

Semenchuk, Philipp; Krab, Eveline J; Hedenström, Mattias; Phillips, Carly A; Murguzur, Francisco Javier Ancin; Cooper, Elisabeth J.

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* 2019; Volume 646. p. 158-167

<https://doi.org/10.1016/j.scitotenv.2018.07.150>

Manuscript Number: STOTEN-D-18-05702R1

Title: Soil organic carbon depletion and degradation in surface soil
after long-term non-growing season warming in High Arctic Svalbard

Article Type: Research Paper

Keywords: snow fence; NMR; carbon loss; decomposition; anthropogenic C
emission feedback; tundra

Corresponding Author: Dr. Philipp R Semenchuk,

Corresponding Author's Institution: University of Vienna

First Author: Philipp R Semenchuk

Order of Authors: Philipp R Semenchuk; Eveline J Krab; Mattias
Hedenström; Carly A Phillips; Francisco J Ancin-Murguzur; Elisabeth J
Cooper

Abstract: Arctic tundra active-layer soils are at risk of soil organic carbon (SOC) depletion and degradation upon global climate warming because they are in a stage of relatively early decomposition. Non-growing season (NGS) warming is particularly pronounced, and observed increases of CO₂ emissions during experimentally warmed NGSs give concern for great SOC losses to the atmosphere. Here, we used snow fences in Arctic Spitsbergen dwarf shrub tundra to simulate 1.86 °C NGS warming for 9 consecutive years, while growing season temperatures remained unchanged. In the snow fence treatment, the 4-11cm thick A-horizon had a 2% lower SOC concentration and a 0.48 kg C m⁻² smaller pool size than the controls, indicating SOC pool depletion. The snow fence treatment's A-horizon's alkyl/ O-alkyl ratio was also significantly increased, indicating an advance of SOC degradation. The underlying 5cm of B/C-horizon did not show these effects. Our results support the hypothesis that SOC depletion and degradation are connected to the long-term transience of observed ecosystem respiration (ER) increases upon soil warming. We suggest that the bulk of warming induced ER increases may originate from surface and not deep active layer or permafrost horizons. The observed losses of SOC might be significant for the ecosystem in question, but are in magnitude comparatively small relative to anthropogenic greenhouse gas enrichment of the atmosphere. We conclude that a positive feedback of carbon losses from surface soils of Arctic dwarf shrub tundra to anthropogenic forcing will be minor, but not negligible.

Response to Reviewers: Dear Dr. Jay Gan, Reviewer #2 and Reviewer #5, We are very thankful that you took your time to review our manuscript "Soil organic carbon depletion and degradation in surface soil after long-term non-growing season warming in High Arctic Svalbard" and happy that you only have minor revision suggestions. Please see below our point-by-point replies (in red italics) to all issues that you raised. We think that all comments are warranted and tried to incorporate them into

the manuscript as good as we could. For any further comments or questions, please feel free to contact us anytime.

All the best,

On behalf of my colleagues,

Philipp Semenchuk

Reviewer #2: General comments

This is an interesting and generally designed study. The ms is generally well written and easy to follow, but some minor typos and editorial changes would need to be made (see the commented ms attached as the pdf file). I would like to caution the authors that perhaps the research findings would need to be further validated in more and longer term field experiments. The authors might also like to exercise caution in making more long-term term and more broad conclusion from the research so far since the global warming and climate change is expected to be much intensified and the non-linear and complex impacts of global warming might cause significantly different outcomes in the future. I would recommend the publication of the ms after some minor revisions would be made in response to my general and specific comments.

Reply:

We are glad that we managed to write a clear and easy to understand story. Thanks for acknowledging that!

We are aware that longer term (e.g. after 20 or more years of experimental warming) and spatially more spread studies (e.g. samples from snow fence sites across the Arctic) would be beneficial to validate our findings, as it would be beneficial for every study based on single field experiments. This is already mentioned in the fourth paragraph of the discussion. It's a question of money and time, since the chemical analyses done here are expensive and time consuming. We neither have the data nor the budget for such an enhancement of this study and need to keep it as it is now.

Your point on non-linear and complex interactions with other climate-change effects is a good one. However, elaborating on it would start a whole new, very big discussion on speculated interactions. We do not want to reach into that bottomless pit. We did add the following sentence at the end of the third paragraph in the discussion:

"Since these non-linear and possibly interactive responses cannot necessarily be generalized across spatial and temporal boundaries, further large-scale and long-term studies (e.g. time series) are warranted to enable us to project the presented findings on possible future climate scenarios."

Specific comments

these can be seen from the commented ms attached.

Reply:

We went through your handwritten comments and changed most of them as suggested. A few comments on individual items we did not change:

1. 171: The sequence of references is predefined by the reference program Mendeley's reference format for STOTEN and we assume it to be the preferred format of the journal.

1. 328: On table 1 you wrote "very simple table!!!". We do not know if that is an acknowledgment or a comment to change it. We therefore kept it unchanged.

Reviewer #5:

In this article the author showed that a small increase of temperature in high arctic environment in subfreezing conditions increases the decomposition soil organic matter in the top soil layer in subfreezing conditions. The article is well written, well-structured and easy to read. The results are clear and the methodology perfectly adapted. The topic treated is very interesting as it has rarely been investigated. It is also really up to date in the current context of climate change.

Reply:

We are glad to see that our message came across and thankful for the praise on our accomplishment.

As a slight critic, the presented results actually originate from an experiment already described in Semenchuk (2016): "Long term experimentally deepened snow decreases growing season respiration in low and high arctic tundra ecosystem". As a consequence some relevant figures and results about ecosystem respiration are located there and it lessens a bit the experience not to get them directly.

Reply:

We understand that it's unpractical for the reader to refer to already published work, but cannot change it being published already. In fact, as you know, the present manuscript's idea stems from our findings in the Semenchuk et al. 2016 paper, and we see our way of designing this study as an example of good scientific work from observation (i.e. findings in Semenchuk et al. 2016) via hypothesis based on common assumptions to new results.

Minor comments:

Line 78: I did not really understand what the author meant by "an extreme event induced active layer detachment".

Reply:

We added the following sentence to clarify: "...where sub-surface active layer soil was exposed to air temperatures via soil movements after extensive rain-fall...".

Line 502: Maybe "suggests that also" should be changed for "suggests also that".

Reply:

We changed it to "...also suggests that...".

In Figures 1, 3 and 4 the authors could add some "*" in the compartments that show significant differences, so that the figures could be directly readable.

Reply:

We think that it suffices to have the filling of the circles denoting significance and like our figures better that way. If wished by the editor, we will add * to the panels showing significant differences.

Title page

Title

Soil organic carbon depletion and degradation in surface soil after long-term non-growing season warming in High Arctic Svalbard

Author names

Philipp R. Semenchuk^{1,2}, Eveline J. Krab^{2,3}, Mattias Hedenström⁴, Carly A. Phillips⁵, Francisco J. Ancin-Murguzur¹, Elisabeth J. Cooper¹

Author affiliations

¹Department of Arctic and Marine Biology, Faculty of Biosciences Fisheries and Economics, UiT-The Arctic University of Norway, N-9037 Tromsø, Norway

²Climate Impacts Research Centre, Department of Ecology and Environmental Science, Umeå University, SE-98107 Abisko, Sweden

³Swedish University of Agricultural Sciences. Department of Soil and Environment, SE-75007, Uppsala, Sweden

⁴Department of Chemistry, Umeå University, SE-901 87 Umeå, Sweden

⁵Odum School of Ecology, University of Georgia, Athens GA 30606, USA

Corresponding author

Philipp R. Semenchuk, +4368864979836, phipserl@protonmail.com

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

Dear Dr. Jay Gan, Reviewer #2 and Reviewer #5,

We are very thankful that you took your time to review our manuscript “*Soil organic carbon depletion and degradation in surface soil after long-term non-growing season warming in High Arctic Svalbard*” and happy that you only have minor revision suggestions. Please see below our point-by-point replies (in *red italics*) to all issues that you raised. We think that all comments are warranted and tried to incorporate them into the manuscript as good as we could. For any further comments or questions, please feel free to contact us anytime.

All the best,

On behalf of my colleagues,

Philipp Semenchuk

Reviewer #2: General comments

This is an interesting and generally designed study. The ms is generally well written and easy to follow, but some minor typos and editorial changes would need to be made (see the commented ms attached as the pdf file). I would like to caution the authors that perhaps the research findings would need to be further validated in more and longer term field experiments. The authors might also like to exercise caution in making more long-term term and more broad conclusion from the research so far since the global warming and climate change is expected to be much intensified and the non-linear and complex impacts of global warming might cause significantly different outcomes in the future. I would recommend the publication of the ms after some minor revisions would be made in response to my general and specific comments.

Reply:

We are glad that we managed to write a clear and easy to understand story. Thanks for acknowledging that!

We are aware that longer term (e.g. after 20 or more years of experimental warming) and spatially more spread studies (e.g. samples from snow fence sites across the Arctic) would be beneficial to validate our findings, as it would be beneficial for every study based on single field experiments. This is already mentioned in the fourth paragraph of the discussion. It's a question of money and time, since the chemical analyses done here are expensive and time consuming. We neither have the data nor the budget for such an enhancement of this study and need to keep it as it is now.

Your point on non-linear and complex interactions with other climate-change effects is a good one. However, elaborating on it would start a whole new, very big discussion on speculated interactions. We do not want to reach into that bottomless pit. We did add the following sentence at the end of the third paragraph in the discussion:

“Since these non-linear and possibly interactive responses cannot necessarily be generalized across spatial and temporal boundaries, further large-scale and long-term studies (e.g. time series) are warranted to enable us to project the presented findings on possible future climate scenarios.”

Specific comments

these can be seen from the commented ms attached.

Reply:

We went through your handwritten comments and changed most of them as suggested. A few comments on individual items we did not change:

I. 171: The sequence of references is predefined by the reference program Mendeley's reference format for STOTEN and we assume it to be the preferred format of the journal.

I. 328: On table 1 you wrote “very simple table!!!”. We do not know if that is an acknowledgment or a comment to change it. We therefore kept it unchanged.

Reviewer #5:

In this article the author showed that a small increase of temperature in high arctic environment in subfreezing conditions increases the decomposition soil organic matter in the top soil layer in subfreezing conditions. The article is well written, well-structured and easy to read. The results are clear and the methodology perfectly adapted. The topic treated is very interesting as it has rarely been investigated. It is also really up to date in the current context of climate change.

Reply:

We are glad to see that our message came across and thankful for the praise on our accomplishment.

As a slight critic, the presented results actually originate from an experiment already described in Semenchuk (2016): "Long term experimentally deepened snow decreases growing season respiration in low and high arctic tundra ecosystem". As a consequence some relevant figures and results about ecosystem respiration are located there and it lessens a bit the experience not to get them directly.

Reply:

We understand that it's unpractical for the reader to refer to already published work, but cannot change it being published already. In fact, as you know, the present manuscript's idea stems from our findings in the Semenchuk et al. 2016 paper, and we see our way of designing this study as

an example of good scientific work from observation (i.e. findings in Semenchuk et al. 2016) via hypothesis based on common assumptions to new results.

Minor comments:

Line 78: I did not really understand what the author meant by "an extreme event induced active layer detachment".

Reply:

We added the following sentence to clarify: "...where sub-surface active layer soil was exposed to air temperatures via soil movements after extensive rain-fall..."

Line 502: Maybe "suggests that also" should be changed for "suggests also that".

Reply:

We changed it to "...also suggests that..."

In Figures 1, 3 and 4 the authors could add some "*" in the compartments that show significant differences, so that the figures could be directly readable.

Reply:

*We think that it suffices to have the filling of the circles denoting significance and like our figures better that way. If wished by the editor, we will add * to the panels showing significant differences.*

1 **Title page**

2 **Title**

3 Soil organic carbon depletion and degradation in surface soil after long-term non-growing
4 season warming in High Arctic Svalbard

6 **Author names**

7 Philipp R. Semenchuk^{1,2,3}, Eveline J. Krab^{2,43}, Mattias Hedenström⁵⁴, Carly A. Phillips⁶⁵,
8 Francisco J. Ancin-Murguzur¹, Elisabeth J. Cooper¹

10 **Author affiliations**

11 ¹Department of Arctic and Marine Biology, Faculty of Biosciences Fisheries and Economics,
12 UiT-The Arctic University of Norway, N-9037 Tromsø, Norway

13 ²Climate Impacts Research Centre, Department of Ecology and Environmental Science, Umeå
14 University, SE-98107 Abisko, Sweden

15 ³[Division of Conservation Biology, Vegetation Ecology and Landscape Ecology, Department of](#)
16 [Botany and Biodiversity Research, Vienna University, Rennweg 14, 1030 Vienna](#)

17 ⁴³Swedish University of Agricultural Sciences. Department of Soil and Environment, SE-
18 75007, Uppsala, Sweden

19 ⁵⁴Department of Chemistry, Umeå University, SE-901 87 Umeå, Sweden

20 ⁶⁵Odum School of Ecology, University of Georgia, Athens GA 30606, USA

22 **Corresponding author**

Formatted: Superscript

23 Philipp R. Semenchuk, +4368864979836,

24 ~~philipp@protonmail.com~~ philipp.semenchuk@univie.ac.at

25

26 **Highlights**

- 27 • Soil was warmed *in situ* for nine consecutive non-growing seasons (NGS) in Svalbard
- 28 • NGS warming depleted soil organic carbon (SOC) pool of the soil's shallow A-
29 horizon
- 30 • NGS warming transitioned the A-horizon SOC to an advanced state of decomposition
- 31 • The underlying B/C-horizon's SOC pool and state was not affected
- 32 • NGS warming mineralizes more C in shallow than in deep soil

33

34 **Abstract**

35 Arctic tundra active-layer soils are at risk of soil organic carbon (SOC) depletion and
36 degradation upon global climate warming because they are in a stage of relatively early
37 decomposition. Non-growing season (NGS) warming is particularly pronounced, and observed
38 increases of CO₂ emissions during experimentally warmed NGSs give concern for great SOC losses
39 to the atmosphere. Here, we used snow fences in Arctic Spitsbergen dwarf shrub tundra to simulate
40 1.86 °C NGS warming for 9 consecutive years, while growing season temperatures remained
41 unchanged. In the snow fence treatment, the 4-11 cm thick A-horizon had a 2% lower SOC
42 concentration and a 0.48 kg C m⁻² smaller pool size than the controls, indicating SOC pool depletion.
43 The snow fence treatment's A-horizon's alkyl/ O-alkyl ratio was also significantly increased,
44 indicating an advance of SOC degradation. The underlying 5 cm of B/C-horizon did not show these
45 effects. Our results support the hypothesis that SOC depletion and degradation are connected to the
46 long-term transience of observed ecosystem respiration (ER) increases upon soil warming. We
47 suggest that the bulk of warming induced ER increases may originate from surface and not deep
48 active layer or permafrost horizons. The observed losses of SOC might be significant for the

49 ecosystem in question, but are in magnitude comparatively small relative to anthropogenic greenhouse
50 gas enrichment of the atmosphere. We conclude that a positive feedback of carbon losses from surface
51 soils of Arctic dwarf shrub tundra to anthropogenic forcing will be minor, but not negligible.

52

53 **Key words**

54 snow fence; NMR; carbon loss; decomposition; anthropogenic C emission feedback; tundra

55

56

57 **1. Introduction**

58 Temperature is one of the main limiting factors for decomposition in Arctic soils (Wallenstein
59 et al., 2009), leading to vast soil organic carbon (SOC) pools exceeding Earth's atmosphere's C stock
60 (Hugelius et al., 2014; Tarnocai et al., 2009). In the face of climate warming, temperature limitations
61 on decomposition processes might be alleviated, putting the biologically degradable part of this SOC
62 pool at risk of being released to the atmosphere (Kleber, 2010; Schmidt et al., 2011). In Arctic
63 regions, climate warming is especially pronounced during the non-growing season (NGS) (Stocker et
64 al., 2014). As the NGS is the predominant part of the year, changes in its climate can have a
65 disproportionally large effect on decomposition processes: relatively low decomposer activities at low
66 temperatures can be offset by the long duration of the NGS and lead to long-term SOC loss. Soil
67 organic C in the Arctic dwarf shrub tundra's active layer consists of a large proportion of readily
68 decomposable compounds (Pautler et al., 2010; Pedersen et al., 2011; Sjögersten et al., 2003), and
69 here we test if long-term *in situ* NGS warming could not only have an effect on its SOC pool size, but
70 also on its bulk chemical composition.

71 Soils from cold dominated ecosystems appear to be in early stages of decomposition and at
72 risk for rapid SOC loss with increasing temperature. Warming may specifically accelerate the
73 degradation of readily decomposable compounds and thereby progress its decomposition stage. As an
74 indicator for the relative degree of a given soil's SOC decomposition stage, the alkyl/O-alkyl ratio has
75 been used (Feng and Simpson, 2008; Pautler et al., 2010; Pedersen et al., 2011; Simpson et al., 2008;
76 Sjögersten et al., 2003). For instance, Sjögersten *et al.* (2003) observed higher alkyl/ O-alkyl ratios in
77 more decomposed forest soils as compared to soils in less decomposed stages from nearby tundra
78 soils in northern Scandinavia; ~~for~~ which they attributed to higher decomposer activities in forest soils
79 due to higher soil temperatures in the more sheltered microclimate. Further, an extreme-event induced
80 active layer detachment in northern Canada where sub-surface active layer soil was exposed to air
81 temperatures via soil movements after extensive rain-fall accelerated SOC decomposition and
82 increased its alkyl/ O-alkyl ratio (Pautler et al., 2010). Similar effects can be expected in response to
83 NGS warming through climate change of Arctic dwarf shrub tundra ecosystems.

Field Code Changed

Formatted: German (Austria)

Formatted: German (Austria)

84 The effects of warming on SOC pool depletion and its alkyl/O-alkyl ratio can be expected to
85 be strongest in surface soil horizons of the active layer for several reasons. Arctic and alpine surface
86 soils are reported to be richer in O-alkyl carbon (C) than deeper soil horizons, i.e. the alkyl/O-alkyl
87 ratio increases with depth, indicating that the stage of decomposition advances with depth, an effect
88 already visible in the upper few cm of soil profiles (Pedersen et al., 2011; Sjögersten et al., 2003).
89 Further, environmental controls in deeper horizons may stabilize otherwise chemically readily
90 decomposable compounds from microbial decomposition by e.g. sorption to the mineral phase
91 (Kawahigashi et al., 2006; Kleber, 2010; Schmidt et al., 2011; Trumbore, 2009), which becomes more
92 prominent in deeper horizons with a higher mineral proportion. Hence, total loss of SOC in deeper
93 horizons upon warming could be lower than in surface near horizons. Increases in ecosystem
94 respiration (ER) by experimental NGS warming in the Arctic (Björkman et al., 2010; Morgner et al.,
95 2010; Nobrega and Grogan, 2007; Schimel et al., 2004; Semenchuk et al., 2016a; Webb et al., 2016)
96 may thus be primarily (but not exclusively) driven by degradation and depletion of SOC substrates
97 from surface rather than deep soil or thawed permafrost (cf. Schuur *et al.*, 2009; Natali *et al.*, 2014).
98 This is supported by recent studies finding significantly higher soil CO₂ fluxes and stronger responses
99 to warming in surface horizons up to 10 cm depth than in deeper soil horizons (Hicks Pries et al.,
100 2017; Lee et al., 2010).

101 In the Arctic, significant ER increases have been shown to respond directly to *in situ* NGS
102 warming in a variety of tundra ecosystems (Björkman et al., 2010; Morgner et al., 2010; Natali et al.,
103 2014; Nobrega and Grogan, 2007; Schimel et al., 2004; Semenchuk et al., 2016a; Webb et al., 2016).
104 ~~(Semenchuk et al., 2016a)~~ demonstrated that these effects were followed by decreased growing
105 season ER after eight years of NGS warming in Svalbard dwarf shrub tundra. Similarly, ER responses
106 to experimental continuous *in situ* soil warming are shown to be transient and decrease after a few
107 years of continuous warming in a mid-latitude forest site (Melillo et al., 2002, 2017). One explanation
108 for these effects suggests that soil warming accelerates decomposition processes and alters SOC pool
109 size and composition; soil OC is transformed from a relatively early stage to a later stage of
110 decomposition, and thus provides a less favourable substrate for respiring decomposing organisms

Field Code Changed

111 (Kirschbaum, 2004; Eliasson et al., 2005; Bradford et al., 2008). Here, we use the opportunity to
112 collect soil and verify that hypothesis within the experiment used by Semenchuk *et al.* (2016a).

Field Code Changed

113 We test whether nine years of continuous *in situ* NGS warming (average 2 degrees warming
114 within a snow manipulation treatment) of relatively C poor (3-25 % C) High Arctic dwarf shrub
115 tundra surface soil (16 cm depth) (i) reduced SOC pool size and (ii) changed the SOC chemical
116 composition towards a more advanced decomposition stage in a snow fence experiment in
117 Adventdalen, Svalbard. In the same experiment, Semenchuk *et al.* (2016a) found that 8 years of
118 continuous NGS warming and connected increased ER during the NGS lead to decreased growing
119 season ER and suggested that changes in SOC pool size and composition could account for this.

Field Code Changed

120 Based on these results, we test the following:

121 1.1 Hypotheses

- 122 (1) Carbon content is depleted in NGS warmed surface soils, i.e. long-term increased NGS ER
123 decreased the C pool.
- 124 (2) Carbon compound composition is altered in NGS warmed soils. More specifically, we expect
125 the alkyl/ O-alkyl ratio to be higher in NGS warmed soils, i.e. that the relative degree of SOC
126 decomposition is advanced.
- 127 (3) The effects from Hypotheses 1 and 2 are larger in the A-horizon than in the top 5 cm of the
128 underlying, C poorer and mineral richer B/C-horizon, i.e. the combination of environmental
129 conditions and initial SOC composition in the B/C-horizon render the bulk SOC there more
130 resistant to warming.

131

132 2. Material and Methods

133 2.1 Site description (location, soil, vegetation, climate, seasonality)

134 The study site is on the southern (left) riverbank in Adventdalen, a large valley about 12 km
135 east of Longyearbyen on Spitsbergen, Svalbard (78°10'N, 16°04'E) with continuous permafrost with
136 an active layer thickness/ maximum thaw depth of about 75 to 90 cm at the study site (own data,
137 Figure S2). The cryoturbated gelisol soils at the study site (Semenchuk et al., 2016a) are dominated by
138 fluvial and aeolian sedimentation and consist of a relatively thin and C poor, dark brown A-horizon of
139 about 2-11 cm thickness with about 15-25% C content and an underlying, grey, silty B/C-horizon with
140 about 3-9% C content, which extends to the permafrost table (see Strebel *et al.*, 2010 and own data
141 below).

142 Situated in the bioclimatic subzone C, the vegetation type is classified as Prostrate/
143 hemiprostrate dwarf-shrub tundra (CAVM Team, 2003), dominated by the dwarf shrubs *Cassiope*
144 *tetragona*, *Dryas octopetala* and *Salix polaris*.

145 Average air temperature 2000 to 2011 at Longyearbyen airport, about 20 km west of the study
146 site, during the approximate NGS months October to April were -9 °C and during the approximate
147 growing season months 3.4 °C (www.eklima.no). Average snow depth in the control area was about
148 40 cm (own data, Figure S1).

149 Non-growing season (NGS) in this study is defined as the time of year when the soil surface
150 is frozen, i.e. has a temperature below 0 °C as measured by temperature loggers employed at around 2
151 cm depth (see S3), and ranges in extreme cases from about early October until early May, depending
152 on year, replicate plot and snow fence treatment (see below).

