon Cycle and Probable Responses to Climatic Warming." *Ecological Applications* 1 (2): 182–195. https://doi.org/10.2307/1941811.

Guimond, J. A., A. A. Mohammed, M. A. Walvoord, V. F. Bense, and B. L. Kurylyk. 2021. “Saltwater Intrusion Intensifies Coastal Permafrost Thaw.” *Geophysical Research Letters* 48(19). https://doi.org/10.1029/2021GL094776.

Heijmans, M. M. P. D., R. Í. Magnússon, M. J. Lara, G. V. Frost, I. H. Myers-Smith, J. Van Huissteden, M. T. Jorgenson, et al. 2022. “Tundra Vegetation Change and Impacts on Permafrost.” *Nature Reviews Earth & Environment* 3 (1): 68–84. https://dx.doi.org/10.1038/s43017-021-00233-0.

IPCC (Intergovernmental Panel on Climate Change). 2023. “Summary for Policymakers.” In *Climate Change 2023: Synthesis Report*. Eds. H. Lee and J. Romero. Geneva: IPCC. https://www.ipcc.ch/report/ar6/syr/downloads/report/IPCC_AR6_SYR_FullVolume.pdf.

Joo, S. J., S. U. Park, M. S. Park, C. S. Lee. 2012. “Estimation of Soil Respiration Using Automated Chamber Systems in an Oak (*Quercus mongolica*) Forest at the Nam-San site in Seoul, Korea.” *Science of the Total Environment* 416: 400–409. https://doi.org/10.1016/j.scitotenv.2011.11.025.

Jorgenson, M. T., T. A. Douglas, A. K. Liljedahl, J. E. Roth, T. C. Cater, W. A. Davis, G. V. Frost, P. F. Miller, and C. H. Racine. 2020. “The Roles of Climate Extremes, Ecological Succession, and Hydrology in Repeated Permafrost Aggradation and Degradation in Fens on the Tanana Flats, Alaska.” *Journal of Geophysical Research: Biogeosciences* 125 (12). https://doi.org/10.1029/2020JG005824.

Kanevskiy, M., Y. Shur, T. Jorgenson, D. R. Brown, N. Moskalenko, J. Brown, D. A. Walker, M. K. Raynolds, and M. Buchhorn. 2017. “Degradation and Stabilization of Ice Wedges: Implications for Assessing Risk of Thermokarst in Northern Alaska.” *Geomorphology* 297: 20–42. https://doi.org/10.1016/j.geomorph.2017.09.001.

Karhu, K., M. D. Auffret, J. A. J. Dungait, D. W. Hopkins, J. I. Prosser, B. K. Singh, J.-A. Subke, 2014. “Temperature Sensitivity of Soil Respiration Rates Enhanced by Microbial Community Response.” *Nature* 513: 81–84. https://doi.org/10.1038/nature13604.

Kechavarzi, C., Q. Dawson, M. Bartlett, and P. B. Leeds-Harrison. “The Role of Soil Moisture, Temperature and Nutrient Amendment on CO2 Efflux from Agricultural Peat Soil Microcosms.” *Geoderma* 154 (3–4): 203–210. https://doi.org/10.1016/j.geoderma.2009.02.018.

Kelsey, K. C., A. J. Leffler, K. H. Beard, J. A. Schmutz, R. T. Choi, and J. M. Welker. 2016. “Interactions Among Vegetation, Climate, and Herbivory Control Greenhouse Gas Fluxes in a Subarctic Coastal Wetland: Herbivory Interactions and GHG Flux.” *Journal of Geophysical Research: Biogeosciences* 121 (12): 2960–2975. https://doi.org/10.1002/2016JG003546.

Kuzyakov, Y., and O. Gavrichkova. 2010. “REVIEW: Time Lag Between Photosynthesis and Carbon Dioxide Efflux from Soil: A Review of Mechanisms and Controls.” *Global Change Biology* 16 (12): 3386–3406. https://doi.org/10.1111/j.1365-2486.2010.02179.x.

Lader, R., J. E. Walsh, U. S. Bhatt, and P. A. Bieniek. 2017. "Projections of Twenty-First-Century Climate Extremes for Alaska via Dynamical Downscaling and Quantile Mapping." *Journal of Applied Meteorology and Climatology* 56 (9): 2393–2409. https://doi.org/10.1175/JAMC-D-16-0415.1.

Liang, S., and J. Wang. 2020. *Advanced Remote Sensing: Terrestrial Information Extraction and Applications*. Amsterdam: Elsevier. https://doi.org/10.1016/C2017-0-03489-4.

Liston, G. E., and C. A. Hiemstra. 2011. "The Changing Cryosphere: Pan-Arctic Snow Trends (1979–2009)." *Journal of Climate* 24 (21): 5691–5712. https://doi.org/10.1175/JCLI-D-11-00081.1.

