

1 Increasing atmospheric dryness reduces boreal forest tree
 2 growth

3 **Supplementary Information**

4 **Supplementary Methods**

5 In a hydrometeorological perspective, higher atmospheric dryness increases atmospheric
 6 demand for water from the land surface, and this drives an increase in evapotranspiration and
 7 thus a lowering of the available soil moisture²⁶. Hence, response to atmospheric dryness can
 8 be due to direct VPD effects on conductance and indirect effects on soil moisture through VPD
 9 driving a rise of the evapotranspiration. To differentiate the two processes apart, we examined
 10 the unique contribution of VPD to the tree growth response. We implemented partial models,
 11 where goodness-of-fit for models of BAI in relation to VPD was obtained after removing the
 12 effects of soil moisture availability index (SMI). We then reported the percentage of sites for
 13 which VPD remained significant.

$$14 \quad (A1.a) \quad \log(BAI_{jk}^t) = \beta_{jk} \cdot \log(BA_{jk}^{t-1}) + s(\text{age}^t) + \text{SMI}^t + \text{corAR1}_{jk}(\sim t | \text{Tree}_{ID}) + \\ 15 \quad \text{Tree}_{ID} + \epsilon_{jkt}$$

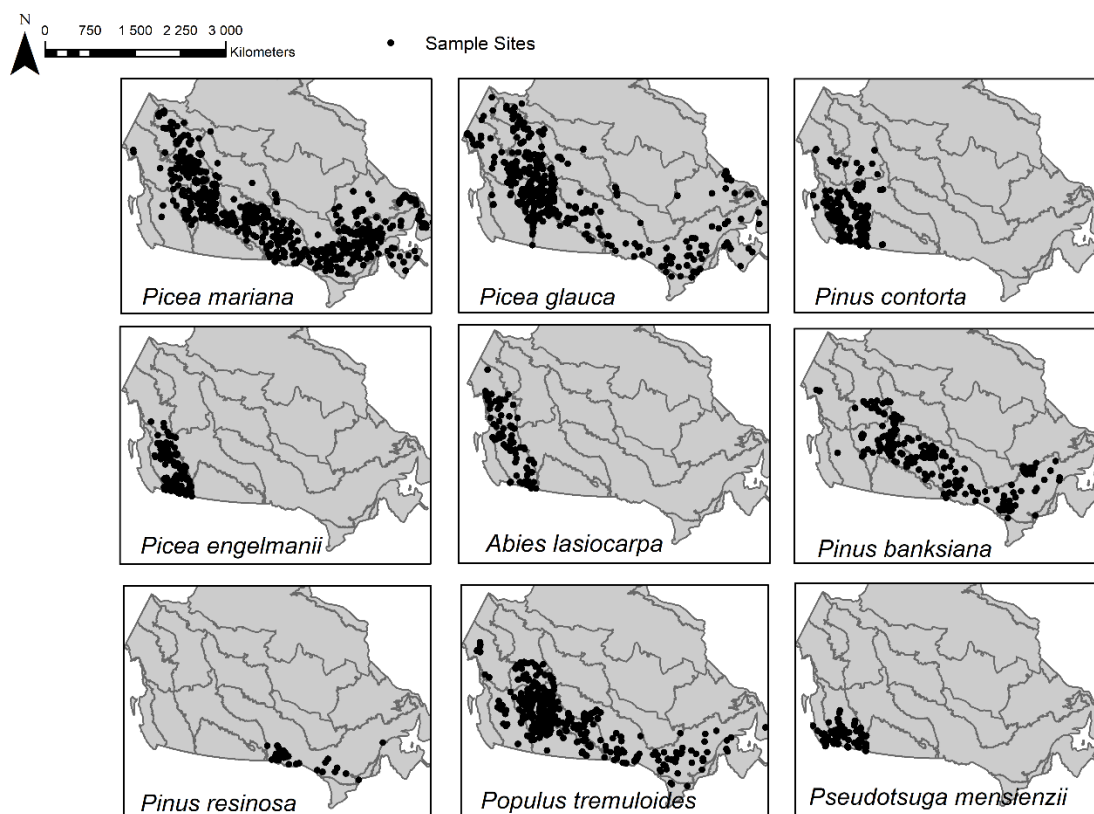
$$16 \quad (A1.b) \quad \text{Residuals}_{jk} = \text{VPD}^{t-1} + \text{VPD}^t + \text{Tree}_{ID} + \epsilon_{jkt}$$