153

154 2.2 Experimental design

155 Eleven 1.5m high snow fences were erected in autumn 2006, i.e. 9 years before the present
156 study was conducted. These created winter snow drifts of maximum 1.5 m depth, i.e. about 1.1 m

157 | deeper than average ambient snow depth of about 0.4_m (see S1), which declined in depth with
158 | distance from the fence. Foci areas behind the fences receiving about 0.7_m snow depth (see S1) were
159 | identified for soil sampling, here referred to as “snow fence treatment”. Each snow fence was
160 | associated with an unmanipulated control area with ambient snow conditions about 10-15_m away
161 | from each fence. The snow drifts’ shapes and extents were very similar each year (own observations)
162 | due to the prevailing easterly wind direction along the valley.

163 | The snow fence treatment chosen for this study increased the average NGS surface soil
164 | temperature (i.e. when soil surface is frozen) by 1.86 °C as determined by continuous hourly
165 | temperature measurements (see S3). There was no diurnal variability within the snow fence
166 | treatment’s temperature effects, and the warming started a few weeks after the start of the NGS when
167 | the snowpack established (see S3). Soil moisture in the snow fence treatment was observed to be
168 | slightly increased at the beginning of the growing season only (Semenchuk et al., 2016a), but was
169 | neither changed in the A- nor B/C-Horizon at time of soil sampling for this study (see S4).

170 | Please note that for the present study we sampled a part of a larger experimental setup.
171 | Samples for this study were taken from areas behind snow fences that in other studies from the same
172 | site are referred to as “medium” snow or similar, in which snow depth was about 0.7 m, as opposed to
173 | “deep” snow, in which snow depth was about 1.5 m (Cooper et al., 2011; Rumpf et al., 2014;
174 | Semenchuk et al., 2016a, 2015, 2013). The reason why we did not use the area with the maximum or
175 | deep snow increase was to preserve that relatively small area for future research and not disturb it
176 | with invasive sampling.

177

178 | 2.3 Soil sampling procedure

179 | On July 23rd 2015, 3 soil cores between 0.5 ~~to~~ and 1_m apart were sampled with a soil corer
180 | with 2 cm diameter (3.14 cm² area) in each plot and treatment (snow fence and control). To exclude
181 | potentially confounding vegetation effects on soil parameters in question for this study, sampling

182 locations were chosen where *Salix polaris*, a dominant dwarf shrub across the study site, was the
183 dominant species.

184 The brown A-horizon of each core was separated visually from the underlying grey B/C-
185 horizon in the field, its thickness/ length measured, and each horizon of the core triplets combined in
186 one plastic bag. Before bagging, above ground litter (O-horizon) and plants were coarsely removed
187 from above the A-horizon. The upper 5 cm of the B/C-horizon directly under the A-horizon of each
188 core were sampled and also combined. The maximum sampled A-horizon thickness was 11 cm, i.e.
189 the deepest B/C-horizon sample was between 11 and 16 cm depth, far above the permafrost table
190 which in our study site is at about 75 to 90 cm depth (see S2).

191

192 2.4 Soil treatment prior to chemical analyses

193 After collection in the field, soil samples were kept at 4 °C for five days in Longyearbyen,
194 Svalbard, then transported to Abisko, Sweden, and processed within two days while being kept at 4
195 °C. Remaining above ground plant material, roots and stones of each sample were removed during 3
196 minutes per sample, the remaining soil mass homogenized, weighed and then directly oven dried at 70
197 °C for 48 h. The dried samples were then weighed again and ground in a ball mill to a fine powder
198 and transported to Umea, Sweden, for NMR analyses and aliquots sent to Copenhagen, Denmark, for
199 elemental analysis (see below).

200 Based on previously published material, we expected the total Fe (iron) content of the soil to
201 be relatively high (Ottesen et al., 2010) with simultaneously low C content (Moni et al., 2015; Strebel
202 et al., 2010) leading to a C:Fe ratio < 6 . Such high concentration of Fe-associated paramagnetic
203 compounds has been shown to have a strong adverse effect on the quality of NMR spectra (Schilling
204 and Cooper, 2004; Schmidt et al., 1997). After initial trials, this turned out to be only the case for the
205 B/C-horizon samples, since NMR spectra of the A-horizon were of sufficiently good quality.

206 Therefore, we demineralized the B/C-horizon following the procedure in Baldock *et al.*
207 (2001). We washed the soil with hydrofluoric acid (HF treatment) to remove paramagnetic and

208 mineral compounds and thus increase the C content of the remaining soil leading to improved NMR
209 spectra (Gélinas et al., 2001; Schilling and Cooper, 2004; Schmidt et al., 1997). In short we exposed 1
210 g of each sample for 12_h in 30_mL of 10% HF in 1N HCl solution, removed the supernatant and
211 exposed the remaining pellet to fresh HF/ HCl solution twice more, then washed 3 times with water
212 and freeze dried the pellet and used it for further analyses.

213 In the following, data based on NMR spectroscopy (spectra, integrals, and alkyl/O-alkyl ratio)
214 are from HF-treated B/C-horizon samples, while data based on bulk soil parameters (bulk density, C
215 concentration and pool size) are from untreated B/C-horizons. The A-horizon was always untreated.

216

217 2.5 Soil *carbon-C* concentrations

218 To measure soil *carbon-C* concentrations (%C), we weighed soils into tin capsules and
219 quantified total C for each sample on an Isoprime isotope ratio mass spectrometer coupled to a
220 Eurovector CN elemental analyser.

221

222 2.6 Bulk density

223 Bulk density of dry soil without roots or stones was calculated by dividing the dry weight of
224 each full sample (which consisteds of three combined, individual soil cores) with its volume. The
225 samples' volumes were calculated by multiplying the average depth of all three cores with three times
226 the area of the soil corer (9.42_cm²).

227

228 2.7 Soil *carbon-C* pool size

229 Soil *carbon-C* pool size per area was calculated by multiplying each full sample's C
230 concentration/ fraction with its dry weight, divided by three times the area of the soil corer (9.42_cm²
231 ²), in unit kg C m⁻².

232

233 | *2.8 Solid state ¹³C CP/MAS NMR spectroscopy*

Formatted: Superscript

234 | Approximately 100 mg of each soil sample was loaded into a 4 mm ZrO₂ rotor with a KEL-F
235 | cap. ¹³C Cross-Polarization Magic Angle Spinning (CP-MAS) experiments were performed on a
236 | Bruker 500 MHz Avance III spectrometer operating at a ¹³C frequency of 125.75 MHz (Bruker
237 | Biospin, Germany). Spinning rate was set to 7 kHz, the contact-time to 1 ms and the sweep-width to
238 | 250 ppm. 4096 scans were recorded with a relaxation delay of 2 s resulting in an experimental time of
239 | approximately 2.3 hours per sample. The FIDs were multiplied with a Gaussian function with LB = -
240 | 10 Hz and GB = 0.01 prior to fourier transform. All spectra were calibrated using adamantane as an
241 | external reference. Processing was performed in Topspin 3.2 (Bruker Biospin, Germany).

242

243 | *2.9 Processing of raw NMR spectra/ separation into integrals*

244 | The processed spectra were transferred to a matrix with each spectrum as a row and the
245 | columns representing the intensity in each of the 4096 data-points that constitutes a CP-MAS
246 | spectrum using an in-house Matlab script. Each spectrum was normalized to a constant sum before
247 | statistical analysis.

248 | Different chemical shift regions of the spectra, containing information about different
249 | functional groups (Preston et al., 1997) were also integrated and analysed as a separate data set. The
250 | regions were defined as follows: 0-50 ppm (alkyl); 50-60 ppm (methoxy/N-alkyl); 60-93 ppm (O-
251 | alkyl); 93-112 ppm (di-O-alkyl); 112-140 ppm (aromatic); 140-165 ppm (O-aromatic) and 165-190
252 | ppm (carbonyl). The integrals were also normalized to a constant sum before statistical analysis.

253

254 | *2.10 Statistical analyses*

255 | All analyses were performed with R version 3.4.3 (R Core Team, 2017) and all packages
256 | mentioned below are R packages.

257 | The effects of the snow fence treatment on A-horizon thickness, bulk density, ~~carbon-C~~
258 | concentration and pool size, integrated regions of the NMR spectra, and alkyl/ O-alkyl ratio were
259 | analysed with linear mixed effects models with plots as random effects using the “lme” package
260 | (Bates et al., 2015). The significance of the snow fence treatment was tested with a likelihood ratio
261 | test between the full model including treatment as predictor variable and the Null model, and a p-
262 | value of lower than 0.05 was considered to be significant. We then refitted the full models with
263 | restricted maximum likelihood estimation and extracted the 95% confidence intervals of the effect
264 | sizes and model term estimates with the “multcomp” package (Hothorn et al., 2008), which we
265 | present here together with the p-value from the likelihood ratio test. All model fits had no trend in
266 | Pearson residuals plotted against fitted values, and residuals were normally distributed (visual
267 | examination).

268 | To test whether NMR spectra from the control and snow fence treated soils differ, partial least
269 | squares discriminant analysis (PLS-DA) was performed with the “caret” package (Kuhn, 2008).
270 | Classification was carried out based on the probability of the normalized NMR spectra belonging to
271 | either group (snow fence or control), having each spectrum assigned to the class with the highest
272 | associated probability. The smallest number of latent variables needed to reach 100% discrimination
273 | between snow fence treatment and controls were chosen. The first two loading variables from each
274 | model were taken to assess which shift regions were responsible for discrimination.

275 | Data from A- and B/C-horizons were analysed separately, because the demineralization
276 | procedure of the B/C-horizon could potentially change a number of factors independent of horizon or
277 | the experimental *in situ* warming treatment (Dai & Johnson, 1999; Gélinas *et al.*, 2001; Keeler *et al.*,
278 | 2003; Schilling & Cooper, 2004; Rumpel *et al.*, 2006), making the two horizons incomparable, while
279 | qualitative treatment effect comparisons are valid (e.g. effect present or not).

280

281 **3. Results**

282 *3.1 A-horizon thickness*

283 Average A-horizon thickness across the study site's control area was 4.7 cm (95% CI: 3.7 –
284 5.7 cm) and 3.8 cm (95% CI: 2.8 – 4.8 cm) in the snow fence treatment, i.e. 0.9 cm lower than in the
285 control area (95% CI: -1.7 - -0.03 cm; $p = 0.0433$).

286

287 *3.2 Bulk density*

288 Average bulk density across the study site's control area was 0.33 g cm⁻³ (95% CI: 0.24 –
289 0.41 g cm⁻³) in the A-horizon, and 1.09 g cm⁻³ (95% CI: 0.94 – 1.24 g cm⁻³) in the upper five cm of the
290 B/C-horizon. The snow fence treatment influenced bulk density of neither A- nor B/C-horizon, i.e. no
291 significant effects were found.

292

293 *3.3 Soil ~~carbon~~-C concentrations (Figure 1 and Table 1)*

294 Average C concentrations across the study site's control area were 16.6% (95% CI: 13.6 -
295 19.7%) in the A-horizon and 5.4% (95% CI: 4.3 - 6.6%) in the upper 5 cm of the untreated B/C-
296 horizon (i.e. the soil aliquot which was not HF treated; Figure 1). Carbon concentrations in the HF
297 treated B/C-horizon soils (i.e. the HF treated soil samples that we will refer to when describing and
298 discussing data from the NMR analysis) were 14.2% (95% CI: 12.1 - 16.3%; data not shown).

299 The snow fence treatment influenced C concentrations of the A-, but not of the B/C-horizon.
300 In the A-horizon, samples from the snow fence treatment had 2% lower (95% CI: -3.7 - -0.5%; $p =$
301 0.021; Table 1) C concentrations than samples from controls. In the untreated B/C-horizon, samples
302 from the snow fence plots had no significantly different C concentration (95% CI: -0.1 to 2%; $p =$
303 0.111; Table 1). In the HF-treated B/C-horizon, samples from the snow fence plots also had no
304 significantly different C concentration (95% CI: -0.4 to 4.1%; $p = 0.073$; Table 1).

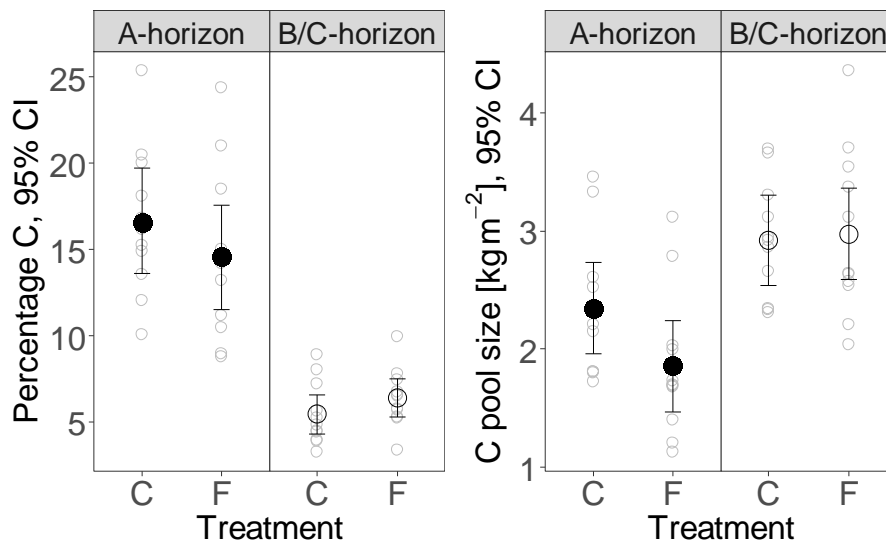
305

306 | 3.4 Soil ~~carbon~~-C pools (Figure 1 and Table 1)

307 Average C pool sizes across the study site's control area were 2.34 kg C m⁻² (95% CI: 1.96 –
308 2.73 kg C m⁻²) in the A-horizon and 2.92 kg C m⁻² (95% CI: 2.54 – 3.3 kg C m⁻²) in the upper five cm
309 of the untreated B/C-horizon (i.e. the soil aliquot which was not HF treated; Figure 1).

310 The snow fence treatment influenced C pools of the A-, but not of the B/C-horizon. In the A-
311 horizon, samples from the snow fence treatment had 0.48 kg C m⁻² lower (95% CI: -0.9 - -0.07 kg C
312 m⁻²; p = 0.032; Table 1) C pool sizes than samples from controls. In the B/C-horizon, samples from
313 the snow fence plots had no significantly different C pool sizes (95% CI: -0.42 to 0.53 kg C m⁻²; p =
314 0.82; Table 1).

315



316

317 Figure 1: Carbon concentration (percentage C, left) and pool size (kg C m⁻², right) in A- and
318 untreated (i.e. non-HF treated) B/C-horizons for each soil sample (raw data, grey open circles) and
319 modelled with 95% confidence intervals (black circles). Solid black circles in the A-horizon data
320 denote statistically significant differences between treatments (see Table 1); open black circles in the
321 B/C-horizon data denote no statistically significant difference between treatments. Treatment C =

322 | Control (ambient conditions, ca. 40 cm snow depth), F = Snow Fence (enhanced snow, ca. 70 cm
 323 | snow depth). See Table 1 for statistical tests between treatments, also including the C concentration
 324 | model for the HF-treated B/C-horizon.

325

326 | **Table 1:** Modelled mean effect sizes and 95% confidence intervals (CI) of the snow fence treatment on
 327 | carbon concentration (%C) and carbon pool size (kg C m⁻²) of A-, untreated B/C-, and HF-treated
 328 | B/C-horizons (only for %C). The values show estimated differences of samples from the snow fence
 329 | treatment compared to controls based on linear mixed effects models. P-values are based on a
 330 | likelihood ratio test between the full and the Null model. Significant effect sizes are in bold ($p < 0.05$
 331 | and CI not overlapping zero). Each line shows results of a separate model.

Response	Horizon	Effect size	Lower 95% CI	Upper 95% CI	p-value
%C	A	-2.0563	-3.6623	-0.4503	0.0205
%C	B/C	0.9525	-0.06051	1.96552	0.1113
%C	B/C (HF-treated)	1.8646	-0.4052	4.1344	0.0729
kg C m⁻²	A	-0.48285	-0.89685	-0.06886	0.03152
kg C m ⁻²	B/C	0.05238	-0.42044	0.52520	0.8201

332

333

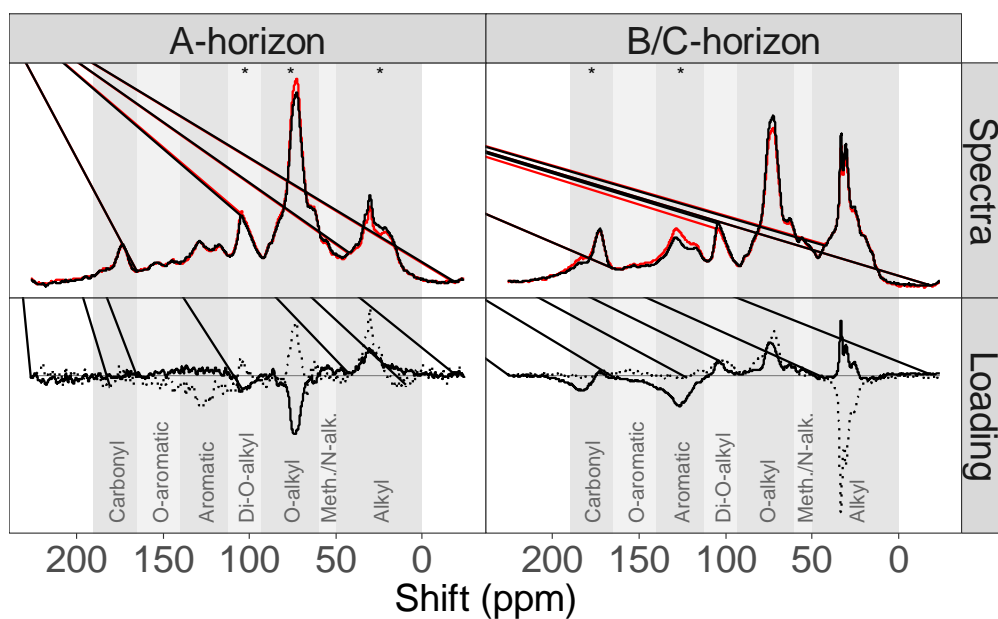
334 | 3.5 Spectral analysis (Figure 2)

335 | PLS-DA models on samples from the snow fence treatment and controls showed a 100%
 336 | discrimination using 3 and 5 latent variables for the A- and HF-treated B/C-horizons, respectively,
 337 | indicating a significant structural difference between treatments in both horizons. The chemical shift
 338 | regions causing the differences were visible in the spectra and the models' first and second loading
 339 | components (Figure 2). In other words, regions with the highest model loadings are the regions with
 340 | the highest importance to distinguish between the treatments.

341 In the A-horizon, clear differences between snow fence and control soil samples were visible
 342 in the O-alkyl and alkyl regions, as well as subtle differences in the aromatic region.

343 In the B/C-horizon, the effect of snow fence treatment differed compared to the A-horizon.
 344 Here we observed a decrease in the signal in the carbonyl and aromatic regions as well as an increase
 345 in O-alkyl and alkyl signals.

346



347

348 *Figure 2:* Top row: Mean NMR spectra for soil samples from snow fence plots (black line)
 349 and controls (red line) in A- (left column) and HF-treated B/C-horizons (right column). Bottom row:
 350 first (solid line) and second (dotted line) loading components of the associated PLS-DA models.
 351 Vertical grey bars denote integrated chemical shift regions as defined in Table 2, from left to right
 352 (with region boundaries): carbonyl (190-165), O-aromatic (165-140), aromatic (140-112), di-O-alkyl
 353 (112-93), O-alkyl (93-60), methoxy/ N-alkyl (60-50), alkyl (50-0). Small stars on top of the top row
 354 denote where statistically significant differences between treatments were found on individual
 355 integrated chemical shift regions (Table 2).

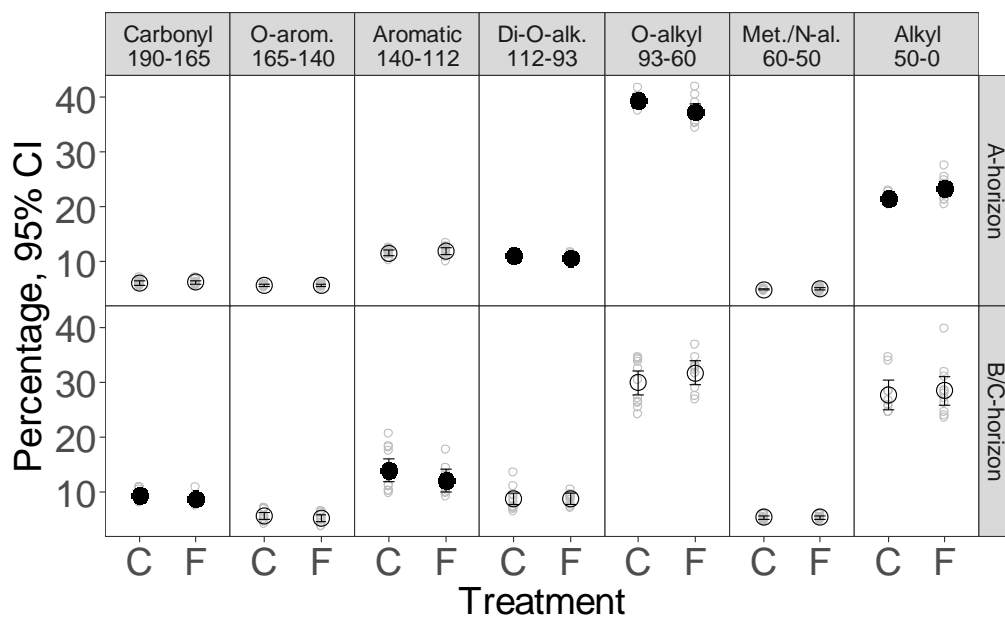
356

357 3.6 Integrated shift regions (Figure 3 and Table 2)

358 In the A-horizon, samples from the snow fence plots had a 2% higher (95% CI: 0.9 – 2.9%; p
 359 = 0.002) concentration of alkyl signals than samples from controls, while the concentrations of di-O-
 360 alkyl and O-alkyl signals were significantly lowered by 0.6% (95% CI: -0.9 - -0.2%; p = 0.007) and
 361 2% (95% CI: -3.3 to -0.7%; p = 0.009), respectively. The other integral regions' contributions to the
 362 A-horizon spectra were not significantly different between the treatments. See Figure 3 and Table 2.

363 In the HF-treated B/C-horizon, samples from the snow fence plots had 2% (95% CI: -3.7 - -
 364 0.2; p = 0.035) and 0.7% (95% CI: -1.3 - -0.1%; p = 0.027) lower concentrations of aromatic and
 365 carbonyl signals, respectively, than samples from controls, while the O-alkyl signals had a non-
 366 significant trend towards 1.8% (95% CI: -0.9 – 4.6%; p = 0.186) concentrations. The other integral
 367 regions' contributions to the B/C-horizon spectra were not significantly different between the
 368 treatments. See Figure 3 and Table 2.

369



370

371 **Figure 3:** Relative contribution of integrated NMR spectra signal regions in A- and HF-
 372 treated B/C-horizons for each soil sample (raw data, grey open circles) and modelled with 95%

373 confidence intervals (black circles). Solid black circles denote statistically significant differences
 374 between treatments; open black circles denote no statistically significant difference between
 375 treatments. Treatment C = Control, F = Snow Fence. See Table 2 for statistical tests between
 376 treatments.

377

378 Table 2: Modelled mean effect sizes and 95% confidence intervals (CI) of the snow fence treatment on
 379 relative contribution of integrated NMR spectra signal regions and alkyl/O-alkyl ratio of A- and HF-
 380 treated B/C-horizon samples. The values show estimated differences of samples from the snow fence
 381 plots compared to controls based on linear mixed effects models. Region denotes the ppm range
 382 chosen to define each integral. P-values are based on a likelihood ratio test between the full and the
 383 Null model, and cases where the full model is statistically significantly better than the Null model with
 384 $p < 0.05$ are in bold. Each line shows results of a separate model.

