**Supplementary information**

Deepened snow promotes evergreen shrub growth - CT Christiansen et al. (GCB)



**Figure S1.** Views of a part of the experimental snow manipulation site in May (a) and July (b) of 2013 (late-winter and mid-summer, respectively). In total, there are five separate snowfences (each 15 m long), and all treatment and control plots (15 x 8 m; n = 5) are located in mesic birch hummock tundra vegetation. The winter photo (a) shows a snowfence plot viewed from east towards west (note the snowdrift created by the fence), and the summer photo (b) shows a snowfence plot viewed from south towards north.

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**Figure S2.** Diel air temperature climate normal (based on data from 1996-2014, black line, with 95% confidence interval in gray), and diel air temperatures for the measurement years 2012 (red line) and 2013 (blue line) separately at the study site. The red and blue boxes on the X-axis show extent of the field campaigns in 2012 and 2013, respectively. The insert shows seasonal air temperature means for December, January, and February (DJF), March, April, and May (MAM), June, July, and August (JJA), and September, October, and November (SON).

Rainfall is monitored at the study site, and average summertime (JJA) rainfall is ~96 mm (1996-2014 JJA climate normal). In 2012 and 2013, JJA rainfall was 97 and 165 mm, respectively, with about half (~85 mm) of JJA 2013 rainfall occurring after our field campaign ended that year (10 July). JJA soil moisture data across 2012 and 2013 indicate that soil moisture regimes (0-5 cm) were very similar across years (27.9 and 29.9% volume, respectively, see Figure S5), similar to JJA air temperature.

Air temperature and rainfall data are from a nearby (~3 km) climate tower (Bob Reid and Shawne Kokelj, unpublished data), and soil moisture data (Campbell Scientific, CSC 616 reflectometers) are from the control plots (n=2) at our study site. We gap-filled a total of 69 missing air temperature days in January and February of 2008, 2010, and 2011, and 56 days in August-October of 2012, using control plot air temperature data from a nearby (~1 km) experimental greenhouse field site (Zamin, 2013). In addition, due to winter power shortage, January air temperature data were not available for years 1996, 2001-2004, and 2006-2007. Due to a gauge malfunction at the main climate tower in 2012, we used 2012-2014 rainfall data from an eddy covariance tower (Peter Lafleur, unpublished data) located ~300 m from the climate tower.

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**Figure S3.** Diel soil temperature differences (5 cm depth) between deepened snow (snowfences) and ambient (controls) snow treatments during the cold season and subsequent growing season (1 September through 31 May; 1 June through 31 August, respectively) of 2011-2012 (black line) and 2012-2013 (red line), n = 1 temperature probe per snow regime. Positive values (i.e. above the zero line) indicate warmer soils in the deepened snow treatment relative to controls. Temperature data are missing from 17 June to 5 July 2013 as some probes had been pulled up by animals.



**Figure S4.** Growing season soil moisture (0-12 cm depth) (a), and soil temperature at 5 cm (b), 10 cm (c), 15 cm (d), and 20 cm (e) depth in ambient (controls, black bars) and deepened snow (snowfences, gray bars) treatments. Each plot was divided into a grid consisting of 39 subplots, and all 39 measurements per plot per biweekly date were then averaged into one datum (n = 5 per treatment; error bars = S.E.s). Note that June to early July measurements were performed in 2013 while July to mid-August measurements were performed in 2012.

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**Figure S5.** Diel difference in volumetric soil water content (within the 0-5 cm depth interval) between deepened snow (snowfences) and ambient (controls) treatments during the cold season and following growing season in 2011-2012 (a) and 2012-2013 (b) (n = 2 per treatment). The cold season was defined as 1 September through 31 May the following year, and the growing season as 1 June through 31 August. Therefore, a full year begins on 1 September and ends on 31 August the following year. Data are missing from 17 June to 5 July 2013 as some probes had been pulled by animals. Note that the probes are not calibrated for volumetric soil water content measurements in frozen soils, and therefore values have been set to zero during that phase of the cold season.



**Figure S6.** Growing season soil thaw depth in ambient (controls, black bars) and deepened snow (snowfences, gray bars) treatments. Each plot was divided into a grid consisting of 39 subplots, and all 39 measurements per plot per biweekly date were then averaged into one datum (n = 5 per treatment; error bars = S.E.s). Note that June to early July measurements were performed in 2013 while July to mid-August measurements were performed in 2012.

