AGU Advances

RESEARCH ARTICLE
10.1029/2023AV000942

More Snow Accelerates Legacy Carbon Emissions From Arctic Permafrost

S. A. Pedron[1], R. G. Jespersen[2], X. Xu[1], Y. Khazindar[1], J. M. Welker[2,3,4], and C. I. Czimczik[1]

[1]Department of Earth System Science, University of California, Irvine, CA, USA, [2]Department of Biological Sciences, University of Alaska, Anchorage, AK, USA, [3]Ecology and Genetics Research Unit, University of Oulu, Oulu, Finland, [4]UArctic, Rovaniemi, Finland

Shawn Alexander Pedron and Robert Gus Jespersen contributed equally to this work.

Peer Review The peer review history for this article is available as a PDF in the Supporting Information.

Key Points:

- Twenty-five years of snow addition to Arctic tundra thawed permafrost and increased carbon and nitrogen available for microbial decomposition 4-fold
- More snow sustained ancient carbon emissions year-round, despite greater productivity associated with a shift from graminoid to shrub tundra
- In the rapidly warming Arctic, increases in snow mass will lead to earlier-than-expected losses of legacy carbon from permafrost

Supporting Information:

Supporting Information may be found in the online version of this article.

Correspondence to:

C. I. Czimczik and J. M. Welker,
czimczik@uci.edu;
jmwelker@alaska.edu

Citation:

Pedron, S. A., Jespersen, R. G., Xu, X., Khazindar, Y., Welker, J. M., & Czimczik, C. I. (2023). More snow accelerates legacy carbon emissions from Arctic permafrost. *AGU Advances*, *4*, e2023AV000942. https://doi.org/10.1029/2023AV000942

Received 10 APR 2023
Accepted 30 JUL 2023

Author Contributions:

Conceptualization: S. A. Pedron, R. G. Jespersen, J. M. Welker, C. I. Czimczik
Data curation: X. Xu, C. I. Czimczik

Abstract

Snow is critically important to the energy budget, biogeochemistry, ecology, and people of the Arctic. While climate change continues to shorten the duration of the snow cover period, snow mass (the depth of the snow pack) has been increasing in many parts of the Arctic. Previous work has shown that deeper snow can rapidly thaw permafrost and expose the large amounts of ancient (legacy) organic matter contained within it to microbial decomposition. This process releases carbonaceous greenhouse gases but also nutrients, which promote plant growth and carbon sequestration. The net effect of increased snow depth on greenhouse gas emissions from Arctic ecosystems remains uncertain. Here we show that 25 years of snow addition turned tussock tundra, one of the most spatially extensive Arctic ecosystems, into a year-round source of ancient carbon dioxide. More snow quadrupled the amount of organic matter available to microbial decomposition, much of it previously preserved in permafrost, due to deeper seasonal thaw, soil compaction and subsidence as well as the proliferation of deciduous shrubs that lead to 10% greater carbon uptake during the growing season. However, more snow also sustained warmer soil temperatures, causing greater carbon loss during winter (+200% from October to May) and year-round. We find that increasing snow mass will accelerate the ongoing transformation of Arctic ecosystems and cause earlier-than-expected losses of climate-warming legacy carbon from permafrost.

Plain Language Summary

Northern ecosystems are shaped by snow. With climate change, the duration of the snow cover period in the Arctic has been decreasing while the amount of snow falling has been increasing. It is not clear how more snow will affect Arctic ecosystems, specifically greenhouse gas emissions from thawing permafrost. We know that deeper snow can rapidly thaw permafrost and the large amounts of ancient organic matter contained within it. The decomposition of this material by soil microbes releases climate-warming carbon dioxide, however, it also stimulates the growth of plants which sequester carbon dioxide from the atmosphere through photosynthesis. Here, we discuss the results of a climate change experiment where more snow was added to a typical and widely-distributed tundra ecosystem in northern Alaska for 25 years. We found that more snow thawed permafrost and led to a four-fold increase in the amount of organic matter available for microbial decomposition. While this stimulated the growth of plants (specifically that of deciduous shrubs) and soil carbon sequestration, microbial decomposition of previously frozen organic matter outpaced the benefits. Our study demonstrates that greater snowfall will cause earlier-than-expected losses of ancient carbon from permafrost and further accelerate climate change.

1. Introduction

Arctic soils contain large amounts of carbon (1,035 ± 150 Pg C (Hugelius et al., 2014)) and nitrogen (22–106 Pg N (Strauss et al., 2022)) in the form of frozen organic matter (0–3 m), much of which was sequestered during the Pleistocene and early Holocene with radiocarbon ages ≥5,000 years before present (BP) (Miner et al., 2022). Rapid climate change and permafrost thaw (Box et al., 2019; Rantanen et al., 2022) renders this "legacy" carbon and nitrogen vulnerable to microbial decomposition, and its emission as carbon dioxide (CO_2), methane, or nitrous oxide will further increase greenhouse gas concentrations in the atmosphere and accelerate climate change (Miner et al., 2022; Schuur et al., 2022; Voigt et al., 2020).

The net impact of climate change on the carbon balance of permafrost ecosystems and soils remains uncertain and excluded from climate mitigation policy (Natali et al., 2022). Some of this uncertainty arises from the

Formal analysis: S. A. Pedron, R. G. Jespersen, C. I. Czimczik
Funding acquisition: J. M. Welker, C. I. Czimczik
Investigation: S. A. Pedron, R. G. Jespersen, Y. Khazindar, C. I. Czimczik
Methodology: S. A. Pedron, R. G. Jespersen, J. M. Welker, C. I. Czimczik
Project Administration: J. M. Welker, C. I. Czimczik
Resources: X. Xu, J. M. Welker, C. I. Czimczik
Supervision: X. Xu, J. M. Welker, C. I. Czimczik
Validation: S. A. Pedron, R. G. Jespersen, X. Xu, C. I. Czimczik
Visualization: S. A. Pedron
Writing – original draft: R. G. Jespersen, C. I. Czimczik
Writing – review & editing: S. A. Pedron, R. G. Jespersen, X. Xu, J. M. Welker, C. I. Czimczik

increasing productivity of Arctic plants (Arndt et al., 2019), which will affect carbon and energy inputs to soils (Shur & Jorgenson, 2007). Climate change and permafrost thaw are expected to alleviate temperature, moisture, and nutrient (nitrogen) constraints on plant growth (Salmon et al., 2018; W. Xu et al., 2021). However, much of this uncertainty also stems from cold season processes (Fahnestock et al., 1999; Welker et al., 2000). Increasing soil temperatures in fall and winter allow soil microorganisms that decompose organic matter to remain active for longer (Pedron et al., 2022). Cold season CO_2 emissions are beginning to offset plant CO_2 uptake during the growing season and turn the Arctic into a source of carbon emissions (Natali et al., 2019; Pedron et al., 2022; Schiferl et al., 2022).

