

## Article

# Short-Distance Variation of Carbon Stocks and Growing-Season Flux Components in Kola Tundra

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## Abstract

Carbon accounting in tundra ecosystems is constrained by spatial heterogeneity below conventional inventory scales. We quantified carbon (C) stocks and growing-season flux components across five 50 × 50 m plots within a 250 × 250 m lichen–dwarf shrub tundra site on the Kola Peninsula, Russia. The study included 15 soil profiles, 15 biomass quadrats, and 30 permanent soil-respiration collars measured on seven dates. Biomass, litter, soil chemical and microbial properties, respiration, temperature, and moisture were assessed across contrasting microrelief positions and Podzol groups. Total standing C pools ranged from 10.8 to 26.0 kg C m<sup>−2</sup> among plots (mean ± SD: 15.8 ± 6.1 kg C m<sup>−2</sup>), with soil contributing 60–85%. Stagnic Podzols in local depressions had the largest organic-horizon C stocks, whereas deeper and better-drained profiles stored a larger fraction in mineral horizons. A repeated-measures linear mixed-effects model with a collar-level random intercept and continuous temporal autocorrelation showed that soil temperature improved the fit to log-transformed soil CO<sub>2</sub> efflux (likelihood-ratio statistic = 55.54, *p* < 0.0001). The evidence for an additional linear moisture effect was weak (*p* = 0.079), and the temperature × moisture interaction was unsupported (*p* = 0.932). Scenario-based growing-season heterotrophic C efflux ranged from 41 to 52, 48 to 62, and 59 to 76 g C m<sup>−2</sup> for Rh/Rs fractions of 0.45, 0.53, and 0.65, respectively. The results support stratification by coupled microrelief–soil–vegetation units for local inventories, while broader inference requires independent replication and year-round flux measurements.

**Keywords:** soil carbon stocks; soil CO<sub>2</sub> emissions; spatial variation; soil–plant interactions; carbon accounting; Arctic



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## 1. Introduction

In the context of global climate change and carbon neutrality commitments, the Arctic region has recently become a “hot” topic [1,2]. Based on global models and regional surveys, tundra ecosystems for a long time have been considered substantial carbon (C) sinks [3–5]. Cold climate and nutrient-poor soils hamper microbial decomposition of

organic matter, resulting in turnover time over hundreds of years [6,7]. However, under the warming climate, permafrost thaw and increasing soil respiration are tending to shift tundra ecosystems toward a net carbon source [8–10]. The warming effect is locally strengthened by anthropogenic disturbances including urban heat island effect and forest fires, leading to substantially higher soil C emissions from urban and industrial areas compared to the natural tundra [11–13]. Recent synthesis shows that tundra remains an overall C sink, yet one third of the region has been converted to C sources [14]. These estimates though remain quite uncertain due to high spatial heterogeneity of C stocks and fluxes across tundra landscapes [15,16], particularly in Russian zonal tundra where ground-based observations are scarce.

Uncertainty is compounded by the uneven spatial distribution of field observations: sampling density is substantially higher in Alaska, Canada, and northern Europe than in Russia [17,18]. This imbalance has increased with the exclusion of Russian monitoring stations from international pan-Arctic networks [19]. In these circumstances, national projects, such as the National System for Monitoring the Dynamics of Climatically Active Substances in Terrestrial Ecosystems of the Russian Federation (RITM Carbon) (<https://ritm-c.ru>) and the Carbon Supersites program (<https://carbon-polygons.ru/>), aim to fill the gaps in monitoring data and develop solutions for C sequestration and climate mitigation across different land uses and biomes [20–22]. Based on existing estimates [23,24], tundra ecosystems in Russia occupy nearly 2.7 million square kilometers, and tundra soil stores at least 46 Pg of C in one-meter layers, of which up to 90% is accumulated in the topsoil. These stocks are vulnerable to climate warming, accelerated by anthropogenic disturbances: urbanization and infrastructure development [25]. In this regard, the preservation of topsoil C stocks would be among the most efficient climate mitigation measures in the region. Spatially explicit, current estimates of soil C stocks are therefore needed as baselines for monitoring and management.

Mapping tundra C stocks is challenging because pronounced patchiness requires dense sampling to characterize spatial patterns [26,27]. High patchiness in soil C stocks originates from complex lithological and microrelief conditions, resulting in short-distance variation in plant biomass and microclimatic conditions [28–30], which are further complicated by climate change patterns. Long-term monitoring in the nearby Khibiny Mountains illustrates the sensitivity of this system: between 2000 and 2023, warming of 2.2 °C coincided with an almost twofold increase in the proportional contribution of evergreen dwarf shrubs, a decline in deciduous shrubs and lichens, and a fivefold increase in moss cover, without a significant change in total aboveground phytomass [31]. Such changes may alter litter quality, microclimate, and soil C dynamics, but their consequences for short-distance variation in C stocks and fluxes remain poorly resolved. Detailed, co-located soil and vegetation surveys are therefore needed to describe the landscape units generated by these interacting factors.

While fine-scale tundra carbon studies have demonstrated large variation associated with patterned ground, permafrost and individual environmental gradients [11,15,25,27], much less is known about how standing C pools and growing-season soil CO<sub>2</sub> efflux covary across the coupled soil–relief–vegetation mosaic. Moreover, most existing studies in European Arctic tundra have been conducted in mountain environments, leaving zonal lowland tundra substantially understudied. Our study addresses this gap by a spatially intensive case study within one 250 × 250 m Kola tundra site, combining full-profile C stocks, biomass and microbial measurements with repeated chamber observations. The design does not isolate independent causal effects of soil, vegetation and microrelief; instead, it quantifies the magnitude and vertical structure of variation among locally recurring landscape units at sub-100 m scales.

The research aimed to quantify fine-scale variation in standing C pools and growing-season soil CO<sub>2</sub> efflux within a natural tundra site on the Kola Peninsula and to examine their associations with coupled differences in microrelief, soil morphology, vegetation and microclimate. We hypothesized that wetter depressions with stagnic soils will contain larger organic-horizon C stocks and will have lower growing-season CO<sub>2</sub> efflux than elevated, better-drained locations. The analysis was intended to identify locally relevant inventory strata for C accounting and mapping in tundra ecosystems rather than to estimate independent causal effects of the constituent landscape factors.

## 2. Materials and Methods

### 2.1. Research Area

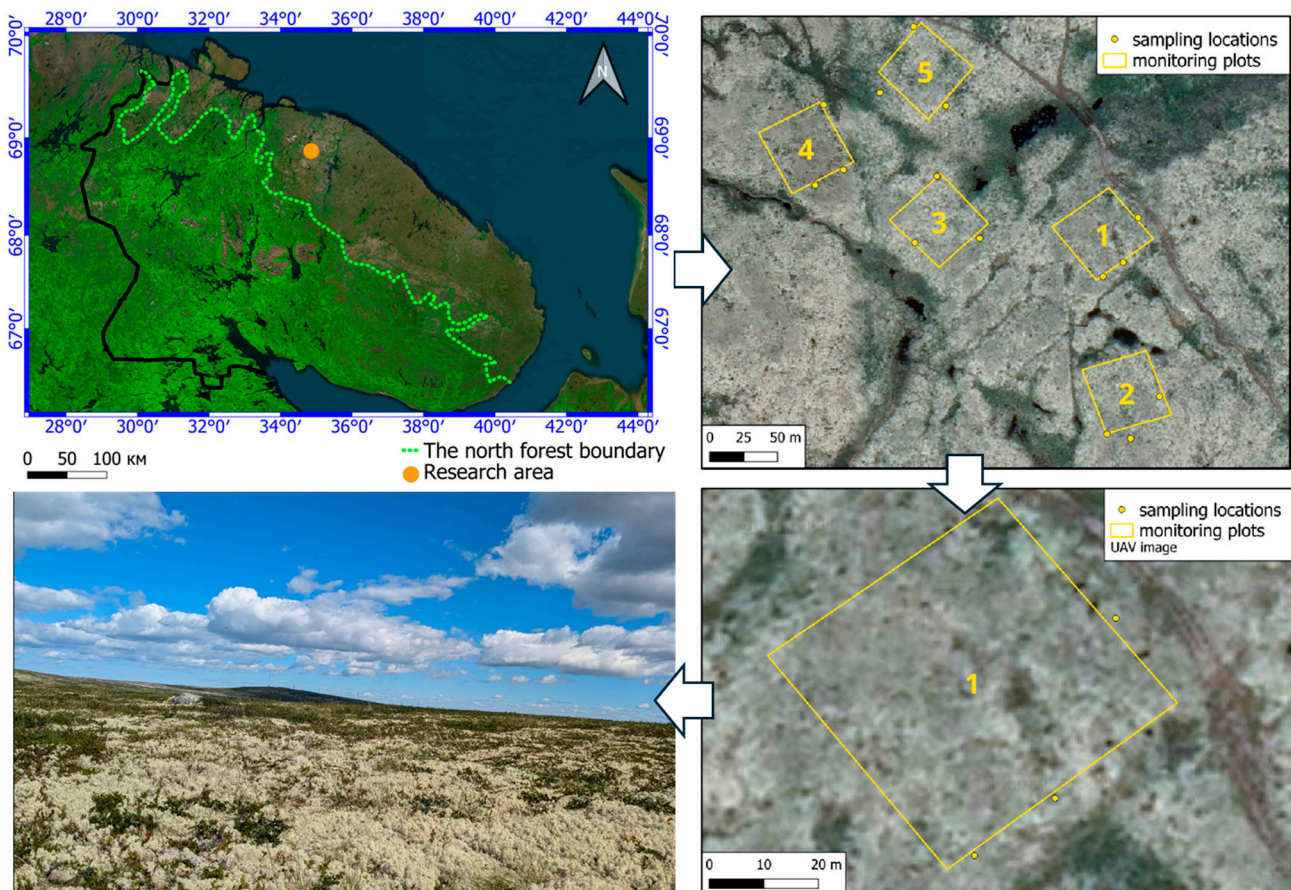
The study area is located on the watershed of the hilly ridge-type basal-denudational plains in the northern part of the central Kola Peninsula, composed of gravelly sandy, heavily boulder-laden greenish moraine and, in places, eluvium derived from local massive crystalline rocks of acidic composition (granitoids). Owing to the influence of the warm North Atlantic Current, the area has a subarctic Dfc climate under the Köppen–Geiger classification and is outside the permafrost zone. At the Teriberka weather station, the 1991–2020 mean annual air temperature was 1.5 °C. Summers are cool (monthly means of 9–11 °C), and winters are relatively mild for the latitude, with a February mean above −10 °C and frequent thaws. Summer relative humidity is approximately 80%, and strong winds redistribute snow and promote cryogenic surface features. In 2024, mean annual air temperature was 2.8 °C and annual precipitation was 534.5 mm. The growing season, defined by stable mean daily temperatures above 5 °C, lasted 125 days, while the active growing season lasted 97 days. The site lies in the southern shrub-tundra zone, bioclimate subzone E (Low Arctic) of the Circumpolar Arctic Vegetation Map. Sandy Al–Fe–humus soils (Albic and Entic Podzols) dominate dry uplands, whereas organic-rich soils occur in wet depressions [32].

