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Attaining whole-ecosystem warming using air and deep-soil heating methods with an elevated CO_2 atmosphere

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Surface Peat Moisture Measurements (Jeff Warren)

Intact *Sphagnum* peat monoliths were extracted from the S1-Bog into plastic containers (~7 L) and 10 replicates were taken to the Oak Ridge National Laboratory (ORNL) for calibration, and four replicates were sent to Decagon for factory calibration. One or two 10HS sensors were installed into each monolith, then water was added to the container to fully saturate the peat monolith and containers were placed into a plant growth chamber. Gravimetric water content was measured periodically as the monoliths dried down over several months and paired with the sensor mV output to create a custom calibration curve. During this period the *Sphagnum* surface (capitulum) water content was periodically assessed to derive a relationship between soil water content and surface water content – thereby providing data that is directly related to *Sphagnum* photosynthetic activity. The ORNL- and Decagon-based soil water calibration curves were similar, and using all 14 replicates resulted in a decent curve, where volumetric water content as $VMC = -0.731+0.508e^{(0.000995mV)}$ where mV is the voltage signal output from the sensors (R^2=0.92; Supplemental Fig. S1).

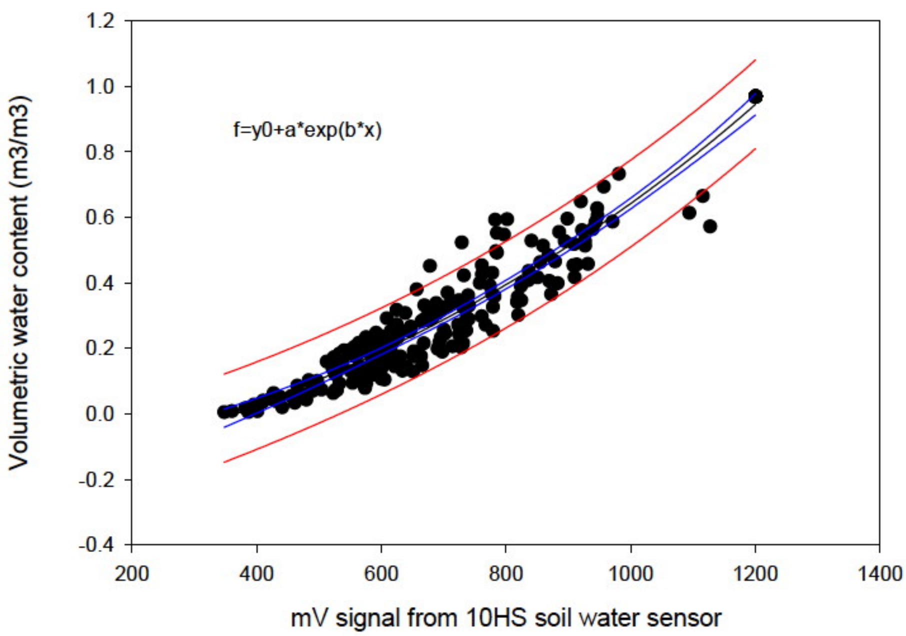

Figure S1: Calibration curve for the 10HS soil water sensor in peat.

The dynamics of surface-peat drying are demonstrated in Figure S2 for a dry period in mid-summer 2016. Changes in peat soil water content are not evident for all rainfall events.