17 Where i stand for tree identity, j for the species, k for the site, and t for the year. BA the basal
 18 area, BAI the basal area increment, age is the age in years, and s a cubic regression spline
 19 smoothing parameter whose degree of smoothness was determined through an iterative fitting
 20 process. Temporal autocorrelation was considered with AR1, an autoregressive term of order
 21 1 accounting for year t and Tree_{ID} that is tree's unique identifier. The significance of variables

22 at the 5% level was determined from t -tests in the second GAMM models (t -value's $p < 0.05$).
23 The GAMM models were fitted using the mgcv R package⁷⁰.

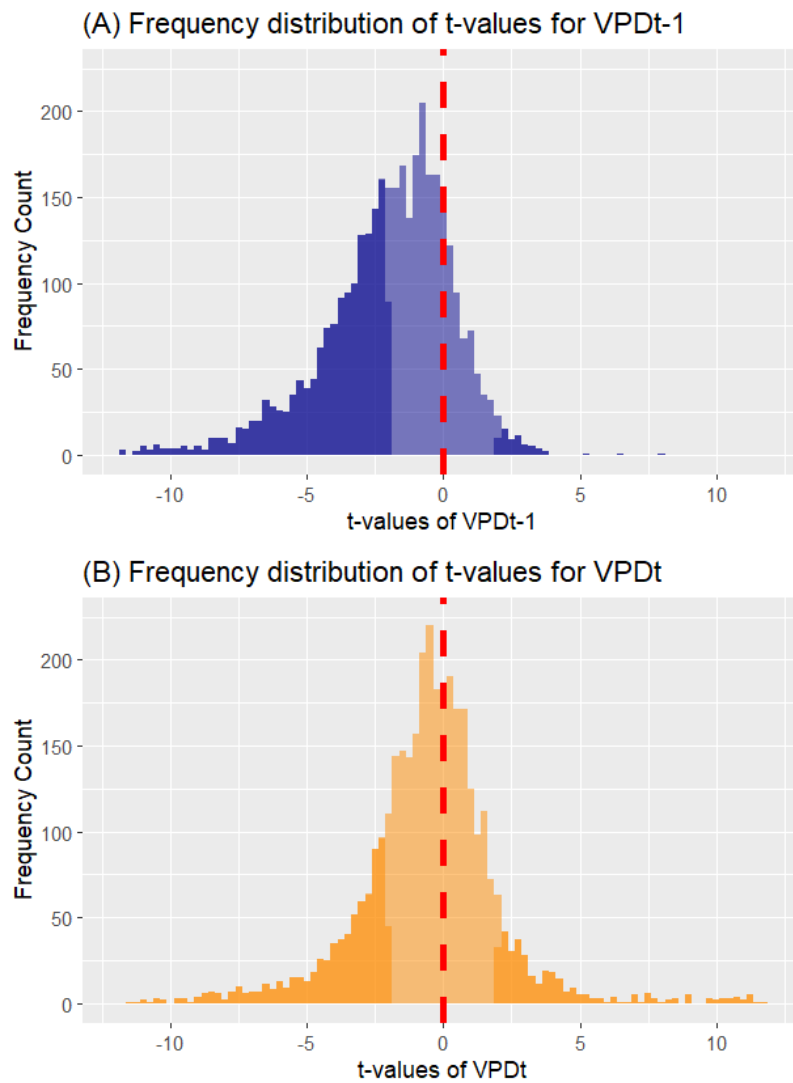
24 After removing the effects of SMI, we found that most of the VPD signal was retained
25 (Fig. S4 and Tables S2-S3). Over 27% of the sites-species combinations still had a significant
26 relationship with VPD. VPD was mostly negatively correlated to growth, with the majority
27 (92%) of the significant sites-species combination showing a negative relationship for VPD_t or
28 VPD_{t-1} . These analyses suggest that stomatal sensitivity to VPD would represent the primary
29 direct response to rising VPD.