<i>Horizon</i>	<i>Integral</i>	<i>Region</i>	<i>Effect size</i>	<i>Lower 95 %CI</i>	<i>Upper 95% CI</i>	<i>p-value</i>
A	Carbonyl	190-165	0.000683	-0.0009593	0.0023253	0.3987
A	O-aromatic	165-140	0.0001435	-0.00281	0.003097	0.92
A	Aromatic	140-112	0.003705	-0.001253	0.008663	0.1437
A	Di-O-alkyl	112-93	-0.005542	-0.009067	-0.002018	0.007272
A	O-alkyl	93-60	-0.019813	-0.032911	-0.006714	0.009047
A	Methoxy/ N-alkyl	60-50	0.001589	-0.0006453	0.0038233	0.1522
A	Alkyl	50-0	0.019235	0.009103	0.029367	0.002273
A	alkyl/ O-alkyl	ratio	0.085	0.03685	0.13316	0.003633
B/C	Carbonyl	190-165	-0.006956	-0.012728	-0.001184	0.02721
B/C	O-aromatic	165-140	-0.0050147	-0.0104986	0.0004692	0.08004
B/C	Aromatic	140-112	-0.019838	-0.037232	-0.002445	0.03473
B/C	Di-O-alkyl	112-93	0.0006397	-0.0134508	0.0147301	0.9257
B/C	O-alkyl	93-60	0.018268	-0.009001	0.045538	0.1859

B/C	<i>Methoxy/ N-alkyl</i>	<i>60-50</i>	0.0007683	-0.0028917	0.0044283	0.6674
B/C	<i>Alkyl</i>	<i>50-0</i>	0.006997	-0.011176	0.025171	0.4351
B/C	<i>alkyl/ O-alkyl</i>	<i>ratio</i>	-0.03617	-0.17731	0.10497	0.6006

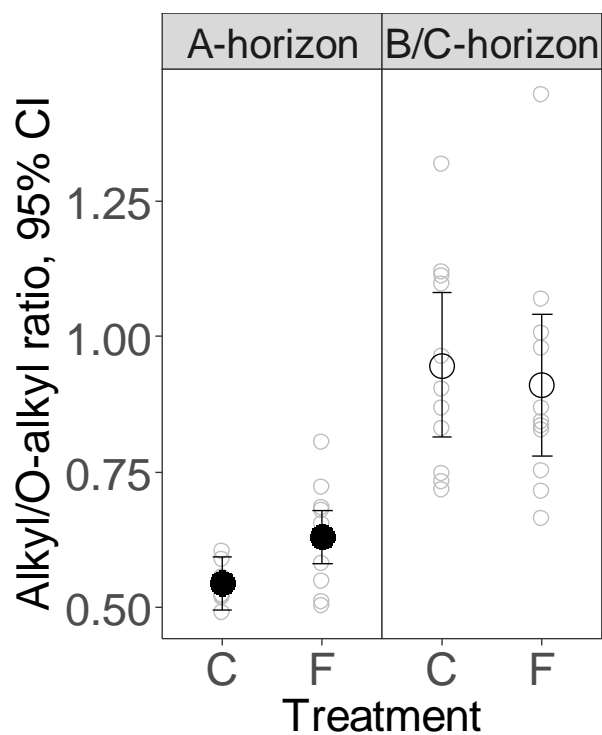
385

386 *3.7 Alkyl/O-alkyl ratio (Figure 4 and Table 2)*

387 Average alkyl/O-alkyl ratios across the study site's control area were 0.55 (95% CI: 0.5 -
388 0.59) in the A-horizon and 0.95 (95% CI: 0.82 - 1.1) in the HF-treated B/C-horizon. See Figure 4.

389 The snow fence treatment influenced the alkyl/O-alkyl ratio of the A-, but not of the B/C-
390 horizon. In the A-horizon, samples from the snow fence plots had a 0.085 higher (95% CI: 0.037 -
391 0.133; $p = 0.004$) alkyl/O-alkyl ratio than controls. In the B/C-horizon, samples from the snow fence
392 plots had no significantly different alkyl/O-alkyl ratio compared to controls (-0.036; 95% CI: -0.18 -
393 0.1; $p = 0.6$).

394



395

396 *Figure 4: Alkyl/O-alkyl ratios in A- and HF-treated B/C-horizons for each soil sample (raw*
 397 *data, grey open circles) and modelled with 95% confidence intervals (black circles). Solid black*
 398 *circles denote statistically significant differences between treatments (only A-horizon); open black*
 399 *circles denote no statistically significant difference between treatments (only B/C-horizon). Treatment*
 400 *C = Control, F = Snow Fence. See Table 2 for statistical tests between treatments.*

401

402 4. Discussion

403 We found that the A-horizon, i.e. the study site's C-richer upper soil layer (average 16.6% C
404 and 4.7 cm thickness), of high Arctic tundra plots which were exposed to 9 years of experimental *in*
405 *situ* NGS warming via snow fences, on average had a 2% lower C concentration, contained 0.48 kg
406 less C m⁻² (hypothesis 1) and was in a more advanced stage of decomposition (as indicated by a 0.09
407 higher alkyl/ O-alkyl ratio, hypothesis 2) compared to unmanipulated control plots. These effects were
408 not observed in the first 5 cm of the underlying, C poorer B/C-horizon (average 5.4% C, hypothesis
409 3). Below we will discuss potential causes, effects and implications of our findings.

410

411 4.1 SOC loss through NGS warming only in A-horizon, not B/C-horizon (hypotheses 1 & 3)

412 The smaller SOC pool in the snow fence plots' A-Horizon compared to [the](#) controls is
413 possibly caused by a temperature induced increase of decomposition and subsequent loss of SOC
414 during the nine preceding warmed NGSs. Non-growing season ER was higher in snow fence
415 treatments in this (Morgner et al., 2010; Semenchuk et al., 2016a) and other Arctic sites (Natali et al.,
416 2014; Nobrega and Grogan, 2007; Schimel et al., 2004; Webb et al., 2016). Further, soil nutrient
417 concentrations were higher in a deeper snow fence treatment with stronger temperature increase in
418 this (Semenchuk *et al.*, 2015; Mörsdorf *et al.*, submitted) and another Arctic site (Schimel et al.,
419 2004), and *Salix polaris*' (and other species') leaf nitrogen content was higher in this (Mörsdorf *et al.*,
420 submitted) and another Arctic site (Welker et al., 2005), suggesting a stabilization of surplus nutrients
421 from the soil. In sum, these findings strongly indicate increased activities of decomposing organisms
422 during warmed NGSs in a variety of Arctic tundra ecosystems, which in the long run possibly lead to
423 more mineralization of SOC than could be replenished by plants during the growing season through
424 e.g. plant litter or root exudate inputs (Bradford et al., 2008; Eliasson et al., 2005; Kirschbaum, 2004).

425 Whether this SOC depletion is a transient phenomenon driven by fast cycling SOC pools as
426 observed in e.g. permafrost soil incubations (e.g. Moni *et al.*, 2015) or plant litter mass loss studies
427 (e.g. Demarco *et al.*, 2014) is uncertain. The observed decrease of growing season ER (Semenchuk et

428 al., 2016a) and degradation of SOC to advanced stages of decomposition indicate that, under current
429 conditions, further depletion might come to a halt. However, as suggested by Melillo et al. (2017), it
430 is possible that the microbial communities in the snow fence plots are undergoing a phase of
431 reorganization as response to the altered SOC pool size and quality, soil nutrient status, and
432 temperature conditions. Once acclimated, further depletion and degradation of the remaining SOC
433 pool could continue. Since these non-linear and possibly interactive responses cannot necessarily be
434 generalized across spatial and temporal boundaries, further large-scale and long-term studies (e.g.
435 time series) are warranted to enable us to project the presented findings on possible future climate
436 scenarios.

437 Whether the findings of SOC depletion from this study are context specific can only be
438 speculated without further long-term and orchestrated biome-wide studies, but a few available long-
439 term studies (>8 years warming) do indicate context specificity. The growing season ER reduction
440 after long-term NGS warming is also reported from Daring Lake, a low-Arctic site (Semenchuk et al.,
441 2016a), and both reduction of long-term effects on ER and depletion of easily degradable SOC after
442 long-term warming are reported from the Harvard Forest, a deciduous hard-wood forest (Bradford et
443 al., 2008; Melillo et al., 2017). However, long-term warming did not result in reductions of growing
444 season ER nor decline of NGS ER effects from a sub-Arctic peat site in Abisko (Dorrepaal et al.,
445 2009). All mentioned studies are from different ecosystems, and taken together it seems that context
446 specificity is given. Which factors are responsible for the contrasting results between these studies is
447 unclear and motivates for further studies. However, the high C and low mineral content in the Abisko
448 peat site might play important roles in determining long-term effects of warming on SOC pool size.

449 Vegetation related variables can partly be ruled out as explanatory factors for SOC pool size
450 in this study. Firstly, soil was exclusively sampled under *Salix polaris*, which excludes potential
451 confounding effects on SOC properties by sampling under different species. Second, neither species
452 composition (Cooper *et al.*, submitted) nor *Salix polaris*' growth (Rumpf et al., 2014) in the snow
453 fence treatment used here were significantly different from the controls. However, the aforementioned
454 higher leaf nitrogen content in the snow fence plots (Mörsdorf *et al.*, submitted) might be forewarning

455 increased performance of *Salix polaris* in the long run. Conversely, results from the same experiment
456 but from a two times deeper snow fence treatment than used here (150 cm vs. 70 cm snow depth)
457 found significantly less seasonal growth (Rumpf et al., 2014) and lower abundance of *Salix polaris*
458 and most other vascular plant species (Cooper et al., submitted). Whether these changes, caused by a
459 more extreme snow depth increase, are representing the future state of the snow fence treatment used
460 here is questionable. While the NGS warming and connected biogeochemical effects are stronger in
461 the deeper snow fence treatment (Semenchuk et al., 2015; Mörsdorf et al., submitted), the negative
462 effects on the vegetation there are possibly caused by an average 7 days later snow melt compared to
463 the snow fence treatment used here (Semenchuk et al., 2016b, 2013) rather than by biogeochemical
464 cascading effects.

465 NGS warming significantly lowered SOC concentrations in the A-horizon but not in the
466 directly underlying 5 cm of B/C-horizon, a result similar to the findings of Melillo et al. (2017). We
467 assume that B/C-horizon properties stabilize SOC, such that it cannot be fully mineralized or accessed
468 by decomposing organisms. In our case especially sorption to mineral particles (Kawahigashi et al.,
469 2006; Kleber, 2010; Schmidt et al., 2011; Trumbore, 2009), but also other environmental controls
470 such as smaller soil pore size (as indicated by the B/C-horizon's higher bulk density) and particle
471 aggregation might have rendered parts of its SOC pool inaccessible to decomposing organisms
472 (Conant et al., 2011; Ekschmitt et al., 2008). Additionally, lower root density (own observation and
473 Strebel et al. (2010)) and possibly different species composition of the B/C-horizon's rhizosphere
474 (Iversen et al., 2015) could be responsible for the initially low SOC concentrations found in the B/C-
475 horizon. This low SOC concentration in the deeper horizons might create microhabitats unsuitable for
476 a bulk population of decomposing organisms capable of mineralizing significant fractions of the
477 existing SOC pool (Ekschmitt et al., 2008; Schmidt et al., 2011).

478 Leaching of dissolved ~~carbon~~C from the A-horizon by additional melt water production from
479 the extra snow pack is conceivable. However, three qualitative observations lead to the assumption
480 that this effect may be minor. First, the total melt water runoff from the large area above the
481 experimental site by far outweighs the amounts produced by the additional snowpack. This runoff is

482 unchanged by the experimental snow addition and hence the additional melt water might not have a
483 significant impact. Second, a large part of the melt water produced by the deepened snow packs after
484 the surrounding snow is gone seems to get diverted by the ice layer at the bottom of the snow pack
485 (Semenchuk et al., 2013) and may not reach the soil until it reaches the edges of the plots. Third, the
486 soil in this study site is frozen solid until a few days after melt out and any melt water flowing over it
487 may only touch the vegetation and soil surface. All three points are based on own qualitative
488 observations only and yield opportunities for further studies on potential artefacts of snow fences as
489 experimental treatments in ecological studies.

490

491 *4.2 Implications of SOC loss on ER and atmosphere*

492 The loss of SOC from the A-horizon possibly explains the decline of growing season ER as
493 reported by Semenchuk *et al.* (2016a) in the same experimental setup. Soil OC availability as
494 substrate for heterotrophic organisms may be depleted by increased consumption below a threshold
495 where steady state respiration can be maintained (Bradford et al., 2008; Eliasson et al., 2005;
496 Kirschbaum, 2004). This phenomenon could be partly confounded with the aforementioned higher
497 soil nutrient availability in NGS warmed plots (Schimel *et al.*, 2004; Semenchuk *et al.*, 2015;
498 Mörsdorf *et al.*, submitted) resulting in ER responses independent of SOC loss. For instance, reduced
499 nutrient limitations could reduce plant roots' foraging for nutrients and thereby reduce root exudate
500 production and connected decomposer stimulation leading to some kind of "negative priming" effects
501 (cf. Fontaine *et al.*, 2004; Hartley *et al.*, 2012). More studies to disentangle the possible mechanisms
502 behind this are needed.

503 Our observation that SOC was only lost from the A-horizon (which with an average thickness
504 of 4.7 cm lies well above the permafrost table at about 90 cm depth) allows the speculation that the
505 increase of ER during warmed NGSs in this study site (Morgner et al., 2010; Semenchuk et al.,
506 2016a) might primarily originate from the A-horizon, too. If this holds true, then the fact that growing
507 season ER was reduced as a response to NGS warming (Semenchuk et al., 2016a) *also* suggests that

508 | ~~also~~ the growing season bulk ER originates from surface horizons, as has been shown in studies
509 | measuring CO₂ fluxes in different soil depths (Hicks Pries et al., 2017; Lee et al., 2010). While
510 | understudied to date, the implications of these thoughts are of importance to determine the relative
511 | contribution of CO₂ emissions from surface and deep soils, such as thawing permafrost. With surface
512 | horizons potentially being the primary source of ER derived CO₂ emissions from tundra ecosystems,
513 | then warming induced increases of C loss from thawing permafrost (Moni et al., 2015; Schuur et al.,
514 | 2009) might be relatively minor compared to CO₂ emissions from surface soils during timescales
515 | relevant for the ongoing anthropogenic forcing (Stocker et al., 2014). In fact, Hicks Pries *et al.* (2017)
516 | found that about 80% of all soil respiration and about 90% of respiration response to 4 °C warming
517 | occurred in the upper 30 cm of temperate forest soil, and Lee *et al.* (2010) found that the upper 10 cm
518 | of upland tundra soil had ten times higher CO₂ fluxes than the underlying 20 cm horizon. In sum, these
519 | findings point towards a predominance of the more exposed surface soils as C sources to the
520 | atmosphere and warrant further studies.

521 | A back of the envelope calculation scaling up the effect size from the C pool model to the
522 | total global area of Prostrate/hemiprostrate dwarf-shrub tundra (i.e. the vegetation type studied here,
523 | worldwide covering 140000 km², CAVM Team, (2003)) estimates a potential total loss of 67.6 Mt C
524 | or 248.1 Mt CO₂ equivalent upon global NGS warming from the 4.7 cm thick A-horizon only. This is
525 | in magnitude comparable with the annual CO₂ emissions of, for instance, Florida (Desai et al., 2017)
526 | or Egypt (EDGARv4.3.2, 2016), but with 0.69% an insignificant contribution to the still rising annual
527 | global anthropogenic CO₂ emissions of 36062 Mt in 2015 (EDGARv4.3.2, 2016).

528

529 | *4.3 Shifts in relative abundance of carbon compounds (hypothesis 2)*

530 | Carbon compound composition was clearly different in the snow fence treatment from ~~the~~
531 | controls in both A- and B/C-horizons. In the A-horizon, the differences were mainly in the alkyl and
532 | O-alkyl groups leading to a higher alkyl/ O-alkyl ratio in the snow fence treatment. This indicates that
533 | NGS warming indeed transformed the A-horizon to a more advanced stage of decomposition (Feng

Field Code Changed

Formatted: German (Austria)

534 and Simpson, 2008; Pautler et al., 2010; Pedersen et al., 2011; Simpson et al., 2008; Sjögersten et al.,
535 2003). Together with the above discussed phenomenon of SOC loss, this supports the idea that the
536 balance between SOC consumption and replenishment was significantly disturbed and could explain
537 the observed decrease of growing-season ER (Semenchuk et al., 2016a).

538 In the B/C-horizon, the main changes were observed in the aromatic regions, indicating a
539 decrease of amino-acids (Simpson and Simpson, 2012). These compounds were possibly transformed
540 to O-alkyl compounds, even though the increase of that group of compounds was not statistically
541 significant (compare with Table 2). The reason for this discrepancy between A- and B/C-horizons is
542 out of the scope of this study, however, may be rooted in selective sorption of O-alkyl compounds to
543 mineral particles, forcing decomposing organisms to use aromatic compounds as substrates.

544

545 *4.4 Conclusions*

546 We found that 9 years of ca. 2 °C NGS warming reduced the A-horizon's C pool and
547 degraded it to a more advanced stage of decomposition. Our results support the hypothesis that the
548 transient nature of increased ER by soil warming as observed elsewhere is connected to excessive and
549 selective consumption of SOC leading to a depletion of favourable substrates for decomposers. We
550 further suggest that the NGS warming induced increases of ER in our study site primarily originate in
551 the relatively shallow A-horizon and dominate total CO₂ emissions compared to deep soil or thawing
552 permafrost. The estimated absolute expected loss over the whole global area of this ecosystem,
553 however, is dwarfed by comparison with still rising global anthropogenic greenhouse gas emissions.
554 We conclude that a positive feedback from surface soils of circumarctic dwarf shrub tundra
555 communities to anthropogenic forcing might be minor during the timescales covered in this study, but
556 due to their dynamic nature deserve a place in modelling studies.

557

558 **5. Acknowledgements**

559 Funding for NMR analyses came from ARCUM to Philipp Semenchuk, from the Norwegian
560 Research Council ('SnoEco' project, number 230970) and the FRAM Centre Terrestrial Flagship
561 ('Arctic GSL' project) to EJC, and an ARCUM travel grant to EK. Thanks to Gesche Blume-Werry
562 and Signe Lett for improvements on earlier versions of this manuscript. Raw data for this manuscript
563 is available in the supplementary section.

564

565 **6. References**

566 Bates, D., Maechler, M., Bolker, B., Walker, S., 2015. Fitting Linear Mixed-Effects Models Using
567 lme4. *J. Stat. Softw.* 67, 1–48. <https://doi.org/10.18637/jss.v067.i01>

568 Björkman, M.P., Morgner, E., Cooper, E.J., Elberling, B., Klemedtsson, L., Björk, R.G., 2010.
569 Winter carbon dioxide effluxes from arctic ecosystems: An overview and comparison of
570 methodologies. *Global Biogeochem. Cycles* 24, 1–10. <https://doi.org/10.1029/2009GB003667>

571 Bradford, M.A., Davies, C.A., Frey, S.D., Maddox, T.R., Melillo, J.M., Mohan, J.E., Reynolds, J.F.,
572 Treseder, K.K., Wallenstein, M.D., 2008. Thermal adaptation of soil microbial respiration to
573 elevated temperature. *Ecol. Lett.* 11, 1316–27. [https://doi.org/10.1111/j.1461-](https://doi.org/10.1111/j.1461-0248.2008.01251.x)
574 [0248.2008.01251.x](https://doi.org/10.1111/j.1461-0248.2008.01251.x)

575 CAVM Team, 2003. Circumpolar Arctic Vegetation Map. (1:7,500,000 scale). Conservation of Arctic
576 Flora and Fauna (CAFF) Map No. 1. U.S. Fish and Wildlife Service, Anchorage, Alaska.

577 Conant, R.T., Ryan, M.G., Ågren, G.I., Birge, H.E., Davidson, E.A., Eliasson, P.E., Evans, S.E., Frey,
578 S.D., Giardina, C.P., Hopkins, F.M., Hyvönen, R., Kirschbaum, M.U.F., Lavalley, J.M., Leifeld,
579 J., Parton, W.J., Megan Steinweg, J., Wallenstein, M.D., Martin Wetterstedt, J.Å., Bradford,
580 M.A., 2011. Temperature and soil organic matter decomposition rates - synthesis of current
581 knowledge and a way forward. *Glob. Chang. Biol.* 17, 3392–3404.
582 <https://doi.org/10.1111/j.1365-2486.2011.02496.x>

583 Cooper, E.J., Dullinger, S., Semenchuk, P., 2011. Late snowmelt delays plant development and results

584 in lower reproductive success in the High Arctic. *Plant Sci.* 180, 157–167.
585 <https://doi.org/10.1016/j.plantsci.2010.09.005>

586 Dai, K.H., Johnson, C.E., 1999. Applicability of solid-state ¹³C CP r MAS NMR analysis in
587 Spodosols : chemical removal of magnetic materials. *Geoderma* 93, 289–310.

588 Demarco, J., Mack, M.C., Bret-Harte, M.S., 2014. Effects of arctic shrub expansion on biophysical vs.
589 biogeochemical drivers of litter decomposition. *Ecology* 95, 1861–1875.
590 <https://doi.org/10.1890/13-2221.1>

591 Desai, M., Harvey, R.P., EPA, 2017. Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-
592 2015. *Fed. Regist.* 82, 10767. [https://doi.org/EPA 430-R-13-001](https://doi.org/EPA%20430-R-13-001)

593 Dorrepaal, E., Toet, S., van Logtestijn, R.S.P., Swart, E., van de Weg, M.J., Callaghan, T. V., Aerts,
594 R., 2009. Carbon respiration from subsurface peat accelerated by climate warming in the
595 subarctic. *Nature* 460, 616–619. <https://doi.org/10.1038/nature08216>

596 EDGARv4.3.2, 2016. Emission Database for Global Atmospheric Research (EDGAR), release
597 version 4.3.2.

598 Ekschmitt, K., Kandeler, E., Poll, C., Brune, A., Buscot, F., Friedrich, M., Gleixner, G., Hartmann,
599 A., Kästner, M., Marhan, S., Miltner, A., Scheu, S., Wolters, V., 2008. Soil-carbon preservation
600 through habitat constraints and biological limitations on decomposer activity. *J. Plant Nutr. Soil*
601 *Sci.* 171, 27–35. <https://doi.org/10.1002/jpln.200700051>

602 Eliasson, P.E., McMurtrie, R.E., Pepper, D.A., Strömgren, M., Linder, S., Ågren, G.I., 2005. The
603 response of heterotrophic CO₂ flux to soil warming. *Glob. Chang. Biol.* 11, 167–181.
604 <https://doi.org/10.1111/j.1365-2486.2004.00878.x>

605 Feng, X., Simpson, M.J., 2008. Temperature responses of individual soil organic matter components.
606 *J. Geophys. Res. Biogeosciences* 113, 1–14. <https://doi.org/10.1029/2008JG000743>

607 Fontaine, S., Bardoux, G., Abbadie, L., Mariotti, A., 2004. Carbon input to soil may decrease soil
608 carbon content. *Ecol. Lett.* 7, 314–320. <https://doi.org/10.1111/j.1461-0248.2004.00579.x>

609 Gélinas, Y., Baldock, J.A., Hedges, J.I., 2001. Demineralization of marine and freshwater sediments
610 for CP / MAS ¹³C NMR analysis. *Org. Geochem.* 32, 677–693.