In the Arctic, winter conditions can persist for two-thirds of the year, and the effect of freezing air temperatures on vegetation and soils is mediated by the depth of the snowpack. Deeper snow, especially in fall, insulates soils from cold air temperatures (Lafrenière et al., 2013) and leads to a deepening of the seasonally freezing/thawing active layer (Pattison & Welker, 2014). Soil thaw occurs even though deeper snow extends the snow cover period and leads to cooler soil temperatures during the growing season (Hinkel & Hurd, 2006; M. D. Walker et al., 1999). Deeper snow also facilitates the mineralization of plant nutrients (such as nitrogen) (Leffler & Welker, 2013; Schimel et al., 2004), changes the composition of vegetation communities (Christiansen et al., 2018; Cooper et al., 2019; Wahren et al., 2005), and often stimulates gross primary productivity (*GPP*) (Leffler et al., 2016). Furthermore, deeper snow can trigger rapid and substantial losses of nitrogen (Salmon et al., 2018; W. Xu et al., 2021) and carbon from soils (Christiansen et al., 2018; Natali et al., 2011; Plaza et al., 2019; Semenchuk et al., 2019). The latter is particularly concerning because snow mass has been increasing across parts of the Arctic (Callaghan et al., 2011; Pulliainen et al., 2020; Stuefer et al., 2020).

Here, we report the impacts of deeper snow on the carbon and nitrogen balance of permafrost ecosystems and soils, capitalizing on a 25-yearlong International Tundra Experiment (ITEX) (Henry et al., 2022; M. D. Walker et al., 1999) snow addition experiment in a common tundra system in Northern Alaska (Jones et al., 1998). The unique duration of this experiment overcomes the challenge posed by large inter-annual weather variability when assessing climate manipulation effects in the Arctic (Lupascu et al., 2013, 2014) and has allowed a realistic cascade of interacting physical and ecological changes to accumulate that offer a unique window into one future Arctic scenario.

2. Materials and Methods

Field research took place at Toolik Field Station (68°38′N, 149°36′W, 760 m a.s.l.) in the northern foothills of the Brooks Range, Alaska, USA, where maximum winter snow depth ranges from 0.5 to 1 m (September through May). The vegetation type is moist acidic tussock tundra, a common form of Low Arctic tundra consisting of raised *Eriophorum vaginatum* L. tussocks and swales covered by dwarf shrubs (*Betula* spp., *Salix* spp., *Rhododendron* spp., and *Vaccinium* spp.), lichens, and mosses. To simulate forecasted increases in Arctic snow, a 2.8 m-tall, 60 m-wide wooden snow fence was installed perpendicular to the prevailing wind direction in 1994 that accumulates a tapered snowdrift on its leeward (north) side (DeFranco et al., 2020). This study was conducted about 30 m from the fence (intermediate zone).

2.1. Bulk Soil Properties and Microbial CO_2 Fluxes (Incubations)

To analyze the effects of deeper snow on bulk soil properties, we harvested soil cores between 2015 and 2019 down to 164 cm depth below the surface ($n = 25$). Cores were collected with a powered auger (2015, $n = 19$) or a hole saw modified to be driven by cordless drill (2019, $n = 6$), and stored frozen. Cores were separated into horizons and further divided for bulk analyses or incubations. Bulk samples were oven dried at 60°C, ground to powder, and analyzed for their elemental (carbon and nitrogen) and stable isotope ($\delta^{13}C$ and $\delta^{15}N$) composition by EA-IRMS (Fisons NA-1500NC, DeltaPlus XL, Thermo, USA) along with processing blanks and standards. We report measurement uncertainties (1σ) of 0.1 and 0.2‰ for $\delta^{13}C$ and $\delta^{15}N$ respectively, based on long term secondary standard records. For ^{14}C analysis, samples were first converted to graphite by sealed-tube zinc reduction, and then analyzed using accelerator mass spectrometry (NEC 0.5MV 1.5SDH-2 AMS) at UC Irvine's KCCAMS facility with a measurement uncertainty of <3‰ from processing standards and blanks (X. Xu et al., 2007).

To assess the rate and isotopic signature of microbial respiration, laboratory incubations of field-moist soils were performed in the dark at −20, 7, and 22°C. Samples were placed in 0.5–2 L glass mason jars with ports in the lids and flushed with CO_2-free air after a 24-hr period. We measured [CO_2] at regular intervals using a LI-COR 820 (LI-COR Biosciences, USA) and terminated incubations before 30% [CO_2] was reached (17–49 days).

To calculate stocks at defined depths and to inform the ecosystem respiration (R_{eco}) $\Delta^{14}C$ model with data spanning the top and bottom of each core segment (rather than just a mean segment depth), we aggregated bulk soil data into 1-cm increments spanning the surface of the top organic horizon (0 cm) to the bottom depth of the deepest +Snow core (88 cm). Core segments which overlap each depth step were averaged into that depth, creating a weighted average that includes multiple unique core segments.

2.2. Sources and Fluxes of CO_2

Sources of soil CO_2 were quantified with passive CO_2 traps (Pedron et al., 2021). We installed 12 access wells (diffusive silicone inlets attached to steel wells, in each zone at 20, 50, and 80 cm depth below the surface ($n = 4$ per depth and zone)) in June 2019. CO_2 was collected continuously via diffusion over periods of 5–18 weeks on molecular sieve traps from June 2019 to April 2021 ($n = 376$ unique samples), and then thermally desorbed, purified, and analyzed for its ^{14}C content at the KCCAMS facility.

We assessed the rate of soil CO_2 fluxes using two different techniques. First, R_{eco} was continuously monitored in swales (excluding shrubs; 5 min to 4 hr observation frequency) via forced diffusion chambers ($n = 1$ per zone, eosFD, eosense, USA) from July 2019 to June 2022. Weather-related power supply issues caused intermittent data loss in both the +Snow and Control probes such that only the Control has a complete year of data averaged by month (13/35 and 20/35 months measured, respectively; June and October were not captured in the +Snow).

