Spruce Leaf, Tree Traits, and Respiration at Range Extremes, AK and NY, USA, 2018

Get Data

Documentation Revision Date: 2022-10-12

Dataset Version: 1

Summary

This dataset provides in situ measurements of needle-level gas-exchange and leaf traits from Picea glauca (white spruce) from a field site located in the northern latitudinal forest-tundra ecotone (FTE) near the Dalton Highway in northern Alaska, and from one study site located in Black Rock Forest, New York, USA. Measurements were collected with an open flow portable photosynthesis system (Li6400XT) and custom-built temperature-controlled cuvette. Respiration as a function of leaf temperature was measured continuously as the needle temperature was ramped from approximately 5 to 65 degrees C, at a constant rate of 1 degree C per minute. Additional data include tree diameter at breast height (dbh), leaf area, photosynthetic rate, intercellular C02, conductance to H20, tree height, and data from raw temperature curves. Results are reported on both a leaf area and leaf mass basis. The data are for the period 2018-06-06 to 2018-06-23 and are provided in comma-separated (CSV) format.

There are five data files in comma-separated (.csv) format with this dataset.

Figure 1. Species distribution for white spruce, Picea glauca. The southern range limit site, Black Rock Forest, Cornwall, NY, is marked with the red star. The arctic treeline site in northern Alaska is marked with a yellow star. Map from USGS from Thompson et al. (1999), in Griffin et al. (2022).

Citation

Griffin, K., S.C. Schmiege, S.G. Bruner, N. Boelman, L. Vierling, J. Eitel, and Z.M. Griffin. 2022. Spruce Leaf, Tree Traits, and Respiration at Range Extremes, AK and NY, USA, 2018. ORNL DAAC, Oak Ridge, Tennessee, USA. https://doi.org/10.3334/ORNLDAAC/1948

Table of Contents

1. Dataset Overview

This dataset provides in situ measurements of needle-level gas-exchange and leaf traits from Picea glauca (white spruce) from a field site located in the northern latitudinal forest-tundra ecotone (FTE) near the Dalton Highway in northern Alaska, and from one study site located in Black Rock Forest, New York, USA. Measurements were collected with an open flow portable photosynthesis system (Li6400XT) and custom-built temperature-controlled cuvette. Respiration as a function of leaf temperature was measured continuously as the needle temperature was ramped from approximately 5 to 65 degrees C, at a constant rate of 1 degree C per minute. Additional data include tree diameter at breast height (dbh), leaf area, photosynthetic rate, intercellular $C0_2$, conductance to H_20, tree height, and data from raw temperature curves. Results are reported on both a leaf area and leaf mass basis. The data are for the period 2018-06-06 to 2018-06-23 .

Project: Arctic-Boreal Vulnerability Experiment

The Arctic-Boreal Vulnerability Experiment (ABoVE) is a NASA Terrestrial Ecology Program field campaign being conducted in Alaska and western Canada, for 8 to 10 years, starting in 2015. Research for ABoVE links field-based, process-level studies with geospatial data products derived from airborne and satellite sensors, providing a foundation for improving the analysis, and modeling capabilities needed to understand and predict ecosystem responses to, and societal implications of, climate change in the Arctic and Boreal regions.

Related Publications

Griffin, K.L., Z.M. Griffin, S.C. Schmiege, S.G. Bruner, N.T. Boelman, L.A. Vierling, and J.U.H. Eitel. 2022. Variation in White spruce needle respiration at the species range limits: a potential impediment to Northern expansion. Plant, Cell & Environment 45:2078-2092. https://doi.org/10.1111/pce.14333

Griffin, K.L., S.C. Schmiege, S.G. Bruner, N.T. Boelman, L.A. Vierling, and J.U.H. Eitel. 2021. High leaf respiration rates may limit the success of white spruce saplings growing in the *Kampfzone* at the Arctic Treeline. Frontiers of Plant Science 12:746464. https://doi.org/10.3389/fpls.2021.746464

Related Datasets

Eitel, J., A.J. Maguire, K. Griffin, N. Boelman, J.E. Jensen, S.C. Schmiege, and L. Vierling. 2020. ABoVE: Photochemical Reflectance and Tree Growth, Brooks Range, Alaska, 2018-2019. ORNL DAAC, Oak Ridge, Tennessee, USA. https://doi.org/10.3334/ORNLDAAC/1781