611 Hartley, I.P., Garnett, M., Sommerkorn, M., Hopkins, D.W., Fletcher, B.J., Sloan, V.L., Phoenix,
612 G.K., Wookey, P. a., 2012. A potential loss of carbon associated with greater plant growth in the
613 European Arctic. *Nat. Clim. Chang.* 2, 875–879. <https://doi.org/10.1038/nclimate1575>

614 Hicks Pries, C.E., Castanha, C., Porras, R.C., Torn, M.S., 2017. The whole-soil carbon flux in
615 response to warming. *Science* (80-.). 1319, 1–9. <https://doi.org/10.1126/science.aal1319>

616 Hothorn, T., Bretz, F., Westfall, P., 2008. Simultaneous Inference in General Parametric Models.
617 *Biometrical J.* 50, 346–363.

618 Hugelius, G., Strauss, J., Zubrzycki, S., Harden, J.W., Schuur, E.A.G., Ping, C.L., Schirmermeister, L.,
619 Grosse, G., Michaelson, G.J., Koven, C.D., O'Donnell, J.A., Elberling, B., Mishra, U., Camill,
620 P., Yu, Z., Palmtag, J., Kuhry, P., 2014. Estimated stocks of circumpolar permafrost carbon with
621 quantified uncertainty ranges and identified data gaps. *Biogeosciences* 11, 6573–6593.
622 <https://doi.org/10.5194/bg-11-6573-2014>

623 Iversen, C.M., Sloan, V.L., Sullivan, P.F., Euskirchen, E.S., McGuire, A.D., Norby, R.J., Walker,
624 A.P., Warren, J.M., Wullschleger, S.D., 2015. The unseen iceberg: Plant roots in arctic tundra.
625 *New Phytol.* 205, 34–58. <https://doi.org/10.1111/nph.13003>

626 Kawahigashi, M., Kaiser, K., Rodionov, A., Guggenberger, G., 2006. Sorption of dissolved organic
627 matter by mineral soils of the Siberian forest tundra. *Glob. Chang. Biol.* 12, 1868–1877.
628 <https://doi.org/10.1111/j.1365-2486.2006.01203.x>

629 Keeler, C., Keeler, C., Maciel, G.E., Maciel, G.E., 2003. Quantitation in the solid-state ¹³C NMR
630 analysis of soil and organic soil fractions. *Anal. Chem.* 75, 2421–32.

631 Kirschbaum, M.U.F., 2004. Soil respiration under prolonged soil warming: are rate reductions caused
632 by acclimation or substrate loss? *Glob. Chang. Biol.* 10, 1870–1877.
633 <https://doi.org/10.1111/j.1365-2486.2004.00852.x>

634 Kleber, M., 2010. What is recalcitrant soil organic matter? *Environ. Chem.* 7, 320–332.
635 <https://doi.org/10.1071/EN10006>

636 Kuhn, M., 2008. Building Predictive Models in R Using the caret Package. *J. Stat. Softw.* 28, 1–26.
637 <https://doi.org/10.1053/j.sodo.2009.03.002>

638 Lee, H., Schuur, E.A.G., Vogel, J.G., 2010. Soil CO₂ production in upland tundra where permafrost
639 is thawing. *J. Geophys. Res.* 115, G01009. <https://doi.org/10.1029/2008JG000906>

640 Melillo, J.M., Frey, S.D., DeAngelis, K.M., Werner, W.J., Bernard, M.J., Bowles, F.P., Pold, G.,
641 Knorr, M.A., Grandy, A.S., 2017. Long-term pattern and magnitude of soil carbon feedback to
642 the climate system in a warming world. *Science* (80-.). 358, 101–105.
643 <https://doi.org/10.1126/science.aan2874>

644 Moni, C., Lerch, T.Z., Knoth de Zarruk, K., Strand, L.T., Forte, C., Certini, G., Rasse, D.P., 2015.
645 Temperature response of soil organic matter mineralisation in arctic soil profiles. *Soil Biol.*
646 *Biochem.* 88, 236–246. <https://doi.org/10.1016/j.soilbio.2015.05.024>

647 Morgner, E., Elberling, B., Strebel, D., Cooper, E.J., 2010. The importance of winter in annual
648 ecosystem respiration in the High Arctic: effects of snow depth in two vegetation types. *Polar*
649 *Res.* 29, 58–74. <https://doi.org/10.1111/j.1751-8369.2010.00151.x>

650 Natali, S.M., Schuur, E.A.G., Webb, E.E., Pries, C.E.H., Crummer, K.G., 2014. Permafrost
651 degradation stimulates carbon loss from experimentally warmed tundra. *Ecology* 95, 602–608.
652 <https://doi.org/10.1890/13-0602.1>

653 Nobrega, S., Grogan, P., 2007. Deeper snow enhances winter respiration from both plant-associated
654 and bulk soil carbon pools in birch hummock tundra. *Ecosystems* 10, 419–431.
655 <https://doi.org/10.1007/s10021-007-9033-z>

656 Ottesen, R., Bogen, J., Finne, T., Andersson, M., Dallmann, W., Eggen, O., Jartun, M., Lundkvist, Q.,
657 Ranestad Pedersen, H., Volden, T., 2010. Geochemical atlas of Norway - Part 2: Geochemical
658 atlas of Spitsbergen. Geological Survey of Norway, Trondheim.

659 Pautler, B.G., Simpson, A.J., McNally, D.J., Lamoureux, S.F., Simpson, M.J., 2010. Arctic Permafrost
660 Active Layer Detachments Stimulate Microbial Activity and Degradation of Soil Organic
661 Matter. *Environ. Sci. Technol.* 44, 4076–4082. <https://doi.org/10.1021/es903685j>

662 Pedersen, J.A., Simpson, M.A., Bockheim, J.G., Kumar, K., 2011. Characterization of soil organic
663 carbon in drained thaw-lake basins of Arctic Alaska using NMR and FTIR photoacoustic
664 spectroscopy. *Org. Geochem.* 42, 947–954. <https://doi.org/10.1016/j.orggeochem.2011.04.003>

665 Preston, C.M., Trofymow, J.A., Sayer, B.G., Niu, J.N., 1997. C-13 nuclear magnetic resonance
666 spectroscopy with cross-polarization and magic-angle spinning investigation of the proximate-
667 analysis fractions used to assess litter quality in decomposition studies. *Can. J. Bot. Can. Bot.*
668 75, 1601–1613. <https://doi.org/10.1139/b97-872>

669 R Core Team, 2017. R: A Language and Environment for Statistical Computing. R Foundation for
670 Statistical Computing, Vienna, Austria.

671 Rumpel, C., Rabia, N., Derenne, S., Quenea, K., Eusterhues, K., Kögel-Knabner, I., Mariotti, A.,
672 2006. Alteration of soil organic matter following treatment with hydrofluoric acid (HF). *Org.*
673 *Geochem.* 37, 1437–1451. <https://doi.org/10.1016/j.orggeochem.2006.07.001>

674 Rumpf, S.B., Semenchuk, P.R., Dullinger, S., Cooper, E.J., 2014. Idiosyncratic responses of high
675 arctic plants to changing snow regimes. *PLoS One* 9, 1–10.
676 <https://doi.org/10.1371/journal.pone.0086281>

677 Schilling, M., Cooper, W.T., 2004. Effects of chemical treatments on the quality and quantitative
678 reliability of solid-state ¹³C NMR spectroscopy of mineral soils. *Anal. Chim. Acta* 508, 207–
679 216. <https://doi.org/10.1016/j.aca.2003.12.001>

680 Schimel, J.P., Bilbrough, C., Welker, J.M., 2004. Increased snow depth affects microbial activity and
681 nitrogen mineralization in two Arctic tundra communities. *Soil Biol. Biochem.* 36, 217–227.
682 <https://doi.org/10.1016/j.soilbio.2003.09.008>

683 Schmidt, M.W.I., Knicker, H., Hatcher, P.G., Kögel-Knabner, I., 1997. Improvement of ¹³C and ¹⁵N

684 CPMAS NMR spectra of bulk soils , particle size fractions and organic material by treatment
685 with 10 % hydrofluoric acid. *Eur. J. Soil Sci.* 48, 319–328. <https://doi.org/10.1111/j.1365->
686 2389.1997.tb00552.x

687 Schmidt, M.W.I., Torn, M.S., Abiven, S., Dittmar, T., Guggenberger, G., Janssens, I.A., Kleber, M.,
688 Kögel-Knabner, I., Lehmann, J., Manning, D.A.C., Nannipieri, P., Rasse, D.P., Weiner, S.,
689 Trumbore, S.E., 2011. Persistence of soil organic matter as an ecosystem property. *Nature* 478,
690 49–56. <https://doi.org/10.1038/nature10386>

691 Schuur, E.A.G., Vogel, J.G., Crummer, K.G., Lee, H., Sickman, J.O., Osterkamp, T.E., 2009. The
692 effect of permafrost thaw on old carbon release and net carbon exchange from tundra. *Nature*
693 459, 556–559. <https://doi.org/10.1038/nature08031>

694 Semenchuk, P.R., Christiansen, C.T., Grogan, P., Elberling, B., Cooper, E.J., 2016a. Long-term
695 experimentally deepened snow decreases growing-season respiration in a low- and high-arctic
696 tundra ecosystem. *J. Geophys. Res. Biogeosciences* 121, 1236–1248.
697 <https://doi.org/10.1002/2015JG003251>

698 Semenchuk, P.R., Elberling, B., Amtorp, C., Winkler, J., Rumpf, S., Michelsen, A., Cooper, E.J.,
699 2015. Deeper snow alters soil nutrient availability and leaf nutrient status in high Arctic tundra.
700 *Biogeochemistry* 124, 81–94. <https://doi.org/10.1007/s10533-015-0082-7>

701 Semenchuk, P.R., Elberling, B., Cooper, E.J., 2013. Snow cover and extreme winter warming events
702 control flower abundance of some, but not all species in high arctic svalbard. *Ecol. Evol.* 3,
703 2586–2599. <https://doi.org/10.1002/ece3.648>

704 Semenchuk, P.R., Gillespie, M.A.K.K., Rumpf, S.B., Baggesen, N., Elberling, B., Cooper, E.J.,
705 2016b. High Arctic plant phenology is determined by snowmelt patterns but duration of
706 phenological periods is fixed: An example of periodicity. *Environ. Res. Lett.* 11, 1–12.
707 <https://doi.org/10.1088/1748-9326/11/12/125006>

708 Simpson, M.J., Otto, A., Feng, X., 2008. Comparison of solid-state carbon-13 nuclear magnetic

709 resonance and organic matter biomarkers for assessing soil organic matter degradation. *Soil Sci.*
710 *Soc. Am. J.* 72, 268–276. <https://doi.org/10.2136/sssaj2007.0045>

711 Simpson, M.J., Simpson, A.J., 2012. The Chemical Ecology of Soil Organic Matter Molecular
712 Constituents. *J. Chem. Ecol.* 38, 768–784. <https://doi.org/10.1007/s10886-012-0122-x>

713 Sjögersten, S., Turner, B.L., Mahieu, N., Condon, L.M., Wookey, P.A., 2003. Soil organic matter
714 biochemistry and potential susceptibility to climatic change across the forest-tundra ecotone in
715 the Fennoscandian mountains. *Glob. Chang. Biol.* 9, 759–772. [https://doi.org/10.1046/j.1365-](https://doi.org/10.1046/j.1365-2486.2003.00598.x)
716 [2486.2003.00598.x](https://doi.org/10.1046/j.1365-2486.2003.00598.x)

717 Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y.,
718 Bex, V., Midgley, P.M., 2014. *Climate Change 2013 - The Physical Science Basis, Climate*
719 *Change 2013: The Physical Science Basis.* Cambridge University Press, Cambridge.
720 <https://doi.org/10.1017/CBO9781107415324>

721 Strebel, D., Elberling, B., Morgner, E., Knicker, H.E., Cooper, E.J., 2010. Cold-season soil respiration
722 in response to grazing and warming in High-Arctic Svalbard. *Polar Res.* 29, 46–57.
723 <https://doi.org/10.1111/j.1751-8369.2010.00154.x>

724 Tarnocai, C., Canadell, J.G., Schuur, E.A.G., Kuhry, P., Mazhitova, G., Zimov, S., 2009. Soil organic
725 carbon pools in the northern circumpolar permafrost region. *Global Biogeochem. Cycles* 23, n/a-
726 n/a. <https://doi.org/10.1029/2008GB003327>

727 Trumbore, S., 2009. Radiocarbon and Soil Carbon Dynamics. *Annu. Rev. Earth Planet. Sci.* 37, 47–
728 66. <https://doi.org/10.1146/annurev.earth.36.031207.124300>

729 Wallenstein, M.D., McMahon, S.K., Schimel, J.P., 2009. Seasonal variation in enzyme activities and
730 temperature sensitivities in Arctic tundra soils. *Glob. Chang. Biol.* 15, 1631–1639.
731 <https://doi.org/10.1111/j.1365-2486.2008.01819.x>

732 Webb, E.E., Schuur, E.A.G., Natali, S.M., Oken, K.L., Bracho, R., Krapek, J.P., Risk, D., Nickerson,
733 N.R., 2016. Increased wintertime CO₂ loss as a result of sustained tundra warming 1–17.

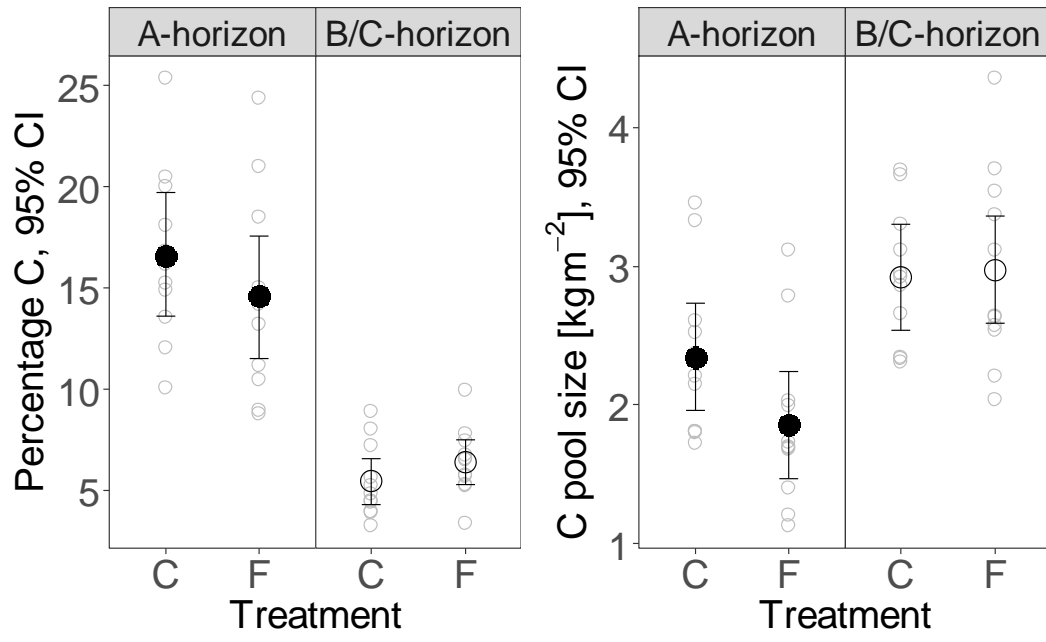
734 <https://doi.org/10.1002/2014JG002795>.Received

735 Welker, J.M., Fahnestock, J.T., Sullivan, P.F., Chimner, R.A., 2005. Leaf mineral nutrition of Arctic

736 plants in response to warming and deeper snow in northern Alaska. *Oikos* 109, 167–177.

737 <https://doi.org/10.1111/j.0030-1299.2005.13264.x>

738



Highlights

- Soil was warmed *in situ* for nine consecutive non-growing seasons (NGS) in Svalbard
- NGS warming depleted soil organic carbon (SOC) pool of the soil's shallow A-horizon
- NGS warming transitioned the A-horizon SOC to an advanced state of decomposition
- The underlying B/C-horizon's SOC pool and state was not affected
- NGS warming mineralizes more C in shallow than in deep soil

1 **Title page**

2 **Title**

3 Soil organic carbon depletion and degradation in surface soil after long-term non-growing
4 season warming in High Arctic Svalbard

5

6 **Author names**

7 Philipp R. Semenchuk^{1,2,3}, Eveline J. Krab^{2,4}, Mattias Hedenström⁵, Carly A. Phillips⁶,
8 Francisco J. Ancin-Murguzur¹, Elisabeth J. Cooper¹

9

10 **Author affiliations**

11 ¹Department of Arctic and Marine Biology, Faculty of Biosciences Fisheries and Economics,
12 UiT-The Arctic University of Norway, N-9037 Tromsø, Norway

13 ²Climate Impacts Research Centre, Department of Ecology and Environmental Science, Umeå
14 University, SE-98107 Abisko, Sweden

15 ³Division of Conservation Biology, Vegetation Ecology and Landscape Ecology, Department of
16 Botany and Biodiversity Research, Vienna University, Rennweg 14, 1030 Vienna

17 ⁴Swedish University of Agricultural Sciences. Department of Soil and Environment, SE-
18 75007, Uppsala, Sweden

19 ⁵Department of Chemistry, Umeå University, SE-901 87 Umeå, Sweden

20 ⁶Odum School of Ecology, University of Georgia, Athens GA 30606, USA

21

22 **Corresponding author**

23 Philipp R. Semenchuk, +4368864979836, philipp.semenchuk@univie.ac.at

24

25 **Highlights**

- 26 • Soil was warmed *in situ* for nine consecutive non-growing seasons (NGS) in Svalbard
- 27 • NGS warming depleted soil organic carbon (SOC) pool of the soil's shallow A-
- 28 horizon
- 29 • NGS warming transitioned the A-horizon SOC to an advanced state of decomposition
- 30 • The underlying B/C-horizon's SOC pool and state was not affected
- 31 • NGS warming mineralizes more C in shallow than in deep soil

32

33 **Abstract**

34 Arctic tundra active-layer soils are at risk of soil organic carbon (SOC) depletion and
35 degradation upon global climate warming because they are in a stage of relatively early
36 decomposition. Non-growing season (NGS) warming is particularly pronounced, and observed
37 increases of CO₂ emissions during experimentally warmed NGSs give concern for great SOC losses
38 to the atmosphere. Here, we used snow fences in Arctic Spitsbergen dwarf shrub tundra to simulate
39 1.86 °C NGS warming for 9 consecutive years, while growing season temperatures remained
40 unchanged. In the snow fence treatment, the 4-11 cm thick A-horizon had a 2% lower SOC
41 concentration and a 0.48 kg C m⁻² smaller pool size than the controls, indicating SOC pool depletion.
42 The snow fence treatment's A-horizon's alkyl/ O-alkyl ratio was also significantly increased,
43 indicating an advance of SOC degradation. The underlying 5 cm of B/C-horizon did not show these
44 effects. Our results support the hypothesis that SOC depletion and degradation are connected to the
45 long-term transience of observed ecosystem respiration (ER) increases upon soil warming. We
46 suggest that the bulk of warming induced ER increases may originate from surface and not deep
47 active layer or permafrost horizons. The observed losses of SOC might be significant for the
48 ecosystem in question, but are in magnitude comparatively small relative to anthropogenic greenhouse

49 gas enrichment of the atmosphere. We conclude that a positive feedback of carbon losses from surface
50 soils of Arctic dwarf shrub tundra to anthropogenic forcing will be minor, but not negligible.

51

52 **Key words**

53 snow fence; NMR; carbon loss; decomposition; anthropogenic C emission feedback; tundra

54

55

56 **1. Introduction**

57 Temperature is one of the main limiting factors for decomposition in Arctic soils (Wallenstein
58 et al., 2009), leading to vast soil organic carbon (SOC) pools exceeding Earth's atmosphere's C stock
59 (Hugelius et al., 2014; Tarnocai et al., 2009). In the face of climate warming, temperature limitations
60 on decomposition processes might be alleviated, putting the biologically degradable part of this SOC
61 pool at risk of being released to the atmosphere (Kleber, 2010; Schmidt et al., 2011). In Arctic
62 regions, climate warming is especially pronounced during the non-growing season (NGS) (Stocker et
63 al., 2014). As the NGS is the predominant part of the year, changes in its climate can have a
64 disproportionally large effect on decomposition processes: relatively low decomposer activities at low
65 temperatures can be offset by the long duration of the NGS and lead to long-term SOC loss. Soil
66 organic C in the Arctic dwarf shrub tundra's active layer consists of a large proportion of readily
67 decomposable compounds (Pautler et al., 2010; Pedersen et al., 2011; Sjögersten et al., 2003), and
68 here we test if long-term *in situ* NGS warming could not only have an effect on its SOC pool size, but
69 also on its bulk chemical composition.

70 Soils from cold dominated ecosystems appear to be in early stages of decomposition and at
71 risk for rapid SOC loss with increasing temperature. Warming may specifically accelerate the
72 degradation of readily decomposable compounds and thereby progress its decomposition stage. As an
73 indicator for the relative degree of a given soil's SOC decomposition stage, the alkyl/O-alkyl ratio has
74 been used (Feng and Simpson, 2008; Pautler et al., 2010; Pedersen et al., 2011; Simpson et al., 2008;
75 Sjögersten et al., 2003). For instance, Sjögersten *et al.* (2003) observed higher alkyl/ O-alkyl ratios in
76 more decomposed forest soils as compared to soils in less decomposed stages from nearby tundra
77 soils in northern Scandinavia for which they attributed to higher decomposer activities in forest soils
78 due to higher soil temperatures in the more sheltered microclimate. Further, an extreme-event induced
79 active layer detachment in northern Canada where sub-surface active layer soil was exposed to air
80 temperatures via soil movements after extensive rain-fall accelerated SOC decomposition and
81 increased its alkyl/ O-alkyl ratio (Pautler et al., 2010). Similar effects can be expected in response to
82 NGS warming through climate change of Arctic dwarf shrub tundra ecosystems.

83 The effects of warming on SOC pool depletion and its alkyl/O-alkyl ratio can be expected to
84 be strongest in surface soil horizons of the active layer for several reasons. Arctic and alpine surface
85 soils are reported to be richer in O-alkyl carbon (C) than deeper soil horizons, i.e. the alkyl/O-alkyl
86 ratio increases with depth, indicating that the stage of decomposition advances with depth, an effect
87 already visible in the upper few cm of soil profiles (Pedersen et al., 2011; Sjögersten et al., 2003).
88 Further, environmental controls in deeper horizons may stabilize otherwise chemically readily
89 decomposable compounds from microbial decomposition by e.g. sorption to the mineral phase
90 (Kawahigashi et al., 2006; Kleber, 2010; Schmidt et al., 2011; Trumbore, 2009), which becomes more
91 prominent in deeper horizons with a higher mineral proportion. Hence, total loss of SOC in deeper
92 horizons upon warming could be lower than in surface near horizons. Increases in ecosystem
93 respiration (ER) by experimental NGS warming in the Arctic (Björkman et al., 2010; Morgner et al.,
94 2010; Nobrega and Grogan, 2007; Schimel et al., 2004; Semenchuk et al., 2016a; Webb et al., 2016)
95 may thus be primarily (but not exclusively) driven by degradation and depletion of SOC substrates
96 from surface rather than deep soil or thawed permafrost (cf. Schuur *et al.*, 2009; Natali *et al.*, 2014).
97 This is supported by recent studies finding significantly higher soil CO₂ fluxes and stronger responses
98 to warming in surface horizons up to 10 cm depth than in deeper soil horizons (Hicks Pries et al.,
99 2017; Lee et al., 2010).

100 In the Arctic, significant ER increases have been shown to respond directly to *in situ* NGS
101 warming in a variety of tundra ecosystems (Björkman et al., 2010; Morgner et al., 2010; Natali et al.,
102 2014; Nobrega and Grogan, 2007; Schimel et al., 2004; Semenchuk et al., 2016a; Webb et al., 2016).
103 Semenchuk et al. (2016a) demonstrated that these effects were followed by decreased growing season
104 ER after eight years of NGS warming in Svalbard dwarf shrub tundra. Similarly, ER responses to
105 experimental continuous *in situ* soil warming are shown to be transient and decrease after a few years
106 of continuous warming in a mid-latitude forest site (Melillo et al., 2002, 2017). One explanation for
107 these effects suggests that soil warming accelerates decomposition processes and alters SOC pool size
108 and composition; soil OC is transformed from a relatively early stage to a later stage of
109 decomposition, and thus provides a less favourable substrate for respiring decomposing organisms

110 (Kirschbaum, 2004; Eliasson et al., 2005; Bradford et al., 2008). Here, we use the opportunity to
111 collect soil and verify that hypothesis within the experiment used by Semenchuk *et al.* (2016a).