30 Supplementary Figures



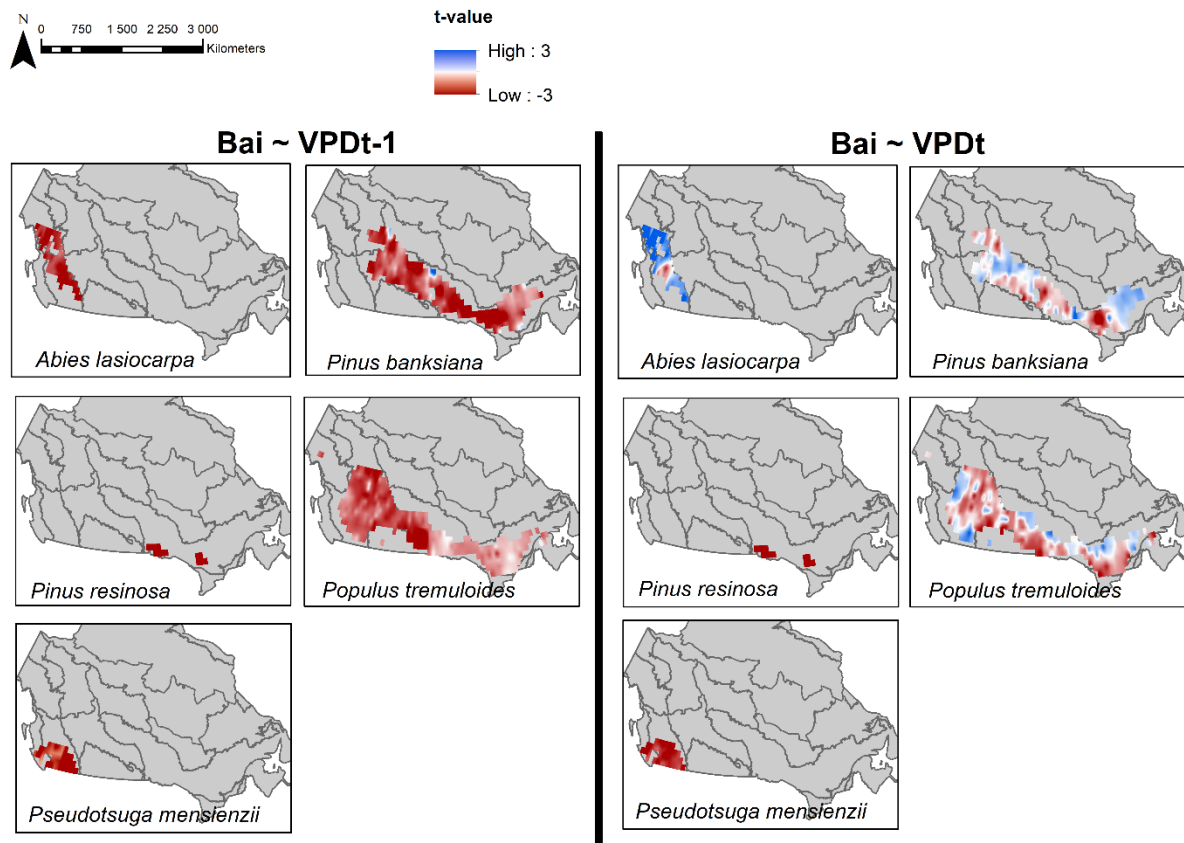
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32 **Supplementary Figure S1. Distribution of sample sites for all nine species.**