Maguire, A.J., J. Eitel, L. Vierling, N. Boelman, K. Griffin, J.S. Jennewein, and J.E. Jensen. 2020. ABoVE: Terrestrial Lidar Scanning Forest-Tundra Ecotone, Brooks Range, Alaska, 2016. ORNL DAAC, Oak Ridge, Tennessee, USA. https://doi.org/10.3334/ORNLDAAC/1782

Maguire, A.J., J. Eitel, K. Griffin, S.C. Schmiege, S.G. Bruner, N. Boelman, and W. Weygint. 2020. ABoVE: Needle-Level Chlorophyll Fluorescence, Alaska and Idaho, USA, 2017 and 2019. ORNL DAAC, Oak Ridge, Tennessee, USA. https://doi.org/10.3334/ORNLDAAC/1785

Acknowledgment

This work was supported by NASA ABoVE grant NNX15AT86A and generally by the Arctic LTER (NSF Grant No. 1637459).

2. Data Characteristics

Spatial Coverage: northern Alaska and Black Rock Forest, New York, USA

ABoVE gridding system:

- Domain: Core
- Grid cells: Ah001v000, Bh007v003, Ch045v022, Ch045v023, Ch046v022, Ch046v023

Spatial Resolution: Point

Temporal Coverage: 2018-06-06 to 2018-06-23

Temporal Resolution: Gas exchange variables and rates were recorded every 20 seconds; other measurements were one-time measurements

Study Area: Latitude and longitude are given in decimal degrees.

Sites	Westernmost Longitude	Easternmost Longitude	Northernmost Latitude	Southernmost Latitude
Alaska, near the Dalton Highway	-149.9551	-149.6063	67.8889	67.6488
Black Rock Forest, New York	-74.0246	-74.0246	41.4011	41.4011

Data File Information

There are five data files in comma-separated (.csv) format with this dataset. The files provide respiration measurements, leaf traits, and tree traits from the Northern and Southern Spruce range extremes.

Table 1. File names and descriptions

File Name	Description
AK_Tundra_Spruce_Raw_RespTemp_Curves.csv	Output of the raw LI-6400xt respiration temperature curves for Alaska site.
AK_Tundra_Spruce_Analysis_RespTemp.csv	Results of the data analysis from the raw temperature curves for Alaska site. A simple polynomial model described by Heskel et al (2016) was used to describe the relationship between temperature and respiration.
BlackRockForest_RespTemp_Results.csv	White spruce respiratory traits for Black Rock Forest, New York, from Griffin et al. (2022).
BlackRockForest_RespTemp_curves_Raw.csv	Raw LI-6400xt respiration temperature curves for Black Rock Forest, New York.

Leaf_Traits_AK_BlackRockForest.csv	Leaf trait results for Alaska and New York white spruce from Griffin et al. (2022).

Table 2. Variables in the file **AK_Tundra_Spruce_Raw_RespTemp_Curves.csv**

Variable	Units	Description
plot		Plot number: 1-6
latitude_north	degrees north	Northernmost latitude of study site
latitude_south	degrees north	Southernmost latitude of study site
longitude_east	degrees east	Easternmost longitude of study site
longitude_west	degrees east	Westernmost longitude of study site
tree		Tree identifier at each Plot: a-f
photo_rate	micromol m^{-2} s^{-1}	Photosynthetic rate
conductance_h2o	mol m^{-2} s^{-1}	Conductance to H_2O
intercellular_co2	micromol m^{-2} s^{-1}	Intercellular CO_2 exchange
transpiration_rte	mmol m^{-2} s^{-1}	Transpiration rate
leaf_area	cm^2	Leaf area of the sample
leaf_thermocouple_temp	Degrees C	Temperature of the leaf thermocouple
co2_reference	micromol mol^{-1}	Reference CO_2 concentration
co2_sample	micromol mol^{-1}	Sample CO_2 concentration
h20_reference	mmol mol^{-1}	Reference H_2O concentration
h20_sample	mmol mol^{-1}	Sample H_2O concentration
flow_rate	micromol s^{-1}	Flow rate to the chamber
date	YYYY-MM-DD	The date the curve was measured
species		*Picea glauca* (pigl)
replication_number	1	Replication number in case any curves were remeasured
canopy_position		Canopy position: "low" or "high"
leaf_fresh_mass	g	Leaf sample wet mass
leaf_dry_mass	g	Leaf sample dry mass
sample		Unique name of each curve/sample (concatenated Plot, Tree, Rep, Canopy)
site		Alaska: AK
dbh	cm	Diameter at breast height of measured trees
height	m	Height of measured trees
size_class		Size class of trees: "large" or "small." Small trees (or saplings) are defined as 5-10 cm DBH, Large trees are >10 cm DBH
resp_area	micromol m^{-2} s^{-1}	Area-based respiration rate
resp_mass	micromol g^{-1} s^{-1}	Mass-based respiration rate

