

Article

Soil CO₂ Efflux in Scots Pine Forests in Central Siberia After Wildfire and Logging: Diurnal and Seasonal Patterns

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Abstract

Boreal forests are sensitive to external factors, and even small variations can completely alter their natural carbon (C) balance. Today, we face not only the consequences of climate change but also intensified human activity. In most cases, forest disturbances decrease ecosystem stability by disrupting key structural components, often transforming ecosystems into C sources. Soil CO₂ efflux is a critical indicator of recovery following disturbances. This study explored the impact of different disturbance types (clear-cutting alone, wildfire alone, and both) on soil CO₂ efflux for various ground-cover vegetation (lichens, green mosses, and *Sphagnum* mosses) in Scots pine forests of the Siberian central taiga. The data indicate that changes in soil CO₂ efflux are predominantly driven by wildfires in lichen-dominated plots, by clear-cutting in green moss-dominated plots, and by both wildfires and clear-cutting in *Sphagnum* moss-dominated plots. Soil CO₂ efflux was reduced by 75 and 40% in lichen- and *Sphagnum* moss-dominated plots, respectively, across burned sites compared to the undisturbed site. The impact of clear-cutting is observed in a decline of the emission rates of from 40 to 60% compared to the undisturbed site for lichen- and moss-dominated plots. The interactive effect of wildfire and logging is established in the reduction of the emission rates, and this decline depends on the type of ground cover. This finding highlights the substantial impact of wildfires and clear-cutting on the C dynamics of Siberian boreal ecosystems. The diurnal and seasonal variations in soil CO₂ efflux were most pronounced for moss-dominated plots at disturbed sites. The main factors determining emission efflux variations are carbon content, type of ground cover, and forest floor thickness. This study contributes to a better quantitative understanding of soil CO₂ efflux in boreal Scots pine forests from the differently disturbed areas.

Keywords: soil CO₂ efflux; carbon cycle; lichen; green moss; *Sphagnum*; soil temperature; soil moisture; Central Siberia

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1. Introduction

Boreal ecosystems are exceptionally vulnerable to contemporary and projected climatic changes [1,2]. High-latitude northern territories are experiencing atmospheric warming rates exceeding twice the global average, a phenomenon attributed to Arctic amplification [3,4]. The responsiveness of these ecosystems to projected climatic shifts is anticipated to be both more rapid and more pronounced than in other global biomes [5].

Soils constitute the major terrestrial C reservoir, storing 1700 Gt C in the top meter, which exceeds global vegetation fourfold, doubles atmospheric carbon, and is 160 times the current annual rate of anthropogenic CO₂ emissions [6–8]. Recent observations indicate a substantial depletion in terrestrial C stocks. Quantitatively, the boreal C sink diminished from 508 to 324 TgC per year between 1990 and 2020 [9]. Emissions of greenhouse gases from high-latitude soils constitute potentially the most significant terrestrial positive feedback to climate change [10]. Although the precise magnitude of this feedback remains uncertain, model projections under current warming scenarios indicate a potential release of 37–174 PgC (as CO₂ and CH₄) by 2100 [11].

Soil respiration is one of the largest sources of C efflux in the forest ecosystem [12]. It consists of two key compartments: microbial respiration (heterotrophic [Rh]) and plant root respiration (autotrophic). Even minor increases in soil respiration fluxes induced by climatic warming can significantly elevate atmospheric CO₂ concentrations, thereby amplifying future global warming trajectories [13,14]. Empirical studies have documented increases in soil respiration with temperature increases [15–17]. The results on warming experiment in boreal forests of Minnesota suggested that an increase in temperature of +1.7 °C stimulated a 7% increase in soil respiration, while +3.3 °C of warming resulted in a 17% escalation [18]. Warming influences soil respiration by modifying microbial metabolic activity and community composition, altering root biomass and functionality, and varying litterfall inputs [18–20]. Although the general stimulatory effect of warming on soil respiration is well established, ambient soil moisture conditions regulate short-term variability in this response. CO₂ efflux from terrestrial ecosystems is predominantly counterbalanced by photosynthetic assimilation [8,21]. However, the immense scale of these annual soil CO₂ efflux raises concerns that relatively minor perturbations to this equilibrium could exert disproportionate impacts on the atmospheric CO₂ budget.

C sequestration in boreal forests faces increasing risks due to heightened wildfire frequency and intensity. Decreasing wildfire return intervals in these slow-growth ecosystems diminish their long-term C accumulation and storage capacity, while concurrently driving post-wildfire successional shifts in vegetation assemblages [22–24]. In a North American boreal forest, the fire return interval under extreme weather conditions decreased from 130 years to 30 years [25]. Wildfires release substantial amounts of C through biomass burning [26–28]. For the last two decades, the carbon emissions after wildfires in Siberia varied from 20 to 220 Tg C per year based on the satellite data [26]. The subsequent recovery trajectory depends on various factors, including pre-disturbance growing conditions, moisture regime [29], ground cover characteristics [30], and topographic features [31], as well as disturbance characteristics such as wildfire intensity [32,33] and harvesting method [34,35]. Furthermore, ecosystems severely disturbed by wildfires persist as net C sources until regenerating or residual vegetation achieves sufficient biomass to re-establish a net C sink. Post-wildfire C losses constitute a significant fraction of total wildfire-induced C emissions [36]. Forest floor respiration represents the dominant component of post-wildfire ecosystem C efflux. Post-wildfire changes in the forest floor respiration assume heightened importance for stand-level net C balance because of the immediate cessation or severe reduction of gross primary production following a wildfire. Soil respiration typically declines by an average of from 10% to 40% following wildfires, depending on the components of soil respiration [37]. The reduction stems

from diminished autotrophic respiration and a concomitant decline in Rh, driven by the cessation of root exudate inputs, which are essential to microbial communities. More severe wildfires can also kill soil microbes and combust a significant proportion of the soil organic horizon, further suppressing Rh [38,39].

Anthropogenic climate forcing induces pervasive transformations in forest ecosystems, directly through altered temperature and precipitation cycles, and indirectly through modifications to natural disturbance cycles [40,41]. Perturbations to disturbance cycles, notably increases in frequency, spatial extent, or intensity, threaten forests' resilience and their capacity to continue to sustain ecosystem functions and associated services in the future [42–45]. Specifically, disturbances that affect a wide area or are more severe can impede recovery processes, which are central to ecosystem resilience [46], potentially triggering successional trajectories toward alternative forest states or non-forested ecosystems [47–50]. Clear-cutting is one of the major causes of anthropogenic disturbances. At the ecosystem scale, this practice can induce a transition from a C sink to a C source, driven by biomass exportation and intensified soil Rh [51,52]. Moreover, clear-cutting induces profound landscape changes, significantly impacting habitat structure and biodiversity [53,54]. Furthermore, harvested sites experience multi-annual changes in root respiration dynamics, organic matter decomposition rates, and associated microbial biomass respiration [55–57]. Soil emissions after clear-cut logging dropped by a huge range from 6 to 60% compared to the initial flux rate [58]. Consequently, changes in soil CO₂ efflux following clear-cutting have been the subject of extensive scientific investigation [59,60].

Most research on the effects of disturbed sites on soil C efflux in boreal forests has focused on either post-logging (without fire) or post-wildfire (without logging) scenarios. The rising frequency of these separate disturbances has driven significant research into their combined impacts. Nowadays, the understanding of the interactive effect of wildfire and logging activities on soil C efflux is limited, and interactions are of particular interest. Conceptually, in some cases, the presence of one disturbance enhances the consequences of the other. However, sometimes, in the short-term time scale of disturbance occurrence, we observe a complex or synergetic effect resulting in a reduction in the recovery rates [61]. One more trajectory is related to the specific condition of the area and its ability to withstand different types of disturbances. The scientific contribution in our case is assessing the combined effects of fire and logging on soil emissions rates, focusing on the interactive non-additive effects. In a few related studies, the opposite results were obtained. In boreal forests in Sweden, salvage logging after a high-severity fire had no significant effects on soil carbon fluxes [32]. However, in a Siberian boreal forest, the combined effect of wildfire and clear-cutting resulted in a significant decrease in CO₂ efflux by 50–80% compared to the undisturbed area [58].

In Siberia, particularly in the Krasnoyarsk krai, wildfires and clear-cutting are the most destructive factors in the forest ecosystems [62–64]. Over the last decade, 6×10^6 hectares of Siberian forests were affected by wildfires, an area twofold larger than during the previous decade [65]. The timber production in Krasnoyarsk krai accounts for 10% of the national total (<https://fedstat.ru/indicator/37848>, accessed on 5 May 2026). This study primarily aimed to characterize soil CO₂ efflux from disturbed areas in the boreal zone of Central Siberia during the vegetation season. To achieve this aim, the following objectives were established: (1) to estimate the diurnal and seasonal variation in soil CO₂ efflux, (2) to assess the relationships between the soil CO₂ efflux and soil environmental conditions, and (3) to quantify the cumulative impact of different disturbance types on the amounts of CO₂ released.

2. Materials and Methods

2.1. Study Area

This study was conducted in the central taiga, located in the Turukhansk district of Krasnoyarsk krai (60°48' N, 89°21' E) near the Zotino Tall Tower Observatory (<http://www.zottoproject.org>, accessed on 11 July 2025). The study area is characterized by a severe continental climate, classified as Dfc according to the Köppen–Geiger system [66]. For the period of instrumental measurements from 1936 to 2024 (Bor Station, World Meteorological Organization ID: 23884), the absolute air temperature ranged from −54 °C to +36 °C, with an average annual air temperature of −3.4 °C. The average annual atmospheric precipitation is 600 mm, and the average atmospheric precipitation during the growing season (GS), spanning June to September, is 263 mm (<http://www.meteo.ru/>, accessed on 21 June 2025).