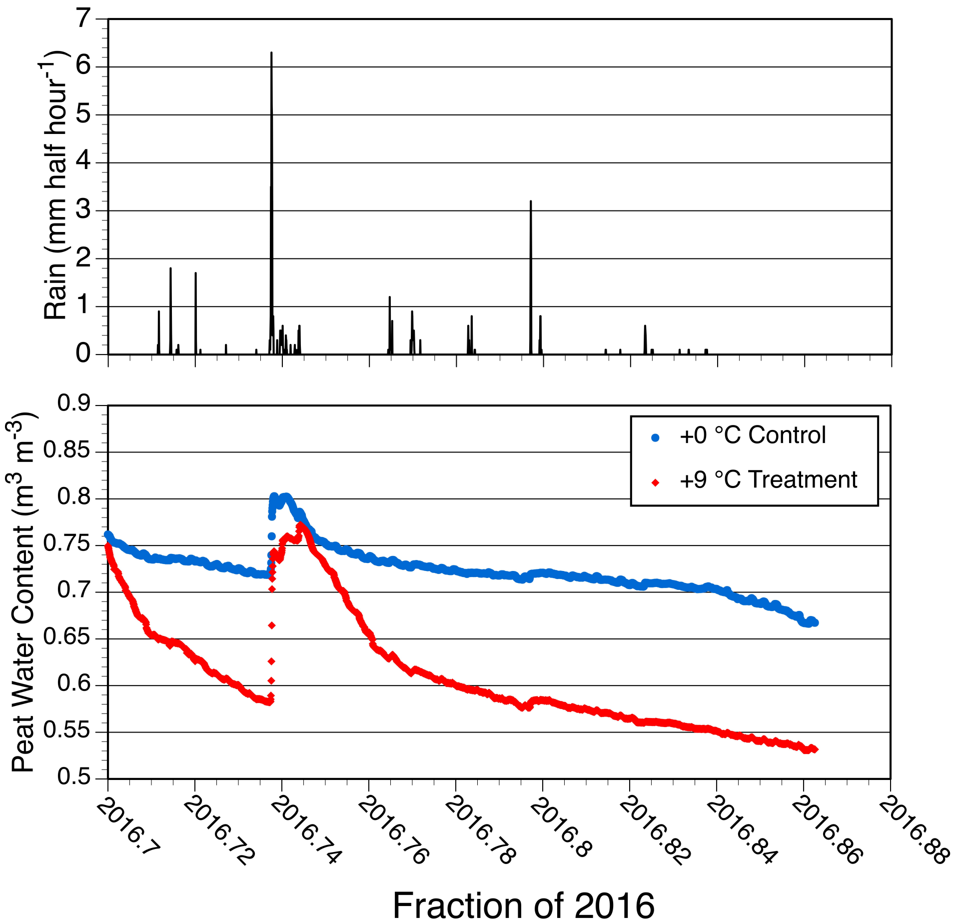

Figure S2: Graph of half-hour rainfall at + 6 m (upper graph) and surface peat water content avarged over 0 to -10 cm (lower graph) during a mid-summer dry period during 2016. SE around the peat water content data are ± 0.06 to 0.07 m^3 m^{-3}. Small precipitation events are intercepted by the canopy and peat *Sphagnum* surface and have limited effects on bulk water content observations.

Spectral Characteristics of the SPRUCE Enclosure Glazing (D. M. Aubrecht)

The spectral characteristics of the SPRUCE enclosure greenhouse panel glazing was evaluated from 250 nm to 20 microns using two radiometrically-calibrated directional hemispherical reflectance (DHR) spectrophotometers. One instrument measures UV/VNIR/SWIR (250 nm - 2.5 micron) and the second measures mid- and long-wave infrared radiation (MWIR/LWIR; 2 - 20 micron). All data include specular reflections.

The UV/VNIR/SWIR instrument is a Perkin-Elmer Lambda 750S spectrometer with a 100mm Spectralon integrating sphere and dual PMT and InGaAs detectors. The sample beam is incident at 8° from the sample surface normal. Data are collect at 1 nm resolution with 1 nm step size, and reflectance values are referenced to 99%R Spectralon. Data shown below are the mean of five independently sampled spectra.

The second instrument is a Thermo Scientific Nicolet iS10 FTIR spectrometer with a 3" Pike IntegratIR roughened gold integrating sphere and liquid nitrogen-cooled MCT detector. The sample beam strikes the sample surface at 12° from the surface normal. The sphere and internal beam path are purged with ultra pure dry nitrogen for 1 hour ahead of data collection in order to minimize absorption signals from CO_2 and H_2O in the atmosphere. Individual spectra are the mean of 64 samples are referenced to roughened gold. Data are presented at 4 cm^{-1} resolution and plots below are the mean of 10 independently sampled individual spectra.

Figure S3, below plots the greenhouse panel reflectance in comparison to the incoming solar spectrum (NREL "Global Tilt" data which accounts for all the solar energy that will interact with the SPRUCE enclosures), and the ideal blackbody radiation spectrum emitted by objects at 30 °C and 0 °C. There are two panel curves in the 2 – 2.5 micron region, where the two spectrophotomers overlap. Though the instruments give slightly different values, the overall magnitudes are in good agreement. Transmission data was also collected for the UV/VNIR, but is not shown. Transmission data for the MWIR was not collected, since at those wavelengths, the panels absorb all energy that they do not reflect.

We note the following characteristics of the greenhouse panels:

1) the panels absorb most of the UV and prevent it from entering the SPRUCE enclosures,
2) the panels transmit the majority of VNIR radiation and reflect only a small portion at these wavelengths,
3) the panels absorb >90% of the incoming MWIR/LWIR radiation (>3 microns), and
4) the one part of the MWIR spectrum the panels reflect coincides with the peak of thermal radiation from objects that are 0-30°C (8-10 microns).

As the SPRUCE greenhouse panels transmit most of the VNIR wavelengths, PAR is reduced inside the enclosure, but only minimally. In the MWIR/LWIR, the story becomes more complicated. Since and the enclosure walls absorb most of the incoming radiation, the panels are likely a couple of degrees warmer than ambient air temperature when the sun is shining. In addition, the panels have a strong reflection feature at ~9 microns that reflects a fraction of the thermal energy emitted by the air, vegetation, and enclosure walls is back into the enclosure.