A research site of approximately 250 × 250 m (68.9 N; 34.9 E), representative of the research area, was established in an undisturbed tundra plot on a watershed section of a hilly ridge bedrock-denudation plain in the northern Murmansk Region, approximately 35 km southwest of Teriberka. Five 50 × 50 m monitoring plots represented contrasting combinations of microtopography, drainage, vegetation and dominant soil morphology. Three soil profiles (15 profiles in total) and two biomass quadrats (10 quadrats in total) were sampled within or adjacent to each plot. These profiles were spatial subsamples within the site and were not treated as independent regional replicates (Figure 1). Repeated soil CO<sub>2</sub> efflux measurements were made at six permanent collars per plot once or twice per month of the growing season 2024 (7 observation dates, 30 collar measurements per day in total). Plot, profile and collar identifiers were retained throughout the analysis. Because soil group, topographic position, vegetation and plot location were partly confounded, their independent causal effects were not estimated; comparisons among soil groups or landscape units are interpreted as local descriptive contrasts.

### 2.2. Plant Survey and Estimation of Biomass Carbon Stocks

All vascular plants, bryophytes, and lichens in the monitoring quadrats were identified. We estimated total vegetation cover, cover by major growth form or layer, and species abundance using the Braun–Blanquet scale [33,34]: r, solitary individuals; +, <1%; 1, 1–5%; 2a, 6–12%; 2b, 13–25%; 3, 26–50%; 4, 51–75%; and 5, 76–100%. Vegetation was classified using the Braun–Blanquet sorted-table method [35]. Species nomenclature followed the relevant floras and databases for vascular plants [36,37], bryophytes [38], and lichens [39], and syntaxonomic affiliation followed Vegetation of Europe [40]. Biomass was sampled in

triplicate within each plot from  $25 \times 25$  cm quadrats co-located with soil sampling. For vascular plants, current-year growth was separated from perennial tissue, and leaves were separated from stems within each fraction. Mosses and lichens were separated by species; liverworts were processed as a combined group. Root biomass and litter were quantified separately. Above- and belowground biomass C stocks were calculated by multiplying dry mass by 0.47, the IPCC default C fraction for herbaceous biomass [41].



**Figure 1.** Location of the study area, monitoring plots, soil profiles, and biomass-sampling locations.

### 2.3. Soil Survey and Estimation of Soil Carbon Stocks

Soil profiles were described in the field, and soil horizons and diagnostic morphological properties were identified. The studied soils were classified according to the WRB [42]. Soil samples were collected from all horizons and delivered to the laboratory for analysis of physical, chemical and microbial properties. Bulk density samples were taken by rings from the surface of the mineral soil and from each horizon. The following soil properties were analyzed: soil texture and coarse-fragment content [43], pH in a 1:5 suspension with distilled water (Ohaus Starter pH-meter, OHAUS Corporation, Parsippany, NJ, USA), and total contents of macroelements on atomic absorption spectrometer Perkin-Elmer AVIO 200 (PerkinElmer, Inc., Shelton, CT, USA) after microwave digestion in a mixture of concentrated hydrochloric, nitric, and hydrofluoric acids [44]. Total carbon and nitrogen contents were determined using an Elementar Vario EL Cube CNSH (Elementar Analysensysteme GmbH, Langenselbold, Germany) analyzer after pre-processing with a Retsch MM 400 vibratory (RETSCH GmbH, Haan, Germany) ball mill in the Laboratory of Radiocarbon Dating and Electronic Microscopy, Institute of Geography, Russian Academy of Sciences. Since the samples were carbonate-free, no pre-treatment with HCl was performed.

Horizon-specific soil C stocks were calculated using the following Formula (1):

$$C_{stock} = C \times BD \times D \times (1 - RF) \times 0.1, \quad (1)$$

where

C<sub>stock</sub>—soil carbon stocks (kg C m<sup>−2</sup>); C—total soil carbon content (%); BD—bulk density (g cm<sup>−3</sup>); D—depth of horizon (cm); and RF is the volumetric coarse-fragment fraction expressed from 0 to 1.

Samples were carbonate-free; total C was therefore interpreted as organic C. Stocks were summed separately for organic and mineral horizons and for the complete profile to bedrock. To distinguish areal storage from differences caused by profile depth, mineral-soil stocks were also calculated to a common depth of 30 cm, with bedrock-truncated volume treated as zero soil volume.

Carbon in soil microbial biomass (C<sub>mic</sub>) was measured by the substrate-induced respiration (SIR) method, based on capturing the respiratory response to the addition of a readily available substrate, glucose. Substrate samples (1 g) were placed in a 15 mL vial, glucose solution (0.1 mL/g soil, 0.5 mg/g) was added dropwise, the vial was sealed, and time was recorded. The vials were incubated (3–5 h of incubation, 22 °C) and the gas sample was collected with a syringe and injected into a gas chromatograph KrystaL 2000 M (Meta-Chrom, Yoshkar-Ola, Russia) equipped with a thermal conductivity detector for measuring CO<sub>2</sub> concentration. Soil C<sub>mic</sub> (μg C g<sup>−1</sup> soil) was calculated from the equation SIR (μL CO<sub>2</sub> g g<sup>−1</sup> soil h<sup>−1</sup>) × 40.04 + 0.37 [45,46]. The basal (microbial) respiration was determined in native (not enriched) soil (24 h of incubation, 22 °C). The BR was measured for SIR, but water (0.1 mL/g soil) was added to the soil samples instead of a glucose solution. The BR rate was expressed in μg CO<sub>2</sub>–C/g soil per hour. The specific respiration of the microbial biomass, or the microbial metabolic quotient (qCO<sub>2</sub>) was calculated as the ratio BR/C<sub>mic</sub> = qCO<sub>2</sub> (μg CO<sub>2</sub>–C/mg C<sub>mic</sub>/h).

#### 2.4. Monitoring Soil Respiration and Estimation of Soil CO<sub>2</sub> Emissions

Soil CO<sub>2</sub> emissions (including both autotrophic and heterotrophic components) were monitored during the growing seasons of (July–October) 2024 at each of the monitoring plots. Measurements were conducted in six replicates per plot, totaling 30 flux measurements per observation day. Observations were performed on the following dates: 10 July, 24 July, 7 August, 14 August, 4 September, 24 September, and 15 October 2024. No measurements were made in June because the onset of the growing season at the study site occurs in early July, which is consistent with local climatic conditions and the phenological development of vegetation. An infrared gas analyzer (EGM-5, PP Systems, Amesbury, MA, USA) was used to measure CO<sub>2</sub> fluxes, while soil temperature and moisture were recorded using Delta-T SM-150 (Delta-T Devices Ltd., Cambridge, UK) and ML3 ThetaProbe (Delta-T Devices Ltd., Cambridge, UK) probes to characterize abiotic conditions. All measurements were conducted under rainless conditions between 10:00 a.m. and 2:00 p.m. to better represent the average daily CO<sub>2</sub> efflux, following previous studies and methodological recommendations [11,13]. Day totals were estimated by multiplying the plot-averaged daily fluxes in mg C-CO<sub>2</sub> m<sup>−2</sup> h<sup>−1</sup> by 24 h. Since the measurements did not resolve the diel cycle or wet-weather events, the totals are treated as scenario-based estimates rather than observed 24 h flux budgets. Total seasonal soil CO<sub>2</sub> emissions were modeled based on the interpolated chamber-level daily soil temperatures (see the model details below). Heterotrophic C efflux was calculated under three illustrative partitioning scenarios (Rh/Rs = 0.45, 0.53 and 0.65), representing the lower and upper bounds of the range reported for tundra ecosystems [47,48].