Table 3. Variables in the file **AK_Tundra_Spruce_Analysis_RespTemp.csv**

Variable	Units	Description
plot		Plot number: 1-6
date	YYYY-MM-DD	The date the curve was measured
latitude_north	degrees north	Northernmost latitude of study site

latitude_south	degrees north	Southernmost latitude of study site
longitude_east	degrees east	Easternmost longitude of study site
longitude_west	degrees east	Westernmost longitude of study site
tree		Tree identifier at each Plot: a-f
canopy		Canopy position: "low" or "high"
sample		Unique name of each curve/sample (concatenated Plot, Tree, Rep, Canopy)
a_area	1	a polynomial coefficient, area-based respiration temperature curve
b_area	1	b polynomial coefficient, area-based respiration temperature curve
c_area	1	c polynomial coefficient, area-based respiration temperature curve
a_mass	1	a polynomial coefficient, mass-based respiration temperature curve
b_mass	1	b polynomial coefficient, mass-based respiration temperature curve
c_mass	1	c polynomial coefficient, mass-based respiration temperature curve
max_temp_resp_area	micromol m^{-2} s^{-1}	Respiration at the maximum temperature of the respiration temperature curve
max_temp_rt_curve	C	Maximum temperature of the RT curve (degrees Celsius)
resp_25c_area	micromol m^{-2} s^{-1}	Respiration at 25° C on an area basis
resp_25c_mass	micromol m^{-2} s^{-1}	Respiration at 25° C on an mass basis
replication_number	1	Replication number in case any curves were remeasured
leaf_area	cm^2	Leaf area of the sample
leaf_fresh_mass	g	Leaf sample wet mass
leaf_dry_mass	g	Leaf sample dry mass
site		Alaska: AK
dbh	cm	Diameter at breast height (DBH) of measured trees (cm)
height	m	Height of measured trees (m)
size_class		Size class of trees: large or small. Small trees (or saplings) are defined as 5-10 cm DBH, Large trees are >10 cm DBH
sla	cm^2 g^{-1}	Specific leaf area of each sample
leaf_dry_matter	g g^{-1}	Leaf dry matter content

Table 4. Variables in the file **BlackRockForest_RespTemp_Results.csv**

Variable	Units	Description
site		BRF (Black Rock Forest, NY)
plot		Plot number: 1
tree		Tree identifier at each plot, 1-6
canopy		Canopy position: "low" or "high"
sample		Unique name of each curve/sample (concatenated Site, “Spruce”, Tree, Canopy)
a_area	1	a polynomial coefficient, area-based respiration temperature curve
b_area	1	b polynomial coefficient, area-based respiration temperature curve
c_area	1	c polynomial coefficient, area-based respiration temperature curve
max_r_area	micromol m^{-2} s^{-1}	Respiration at the maximum temperature of the respiration temperature curve
max_temp	C	Maximum temperature of the RT curve in degrees Celsius
r25_area	micromol m^{-2} s^{-1}	Respiration at 25° C on an area basis
species		*Picea glauca* (pigl)
rep	1	Replication number in case any curves were remeasured
size_class		Size class of trees- large (DBH > 10cm)

dbh	cm	Diameter at breast height (DBH) of measured trees (cm)
height	m	Height of measured trees (m)
leaf_area	cm^2	Leaf area of the sample
leaf_fresh_mass	g	Leaf sample wet mass
Leaf_dry_mass	g	Leaf sample dry mass
leaf_dry_matter	mg g^{-1}	Leaf dry matter content (mg dry mass for each gram of fresh mass)
sla	cm^2 g^{-1}	Specific leaf area of each sample