112 We test whether nine years of continuous *in situ* NGS warming (average 2 degrees warming
113 within a snow manipulation treatment) of relatively C poor (3-25 % C) High Arctic dwarf shrub
114 tundra surface soil (16 cm depth) (i) reduced SOC pool size and (ii) changed the SOC chemical
115 composition towards a more advanced decomposition stage in a snow fence experiment in
116 Adventdalen, Svalbard. In the same experiment, Semenchuk *et al.* (2016a) found that 8 years of
117 continuous NGS warming and connected increased ER during the NGS lead to decreased growing
118 season ER and suggested that changes in SOC pool size and composition could account for this.

119 Based on these results, we test the following:

120 *1.1 Hypotheses*

- 121 (1) Carbon content is depleted in NGS warmed surface soils, i.e. long-term increased NGS ER
122 decreased the C pool.
- 123 (2) Carbon compound composition is altered in NGS warmed soils. More specifically, we expect
124 the alkyl/ O-alkyl ratio to be higher in NGS warmed soils, i.e. that the relative degree of SOC
125 decomposition is advanced.
- 126 (3) The effects from Hypotheses 1 and 2 are larger in the A-horizon than in the top 5 cm of the
127 underlying, C poorer and mineral richer B/C-horizon, i.e. the combination of environmental
128 conditions and initial SOC composition in the B/C-horizon render the bulk SOC there more
129 resistant to warming.

130

131 **2. Material and Methods**

132 *2.1 Site description (location, soil, vegetation, climate, seasonality)*

133 The study site is on the southern (left) riverbank in Adventdalen, a large valley about 12 km
134 east of Longyearbyen on Spitsbergen, Svalbard (78°10'N, 16°04'E) with continuous permafrost with
135 an active layer thickness/ maximum thaw depth of about 75 to 90 cm at the study site (own data,
136 Figure S2). The cryoturbated gelisol soils at the study site (Semenchuk et al., 2016a) are dominated by
137 fluvial and aeolian sedimentation and consist of a relatively thin and C poor, dark brown A-horizon of
138 about 2-11 cm thickness with about 15-25% C content and an underlying, grey, silty B/C-horizon with
139 about 3-9% C content, which extends to the permafrost table (see Strebel *et al.*, 2010 and own data
140 below).

141 Situated in the bioclimatic subzone C, the vegetation type is classified as Prostrate/
142 hemiprostrate dwarf-shrub tundra (CAVM Team, 2003), dominated by the dwarf shrubs *Cassiope*
143 *tetragona*, *Dryas octopetala* and *Salix polaris*.

144 Average air temperature 2000 to 2011 at Longyearbyen airport, about 20 km west of the study
145 site, during the approximate NGS months October to April were -9 °C and during the approximate
146 growing season months 3.4 °C (www.eklima.no). Average snow depth in the control area was about
147 40 cm (own data, Figure S1).

148 Non-growing season (NGS) in this study is defined as the time of year when the soil surface
149 is frozen, i.e. has a temperature below 0 °C as measured by temperature loggers employed at around 2
150 cm depth (see S3), and ranges in extreme cases from about early October until early May, depending
151 on year, replicate plot and snow fence treatment (see below).

152

153 *2.2 Experimental design*

154 Eleven 1.5m high snow fences were erected in autumn 2006, i.e. 9 years before the present
155 study was conducted. These created winter snow drifts of maximum 1.5 m depth, i.e. about 1.1 m

156 deeper than average ambient snow depth of about 0.4 m (see S1), which declined in depth with
157 distance from the fence. Foci areas behind the fences receiving about 0.7 m snow depth (see S1) were
158 identified for soil sampling, here referred to as “snow fence treatment”. Each snow fence was
159 associated with an unmanipulated control area with ambient snow conditions about 10-15 m away
160 from each fence. The snow drifts’ shapes and extents were very similar each year (own observations)
161 due to the prevailing easterly wind direction along the valley.

162 The snow fence treatment chosen for this study increased the average NGS surface soil
163 temperature (i.e. when soil surface is frozen) by 1.86 °C as determined by continuous hourly
164 temperature measurements (see S3). There was no diurnal variability within the snow fence
165 treatment’s temperature effects, and the warming started a few weeks after the start of the NGS when
166 the snowpack established (see S3). Soil moisture in the snow fence treatment was observed to be
167 slightly increased at the beginning of the growing season only (Semenchuk et al., 2016a), but was
168 neither changed in the A- nor B/C-Horizon at time of soil sampling for this study (see S4).

169 Please note that for the present study we sampled a part of a larger experimental setup.
170 Samples for this study were taken from areas behind snow fences that in other studies from the same
171 site are referred to as “medium” snow or similar, in which snow depth was about 0.7 m, as opposed to
172 “deep” snow, in which snow depth was about 1.5 m (Cooper et al., 2011; Rumpf et al., 2014;
173 Semenchuk et al., 2016a, 2015, 2013). The reason why we did not use the area with the maximum or
174 deep snow increase was to preserve that relatively small area for future research and not disturb it
175 with invasive sampling.

176

177 2.3 Soil sampling procedure

178 On July 23rd 2015, 3 soil cores between 0.5 and 1 m apart were sampled with a soil corer with
179 2 cm diameter (3.14 cm² area) in each plot and treatment (snow fence and control). To exclude
180 potentially confounding vegetation effects on soil parameters in question for this study, sampling

181 locations were chosen where *Salix polaris*, a dominant dwarf shrub across the study site, was the
182 dominant species.

183 The brown A-horizon of each core was separated visually from the underlying grey B/C-
184 horizon in the field, its thickness/ length measured, and each horizon of the core triplets combined in
185 one plastic bag. Before bagging, above ground litter (O-horizon) and plants were coarsely removed
186 from above the A-horizon. The upper 5 cm of the B/C-horizon directly under the A-horizon of each
187 core were sampled and also combined. The maximum sampled A-horizon thickness was 11 cm, i.e.
188 the deepest B/C-horizon sample was between 11 and 16 cm depth, far above the permafrost table
189 which in our study site is at about 75 to 90 cm depth (see S2).

190

191 2.4 Soil treatment prior to chemical analyses

192 After collection in the field, soil samples were kept at 4 °C for five days in Longyearbyen,
193 Svalbard, then transported to Abisko, Sweden, and processed within two days while being kept at 4
194 °C. Remaining above ground plant material, roots and stones of each sample were removed during 3
195 minutes per sample, the remaining soil mass homogenized, weighed and then directly oven dried at 70
196 °C for 48 h. The dried samples were then weighed again and ground in a ball mill to a fine powder
197 and transported to Umea, Sweden, for NMR analyses and aliquots sent to Copenhagen, Denmark, for
198 elemental analysis (see below).

199 Based on previously published material, we expected the total Fe (iron) content of the soil to
200 be relatively high (Ottesen et al., 2010) with simultaneously low C content (Moni et al., 2015; Strebel
201 et al., 2010) leading to a C:Fe ratio < 6 . Such high concentration of Fe-associated paramagnetic
202 compounds has been shown to have a strong adverse effect on the quality of NMR spectra (Schilling
203 and Cooper, 2004; Schmidt et al., 1997). After initial trials, this turned out to be only the case for the
204 B/C-horizon samples, since NMR spectra of the A-horizon were of sufficiently good quality.

205 Therefore, we demineralized the B/C-horizon following the procedure in Baldock *et al.*
206 (2001). We washed the soil with hydrofluoric acid (HF treatment) to remove paramagnetic and

207 mineral compounds and thus increase the C content of the remaining soil leading to improved NMR
208 spectra (Gélinas et al., 2001; Schilling and Cooper, 2004; Schmidt et al., 1997). In short we exposed 1
209 g of each sample for 12 h in 30 mL of 10% HF in 1N HCl solution, removed the supernatant and
210 exposed the remaining pellet to fresh HF/ HCl solution twice more, then washed 3 times with water
211 and freeze dried the pellet and used it for further analyses.

212 In the following, data based on NMR spectroscopy (spectra, integrals, and alkyl/O-alkyl ratio)
213 are from HF-treated B/C-horizon samples, while data based on bulk soil parameters (bulk density, C
214 concentration and pool size) are from untreated B/C-horizons. The A-horizon was always untreated.

215

216 *2.5 Soil C concentrations*

217 To measure soil C concentrations (%), we weighed soils into tin capsules and quantified total
218 C for each sample on an Isoprime isotope ratio mass spectrometer coupled to a Eurovector CN
219 elemental analyser.

220

221 *2.6 Bulk density*

222 Bulk density of dry soil without roots or stones was calculated by dividing the dry weight of
223 each full sample (which consisted of three combined, individual soil cores) with its volume. The
224 samples' volumes were calculated by multiplying the average depth of all three cores with three times
225 the area of the soil corer (9.42 cm²).

226

227 *2.7 Soil C pool size*

228 Soil C pool size per area was calculated by multiplying each full sample's C concentration/
229 fraction with its dry weight, divided by three times the area of the soil corer (9.42 cm²), in unit kg C
230 m⁻².

231

232 *2.8 Solid state ¹³C CP/MAS NMR spectroscopy*

233 Approximately 100 mg of each soil sample was loaded into a 4 mm ZrO₂ rotor with a KEL-F
234 cap. ¹³C Cross-Polarization Magic Angle Spinning (CP-MAS) experiments were performed on a
235 Bruker 500 MHz Avance III spectrometer operating at a ¹³C frequency of 125.75 MHz (Bruker
236 Biospin, Germany). Spinning rate was set to 7 kHz, the contact-time to 1 ms and the sweep-width to
237 250 ppm. 4096 scans were recorded with a relaxation delay of 2 s resulting in an experimental time of
238 approximately 2.3 hours per sample. The FIDs were multiplied with a Gaussian function with LB = -
239 10 Hz and GB = 0.01 prior to fourier transform. All spectra were calibrated using adamantane as an
240 external reference. Processing was performed in Topspin 3.2 (Bruker Biospin, Germany).

241

242 *2.9 Processing of raw NMR spectra/ separation into integrals*

243 The processed spectra were transferred to a matrix with each spectrum as a row and the
244 columns representing the intensity in each of the 4096 data-points that constitutes a CP-MAS
245 spectrum using an in-house Matlab script. Each spectrum was normalized to a constant sum before
246 statistical analysis.

247 Different chemical shift regions of the spectra, containing information about different
248 functional groups (Preston et al., 1997) were also integrated and analysed as a separate data set. The
249 regions were defined as follows: 0-50 ppm (alkyl); 50-60 ppm (methoxy/N-alkyl); 60-93 ppm (O-
250 alkyl); 93-112 ppm (di-O-alkyl); 112-140 ppm (aromatic); 140-165 ppm (O-aromatic) and 165-190
251 ppm (carbonyl). The integrals were also normalized to a constant sum before statistical analysis.

252

253 *2.10 Statistical analyses*

254 All analyses were performed with R version 3.4.3 (R Core Team, 2017) and all packages
255 mentioned below are R packages.

256 The effects of the snow fence treatment on A-horizon thickness, bulk density, C concentration
257 and pool size, integrated regions of the NMR spectra, and alkyl/ O-alkyl ratio were analysed with
258 linear mixed effects models with plots as random effects using the “lme” package (Bates et al., 2015).
259 The significance of the snow fence treatment was tested with a likelihood ratio test between the full
260 model including treatment as predictor variable and the Null model, and a p-value of lower than 0.05
261 was considered to be significant. We then refitted the full models with restricted maximum likelihood
262 estimation and extracted the 95% confidence intervals of the effect sizes and model term estimates
263 with the “multcomp” package (Hothorn et al., 2008), which we present here together with the p-value
264 from the likelihood ratio test. All model fits had no trend in Pearson residuals plotted against fitted
265 values, and residuals were normally distributed (visual examination).

266 To test whether NMR spectra from the control and snow fence treated soils differ, partial least
267 squares discriminant analysis (PLS-DA) was performed with the “caret” package (Kuhn, 2008).
268 Classification was carried out based on the probability of the normalized NMR spectra belonging to
269 either group (snow fence or control), having each spectrum assigned to the class with the highest
270 associated probability. The smallest number of latent variables needed to reach 100% discrimination
271 between snow fence treatment and controls were chosen. The first two loading variables from each
272 model were taken to assess which shift regions were responsible for discrimination.

273 Data from A- and B/C-horizons were analysed separately, because the demineralization
274 procedure of the B/C-horizon could potentially change a number of factors independent of horizon or
275 the experimental *in situ* warming treatment (Dai & Johnson, 1999; Gélinas *et al.*, 2001; Keeler *et al.*,
276 2003; Schilling & Cooper, 2004; Rumpel *et al.*, 2006), making the two horizons incomparable, while
277 qualitative treatment effect comparisons are valid (e.g. effect present or not).

278

279 **3. Results**

280 *3.1 A-horizon thickness*

281 Average A-horizon thickness across the study site's control area was 4.7 cm (95% CI: 3.7 –
282 5.7 cm) and 3.8 cm (95% CI: 2.8 – 4.8 cm) in the snow fence treatment, i.e. 0.9 cm lower than in the
283 control area (95% CI: -1.7 - -0.03 cm; $p = 0.0433$).

284

285 *3.2 Bulk density*

286 Average bulk density across the study site's control area was 0.33 g cm^{-3} (95% CI: 0.24 –
287 0.41 g cm^{-3}) in the A-horizon, and 1.09 g cm^{-3} (95% CI: $0.94 - 1.24 \text{ g cm}^{-3}$) in the upper five cm of the
288 B/C-horizon. The snow fence treatment influenced bulk density of neither A- nor B/C-horizon, i.e. no
289 significant effects were found.

290

291 *3.3 Soil C concentrations (Figure 1 and Table 1)*

292 Average C concentrations across the study site's control area were 16.6% (95% CI: 13.6 -
293 19.7%) in the A-horizon and 5.4% (95% CI: 4.3 - 6.6%) in the upper 5 cm of the untreated B/C-
294 horizon (i.e. the soil aliquot which was not HF treated; Figure 1). Carbon concentrations in the HF
295 treated B/C-horizon soils (i.e. the HF treated soil samples that we will refer to when describing and
296 discussing data from the NMR analysis) were 14.2% (95% CI: 12.1 - 16.3%; data not shown).

297 The snow fence treatment influenced C concentrations of the A-, but not of the B/C-horizon.
298 In the A-horizon, samples from the snow fence treatment had 2% lower (95% CI: -3.7 - -0.5%; $p =$
299 0.021 ; Table 1) C concentrations than samples from controls. In the untreated B/C-horizon, samples
300 from the snow fence plots had no significantly different C concentration (95% CI: -0.1 to 2%; $p =$
301 0.111 ; Table 1). In the HF-treated B/C-horizon, samples from the snow fence plots also had no
302 significantly different C concentration (95% CI: -0.4 to 4.1%; $p = 0.073$; Table 1).

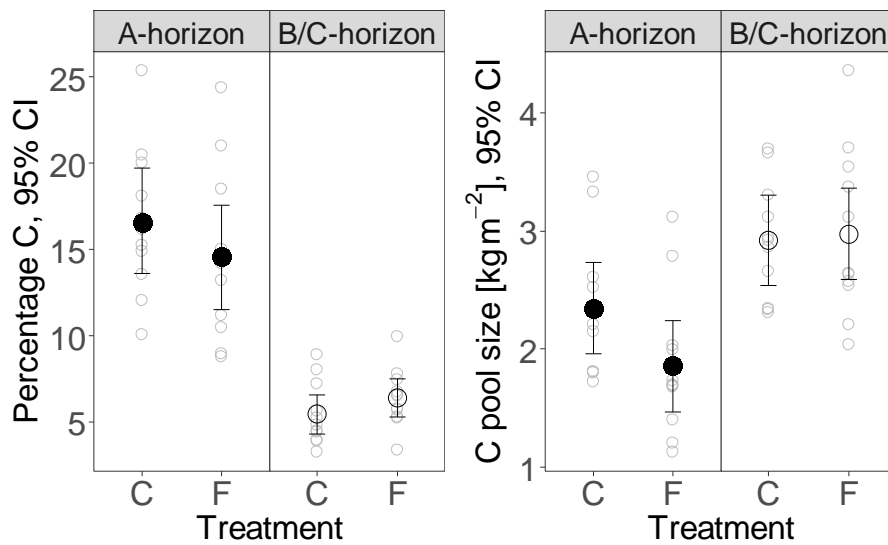
303

304 *3.4 Soil C pools (Figure 1 and Table 1)*

305 Average C pool sizes across the study site's control area were 2.34 kg C m⁻² (95% CI: 1.96 –
306 2.73 kg C m⁻²) in the A-horizon and 2.92 kg C m⁻² (95% CI: 2.54 – 3.3 kg C m⁻²) in the upper five cm
307 of the untreated B/C-horizon (i.e. the soil aliquot which was not HF treated; Figure 1).

308 The snow fence treatment influenced C pools of the A-, but not of the B/C-horizon. In the A-
309 horizon, samples from the snow fence treatment had 0.48 kg C m⁻² lower (95% CI: -0.9 - -0.07 kg C
310 m⁻²; p = 0.032; Table 1) C pool sizes than samples from controls. In the B/C-horizon, samples from
311 the snow fence plots had no significantly different C pool sizes (95% CI: -0.42 to 0.53 kg C m⁻²; p =
312 0.82; Table 1).

313



314

315 *Figure 1: Carbon concentration (percentage C, left) and pool size (kg C m⁻², right) in A- and*
316 *untreated (i.e. non-HF treated) B/C-horizons for each soil sample (raw data, grey open circles) and*
317 *modelled with 95% confidence intervals (black circles). Solid black circles in the A-horizon data*
318 *denote statistically significant differences between treatments (see Table 1); open black circles in the*
319 *B/C-horizon data denote no statistically significant difference between treatments. Treatment C =*

320 Control (ambient conditions, ca. 40 cm snow depth), F = Snow Fence (enhanced snow, ca. 70 cm
 321 snow depth). See Table 1 for statistical tests between treatments, also including the C concentration
 322 model for the HF-treated B/C-horizon.

323

324 **Table 1:** Modelled mean effect sizes and 95% confidence intervals (CI) of the snow fence treatment on
 325 carbon concentration (%C) and carbon pool size (kg C m^{-2}) of A-, untreated B/C-, and HF-treated
 326 B/C-horizons (only for %C). The values show estimated differences of samples from the snow fence
 327 treatment compared to controls based on linear mixed effects models. P-values are based on a
 328 likelihood ratio test between the full and the Null model. Significant effect sizes are in bold ($p < 0.05$
 329 and CI not overlapping zero). Each line shows results of a separate model.

Response	Horizon	Effect size	Lower 95% CI	Upper 95% CI	p-value
%C	A	-2.0563	-3.6623	-0.4503	0.0205
%C	B/C	0.9525	-0.06051	1.96552	0.1113
%C	B/C (HF-treated)	1.8646	-0.4052	4.1344	0.0729
kg C m⁻²	A	-0.48285	-0.89685	-0.06886	0.03152
kg C m ⁻²	B/C	0.05238	-0.42044	0.52520	0.8201

330

331

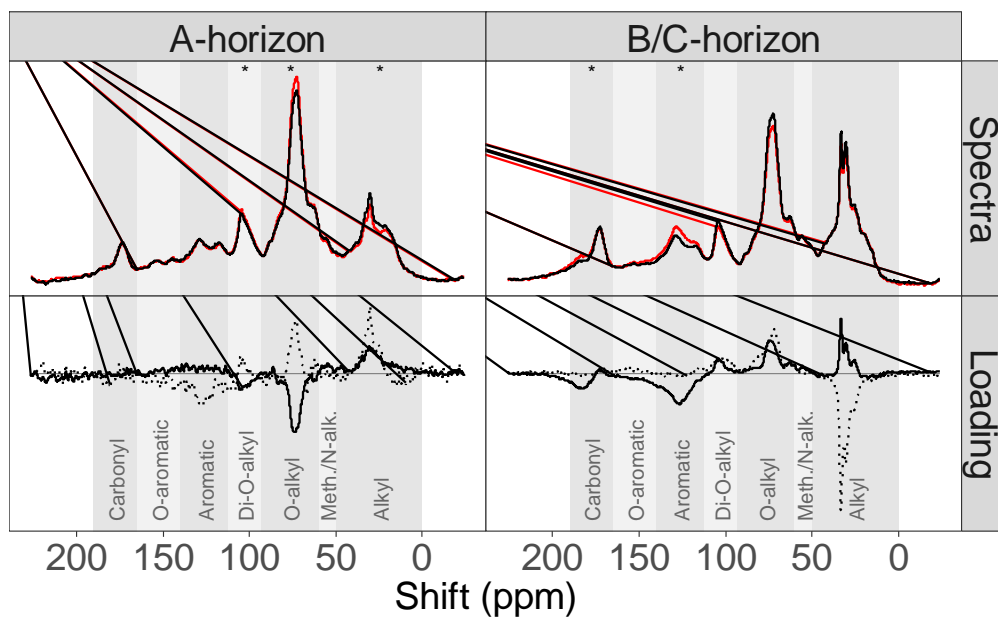
332 3.5 Spectral analysis (Figure 2)

333 PLS-DA models on samples from the snow fence treatment and controls showed a 100%
 334 discrimination using 3 and 5 latent variables for the A- and HF-treated B/C-horizons, respectively,
 335 indicating a significant structural difference between treatments in both horizons. The chemical shift
 336 regions causing the differences were visible in the spectra and the models' first and second loading
 337 components (Figure 2). In other words, regions with the highest model loadings are the regions with
 338 the highest importance to distinguish between the treatments.

339 In the A-horizon, clear differences between snow fence and control soil samples were visible
340 in the O-alkyl and alkyl regions, as well as subtle differences in the aromatic region.

341 In the B/C-horizon, the effect of snow fence treatment differed compared to the A-horizon.
342 Here we observed a decrease in the signal in the carbonyl and aromatic regions as well as an increase
343 in O-alkyl and alkyl signals.

344



345

346 *Figure 2:* Top row: Mean NMR spectra for soil samples from snow fence plots (black line)
347 and controls (red line) in A- (left column) and HF-treated B/C-horizons (right column). Bottom row:
348 first (solid line) and second (dotted line) loading components of the associated PLS-DA models.
349 Vertical grey bars denote integrated chemical shift regions as defined in Table 2, from left to right
350 (with region boundaries): carbonyl (190-165), O-aromatic (165-140), aromatic (140-112), di-O-alkyl
351 (112-93), O-alkyl (93-60), methoxy/ N-alkyl (60-50), alkyl (50-0). Small stars on top of the top row
352 denote where statistically significant differences between treatments were found on individual
353 integrated chemical shift regions (Table 2).