2.2. Study Sites

Study sites were established in Scots pine (*Pinus sylvestris* L.) forests and represented different disturbance types (Figure 1): unlogged/unburned, unlogged/burned (following a very severe wildfire), logged/unburned (following clear-cutting), and logged/burned (affected by both wildfires and clear-cutting). The adjacent study sites featured stands with similar baseline characteristics before the fire and logging disturbances. All of these disturbances occurred in 2018. Originating from past wildfires, these pure Scots pine stands comprised four distinct age classes: 275, 235, 80, and 40 years. The trees averaged 40.8 cm in diameter at breast height (DBH) and 19.3 m in height [67]. The understory layer is also presented by Scots pine and includes two age classes: 5 and 14 years, with a mean height of 0.2 m [63].

At each of the four sites, two study plots were identified—lichen-dominated and moss-dominated—depending on the dominant living ground vegetation before the disturbance. At the unlogged/unburned or control site, the ground cover was also represented by both lichen- and moss-dominated plots (Figure 1b). The lichen-dominated plots were primarily covered by *Cladonia stellaris* (Opiz) Pouzaret Vezda, *C. arbuscula* (Wallr) Flot., and *C. rangiferina* (L.) Weber ex F.H.Wigg. The green moss-dominated plots were covered by *Pleurozium schreberi* (Brid.) Mitt, while the *Sphagnum* moss-dominated plots were primarily covered by *S. magellanicum* Brid., *S. rubellum* Wilson, and *S. palustre* L. Because clearcutting occurred during winter, the living ground cover at all logged sites remained largely undisturbed. Severe surface fire occurred in summer and completely consumed the lichen-dominated plots. However, in moss-dominated plots, the fire consumed only the upper layer. The thickness of the forest floor layer [63] for lichen-dominated disturbed plots varied from 0.5 cm at the burned site to 4.5 cm at the logged site. In moss-dominated disturbed plots, the thickness varied from 3.5 cm at the logged/burned site with feather mosses to 18.5 cm at the logged site with *Sphagnum* mosses.

In the study area, the soils were formed from glaciofluvial deposits and characterized by a predominance of sand in the upper part of the profile (top 1–2 m). The soils in the lichen-dominated plots were Albic Podzols, and the soils in the moss-dominated plots were Hiatic Podzols. Porosity of the Albic Podzol (E horizon) typically ranges from 40% to 50% [68]. The pore scape is mainly consists of macropores, and as a consequence is characterized by a poor water-holding capacity and excessive drainage. Porosity of the Histic Podzol (O horizon) ranges from 75% to 85% by volume. Predominantly consisting of macropores and mesopores, this material retains significant moisture but is prone to frequent waterlogging. The H₂O pH for these four sites and both lichen-dominated and moss-dominated plots is strongly acidic (H₂O pH is 3.8–3.9 in the O horizon). At the burned site, the upper horizons for lichen plots are 4.6, and for moss plots are 4.3. After

logging, the pH does not change dramatically compared to the control site, and for both plot types is around 4. In terms of soil organic matter, the main differences occurred mostly in the upper O horizon at the burned and burned/logged sites and between lichen- and moss-dominated plots. The carbon content for moss-dominated plots was 1.4–2.8 times higher than for lichen-dominated plots. At the burned site with lichen cover, carbon content was 16.2%, whereas with moss cover it was 36.7%. At the burned/logged site with lichen cover, C content was 13.5%, and with moss cover it was 38.4% [66]. The soil texture analysis was performed by standard Kachinsky's pipette method according to GOST R 12536-2014 [69].

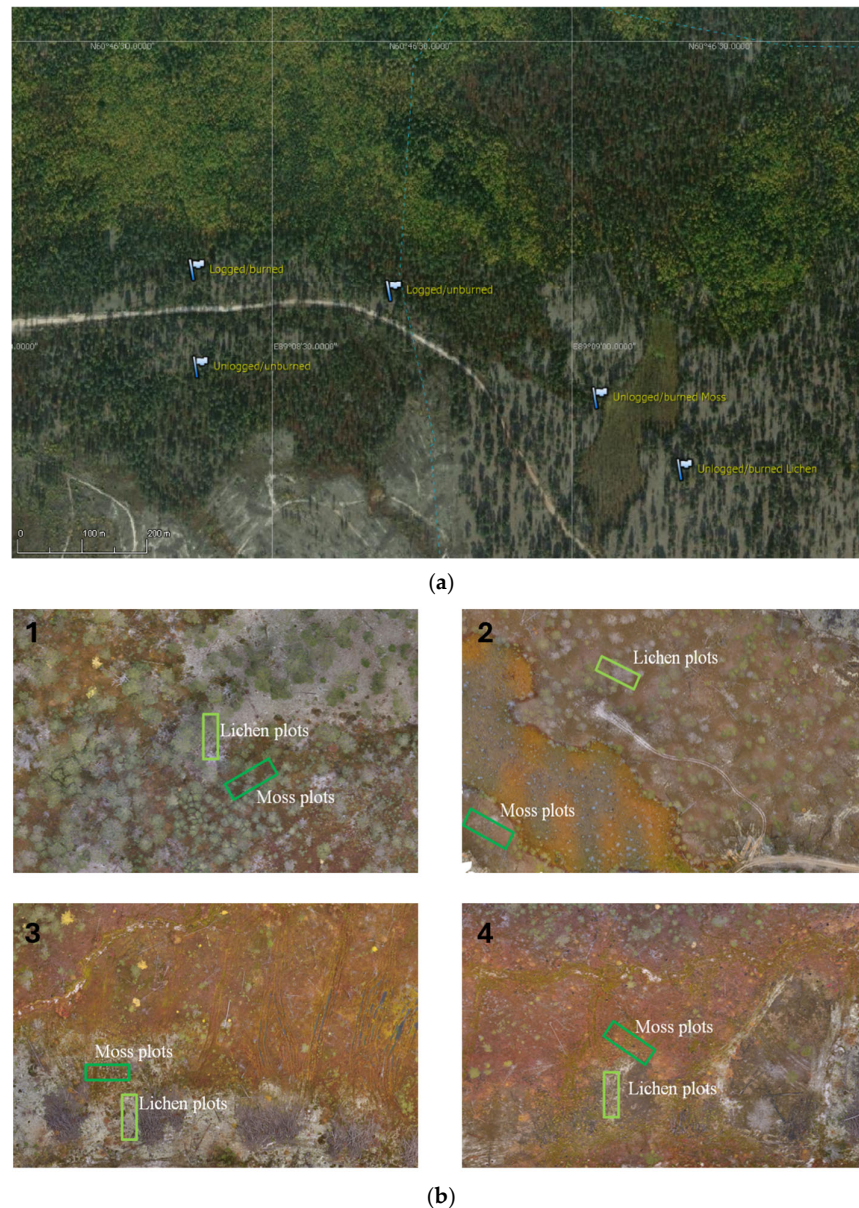


Figure 1. The map of study sites from SASPlanet GIS software version v.230909 (a) and aerial orthogonal images (b) of the study sites: (1) unlogged/unburned, (2) unlogged/burned, (3) logged/unburned, and (4) logged/burned.

The meteorological conditions of the study sites were obtained from the stations located at each site on lichen plots. Measurements were recorded at 30 min intervals during

the whole year. For our estimation, we chose the period from 1 June to 30 September 2024. The highest mean air temperature for the season was recorded at the logged/unburned site (Table 1), whereas the minimum temperature was observed at the unlogged/unburned site. These disparities are likely attributable to canopy density, which directly regulates surface heating and radiative forcing. The lowest temperatures for the season were recorded at the unlogged/unburned and logged/burned sites. Soil temperatures exhibited more pronounced differentiation between sites. The largest temperature gradient was at the logged/burned site: the max soil temperature was 26.0 °C, and the min temperature was 0.6 °C. However, the highest mean seasonal soil temperature was at the unlogged site burned by high-severity fire. Regarding the soil moisture conditions, the highest mean seasonal soil moisture was observed at the unlogged/burned site ($0.08 \pm 0.01 \text{ m}^3 \text{ m}^{-3}$), while the smallest values occurred at the logged/unburned site ($0.02 \pm 0.01 \text{ m}^3 \text{ m}^{-3}$). The largest moisture gradient was observed at the undisturbed site. On a scale of 30 min measurement resolution, the range of soil moisture values was much wider: at the unlogged/unburned site it was from 0.03 to $0.19 \text{ m}^3 \text{ m}^{-3}$, at the logged/unburned site it was from 0.01 to $0.07 \text{ m}^3 \text{ m}^{-3}$, at the unlogged/burned site it was from 0.06 to $0.22 \text{ m}^3 \text{ m}^{-3}$, and at the logged/burned site it was from 0.02 to $0.14 \text{ m}^3 \text{ m}^{-3}$.

Table 1. Meteorological characteristics at the study sites during the growing season (GS, June–September).