Thermal energy from the interior that is not reflected ends up being absorbed by the panels and reemitted back into the chamber.

Therefore, the presence of the SPRUCE enclosure walls do not have a drastic effect on ambient PAR for the enclosed vegetation (20% reduction, as shown in Fig. 11), with the exception of shadows cast by the structure. However, the enclosure will minimize heat loss to the surroundings, and keep surface conditions within the enclosures warmer day and night than similar surfaces in the bog that are fully open to the sky. Since the frustum opening restricts radiation losses to the sky (in terms of solid angle), the interior of the enclosure cool slower than unchambered ambient plots, and the interior microenvironment of the enclosure behaves more like the understory of a closed forest canopy. Instead of seeing 180° of cold, clear sky, as the unchambered ambient plots do, the interior of SPRUCE enclosures experience a warmer apparent sky temperature with increased incoming longwave radiation, as shown in Fig. 12.

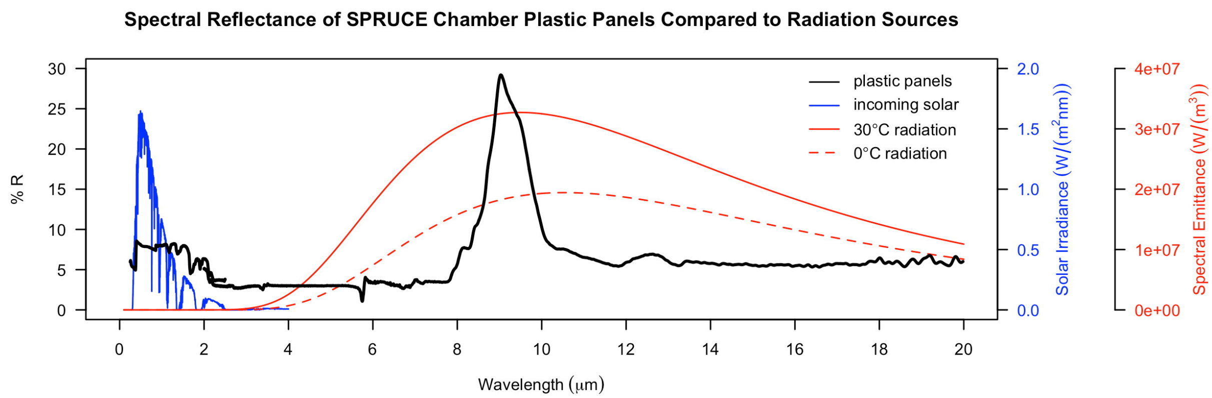

Figure S3: Spectral reflectance of SPRUCE enclosure plastic panels compared to radiation sources.

Air warming PID details

MAU_Control = TA_2M_AVG_5minAmb + (Temp_target + Bias_Air)
AirTemp_Diff = TA_2M_AVG_5min - TA_2M_AVG_5minAmb
PID_Diff_Air = MAU_Control - TA_2M_AVG_5min
I_Air = I_Air + P_Air
If I > MaxI_Air Then I = MaxI_Air
If I < MaxI_Air Then I = -MaxI_Air
P_Air_Output = P_Air * PFact_Air
I_Air_Output = I_Air * IFact_Air
PID_Scale = The range of temperature to scale the 4 to 20 mAmp control signal for the LP gas furnaces.
Bias_Air = offset

Code from the Campbell Logger

```
P_Air = PID_Diff_Air
        I_Air = I_Air + P_Air
        If I_Air = NAN Then I_Air = 0
        If I_Air > MaxI_Air Then I_Air = MaxI_Air
        If I_Air < -MaxI_Air Then I_Air = -MaxI_Air
        P_Air_Output = P_Air * PFact_Air
        I_Air_Output = I_Air * IFact_Air
        PID_Air_Output = ((P_Air_Output + I_Air_Output) * PID_Scale_Air)-3000
```

The 4 to 20 mAmp interface is scaled as -3000 = 4 mAmps and 5000 = 20 mAmps
5000 + 3000 = 8000
20 - 4 = 16
16 / 8000 = .0.002

Example ((5000 + 3000) * 0.002) + 4 = 20

PID_Scale Example (1)
If we want the range of control to be 0.6 degrees C Then 8000 / 0.6 = 13333.333

PID_Scale Example (2)
If we want the range of control to be 3.0 degrees C Then 8000 / 3 = 2666.6666

Table S1. Air Temperature PID Control Settings

Treatment	Plot #	P_Fact_**Air**	I_Fact_**Air**	PID_Scale_**Air**	MaxI_AIR	Bias_Air
+2.25	Plot_11	0.25	0.015	8000	20	0.02
+2.25	Plot_20	0.25	0.015	8000	20	0
+4.5	Plot_4	0.3	0.08	3555.5555	20	0
+4.5	Plot_13	0.3	0.1	3555.5555	20	0
+6.75	Plot_8	0.4	0.03	2666.6666	20	0

+6.75	Plot_16	0.4	0.04	2666.6666	20	0
+9	Plot_10	0.25	0.025	2666.6666	30	0
+9	Plot_17	0.3	0.025	5333.3333	30	0

Control settings for air temperature control as seen in Table S1. Air Temperature PID Control Settings are very similar but not always the same for the same treatments. This may be explained by slight differences in wind patterns across the S1 bog, differences in the efficiencies of the LP gas furnaces, and vegetation differences inside the individual plots.