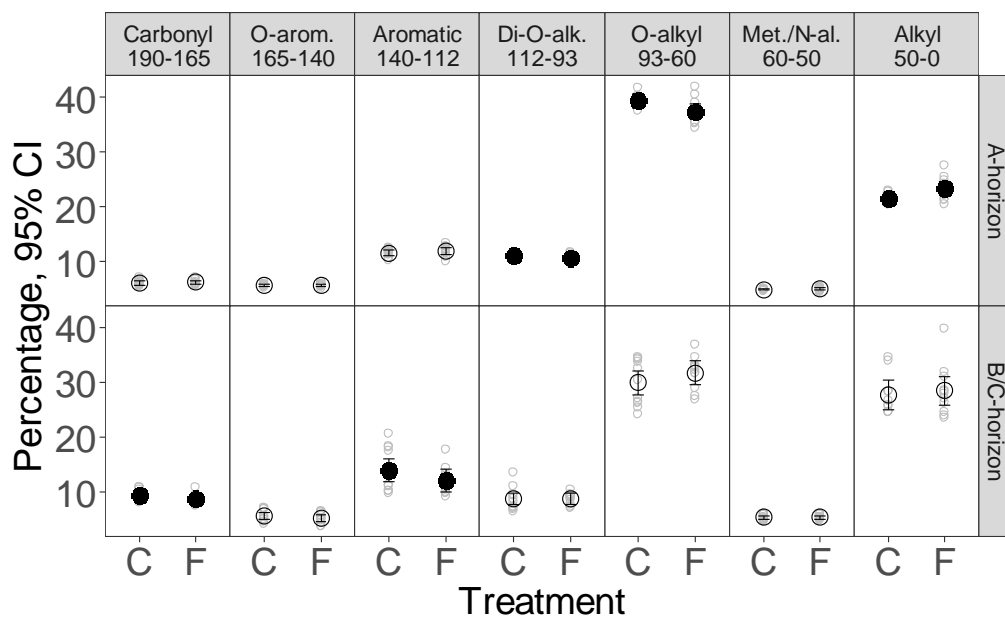
354

355 3.6 Integrated shift regions (Figure 3 and Table 2)

356 In the A-horizon, samples from the snow fence plots had a 2% higher (95% CI: 0.9 – 2.9%; p
 357 = 0.002) concentration of alkyl signals than samples from controls, while the concentrations of di-O-
 358 alkyl and O-alkyl signals were significantly lowered by 0.6% (95% CI: -0.9 - -0.2%; p = 0.007) and
 359 2% (95% CI: -3.3 to -0.7%; p = 0.009), respectively. The other integral regions' contributions to the
 360 A-horizon spectra were not significantly different between the treatments. See Figure 3 and Table 2.

361 In the HF-treated B/C-horizon, samples from the snow fence plots had 2% (95% CI: -3.7 - -
 362 0.2; p = 0.035) and 0.7% (95% CI: -1.3 - -0.1%; p = 0.027) lower concentrations of aromatic and
 363 carbonyl signals, respectively, than samples from controls, while the O-alkyl signals had a non-
 364 significant trend towards 1.8% (95% CI: -0.9 – 4.6%; p = 0.186) concentrations. The other integral
 365 regions' contributions to the B/C-horizon spectra were not significantly different between the
 366 treatments. See Figure 3 and Table 2.

367



368

369 **Figure 3:** Relative contribution of integrated NMR spectra signal regions in A- and HF-
 370 treated B/C-horizons for each soil sample (raw data, grey open circles) and modelled with 95%

371 confidence intervals (black circles). Solid black circles denote statistically significant differences
 372 between treatments; open black circles denote no statistically significant difference between
 373 treatments. Treatment C = Control, F = Snow Fence. See Table 2 for statistical tests between
 374 treatments.

375

376 Table 2: Modelled mean effect sizes and 95% confidence intervals (CI) of the snow fence treatment on
 377 relative contribution of integrated NMR spectra signal regions and alkyl/O-alkyl ratio of A- and HF-
 378 treated B/C-horizon samples. The values show estimated differences of samples from the snow fence
 379 plots compared to controls based on linear mixed effects models. Region denotes the ppm range
 380 chosen to define each integral. P-values are based on a likelihood ratio test between the full and the
 381 Null model, and cases where the full model is statistically significantly better than the Null model with
 382 $p < 0.05$ are in bold. Each line shows results of a separate model.

<i>Horizon</i>	<i>Integral</i>	<i>Region</i>	<i>Effect size</i>	<i>Lower 95 %CI</i>	<i>Upper 95% CI</i>	<i>p-value</i>
A	Carbonyl	190-165	0.000683	-0.0009593	0.0023253	0.3987
A	O-aromatic	165-140	0.0001435	-0.00281	0.003097	0.92
A	Aromatic	140-112	0.003705	-0.001253	0.008663	0.1437
A	Di-O-alkyl	112-93	-0.005542	-0.009067	-0.002018	0.007272
A	O-alkyl	93-60	-0.019813	-0.032911	-0.006714	0.009047
A	Methoxy/ N-alkyl	60-50	0.001589	-0.0006453	0.0038233	0.1522
A	Alkyl	50-0	0.019235	0.009103	0.029367	0.002273
A	alkyl/ O-alkyl	ratio	0.085	0.03685	0.13316	0.003633
B/C	Carbonyl	190-165	-0.006956	-0.012728	-0.001184	0.02721
B/C	O-aromatic	165-140	-0.0050147	-0.0104986	0.0004692	0.08004
B/C	Aromatic	140-112	-0.019838	-0.037232	-0.002445	0.03473
B/C	Di-O-alkyl	112-93	0.0006397	-0.0134508	0.0147301	0.9257
B/C	O-alkyl	93-60	0.018268	-0.009001	0.045538	0.1859

B/C	<i>Methoxy/ N-alkyl</i>	<i>60-50</i>	0.0007683	-0.0028917	0.0044283	0.6674
B/C	<i>Alkyl</i>	<i>50-0</i>	0.006997	-0.011176	0.025171	0.4351
B/C	<i>alkyl/ O-alkyl</i>	<i>ratio</i>	-0.03617	-0.17731	0.10497	0.6006

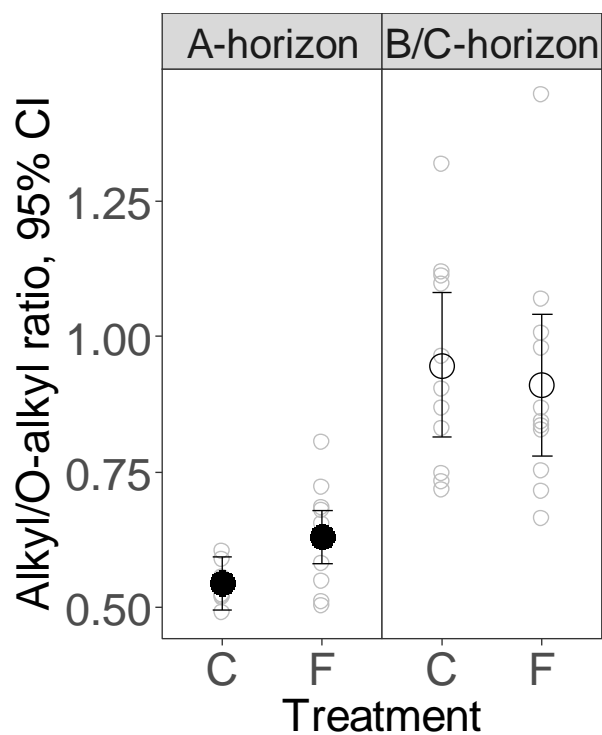
383

384 *3.7 Alkyl/O-alkyl ratio (Figure 4 and Table 2)*

385 Average alkyl/O-alkyl ratios across the study site's control area were 0.55 (95% CI: 0.5 -
386 0.59) in the A-horizon and 0.95 (95% CI: 0.82 - 1.1) in the HF-treated B/C-horizon. See Figure 4.

387 The snow fence treatment influenced the alkyl/O-alkyl ratio of the A-, but not of the B/C-
388 horizon. In the A-horizon, samples from the snow fence plots had a 0.085 higher (95% CI: 0.037 -
389 0.133; $p = 0.004$) alkyl/O-alkyl ratio than controls. In the B/C-horizon, samples from the snow fence
390 plots had no significantly different alkyl/O-alkyl ratio compared to controls (-0.036; 95% CI: -0.18 -
391 0.1; $p = 0.6$).

392



393

394 *Figure 4: Alkyl/O-alkyl ratios in A- and HF-treated B/C-horizons for each soil sample (raw*
 395 *data, grey open circles) and modelled with 95% confidence intervals (black circles). Solid black*
 396 *circles denote statistically significant differences between treatments (only A-horizon); open black*
 397 *circles denote no statistically significant difference between treatments (only B/C-horizon). Treatment*
 398 *C = Control, F = Snow Fence. See Table 2 for statistical tests between treatments.*

399

400 4. Discussion

401 We found that the A-horizon, i.e. the study site's C-richer upper soil layer (average 16.6% C
402 and 4.7 cm thickness), of high Arctic tundra plots which were exposed to 9 years of experimental *in*
403 *situ* NGS warming via snow fences, on average had a 2% lower C concentration, contained 0.48 kg
404 less C m⁻² (hypothesis 1) and was in a more advanced stage of decomposition (as indicated by a 0.09
405 higher alkyl/ O-alkyl ratio, hypothesis 2) compared to unmanipulated control plots. These effects were
406 not observed in the first 5 cm of the underlying, C poorer B/C-horizon (average 5.4% C, hypothesis
407 3). Below we will discuss potential causes, effects and implications of our findings.

408

409 4.1 SOC loss through NGS warming only in A-horizon, not B/C-horizon (hypotheses 1 & 3)

410 The smaller SOC pool in the snow fence plots' A-Horizon compared to the controls is
411 possibly caused by a temperature induced increase of decomposition and subsequent loss of SOC
412 during the nine preceding warmed NGSs. Non-growing season ER was higher in snow fence
413 treatments in this (Morgner et al., 2010; Semenchuk et al., 2016a) and other Arctic sites (Natali et al.,
414 2014; Nobrega and Grogan, 2007; Schimel et al., 2004; Webb et al., 2016). Further, soil nutrient
415 concentrations were higher in a deeper snow fence treatment with stronger temperature increase in
416 this (Semenchuk *et al.*, 2015; Mörsdorf *et al.*, submitted) and another Arctic site (Schimel et al.,
417 2004), and *Salix polaris*' (and other species') leaf nitrogen content was higher in this (Mörsdorf *et al.*,
418 submitted) and another Arctic site (Welker et al., 2005), suggesting a stabilization of surplus nutrients
419 from the soil. In sum, these findings strongly indicate increased activities of decomposing organisms
420 during warmed NGSs in a variety of Arctic tundra ecosystems, which in the long run possibly lead to
421 more mineralization of SOC than could be replenished by plants during the growing season through
422 e.g. plant litter or root exudate inputs (Bradford et al., 2008; Eliasson et al., 2005; Kirschbaum, 2004).

423 Whether this SOC depletion is a transient phenomenon driven by fast cycling SOC pools as
424 observed in e.g. permafrost soil incubations (e.g. Moni *et al.*, 2015) or plant litter mass loss studies
425 (e.g. Demarco *et al.*, 2014) is uncertain. The observed decrease of growing season ER (Semenchuk et

426 al., 2016a) and degradation of SOC to advanced stages of decomposition indicate that, under current
427 conditions, further depletion might come to a halt. However, as suggested by Melillo et al. (2017), it
428 is possible that the microbial communities in the snow fence plots are undergoing a phase of
429 reorganization as response to the altered SOC pool size and quality, soil nutrient status, and
430 temperature conditions. Once acclimated, further depletion and degradation of the remaining SOC
431 pool could continue. Since these non-linear and possibly interactive responses cannot necessarily be
432 generalized across spatial and temporal boundaries, further large-scale and long-term studies (e.g.
433 time series) are warranted to enable us to project the presented findings on possible future climate
434 scenarios.

435 Whether the findings of SOC depletion from this study are context specific can only be
436 speculated without further long-term and orchestrated biome-wide studies, but a few available long-
437 term studies (>8 years warming) do indicate context specificity. The growing season ER reduction
438 after long-term NGS warming is also reported from Daring Lake, a low-Arctic site (Semenchuk et al.,
439 2016a), and both reduction of long-term effects on ER and depletion of easily degradable SOC after
440 long-term warming are reported from the Harvard Forest, a deciduous hard-wood forest (Bradford et
441 al., 2008; Melillo et al., 2017). However, long-term warming did not result in reductions of growing
442 season ER nor decline of NGS ER effects from a sub-Arctic peat site in Abisko (Dorrepaal et al.,
443 2009). All mentioned studies are from different ecosystems, and taken together it seems that context
444 specificity is given. Which factors are responsible for the contrasting results between these studies is
445 unclear and motivates for further studies. However, the high C and low mineral content in the Abisko
446 peat site might play important roles in determining long-term effects of warming on SOC pool size.

447 Vegetation related variables can partly be ruled out as explanatory factors for SOC pool size
448 in this study. Firstly, soil was exclusively sampled under *Salix polaris*, which excludes potential
449 confounding effects on SOC properties by sampling under different species. Second, neither species
450 composition (Cooper *et al.*, submitted) nor *Salix polaris*' growth (Rumpf et al., 2014) in the snow
451 fence treatment used here were significantly different from the controls. However, the aforementioned
452 higher leaf nitrogen content in the snow fence plots (Mörsdorf *et al.*, submitted) might be forewarning

453 increased performance of *Salix polaris* in the long run. Conversely, results from the same experiment
454 but from a two times deeper snow fence treatment than used here (150 cm vs. 70 cm snow depth)
455 found significantly less seasonal growth (Rumpf et al., 2014) and lower abundance of *Salix polaris*
456 and most other vascular plant species (Cooper *et al.*, submitted). Whether these changes, caused by a
457 more extreme snow depth increase, are representing the future state of the snow fence treatment used
458 here is questionable. While the NGS warming and connected biogeochemical effects are stronger in
459 the deeper snow fence treatment (Semenchuk et al., 2015; Mörsdorf et al., submitted), the negative
460 effects on the vegetation there are possibly caused by an average 7 days later snow melt compared to
461 the snow fence treatment used here (Semenchuk et al., 2016b, 2013) rather than by biogeochemical
462 cascading effects.

463 NGS warming significantly lowered SOC concentrations in the A-horizon but not in the
464 directly underlying 5 cm of B/C-horizon, a result similar to the findings of Melillo *et al.* (2017). We
465 assume that B/C-horizon properties stabilize SOC, such that it cannot be fully mineralized or accessed
466 by decomposing organisms. In our case especially sorption to mineral particles (Kawahigashi et al.,
467 2006; Kleber, 2010; Schmidt et al., 2011; Trumbore, 2009), but also other environmental controls
468 such as smaller soil pore size (as indicated by the B/C-horizon's higher bulk density) and particle
469 aggregation might have rendered parts of its SOC pool inaccessible to decomposing organisms
470 (Conant et al., 2011; Ekschmitt et al., 2008). Additionally, lower root density (own observation and
471 Strebel *et al.* (2010)) and possibly different species composition of the B/C-horizon's rhizosphere
472 (Iversen et al., 2015) could be responsible for the initially low SOC concentrations found in the B/C-
473 horizon. This low SOC concentration in the deeper horizons might create microhabitats unsuitable for
474 a bulk population of decomposing organisms capable of mineralizing significant fractions of the
475 existing SOC pool (Ekschmitt et al., 2008; Schmidt et al., 2011).

476 Leaching of dissolved C from the A-horizon by additional melt water production from the
477 extra snow pack is conceivable. However, three qualitative observations lead to the assumption that
478 this effect may be minor. First, the total melt water runoff from the large area above the experimental
479 site by far outweighs the amounts produced by the additional snowpack. This runoff is unchanged by

480 the experimental snow addition and hence the additional melt water might not have a significant
481 impact. Second, a large part of the melt water produced by the deepened snow packs after the
482 surrounding snow is gone seems to get diverted by the ice layer at the bottom of the snow pack
483 (Semenchuk et al., 2013) and may not reach the soil until it reaches the edges of the plots. Third, the
484 soil in this study site is frozen solid until a few days after melt out and any melt water flowing over it
485 may only touch the vegetation and soil surface. All three points are based on own qualitative
486 observations only and yield opportunities for further studies on potential artefacts of snow fences as
487 experimental treatments in ecological studies.

488

489 *4.2 Implications of SOC loss on ER and atmosphere*

490 The loss of SOC from the A-horizon possibly explains the decline of growing season ER as
491 reported by Semenchuk *et al.* (2016a) in the same experimental setup. Soil OC availability as
492 substrate for heterotrophic organisms may be depleted by increased consumption below a threshold
493 where steady state respiration can be maintained (Bradford et al., 2008; Eliasson et al., 2005;
494 Kirschbaum, 2004). This phenomenon could be partly confounded with the aforementioned higher
495 soil nutrient availability in NGS warmed plots (Schimel *et al.*, 2004; Semenchuk *et al.*, 2015;
496 Mörsdorf *et al.*, submitted) resulting in ER responses independent of SOC loss. For instance, reduced
497 nutrient limitations could reduce plant roots' foraging for nutrients and thereby reduce root exudate
498 production and connected decomposer stimulation leading to some kind of "negative priming" effects
499 (cf. Fontaine *et al.*, 2004; Hartley *et al.*, 2012). More studies to disentangle the possible mechanisms
500 behind this are needed.

501 Our observation that SOC was only lost from the A-horizon (which with an average thickness
502 of 4.7 cm lies well above the permafrost table at about 90 cm depth) allows the speculation that the
503 increase of ER during warmed NGSs in this study site (Morgner et al., 2010; Semenchuk et al.,
504 2016a) might primarily originate from the A-horizon, too. If this holds true, then the fact that growing
505 season ER was reduced as a response to NGS warming (Semenchuk et al., 2016a) also suggests that

506 the growing season bulk ER originates from surface horizons, as has been shown in studies measuring
507 CO₂ fluxes in different soil depths (Hicks Pries et al., 2017; Lee et al., 2010). While understudied to
508 date, the implications of these thoughts are of importance to determine the relative contribution of
509 CO₂ emissions from surface and deep soils, such as thawing permafrost. With surface horizons
510 potentially being the primary source of ER derived CO₂ emissions from tundra ecosystems, then
511 warming induced increases of C loss from thawing permafrost (Moni et al., 2015; Schuur et al., 2009)
512 might be relatively minor compared to CO₂ emissions from surface soils during timescales relevant
513 for the ongoing anthropogenic forcing (Stocker et al., 2014). In fact, Hicks Pries *et al.* (2017) found
514 that about 80% of all soil respiration and about 90% of respiration response to 4 °C warming occurred
515 in the upper 30 cm of temperate forest soil, and Lee *et al.* (2010) found that the upper 10 cm of upland
516 tundra soil had ten times higher CO₂ fluxes than the underlying 20 cm horizon. In sum, these findings
517 point towards a predominance of the more exposed surface soils as C sources to the atmosphere and
518 warrant further studies.

519 A back of the envelope calculation scaling up the effect size from the C pool model to the
520 total global area of Prostrate/hemiprostrate dwarf-shrub tundra (i.e. the vegetation type studied here,
521 worldwide covering 140000 km², CAVM Team, (2003)) estimates a potential total loss of 67.6 Mt C
522 or 248.1 Mt CO₂ equivalent upon global NGS warming from the 4.7 cm thick A-horizon only. This is
523 in magnitude comparable with the annual CO₂ emissions of, for instance, Florida (Desai et al., 2017)
524 or Egypt (EDGARv4.3.2, 2016), but with 0.69% an insignificant contribution to the still rising annual
525 global anthropogenic CO₂ emissions of 36062 Mt in 2015 (EDGARv4.3.2, 2016).

526

527 *4.3 Shifts in relative abundance of carbon compounds (hypothesis 2)*

528 Carbon compound composition was clearly different in the snow fence treatment from the
529 controls in both A- and B/C-horizons. In the A-horizon, the differences were mainly in the alkyl and
530 O-alkyl groups leading to a higher alkyl/ O-alkyl ratio in the snow fence treatment. This indicates that
531 NGS warming indeed transformed the A-horizon to a more advanced stage of decomposition (Feng

532 and Simpson, 2008; Pautler et al., 2010; Pedersen et al., 2011; Simpson et al., 2008; Sjögersten et al.,
533 2003). Together with the above discussed phenomenon of SOC loss, this supports the idea that the
534 balance between SOC consumption and replenishment was significantly disturbed and could explain
535 the observed decrease of growing-season ER (Semenchuk et al., 2016a).

536 In the B/C-horizon, the main changes were observed in the aromatic regions, indicating a
537 decrease of amino-acids (Simpson and Simpson, 2012). These compounds were possibly transformed
538 to O-alkyl compounds, even though the increase of that group of compounds was not statistically
539 significant (compare with Table 2). The reason for this discrepancy between A- and B/C-horizons is
540 out of the scope of this study, however, may be rooted in selective sorption of O-alkyl compounds to
541 mineral particles, forcing decomposing organisms to use aromatic compounds as substrates.

542

543 *4.4 Conclusions*

544 We found that 9 years of ca. 2 °C NGS warming reduced the A-horizon's C pool and
545 degraded it to a more advanced stage of decomposition. Our results support the hypothesis that the
546 transient nature of increased ER by soil warming as observed elsewhere is connected to excessive and
547 selective consumption of SOC leading to a depletion of favourable substrates for decomposers. We
548 further suggest that the NGS warming induced increases of ER in our study site primarily originate in
549 the relatively shallow A-horizon and dominate total CO₂ emissions compared to deep soil or thawing
550 permafrost. The estimated absolute expected loss over the whole global area of this ecosystem,
551 however, is dwarfed by comparison with still rising global anthropogenic greenhouse gas emissions.
552 We conclude that a positive feedback from surface soils of circumarctic dwarf shrub tundra
553 communities to anthropogenic forcing might be minor during the timescales covered in this study, but
554 due to their dynamic nature deserve a place in modelling studies.

555

556 **5. Acknowledgements**

557 Funding for NMR analyses came from ARCUM to Philipp Semenchuk, from the Norwegian
558 Research Council ('SnoEco' project, number 230970) and the FRAM Centre Terrestrial Flagship
559 ('Arctic GSL' project) to EJC, and an ARCUM travel grant to EK. Thanks to Gesche Blume-Werry
560 and Signe Lett for improvements on earlier versions of this manuscript. Raw data for this manuscript
561 is available in the supplementary section.

562

563 **6. References**

564 Bates, D., Maechler, M., Bolker, B., Walker, S., 2015. Fitting Linear Mixed-Effects Models Using
565 lme4. *J. Stat. Softw.* 67, 1–48. <https://doi.org/10.18637/jss.v067.i01>

566 Björkman, M.P., Morgner, E., Cooper, E.J., Elberling, B., Klemetsson, L., Björk, R.G., 2010.
567 Winter carbon dioxide effluxes from arctic ecosystems: An overview and comparison of
568 methodologies. *Global Biogeochem. Cycles* 24, 1–10. <https://doi.org/10.1029/2009GB003667>

569 Bradford, M.A., Davies, C.A., Frey, S.D., Maddox, T.R., Melillo, J.M., Mohan, J.E., Reynolds, J.F.,
570 Treseder, K.K., Wallenstein, M.D., 2008. Thermal adaptation of soil microbial respiration to
571 elevated temperature. *Ecol. Lett.* 11, 1316–27. [https://doi.org/10.1111/j.1461-](https://doi.org/10.1111/j.1461-0248.2008.01251.x)
572 [0248.2008.01251.x](https://doi.org/10.1111/j.1461-0248.2008.01251.x)

573 CAVM Team, 2003. Circumpolar Arctic Vegetation Map. (1:7,500,000 scale). Conservation of Arctic
574 Flora and Fauna (CAFF) Map No. 1. U.S. Fish and Wildlife Service, Anchorage, Alaska.

575 Conant, R.T., Ryan, M.G., Ågren, G.I., Birge, H.E., Davidson, E.A., Eliasson, P.E., Evans, S.E., Frey,
576 S.D., Giardina, C.P., Hopkins, F.M., Hyvönen, R., Kirschbaum, M.U.F., Lavelle, J.M., Leifeld,
577 J., Parton, W.J., Megan Steinweg, J., Wallenstein, M.D., Martin Wetterstedt, J.Å., Bradford,
578 M.A., 2011. Temperature and soil organic matter decomposition rates - synthesis of current
579 knowledge and a way forward. *Glob. Chang. Biol.* 17, 3392–3404.
580 <https://doi.org/10.1111/j.1365-2486.2011.02496.x>

581 Cooper, E.J., Dullinger, S., Semenchuk, P., 2011. Late snowmelt delays plant development and results

582 in lower reproductive success in the High Arctic. *Plant Sci.* 180, 157–167.
583 <https://doi.org/10.1016/j.plantsci.2010.09.005>

584 Dai, K.H., Johnson, C.E., 1999. Applicability of solid-state ^{13}C CP r MAS NMR analysis in
585 Spodosols : chemical removal of magnetic materials. *Geoderma* 93, 289–310.