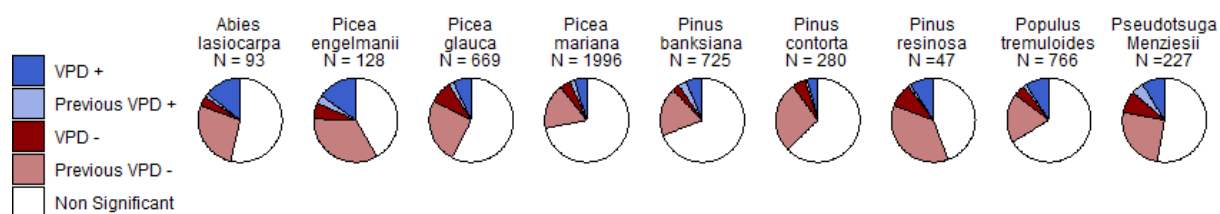
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34 **Supplementary Figure S2. Frequency distribution of t-values for the relationship**
 35 **between annual growth fluctuations estimated from tree rings (BAI) and summer**
 36 **vapour pressure deficit (VPD) of prior (t-1) and current (t) years to growth. Darker**
 37 colors delineate the distribution of significant ($P < 0.05$) values. Sample size: $N = 3,559$
 38 species-site combinations.