Soil warming PID details

```
PV =  Process Variable (TS_200cm) A,B or C Probes
P =  (TS_200cm_Amb_Avg + Temp Treatment) - PV
I = I + P
If I > MaxI Then I = MaxI
If I < MaxI Then I =  -MaxI
P_Output  = P * Pfact
I_Output = I * Ifact
PID_Scale = The range of temperature to scale the 4 to 20 mAmp control signal for the SCR's
Bias_A(B,C) = offset
```

Code from Logger Program

```
RingA= TS_200cm_Amb_Avg + (Temp_target + Bias_A)
PID_Diff_A = RingA - A_200cm
 P_A = PID_Diff_A
        I_A=I_A+P_A
        If I_A > MaxI Then  I_A = MaxI
        If I_A < -MaxI Then I_A = -MaxI
        P_A_Output = P_A * PFact_A
        I_A_Output = I_A * IFact_A
        PID_A_Output = ((P_A_Output + I_A_Output) * PID_Scale_A)-3000
```

The 4 to 20 mAmp interface is scaled as -3000 = 4 mAmps and 5000 = 20 mAmps

5000 + 3000 = 8000
20 - 4 = 16
16 / 8000 = .0.002

Example ((5000 + 3000) * 0.002) + 4 = 20

PID_Scale Example (1)
If we want the range of control to be 0.6 degrees C Then 8000 / 0.6 = 13333.333

PID_Scale Example (2)
If we want the range of control to be 3.0 degrees C Then 8000 / 3 = 2666.6666

Table S2. Soil temperature PID control settings

Treatment	Plot #	P_Fact_A	I_Fact_A	PID_Scale_A	P_Fact_B	I_Fact_B	PID_Scale_B	P_Fact_C	I_Fact_C	PID_Scale_C	MaxI	Bias_A	Bias_B	Bias_C
+2.25	PLOT_11	0.6	0.0015	4000	0.6	0.0015	4000	0.6	0.0015	4000	100	0	0	0.11
+2.25	PLOT_20	0.6	0.0015	4000	0.6	0.0015	4000	0.6	0.0015	4000	100	0	0	0
+4.5	PLOT_4	1.5	0.00113	3555.5555	1.6	0.00113	3555.5555	1.85	0.00113	3555.555	100	0	0.07	0.07
+4.5	PLOT_13	1.65	0.00113	3555.5555	1.6	0.00113	3555.5555	1.85	0.00113	3555.5555	100	0.15	0	0.1
+6.75	PLOT_8	2.1	0.0085	2666.6666	2.1	0.0015	2666.6666	2.2	0.0015	2666.6666	100	0.12	0.15	0.3
+6.75	PLOT_16	2.1	0.0035	2666.6666	0.0015	0.0085	2666.6666	0.0015	0.003	2666.6666	100	0.26	0.2	0.15
+9	PLOT_10	2.1	0.0015	2666.6666	2.1	0.0015	2666.6666	1.7	0.0015	2666.6666	100	0.0	0.43	0.2
+9	PLOT_17	2.1	0.0015	2666.667	2.1	0.0015	2666.667	1.7	0.0015	2666.667	100	0.0	0.13	0.34

Table S3. Time required to reach DPH differentials by treatment plot.

Plot	Treatment (°C)	Date Soil Temp Monitoring Began	Date Treatment Began	Time Treatment Began (CST)	Days to Achieve Target °C Differentials for A and B Series within each plot
6	Control (+0)	2/25/14	NA	NA	0
19	Control (+0)	6/18/14	NA	NA	0
10	+9	5/19/14	6/17/14	14:00	81
17	+9	6/9/14	6/17/14	16:00	66
8	+6.75	5/20/14	6/25/14	9:30	94
16	+6.75	6/9/14	6/23/14	15:55	71
4	+4.5	2/25/14	7/2/14	13:00	58
13	+4.5	5/20/14	6/26/14	13:30	51
11	+2.25	5/20/14	7/1/14	13:00	22
20	+2.25	6/17/14	6/25/14	10:00	24

Figure S4: Left photograph is a completed SPRUCE warming enclosure, and the right photograph shows the subtending hydrologic corral that lies beneath each enclosure. The encircling and interlocked sheet piles extend through the peat to the ancient lake bed below, and effectively isolate the hydrology of the enclosure.