Second, R_{eco} and net ecosystem exchange (*NEE*) were measured at weekly intervals during the 2021 growing season at the plot level (including shrubs) during snow-free periods via a closed dynamic chamber technique (Leffler et al., 2016). A clear acrylic chamber (70 cm^2 by 70 cm height) containing four small fans and a quantum sensor (LI-COR 190) was sealed against the tundra with a 30 cm-wide flexible plastic skirt weighted with a heavy chain and attached to a CO_2/CH_4 sensor (LI-COR 7810). We measured the CO_2 concentration in the chamber every second for 2 min and calculated *NEE* using the *FluxCalR* package in R (Zhao, 2019). At each plot ($n = 5$ per zone) we measured NEE under five light levels (implemented with shade cloths), ventilating the chamber between light levels by tipping it upright for 30 s to allow the CO_2 concentration to return to the ambient level. From these measurements, *GPP* was estimated by fitting rectangular hyperbola light response curves with the *minpack.lm* package (Elzhov et al., 2016) using the equation: $NEE = R_{eco} - (GPP \times \mathrm{PAR})/(k + \mathrm{PAR})$ where *NEE* is the flux of CO_2 measured in the chamber, R_{eco} is modeled ecosystem respiration, *GPP* is a fitted parameter indicating maximum assimilation rate of CO_2 measured in μmol m^{-2} s^{-1}, PAR is the incident flux of photosynthetically active radiation measured in the chamber as μmol photons m^{-2} s^{-1}, and the modeled parameter k is the PAR value at half *GPP* in μmol photons m^{-2} s^{-1}.

3. Ancillary Data

To gauge the effect of deeper snow on soil temperature and volumetric water content, we installed soil temperature (105T-L, Campbell Scientific, USA) and moisture (EC5, Decagon, USA) sensors at equivalent depths to the passive trap inlet depths (at 20 and 50 cm below the surface, $n = 3$ per zone and at 80 cm $n = 2$ per zone). Site conditions have also been monitored by the Toolik Field Station Environmental Data Center for over 10 years with meteorological stations that measure air temperature, relative humidity, and wind direction and speed in each zone, and monthly snow depth surveys.

3.1. Thaw Depth

Our team intermittently measured thaw depth in the Control and +Snow zone between May and September 2015 to 2020 by pushing a steel rod to the frost table. We also compiled data collected at the experimental site by the Boreal Ecology Cooperative Research Unit (1994–2002) and M. Ricketts (2012–2016, Pers. Com. 2018), and nearby within the 1 km-Toolik grid (U12A) by the Circumpolar Active Layer Monitoring network (1995–2020) (Figure S1 in Supporting Information S1).

3.2. Snow Depth

We use snow depth data collected on request by the Toolik Environmental Data Center team (Environmental Data Center Team, 2022), and for ITEX (1995–2001, 2002) (M. D. Walker, 2007a, 2007b).

10.1029/2023AV000942

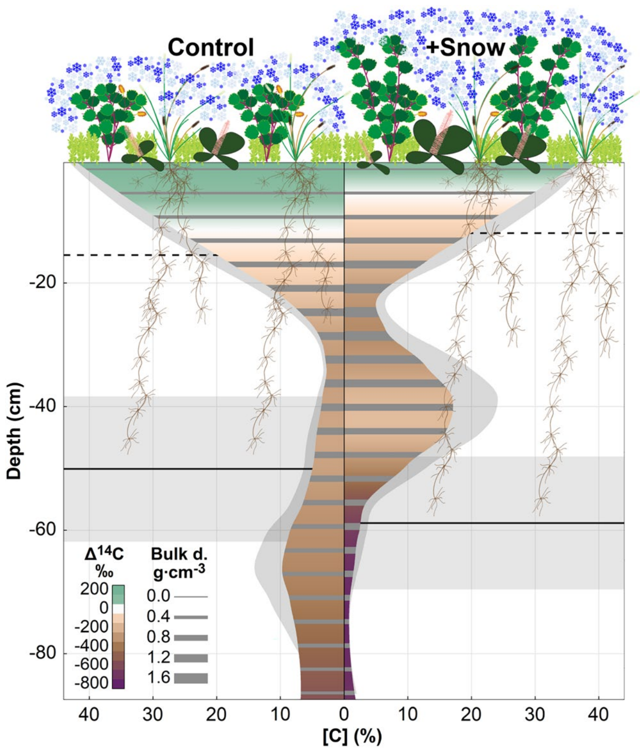

Figure 1. Transformation of Arctic tundra under ambient climate (Control) and in response to long-term snow addition (+Snow). Fraction of soil organic carbon (ave. ±SE) as a function of depth below the soil surface, shaded by bulk soil age (radiocarbon content (Δ^{14}C)) and density. Legacy carbon has $\Delta^{14}C < -470‰$ (radiocarbon ages >5,000 years before present), modern carbon has $\Delta^{14}C \geq 0‰$ (CO_2 assimilated by photosynthesis from the atmosphere since 1950). Dashed horizontal lines indicate the interface of organic and mineral soil and solid lines with shading the depth of the seasonally thawed active layer (Aug. ave. ±SD, 1995–2022).

3.3. Vegetation Community Composition

Vegetation composition has been monitored intermittently using the point-frame technique since the snow fence installation. All previously available data (Leffler, 2015; M. Walker, 2007) and surveys conducted by us in 2021 ($n = 5$ per zone) are shown in Figure S2 of Supporting Information S1. However, we excluded the 2021 data from our statistical analysis because some shrubs had been partially harvested from the +Snow zone for a different project in 2016.

3.4. Statistical Analyses

To examine the effects of added snow on the vegetation communities, we used a 2-way ANOVA for each vegetation type (e.g., deciduous shrubs, graminoids) with year and snow (and their interaction) as fixed effects. To examine the effects of added snow on *GPP*, soil temperature, bulk soil properties, as well as passive trap Δ^{14}C values, we used Welch's Two Sample *t*-test.

To develop full growing season estimates of R_{eco} and *NEE* from our 2021 static chamber-based point estimates, we used an ensemble stack of machine learning-based regression models (LeDell et al., 2022). Features included in the models were our chamber environmental data (PAR, air temperature and relative humidity), *NEE* data from a local tussock tundra Ameriflux site collected at 30-min intervals (Euskirchen et al., 2022), and the continuous meteorological record from Toolik Field Station collected at 1-min intervals (Environmental Data Center Team, 2022). The individual models were gradient-boosted regression (h2o.gbm), random-forest regression (h2o.randomForest), general linear model (h2o.glm), and deep learning (h2o.deeplearning). To avoid overfitting, our data were split into training and validation sets, and individual models were fit to a training set. Ensemble stacks were then developed while allowing h2o to select the optimum metalearner algorithm. Confidence intervals were formed by bootstrapping the data set with replacement and repeating the fitting and ensemble stack process 1,000 times. *NEE* predictions from this approach fit observed values better when developed from separately modeled *GPP* and R_{eco} rather than from a modeled *NEE* value, thus we used the sum of modeled *GPP* and R_{eco} as our *NEE* estimate.