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Functional group** |  |  | ***r2*** | ***P*** | ***Slope (a)*** | | ***Intercept (b*)** | | **%Carbon**¥ | | **%Nitrogen**¥ | | **%Phosphorus**¥ | |
| Deciduous | *Betula glandulosa* | Leaves | 0.38 | **0.0003** | 0.491 | ±0.13 | 0.947 | ±0.28 | 48.92 | ±0.22 | 1.69 | ±0.08 | 0.18 | ±0.01 |
|  |  | Stem | 0.26 | **0.0038** | 0.707 | ±0.22 | 2.335 | ±0.31 | 52.13 | ±0.1 | 0.55 | ±0.02 | 0.06 | ±0.00 |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
|  | *Vaccinium uliginosum* | Leaves | 0.71 | **<0.0001** | 0.475 | ±0.06 | 0.277 | ±0.09 | 47.78 | ±0.2 | 1.39 | ±0.06 | 0.09 | ±0.01 |
|  |  | Stem | 0.27 | **0.0033** | 0.829 | ±0.26 | 1.074 | ±0.25 | 44.82 | ±0.45 | 0.58 | ±0.01 | 0.06 | ±0.00 |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Evergreen | *Rhododendron subarcticum* | Leaves | 0.86 | **<0.0001** | 0.745 | ±0.06 | 0.525 | ±0.2 | 52.96 | ±0.43 | 1.57 | ±0.05 | 0.11 | ±0.01 |
|  |  | Stem | 0.50 | **<0.0001** | 0.822 | ±0.12 | 2.136 | ±0.36 | 53.93 | ±0.3 | 0.52 | ±0.01 | 0.05 | ±0.00 |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
|  | *Vaccinium vitis-idaea* | Leaves | 0.90 | **<0.0001** | 0.827 | ±0.05 | 0.360 | ±0.18 | 48.46 | ±0.44 | 0.95 | ±0.02 | 0.09 | ±0.00 |
|  |  | Stem | 0.38 | **0.0003** | 0.653 | ±0.16 | 1.572 | ±0.26 | 49.96 | ±0.13 | 0.70 | ±0.02 | 0.08 | ±0.00 |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
|  | *Andromeda polifolia* | Leaves | 0.57 | **<0.0001** | 0.705 | ±0.12 | 0.523 | ±0.17 | 50.52 | ±0.22 | 1.09 | ±0.04 | 0.10 | ±0.00 |
|  |  | Stem | 0.18 | **0.0211** | 0.671 | ±0.27 | 1.024 | ±0.22 | 46.78 | ±0.8 | 0.53 | ±0.01 | 0.06 | ±0.00 |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Graminoid | *Eriophorum vaginatum* | Blades + sheaths | 0.79 | **<0.0001** | 0.581 | ±0.06 | 0.903 | ±0.21 | 44.05 | ±0.33 | 1.20 | ±0.02 | 0.15 | ±0.02 |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Forb | *Rubus chamaemorus* | Shoots | 0.80 | **<0.0001** | 0.741 | ±0.07 | 0.208 | ±0.1 | 46.04 | ±0.14 | 2.06 | ±0.06 | 0.11 | ±0.01 |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Mosses | All species combined |  | 0.59 | **<0.0001** | 0.640 | ±0.10 | 2.493 | ±0.29 | 43.05 | ±0.36 | 0.71 | ±0.05 | 0.08 | ±0.00 |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Lichens | All species combined |  | 0.34§ | 0.0794§ | 0.497§ | ±0.25§ | 3.05§ | ±1.17§ | 42.82 | ±0.07 | 0.41 | ±0.01 | 0.11 | ±0.06 |

**Table S1.** Regression parameters and tissue-type differentiated carbon, nitrogen, and phosphorus concentrations for each vascular plant species, and mosses and lichens, obtained from studies conducted nearby (~300 meters away) in the same mesic birch hummock vegetation type as in our study. Regression parameters were calculated using the power equation: *Y = kXn,* where *X* is point-framing hits, *Y* is biomass, and *k* and *n* are constants, solved as a linear model: *Y = e(a \* ln(X) + b)*, where *X* and *Y* are as above, and *a* and *b* are constants (see Zamin *et al.* (2014) for further details). Data are means ±1 S.E. (where applicable), and all data are from Zamin *et al.* (2014), except ¥, which was obtained from Zamin (2013), and §, which was obtained from (Zamin & Grogan, 2013).