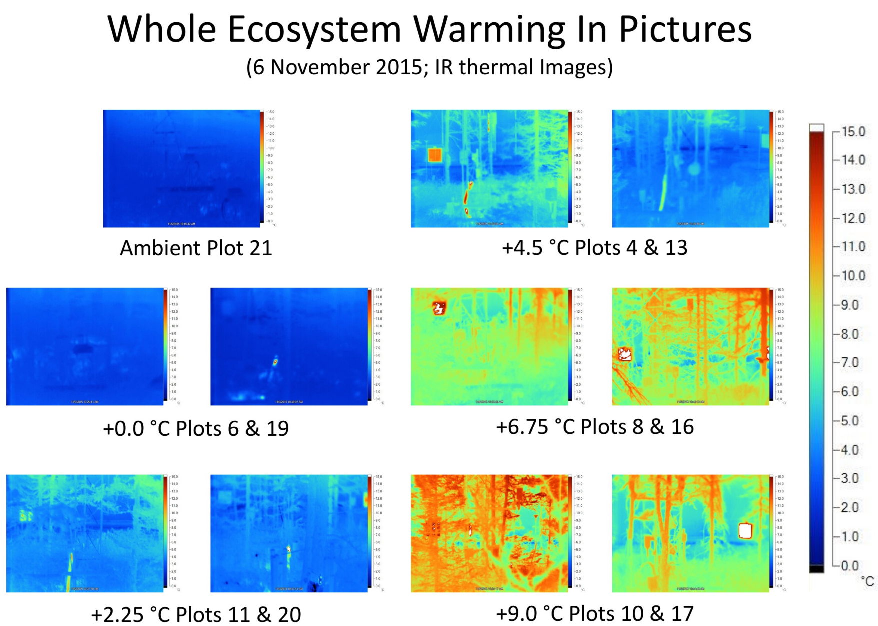

Figure S5: Color infrared images for the space within the designated treatment enclosures and an unchambered ambient plot recorded on November 6, 2015 just before sunrise within a 30-minute period. The thermal color scale in °C applies to all images. Non-biological metal or plastic surfaces in the images may not provide an accurate temperature due to their emissivity difference from biological surfaces.

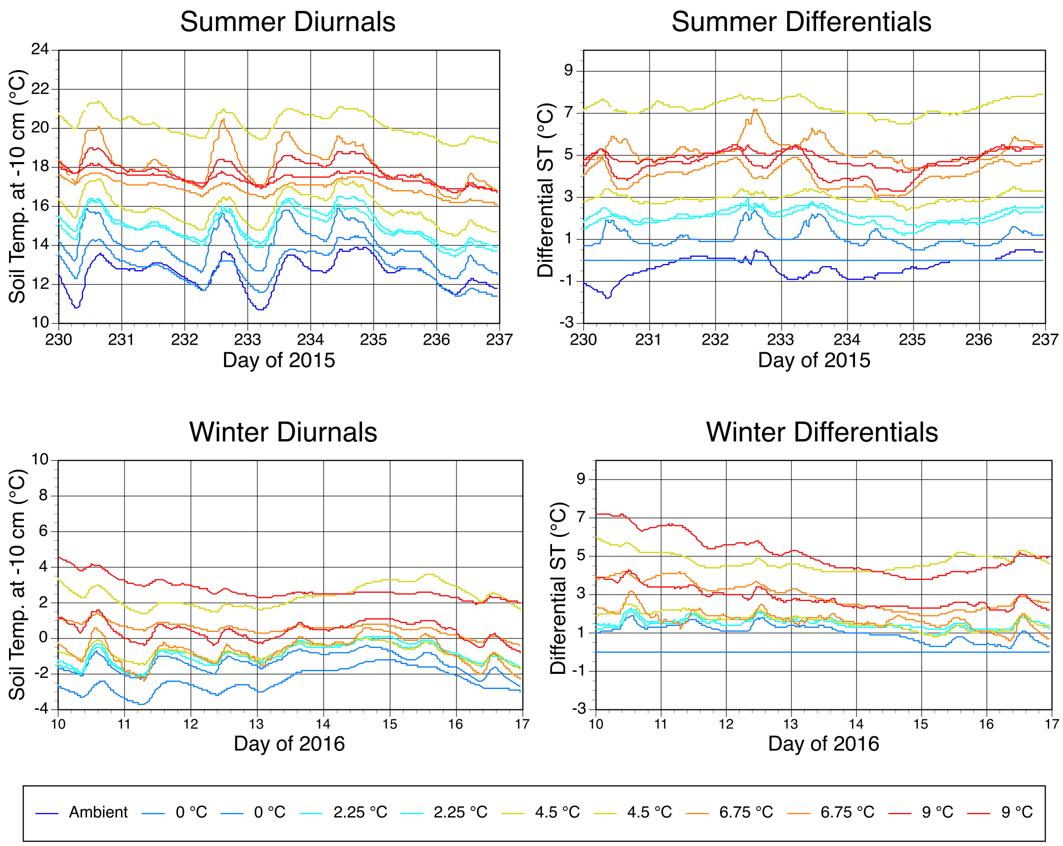

Figure S6: Warm and cold season, seven-day example data for the diurnal variations in soil temperatures at -0.1 m. Calculated differentials with respect to reference Plot 6 are provided in the right hand column.