586 Demarco, J., Mack, M.C., Bret-Harte, M.S., 2014. Effects of arctic shrub expansion on biophysical vs.
587 biogeochemical drivers of litter decomposition. *Ecology* 95, 1861–1875.
588 <https://doi.org/10.1890/13-2221.1>

589 Desai, M., Harvey, R.P., EPA, 2017. Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-
590 2015. *Fed. Regist.* 82, 10767. [https://doi.org/EPA 430-R-13-001](https://doi.org/EPA%20430-R-13-001)

591 Dorrepaal, E., Toet, S., van Logtestijn, R.S.P., Swart, E., van de Weg, M.J., Callaghan, T. V., Aerts,
592 R., 2009. Carbon respiration from subsurface peat accelerated by climate warming in the
593 subarctic. *Nature* 460, 616–619. <https://doi.org/10.1038/nature08216>

594 EDGARv4.3.2, 2016. Emission Database for Global Atmospheric Research (EDGAR), release
595 version 4.3.2.

596 Ekschmitt, K., Kandeler, E., Poll, C., Brune, A., Buscot, F., Friedrich, M., Gleixner, G., Hartmann,
597 A., Kästner, M., Marhan, S., Miltner, A., Scheu, S., Wolters, V., 2008. Soil-carbon preservation
598 through habitat constraints and biological limitations on decomposer activity. *J. Plant Nutr. Soil*
599 *Sci.* 171, 27–35. <https://doi.org/10.1002/jpln.200700051>

600 Eliasson, P.E., McMurtrie, R.E., Pepper, D.A., Strömngren, M., Linder, S., Ågren, G.I., 2005. The
601 response of heterotrophic CO₂ flux to soil warming. *Glob. Chang. Biol.* 11, 167–181.
602 <https://doi.org/10.1111/j.1365-2486.2004.00878.x>

603 Feng, X., Simpson, M.J., 2008. Temperature responses of individual soil organic matter components.
604 *J. Geophys. Res. Biogeosciences* 113, 1–14. <https://doi.org/10.1029/2008JG000743>

605 Fontaine, S., Bardoux, G., Abbadie, L., Mariotti, A., 2004. Carbon input to soil may decrease soil
606 carbon content. *Ecol. Lett.* 7, 314–320. <https://doi.org/10.1111/j.1461-0248.2004.00579.x>

Formatted: German (Austria)

- 607 Gélinas, Y., Baldock, J.A., Hedges, J.I., 2001. Demineralization of marine and freshwater sediments
608 for CP / MAS 13 C NMR analysis. *Org. Geochem.* 32, 677–693.
- 609 Hartley, I.P., Garnett, M., Sommerkorn, M., Hopkins, D.W., Fletcher, B.J., Sloan, V.L., Phoenix,
610 G.K., Wookey, P. a., 2012. A potential loss of carbon associated with greater plant growth in the
611 European Arctic. *Nat. Clim. Chang.* 2, 875–879. <https://doi.org/10.1038/nclimate1575>
- 612 Hicks Pries, C.E., Castanha, C., Porras, R.C., Torn, M.S., 2017. The whole-soil carbon flux in
613 response to warming. *Science* (80-.). 1319, 1–9. <https://doi.org/10.1126/science.aal1319>
- 614 Hothorn, T., Bretz, F., Westfall, P., 2008. Simultaneous Inference in General Parametric Models.
615 *Biometrical J.* 50, 346–363.
- 616 Hugelius, G., Strauss, J., Zubrzycki, S., Harden, J.W., Schuur, E.A.G., Ping, C.L., Schirmermeister, L.,
617 Grosse, G., Michaelson, G.J., Koven, C.D., O'Donnell, J.A., Elberling, B., Mishra, U., Camill,
618 P., Yu, Z., Palmtag, J., Kuhry, P., 2014. Estimated stocks of circumpolar permafrost carbon with
619 quantified uncertainty ranges and identified data gaps. *Biogeosciences* 11, 6573–6593.
620 <https://doi.org/10.5194/bg-11-6573-2014>
- 621 Iversen, C.M., Sloan, V.L., Sullivan, P.F., Euskirchen, E.S., McGuire, A.D., Norby, R.J., Walker,
622 A.P., Warren, J.M., Wullschleger, S.D., 2015. The unseen iceberg: Plant roots in arctic tundra.
623 *New Phytol.* 205, 34–58. <https://doi.org/10.1111/nph.13003>
- 624 Kawahigashi, M., Kaiser, K., Rodionov, A., Guggenberger, G., 2006. Sorption of dissolved organic
625 matter by mineral soils of the Siberian forest tundra. *Glob. Chang. Biol.* 12, 1868–1877.
626 <https://doi.org/10.1111/j.1365-2486.2006.01203.x>
- 627 Keeler, C., Keeler, C., Maciel, G.E., Maciel, G.E., 2003. Quantitation in the solid-state 13C NMR
628 analysis of soil and organic soil fractions. *Anal. Chem.* 75, 2421–32.
- 629 Kirschbaum, M.U.F., 2004. Soil respiration under prolonged soil warming: are rate reductions caused
630 by acclimation or substrate loss? *Glob. Chang. Biol.* 10, 1870–1877.
631 <https://doi.org/10.1111/j.1365-2486.2004.00852.x>

Formatted: German (Austria)

Formatted: German (Austria)

Formatted: German (Austria)

- 632 Kleber, M., 2010. What is recalcitrant soil organic matter? *Environ. Chem.* 7, 320–332.
633 <https://doi.org/10.1071/EN10006>
- 634 Kuhn, M., 2008. Building Predictive Models in R Using the caret Package. *J. Stat. Softw.* 28, 1–26.
635 <https://doi.org/10.1053/j.sodo.2009.03.002>
- 636 Lee, H., Schuur, E.A.G., Vogel, J.G., 2010. Soil CO₂ production in upland tundra where permafrost
637 is thawing. *J. Geophys. Res.* 115, G01009. <https://doi.org/10.1029/2008JG000906>
- 638 Melillo, J.M., Frey, S.D., DeAngelis, K.M., Werner, W.J., Bernard, M.J., Bowles, F.P., Pold, G.,
639 Knorr, M.A., Grandy, A.S., 2017. Long-term pattern and magnitude of soil carbon feedback to
640 the climate system in a warming world. *Science* (80-.). 358, 101–105.
641 <https://doi.org/10.1126/science.aan2874>
- 642 Moni, C., Lerch, T.Z., Knoth de Zarruk, K., Strand, L.T., Forte, C., Certini, G., Rasse, D.P., 2015.
643 Temperature response of soil organic matter mineralisation in arctic soil profiles. *Soil Biol.*
644 *Biochem.* 88, 236–246. <https://doi.org/10.1016/j.soilbio.2015.05.024>
- 645 Morgner, E., Elberling, B., Strebel, D., Cooper, E.J., 2010. The importance of winter in annual
646 ecosystem respiration in the High Arctic: effects of snow depth in two vegetation types. *Polar*
647 *Res.* 29, 58–74. <https://doi.org/10.1111/j.1751-8369.2010.00151.x>
- 648 Natali, S.M., Schuur, E.A.G., Webb, E.E., Pries, C.E.H., Crummer, K.G., 2014. Permafrost
649 degradation stimulates carbon loss from experimentally warmed tundra. *Ecology* 95, 602–608.
650 <https://doi.org/10.1890/13-0602.1>
- 651 Nobrega, S., Grogan, P., 2007. Deeper snow enhances winter respiration from both plant-associated
652 and bulk soil carbon pools in birch hummock tundra. *Ecosystems* 10, 419–431.
653 <https://doi.org/10.1007/s10021-007-9033-z>
- 654 Ottesen, R., Bogen, J., Finne, T., Andersson, M., Dallmann, W., Eggen, O., Jartun, M., Lundkvist, Q.,
655 Ranestad Pedersen, H., Volden, T., 2010. Geochemical atlas of Norway - Part 2: Geochemical
656 atlas of Spitsbergen. Geological Survey of Norway, Trondheim.

Formatted: German (Austria)

Formatted: German (Austria)

657 Pautler, B.G., Simpson, A.J., McNally, D.J., Lamoureux, S.F., Simpson, M.J., 2010. Arctic Permafrost
658 Active Layer Detachments Stimulate Microbial Activity and Degradation of Soil Organic
659 Matter. *Environ. Sci. Technol.* 44, 4076–4082. <https://doi.org/10.1021/es903685j>

660 Pedersen, J.A., Simpson, M.A., Bockheim, J.G., Kumar, K., 2011. Characterization of soil organic
661 carbon in drained thaw-lake basins of Arctic Alaska using NMR and FTIR photoacoustic
662 spectroscopy. *Org. Geochem.* 42, 947–954. <https://doi.org/10.1016/j.orggeochem.2011.04.003>

663 Preston, C.M., Trofymow, J.A., Sayer, B.G., Niu, J.N., 1997. C-13 nuclear magnetic resonance
664 spectroscopy with cross-polarization and magic-angle spinning investigation of the proximate-
665 analysis fractions used to assess litter quality in decomposition studies. *Can. J. Bot. Can. Bot.*
666 75, 1601–1613. <https://doi.org/10.1139/b97-872>

667 R Core Team, 2017. R: A Language and Environment for Statistical Computing. R Foundation for
668 Statistical Computing, Vienna, Austria.

669 Rumpel, C., Rabia, N., Derenne, S., Quenea, K., Eusterhues, K., Kögel-Knabner, I., Mariotti, A.,
670 2006. Alteration of soil organic matter following treatment with hydrofluoric acid (HF). *Org.*
671 *Geochem.* 37, 1437–1451. <https://doi.org/10.1016/j.orggeochem.2006.07.001>

672 Rumpf, S.B., Semenchuk, P.R., Dullinger, S., Cooper, E.J., 2014. Idiosyncratic responses of high
673 arctic plants to changing snow regimes. *PLoS One* 9, 1–10.
674 <https://doi.org/10.1371/journal.pone.0086281>

675 Schilling, M., Cooper, W.T., 2004. Effects of chemical treatments on the quality and quantitative
676 reliability of solid-state ¹³C NMR spectroscopy of mineral soils. *Anal. Chim. Acta* 508, 207–
677 216. <https://doi.org/10.1016/j.aca.2003.12.001>

678 Schimel, J.P., Bilbrough, C., Welker, J.M., 2004. Increased snow depth affects microbial activity and
679 nitrogen mineralization in two Arctic tundra communities. *Soil Biol. Biochem.* 36, 217–227.
680 <https://doi.org/10.1016/j.soilbio.2003.09.008>

681 Schmidt, M.W.I., Knicker, H., Hatcher, P.G., Kögel-Knabner, I., 1997. Improvement of ¹³C and ¹⁵N

Formatted: German (Austria)

682 CPMAS NMR spectra of bulk soils , particle size fractions and organic material by treatment
683 with 10 % hydrofluoric acid. *Eur. J. Soil Sci.* 48, 319–328. [https://doi.org/10.1111/j.1365-](https://doi.org/10.1111/j.1365-2389.1997.tb00552.x)
684 [2389.1997.tb00552.x](https://doi.org/10.1111/j.1365-2389.1997.tb00552.x)

685 Schmidt, M.W.I., Torn, M.S., Abiven, S., Dittmar, T., Guggenberger, G., Janssens, I.A., Kleber, M.,
686 Kögel-Knabner, I., Lehmann, J., Manning, D.A.C., Nannipieri, P., Rasse, D.P., Weiner, S.,
687 Trumbore, S.E., 2011. Persistence of soil organic matter as an ecosystem property. *Nature* 478,
688 49–56. <https://doi.org/10.1038/nature10386>

689 Schuur, E.A.G., Vogel, J.G., Crummer, K.G., Lee, H., Sickman, J.O., Osterkamp, T.E., 2009. The
690 effect of permafrost thaw on old carbon release and net carbon exchange from tundra. *Nature*
691 459, 556–559. <https://doi.org/10.1038/nature08031>

692 Semenchuk, P.R., Christiansen, C.T., Grogan, P., Elberling, B., Cooper, E.J., 2016a. Long-term
693 experimentally deepened snow decreases growing-season respiration in a low- and high-arctic
694 tundra ecosystem. *J. Geophys. Res. Biogeosciences* 121, 1236–1248.
695 <https://doi.org/10.1002/2015JG003251>

696 Semenchuk, P.R., Elberling, B., Amtorp, C., Winkler, J., Rumpf, S., Michelsen, A., Cooper, E.J.,
697 2015. Deeper snow alters soil nutrient availability and leaf nutrient status in high Arctic tundra.
698 *Biogeochemistry* 124, 81–94. <https://doi.org/10.1007/s10533-015-0082-7>

699 Semenchuk, P.R., Elberling, B., Cooper, E.J., 2013. Snow cover and extreme winter warming events
700 control flower abundance of some, but not all species in high arctic svalbard. *Ecol. Evol.* 3,
701 2586–2599. <https://doi.org/10.1002/ece3.648>

702 Semenchuk, P.R., Gillespie, M.A.K.K., Rumpf, S.B., Baggesen, N., Elberling, B., Cooper, E.J.,
703 2016b. High Arctic plant phenology is determined by snowmelt patterns but duration of
704 phenological periods is fixed: An example of periodicity. *Environ. Res. Lett.* 11, 1–12.
705 <https://doi.org/10.1088/1748-9326/11/12/125006>

706 Simpson, M.J., Otto, A., Feng, X., 2008. Comparison of solid-state carbon-13 nuclear magnetic

707 resonance and organic matter biomarkers for assessing soil organic matter degradation. *Soil Sci.*
708 *Soc. Am. J.* 72, 268–276. <https://doi.org/10.2136/sssaj2007.0045>

709 Simpson, M.J., Simpson, A.J., 2012. The Chemical Ecology of Soil Organic Matter Molecular
710 Constituents. *J. Chem. Ecol.* 38, 768–784. <https://doi.org/10.1007/s10886-012-0122-x>

711 Sjögersten, S., Turner, B.L., Mahieu, N., Condrón, L.M., Wookey, P.A., 2003. Soil organic matter
712 biochemistry and potential susceptibility to climatic change across the forest-tundra ecotone in
713 the Fennoscandian mountains. *Glob. Chang. Biol.* 9, 759–772. [https://doi.org/10.1046/j.1365-](https://doi.org/10.1046/j.1365-2486.2003.00598.x)
714 [2486.2003.00598.x](https://doi.org/10.1046/j.1365-2486.2003.00598.x)

715 Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y.,
716 Bex, V., Midgley, P.M., 2014. *Climate Change 2013 - The Physical Science Basis*, Climate
717 Change 2013: The Physical Science Basis. Cambridge University Press, Cambridge.
718 <https://doi.org/10.1017/CBO9781107415324>

719 Strebel, D., Elberling, B., Morgner, E., Knicker, H.E., Cooper, E.J., 2010. Cold-season soil respiration
720 in response to grazing and warming in High-Arctic Svalbard. *Polar Res.* 29, 46–57.
721 <https://doi.org/10.1111/j.1751-8369.2010.00154.x>

722 Tarnocai, C., Canadell, J.G., Schuur, E.A.G., Kuhry, P., Mazhitova, G., Zimov, S., 2009. Soil organic
723 carbon pools in the northern circumpolar permafrost region. *Global Biogeochem. Cycles* 23, n/a-
724 n/a. <https://doi.org/10.1029/2008GB003327>

725 Trumbore, S., 2009. Radiocarbon and Soil Carbon Dynamics. *Annu. Rev. Earth Planet. Sci.* 37, 47–
726 66. <https://doi.org/10.1146/annurev.earth.36.031207.124300>

727 ▲ [Wallenstein, M.D., McMahon, S.K., Schimel, J.P., 2009. Seasonal variation in enzyme activities and](#)
728 [temperature sensitivities in Arctic tundra soils. *Glob. Chang. Biol.* 15, 1631–1639.](#)
729 <https://doi.org/10.1111/j.1365-2486.2008.01819.x>

730 Webb, E.E., Schuur, E.A.G., Natali, S.M., Oken, K.L., Bracho, R., Krapek, J.P., Risk, D., Nickerson,
731 N.R., 2016. Increased wintertime CO₂ loss as a result of sustained tundra warming 1–17.

Formatted: German (Austria)

732 <https://doi.org/10.1002/2014JG002795>.Received

733 Welker, J.M., Fahnestock, J.T., Sullivan, P.F., Chimner, R.A., 2005. Leaf mineral nutrition of Arctic

734 plants in response to warming and deeper snow in northern Alaska. *Oikos* 109, 167–177.

735 <https://doi.org/10.1111/j.0030-1299.2005.13264.x>

736

Table 1[Click here to download Table: Table_1_STOTEN.docx](#)

<i>Response</i>	<i>Horizon</i>	<i>Effect size</i>	<i>Lower 95% CI</i>	<i>Upper 95% CI</i>	<i>p-value</i>
%C	A	-2.0563	-3.6623	-0.4503	0.0205
%C	B/C	0.9525	-0.06051	1.96552	0.1113
%C	B/C (HF-treated)	1.8646	-0.4052	4.1344	0.0729
kg C m⁻²	A	-0.48285	-0.89685	-0.06886	0.03152
kg C m ⁻²	B/C	0.05238	-0.42044	0.52520	0.8201

Table 2

[Click here to download Table: Table_2_STOTEN.docx](#)

<i>Horizon</i>	<i>Integral</i>	<i>Region</i>	<i>Effect size</i>	<i>Lower 95 %CI</i>	<i>Upper 95% CI</i>	<i>p-value</i>
<i>A</i>	<i>Carbonyl</i>	<i>190-165</i>	0.000683	-0.0009593	0.0023253	0.3987
<i>A</i>	<i>O-aromatic</i>	<i>165-140</i>	0.0001435	-0.00281	0.003097	0.92
<i>A</i>	<i>Aromatic</i>	<i>140-112</i>	0.003705	-0.001253	0.008663	0.1437
<i>A</i>	<i>Di-O-alkyl</i>	<i>112-93</i>	-0.005542	-0.009067	-0.002018	0.007272
<i>A</i>	<i>O-alkyl</i>	<i>93-60</i>	-0.019813	-0.032911	-0.006714	0.009047
<i>A</i>	<i>Methoxy/ N-alkyl</i>	<i>60-50</i>	0.001589	-0.0006453	0.0038233	0.1522
<i>A</i>	<i>Alkyl</i>	<i>50-0</i>	0.019235	0.009103	0.029367	0.002273
<i>A</i>	<i>alkyl/ O-alkyl</i>	<i>ratio</i>	0.085	0.03685	0.13316	0.003633
<i>B/C</i>	<i>Carbonyl</i>	<i>190-165</i>	-0.006956	-0.012728	-0.001184	0.02721
<i>B/C</i>	<i>O-aromatic</i>	<i>165-140</i>	-0.0050147	-0.0104986	0.0004692	0.08004
<i>B/C</i>	<i>Aromatic</i>	<i>140-112</i>	-0.019838	-0.037232	-0.002445	0.03473
<i>B/C</i>	<i>Di-O-alkyl</i>	<i>112-93</i>	0.0006397	-0.0134508	0.0147301	0.9257
<i>B/C</i>	<i>O-alkyl</i>	<i>93-60</i>	0.018268	-0.009001	0.045538	0.1859
<i>B/C</i>	<i>Methoxy/ N-alkyl</i>	<i>60-50</i>	0.0007683	-0.0028917	0.0044283	0.6674
<i>B/C</i>	<i>Alkyl</i>	<i>50-0</i>	0.006997	-0.011176	0.025171	0.4351
<i>B/C</i>	<i>alkyl/ O-alkyl</i>	<i>ratio</i>	-0.03617	-0.17731	0.10497	0.6006

Figure
[Click here to download Figure: Figure_1.eps](#)

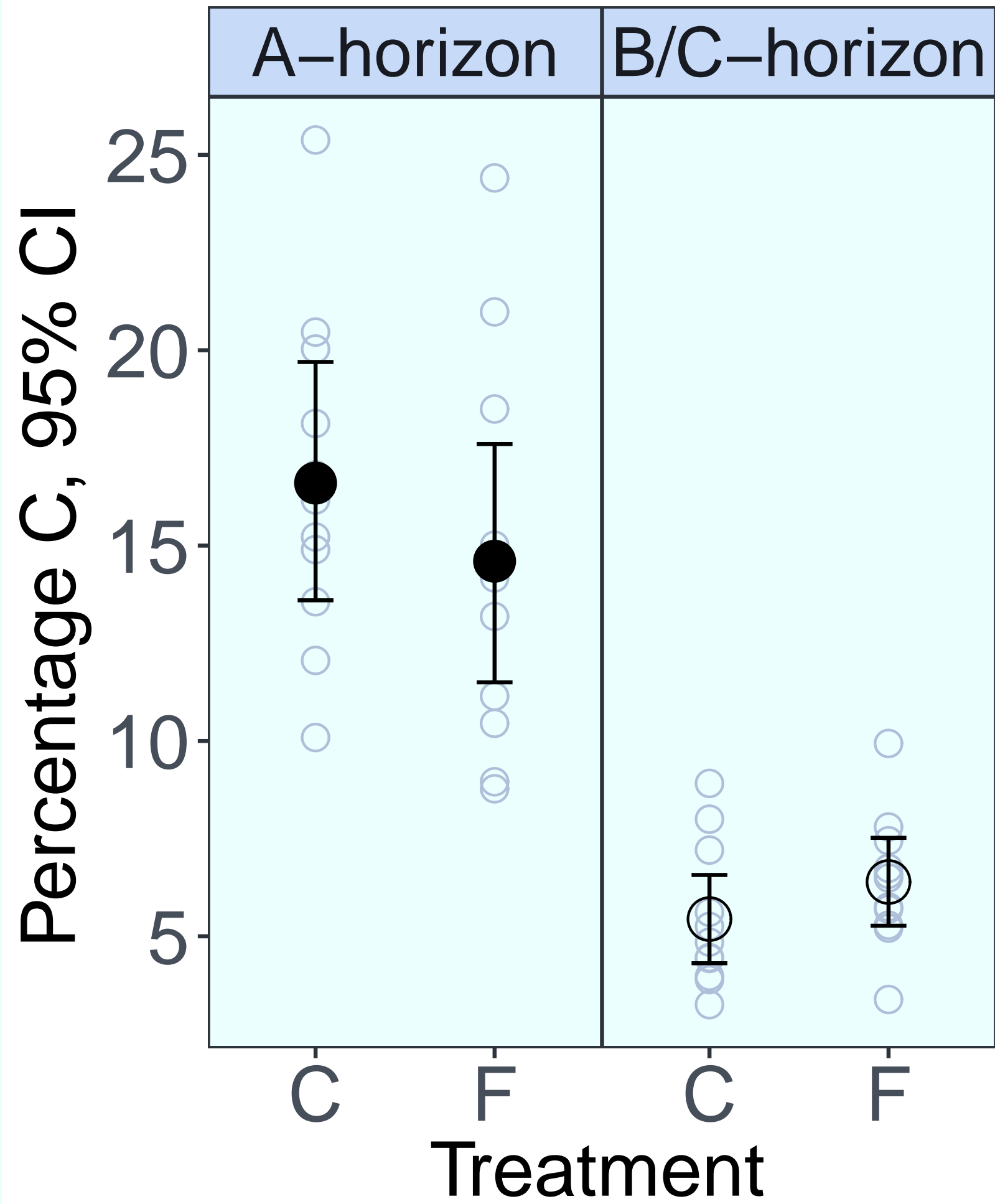


Figure
[Click here to download Figure: Figure_1b.eps](#)