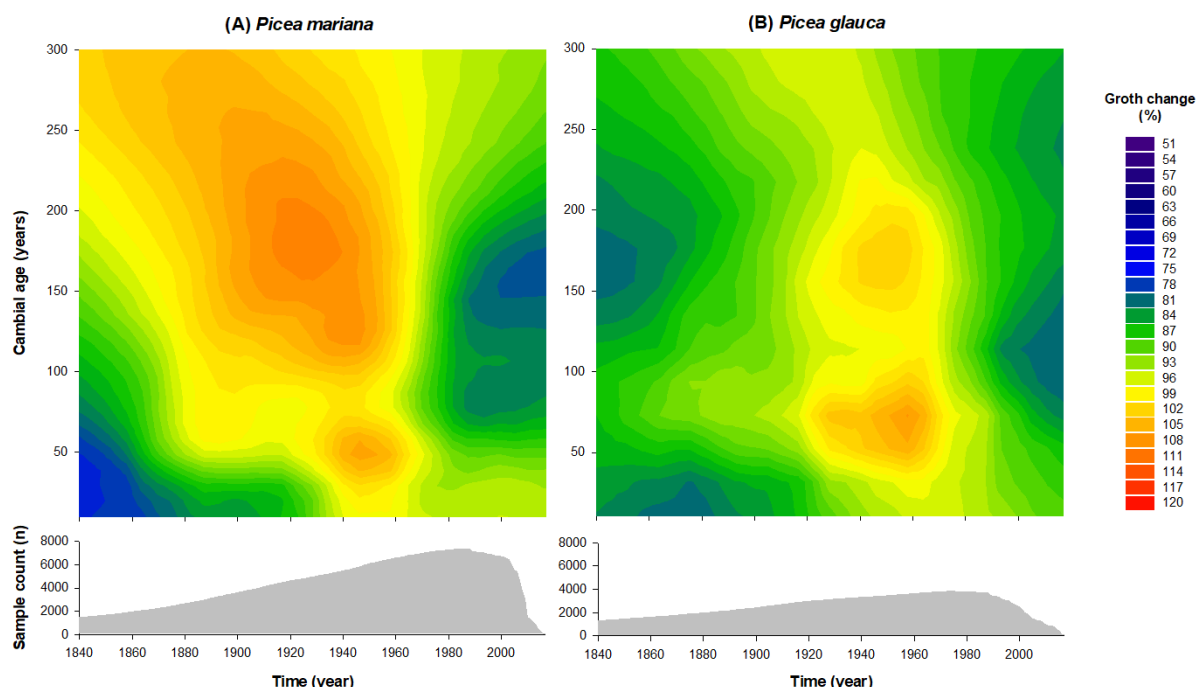


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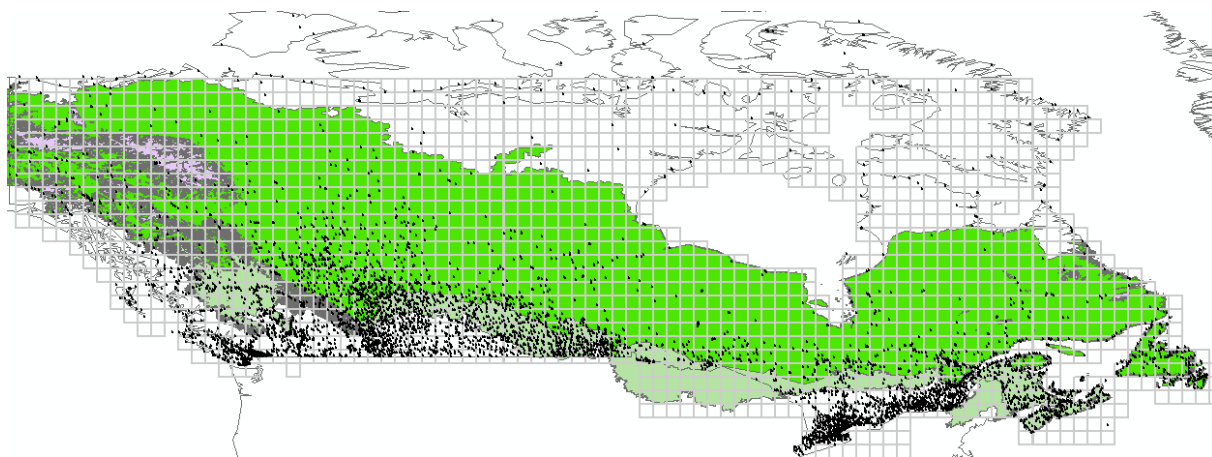
40 **Supplementary Figure S3. Pointwise t -values of the regression between annual growth**
 41 **fluctuations estimated from tree rings (BAI) and vapour pressure deficit (VPD) for the**
 42 **species *Abies lasiocarpa*, *Pinus banksiana*, *Pinus resinosa*, *Populus tremuloides* and**
 43 ***Pseudotsuga mensienzii*.** Maps display site-species t -values; a bidimensional interpolation
 44 was performed on a spatial resolution of 1 x 1 degree, using the inverse distance weighting
 45 method based on the 12 closest neighbours. Interpolations were bounded using boreal mask
 46 and species distribution area (species maps)^{81,82}.



Supplementary Figure S4. Proportion of significant ($p < 0.05$), positive and negative t -values for VPD_t and VPD_{t-1} from the regression between annual growth and VPD for the nine tree species obtained after removing the effects of soil moisture availability index (SMI). N indicates the number of corresponding sites.



Supplementary Figure S5. Changes in the annual growth of *Picea mariana* and *Picea glauca* in the cambial age and time continuums. Annual growth changes are percent deviation from predicted values generated by the generalized additive mixed models representing the BAI variations unrelated to tree development stage (see Methods, eq. 3). Red indicates periods for a given cambial age above typical growth in the two-dimensional continuums; blue indicates periods for a given cambial age below typical growth. Contour interpolations was done using a running median smoother with the bandwidth radius set to 5% of the data. Distributions of sampled rings across years are shown by the area plots. The contour plots suggest that decreases in tree growth from 1951 to present were apparent in both species and across all cambial ages.



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64 **Supplementary Figure S6. Distribution of weather stations across Canada covering in**
 65 **full or partly the period of 1950 to 2018.** The shaded areas delineate the studied regions
 66 (green: boreal, grey: hemiboreal). For this study, weather data were resampled to a 1° x 1°
 67 grid (n = 1705 grid points) to produce homogeneous and long-term time series for
 68 establishing climate–growth relationships.

69 **Supplementary Table S1. Proportion of the GAMM convergent species-site models**

70 **Supplementary Table S1. Proportion of the GAMM convergent species-site models** for
 71 which VPD_{t-1} or VPD_t were significant predictors for growth. Columns detail the proportions
 72 of models for which VPD_{t-1} / VPD_t were positively/negatively correlated to growth.