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  |  | **Mean cold season soil temperature** | | **Mean deep winter soil temperature** | |  | **Mean growing season soil temperature** | | **Mean annual soil temperature** | | **Annual freezing degree days** | | **Annual thawing degree days** | | **Cumulative degree days** | |
| **Single probe data** | **5 cm depth**  **(organic soil)** | Controls | Snow-fences | Controls | Snow-fences |  | Controls | Snow-fences | Controls | Snow-fences | Controls | Snow-fences | Controls | Snow-fences | Controls | Snow-fences |
|  | 2007-2008a | -9.6 | -9.3 | -17.2 | -15.0 |  | 6.5 | 7.8 | -5.6 | -5.0 | -2682 | -2608 | 652 | 772 | -2030 | -1836 |
|  | 2008-2009a | -8.2 | -7.3 | -14.1 | -13.0 |  | 5.4 | 6.2 | -4.8 | -4.0 | -2311 | -2099 | 563 | 652 | -1748 | -1447 |
|  | 2009-2010a | -6.3 | -5.3 | -11.3 | -9.7 |  | 7.1 | 8.1 | -3.0 | -2.0 | -1857 | -1611 | 777 | 892 | -1080 | -720 |
|  | 2010-2011a | -5.6 | -3.8 | -11.3 | -8.3 |  | 7.6 | 8.3 | -2.3 | -0.8 | -1632 | -1149 | 798 | 865 | -834 | -283 |
|  | 2011-2012a | -5.6 | -2.2 | -12.1 | -5.5 |  | 8.5 | 9.5 | -2.0 | 0.8 | -1667 | -752 | 928 | 1034 | -739 | 283 |
|  | 2012-2013a | -5.6 | -4.0 | -10.5 | -8.1 |  | 7.5 | 8.7 | -2.7 | -1.2 | -1684 | -1283 | 748 | 862 | -935 | -421 |
|  | 2013-2014a | -7.9 | -5.5 | -15.2 | -11.1 |  | - | - | - | - | -2308 | -1648 | - | - |  |  |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
|  | 2007-2013 overall meana | -6.8 | -5.3 | -12.7 | -9.9 |  | 7.1 | 8.1 | -3.4 | -2.0 |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
|  | 2007-2013 cumulativea |  |  |  |  |  |  |  |  |  | -11834 | -9502 | 4467 | 5078 | -7367 | -4424 |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| **Multi-probe data** | **5 cm depth**  **(organic soil)** |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
|  | 2013-2014b | **-9.76 (0.3)** | **-5.78 (0.2) \*\*** | **-15.6 (0.4)** | **-9.1 (0.3) \*\*** |  | 7.0 (0.2) | 5.9 (0.6) | **-5.9 ( 0.2)** | **-3.1 (0.1) \*\*** | **-2279 (71)** | **-1350 (45) \*\*** | 503 (16) | 423 (43) | **-1776 (65)** | **-927 (41) \*\*** |
|  | **30 cm depth**  **(mineral soil)** |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
|  | 2013-2014b | **-9.09 (0.2)** | **-5.55 (0.2) \*\*** | **-14.95 (0.26)** | **-9.0 (0.3) \*\*** |  | 2.2 (0.3) | 2.3 (0.3) | **-6.5 (0.2)** | **-3.8 (0.1) \*\*** | **-2117 (59)** | **-1302 (39) \*\*** | 163 (22) | 171 (16) | **-1954 (72)** | **-1131 (43) \*\*** |

**Table S2.** Effects of deepened snow (snowfences) onseasonal mean soil temperatures (5 and 30 cm depths) and cumulative degree days from 1 September 2007 to 1 June 2014 (a Campbell single probe dataloggers; n = 1 per treatment), and from 12 October 2013 to 7 August 2014 (b iButton dataloggers; n = 10-12 per treatment at each soil depth). The cold season was defined as 1 September through 31 May of the following year, deep winter as 1 January through 30 April, and the growing season as 1 June through 31 August. Therefore, a full year begins on 1 September and ends on 31 August the following year. No temperature data were available from 17 June to 5 July 2013 as some probes had been pulled up by animals and were on the top soil surface over that period, and no data were available after 1 June 2014. For the iButton datalogger temperature values are means ± 1 S.E., and means that differ significantly from each other within soil layers are highlighted in bold with the following statistical significance indicators: †, P ≤ 0.1; \*, P ≤ 0.05; and \*\*, P ≤ 0.01.