## 2.5. Data Analysis and Statistics

Statistical analyses respected the nested observational design. Soil and biomass variables were summarized at profile or quadrat levels, with sample size, mean and standard deviation and, for skewed variables, median and interquartile range. Individual observations are shown in all group figures. Soil group, microrelief, vegetation and plot location were partly confounded; therefore, group contrasts were treated as exploratory descriptions of coupled landscape units. Organic- and mineral-horizon stocks were first aggregated within each profile before paired comparison. Spearman rank correlations were calculated only for profile-level variables because several distributions remained skewed and group sizes were small and unbalanced; no combination of transformed and untransformed variables was used in a parametric group test.

Temporal variation in soil CO<sub>2</sub> emissions and differences among the five plots were evaluated using a linear mixed-effects model (LME):

$$\log(Rs_{ij}) = \beta_0 + \beta_{\text{Plot}} + \beta_{\text{Tz}}(T_{ij}) + b_i + \varepsilon_{ij},$$

where  $Rs_{ij}$  is flux from collar  $i$  on date  $j$ , Plot is a five-level categorical fixed effect,  $z(T)$  is standardized 5 cm soil temperature, and  $b_i$  is a normally distributed random intercept for collar identity. A continuous first-order autoregressive structure was used for within-collar residuals, with  $\text{cor}(\varepsilon_{ij}, \varepsilon_{ik}) = \varphi^{| \text{day}j - \text{day}k |}$ . Candidate models tested the incremental contributions of soil temperature, moisture and their interaction using maximum-likelihood likelihood-ratio tests. Temperature and moisture were standardized within the analysis dataset; mean soil temperature was 9.58 °C (SD = 4.08 °C) and mean volumetric water content was 14.26% (SD = 10.41%). The selected model was refitted by restricted maximum likelihood for coefficient estimation. Fixed-effect estimates, standard errors, approximate 95% confidence intervals, AIC, BIC, random-effect variances, and the temporal-correlation parameter are reported. Residual-versus-fitted and normal Q–Q plots were inspected for heteroscedasticity and major departures from normality; standardized conditional residuals ranged from −2.66 to 3.41, with no pronounced fitted-value pattern. A combined plot × soil-group factor was also tested, but did not improve fit beyond Plot ID and temperature (LR = 1.47,  $p = 0.689$ ;  $\Delta\text{AIC} = +4.53$ ). The plot-level model was therefore used for inference and daily prediction. All statistical analyses were conducted in R Studio (version 4.3.1, nlme package), while spatial modeling and mapping were performed in QGIS (version 3.32.3).

## 3. Results

### 3.1. Botanical Composition of the Research Site

The vegetation comprised lichen–dwarf shrub communities typical of the southern tundra, including the association Empetro–Betuletum nanae Nordhagen 1943, alliance Loiseleurio–Arctostaphylion Kalliola ex Nordhagen 1943, order Deschampsio flexuosae–Vaccinietalia myrtillin Dahl 1957, and class Loiseleurio procumbentis–Vaccinietea Eggler ex Schubert 1960. Vegetation cover was closed but horizontally heterogeneous. Lichens dominated the ground layer (50–75%), particularly *Cladonia stellaris*, *C. arbuscula*, *C. stygia*, and *C. rangiferina*, consistent with strong wind exposure and cryogenic disturbance [49]. *Cetraria islandica* and *Flavocetraria nivalis* occurred consistently at low cover. *Betula nana* and *Empetrum nigrum* subsp. *nigrum* dominated the shrub layer, whereas *Vaccinium myrtillus* and *V. vitis-idaea* generally remained below 5% cover. Dwarf shrubs were typically 3–10 cm tall, although *B. nana* reached 20–30 cm in small depressions. Graminoids, including *Avenella flexuosa*, *Carex bigelowii*, and *Oreojuncus trifidus*, reached 25–40 cm late in the growing season. Bryophytes were sparse and largely restricted to moist depressions (Table 1).

**Table 1.** Vegetation of the sampled plots. In each relevé identifier, the first number denotes the plot and the second denotes the replicate.

| Relevé Nr. by Author                        | 1-1 | 1-2 | 2-1 | 2-2 | 3-1 | 3-2 | 4-1 | 4-2 | 5-1 | 5-2 |
|---------------------------------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| <b>Cover, %</b>                             |     |     |     |     |     |     |     |     |     |     |
| <b>Total</b>                                | 99  | 90  | 99  | 98  | 98  | 99  | 95  | 95  | 100 | 97  |
| <b>Dwarf Shrubs and Herbs</b>               | 45  | 30  | 47  | 35  | 60  | 35  | 45  | 35  | 25  | 35  |
| <b>Bryophytes</b>                           | 3   | 3   | 2   | 2   | 1   | 1   | 1   | 1   | 3   | 4   |
| <b>Lichens</b>                              | 55  | 60  | 50  | 60  | 35  | 65  | 55  | 65  | 75  | 60  |
| <b>Number of Species</b>                    | 21  | 28  | 19  | 20  | 14  | 23  | 20  | 24  | 20  | 22  |
| <i>Betula nana</i>                          | 3   | 2b  | 3   | 2b  | 4   | 2b  | 2b  | 2b  | 2a  | 2b  |
| <i>Cladonia stellaris</i>                   | 2b  | 3   | 3   | 3   | 2b  | 3   | 2b  | 2b  | 3   | 3   |
| <i>Cladonia arbuscula</i>                   | 2a  | 2a  | 1   | 2a  | 1   | 1   | 1   | 2a  |     | 1   |
| <i>Cladonia stygia</i>                      |     | 1   | 2a  | 2a  | 2a  | 2a  | 2a  | 2a  | 2a  | 2a  |
| <i>Cetraria islandica</i>                   | 1   | 2a  | 2a  | 2a  | 2a  | 2a  | 2a  | 2a  | 2a  | 2a  |
| <i>Empetrum nigrum</i> subsp. <i>nigrum</i> | 2a  | 2b  | 1   | 2b  | 1   | 1   | 1   | 2a  | 1   | 2b  |
| <i>Vaccinium vitis-idaea</i>                | 1   | 1   | +   | +   | 1   | 1   | 1   | 2a  | +   | 1   |
| <i>Cladonia gracilis</i>                    | 1   | 2a  | 1   | 2a  | 2a  | 1   | 1   | 1   | +   | 1   |
| <i>Vaccinium myrtillus</i>                  | 1   | 1   | 1   | 1   | 1   | 1   |     | 1   | 1   | 1   |
| <i>Avenella flexuosa</i>                    | 1   | 1   | 1   | 1   | 1   |     |     |     | 2a  | 2a  |
| <i>Carex bigelowii</i>                      | 1   | +   | +   | +   |     | 1   | 1   | 1   | +   | +   |
| <i>Flavocetraria nivalis</i>                | 1   | 1   | 1   | 1   |     | 1   | 2a  | 2a  | 2a  | 2a  |
| <i>Dicranum flexicaule</i>                  | 1   | 1   | 1   | 1   |     | +   | +   | 1   | +   | 1   |
| <i>Polytrichum juniperinum</i>              | 1   | 1   |     | +   | 1   | 1   |     | +   | +   | 1   |
| <i>Cladonia coccifera</i>                   | 1   | 1   |     | +   | 1   | +   | +   | +   |     | 1   |
| <i>Cladonia uncialis</i>                    | 1   | 1   | 1   | 1   |     |     |     | 2a  | 1   |     |
| <i>Arctous alpina</i>                       |     | 1   |     | 1   |     | 2a  | 2a  |     |     | 1   |
| <i>Pohlia nutans</i>                        | +   | +   |     |     |     | +   | +   | +   |     |     |
| <i>Cladonia rangiferina</i>                 | 2a  | 2a  | 1   |     |     | +   |     |     |     |     |
| <i>Alectoria nigricans</i>                  |     | +   |     |     |     | +   | 1   | +   |     |     |
| <i>Cladonia bellidiflora</i>                | +   | +   |     |     |     |     |     | +   | +   |     |
| <i>Cladonia sulphurina</i>                  |     | +   |     |     |     |     | +   |     | 1   | +   |
| <i>Pleurozium schreberi</i>                 |     |     | 1   | 1   |     |     |     |     | 1   | 1   |