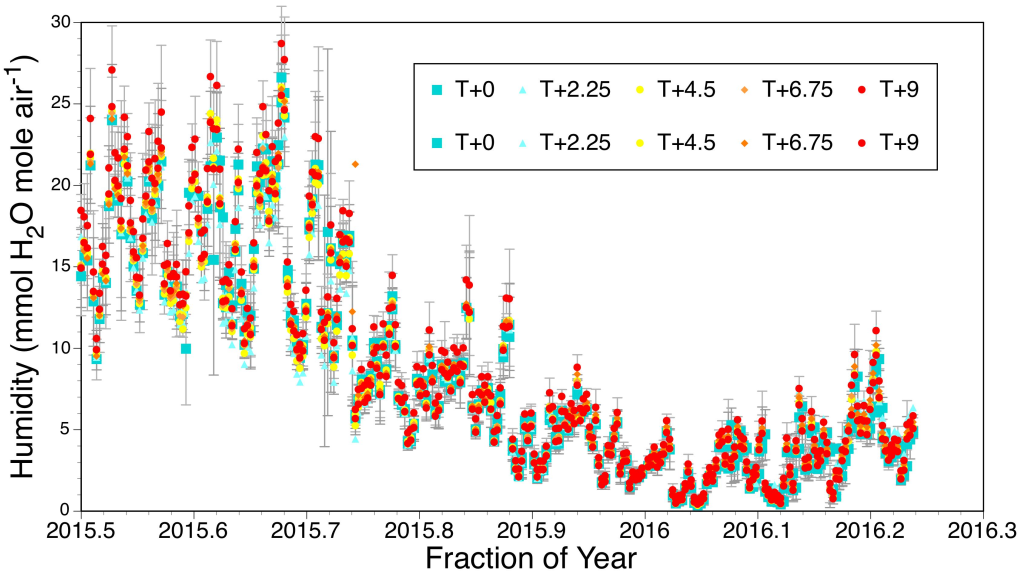

Figure S7: Absolute humidity by treatment enclosure from mid-year 2015 through early 2016. For clarity of the image, standard error bars all in grey are included only for the control (T+0) and the warmest (T+9) plots.

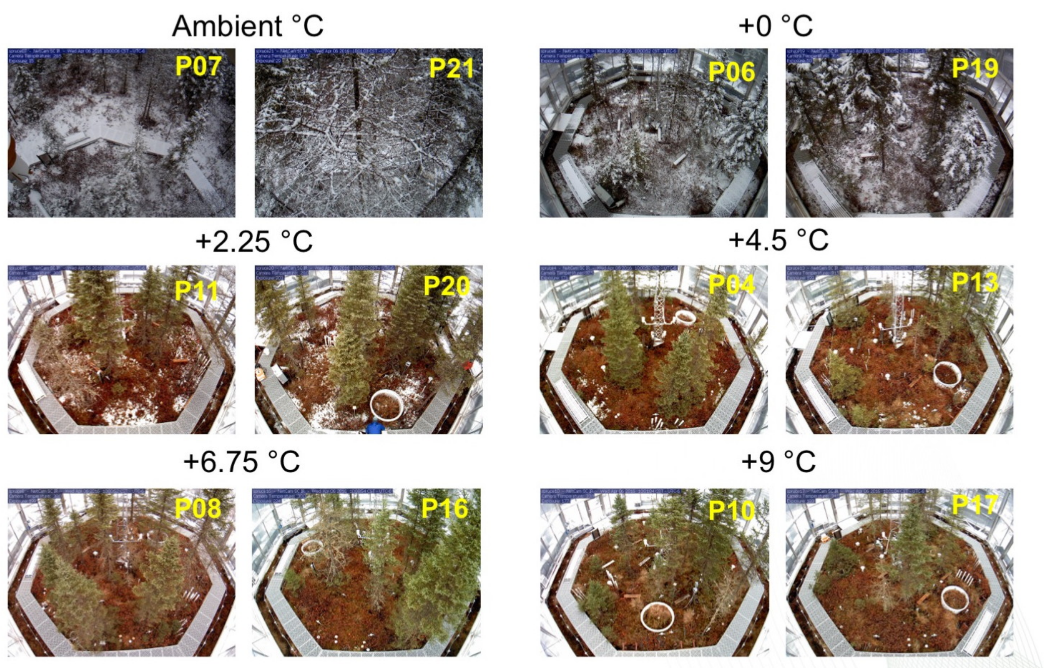

Figure S8: Images of snow accumulation at unchambered ambient locations and within all treatment enclosures by target warming temperature differentials at 10:00 on 6 April 2016. Little obvious snow accumulation is apparent above the +4.5 °C treatment, even though precipitation in the form of snow does enter all enclosures.