Site	Air Temperature, °C		
	mean $\pm$ SD	Max	Min
Unlogged/unburned	12.98 ± 6.73	24.76	−1.00
Logged/unburned	15.08 ± 5.00	24.59	1.12
Unlogged/burned	14.36 ± 4.98	24.74	1.17
Logged/burned	13.82 ± 5.54	24.91	−1.01
	Soil temperature, °C		
	mean $\pm$ SD	Max	Min
Unlogged/unburned	12.78 ± 4.62	20.31	3.15
Logged/unburned	15.60 ± 3.55	21.55	5.32
Unlogged/burned	18.29 ± 6.83	28.19	5.50
Logged/burned	14.82 ± 5.71	25.97	0.61
	Soil moisture, $\text{m}^3 \text{ m}^{-3}$		
	mean $\pm$ SD	Max	Min
Unlogged/unburned	0.07 ± 0.02	0.12	0.03
Logged/unburned	0.02 ± 0.01	0.04	0.01
Unlogged/burned	0.08 ± 0.01	0.11	0.06
Logged/burned	0.04 ± 0.01	0.09	0.02

The meteorological stations are located on the lichen-dominated plot at each site. The data are presented as the mean $\pm$ standard deviation (SD) of daily measurements.

2.3. CO₂ Efflux Measurements

Soil CO₂ efflux was measured throughout the GS (June–September) in 2024. Ten measurements were taken at each site for each plot, yielding 280 measurements in total. Before the measurements, polyvinyl chloride collars with a 20 cm inner diameter were installed at each study site: three in lichen-dominated plots, and four in moss-dominated plots (two each for green and *Sphagnum* mosses). Soil CO₂ efflux was measured using an infrared gas analyzer (LI-8100A; Li-cor Biosciences Inc., Lincoln, NE, USA) during the daylight period from 10:00 to 16:00 using a survey chamber (8100-103; Li-cor Biosciences Inc.). Diurnal measurements of soil CO₂ efflux were conducted for all collars to account for the high variability in soil CO₂ efflux across ground cover types. Four 6-h measurement cycles were conducted over 24 h. We conducted the diurnal cycle measurements in two periods of the growing season (GS). These periods were chosen for the several conditions

they represent. Early GS, or the start of the growing season for our region, characterizes the ecosystem behavior when the system is in the stage of stable initial conditions after spring, and most of the biogeochemical processes are controlled by temperature rise. Peak GS usually lasts from the second half of July to the first half of August. This period is specified as the peak of air and soil temperatures, combined with regulation of the ecosystem processes from the soil moisture side. In our case, we decided to focus on both of these periods to catch the environmental control factors in different periods of the growing season for three types of ground cover.

Measurements were performed in triplicate for each collar, and the mean was calculated. The measurement time was set to 2 min, with a 30 s interval between replicates, yielding 21 measurements per sampling day at each site.

Soil CO₂ efflux measurements were coupled with soil temperature records at depths of 5, 10, and 15 cm with a type E soil temperature probe (Omega, GA, USA) and SWC measurements at a depth of 5 cm with a soil moisture sensor (ML3 ThetaProbe; Delta-T Devices Ltd., Cambridge, UK).

2.4. Analytic Procedure

The raw data series were processed and analyzed using the LI-8100A data analysis software for Windows (version 4.0.0). Prior to analysis, the data were checked for normal distribution and homogeneity of variance by using the Shapiro–Wilk normality test. The results obtained for SR data were $W = 0.90668$, $p < 0.001$, and for NSE fluxes distribution $W = 0.96689$, $p < 0.001$. All statistical analyses were performed using the R statistical software [70] with specialized libraries, including *dplyr* [71], *tidyverse* [72], *lubridate* [73], *ggplot2* [74], *data.table* [75], *corrplot* [76], and *PerformanceAnalytics* [77]. A $p < 0.05$ was considered statistically significant. Daily averages of soil CO₂ efflux were used to examine the effect of soil temperature and SWC. The relationships between soil CO₂ efflux and environmental factors were examined using exponential and quadratic functions. Soil CO₂ efflux was compared between plots using *t*-tests (equal variances). Correlations between soil CO₂ efflux and soil microclimatic factors were assessed using Pearson's correlation coefficient (r). The effects of soil temperature and SWC on soil CO₂ efflux were explored using one- and two-way repeated-measures analysis of variance (ANOVA).

To adjust for the nested structure of the data and repeated measurements within subjects, we fitted a linear mixed-effects model (LMM) using the *lme4* package [78]. The model included nine independent variables (predictors) as fixed effects, and a random intercept for each participant (soil temperature— T_{soil}) to account for baseline individual differences. *P*-values for fixed effects were calculated using Satterthwaite's degrees of freedom approximation via the *lmerTest* package [79].

3. Results

3.1. Diurnal Cycle

The diurnal cycle of soil CO₂ efflux was analyzed for the two periods (Figure 2), early GS (11–13 June) and peak GS (23–25 July), when we expected the lowest and highest soil CO₂ efflux, respectively [80]. The diurnal CO₂ efflux varied significantly both between study sites with different disturbance histories and plots dominated by specific vegetation types. In the early GS, soil CO₂ efflux was generally twofold lower ($p < 0.05$) across disturbed sites than across undisturbed sites. However, a notable exception was observed at the unlogged/burned site, where the soil CO₂ efflux from the *Sphagnum* moss-dominated plots was 55% higher on average compared to the unlogged/unburned site ($p < 0.001$).

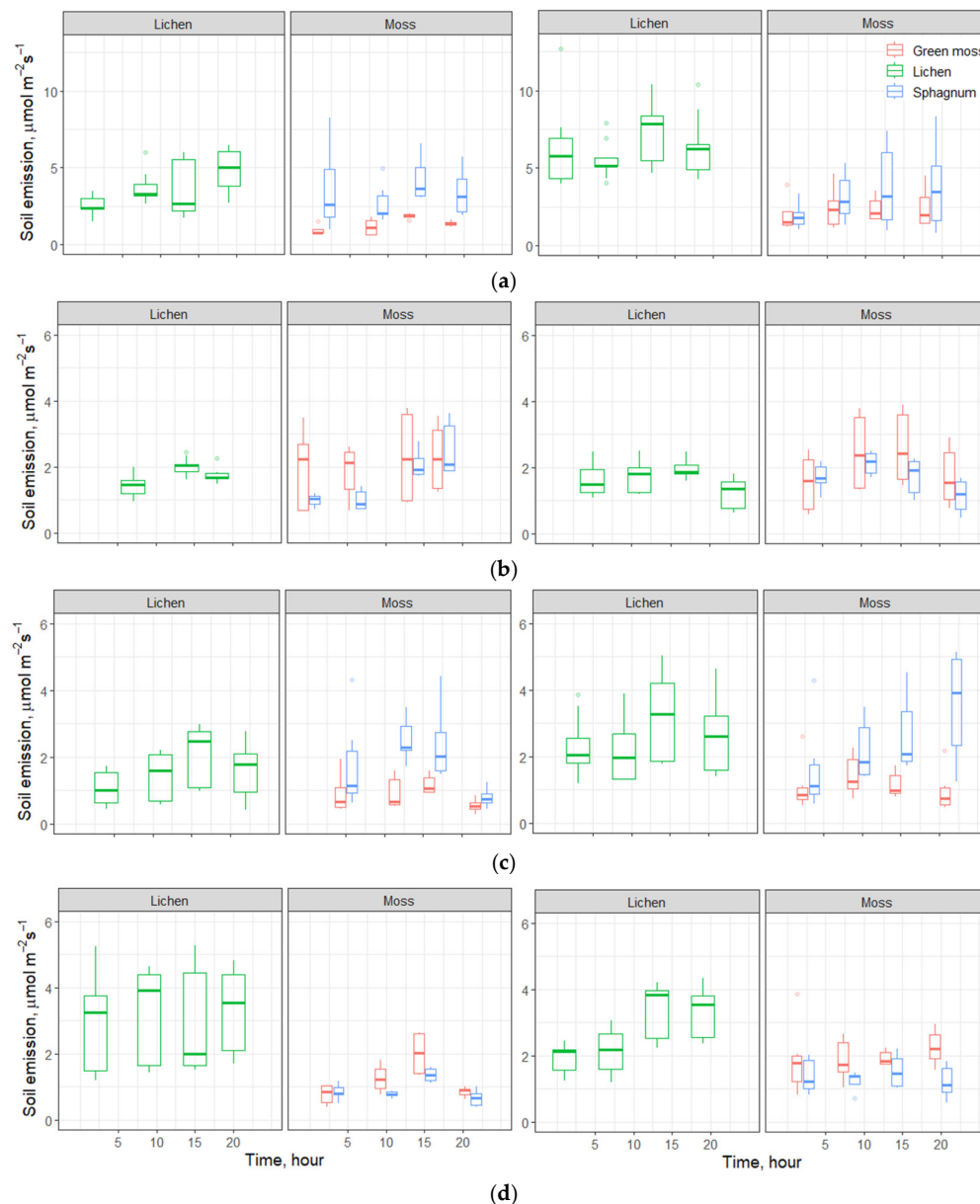


Figure 2. Diurnal variations in soil CO₂ effluxes for the early (left panel) and peak (right panel) GS for plots with different dominant ground-cover vegetation (lichens and mosses) across study sites with different disturbance histories: (a) unlogged/unburned, (b) unlogged/burned, (c) logged/unburned, and (d) logged/burned. The box represents 25th–75th percentiles, the center line indicates the median, the dot inside the box stands for the mean value, the whiskers indicate minimum/maximum values, and dots outside the whiskers show outliers.