We used a multivariate adaptive regression spline (*earth* package (Milborrow, 2023)) model to evaluate the complete profile of R_{eco} Δ^{14}C values, extrapolating between the shallowest inlet depth (20 cm) and the soil surface for each month of year. The model uses nonparametric regression with generalized cross-validation to deduce nonlinearities and interactions between multiple predictors, penalizing the number of terms while optimizing for goodness of fit. The model was driven by simple, easily measured predictor variables anticipated to be potential drivers of soil respiration source apportionment: snow depth, day-of-year, incubation Δ^{14}C, bulk soil Δ^{14}C, treatment (i.e., +Snow vs. Control), and depth from surface. To fully utilize the available, highly depth-resolved predictor data, the model was driven by linear interpolations between the individual inlet depths for incubation and bulk soil Δ^{14}C. Nonetheless, these were eliminated in favor of simpler predictors (in decreasing importance): treatment, snow depth, and depth from surface (Figure S3 in Supporting Information S1).

4. Results and Discussion

4.1. More Snow Transforms Tussock Tundra Into a Shrubland

Twenty-five years of deeper snow has transformed the tundra from a graminoid- to a deciduous shrub-dominated ecosystem, which coincides with increases in plant-available nitrogen, leaf-level photosynthesis, and active layer depth (ALD) (Figure 1). Between 1994 and 2021, deciduous shrubs have expanded in both zones, from 16% to

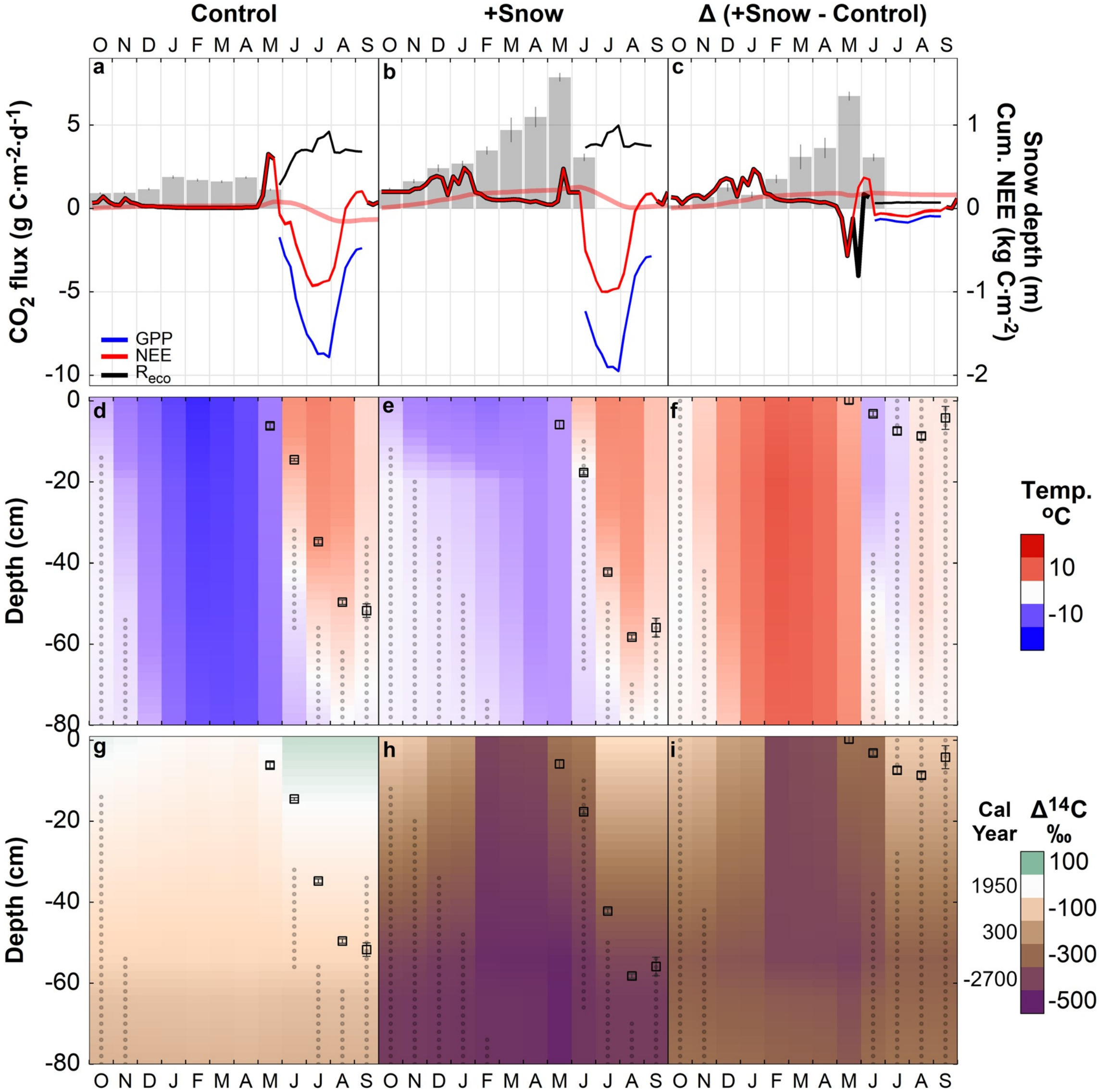

Figure 2. Soil properties of Arctic tundra under (left panels) ambient climate (Control), (center) after long-term snow addition (+Snow), and (right) expressed as treatment difference. (a–c) Monthly net ecosystem CO_2 exchange (net ecosystem exchange (*NEE*), ave. with shrubs (2021) and without shrubs (derived from eosFD R_{eco} for non-growing season, 2019–2021); positive values connote release to the atmosphere) and gross primary productivity (*GPP*, ecosystem-scale photosynthesis, with shrubs, 2021), and monthly winter ecosystem respiration (R_{eco}, CO_2 emissions from soil microbes and, or plants (with shrubs, 2021) and without shrubs (thicker black line, 2019–2021)) measured with closed dynamic or forced-diffusion chambers, and snow depth (gray bars, ave. ±SE, 1995–2022). Cumulative *NEE* is shown by the thick translucent red line. (d–f) Monthly soil temperature as a function of depth. (g–i) Monthly age of soil CO_2 ($\Delta^{14}C$) as a function of depth. Dots indicate when soil temperatures are near freezing (zero-curtain conditions). Squares indicate tile-probe of active layer depth (ave. ±SE, 1995–2022).