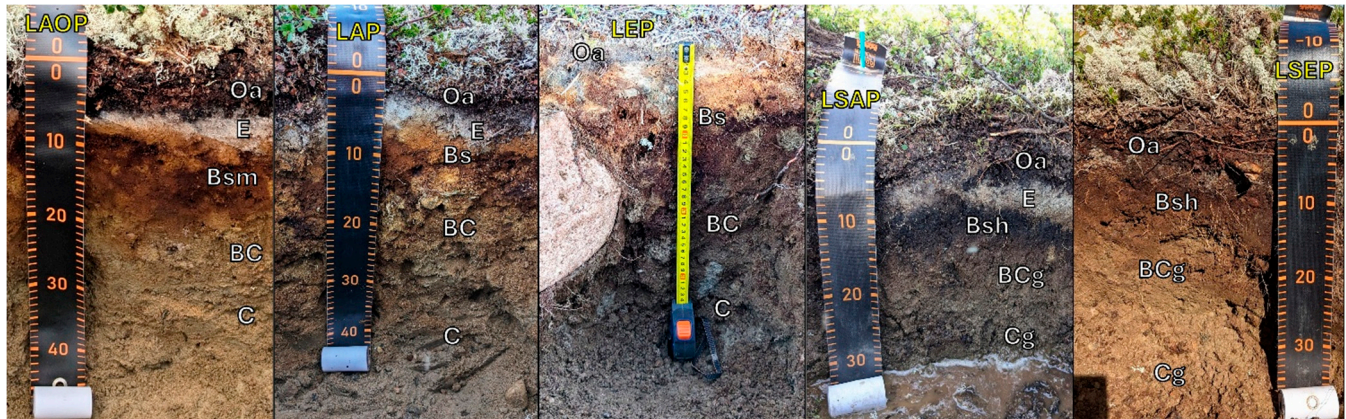
Species found in 1–3 relevés with an abundance of + (others are indicated in brackets): *Alectoria ochroleuca* 6, 7(1); *Barbilophozia lycopodioides* 5; *Cetraria ericetorum* 8; *Cetrariella delisei* 2(1); *Cladonia* sp. 8(1); *C. cornuta* 10; *C. crispata* 1, 8, 10; *Dicranum elongatum* 8(1); *D. scoparium* 3, 9; *Flavocetraria cucullata* 6(1), 10; *Kalmia procumbens* 2(1), 5(1), 6(3); *Lecidoma demissum* 2; *Lycopodium annotinum* 6(1); *Lycopodium* sp. 1; *Ochrolechia frigida* 2, 7, 8; *Oreojuncus trifidus* 2(1), 4; *Phyllodoce coerulea* 1(1); *Polytrichum hyperboreum* 7, 8; *Ptilidium ciliare* 2, 3; *Salix herbacea* 9; *Solidago virgaurea* 9(1); *Stereocaulon alpinum* 4(1), 6; *S. grande* 3; *Thamnolia vermicularis* 7.

Satellite data revealed no significant differences in the Normalized Difference Vegetation Index (NDVI) among the study plots. Observed NDVI ranged from 0.27 to 0.35 on June 29th and from 0.30 to 0.42 on August 6th indicating low productivity of tundra vegetation with slight increases throughout the growing season.

### 3.2. Local Variation in Soil Formation and Soil Properties

On meso-uplands, the soil cover consists of Al–Fe–humus soils (Leptic Albic/Entic Podzols), and—over a significantly smaller area in large micro-depressions with dense bedrock immediately beneath—Folic/Histis Leptosols. On the micro-uplands, Leptic Albic Ortsteinic Podzols and Leptic Albic Podzols dominate, while Leptic Entic Podzols are present to a smaller extent, due to the uneven distribution of boulders across the area. Microdepressions in the relief are characterized by Leptic Stagnic Albic/Entic Podzols with illuvial humus horizon Bsh (Figure 2). Based on the soil profile description and

classification, the following soil groups were identified: Leptic Albic Ortsteinic Podzol (LAOP,  $n = 6$ ), Leptic Albic Podzol (LAP,  $n = 4$ ), Leptic Entic Podzol (LEP,  $n = 2$ ), Leptic Stagnic Albic Podzol (LSAP,  $n = 2$ ), and Leptic Stagnic Entic Podzol (LSEP,  $n = 1$ ). These soil groups were used for further data analysis and interpretation. Given these small and unbalanced sample sizes, soil-group summaries are descriptive.

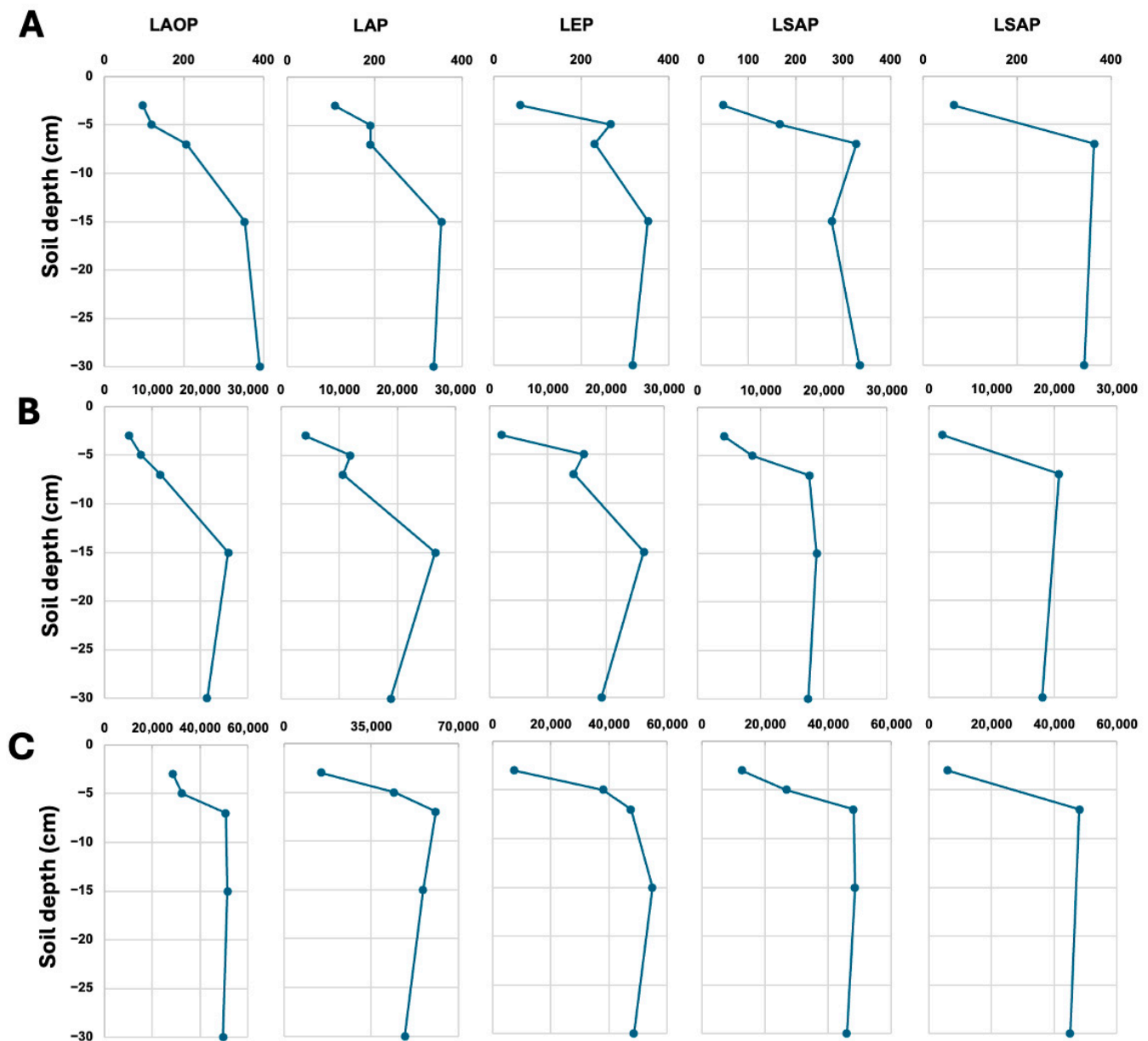


**Figure 2.** Soil profiles observed at the research site: LAOP—Leptic Albic Ortsteinic Podzol (Arenic, Folic), LAP—Leptic Albic Podzol (Arenic, Folic), LEP—Leptic Entic Podzol (Arenic, Folic), LSAP—Leptic Stagnic Albic Podzol (Arenic, Folic), LSEP—Leptic Stagnic Entic Podzol (Arenic, Folic).