The diurnal pattern also differed between sites. For example, the undisturbed sites showed prominent diurnal variations in soil CO₂ efflux: a single peak generally in the evening hours (~19:00) in the lichen-dominated plots, but two peaks, one at night and one at noon, in the moss-dominated plots. In contrast, the disturbed sites exhibited no evidence of diurnal variation in soil CO₂ efflux, except for a slight increase during the daytime (16:00–18:00). In the peak GS, the diurnal dynamic was observed on the logged/unburned and logged/burned sites, both for lichen-dominated and *Sphagnum* moss-dominated plots; the logged/unburned site demonstrates enhanced CO₂ rates in the evening. The increase in soil CO₂ efflux in July (the peak GS) compared with June (the early GS)

across the disturbed sites occurred once at the logged/unburned site: the daytime effluxes were twofold higher compared to the nighttime for lichen-dominated plots, while the *Sphagnum* moss-dominated plots showed a similar behavior at nighttime.

3.2. Seasonal Dynamics of Soil Environmental Conditions and Soil CO₂ Efflux

Environmental conditions (soil temperature and SWC) were compared between undisturbed and disturbed sites (Figure 3). All disturbed sites exhibited higher mean seasonal soil temperatures than undisturbed sites, with the difference largest for lichen-dominated plots. The mean seasonal soil temperature was 20% higher in disturbed sites than in undisturbed sites ($p < 0.001$). For green moss-dominated plots, the mean seasonal soil temperature was 15% higher in disturbed sites than in undisturbed sites ($p < 0.005$). For *Sphagnum* moss-dominated plots, the mean seasonal soil temperature was 15% higher in unlogged/burned and logged/burned sites than in the unlogged/unburned site ($p < 0.001$), whereas it was similar between logged/unburned and unlogged/unburned sites.

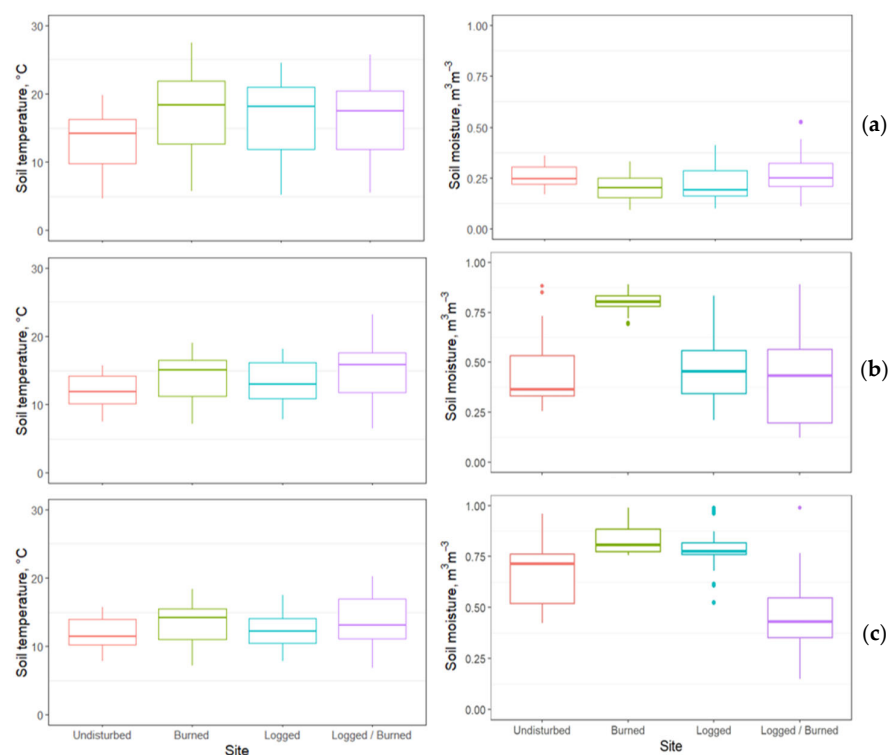
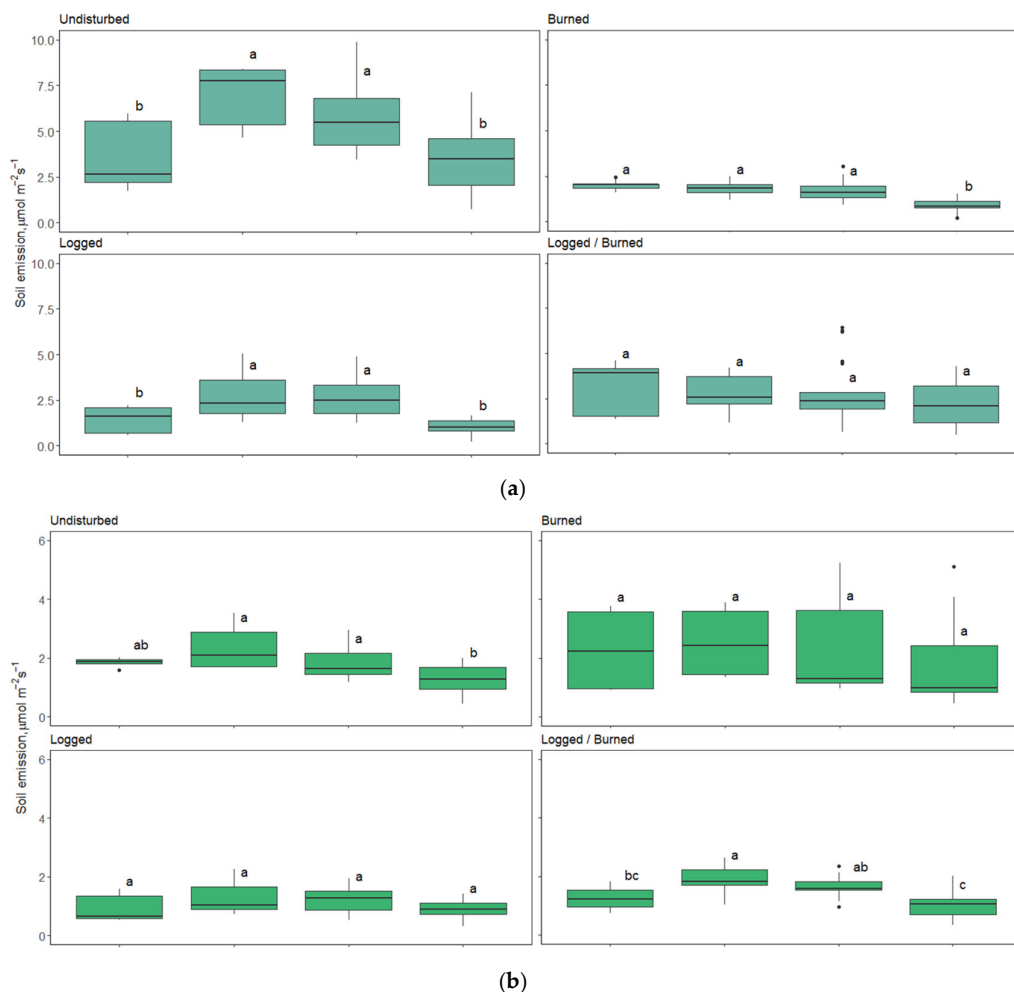


Figure 3. Soil environmental conditions at the study sites in plots with different dominant ground-cover vegetation: (a) lichen-dominated, (b) green moss-dominated, and (c) *Sphagnum* moss-dominated.

SWC differed significantly between lichen-dominated and moss-dominated plots across the disturbed sites compared with the undisturbed sites. For the lichen-dominated plots, the mean seasonal SWC was 30% lower at the logged/burned site than at the unlogged/unburned site ($0.25 \pm 0.05 \text{ m}^3 \text{ m}^{-3}$; $p < 0.005$). The moss-dominated plots showed the opposite pattern. For the *Sphagnum* moss-dominated plots, the mean seasonal SWC was 24% and 33% higher in logged/unburned ($0.78 \pm 0.11 \text{ m}^3 \text{ m}^{-3}$) and unlogged/burned ($0.84 \pm 0.07 \text{ m}^3 \text{ m}^{-3}$) sites compared to the unlogged/unburned site ($p < 0.001$), respectively. However, the mean seasonal SWC was 29% lower in the logged/burned site ($0.45 \pm 0.21 \text{ m}^3 \text{ m}^{-3}$) than in the unlogged/unburned site ($0.63 \pm 0.16 \text{ m}^3 \text{ m}^{-3}$; $p < 0.001$). Notably, mean seasonal SWC at two of the three green moss-dominated plots in logged/unburned and

logged/burned sites was similar to that in the unlogged/unburned site. However, the mean seasonal SWC was 45% higher in the unlogged/burned site ($0.81 \pm 0.04 \text{ m}^3 \text{ m}^{-3}$) than in the unlogged/unburned site ($0.44 \pm 0.16 \text{ m}^3 \text{ m}^{-3}$; $p < 0.001$).