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Functional group** |  | **Shoot biomass**  (g dry weight m-2) | | **Shoot carbon**  (g C m-2) | | **Shoot nitrogen**  (g N m-2) | | **Shoot phosphorus**  (g P m-2) | |
|  |  | Controls | Snowfences | Controls | Snowfences | Controls | Snowfences | Controls | Snowfences |
| Deciduous | *Betula glandulosa* | 28.8 (8.8) | 18.5 (7.9) | 14.8 (4.6) | 9.5 (4.1) | 0.22 (0.06) | 0.15 (0.06) | 0.02 (0.006) | 0.02 (0.006) |
|  | *Vaccinium uliginosum* | 7 (3.2) | 3.7 (2.1) | 3.2 (1.4) | 1.7 (1) | 0.06 (0.03) | 0.04 (0.02) | 0.005 (0.002) | 0.003 (0.001) |
|  | Total | 35.7 (8.9) | 22.2 (8.7) | 18 (4.6) | 11.2 (4.4) | 0.29 (0.06) | 0.19 (0.07) | 0.03 (0.01) | 0.02 (0.01) |
|  |  |  |  |  |  |  |  |  |  |
| Evergreen | *Rhododendron subarcticum* | **45.8 (6.5)** | **109.5 (12.5) \*\*** | **24.5 (3.5)** | **58.8 (6.7) \*\*** | **0.42 (0.05)** | **0.83 (0.09) \*\*** | **0.03 (0.004)** | **0.07 (0.008) \*\*** |
|  | *Vaccinium vitis-idaea* | 25.5 (4.2) | 33.9 (5.9) | 12.4 (2.1) | 16.5 (2.9) | 0.24 (0.03) | 0.31 (0.05) | 0.02 (0.004) | 0.03 (0.005) |
|  | *Andromeda polaris* | 5.3 (3.4) | 2.8 (1.3) | 2.7 (1.7) | 1.4 (0.6) | 0.06 (0.04) | 0.03 (0.01) | 0.005 (0.003) | 0.003 (0.001) |
|  | Total | **76.6 (9)** | **146.2 (10) \*\*** | **39.6 (4.7)** | **76.7 (5.4) \*\*** | **0.72 (0.07)** | **1.2 (0.07) \*\*** | **0.06 (0.01)** | **0.1 (0.01) \*\*** |
|  |  |  |  |  |  |  |  |  |  |
| Graminoid | *Eriophorum vaginatum* | 4.6 (1.7) | 10.8 (3.2) | 2 (0.8) | 4.7 (1.4) | 0.06 (0.02) | 0.13 (0.04) | 0.007 (0.003) | 0.017 (0.005) |
|  | Total | 6.4 (1.4) | 10.9 (3.2) | 2.8 (0.6) | 4.8 (1.4) | 0.08 (0.02) | 0.13 (0.04) | 0.01 (0.002) | 0.016 (0.002) |
|  |  |  |  |  |  |  |  |  |  |
| Forb | *Rubus chamaemorus* | 0.49 (0.3) | 1.5 (0.4) | 0.23 (0.14) | 0.68 (0.19) | **0.01 (0.01)** | **0.03 (0.01) †** | **0.001 (0.0003)** | **0.002 (0.0004) †** |
|  |  |  |  |  |  |  |  |  |  |
| Lichen |  | 157.9 (6) | 149.9 (9.1) | 67.6 (2.6) | 64.2 (3.9) | 0.65 (0.02) | 0.61 (0.04) | 0.18 (0.01) | 0.17 (0.01) |
| Moss |  | 97.5 (10.6) | 102 (21) | 42 (4.5) | 43.9 (9.1) | 0.69 (0.08) | 0.73 (0.15) | 0.08 (0.01) | 0.09 (0.02) |

**Table S3.** Effects of 7 years of deepened snow on estimated vascular plant shoot, lichen, and moss biomass, carbon, nitrogen and phosphorus pools. Values are based on species percent cover measured in 2011 (Table 1 – main manuscript), converted to biomass using regression parameters estimated separately for leaf and stem components of individual plant(see Table S1 for parameters, and see *Methods* for detailed methodology). Carbon and nutrient contents were estimated using species-specific nutrient concentrations for each vascular species, and as functional groups for lichens and mosses (see *Methods*). Values are means ± 1 S.E. (n = 5), and means that differ significantly are indicated as in Table 2.