All plots had sandy soil (1–7% clay) and a substantial coarse-fragment fraction reaching 35% in the LSAP soil. LSAP and LSEP soils were also the most compacted, with bulk density reaching  $1.6 \text{ g cm}^{-3}$  in the mineral horizon, whereas bulk density of the surface layer remained below  $1.0 \text{ g cm}^{-3}$  and did not differ significantly among plots. All soils were acidic. The pH of the topsoil (horizons of Oa) ranged from  $3.9 \pm 0.1$  to  $5.2 \pm 0.1$ . In the profile, pH increases to  $5.2 \pm 0.2$  in the Bs, Bsm and Bsh horizons and to  $5.6 \pm 0.2$  in the BC and C horizons. This depth distribution was similar across all soil groups. The distribution of total macroelements contents along the profiles followed an illuvial pattern, most clearly visible in the LAOP and LAP profiles. In the E horizon, Fe, Mn, Mg, and P contents were substantially lower than in the Bs and BC horizons, where macroelements accumulated (Figure 3).

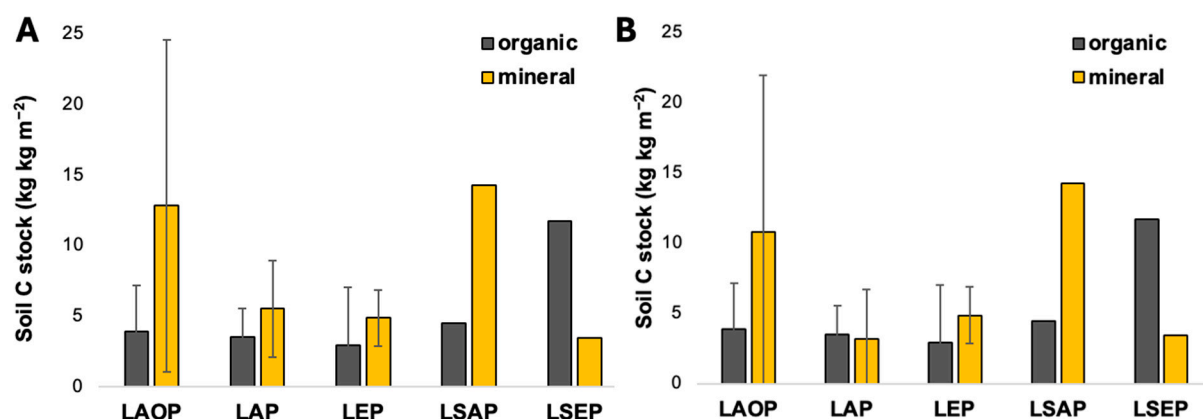
### 3.3. Variation in Soil Carbon Stocks

Total C content in the organic horizons ranged widely from  $14.1 \pm 4.3\%$  to  $43.0 \pm 1.3\%$ . The highest contents were observed in soil profiles with stagnic properties, with average C content in organic horizons reaching 34.8% in the LSAP group and 29.0% in the LSEP group. In LAP soils, located on elevated and better-drained spots, the average C content in organic (O and Oa) horizons was less than half of that, but more variable ( $13.0 \pm 6.4\%$ ). Down the profile, the C content decreased significantly at all plots, reaching minimum values in the E horizon. A slight increase was observed in the illuvial Bs, Bsm and Bsh horizons, indicating partial immobilization of organic matter leached from the upper horizons. A similar depth distribution was observed for the N content, with topsoil values ranging from  $0.55 \pm 0.16\%$  to  $1.10 \pm 0.02\%$  in Oa horizons and decreasing to less than 0.01% on the E and C horizons. The average C/N ratio in organic horizons ranged from 34 (LAP) to 50 (LEP) soil groups, whereas subsoil C/N ratios remained close to 30 for all soil groups.



**Figure 3.** Profile distribution of Mn,  $\text{mg kg}^{-1}$  (A), Fe,  $\text{mg kg}^{-1}$  (B), and Al,  $\text{mg kg}^{-1}$  (C), averaged per soil group: Leptic Albic Ortsteinic Podzol (LAOP), Leptic Albic Podzol (LAP), Leptic Entic Podzol (LEP), Leptic Stagnic Albic Podzol (LSAP), and Leptic Stagnic Entic Podzol (LSEP).

Soil C stocks were calculated for each profile to bedrock and for a standardized depth of 30 cm. The average total profile stock at the research site was  $13.5 \pm 8.0 \text{ kg m}^{-2}$  (mean  $\pm$  standard deviation). The largest profile stock ( $18.7 \text{ kg C m}^{-2}$ ) occurred in an LSAP profile, located in the local depression in the Plot 5, and was almost twice the stocks in LAP and LEP profiles located at more elevated and better-drained Plots 3 and 4. Mineral horizons contributed to 60–70% of the total profile stocks. Their contribution was greatest in deep LAOP profiles with well-developed Bs and Bsm horizons. By contrast, at Plot 5 a relatively thick O horizon overlaid a mineral BHF horizon <10 cm thick, with bedrock at approximately 15 cm. Standardizing the calculation to 30 cm reduced absolute values and variance but retained the overall pattern (Figure 4).



**Figure 4.** Full-profile (A) and standardized 0–30 cm (B) soil C stocks in organic and mineral horizons by soil group: LAOP (n = 6), LAP (n = 4), LEP (n = 2), LSAP (n = 2), and LSEP (n = 1). Here, n denotes the number of soil profiles. Bars show means, and error bars show standard deviations where n > 1. See Figure 3 for abbreviations.

### 3.4. Soil Microbial Properties and Soil Respiration

The highest average  $C_{mic}$  in organic horizons coincided with a high total C content and was observed in LEP (2952  $\mu\text{g C g}^{-1}$  soil) and LSAP (2810  $\mu\text{g C g}^{-1}$  soil), while the values for LAP were one-third lower. A similar pattern was observed for basal respiration, which reached 12.6  $\mu\text{g CO}_2\text{-C g}^{-1}$  soil  $\text{h}^{-1}$  in LEP. Basal respiration was highly heterogeneous in space, with a variance coefficient of 73%, higher than for any other variable. The average  $C_{mic}$  and BR in the mineral horizons were several orders of magnitude lower than in the organic layer. However, a similar spatial pattern was observed, with values for LSAP being 30–50% higher than for the other soil groups. The ratio of  $C_{mic}$  and total (organic) C was used to characterize organic matter quality and its availability to microbes. The  $C_{mic}/C_{org}$  ratio for mineral horizons ranged between 0.5 and 1.5, indicating low to moderate microbial availability. The values obtained for organic horizons were substantially higher and extremely variable with variance coefficients exceeding 100%. The  $q\text{CO}_2$  ranged between 1.6 and 4.5 both in organic and mineral horizons (Table 2).

**Table 2.** Microbial properties (mean and standard deviation) averaged for organic and mineral layers of soil groups.

| Soil Group       | $C_{mic}$<br>( $\mu\text{g C g}^{-1}$ Soil) | BR<br>( $\mu\text{g CO}_2\text{-C g}^{-1}$ Soil $\text{h}^{-1}$ ) | $q\text{CO}_2$<br>( $\mu\text{g CO}_2\text{-C mg}^{-1} C_{mic} \text{ h}^{-1}$ ) | $C_{mic}/C_{org}$ |
|------------------|---------------------------------------------|-------------------------------------------------------------------|----------------------------------------------------------------------------------|-------------------|
| Organic horizons |                                             |                                                                   |                                                                                  |                   |
| LAOP             | 2282 $\pm$ 680                              | 3.62 $\pm$ 1.47                                                   | 1.58 $\pm$ 0.37                                                                  | 4.7 $\pm$ 10.9    |
| LAP              | 2058 $\pm$ 1051                             | 4.03 $\pm$ 2.59                                                   | 1.83 $\pm$ 0.45                                                                  | 3.1 $\pm$ 3.2     |
| LEP              | 2953                                        | 12.66                                                             | 4.29                                                                             | 17.3 $\pm$ 23.5   |
| LSAP             | 2810 $\pm$ 271                              | 5.58 $\pm$ 0.78                                                   | 2.01 $\pm$ 0.46                                                                  | 1.4 $\pm$ 0.6     |
| LSEP             | 2481 $\pm$ 2239                             | 2.12 $\pm$ 1.24                                                   | 1.06 $\pm$ 0.45                                                                  | 0.7               |
| Mineral horizons |                                             |                                                                   |                                                                                  |                   |
| LAOP             | 115 $\pm$ 49                                | 0.22 $\pm$ 0.10                                                   | 2.23 $\pm$ 1.28                                                                  | 1.4 $\pm$ 1.4     |
| LAP              | 69 $\pm$ 51                                 | 0.23 $\pm$ 0.19                                                   | 3.03 $\pm$ 1.53                                                                  | 1.1 $\pm$ 1.1     |
| LEP              | 61 $\pm$ 28                                 | 0.17 $\pm$ 0.09                                                   | 2.93 $\pm$ 0.82                                                                  | 0.7 $\pm$ 1.0     |
| LSAP             | 200 $\pm$ 344                               | 0.71 $\pm$ 1.28                                                   | 3.25 $\pm$ 1.45                                                                  | 0.4 $\pm$ 0.1     |
| LSEP             | 76 $\pm$ 59                                 | 0.44 $\pm$ 0.55                                                   | 4.49 $\pm$ 2.86                                                                  | 0.2               |

While microbial properties characterize the potential of soil microorganisms to decompose organic matter and produce  $\text{CO}_2$ , the actual  $\text{CO}_2$  efflux (soil respiration) depends on

abiotic conditions and varies seasonally. The seasonal dynamics of soil respiration observed in the monitoring plots followed changes in air and soil temperature, with the highest values in late July to early August and the lowest values in October. Soil temperature at 5 cm reached 15.5 °C in July and remained above 10 °C for less than two months. Mean volumetric water content across collars declined from 32.5% on 10 July to 5.5% on 14 August and increased to 17.1% by 15 October. Thus, the seasonal temperature maximum coincided with comparatively dry soil, although temperature and moisture covaried and their independent effects cannot be inferred from these temporal patterns alone.