Table 5. Variables in the file **BlackRockForest_RespTemp_Curves_Raw.csv**

Variable	Units	Description
site		BRF (Black Rock Forest, New York)
plot		Plot number- 1
tree		Tree identifier at each plot, 1-6
photosynthetic_rate	micromol m^{-2} s^{-1}	Photosynthetic rate
conductance	mol m^{-2} s^{-1}	Conductance to H_2O
intercellular_co2	micromol mol^{-1}	Intercellular CO_2
transpiration_rate	mmol m^{-2} s^{-1}	Transpiration rate
leaf_area	cm^2	Leaf area of the sample
t_leaf	Degrees C	Temperature of the leaf thermocouple
co2_reference	micromol mol^{-1}	Reference CO_2 concentration
co2_sample	micromol mol^{-1}	Sample CO_2 concentration
h2o_reference	mmol mol^{-1}	Reference H_2O concentration
h2o_sample	mmol mol^{-1}	Sample H_2O concentration
flow	micromol s^{-1}	Flow rate to the chamber
canopy		Canopy position: "low" or "high"
leaf_fresh_mass	g	Leaf sample wet mass
leaf_dry_mass	g	Leaf sample dry mass
sample		Unique name of each curve/sample (concatenated Site, “Spruce”, Tree, Canopy)
r_area	micromol m^{-2} s^{-1}	Area-based respiration rate
date	YYYY-MM-DD	The date the curve was measured
species		*Picea glauca* (pigl)
rep		Replication number in case any curves were remeasured
size_class		Size class of trees, large (DBH >10cm)
dbh	cm	Diameter at breast height (DBH) of measured trees
height	m	Height of measured trees
size_class		Size class of trees, large (DBH >10cm)

Table 6. Variables in the file **Leaf_Traits_AK_BlackRockForest.csv**

Variable	Units	Description
sample		Unique name of each curve/sample (for AK concatenated Plot, Tree, Rep, Canopy; for BRF- concatenated Site, “Spruce”, Tree, Canopy)
site		Alaska or BRF (Black Rock Forest, New York)
plot		Plot number- for AK- 1-6; for BRF- 1
tree		Tree identifier at each Plot- 1-6
canopy		Canopy position- low or high
carbon	percent	Foliar percent carbon

nitrogen	percent	Foliar percent nitrogen
ratio_carbon_nitrogen	ratio	Ratio of carbon to nitrogen
delta13C	C isotope ratio ml^{-1}	Foliar carbon isotope ratio (per ml)
delta15N	Nitrogen isotope ratio ml^{-1}	Foliar nitrogen isotope ratio (per mil)
leaf_fresh_mass	g	Leaf sample wet mass
leaf_dry_mass	g	Leaf sample dry mass
leaf_dry_matter	mg g^{-1}	Leaf dry matter content (mg dry mass for each gram of fresh mass)
percent_water	percent	Foliar percent water
sla	cm^2 g^{-1}	Specific leaf area of each sample
leaf_area	cm^2	Leaf area of the sample
nitrogen_per_leaf_area	mg m^{-2}	Foliar nitrogen per leaf area (mg N per m^2)
resp_25c_mass	micromol g^{-1} s^{-1}	Mass-based respiration at 25C
rep		Replication number in case any curves were remeasured
species		*Picea glauca* (pigl)

3. Application and Derivation

Arctic Treeline is the transition from the boreal forest to the treeless tundra and may be determined by growing season temperatures. The environmental and physiological mechanisms that determine the location of treeline are not fully understood. This study demonstrates that the respiratory characteristics of white spruce saplings at treeline impose a significant carbon cost that may contribute to their lack of perseverance beyond treeline. In the absence of thermal acclimation, the rate of leaf respiration could increase by 57% by the end of the century, posing further challenges to the ecology of this massive ecotone.

4. Quality Assessment

Raw data are analyzed for stability during the gas exchange measurements. Typical measures of statistical confidence are used throughout.

5. Data Acquisition, Materials, and Methods

Methods are the same for both sites unless stated otherwise. Refer to Griffin et al. (2021, 2022) for additional details.

Study Sites and Sampling

Leaf samples were collected from two locations at the northern and southern range extremes of the White Spruce (*Picea glauca*) distribution. During June and July 2018, samples were collected from six field sites located in northern Alaska on the southern side of the Brooks Range along a 5.5 km stretch of the Dalton Highway, and in June 2018 at the southern range extreme, from a single site located in Black Rock Forest, New York, USA, along Continental Road. Samples were collected from branches of upper and lower canopy adult White Spruce trees.