Additional graphics from the SPRUCE Enclosure Energy Simulations (D. Ricciuto)

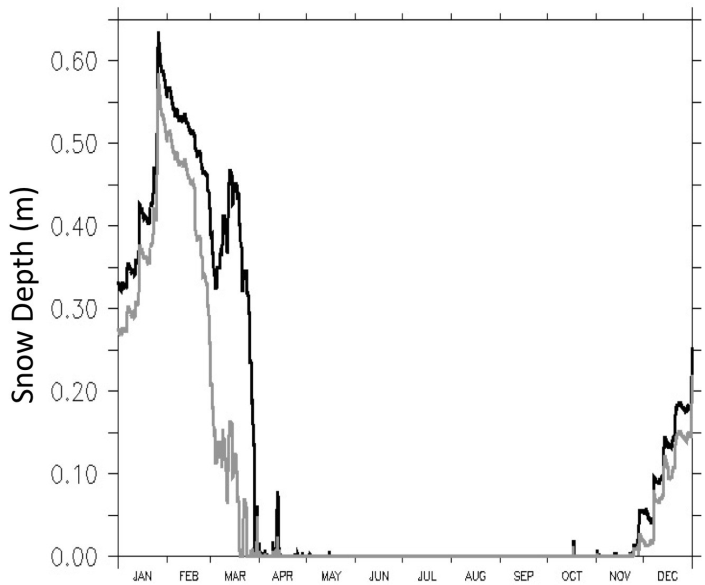

Figure S9: Simulations of snow depth for ambient conditions (black) and within an enclosure (grey) using driver meteorology data from 2013.

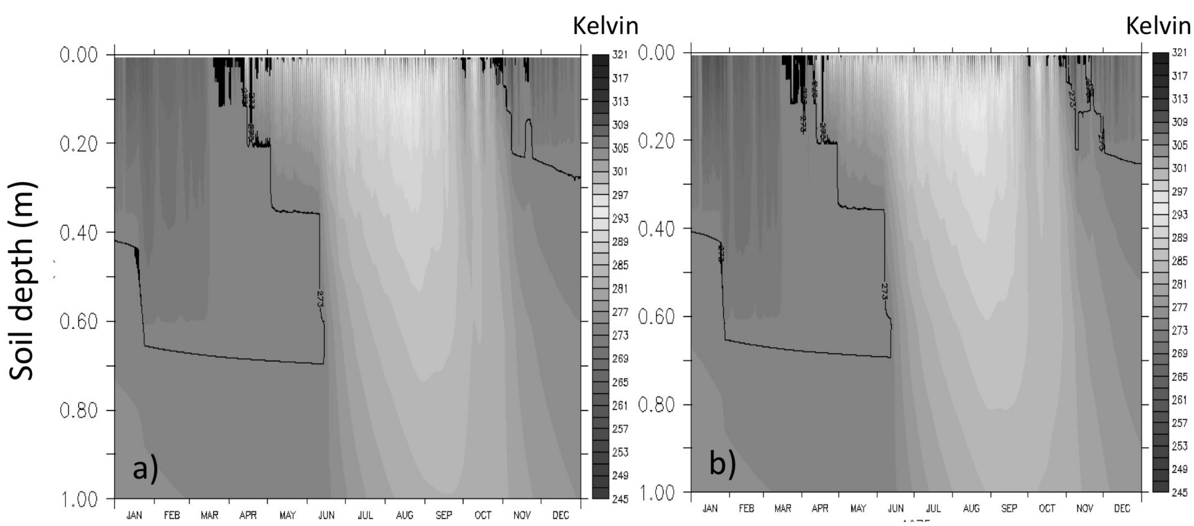

Figure S10: Profiles of simulated top 1m soil temperature in ambient (a) and enclosure (b) simulations. Contour colors represent peat temperatures in degrees kelvin, and the black contour indicates those layers that are below freezing during the year. Ice depths are similar between the simulations.