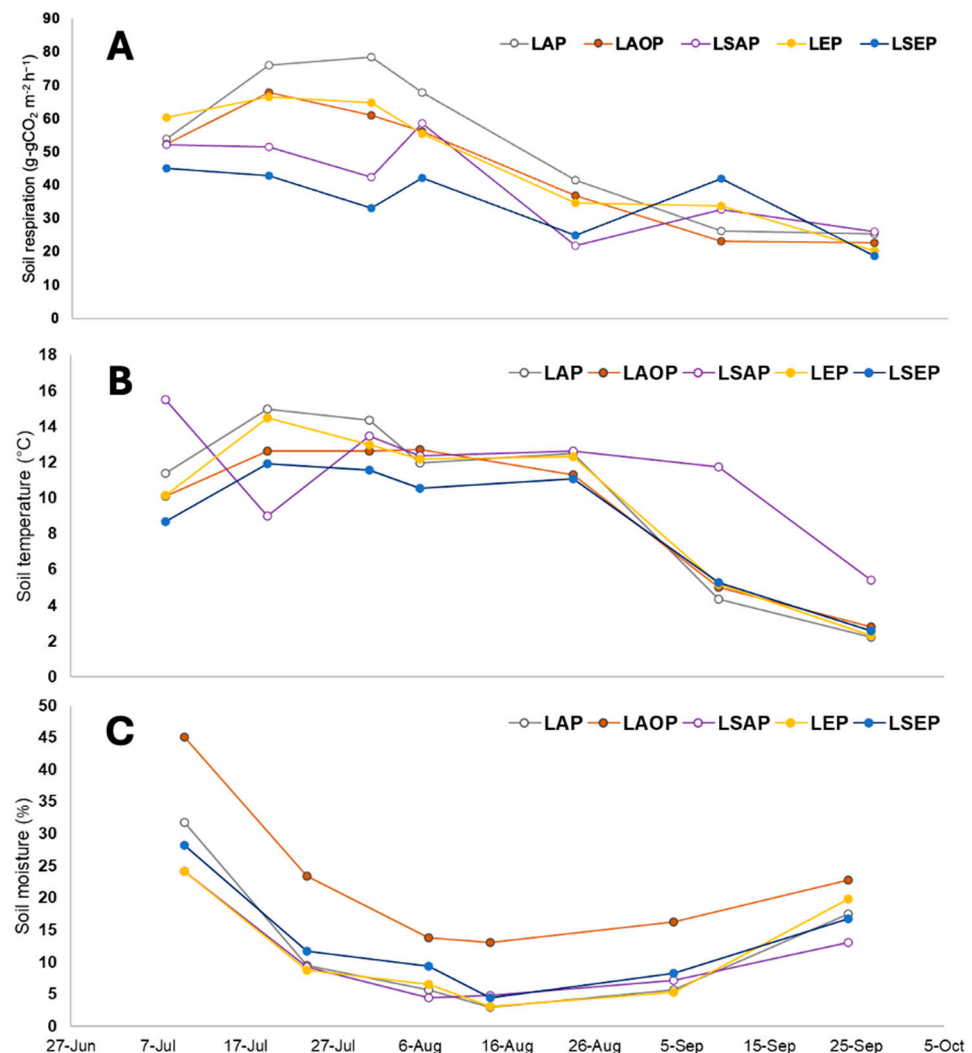
Across soil groups, mean growing-season soil CO<sub>2</sub> efflux ranged from 36 mg C m<sup>-2</sup> h<sup>-1</sup> in LSEP to 53 mg C m<sup>-2</sup> h<sup>-1</sup> in LAP. For the 205 complete observations used in all nested model comparisons, adding standardized soil temperature to Plot ID markedly improved fit (LR = 55.54,  $p < 0.0001$ ;  $\Delta\text{AIC} = -53.54$ ). Adding standardized moisture produced only weak evidence of further improvement (LR = 3.08,  $p = 0.079$ ); AIC decreased by 1.08 but BIC increased by 2.24. The temperature  $\times$  moisture interaction was unsupported (LR = 0.007,  $p = 0.932$ ). The temperature-only model (MT) was therefore retained as the parsimonious model. Its standardized temperature coefficient was 0.328 (95% CI: 0.261–0.394), equivalent to a 38.8% increase in median efflux per 4.08 °C (one SD), or approximately 8.4% °C<sup>-1</sup> within the observed range. Plot contrasts were small and imprecise, and none differed from Plot 1 (Table 3; Figure 5).

**Table 3.** Comparison of nested linear mixed-effects models and fixed-effect estimates from the selected temperature model (MT). Models were fitted to the same 205 complete observations.

| Maximum-Likelihood Comparison of Nested Models |     |          |       |            |                 |
|------------------------------------------------|-----|----------|-------|------------|-----------------|
| Model                                          | df  | AIC      | BIC   | LR         | <i>p</i> -Value |
| M0 (Plot ID)                                   | 8   | 302.8    | 329.4 | -          | -               |
| MT (Plot ID + temperature)                     | 9   | 249.2    | 379.1 | 55.5       | <0.0001         |
| MM (Plot ID + temperature + moisture)          | 10  | 248.1    | 281.4 | 3.1        | 0.079           |
| MI (Plot ID + temperature $\times$ moisture)   | 11  | 250.1    | 286.7 | 0.007      | 0.932           |
| REML Fixed Effects of Selected MT Model        |     |          |       |            |                 |
| Factor                                         | df  | Estimate | SE    | 95% CI     | <i>p</i> -value |
| Intercept                                      | 174 | 3.58     | 0.12  | 3.34–3.83  | <0.0001         |
| Plot 2 vs. Plot 1                              | 25  | 0.12     | 0.18  | −0.23–0.46 | 0.512           |
| Plot 3 vs. Plot 1                              | 25  | 0.16     | 0.18  | −0.19–0.50 | 0.378           |
| Plot 4 vs. Plot 1                              | 25  | 0.13     | 0.18  | −0.22–0.47 | 0.483           |
| Plot 5 vs. Plot 1                              | 25  | −0.013   | 0.18  | −0.36–0.33 | 0.94            |
| Temperature, z-score                           | 174 | 0.33     | 0.03  | 0.26–0.39  | <0.0001         |
| Random Effects and Correlation Parameters      |     |          |       |            |                 |
| Parameter                                      |     |          |       |            | Estimate        |
| Collar-level random-intercept variance         |     |          |       |            | 0.0447          |
| Collar-level random-intercept SD               |     |          |       |            | 0.211           |
| Residual variance                              |     |          |       |            | 0.1925          |
| Residual SD                                    |     |          |       |            | 0.439           |
| Continuous AR(1) parameter, $\phi$             |     |          |       |            | 0.932           |

Exploratory correlation analysis revealed positive associations of laboratory-measured basal respiration and microbial biomass carbon with the contents of the major biophilic elements C, N, and P. Statistically significant Spearman correlation coefficients ranged from 0.23 to 0.45 ( $p < 0.05$ ), indicating weak-to-moderate covariation between microbial activity or biomass and soil resource availability. By contrast, field-measured soil CO<sub>2</sub> emission was negatively associated with C content in the organic horizons. The C-rich organic horizons

were mainly associated with LSAP and LSEP soils occurring in local depressions, where comparatively high moisture and low temperature coincided with lower CO<sub>2</sub> emission. Considering that topsoil C contents were relatively high across all soil groups, abiotic factors became the main drivers of soil respiration.