20% cover under ambient snow and to more than 26% under deeper snow (Figure S2 in Supporting Information S1) (Leffler et al., 2016; Leffler & Welker, 2013). This shift in vegetation raised the productivity of the tundra (*GPP* was 45% greater in +Snow in 2021, $P < 0.05$) and resulted in approximately 6%–13% greater carbon sequestration during the growing season (Figure 2a–2c), when *NEE* was -229 ± 4 g C m^{-2} in +Snow (weeks 25–38) versus -203 ± 4 or -217 ± 4 g C m^{-2} in Control during weeks 25–38 or the total snow free period (weeks 22–38), respectively.

Belowground, this vegetation shift was accompanied by a 20% increase in ALD (Figure 1, Table 1). Under deeper snow, soil temperatures (20–80 cm below the surface) were higher and remained near zero for longer during the winter (Figure 2d–2f; +Snow = -0.75 ± 0.55°C, Control = -8.6 ± 4.1°C, December through May ($P = 0.01$)). These findings align with other studies showing that cold season, not growing season, soil temperatures dominate the thermal regime of permafrost soils (Kropp et al., 2020; Way & Lapalme, 2021).

Table 1
Soil Properties Under Ambient (Control) and Deeper Snow (+Snow)

Scenario		Active layer depth		Carbon		Nitrogen	
		Average	SD	Average	SE	Average	SE
Snow level	Soil processes	cm		kg C m^{-2}		kg N m^{-2}	
+Snow	Observed ALD[a]	59	11	5.0	1.7	0.27	0.08
Control (ambient climate[b])	Observed ALD[a]	50	12	1.3	0.2	0.06	0.01
	Thaw[c]	59	NA	1.2	0.2	0.07	0.01
	Compaction and Subsidence[d]	89	NA	1.9	NA	0.11	NA
	Compaction and Subsidence and Thaw[e]	97	NA	2.1	NA	0.13	NA

Note. Twenty-five years of experimentally increased snowpack (+Snow) in Northern Alaska resulted in a quadrupling of the amount of total soil organic carbon and nitrogen available for microbial decomposition. Approximately half of the greater amounts in +Snow can be attributed to a combination of the thaw of the permafrost surface and the compaction and subsidence of the permafrost surface and overlying soil. NA, not applicable.

[a]Depth of seasonal thaw of the surface soil (active layer depth (ALD) as measured from the soil surface to the permafrost table between 1995 and 2022). [b]Maximum winter snow depth ranges from 0.5 to 1 m (September–May); amount of carbon or nitrogen in Control assuming. [c]Observed Control-ALD is equal to observed +Snow-ALD, [d]Bulk soil ^{14}C in Control matches that of bulk soil ^{14}C in +Snow, or [e]Bulk soil ^{14}C in Control matches that in +Snow and ALD is 9 cm deeper (as observed in +Snow).

Deeper snow quadrupled the amount of carbon and nitrogen in the active layer (Figure 1, Table 1). This increase is not just a consequence of active layer deepening due to the higher soil temperatures under +Snow but of soil compaction and subsidence. Organic horizons were four times denser with added snow ($P < 0.01$) and the age of the bulk soil (estimated from its ^{14}C content) increased nearly 10-fold, from 200 to 2,000 years BP (Figure 1). From the differences in soil density and age, we conclude that the heavier snowpack, higher rates of decomposition and/or a loss of ground ice caused approximately 40 cm of soil loss (Table 1). More importantly, we find that deeper snow exposed ancient legacy nitrogen and carbon (with a mean $\Delta^{14}C$ of about −470‰ or ~6,000 years BP) formerly preserved below the long-term average ALD (Table 1). This dramatic increase in the amount of available legacy carbon and nitrogen, which cannot be estimated from routinely monitored permafrost properties such as ALD, further highlights the significant risk of thermokarst (Hinkel & Hurd, 2006) and greenhouse gas emissions (Natali et al., 2011; Plaza et al., 2019; Rodenhizer et al., 2020; Turetsky et al., 2020; Voigt et al., 2020) associated with increasing snow mass.

The amounts of carbon and nitrogen found under deeper snow are larger than expected from active layer deepening and compaction and, or subsidence (Table 1). Some of this difference can be explained by the large spatial variability of carbon pools in cryoturbated soils. However, we also see evidence for greater rates of carbon sequestration in the topsoil under deeper snow. A younger soil age at the organic-mineral interface (at 25–40 cm below the surface, Figure 1) indicates greater inputs of modern carbon (CO_2 assimilated by photosynthesis since 1950), presumably from the rhizosphere. This modern carbon input is consistent with our observations of greater *GPP* (Figure 2a–2c) and with earlier work that reported two to three times greater carbon accumulation rates in the topsoil (2.8 ± 0.2 to 4.6 ± 0.3 mg cm^{-2} yr^{-1}, 0–15 cm depth) (DeFranco et al., 2020). In summary, more snow triggered soil thaw, compaction, and subsidence, which together with greater plant activity, greatly increased the amount of carbon and nitrogen in the active layer.

4.2. More Snow Accelerates Legacy Carbon Emissions From Permafrost

Our year-round CO_2 efflux observations show that more snow resulted in three times greater carbon loss during the winter (October–May 2021), when R_{eco} was about 267 g C m^{-2} in +Snow versus 87 g C m^{-2} in Control (Figure 2a–2c). Our cold season estimates are slightly higher than previous estimates for tussock tundra of 20–70 g C m^{-2} (Sullivan et al., 2008). Our results also indicate that the deeper snow turned the tundra into a year-round carbon source (Figure 2a–2c).

Continuous monitoring of the age of soil CO_2 (Pedron et al., 2021) reveals that the higher CO_2 emissions under deeper snow during the cold season are fueled by newly exposed legacy carbon that is being actively decomposed year-round (Figure 2g–2i). At similar depths, pore space CO_2 was significantly older (3.5 times lower $\Delta^{14}CO_2$

under +Snow (−350‰) than Control (−100‰), $P < 0.001$). While both treatments follow the expected seasonal trend toward younger CO_2 during the growing season (Pedron et al., 2022), legacy carbon is a dominant fraction of the CO_2 produced under deeper snow during the growing season. These data prove that legacy carbon is readily metabolized, possibly because more fresh seasonal carbon is also available (Keuper et al., 2020).

Most of the legacy carbon is emitted, however, during the fall and winter, when seasonal inputs of fresh carbon have ceased. Cold season emissions are amplified under deeper snow, where emissions of CO_2 were larger (Figure 2a–2c) and much older (Figure 2g–2i). As such, our study provides further evidence that microbial decomposition of soil organic matter during fall and winter drives the losses of (legacy) carbon from permafrost soils (Natali et al., 2019; Pedron et al., 2022).