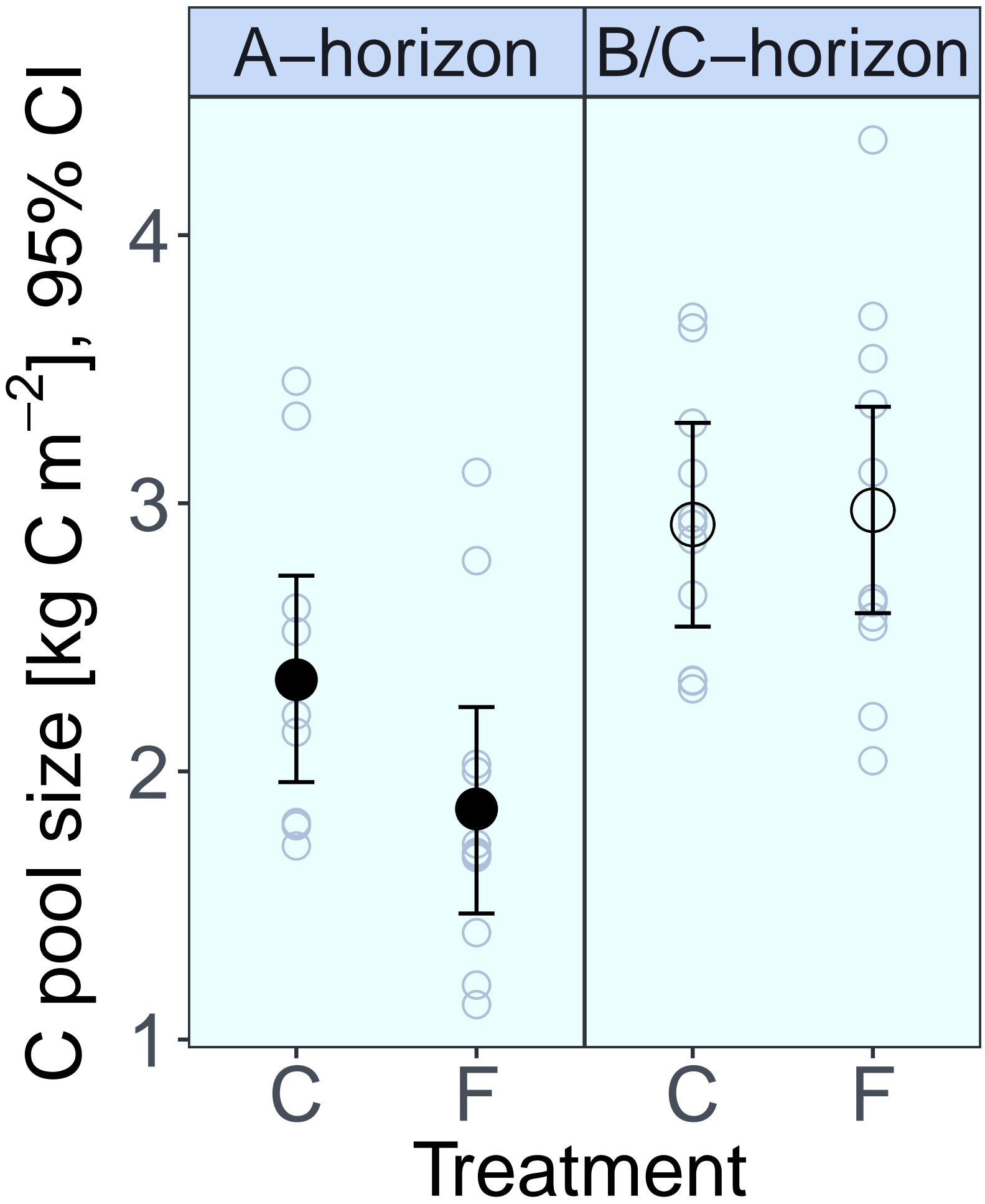


Figure
[Click here to download Figure: Figure_2.eps](#)

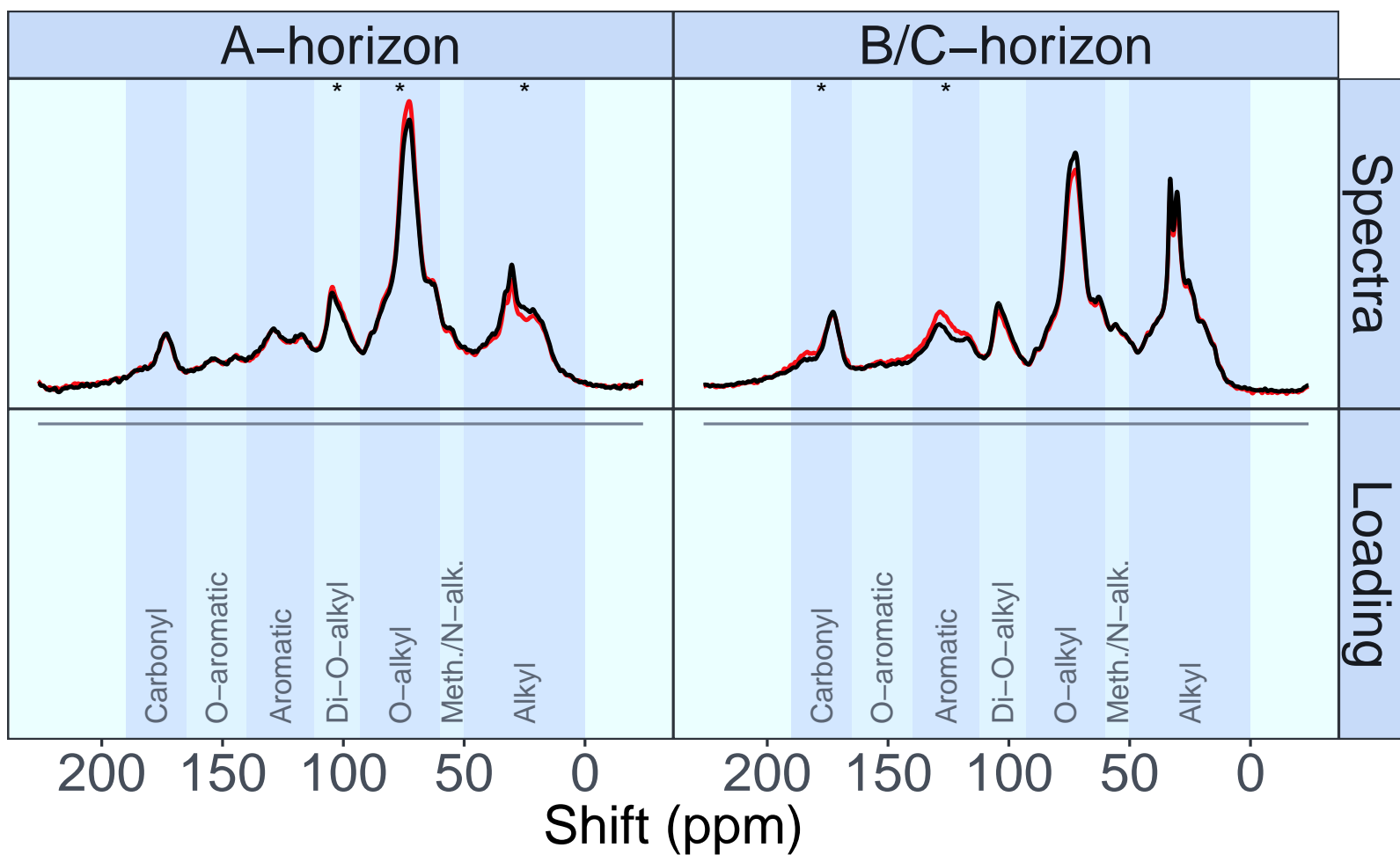


Figure
[Click here to download Figure: Figure_3.eps](#)

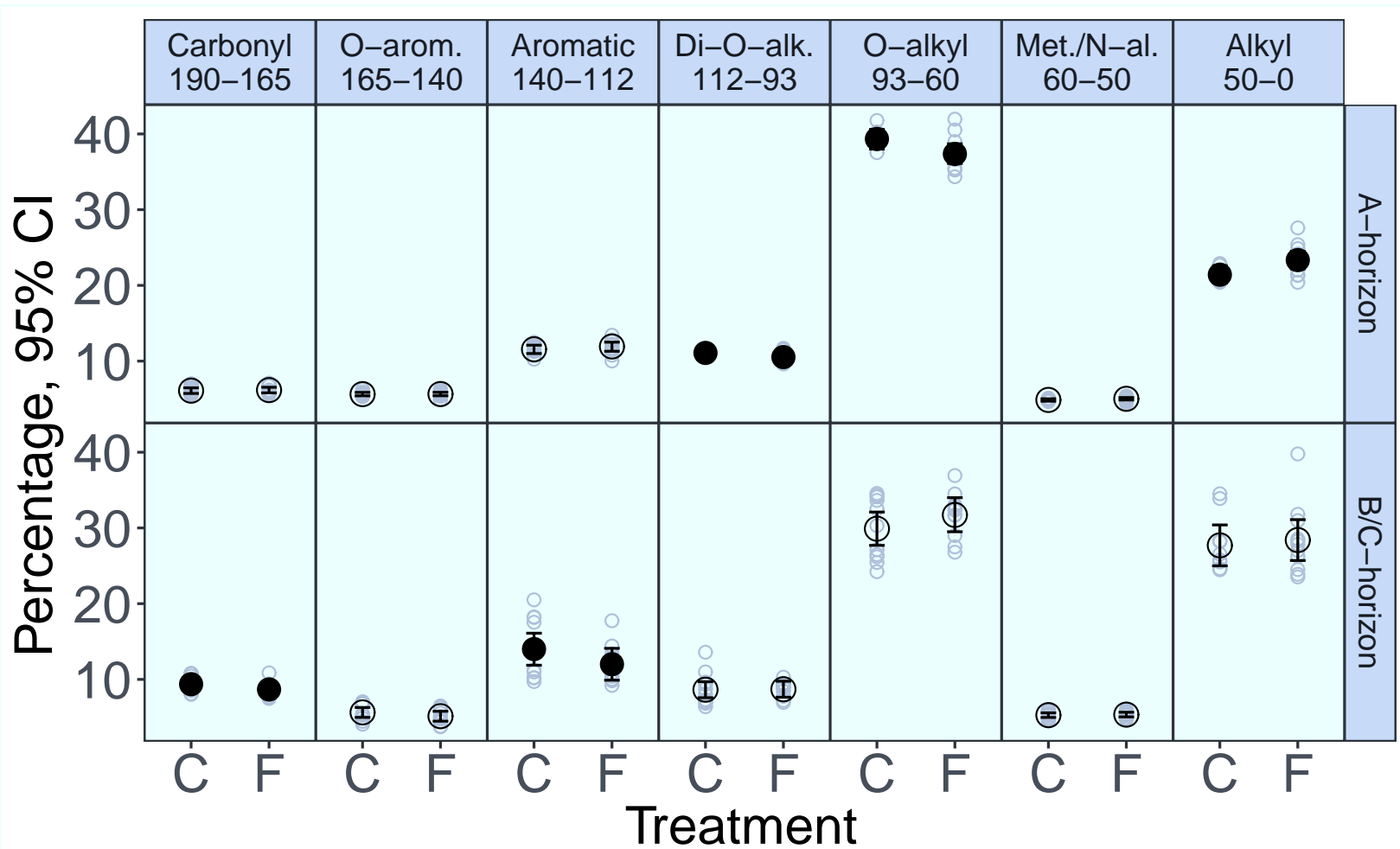
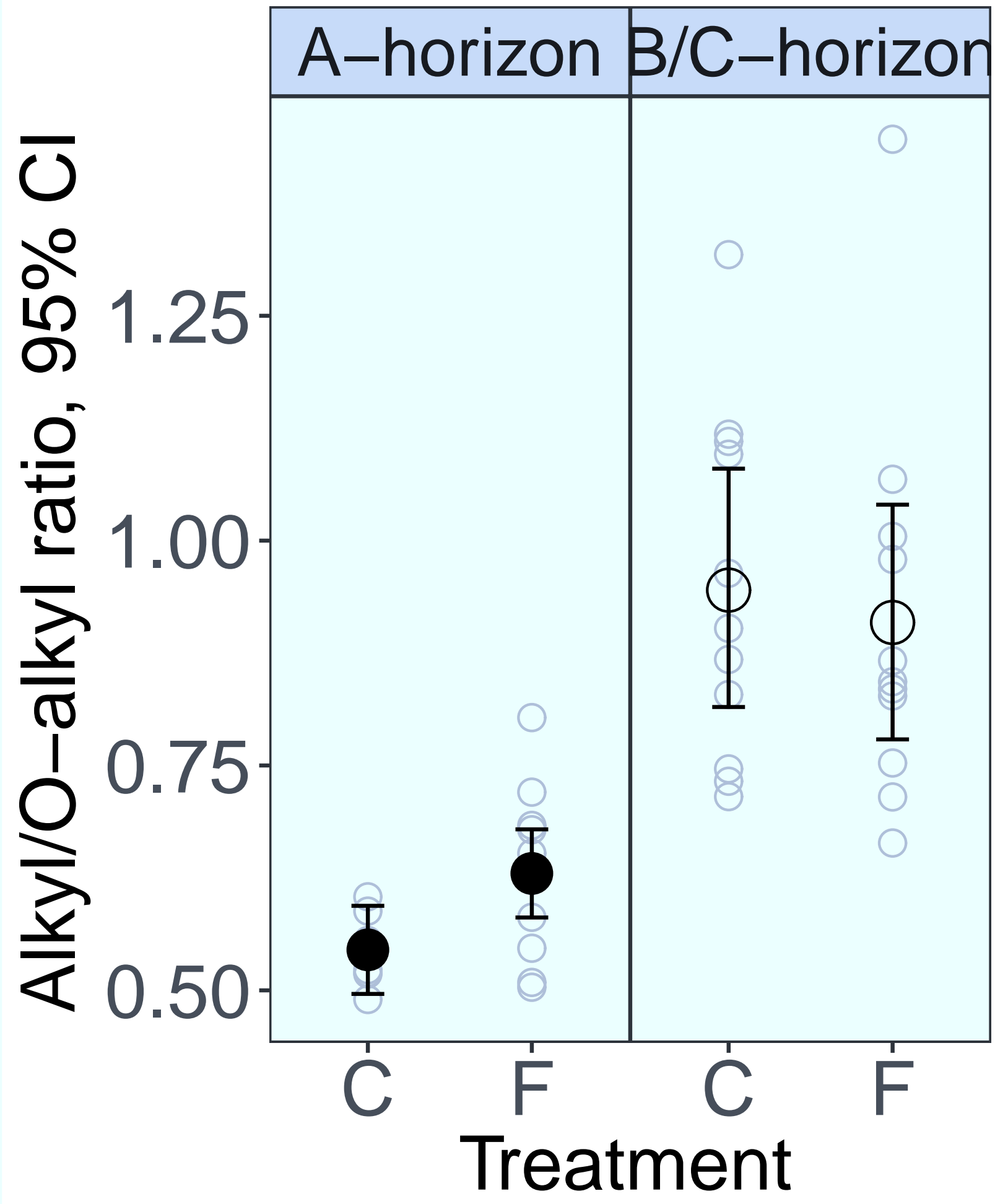


Figure
[Click here to download Figure: Figure_4.eps](#)



Supplementary material for on-line publication only

[Click here to download Supplementary material for on-line publication only: SnoEco_NMR_Manuscript_Supp.doc](#)

Supporting Information for

Soil organic carbon depletion and degradation after long term non-growing season warming in High Arctic Svalbard

Philipp R. Semenchuk^{1,2}, Eveline J. Krab^{2,3}, Mattias Hedenström⁴, Carly A. Phillips⁵, Francisco J. Ancin-Murguzur¹, Elisabeth J. Cooper¹

¹Department of Arctic and Marine Biology, Faculty of Biosciences Fisheries and Economics, UiT-The Arctic University of Norway, N-9037 Tromsø

²Climate Impacts Research Centre, Department of Ecology and Environmental Science, Umeå University, SE-98107 Abisko, Sweden

³Swedish University of Agricultural Sciences. Department of Soil and Environment, SE-75007, Uppsala, Sweden

⁴Department of Chemistry, Umeå University, SE-901 87 Umeå, Sweden

⁵Odum School of Ecology, University of Georgia, Athens GA 30606, USA

Figure S1. Snow depth

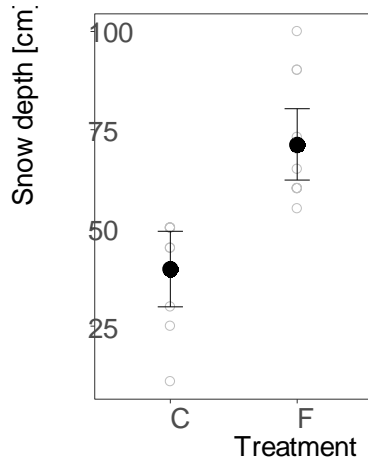


Figure S1: Snow depth in control (C) and snow fence (F) areas from each plot (raw data, grey open circles) and modelled with 95% confidence intervals (black circles). Measurements were undertaken between 4 and 12 May 2017, i.e. almost two years after the soil sampling for this study. However, we observed that snow depths in the study site are uniform across seasons and are confident that these measurements are representative for all years preceding soil sampling. Data were obtained by digging snow pits and analysed with linear mixed effects models analogous to other analyses in the main article (see there).

Figure S2. Active layer thickness/ maximum thaw depth

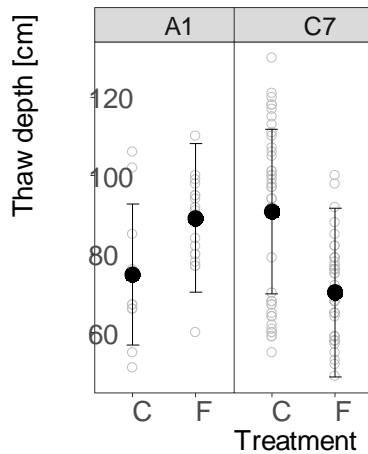


Figure S2: Active layer thickness/ maximum thaw depth from two of eleven plots (coded A1 and C7) in control (C) and snow fence (F) areas from each plot (raw data, grey open circles) and modelled with 95% confidence intervals (black circles). Measurements were undertaken between 4 and 07 September 2011, i.e. towards the end of the growing season four years prior to soil sampling for this study, in these two plots only. Data were obtained by probing with a 1cm diameter steel rod. Statistical analyses were performed with linear mixed effects models analogous to other analyses in the main article (see there) with snow fence treatment and plot (here only A1 and C7) and their interaction as significant fixed effects.

Figure S3. Soil temperature

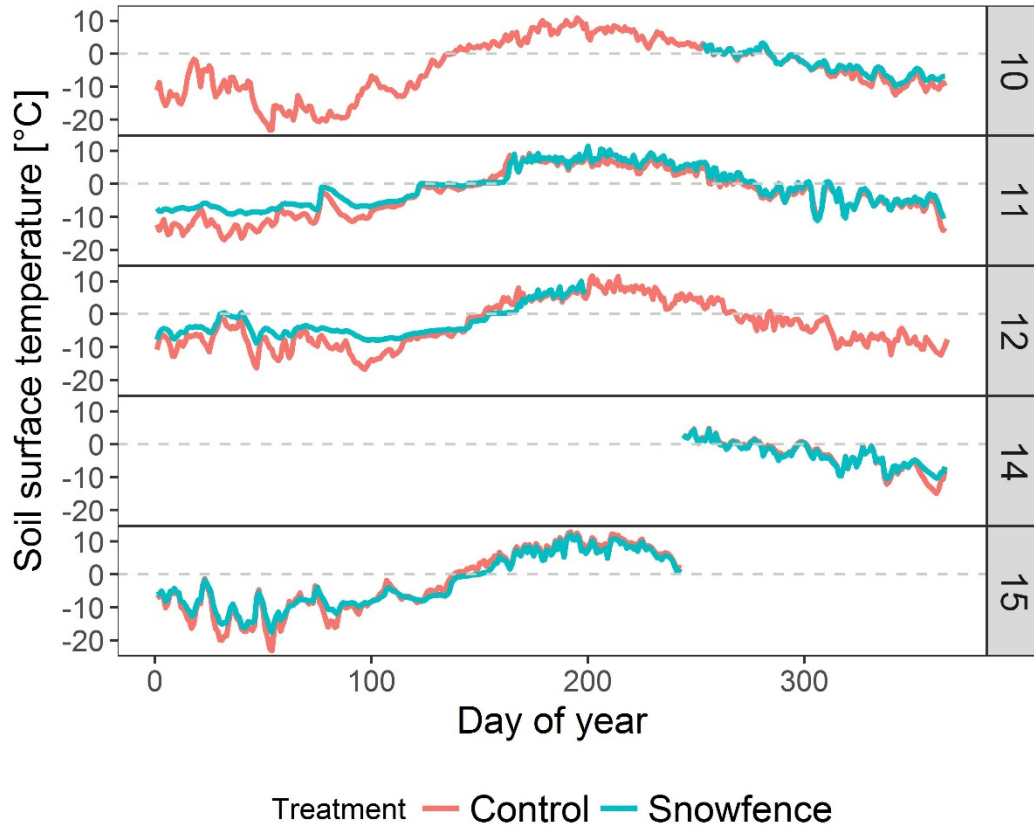


Figure S3: Soil surface temperature averaged over hourly measurements and 2 plots in 2010-12 and 10 plots in 2014-15 by Tiny Tag thermistors and data loggers at around 2 cm soil depth during years 2010 to 2015. Missing data in the figure are caused by logger failure, later deployment or because the data were not downloaded at the time of writing. The average effect of the snow fence treatment during the non-growing season (i.e. when thermistors measured below 0 degC) was 1.86 degC (95% CI: 1.83 – 1.9 degC; $p < 0.00001$; linear mixed effects model based on hourly raw data analogous to other models in the main article).

Figure S4. Soil moisture

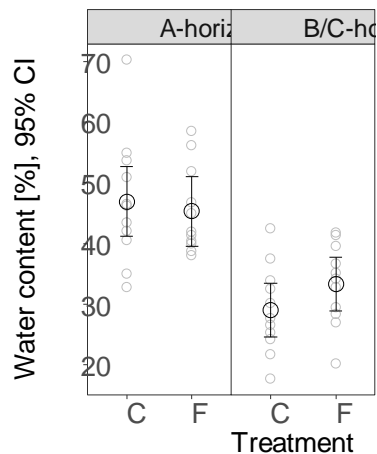


Figure S4: Soil moisture from all soil samples in control (C) and snow fence (F) areas from each plot (raw data, grey open circles) and modelled with 95% confidence intervals (black circles). Data were obtained by comparing sample weights before and after drying (see main article text). Statistical analyses were performed with linear mixed effects models analogous to other analyses in the main article (see there) and snow fence treatment effects were found to be non-significant ($p = 0.5399$ and 0.05592 for A- and B/C-Horizon, respectively). However, other studies from the same field site found that soil moisture in the upper 6cm was slightly higher shortly after snow melt, i.e. at the beginning of the growing season, while these changes disappeared quickly as the growing season progressed (Semenchuk, Christiansen, Grogan, Elberling, & Cooper, 2016).

References for supporting information

- Semenchuk, P. R., Christiansen, C. T., Grogan, P., Elberling, B., & Cooper, E. J. (2016). Long-term experimentally deepened snow decreases growing-season respiration in a low- and high-arctic tundra ecosystem. *Journal of Geophysical Research: Biogeosciences*, *121*(5), 1236–1248. <https://doi.org/10.1002/2015JG003251>
- Semenchuk, P. R., Elberling, B., & Cooper, E. J. (2013). Snow cover and extreme winter warming events control flower abundance of some, but not all species in high arctic svalbard. *Ecology and Evolution*, *3*(8), 2586–2599. <https://doi.org/10.1002/ece3.648>