The seasonal dynamics of soil CO_2 efflux at disturbed sites showed distinct features depending on the disturbance type (Figure 4). At the unlogged/burned site, no seasonal trends in soil CO_2 efflux were identified for all ground-cover types. However, at burned sites, soil CO_2 efflux varied greatly throughout the GS in green moss-dominated plots (Figure 4b). At the logged/unburned site, soil CO_2 efflux in *Sphagnum* moss-dominated plots peaked in the middle of the GS (second half of July to the beginning of August; $4.26 \pm 0.99 \mu\text{mol m}^{-2} \text{ s}^{-1}$). At the logged/unburned site, the lichen-dominated plots also exhibited visible seasonal variation in soil CO_2 efflux. At all disturbed sites, lichen-dominated plots showed at least twofold lower soil CO_2 efflux compared to the undisturbed site throughout the GS. At the logged/burned site, seasonal variation in soil CO_2 efflux was evident in moss-dominated plots, peaking in the middle of the GS in both *Sphagnum* moss-dominated ($2.20 \mu\text{mol m}^{-2} \text{ s}^{-1}$) and green moss-dominated ($2.65 \mu\text{mol m}^{-2} \text{ s}^{-1}$) plots. One additional feature was that *Sphagnum* moss-dominated plots in two of the three disturbed sites exhibited seasonality in soil CO_2 efflux.



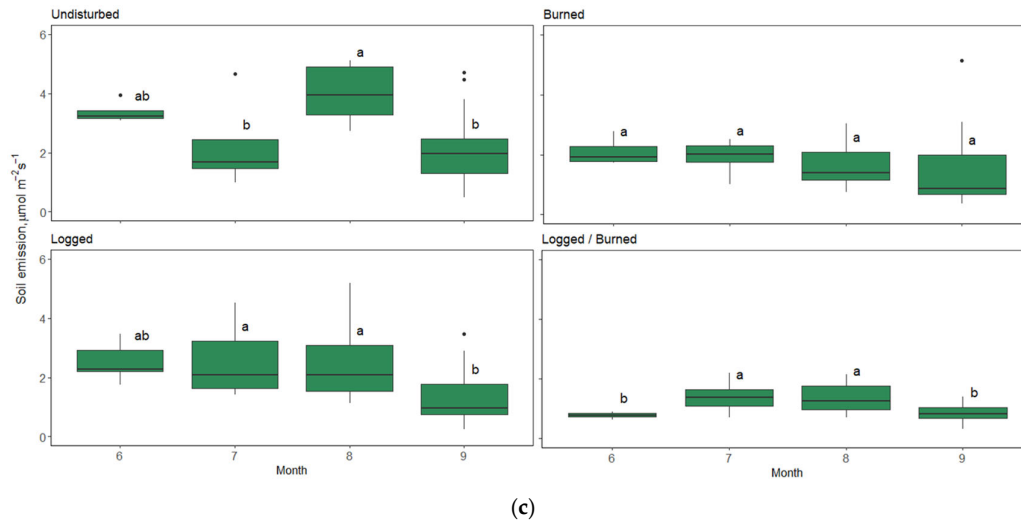


Figure 4. Monthly dynamics in soil CO₂ efflux during the GS for plots with different dominant ground-cover vegetation: (a) lichen-dominated, (b) green moss-dominated, and (c) *Sphagnum* moss-dominated. The letters indicate significant differences (Tukey HSD test, $p < 0.05$) between the soil efflux values for different months.

3.3. Relationships Between Soil CO₂ Efflux, Soil Temperature, and SWC

The relationship between soil CO₂ efflux and soil temperature was examined using the exponential function (Figure 5). The correlation was strongest in the lichen-dominated plots in the unlogged/burned ($R^2_{adj.} = 0.60$, $p < 0.001$) and logged/unburned ($R^2_{adj.} = 0.42$, $p < 0.001$) sites, and notably weaker in the unlogged/unburned site ($R^2_{adj.} = 0.27$, $p < 0.001$). Due to the high variability in soil CO₂ efflux in the logged/burned site, no correlation between soil CO₂ efflux and soil temperature was observed. Unlike the lichen-dominated plots, soil CO₂ efflux was moderately correlated with soil temperature in both *Sphagnum* moss-dominated ($R^2_{adj.} = 0.49$, $p < 0.001$) and green moss-dominated ($R^2_{adj.} = 0.43$, $p < 0.001$) plots in the logged/burned site. However, soil CO₂ efflux did not correlate significantly with soil temperature in the moss-dominated plots in the unlogged/burned and logged/unburned sites.

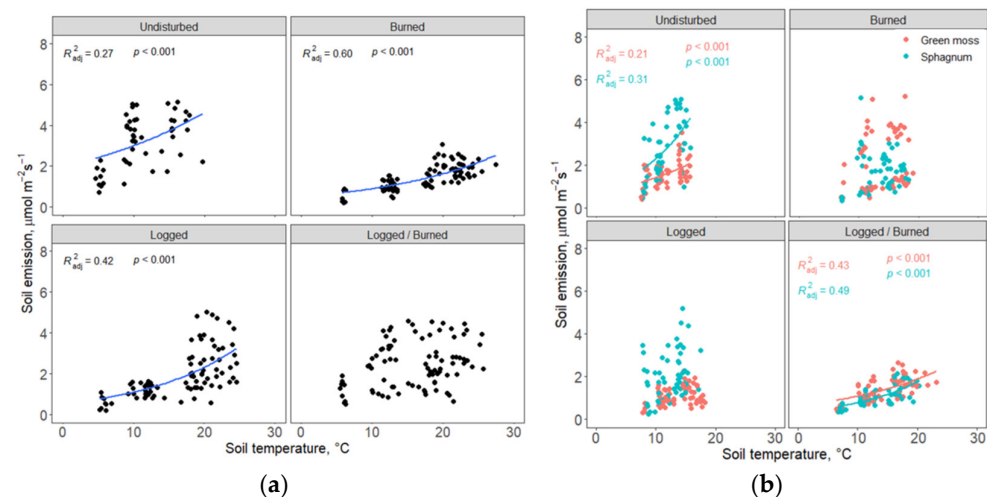


Figure 5. Seasonal soil CO₂ efflux as a function of soil temperature for plots with the different dominant ground-cover vegetation across sites with different disturbance histories: (a) lichen-dominated and (b) moss-dominated plots.

In contrast, soil CO₂ efflux appeared less influenced by SWC (Figure 6). For lichen-dominated plots, soil CO₂ efflux correlated weakly with SWC at burned sites ($R^2_{adj.} = 0.17$, $p < 0.001$). In contrast, for *Sphagnum* moss-dominated and green moss-dominated plots, soil CO₂ efflux did not correlate significantly with SWC at undisturbed and disturbed sites. Notably, soil CO₂ efflux varied greatly across lichen-dominated plots at disturbed sites at the same SWC.

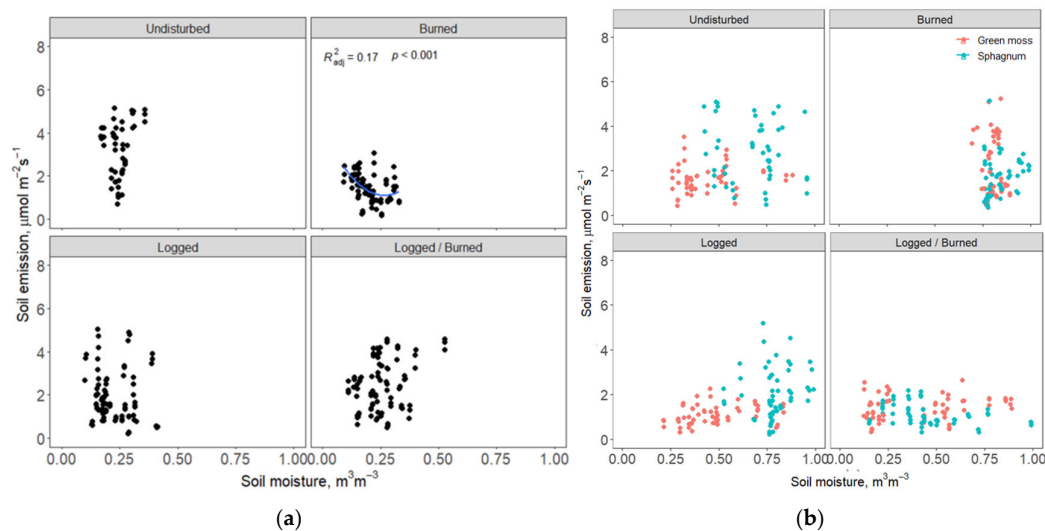


Figure 6. Seasonal soil CO₂ efflux as a function of soil water content (SWC) for plots with the different dominant ground-cover vegetation across sites with different disturbance histories: (a) lichen-dominated and (b) moss-dominated plots.

To detect the effect of the whole list of external parameters on soil CO₂ emission rates, we applied the mixed-effects model (Table 2). The fitted linear mixed-effects model demonstrated a robust fit, with the fixed and random effects combined accounting for 44% of the total variance (Conditional $R^2 = 0.44$). Notably, the 9 fixed predictors alone explained 41% of the variance in soil CO₂ efflux (Marginal $R^2 = 0.41$), indicating that the identified independent variables possess substantial explanatory power. The minimal difference between the conditional and marginal R^2 values (3%) suggests that the observed effects are highly consistent across individual subjects, rather than being driven by baseline group-level variations. Among the 9 predictors analyzed, carbon content (Corg) emerged as a statistically significant positive predictor of the soil emission rates ($\beta = 0.75$, $SE = 0.06$, $p < 0.001$). Since predictors were standardized, a one-standard-deviation increase in Corg was associated with a 0.75-unit increase in the soil emission rates. The characteristics of the study site, such as lichen- or moss-dominated cover (Plot), also showed a significant positive effect ($\beta = 0.63$, $SE = 0.16$, $p < 0.001$). The following two predictors—soil temperature (Tsoil) and the thickness of the forest floor layer (Forest floor)—may also significantly change the soil CO₂ emission. Just one out of nine predictors demonstrated a negative and not statistically significant relationship (Clay content).