Previous research at this site documented the slow, but lengthy loss of CO_2 during the winter and suggested that these systems may be net carbon emitters (Fahnestock et al., 1999; Sullivan et al., 2008; Welker et al., 2000). Yet, it is only with this study that we can attribute these cold season emissions to the decomposition of legacy carbon that, like the combustion of fossil fuels, are injecting ancient carbon into the modern atmosphere and contributing to climate change.

5. Conclusions

Twenty-five years of snow addition to Arctic tundra reveal that increases in snow mass associated with the ongoing wetting of the Arctic climate (Box et al., 2019) will significantly accelerate the thaw of permafrost with severe implications for Arctic ecosystems, communities, and global climate. Deeper snow liberates plant nutrients (nitrogen) and promotes the expansion of deciduous shrubs (Sturm et al., 2005; W. Xu et al., 2021), which results in greater carbon uptake by the ecosystem during the growing season. Greater carbon sequestration in woody biomass and the topsoil, however, is accompanied by microbial decomposition of legacy carbon at depth year-round and converts the tundra into a year-round source of climate-warming legacy carbon. Our unique long-term climate manipulation experiment in Northern Alaska demonstrates that we urgently need a comprehensive observation system to quantify legacy carbon emissions from permafrost and can no longer afford to ignore the Arctic in climate change projections and mitigation policy.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

The datasets generated during and/or analyzed during the current study are available in the Arctic Data Center repository (Jespersen et al., 2022).

Acknowledgments
This work was supported by the U.S. National Science Foundation (OPP 1649664 to C.I.C. and OPP 1836873, 1650084, 1504141, 1433063, 0856728, 0612534, 0632184, 9617643, 9321730 to J.M.W.). Snow and meteorological datasets were provided by the Toolik Field Station Environmental Data Center (OPP 1623461). The authors thank the staff of UC Irvine's KCCAMS facility (J. Southon) for supporting elemental and isotope analyses, the staff of NSF Toolik Field Station (A. Young) for supporting sample and data collection and fieldwork logistics, and S. Holden, T. Nguyen, and Y. Liu for help with sample collection and, or analysis.

References

Arndt, K. A., Santos, M. J., Ustin, S., Davidson, S. J., Stow, D., Oechel, W. C., et al. (2019). Arctic greening associated with lengthening growing seasons in Northern Alaska. *Environmental Research Letters*, *14*(12), 125018. https://doi.org/10.1088/1748-9326/ab5e26

Box, J. E., Colgan, W. T., Christensen, T. R., Schmidt, N. M., Lund, M., Parmentier, F.-J. W., et al. (2019). Key indicators of Arctic climate change: 1971–2017. *Environmental Research Letters*, *14*(4), 045010. https://doi.org/10.1088/1748-9326/aafc1b

Callaghan, T. V., Johansson, M., Brown, R. D., Groisman, P. Y., Labba, N., Radionov, V., et al. (2011). The changing face of Arctic snow cover: A synthesis of observed and projected changes. *Ambio*, *40*(1), 17–31. https://doi.org/10.1007/s13280-011-0212-y

Christiansen, C. T., Lafreniére, M. J., Henry, G. H., & Grogan, P. (2018). Long-term deepened snow promotes tundra evergreen shrub growth and summertime ecosystem net CO_2 gain but reduces soil carbon and nutrient pools. *Global Change Biology*, *24*(8), 3508–3525. https://doi.org/10.1111/gcb.14084

Cooper, E. J., Little, C. J., Pilsbacher, A. K., & Mörsdorf, M. A. (2019). Disappearing green: Shrubs decline and bryophytes increase with nine years of increased snow accumulation in the High Arctic. *Journal of Vegetation Science*, *30*(5), 857–867. https://doi.org/10.1111/jvs.12793

DeFranco, K. C., Ricketts, M. P., Blanc-Betes, E., Welker, J. M., Gonzalez-Meler, M. A., & Sturchio, N. C. (2020). Deeper snow increases the net soil organic carbon accrual rate in moist acidic tussock tundra: 210Pb evidence from Arctic Alaska. *Arctic Antarctic and Alpine Research*, *52*(1), 461–475. https://doi.org/10.1080/15230430.2020.1802864

Elzhov, T. V., Mullen, K. M., Spiess, A.-N., & Bolker, B. (2016). Package 'minpack.lm' (Version 1.2-1) [Software]. CRAN. https://cran.r-project.org/package=minpack.lm

Environmental Data Center Team. (2022). Meteorological monitoring program at Toolik, Alaska [Dataset]. Toolik Field Station, Institute of Arctic Biology, University of Alaska Fairbanks. Retrieved from https://toolik.alaska.edu/edc/monitoring/abiotic/met-data-query.php

Euskirchen, E. S., Shaver, G. R., & Bret-Harte, M. S. (2022). AmeriFlux BASE US-ICt Imnavait Creek Watershed Tussock Tundra, Ver. 5-5, AmeriFlux AMP [Dataset]. AmeriFlux. https://doi.org/10.17190/AMF/1246131

Fahnestock, J. T., Jones, M. H., & Welker, J. M. (1999). Wintertime CO_2 efflux from Arctic soils: Implications for annual carbon budgets. *Global Biogeochemical Cycles*, *13*(3), 775–779. https://doi.org/10.1029/1999gb900006

Henry, G. H., Hollister, R. D., Klanderud, K., Björk, R. G., Bjorkman, A. D., Elphinstone, C., et al. (2022). The International Tundra Experiment (ITEX): 30 years of research on tundra ecosystems. *Arctic Science*, *8*(3), 550–571. https://doi.org/10.1139/as-2022-0041

Hinkel, K. M., & Hurd, J. K. (2006). Permafrost destabilization and thermokarst following snow fence installation, Barrow, Alaska, U.S.A. *Arctic Antarctic and Alpine Research*, *38*(4), 530–539. https://doi.org/10.1657/1523-0430(2006)38[530:PDATFS]2.0.CO;2

Hugelius, G., Strauss, J., Zubrzycki, S., Harden, J. W., Schuur, E. A. G., Ping, C.-L., et al. (2014). Estimated stocks of circumpolar permafrost carbon with quantified uncertainty ranges and identified data gaps. *Biogeosciences*, *11*(23), 6573–6593. https://doi.org/10.5194/bg-11-6573-2014

Jespersen, R. G., Pedron, S. A., Czimczik, C. I., & Welker, J. M. (2022). Sources and ages of soil respiration, Toolik Lake, AK, 2019–2022 [Dataset]. Arctic Data Center. https://doi.org/10.18739/A2FQ9Q664

Jones, M., Fahnestock, J., Walker, D. A., Walker, M. D., & Welker, J. M. (1998). Carbon dioxide fluxes in moist and dry arctic tundra during the snow-free season: Responses to increases in summer temperature and winter snow accumulation. *Arctic and Alpine Research*, *30*(4), 373–380. https://doi.org/10.1080/00040851.1998.12002912