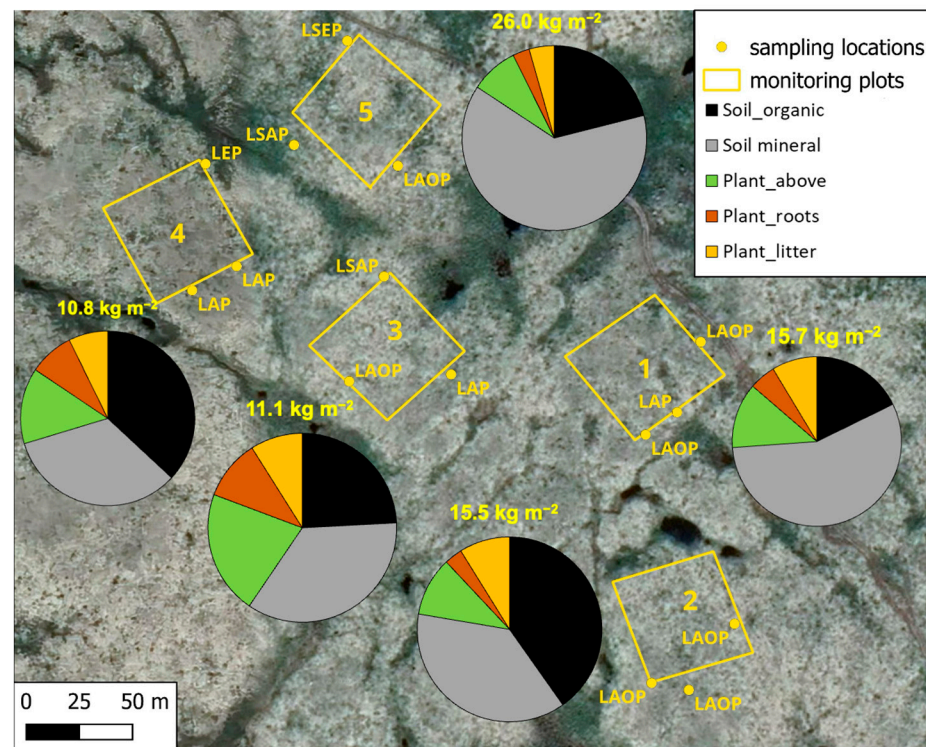
**Figure 5.** Chamber-level soil CO<sub>2</sub> efflux (A), soil temperature at 5 cm depth (B), and volumetric water content at 5 cm depth (C) by observation date and soil group. The numbers of permanent collars were LAOP, n = 14; LAP, n = 8; LEP, n = 4; LSAP, n = 2; and LSEP, n = 2. Each collar was measured on up to seven dates. Points show date-specific soil-group means. The nested model comparison used 205 complete observations.

### 3.5. Comparison Between Carbon Stocks and Growing-Season Fluxes in Soil and Biomass

The results of the soil and vegetation survey, as well as soil respiration monitoring, were used to characterize carbon stocks and growing-season fluxes in tundra ecosystems and explore their fine-scale variation at the research site. C stocks were calculated for soil (organic and mineral horizons with the standard 30 cm depth), plant biomass (aboveground and roots), and litter. Carbon efflux (CO<sub>2</sub> emissions from soils) was estimated as the heterotrophic component of the growing-season soil respiration. Since field segregation was not possible at the site, three scenario-based ratios (Rh/Rs) were used, 0.45, 0.53 and 0.65, to estimate C efflux. These ratios represent the lower and upper bounds of the range reported for tundra ecosystems [47,48]. The estimated soil C efflux was compared to the

measured aboveground annual phytomass production. All results were aggregated for the sampling plots and interpreted in the context of local soil variation.

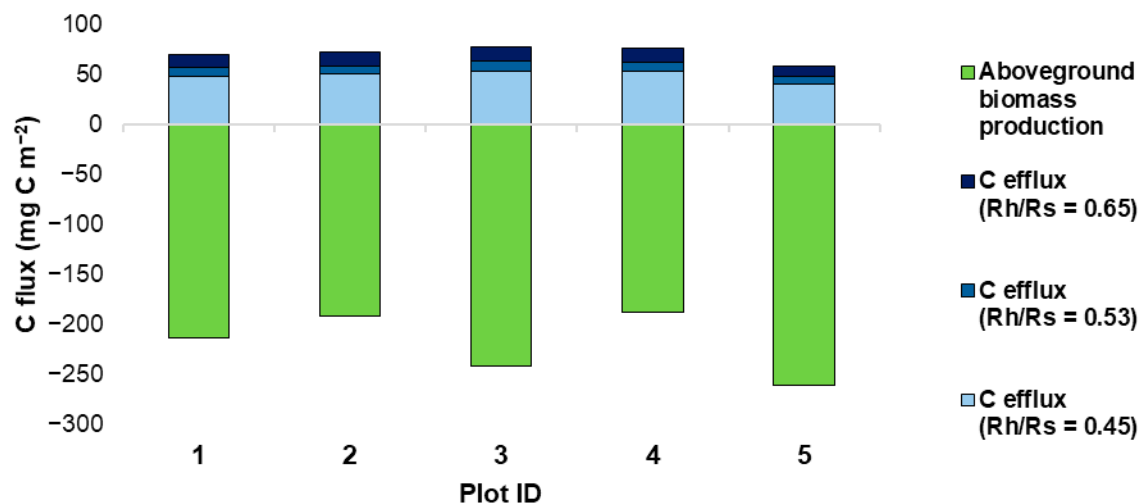
Total standing C stocks ranged from 10.8 to 26.0 kg C m<sup>-2</sup> with a mean of 15.8 ± 6.1 kg C m<sup>-2</sup>. Soil was the largest pool (60–85% of total C), followed by above-ground biomass (10–21%). Plot 5, a local depression with the most heterogeneous soil mosaic (LAOP, LSAP, and LSEP), had the largest total stock. Plots 3 and 4, dominated by LAP, had the smallest stocks; their soil stocks were less than half that at Plot 5. Aboveground biomass C was greatest at Plot 3 (Figure 6).



**Figure 6.** Fine-scale variation in standing C stocks in soil, biomass, and litter among the five monitoring plots.

Modeled growing-season heterotrophic C efflux at the site ranged from 41 to 52 g C m<sup>-2</sup> for Rh/Rs = 0.45, from 48 to 62 g C m<sup>-2</sup> for Rh/Rs = 0.53, and from 59 to 76 g C m<sup>-2</sup> for Rh/Rs = 0.65. Changing the assumed fraction from 0.45 to 0.65 altered each estimate by −15% to +23% relative to the central scenario. C efflux obtained at the Plot 3 was 5 to 15% higher compared to the other Plots. The highest aboveground biomass production was observed at Plot 5 (dominated by LSEP and LSAP) and coincided with the lowest C efflux. Across scenarios, estimated growing-season Rh was 15–40% of directly measured current-year aboveground biomass production. This ratio is a comparison of partial flux components, not an estimate of net ecosystem C exchange (Figure 7).

Although the estimated fluxes are insufficient to calculate a full C budget, they provide a clear indication of the patchiness of its components. For instance, lower C efflux and higher biomass production in the more humid and less elevated patches—dominated by LSEP and LSAP soils with higher plant biomass and vegetation diversity—coincided with substantially higher C stocks compared to other locations. Such patches can be considered local hotspots of C standing stocks and should be given special attention in C accounting for highly heterogeneous tundra ecosystems.



**Figure 7.** Comparison of measured current-year aboveground biomass production with scenario-based growing-season heterotrophic soil C efflux.

## 4. Discussion

### 4.1. Local Variation in Soil and Vegetation

Located on the watershed of the hilly ridge-type basal-denudational plains in the permafrost-free zone, the research site exhibits a remarkable heterogeneity in soil-forming conditions. Soil formation is mainly driven by the AlFeHumus process, traditionally reported among the main soil-forming processes in the north of the Kola Peninsula [32,50–52]. Microelevations had drier, freely drained conditions, whereas microdepressions were wetter and locally semihydromorphic. The granitoid-derived parent material was nutrient-poor, and soil profiles were generally <50 cm deep. Better-drained Leptic Albic Podzols had thin organic horizons. Down-profile translocation promoted Ortsteinic properties and the accumulation of Al, Fe, and C in Bs, Bsm, and Bsh horizons. In contrast, Leptic Stagnic Albic and Entic Podzols in depressions had thicker, C-rich organic horizons and less-developed mineral horizons.

Lithology, soil, and microrelief jointly structure vegetation in mountain and zonal tundra dominated by shrub–lichen communities [53]. Vegetation at our site—dominated by *Cladonia* lichens, *Betula nana*, and *Empetrum nigrum*—resembled the dwarf-shrub and lichen communities of the Khibiny Mountains [31]. Lichen cover at our site (50–75%) was comparable to or greater than the 62% reported for Khibiny lichen communities and far exceeded the 18% in Khibiny dwarf-shrub communities. Moss cover was almost absent at our site, compared with 6–10% in the Khibiny communities. These contrasts are consistent with thinner and more wind-redistributed snow on the coastal lowland. Mean aboveground phytomass at our site was also below the 908 g m<sup>-2</sup> reported for Khibiny dwarf-shrub communities.

The observed contrasts should be interpreted as variation among coupled landscape units rather than as independent effects of soil type, vegetation or microrelief. Within the single study site, stagnic soils occurred mainly in wetter depressions that also differed in temperature and vegetation. This covariance is ecologically meaningful because these attributes jointly organize tundra patches, but it prevents their causal contributions from being separated with the present 15-profile design.