At each site of the six sites in Alaska, a circular plot with 10-m radius (314 m^2 area) was established, and six white spruce trees from two different size classes were tagged. The size classes were chosen to differentiate “trees” (≥ 10 cm DBH) from “saplings” (<10 cm DBH). Leaves were sampled from the lower canopy and the upper canopy on each of the 36 target trees, made up of 18 saplings and 18 trees, for gas exchange analysis. Leaves were sampled from one site in Black Rock Forest, New York from trees ≥ 10 cm DBH (Griffin et al., 2022). The terminal portions of several branches were cut with sharp pruners (bottom of the canopy) or a pole clipper (top of the canopy), and the removed portion of the stem was immediately wrapped with wet paper towels, sealed in a plastic bag with ample air and placed in a cooler where they were kept in the dark until arriving in the lab. The location of the lower samples was approximately 1.37 m above the ground and were collected from the south side of the canopy. The location of upper samples was approximately 1 m from the terminal apex of each tree and were collected from the south side of the canopy. Once returned to the lab, the stems were recut underwater and placed in a beaker containing enough water to keep the cut end submerged until analyzed, typically within 8, but no more than 24 hours.

Respiration Temperature Response Curves

To assess average respiration rates, CO_2 exchange rates were measured at a common temperature (25°C, R25) and at various temperatures to quantify the response of respiration to temperature, . The individual leaves (needles) were carefully removed from the stems to avoid the large contribution the stem would otherwise have made to the CO_2 flux thereby confounding the results (e.g. (Heskel et al., 2014)). These needles were weighed to determine the initial fresh mass (g) and then placed in a fine nylon mesh bag, allowing for easy air flow through the bag while keeping the leaves from entering the optical bench of the infrared gas analyzer or becoming lost in the leaf cuvette. The mesh bag containing the leaves was placed inside a custom-made cuvette milled from a solid block of aluminum with a plexiglass lid sealed with a Viton gasket (Patterson et al., 2018; Li et al., 2019; Schmiege et al., 2021)). The cuvette contained a mixing fan and two fine wire thermocouples to measure leaf and air temperatures. Temperature was thermoelectrically controlled from a laptop computer (using a CP-121 Thermoelectric Peltier Cooling Unit, TE Technology, Traverse City, MI USA). The custom cuvette was interfaced with a portable photosynthesis system (Li-6800XT, LiCor, Lincoln, Nebraska USA).

Respiration temperature curves were collected using an LI-6400xt with a modified leaf chamber attached to a temperature controller. Before each measurement, the system was both equilibrated to 5° C and zeroed. The mesh bag holding the leaves was then sealed inside the cuvette and the system was again equilibrated to 5° C. Once stability was reached, the response curve was measured as described in previous studies (O'Sullivan et al., 2013; Heskel et al., 2016; Schmiege et al. 2021). During measurement, the cuvette temperature was ramped continuously from 5° to 65° C at a constant rate of 1° C min^{-1}. All gas exchange variables and calculated rates were recorded every 20 seconds by the Li-6400XT.