Keuper, F., Wild, B., Kummu, M., Beer, C., Blume-Werry, G., Fontaine, S., et al. (2020). Carbon loss from northern circumpolar permafrost soils amplified by rhizosphere priming. *Nature Geoscience*, *13*(8), 8–565. https://doi.org/10.1038/s41561-020-0607-0

Kropp, H., Loranty, M. M., Natali, S. M., Kholodov, A. L., Rocha, A. V., Myers-Smith, I., et al. (2020). Shallow soils are warmer under trees and tall shrubs across Arctic and Boreal ecosystems. *Environmental Research Letters*, *16*(1), 015001. https://doi.org/10.1088/1748-9326/abc994

Lafrenière, M. J., Laurin, E., & Lamoureux, S. F. (2013). The impact of snow accumulation on the active layer thermal regime in high arctic soils. *Vadose Zone Journal*, *12*(1), vzj2012.0058. https://doi.org/10.2136/vzj2012.0058

LeDell, E., Gill, N., Ariello, S., Fu, A., Candel, A., Click, C., et al. (2022). Package “h2o” (Version 3.38.0.1) [Software]. CRAN. https://CRAN.R-project.org/package=h2o

Leffler, A. J. (2015). Toolik Lake, Alaska Species cover—2014 [Dataset]. Arctic Data Center. https://doi.org/10.18739/A24C9M

Leffler, A. J., Klein, E. S., Oberbauer, S. F., & Welker, J. M. (2016). Coupled long-term summer warming and deeper snow alters species composition and stimulates gross primary productivity in tussock tundra. *Oecologia*, *181*(1), 287–297. https://doi.org/10.1007/s00442-015-3543-8

Leffler, A. J., & Welker, J. M. (2013). Long-term increases in snow pack elevate leaf N and photosynthesis in Salix arctica: Responses to a snow fence experiment in the High Arctic of NW Greenland. *Environmental Research Letters*, *8*(2), 025023. https://doi.org/10.1088/1748-9326/8/2/025023

Lupascu, M., Welker, J. M., Seibt, U., Maseyk, K., Xu, X., & Czimczik, C. I. (2013). High Arctic wetting reduces permafrost carbon feedbacks to climate warming. *Nature Climate Change*, *4*(1), 51–55. https://doi.org/10.1038/nclimate2058

Lupascu, M., Welker, J. M., Xu, X., & Czimczik, C. I. (2014). Rates and radiocarbon content of summer ecosystem respiration in response to long-term deeper snow in the High Arctic of NW Greenland. *Journal of Geophysical Research: Biogeosciences*, *119*(6), 1180–1194. https://doi.org/10.1002/2013jg002494

Milborrow, S. (2023). Package ‘earth’ (Version 5.3.2) [Software]. CRAN. https://cran.r-project.org/package=earth

Miner, K. R., Turetsky, M. R., Malina, E., Bartsch, A., Tamminen, J., McGuire, A. D., et al. (2022). Permafrost carbon emissions in a changing Arctic. *Nature Reviews Earth & Environment*, *3*(1), 55–67. https://doi.org/10.1038/s43017-021-00230-3

Natali, S. M., Bronen, R., Cochran, P., Holdren, J. P., Rogers, B. M., & Treharne, R. (2022). Incorporating permafrost into climate mitigation and adaptation policy. *Environmental Research Letters*, *17*(9), 091001. https://doi.org/10.1088/1748-9326/ac8c5a

Natali, S. M., Schuur, E. A. G., Trucco, C., Hicks Pries, C. E., Crummer, K. G., & Baron Lopez, A. F. (2011). Effects of experimental warming of air, soil and permafrost on carbon balance in Alaskan tundra. *Global Change Biology*, *17*(3), 1394–1407. https://doi.org/10.1111/j.1365-2486.2010.02303.x

Natali, S. M., Watts, J. D., Rogers, B. M., Potter, S., Ludwig, S. M., Selbmann, A.-K., et al. (2019). Large loss of CO_2 in winter observed across the northern permafrost region. *Nature Climate Change*, *9*(11), 852–857. https://doi.org/10.1038/s41558-019-0592-8

Pattison, R. R., & Welker, J. M. (2014). Differential ecophysiological response of deciduous shrubs and a graminoid to long-term experimental snow reductions and additions in moist acidic tundra, Northern Alaska. *Oecologia*, *174*(2), 339–350. https://doi.org/10.1007/s00442-013-2777-6

Pedron, S. A., Welker, J. M., Euskirchen, E. S., Klein, E. S., Walker, J. C., Xu, X., & Czimczik, C. I. (2022). Closing the winter gap—Year-round measurements of soil CO_2 emission sources in arctic tundra. *Geophysical Research Letters*, *49*(6). https://doi.org/10.1029/2021gl097347

Pedron, S. A., Xu, X., Walker, J., Ferguson, J., Jespersen, R., Welker, J. M., et al. (2021). Time-integrated collection of CO_2 for ^{14}C analysis from soils. *Radiocarbon*, *63*(4), 1303–1319. https://doi.org/10.1017/rdc.2021.42

Plaza, C., Pegoraro, E., Bracho, R., Celis, G., Crummer, K. G., Hutchings, J. A., et al. (2019). Direct observation of permafrost degradation and rapid soil carbon loss in tundra. *Nature Geoscience*, *12*(8), 627–631. https://doi.org/10.1038/s41561-019-0387-6

Pulliainen, J., Luojus, K., Derksen, C., Mudryk, L., Lemmetyinen, J., Salminen, M., et al. (2020). Patterns and trends of Northern Hemisphere snow mass from 1980 to 2018. *Nature*, *581*(7808), 294–298. https://doi.org/10.1038/s41586-020-2258-0

Rantanen, M., Karpechko, A. Y., Lipponen, A., Nordling, K., Hyvärinen, O., Ruosteenoja, K., et al. (2022). The Arctic has warmed nearly four times faster than the globe since 1979. *Communications Earth & Environment*, *3*(1), 168. https://doi.org/10.1038/s43247-022-00498-3

Rodenhizer, H., Ledman, J., Mauritz, M., Natali, S. M., Pegoraro, E., Plaza, C., et al. (2020). Carbon thaw rate doubles when accounting for subsidence in a permafrost warming experiment. *Journal of Geophysical Research: Biogeosciences*, *125*(6), e2019JG005528. https://doi.org/10.1029/2019jg005528

Salmon, V. G., Schädel, C., Bracho, R., Pegoraro, E., Celis, G., Mauritz, M., et al. (2018). Adding depth to our understanding of nitrogen dynamics in permafrost soils. *Journal of Geophysical Research: Biogeosciences*, *123*(8), 2497–2512. https://doi.org/10.1029/2018jg004518