Elevated CO_2 Protocol Details

During the period from January through March 2016 when biological activities were minimal, various test were conducted on Plot 19 (a constructed control), Plot 11 (+2.25 °C), Plot 4 (+4.5 °C), Plot 8 (+6.75 °C) and Plot 10 (+9 °C) to establish the CO_2 addition control protocols. Over a multi-day period with variable winds, a fixed amount of CO_2 ranging from 150 to 300 l min^{-1} of pure CO_2, depending on target temperature levels, was added to the enclosure for a multiple day period to generate a profile of achieved CO_2 differentials (mean at 0.5, 1 and 2 m heights) as a function of the wind velocities measured at +10 m. A fitted relationship between wind velocity at +10 m and enclosure fractional air turnover volumes (assuming and enclosure volume of 911 m^3) was derived from these data. Instantaneous measured wind velocities were then applied to a turnover fraction equation to estimate the amount of CO_2 to be added to achieve a +500 µmol mol^{-1} value over ambient-CO2 measured within the constructed control plot (i.e., Plot 6). An example is as follows:

TF = (0.00001330297 *WS^6) + (-0.0003804215 *WS^5) + (0.003932579 * WS^4) + (-0.01517648 * WS^3) + (-0.004974471 * WS^2) + (0.2532064 * WS)

where TF is enclosure turnover fraction (unit less), and WS is wind velocity (m s^{-1}). The form of the TF equation might also be a simple exponential function depending on the calibration data set for a given plot.

Using the TF value, an initial coarse control value for CO_2 addition was calculated as:

Course CO_2 Addition = CCO2 = EV * TF * DetaCO2 * 1000

where CCCO2 is the CO_2 addition rate in l min^{-1}, EV is the enclosure volume in m3 (~910 m3), DeltaCO_2 is the desired target increase in CO_2 above ambient conditions (500 µmol mol^{-1} or 0.0005 m^3 m^{-3}), and 1000 allows for the conversion from m^3 to liters. To further account for the variation in enclosure turnover times with external winds the DeltaCO2 values were supplemented with added amounts as shown in the following table.

Table S4. DeltaCO_2 adjustment values for low, medium and high winds by treatment plot.

CO_2 Treatment Plot #	Low Wind Adjustment (ppm)	Medium Wind Adjustment (ppm)	High Wind Adjustment (ppm)
4	50	50	50
10	125	75	40
11	75	75	75
16	50	25	0
19	75	50	0

Yet additional fine control to achieve target differential CO_2 concentrations within the enclosure was based on a feedback adjustment defined by the error in achieving +500 µmol mol^{-1}.

CO2ERR = 500 – (CO2Enclosure – CO2Ambient)

Final CO_2 Addition = FCO2 = (910.6 * CO2ERR)/1000000*1000*1.15

where CO2ERR is the observed difference of enclosure CO_2 when compared with CO_2 in the constructed control (Plot 6), 1000000 and 1000 convert m^3 to L, and 1.15 is an arbitrary valued needed to achieve good results (probably accounting for unmeasured vertical winds). This combined control algorithm reevaluated every 10 seconds during active CO_2 additions, allowed us to achieve target CO_2 levels within the enclosure within a ± 50 µmol mol^{-1} band around our target of + 500 µmol mol^{-1} CO_2. We will continue to adjust the algorithm for CO_2 additions as we operate to allow each enclosure to achieve +500 ± 25 µmol mol^{-1} for all wind conditions and temperature treatments.

Elevated CO_2 additions are only made during daytime hours as a cost reducing measure, because past studies have shown that there is no direct effect of elevated CO_2 on respiratory processes (Amthor 2000; Amthor et al. 2001; Tjoelker et al. 2001). The elevated CO_2 treatments are initiated or stopped each day based on calculated solar angles for each day of the year using the Solpos algorithm developed by the National Renewable Energy Laboratory (NREL).

Table S5. Mean daily differential CO_2 achieved from 19 August to 1 September 2016. NA = not applicable.

Warming Level and Plot	Differential [CO_2] in ppm ± sd
Reference Plot - +0.00 °C Plot 06	NA
+2.25 °C Plot 20	-9 ± 8
+4.50 °C Plot 13	-0.1 ± 8
+6.75 °C Plot 13	-13 ± 9
+9.00 °C Plot 04	1 ± 11
eCO_2 +0.00 °C Plot 19	483 ± 22
eCO_2 +2.25 °C Plot 11	471 ± 21
eCO_2 +4.50 °C Plot 04	490 ± 13
eCO_2 +2.25 °C Plot 16	511± 15
eCO_2 +9.00 °C Plot 10	480 ±73

Supplemental Literature

Amthor, J.S.: Direct effect of elevated CO_2 on nocturnal in situ leaf respiration in nine temperate deciduous tree species is small. *Tree Physiol.* 20, 139-144, 2000.

Amthor, J.S., Koch, G.W., Willms, J.R., Layzell, D.B.: Leaf O_2 uptake in the dark is independent of coincident CO_2 partial pressure. *J Exper Bot,* 52, 2235–2238, 2001.

Tjoelker, M.G., Oleksyn, J., Lee, T.D., Reich, P.B.: Direct inhibition of leaf dark respiration by elevated CO2 is minor in 12 grassland species. *New Phytol,* 150, 419–424. doi:10.1046/j.1469-8137.2001.00117.x, 2001.