Table 2. Results of mixed-effects model analysis of the soil emission in a seasonal scale at four sites.

Predictor	Estimate (β)	Standard Error (SE)	t-Value	p-Value
(Intersept)	1.87	0.03	58.50	<0.001
Corg	0.75	0.06	13.63	<0.001
Plot	0.63	0.16	4.04	<0.001
Forest floor	0.54	0.09	5.82	<0.001
Tsoil	0.52	0.04	14.66	<0.001
SWC	0.37	0.06	6.22	<0.001
pH	0.36	0.08	4.25	<0.001
Cover type	0.40	0.12	3.27	<0.01
Site	0.29	0.07	4.04	<0.001
Clay content	−0.20	0.16	−1.25	0.21

3.4. Cumulative Seasonal Soil CO₂ Efflux

The cumulative seasonal soil CO₂ efflux varied significantly ($p < 0.05$) across sites with different disturbance histories and plots with different dominant ground-cover vegetation (Figure 7). Surprisingly, the cumulative seasonal soil CO₂ efflux was highest across the lichen-dominated plots (Figure 7a). In the unlogged/unburned site, the cumulative seasonal soil CO₂ efflux for the lichen-dominated plots (672.0 g C m^{−2}) was 70% higher than that of the green moss-dominated plots and 40% higher than that of the *Sphagnum* moss-dominated plots. Among the disturbed sites, the greatest difference among plots with different dominant ground-cover vegetation was observed at the logged/burned site. At these sites, the cumulative seasonal soil CO₂ efflux in the lichen-dominated plots (324.1 g C m^{−2}) was 45% higher than that in the green moss-dominated plots and 56% higher than that in the *Sphagnum* moss-dominated plots. At the logged/unburned site, the cumulative seasonal soil CO₂ efflux was similar between the lichen-dominated and *Sphagnum* moss-dominated plots. At the unlogged/burned site, the cumulative seasonal soil CO₂ efflux in the lichen-dominant plots was 38% lower than in the green moss-dominated plots and 28% lower than in the *Sphagnum* moss-dominated plots.

In the green moss-dominated plots (Figure 7b), the cumulative seasonal soil CO₂ efflux was highest at the unlogged/burned site (279.2 g C m^{−2}), which was 30% higher compared to the unlogged/unburned site. For the lichen-dominated plots, the most pronounced difference in cumulative soil CO₂ efflux during the entire GS was between the unlogged/unburned and unlogged/burned sites ($p < 0.05$). For the green moss-dominated plots, the most pronounced difference in cumulative soil CO₂ efflux during the entire GS was between the unlogged/unburned and logged/unburned sites ($p < 0.005$). The cumulative seasonal soil CO₂ efflux was lowest at the logged/unburned site (124.1 g C m^{−2}), 40% lower than at the unlogged/unburned site (214.3 g C m^{−2}). In contrast, the cumulative seasonal soil CO₂ efflux was 15% lower at the logged/burned site (176.3 g C m^{−2}) than at the unlogged/unburned site (214.3 g C m^{−2}).

The cumulative seasonal soil CO₂ efflux differed significantly between the *Sphagnum* moss-dominated plots and the green moss-dominated plots (Figure 7c, $p < 0.005$). The cumulative seasonal soil CO₂ efflux was twofold higher from *Sphagnum* moss-dominated plots than from green moss-dominated plots in the logged/unburned site. However, at the unburned/burned and logged/burned sites, the seasonal cumulative soil CO₂ efflux from *Sphagnum* moss-dominated plots was 15% (239.8 g C m^{−2}) and 20% (142.3 g C m^{−2}) lower than from the green moss-dominated plots, respectively.

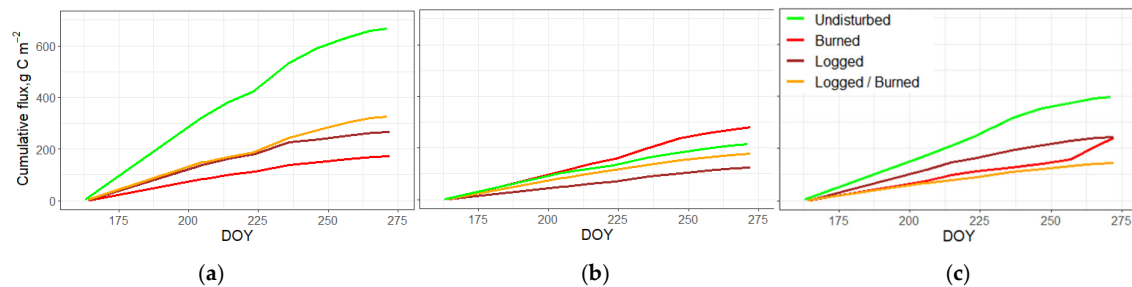


Figure 7. Cumulative seasonal soil CO₂ efflux from plots with different dominant ground-cover vegetation across sites with different disturbance histories: (a) lichen-dominated, (b) green moss-dominated, and (c) *Sphagnum* moss-dominated plots.

During the first part of the GS, increases in soil CO₂ efflux were highest in the lichen-dominated plots at the logged/burned site. Similar increases in soil CO₂ efflux were observed in the green moss-dominated plot at the unlogged/burned site and the *Sphagnum* moss-dominated plot at the logged/unburned site. Among the lichen-dominated plots at disturbed sites, cumulative soil CO₂ efflux during the first part of the GS was highest at the logged/burned site (186.0 g C m⁻²), followed by the logged/unburned site (180.5 g C m⁻²). During the second part of the GS, soil CO₂ efflux patterns varied across disturbed sites. Soil CO₂ efflux decreased significantly in four plots: green moss-dominated plots in the unlogged/burned and logged/burned sites, the *Sphagnum* moss-dominated plot in the logged/unburned site, and the lichen-dominated plot in the unlogged/burned site. No notable changes in soil CO₂ efflux were observed for the other plots at disturbed sites. Notably, soil CO₂ efflux increased further in the *Sphagnum* moss-dominated plot in the burned site during the second half of the GS.

4. Discussion

4.1. Soil CO₂ Efflux Dynamics

Most of the studied disturbed sites showed lower seasonal soil CO₂ efflux than the undisturbed site. Moreover, seasonal variations in soil CO₂ efflux were observed at only a few of the studied sites. Soil CO₂ efflux in the lichen-dominated plots was primarily driven by wildfires. For the moss-dominated plots, which exhibited distinct soil moisture levels compared with the lichen-dominated plots, soil CO₂ efflux was driven by both wildfires and clear-cutting. Therefore, our findings clearly distinguish the impact of ground-cover vegetation type on soil CO₂ efflux and highlight which disturbance type is more influential across different ground-cover vegetation types.

Interestingly, soil CO₂ efflux differed between lichen- and moss-dominated plots, potentially due to differences in microclimatic conditions, primarily soil moisture content (Figure 3). Another important point related to the seasonal dynamics of soil CO₂ efflux is the largely similar range and rates at the undisturbed and disturbed sites for green moss-dominated and *Sphagnum* moss-dominated plots. However, soil CO₂ efflux was twofold lower at the logged/burned site than at the unlogged/unburned site. Therefore, our data support the notion that moss cover better protects against the impacts of disturbances due to wetter soil conditions and thicker ground cover. The main difference in responses between *Sphagnum* moss-dominated and green moss-dominated plots at disturbed and undisturbed sites is that soil CO₂ efflux was significantly higher in the former.

Some studies have suggested that clear-cutting can increase CO₂ efflux by 40–50% [81–83]. However, the increase in emission rates is possible when the measurements are conducted right after the occurrence of disturbance, and we observed the results of several stress mechanisms as a response. The other studies have reported the opposite, showing

an evident decrease in soil CO₂ efflux after clear-cutting, especially in spring and summer [84,85]. In their study of mixed forests in the northernmost part of Japan, Aguilos et al. [86] found that the exact point, the so-called “C compensation point,” when the ecosystem turns back to a sink of atmospheric CO₂ was 7 years. In our study, the influence of clear-cutting varied with the type of ground-cover vegetation. For instance, in 6 years, the soil CO₂ efflux from the moss-dominated plots after clear-cutting was comparable to the undisturbed site, whereas the lichen-dominated plots still showed significantly lower CO₂ efflux at the disturbed sites. Here, we may turn to the carbon content in lichen- and moss-dominated plots, where, after disturbances in lichen-dominated plots from severe surface fire and clear-cutting, we monitored a significant decline in carbon content compared to the undisturbed site by 70 and 50%, respectively. Another reason is the destruction of the forest floor layer itself. After fire and logging at lichen-dominated plots, the thickness of the forest floor layer dropped by 80–90% compared to the undisturbed site.