Schiferl, L. D., Watts, J. D., Larson, E. J. L., Arndt, K. A., Biraud, S. C., Euskirchen, E. S., et al. (2022). Using atmospheric observations to quantify annual biogenic carbon dioxide fluxes on the Alaska North Slope. *Biogeosciences*, *19*(24), 5953–5972. https://doi.org/10.5194/bg-19-5953-2022

Schimel, J. P., Bilbrough, C., & Welker, J. M. (2004). Increased snow depth affects microbial activity and nitrogen mineralization in two Arctic tundra communities. *Soil Biology and Biochemistry*, *36*(2), 217–227. https://doi.org/10.1016/j.soilbio.2003.09.008

Schuur, E. A. G., Abbott, B. W., Commane, R., Ernakovich, J., Euskirchen, E., Hugelius, G., et al. (2022). Permafrost and climate change: Carbon cycle feedbacks from the warming Arctic. *Annual Review of Environment and Resources*, *47*(1), 343–371. https://doi.org/10.1146/annurev-environ-012220-011847

Semenchuk, P. R., Krab, E. J., Hedenström, M., Phillips, C. A., Ancin-Murguzur, F. J., & Cooper, E. J. (2019). Soil organic carbon depletion and degradation in surface soil after long-term non-growing season warming in High Arctic Svalbard. *Science of the Total Environment*, *646*, 158–167. https://doi.org/10.1016/j.scitotenv.2018.07.150

Shur, Y. L., & Jorgenson, M. T. (2007). Patterns of permafrost formation and degradation in relation to climate and ecosystems. *Permafrost and Periglacial Processes*, *18*(1), 7–19. https://doi.org/10.1002/ppp.582

Strauss, J., Biasi, C., Sanders, T., Abbott, B. W., von Deimling, T. S., Voigt, C., et al. (2022). A globally relevant stock of soil nitrogen in the Yedoma permafrost domain. *Nature Communications*, *13*(1), 6074. https://doi.org/10.1038/s41467-022-33794-9

Stuefer, S. L., Kane, D. L., & Dean, K. M. (2020). Snow water equivalent measurements in remote arctic Alaska watersheds. *Water Resources Research*, *56*(4), e2019WR025621. https://doi.org/10.1029/2019wr025621

Sturm, M., Schimel, J., Michaelson, G., Welker, J. M., Oberbauer, S. F., Liston, G. E., et al. (2005). Winter biological processes could help convert arctic tundra to shrubland. *BioScience*, *55*(1), 17–26. https://doi.org/10.1641/0006-3568(2005)055[0017:WBPCHC]2.0.CO;2

Sullivan, P. F., Welker, J. M., Arens, S. J., & Sveinbjörnsson, B. (2008). Continuous estimates of CO_2 efflux from arctic and boreal soils during the snow-covered season in Alaska. *Journal of Geophysical Research*, *113*(G4), G04009. https://doi.org/10.1029/2008jg000715

Turetsky, M. R., Abbott, B. W., Jones, M. C., Anthony, K. W., Olefeldt, D., Schuur, E. A. G., et al. (2020). Carbon release through abrupt permafrost thaw. *Nature Geoscience*, *13*(2), 138–143. https://doi.org/10.1038/s41561-019-0526-0

Voigt, C., Marushchak, M. E., Abbott, B. W., Biasi, C., Elberling, B., Siciliano, S. D., et al. (2020). Nitrous oxide emissions from permafrost-affected soils. *Nature Reviews Earth & Environment*, *1*(8), 420–434. https://doi.org/10.1038/s43017-020-0063-9

Wahren, C.-H. A., Walker, M. D., & Bret-Harte, M. S. (2005). Vegetation responses in Alaskan arctic tundra after 8 years of a summer warming and winter snow manipulation experiment. *Global Change Biology*, *11*(4), 537–552. https://doi.org/10.1111/j.1365-2486.2005.00927.x

Walker, M. (2007). Toolik Snowfence Experiment: 1994–2000 Plant Community Data [Dataset]. UCAR/NCAR - Earth Observing Laboratory. https://doi.org/10.5065/D6988585

Walker, M. D. (2007a). Toolik Snowfence Experiment: Snow Drift Depth Data 1995–2001 [Dataset]. UCAR/NCAR - Earth Observing Laboratory. https://doi.org/10.5065/D62V2DCT

Walker, M. D. (2007b). Toolik Snowfence Experiment: Snow Drift Depth Data 2001–2002 [Dataset]. UCAR/NCAR - Earth Observing Laboratory. https://doi.org/10.5065/D6BC3WS1

Walker, M. D., Walker, D. A., Welker, J. M., Arft, A., Bardsley, T., Brooks, P., et al. (1999). Long-term experimental manipulation of winter snow regime and summer temperature in arctic and alpine tundra. *Hydrological Processes*, *13*(14–15), 2315–2330. https://doi.org/10.1002/(sici)1099-1085(199910)13:14/15<2315::aid-hyp888>3.0.co;2-a

Way, R. G., & Lapalme, C. M. (2021). Does tall vegetation warm or cool the ground surface? Constraining the ground thermal impacts of upright vegetation in northern environments. *Environmental Research Letters*, *16*(5), 054077. https://doi.org/10.1088/1748-9326/abef31

Welker, J. M., Fahnestock, J., & Jones, M. (2000). Annual CO_2 flux in dry and moist arctic tundra: Field responses to increases in summer temperatures and winter snow depth. *Climatic Change*, *44*(1), 139–150. https://doi.org/10.1023/a:1005555012742

Xu, W., Prieme, A., Cooper, E. J., Mörsdorf, M. A., Semenchuk, P., Elberling, B., et al. (2021). Deepened snow enhances gross nitrogen cycling among Pan-Arctic tundra soils during both winter and summer. *Soil Biology and Biochemistry*, *160*, 108356. https://doi.org/10.1016/j.soilbio.2021.108356

Xu, X., Trumbore, S. E., Zheng, S., Southon, J. R., McDuffee, K. E., Luttgen, M., & Liu, J. C. (2007). Modifying a sealed tube zinc reduction method for preparation of AMS graphite targets: Reducing background and attaining high precision. *Nuclear Instruments and Methods in Physics Research, Section B: Beam Interactions with Materials and Atoms*, *259*(1), 320–329. https://doi.org/10.1016/j.nimb.2007.01.175

Zhao, J. (2019). FluxCalR: A R package for calculating CO_2 and CH_4 fluxes from static chambers [Software]. Journal of Open Source Software, *4*(43), 1751. https://doi.org/10.21105/joss.01751