Species	VPD_t or VPD_{t-1}	VPD_{t-1}	Pos. VPD_{t-1}	Neg. VPD_{t-1}	VPD_t	Pos. VPD_t	Neg. VPD_t
<i>Abies lasiocarpa</i>	0.71	0.52	0.02	0.49	0.45	0.39	0.06
<i>Picea engelmannii</i>	0.80	0.67	0.02	0.66	0.61	0.48	0.12
<i>Picea glauca</i>	0.61	0.54	0.02	0.52	0.36	0.08	0.28
<i>Picea mariana</i>	0.24	0.20	0.01	0.19	0.10	0.03	0.06
<i>Pinus banksiana</i>	0.28	0.24	0.01	0.22	0.11	0.06	0.05
<i>Pinus contorta</i>	0.68	0.61	0.02	0.59	0.35	0.09	0.26
<i>Pinus resinosa</i>	0.85	0.74	0.00	0.74	0.83	0.04	0.79
<i>Populus tremuloides</i>	0.48	0.34	0.01	0.33	0.29	0.08	0.21
<i>Pseudotsuga menziesii</i>	0.67	0.53	0.01	0.52	0.48	0.01	0.47

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74 **Supplementary Table S2. Proportion of the GAMM convergent species-site models** for
 75 which VPD_{t-1} or VPD_t were significant predictors for growth, obtained after removing the
 76 effects of soil moisture availability index (SMI). Columns detail the proportions of models for
 77 which VPD_{t-1}/VPD_t were positively/negatively correlated to growth.

Species	VPD_t or VPD_{t-1}	VPD_{t-1}	Pos. VPD_{t-1}	Neg. VPD_{t-1}	VPD_t	Pos. VPD_t	Neg. VPD_t
<i>Abies lasiocarpa</i>	0.54	0.41	0.02	0.39	0.26	0.20	0.05
<i>Picea engelmannii</i>	0.68	0.62	0.05	0.56	0.35	0.25	0.10
<i>Picea glauca</i>	0.39	0.32	0.02	0.29	0.18	0.08	0.10
<i>Picea mariana</i>	0.15	0.12	0.01	0.11	0.05	0.03	0.03
<i>Pinus banksiana</i>	0.20	0.16	0.02	0.14	0.07	0.05	0.02
<i>Pinus contorta</i>	0.46	0.40	0.01	0.39	0.13	0.06	0.07
<i>Pinus resinosa</i>	0.79	0.70	0.02	0.68	0.34	0.17	0.17
<i>Populus tremuloides</i>	0.30	0.21	0.01	0.19	0.14	0.09	0.04
<i>Pseudotsuga menziesii</i>	0.51	0.44	0.07	0.37	0.25	0.13	0.12

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Supplementary Table S3. Statistics of species-specific Generalized Additive Mixed Models (GAMM). The r-squared (r^2) and mean squared error (mse) are computed from the square of the Pearson correlation between observed and predicted log-transformed BAI (LBAI) and power-scaled BAI (BAI). The count of sampled rings, trees and sites for each GAMM is given by No rings, No trees and No sites. Mean series length (years) is indicated by avg series.

<i>Species</i>	<i>No rings</i>	<i>No sites</i>	<i>No trees</i>	<i>avg series</i>	<i>LBAI r²</i>	<i>LBAI mse</i>	<i>BAI r²</i>	<i>BAI mse</i>
<i>Abies lasiocarpa</i>	139400	89	923	151	0.889	0.130	0.812	2.403
<i>Pseudotsuga menziesii</i>	352003	227	2754	128	0.766	0.295	0.714	29.786
<i>Picea engelmannii</i>	318373	122	1632	195	0.902	0.137	0.822	8.785
<i>Picea glauca</i>	612695	642	4522	135	0.908	0.208	0.837	127.344
<i>Picea mariana</i>	998924	1937	9481	105	0.858	0.145	0.687	1.256
<i>Pinus banksiana</i>	260364	573	3586	73	0.835	0.210	0.759	3.956
<i>Pinus contorta</i>	270095	268	2859	94	0.783	0.172	0.721	3.344
<i>Pinus resinosa</i>	102927	47	868	119	0.773	0.239	0.771	36.620
<i>Populus tremuloides</i>	194580	706	3164	61	0.633	0.351	0.589	15.116