Makita, N., Y. Kosugi, A. Sakabe, A. Kanazawa, S. Ohkubo, and M. Tani. 2018. "Seasonal and Diurnal Patterns of Soil Respiration in an Evergreen Coniferous Forest: Evidence from Six Years of Observation with Automatic Chambers." *PLoS One* 13 (2). https://doi.org/10.1371/journal.pone.0192622.

Manzoni, S., J. P. Schimel, and A. Porporato, 2012. "Responses of Soil Microbial Communities to Water Stress: Results from a Meta-Analysis." *Ecology*, 93 (4): 930–938. https://doi.org/10.1890/11-0026.1.

Moyano, F. E., S. Manzoni, and C. Chenu. 2013. "Responses of Soil Heterotrophic Respiration to Moisture Availability: An Exploration of Processes and Models." *Soil Biology and Biochemistry* 59: 72–85. https://dx.doi.org/10.1016/j.soilbio.2013.01.002.

Rodenhizer, H., F. Belshe, G. Celis, J. Ledman, M. Mauritz, S. Goetz, T. Sankey, and E. A. G. Schuur. 2022. "Abrupt Permafrost Thaw Accelerates Carbon Dioxide and Methane Release at a Tussock Tundra Site." *Arctic, Antarctic, and Alpine Research* 54 (1): 443–464. https://doi.org/10.1080/15230430.2022.2118639.

Schlentner, R. E., and K. Van Cleve. 1985. "Relationships Between CO_2 Evolution from Soil, Substrate Temperature, and Substrate Moisture in Four Mature Forest Types in Interior Alaska." *Canadian Journal of Forest Research* 15 (1): 97–106. https://doi.org/10.1139/x85-018.

Schuur, E. A. G., A. D. McGuire, C. Schädel, G. Grosse, J. W. Harden, D. J. Hayes, G. Hugelius, et al. 2015. "Climate Change and the Permafrost Carbon Feedback." *Nature* 520 (7546): 171–179. https://doi.org/10.1038/nature14338.

Scott-Denton, L. K. L. Sparks, and R. K. Monson. 2003. "Spatial and Temporal Controls of Soil Respiration Rate in a High-Elevation, Subalpine Forest." *Soil Biology and Biochemistry* 35 (4): 525–534. https://doi.org/10.1016/S0038-0717(03)00007-5.

Serreze, M. C., and J. A. Francis. 2006. "The Arctic Amplification Debate." *Climatic Change* 76 (3–4): 241–264. https://doi.org/10.1007/s10584-005-9017-y.

Shiklomanov, N. I., D. A. Streletskiy, J. D. Little, and F. E. Nelson. 2013. "Isotropic Thaw Subsidence in Undisturbed Permafrost Landscapes." *Geophysical Research Letters* 40 (24): 6356–6361. https://doi.org/10.1002/2013GL058295.

Streit, K., F. Hagedorn, D. Hiltbrunner, M. Portmann, M. Saurer, N.Buchmann, B. Wild, A. Richter, S. Wipf, and R. T. W. Siegwolf. 2014. "Soil Warming Alters Microbial Substrate Use in Alpine Soils." *Global Change Biology* 20 (4): 1327–1338. https://doi.org/10.1111/gcb.12396.

Suh, S. U., Y-M. Chun, N-y. Chae, J. Kim, J-H. Lim, M. Yokozawa, M-S. Lee, and J-S. Lee. 2006. "A Chamber System with Automatic Opening and Closing for Continuously Measuring Soil Respiration Based on an Open-Flow Dynamic Method." *Ecology Research* 21 (3): 405–414. https://doi.org/10.1007/s11284-005-0137-7.

Treat, C. C., J. L. Bubier, R. K. Varner, and P. M. Crill. 2007. "Timescale Dependence of Environmental and Plant-Mediated Controls on CH 4 Flux in a Temperate Fen." *Journal of Geophysical Research* 112 (G1). https://doi.org/10.1029/2006JG000210.

Turetsky, M. R., M. C. Mack, T. N. Hollingsworth, and J. W. Harden. 2010. "The Role of Mosses in Ecosystem Succession and Function in Alaska's Boreal Forest." *Canadian Journal of Forest Research* 40 (7): 1237–1264. https://doi.org/10.1139/X10-072.

Wagner-Riddle, C., K. Park, and G. Thurtell. 2006. "A Micrometeorological Mass Balance Approach for Greenhouse Gas Flux Measurements from Stored Animal Manure." *Agricultural and Forest Meteorology* 136 (3–4): 175–87. https://doi.org/10.1016/j.agrformet.2004.11.014.

Waldrop, M. P., J. McFarland, K. L. Manies, M. C. Leewis, S. J. Blazewicz, M. C. Jones, R. B. Neumann, et al. 2021. "Carbon Fluxes and Microbial Activities From Boreal Peatlands Experiencing Permafrost Thaw." *Journal of Geophysical Research: Biogeosciences* 126 (3). https://doi.org/10.1029/2020JG005869.