The influence of wildfires on soil CO₂ efflux varies significantly by fire severity [32], forest type [87], and forest management strategy [20,88], with further increases in soil CO₂ efflux following succession. In most cases, observations show a decline in soil CO₂ efflux after wildfires [89], as was observed in the lichen-dominated and *Sphagnum* moss-dominated plots in our study. In particular, in the lichen-dominated and *Sphagnum* moss-dominated plots, soil CO₂ efflux was 55% and 40% lower, respectively, at the burned/unlogged site compared with the unlogged/unburned site. In contrast, green moss-dominated plots showed the opposite pattern, with soil CO₂ efflux higher in the first half of the GS and varying throughout the GS. Here, we should account for the soil moisture conditions at this site (Figure 3b), which were extremely high throughout the entire GS (on average 45% higher compared to the unlogged/unburned site). The combined effect of the wildfire and clear-cutting at the logged/burned site differed significantly ($p < 0.005$) between the moss-dominated and lichen-dominated plots. The smallest effect was observed in the green moss-dominated plots, where soil CO₂ efflux was 20% lower compared with the unlogged/unburned site ($p < 0.05$). In contrast, soil CO₂ efflux was on average 62% lower in the *Sphagnum* moss-dominated plots compared with the unlogged/unburned site.

Regarding the diurnal cycle of soil CO₂ efflux, we found that it was most pronounced in the lichen-dominated plot at the unlogged/burned site. No diurnal dynamics in soil CO₂ efflux were evident in June and July, where soil CO₂ efflux remained consistently low. The logged/unburned site showed slight diurnal variations in soil CO₂ efflux, peaking around 15:00. Diurnal changes in soil CO₂ efflux were primarily related to soil temperature in the lichen-dominated and *Sphagnum* moss-dominated plots ($r = 0.45$ and 0.53 , $p < 0.05$; Table S1), but to soil moisture content in the green moss-dominated plots ($r = 0.51$, $p < 0.05$; Table S1). The logged/burned site showed no significant diurnal variation in soil CO₂ efflux in June, whereas the lichen-dominated plots showed increased soil CO₂ efflux in the afternoon in July, which was primarily related to increasing soil temperature ($r = 0.64$, $p < 0.001$; Table S2). In general, the lichen-dominated plots showed twofold lower soil CO₂ efflux across disturbed sites than at the undisturbed site.

However, the moss-dominated plots showed comparable soil CO₂ efflux across the disturbed and undisturbed sites. Notably, soil CO₂ efflux did not show a pronounced diurnal pattern at the logged/burned site. Hence, for the moss-dominated plots, our data support 6 years as a starting point for the recovery of the initial soil CO₂ efflux following wildfire and clear-cutting, depending on the microclimatic conditions. In these plots, wildfires and clear-cutting only damage the top layer of living moss, which can recover quite quickly. It should also be noted that Podzol soils exhibit quite low microbial activity, and the main sources of C efflux are plant roots and decomposition processes [90,91]. Thus, in this case, recovery after both wildfires and logging would likely also depend on ground cover thickness and the severity of plant root damage.

Based on measurements taken throughout the GS, we estimated cumulative soil CO₂ efflux to assess the impact of different disturbance types on its seasonal patterns (Figure 7), finding significant differences. As mentioned above, the response of soil CO₂ efflux to the disturbance varied across the GS. Soil CO₂ efflux decreased significantly in the second half of the GS at the burned sites, reflecting more rapid soil cooling and a 30% increase in rainfall events (Figures 3 and 6). Notably, the burned sites predominantly showed a decrease in soil CO₂ efflux [39] in the second half of the GS, whereas the clear-cutting sites showed consistent soil CO₂ efflux throughout the GS.

In a study on the effects of different logging types in a drained forested area that was previously a fen, Korkiakoski et al. [92] found that partial cutting had a much weaker effect on soil CO₂ efflux than clear-cutting. C sink recovery took 3 years at the partial cutting site, whereas it took at least 6 years at the clear-cutting site. Therefore, partial cutting could be one approach to mitigate the effects of disturbances on natural intact forests and help them recover their C sink function.

Another study examining harvesting methods and changes in soil efflux in the hemiboreal Scots pine forests of Estonia [35] also found that less intensive cutting (shelterwood cutting) reduced the soil efflux, though not as much as clear-cutting, even in nutrient-poor soils. The cumulative annual efflux was significantly lower in the clear-cutting area ($3.6 \pm 0.2 \text{ t C ha}^{-1}$) than in the shelterwood cut area ($5.5 \pm 0.2 \text{ t C ha}^{-1}$). In that area, where mosses are the dominant ground-cover vegetation, the cumulative soil efflux from June to September is typically 250 g C m^{-2} . Our moss-dominated plots at the disturbed sites showed distinct responses to the disturbances. For green moss-dominated plots, cumulative soil CO₂ efflux after clear-cutting was reduced by 55% compared to the unlogged/unburned site (279.1 g C m^{-2}); for *Sphagnum* moss-dominated plots, cumulative soil CO₂ efflux was 40% lower at the logged/unburned site (245.0 g C m^{-2}) than at the unlogged/unburned site. Across the Russian regions, the particular cutting is not common and usually involves clear-cuttings with a complete extraction of commercial timber [64]. The clear-cutting, combined with the sensitive boreal zone conditions, reduces emissions with the loss of carbon sink function.

The opposite response to the clear-cutting observed in red pine forests of Korea showed that soil CO₂ efflux was higher in the clear-cut site than at the undisturbed site [80], which was attributed to changes in soil temperature, pH, organic C content, and moisture content following the removal of woody plants. In our study, the changes in soil CO₂ efflux were primarily attributed (Table 2) to soil temperature differences, carbon content, thickness of forest floor, and dominant type of ground cover for the studied area, which greatly control decomposition and respiration processes [87,93].

Wildfires have a range of consequences for forest ecosystems depending on their severity, as well as on the species of trees present and the severity of damage to ground cover vegetation. A study on Scots pine boreal forests in central Sweden recovering from low- and high-severity wildfires found that the ecosystems remained C sources 4 years later [94]. However, the difference in C budget was not significant: 4 years after the event, the net ecosystem exchange was 113 g C m^{-2} following a low-severity wildfire and 92 g C m^{-2} following a high-severity wildfire. These similar C budgets reflect the effects of salvage logging after the low-severity wildfire. Thus, these findings suggest that low-severity wildfires have a similar impact on the ecosystem to high-severity wildfires. In our study, when we compared the effects of an intense surface wildfire with the combined effects of clear-cutting and a low-severity fire, we found that soil CO₂ efflux differed depending on the dominant ground-cover vegetation. Based on the cumulative soil CO₂ efflux, the lichen-dominated plot at the unlogged/burned site was the most sensitive, whereas the moss-dominated plots at the logged/burned site were the most sensitive (Figure 7). These

results were supported by the results of the mixed-effects model (Table 2), where the “Plot” predictor was one of the most significant factors to moderate soil emission rates.

The impact of ground cover is a questionable area of scientific debate. In our study, ground-cover vegetation was not removed at the study sites, and total CO₂ efflux was estimated from the soil surface, including from ground-cover vegetation, to capture the combined soil–vegetation behavior after disturbances. However, another study examining the effects of wildfires of different intensities on tundra ecosystems [33] reported no changes in soil respiration following the removal of ground-cover vegetation in the first 2–3 years after low- and high-intensity wildfires. According to the findings, the lack of observed changes could be explained by decreased root respiration and increased microbial respiration. However, overall ecosystem respiration estimated from transparent chamber measurements decreased significantly following the burning of aboveground plants. From our point of view, the presence of ground cover allows us to catch the whole process of soil emission behavior at any time with or without disturbances, and removing the living ground cover is just an additional disturbance effect to take into account.

4.2. Dependencies on Soil Environmental Conditions

Wildfires and logging significantly altered ($p < 0.05$) soil environmental conditions, specifically soil temperature and SWC (Table S3). However, the well-known relationships between soil CO₂ efflux and soil environmental conditions [95,96] were not evident at several disturbed sites (Table S3).

Our data showed significant correlations between soil CO₂ efflux and soil temperature in lichen-dominated plots at the burned/unlogged ($R^2_{\text{adj.}} = 0.60$) and unburned/logged ($R^2_{\text{adj.}} = 0.42$) sites (Figure 5a). For the moss-dominated plots (Figure 5b), a significant temperature dependency was observed only at the burned/logged site ($r = 0.43$ and 0.49 for green moss-dominated and *Sphagnum* moss-dominated, respectively). The specific feature of *Sphagnum* moss-dominated plots is mostly waterlogged conditions enhanced by disturbing factors. At the same time, these plots are underlain by the same Podzol soil; however, the clay lenses are distributed closer to the surface and determine the high soil moisture values. Additionally, *Sphagnum* mosses have an extraordinary water-holding capacity [97], and they can retain a volume of water equivalent to more than 20 times their dry mass.

Across all plots in the undisturbed site, the $R^2_{\text{adj.}}$ varied between 0.21 and 0.31, indicating weak correlations. This difference in soil temperature dependency between undisturbed and disturbed sites could be related to the lower variability in soil CO₂ efflux across disturbed sites compared to the undisturbed site. One possible reason for the low variation in soil CO₂ efflux during the GS may be the severity of damage to ground vegetation [33,98,99]. In our study, at least three plots were disturbed more than the others: the lichen-dominated plot at the unlogged/burned site, the lichen-dominated plot at the logged/unburned site, and the moss-dominated plots at the logged/burned site.