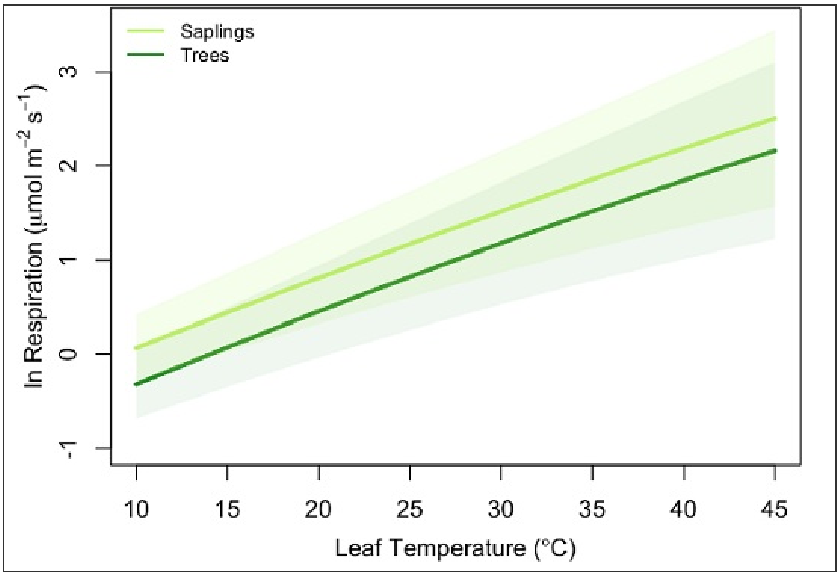

Figure 2. Average model results (log of leaf respiration) for trees (≥ 10 cm DBH – dark green) and saplings (5-10 cm DBH – light green) of *Picea glauca* growing in the Forest Tundra Ecotone in Alaska. Line presents the mean response (n = 36) and shaded area = 95% confidence interval for size class (Griffin et al., 2021).

Leaf Traits

Upon the completion of the temperature response curve, the leaves were removed from the cuvette and photographed with a known scale. ImageJ software (Schneider et al., 2012) was used to determine the projected area of these needles. The leaves were transferred to coin envelopes and dried at 65° C for a minimum of 48 hours. Dried leaves were again weighed to determine leaf dry mass (g). Specific leaf area (SLA $cm^2\ g^{-1}$) was calculated and used to interconvert between area- and mass-based respiratory fluxes. Leaf water content (%) and leaf dry matter content (LDMC) were calculated from the fresh and dry masses. Leaf nitrogen was estimated using the %N measured from these same trees, sampled at the same canopy locations in 2017 (Schmiege et al., unpublished data).

Data Analyses

A simple polynomial model described by Heskel et al. (2016) was used to describe the relationship between temperature and respiration. The model has three coefficients (a, b and c). Estimates of these parameters are provided on both a leaf area and a leaf mass basis. Other derived variables in the dataset include the rate of respiration at 25 °C (on both a leaf area and leaf mass basis) as well as the data needed to convert between the two (specific leaf area and leaf dry matter content).

The respiration-temperature response curves were analyzed as in Heskel et al. (2016) by fitting a second-order polynomial model to the log transformed respiration rates [Ln(R)] between 10° and 45° C:

$$Ln(R) = a + bT + cT^2,$$

where *a* represents the basal respiration rate (y-intercept), and *b* and *c* describe the slope and curvature of the response to temperature (T) (Heskel et al., 2016). From these modeled curves, the respiration rate was derived at a common temperature of 25° C (R25). Using the entire data set between 5° and 65° C, the temperature of the maximum respiration rate was extracted (Tmax).

Before statistical analysis, all traits were transformed as necessary to fulfill statistical assumptions of normality. Statistical differences in *P. glauca* traits between large trees and small saplings including DBH and tree height were assessed using an independent sample t-test. A linear mixed effects model was used to test the main effects of canopy position and tree size on all respiratory parameters (including the polynomial model parameters a, b, and c, area- and mass-based R25, and Tmax) and leaf traits (including SLA, LDMC and %N). This model was used to the incorporate effects of each unique tree as a random effect (using the lme4 and the lmerTest packages; Bates et al., 2015; Kuznetsova et al., 2017, respectively). Finally, model coefficients from the study were compared to those from Heskel et al. (2016) for the Tundra and Boreal biomes, as well as the needle-leaved evergreen (NLEv) plant functional type using the information contained within their Table 1, with an independent sample t-test. For all analyses, statistical significance was assessed using a p-value of 0.05.

Refer to Griffin et al. (2021, 2022) for additional details.

6. Data Access

These data are available through the Oak Ridge National Laboratory (ORNL) Distributed Active Archive Center (DAAC).

Spruce Leaf, Tree Traits, and Respiration at Range Extremes, AK and NY, USA, 2018

Contact for Data Center Access Information:

- E-mail: uso@daac.ornl.gov
- Telephone: +1 (865) 241-3952

7. References

Bates, D., M. Mächler, B. Bolker, and S. Walker. 2015. Fitting linear mixed-effects models using lme4. *Journal of Statistical Software* 67:1–48. https://doi.org/10.18637/jss.v067.i01

Eitel, J., A.J. Maguire, K. Griffin, N. Boelman, J.E. Jensen, S.C. Schmiege, and L. Vierling. 2020. ABoVE: Photochemical Reflectance and Tree Growth, Brooks Range, Alaska, 2018-2019. ORNL DAAC, Oak Ridge, Tennessee, USA. https://doi.org/10.3334/ORNLDAAC/1781