Wang, X., X. Li, Y. Hu, J. Lv, J. Sun, Z. Li, and Z. Wu. 2010. "Effect of Temperature and Moisture on Soil Organic Carbon Mineralization of Predominantly Permafrost Peatland in the Great Hing'an Mountains, Northeastern China." *Journal of Environmental Sciences* 22 (7): 1057–1066. https://doi.org/10.1016/S1001-0742(09)60217-5.

Watts, J. D., S. M. Natali, C. Minions, D. Risk, K. Arndt, D. Zona, E.S. Euskirchen, et al. 2021. "Soil Respiration Strongly Offsets Carbon Uptake in Alaska and Northwest Canada." *Environmental Research Letters* 16 (8): 084051. https://doi.org/10.1088/1748-9326/ac1222.

Wildung, R. E., T. R. Garland, and R. L. Buschbom. 1975. "The Interdependent Effects of Soil Temperature and Water Content on Soil Respiration Rate and Plant Root Decomposition in Arid Grassland Soils." *Soil Biology and Biochemistry* 7 (6): 373–378. https://doi.org/10.1016/0038-0717(75)90052-8.

Zhao, J-y., J. Chen, Q-b. Wu, and X. Hou. 2018. “Snow Cover Influences the Thermal Regime of Active Layer in Urumqi River Source, Tianshan Mountains, China.” *Journal of Mountain Science* 15: 2622–2636. https://doi.org/10.1007/s11629-018-4856-y.

Abbreviations

AC	Alternating current
CRREL	Cold Regions Research and Engineering Laboratory
DC	Direct current
DRTSPORE	Dynamic Representation of Terrestrial Soil Predictions of Organisms' Response to the Environment
ERDC	US Army Engineer Research and Development Center
IPCC	Intergovernmental Panel on Climate Change
PTRF	Permafrost Tunnel Research Facility
QA/QC	Quality assurance/quality control
SE	Standard error
VAC	Volts alternating current
VS	Vegetated site
VWC	Volumetric water content

REPORT DOCUMENTATION PAGE

1. REPORT DATE December 2023	**2. REPORT TYPE** Final	**3. DATES COVERED** **START DATE** FY21	**END DATE** FY22

4. TITLE AND SUBTITLE

Challenges and Limitations of Using Autonomous Instrumentation for Measuring In Situ Soil Respiration in a Subarctic Boreal Forest in Alaska, USA

5a. CONTRACT NUMBER	**5b. GRANT NUMBER**	**5c. PROGRAM ELEMENT** 0602144A
5d. PROJECT NUMBER BN8	**5e. TASK NUMBER**	**5f. WORK UNIT NUMBER**

6. AUTHOR(S)

Dragos A. Vas, Elizabeth J. Corriveau, Lindsay W. Gaimaro, and Robyn A. Barbato

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

US Army Engineer Research and Development Center (ERDC)
Cold Regions Research and Engineering Laboratory (CRREL)
72 Lyme Road
Hanover, NH 03755-1290

8. PERFORMING ORGANIZATION REPORT NUMBER

ERDC/CRREL TR-23-18

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

US Army Corps of Engineers (USACE)
Washington, DC 20314-1000

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

Distribution Statement A. Approved for public release: distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

Subarctic and Arctic environments are sensitive to warming temperatures due to climate change. As soils warm, soil microorganisms break down carbon and release greenhouse gases such as methane (CH_4) and carbon dioxide (CO_2). Recent studies examining CO_2 efflux note heterogeneity of microbial activity across the landscape. To better understand carbon dynamics, our team developed a predictive model, Dynamic Representation of Terrestrial Soil Predictions of Organisms' Response to the Environment (DRTSPORE), to estimate CO_2 efflux based on soil temperature and moisture estimates. The goal of this work was to acquire respiration rates from a boreal forest located near the town of Fairbanks, Alaska, and to provide in situ measurements for the future validation effort of the DRTSPORE model estimates of CO_2 efflux in cold climates. Results show that soil temperature and seasonal soil thaw depth had the greatest impact on soil respiration. However, the instrumentation deployed significantly altered the soil temperature, moisture, and seasonal thaw depth at the survey site and very likely the soil respiration rates. These findings are important to better understand the challenges and limitations associated with the in situ data collection used for carbon efflux modeling and for estimating soil microbial activity in cold environments.

15. SUBJECT TERMS

Climate change; Cold climate; Instrument modification; Permafrost; Seasonal thaw depth; Soil respiration

16. SECURITY CLASSIFICATION OF:

a. REPORT Unclassified	**b. ABSTRACT** Unclassified	**C. THIS PAGE** Unclassified	**17. LIMITATION OF ABSTRACT** SAR	**18. NUMBER OF PAGES** 35

19a. NAME OF RESPONSIBLE PERSON Dragos Vas	**19b. TELEPHONE NUMBER (include area code)** Dragos.A.Vas@erdc.dren.mil

STANDARD FORM 298 (REV. 5/2020)

PREVIOUS EDITION IS OBSOLETE.

Prescribed by ANSI Std. Z39.18