In a study of red pine forests after clear-cutting, Kim [81] found a stronger correlation between soil CO₂ efflux and soil temperature at the clear-cutting site ($r = 0.90$) than at the undisturbed site ($r = 0.81$). This difference between undisturbed and disturbed sites aligns with our findings, in which the correlation between soil CO₂ efflux and soil temperature was weaker at the undisturbed site than at the lichen-dominated disturbed sites. However, at the moss-dominated burned and logged site, the correlation with soil temperature was much lower than at the undisturbed site. The exception was found at the logged/burned site, where the opposite behavior was found. In this case, the combined effects of fire and clear-cutting completely destroyed the lichen-dominated plot; however, the moss-dominated plots survived to a greater extent, and the disturbance effect was evident only in the upper part of the moss layer. So far, mosses grow in wetter places;

there is expected soil emission limitation just from temperature. At the same time, the lichen-dominated plot is experiencing drought conditions due to the lack of a formed forest floor layer to save water sources and provide protection from strong heating.

In a study of the impact of logging on soil CO₂ efflux in the middle taiga of the European part of the Russian boreal zone, Osipov [85] found a significant linear relationship between soil CO₂ efflux and soil temperature at logged sites ($R^2 = 0.60\text{--}0.73$); however, those observations were performed directly after the disturbance occurrence. It is most likely that the high increase in CO₂ release is happening right after disturbances as a stress mechanism. Our study was performed in already stable conditions 6 years after the disturbances, and the emission significantly declined at the plots where the disturbance effect was the most severe.

Nevertheless, other studies have reported the opposite strategies. For instance, one study examining burned and cut areas across Canadian mixedwood boreal forests [100] found no significant relationships between soil CO₂ efflux and soil temperature. However, SWC was a significant predictor of CO₂ fluxes for both disturbance types 15 years after the disturbance. That region is underlain by Cambisol soils with a coarse-loamy texture, which are characterized by good water retention and, even after disturbance occurrence, may contribute to maintaining more stable soil temperature and moisture conditions. Another point is that the results of this study support the statement that moisture conditions are a limiting factor in the boreal zone.

Another study reported a weak relationship between soil CO₂ efflux and soil moisture content. In a study examining the effects of clear-cutting in Canadian forests comprised of spruce and fir, Lavoie et al. [83] found no relationship between soil CO₂ efflux and soil moisture content ($R^2 = 0.01\text{--}0.04$). Our study supports those results, and, for the logged site, we did not find any significant relationship between soil CO₂ efflux and SWC for all types of forest floor. Regarding this point, at the lichen-dominated plot, the reason, in our opinion, is related to the high variation of soil emission rates at one moisture level and the main response addressed to the soil temperature [101–103]. The *Sphagnum*-dominated plot is often presented by over-watered conditions due to the closely located open water area, and also demonstrates high variation at a similar moisture level. In the green moss-dominated plot, we found permanent emission flux rates under different moisture values, which could be related to the low forest layer thickness (70% lower than at the undisturbed plot).

In a study of feathermoss-covered areas in Scots pine forests in the southern Siberian taiga, Kukavskaya et al. [58] found a negative exponential relationship between soil temperature and soil CO₂ efflux at the burned sites ($R^2_{\text{adj.}} = 0.31$, $p < 0.05$). They attributed this relationship to the measurements being taken in the first year after the wildfire, when higher soil temperatures coincided with more severely burned areas, where the canopy had been completely removed, and a black pyrogenic charcoal layer had formed on the soil surface. In these areas, the substantial reduction in both vegetation and microbial biomass led to a significant decrease in soil CO₂ efflux. In our study sites, such patterns were not observed, likely because the measurements were taken 6 years after the disturbances.

Prior studies [104,105] have established that, in our study area, stand type and chemical soil characteristics are the most influential factors, especially after wildfires. This idea was highly supported by the results of the mixed-effects model (Table 2). The obtained results highlighted the most important factors for soil CO₂ emission rates during the vegetation season. Interestingly, soil temperature and soil moisture are not the main controlling factors, as commonly used parameters to model soil efflux. The most powerful factors based on our results are carbon content and plot type (lichen- or moss-dominated). The existing research has also highlighted that several external factors related to soil CO₂ efflux include stand type, forest management strategy, habitat conditions [94], normalized dif-

ference vegetation index [106], and soil chemical, physical, and biological properties [17,18]. For our territory, the suggested model predictors (Table 2), including soil physical and chemical properties, explained 44% of the soil emission rates. Another portion of predictors should be related to soil microbial biomass, root distribution, and also reflectivity of the ground cover surface.

4.3. Research Implications, Limitations, and Future Directions

Wildfires and logging are becoming increasingly frequent and severe, posing significant threats to human everyday life and altering ecological processes and C storage [24,53,87]. The boreal forest ecosystems after these disturbances are functioning as a source of carbon to the atmosphere, and the period to achieve the “compensation point” lasts for a long time [39,51,83]. The results of our study demonstrate that, after severe surface fire and clear-cutting, we found a significant reduction in soil emission rates. The type of ground cover plays a big role in the mechanisms of recovery after disturbances. The lichen-dominated plots are more sensitive to suppression by wildfire, which strongly decreased the emission flux from these areas (Figure 7a). The moss-dominated plots should be specified by the moss type. For green mosses (Figure 7b), the impact of clear-cutting declined the soil emission rates more. However, for *Sphagnum* mosses (Figure 7c), the interactive effect of wildfire and logging significantly reduced the emission rates. These findings build on existing evidence of cover type-specific response to the different types of disturbances. The results of the mixed-effects model provide insights into the main controlling factors to predict the soil emission rates.

The main limitation of this study is the limited data scope, covering only a single year of measurements. The observed relationships between soil emissions and environmental factors may also depend on the specific conditions of a particular season. As 2024 was the first year of our project, we plan to incorporate additional years with varying meteorological conditions during the growing season into future analysis. Future research should also scale these localized chamber measurements up to the landscape level using eddy covariance towers. This will help validate macro-level emission models across different forest biomes in boreal zones. Another direction is related to the further analysis of additional external factors to predict the soil emission efflux.

5. Conclusions

Our findings demonstrated significantly lower soil CO₂ efflux at sites disturbed by wildfires and clear-cutting compared to the undisturbed sites in Siberian boreal forests. The interactive effect of wildfire and logging is demonstrated in the reduction of the emission rates, and this decline depends on the type of ground cover. Prominent diurnal variations in soil CO₂ efflux were observed at lichen-dominated and *Sphagnum* moss-dominated plots at the logged/unburned and logged/burned sites, but not at the unlogged/burned site. Variations in soil CO₂ efflux were more pronounced at a seasonal scale. The lichen-dominated plots exhibited a seasonal pattern in soil CO₂ efflux, which peaked in the middle of the GS only at the logged/unburned site. In contrast, the moss-dominated plots showed seasonal variations in soil CO₂ efflux across all disturbed sites, indicating mosses are more resilient to logging and wildfires than lichens.

The roles of soil temperature and SWC in regulating soil CO₂ efflux rates were examined across sites with different disturbance histories. Regarding the diurnal cycle, soil temperature was the most significant factor regulating soil CO₂ efflux at lichen-dominated plots during early GS. In contrast, SWC was the most significant factor regulating soil CO₂ efflux at the unlogged/burned and logged/burned sites during the peak GS, regardless of the dominant ground-cover vegetation. At the seasonal scale, soil temperature was a major factor regulating soil CO₂ efflux in the lichen-dominated plots at the logged/unburned

and unlogged/burned sites, and the moss-dominated plots at the logged/burned site. We estimated cumulative soil CO₂ efflux across Scots pine ecosystems with different dominant ground-cover vegetation and disturbance histories. Cumulative soil CO₂ efflux was highest at the logged/burned site for lichen-dominated plots (327 g C m⁻²), the unlogged/burned site for the green moss-dominated plots (279 g C m⁻²), and both the logged/unburned (245 g C m⁻²) and unlogged/burned (240 g C m⁻²) sites for the *Sphagnum* moss-dominated plots. For lichen-dominated plots, cumulative CO₂ efflux was twofold lower at the disturbed sites than at the undisturbed site. However, for moss-dominated plots, cumulative CO₂ efflux was similar between disturbed and undisturbed sites. These findings suggest that while intense wildfires have the greatest detrimental effect on soil CO₂ efflux in areas where lichens are the dominant ground-cover vegetation, clear-cutting has the greatest detrimental effect in areas where green mosses are the dominant ground-cover vegetation. In contrast, both wildfires and clear-cutting have similar detrimental effects on soil CO₂ efflux in areas where *Sphagnum* mosses are the dominant ground-cover vegetation.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/cli14070147/s1>, Table S1: Correlation of diurnal SR fluxes with soil microclimatic parameters in June; Table S2: Correlation of diurnal SR fluxes with soil microclimatic parameters in July; Table S3: Pearson’s correlation of seasonal SR with soil microclimatic parameters: ST—soil temperature in °C, SWC—soil water content (volumetric soil moisture) in m³ m⁻³.

Author Contributions: Conceptualization, A.V.M., A.V.P., E.A.K., and E.A.V.; methodology, A.V.M., E.A.V., and A.V.P.; formal analysis, A.V.M. and A.V.P.; investigation, A.V.M. and A.V.P.; resources, A.V.M. and E.A.V.; data curation, A.V.M., E.A.K., A.V.P., and; writing—original draft preparation, A.V.M., E.A.K., A.V.P., A.S.P., E.A.V., and P.Y.G.; visualization, A.V.M. and A.V.P.; funding acquisition, A.V.M. and A.V.P. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The original fieldwork data presented in this study are available upon reasonable request from the corresponding and first authors.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

GS	Growing season
Rh	Heterotrophic respiration
ST	Soil temperature (in °C)
SWC	Soil water content (in m ³ m ⁻³)

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