**Table S4.** Results of repeated measures linear mixed model analyses on daytime rates of net ecosystem exchange (NEE), gross ecosystem production (GEP), and ecosystem respiration (Reco) (c) during the growing season. For all models, plot and sampling date were specified as separate random factors with sampling date also set as repeated factor within plot, and the deepened snow treatment specified as a fixed main effect. Additionally, soil moisture and temperature were included as linear covariates with fixed effect interactions. The full models were step-wise simplified using the AIC output.

|  |  |  |
| --- | --- | --- |
| **Model parameters** | **Parameter statistics** |  |
|  |  |  |
| **NEE** |  |  |
| *Treatment* | F1,9.6 = 5.71; *P* = 0.04 | **\*** |
| *Temperature* | F1,23.9 = 144.8; *P* < 0.01 | **\*\*** |
| *Moisture* | NS |  |
| *Treatment × temperature* | F1,23.8 = 11.7; P < 0.01 | **\*\*** |
| *Treatment × moisture* | NS |  |
|  |  |  |
| **GEP** |  |  |
| *Treatment* | NS |  |
| *Temperature* | NS |  |
| *Moisture* | F1,17.6 = 4.27; P = 0.05 | **\*** |
| *Treatment × temperature* | NS |  |
| *Treatment × moisture* | NS |  |
|  |  |  |
| **Reco** |  |  |
| *Treatment* | F1,20 = 11.86; P < 0.01 | **\*\*** |
| *Temperature* | F1,27 = 211.16; P < 0.01 | **\*\*** |
| *Moisture* | NS |  |
| *Treatment × temperature* | F1,10.3 = 6.60; P = 0.03 | **\*** |
| *Treatment × moisture* | NS |  |

**Supplementary methodology used to estimate the total enhanced respiratory carbon loss in the sampled mineral soil layer due to the deepened snow treatment over 9 years**

Assuming that the snowfences at our site increased mean annual total winter respiration by ~70% (Nobrega & Grogan, 2007; and unpublished winter 2014 data, using differently placed collars in the same plots) and that annual winter CO2 release in tundra ecosystems is ~60 to 120 g C m-2 (Björkman *et al.*, 2010, Grogan, 2012, Nobrega & Grogan, 2007, Schimel *et al.*, 2006), then the total C lost over 9 years would range from 378-756 g C m-2. Mineral soil layers are estimated to contribute ~80% of tundra winter efflux (Schimel *et al.*, 2006), with the contribution from organic-enriched upper mineral soils (with C% < 20%, similar to our 15-25 cm soil layer) being about three times greater than deeper, less C-rich mineral soils at sub-zero temperatures (Michaelson & Ping, 2003). Therefore, assuming that ~75% of all mineral soil CO2 was emitted from the 15-25 cm sampling depth, our computational approach suggests that the snowfences would result in an additional loss of **227-453** g C m-2 from this soil layer alone.

Alternatively, assuming a Q10 of 3, and using the same range in annual winter CO2 release and the same proportional contribution from mineral soil layers as above, then the observed 6 degree soil temperature rise in the deepened snow treatment (2014 winter soil temperature data) would nearly double winter respiration rates in the snowfence plots, and the predicted increase in wintertime loss over the 9 years would range from **259-518** g C m-2 in the upper (15-25 cm) mineral soil layer. Both of the above approaches are conservative in that: a) deepened snow can enhance winter respiration rates from comparable tundra by a factor of 200% (Björkman *et al.*, 2010); b) field measurements of Q10 values in sub-zero tundra soils range from 3-18 (Morgner *et al.*, 2010, Sullivan *et al.*, 2008); c) large abrupt CO2 flushes associated with springtime soil thaw and snow ice-layer melting reflect substantial wintertime CO2 production (Oechel *et al.*, 1997) that is generally not included in total winter estimates based on interpolated instantaneous fluxes, and that may be exacerbated by deepened snow: and d) this calculation does not include potential C loss as CH4, which can be substantial during winter (Zona *et al.*, 2016) and even increased during the growing season as a legacy effect of experimentally deepened snow (Blanc-Betes *et al.*, 2016).

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