### 4.2. C Stocks and Fluxes in Tundra Ecosystems

The mean standing C stock of  $15.8 \pm 6.1$  kg C m<sup>-2</sup>, with soils contributing 60–85%, confirms that belowground pools dominate C stocks at the site. The observed 11–26 kg C m<sup>-2</sup>

range across plots over tens of meters is a vivid illustration of the tundra soil and vegetation mosaic that is poorly represented by coarse land-cover classes. The profile data add an important nuance: high surface C in stagnic soils and the secondary C maximum in Bs, Bsm and Bsh horizons of deeper LAOP profiles represent different stabilization domains. Inventory protocols that sample only a fixed shallow layer or omit the coarse-fragment correction could therefore rank these microsites differently from a full-profile assessment.

Compared with the nearby Khibiny mountain tundra [31], mean aboveground biomass C at the Kola lowland site was similar (approximately  $440 \text{ g C m}^{-2}$ ), whereas soil C stocks were larger. High organic-horizon C/N ratios (34–50) are consistent with slowly decomposing substrates. Changes in evergreen-shrub litter quality and moss cover could alter decomposition and soil moisture over time [30,54], but the present one-year study cannot establish accumulation rates. A broader comparison places the observed stocks within reported tundra ranges. In permafrost-free tundra on the Varanger Peninsula, mean soil organic C stock to 100 cm was  $9.87 \pm 2.26 \text{ kg C m}^{-2}$ , whereas wetlands stored up to  $45.5 \text{ kg C m}^{-2}$  [55]. On South Baffin Island, 0–20 cm stocks ranged from  $2.17 \pm 0.48 \text{ kg C m}^{-2}$  in polar desert to  $13.07 \pm 0.69 \text{ kg C m}^{-2}$  in wet meadow [56]. Alaskan 0–100 cm stocks range from approximately  $14 \text{ kg C m}^{-2}$  in intermontane boreal forest to  $44 \text{ kg C m}^{-2}$  in Arctic tundra [29]. Differences in sampled depth, coarse fragments, parent material, and landscape composition limit direct comparisons among these studies.

Microbial measurements distinguish C quantity from potential availability for microbial decomposition. High  $C_{mic}$  and basal respiration in some organic horizons indicate a larger active microbial pool, but field  $\text{CO}_2$  efflux was lower at the coolest and wettest site. Laboratory indices measured under standardized temperature and moisture quantify potential activity, whereas field efflux integrates current temperature, aeration, roots, and substrate supply. The LME model comparison supports this distinction: soil temperature explained additional temporal variation after Plot ID was controlled, but moisture provided only weak incremental evidence ( $p = 0.079$ ). This does not demonstrate that water availability is irrelevant. Moisture can constrain respiration at both dry and water-saturated extremes, and temperature–moisture responses can be nonlinear or history dependent, particularly around freeze–thaw events [57]. Sparse sampling and covariance between wetness, temperature, and topographic position reduce the power to resolve these effects. The observed temperature response is consistent with chamber studies and synthesis experiments showing widespread stimulation of tundra respiration by warming [58,59]. In addition, a growing-season chamber series cannot be interpreted as an annual C exchange. Arctic chamber studies remain seasonally and geographically biased, and winter or shoulder-season losses can offset summer uptake [11,14].

The comparison of stocks and partial fluxes enables a better understanding of the C cycle heterogeneity in tundra ecosystems. Large standing stocks in wet depressions integrate the history of inputs, decomposition, stabilization, and redistribution and do not demonstrate current accumulation [60,61]. We therefore refer to these areas as high-carbon microsites. Their large organic-layer pools and lower observed growing-season efflux are consistent with conditions that can slow decomposition, but this mechanistic interpretation remains provisional because winter respiration, belowground production and lateral C transfers were not measured [24,62,63]. The estimated C efflux was also based on two assumptions: sparse rain-free midday measurements were extended across unsampled days, and total soil respiration was partitioned using an assumed  $R_h/R_s$  fraction. Across plots, changing  $R_h/R_s$  from 0.45 to 0.65 expanded the estimated growing-season  $R_h$  range from 41–52 to 59–76  $\text{g C m}^{-2}$ . These scenarios quantify partitioning sensitivity but are not confidence intervals because diel and event-scale variability was not observed. Direct partitioning by root exclusion or isotopic methods, belowground

production measurements, and year-round flux monitoring are required before assigning sink or source status [48,64,65].

#### 4.3. How to Consider Short-Distance Variation for C Accounting in Tundra Ecosystems

The principal accounting implication of the study is that local heterogeneity should be represented by explicit strata rather than absorbed into a single site mean. The combination of elevation or wetness position, vegetation structure, and soil morphology provides a practical minimum stratification for this landscape. Depressions with stagnic soils formed hotspots of standing C stocks and lower growing-season efflux, whereas elevated, better-drained patches stored less C in surface horizons and showed different pool partitioning. A similar conclusion emerged from decadal modeling in the western Russian Arctic, where land-cover differences exceeded interannual variability and coarse classification biased regional CO<sub>2</sub> and CH<sub>4</sub> estimates [24]. Thus, high-resolution terrain and vegetation maps can guide a stratified random design, but field profiles remain necessary to calibrate stock depth and bulk density.

A defensible upscaling workflow would first delineate recurring landscape units from UAV elevation, hydrological indices, surface cover, and, where possible, snow persistence. Independent soil profiles and flux collars should then be replicated within each unit and across more than one local site. Unit-specific means and variances can be combined using mapped area fractions, with uncertainty propagated from field sampling, stock calculations, flux models and the Ra/Rh partition. Continuous year-round monitoring would also improve the assessment accuracy compared to the current monitoring during the growing season since accounting for winter respiration may reverse the sign inferred from summer measurements as it was shown by the previous studies in Arctic [13,27]. Representing fine-scale units within a multiscale, uncertainty-aware design is therefore essential if Kola tundra observations are to support regional carbon maps, national inventories and international monitoring programs.

The long-term vegetation monitoring from the Khibiny Mountains [36] underscores the importance of repeated observations in detecting climate-driven changes that may not be captured by single-year surveys. Their finding—that aboveground phytomass has not significantly increase despite warming, while functional composition has shifted substantially—highlights the need for continuous monitoring of both vegetation and soil C stocks. Our study provides a baseline for such monitoring in zonal tundra, but the repeated surveys will be essential to determine whether similar compositional shifts are occurring and how they affect soil C stocks and fluxes.

## 5. Conclusions

Standing carbon stocks and growing-season flux components varied markedly within a 250 × 250 m lichen–dwarf shrub tundra site on the Kola Peninsula. Total standing stocks ranged from 10.8 to 26.0 kg C m<sup>−2</sup> among plots; soil accounted for 60–85%. The study demonstrated pronounced within-site variation in C stocks associated with coupled differences in microrelief, soil morphology, and vegetation. The largest standing stocks occurred in microdepressions with stagnic soils and were driven mainly by organic-horizon C, whereas deeper, better-drained podzolized profiles stored a larger fraction in mineral horizons. Repeated-measures modeling identified soil temperature as the principal measured predictor of short-term soil CO<sub>2</sub> efflux: a one-standard-deviation increase in temperature corresponded to a 38.8% increase in median efflux. Evidence for an additional linear moisture effect was weak, and no temperature × moisture interaction was detected. Together, these findings show that microrelief, vegetation, and soil morphology form coupled local units that can improve the design of tundra C inventories.

The results do not yet provide a complete ecosystem C balance. The comparison of aboveground annual increment with an average growing-season heterotrophic respiration estimate omits belowground net primary production, non-growing-season respiration and non-CO<sub>2</sub> or lateral transfers. We therefore recommend reporting the study as a fine-scale assessment of standing pools and partial flux components. Replicated landscape strata, continuous or model-assisted year-round flux measurements, direct respiration partitioning, and explicit uncertainty propagation are the next steps required to scale these observations and determine whether individual Kola tundra units are annual C sinks or sources.

**Author Contributions:** Conceptualization, D.D., V.V. and N.S.; methodology, D.D., V.V. and E.K.; validation, V.V. and E.K.; formal analysis, V.V., V.M., M.K. and E.K.; investigation, V.V., A.D., V.M., M.K. and E.K.; resources, V.V. and D.D.; data curation, V.V., V.M., A.D., E.K. and M.K.; writing—original draft preparation, V.V.; writing—review and editing, V.V., E.K., N.S., V.M. and M.K.; visualization, V.V. and E.K.; supervision, V.V.; project administration, D.D.; funding acquisition, D.D. All authors have read and agreed to the published version of the manuscript.

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**Data Availability Statement:** The chamber-level soil CO<sub>2</sub> efflux dataset and associated soil temperature and moisture measurements used in the repeated-measures analysis, together with the soil, microbial, biomass, and plot-level carbon-stock data supporting the reported results, are available from the corresponding author upon reasonable request. The R code used for model fitting and growing-season scenario calculations is also available upon request.

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