Griffin, K.L., Z.M. Griffin, S.C. Schmiege, S.G. Bruner, N.T. Boelman, L.A. Vierling, and J.U.H. Eitel. 2022. Variation in white spruce needle respiration at the species range limits: a potential impediment to Northern expansion. Plant, Cell & Environment 45:2078-2092. https://doi.org/10.1111/pce.14333

Griffin, K.L., S.C. Schmiege, S.G. Bruner, N.T. Boelman, L.A. Vierling, and J.U.H. Eitel. 2021. High leaf respiration rates may limit the success of white spruce saplings growing in the *Kampfzone* at the Arctic Treeline. Frontiers of Plant Science 12:746464. https://doi.org/10.3389/fpls.2021.746464

Heskel, M.A., O.S. O'Sullivan, P.B. Reich, M.G. Tjoelker, L.K. Weerasinghe, A. Penillard, J.J.G. Egerton, D. Creek, K.J. Bloomfield, J. Xiang, F. Sinca, Z.R. Stangl, A. Martinez-De La Torre, K.L. Griffin, C. Huntingford, V. Hurry, P. Meir, M.H. Turnbull, and O.K. Atkin. 2016. Convergence in the temperature response of leaf respiration across biomes and plant functional types. Proceedings of the National Academy of Sciences of the United States of America 113:3832-3837. https://doi.org/10.1073/pnas.1520282113

Kuznetsova, A., P.B. Brockhoff, and R.H.B. Christensen. 2017. lmerTest package: Tests in linear mixed effects models. Journal of Statistical Software 82:1–26. https://doi.org/10.18637/jss.v082.i13

Li, X.M., C.Y. Xu, Z.Z. Li, J.C. Feng, D.T. Tissue, and K.L. Griffin. 2019. Late growing season carbon subsidy in native gymnosperms in a northern temperate forest. *T*ree Physiology 39:971–982. https://doi.org/10.1093/treephys/tpz024

Maguire, A.J., J. Eitel, L. Vierling, N. Boelman, K. Griffin, J.S. Jennewein, and J.E. Jensen. 2020. ABoVE: Terrestrial Lidar Scanning Forest-Tundra Ecotone, Brooks Range, Alaska, 2016. ORNL DAAC, Oak Ridge, Tennessee, USA. https://doi.org/10.3334/ORNLDAAC/1782

Maguire, A.J., J. Eitel, K. Griffin, S.C. Schmiege, S.G. Bruner, N. Boelman, and W. Weygint. 2020. ABoVE: Needle-Level Chlorophyll Fluorescence, Alaska and Idaho, USA, 2017 and 2019. ORNL DAAC, Oak Ridge, Tennessee, USA. https://doi.org/10.3334/ORNLDAAC/1785

O'Sullivan, O.S., K. Weerasinghe, J.R. Evans, J.J.G. Egerton, M.G. Tjoelker, and O.K. Atkin. 2013. High-resolution temperature responses of leaf respiration in snow gum (*Eucalyptus pauciflora*) reveal high-temperature limits to respiratory function. Plant Cell and Environment 36:1268–1284. https://doi.org/10.1111/pce.12057

Patterson, A.E., R. Arkebauer, C. Quallo, M.A. Heskel, X.M. Li, N. Boelman, and K.L. Griffin. 2018. Temperature response of respiration and respiratory quotients of 16 co-occurring temperate tree species. Tree Physiology 38:1319–1332. https://doi.org/10.1093/treephys/tpx176

Schmiege, S.C., B.M. Buckley, D.W. Stevenson, M.A. Heskel, T.Q. Cuong, L. Nam, and K.L. Griffin. 2021. Respiratory temperature responses of tropical conifers differ with leaf morphology. Functional Ecology 35:1408-1423. https://doi.org/10.1111/1365-2435.13814

Schneider, C.A., W.S. Rasband, and K.W. Eliceiri. 2012. NIH Image to ImageJ: 25 years of image analysis. Nature Methods 9:671–675. https://doi.org/10.1038/nmeth.2089

Thompson, R.S., K.H. Anderson, and P.J. Bartlein. 1999. Atlas of relations between climatic parameters and distributions of important trees and shrubs in North America: Introduction and conifers. U.S. Geological Survey Report 1650. USGS Publications Warehouse. Accessed 2015-05-12. https://doi.org/10.3133/pp1650AB