

Tree-ring chronologies reveal unexpected geographic patterns of drought vulnerability in western Canadian forests

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ABSTRACT

Adaptive reforestation under climate warming will increasingly involve northward or upslope movement of tree species and seed sources. However, in western Canadian boreal and sub-boreal forests, release from cold constraints may be offset by emerging drought limitations, where low evapotranspiration has historically supported tree growth despite modest precipitation. We used 392 tree-ring chronologies from western Canada to compare drought resistance, recovery, and resilience among seven common conifer tree species across regional climatic gradients. Drought vulnerability metrics were not strongest at the southern forest-grassland transition, as might be expected from current moisture deficits alone. Instead, drought impacts were most pronounced further north in dry boreal mixedwood regions. Specifically, white spruce and jack pine showed lower post-drought resilience in northern boreal regions than in their southern boreal populations. We interpret this pattern as consistent with limited historical selection for drought tolerance in northern populations, where cold temperatures have historically moderated moisture stress. Similarly, interior Douglas-fir showed particularly low resilience in its sub-boreal distribution, near its northern range limit. These results suggest practical limits to northward planting of interior Douglas-fir, while southern boreal populations of white spruce and jack pine may be useful seed sources for improving drought resilience in central and northern boreal forests. More broadly, these results suggest that drought vulnerability in western Canadian forests is not confined to the southern boreal fringe, but also affects northern boreal and sub-boreal populations, where adaptive reforestation may be needed to maintain forest resilience under continued warming.

1. Introduction

Forests face increasing moisture limitations under climate warming when water demand from higher evapotranspiration exceeds water availability for trees (Allen et al., 2010; Babst et al., 2019). Western Canadian boreal forests are among the ecosystems most vulnerable in this regard, because growing conditions are generally dry, yet these ecosystems support forest growth because cold temperatures result in low evapotranspirative demand. Above-average warming trends over the last several decades across northern forest regions threaten this evapotranspirative balance. This creates a management challenge for western Canadian forests: warming may reduce cold limitations in some regions, but it may also increase drought stress where forest growth has historically depended on low evapotranspirative demand. For western Canada, Zhang et al. (2019) report a mean annual temperature increase between 1.5°C in the south and 3.5°C in the north since the 1950s,

compared to a global average increase of 0.8°C. Over the same period, precipitation was observed to increase by up to 10% in the north, while remaining unchanged at the southern fringe of the boreal forest. Identifying where this shift is already reflected in tree-growth responses can provide a useful regional screen for climate-informed reforestation.

Although the overall changes to the evapotranspirative balance in northern ecosystems have been moderate (Levesque and Hamann, 2022), recent drought-related forest impacts are widespread in western Canada. Recent fire seasons have illustrated the sensitivity of western Canadian forests to heat waves and drought conditions, including record-breaking wildfire seasons (Jain et al., 2024). Interactions of climate change with forest pests have led to large-scale insect outbreaks (Kurz et al., 2008), and direct drought impacts have also been observed in tree growth and mortality. Severe drought contributed to widespread aspen mortality along the southern edge of the western boreal forest (Michaelian et al., 2011), and permanent plot

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analyses have shown increases in tree mortality across Canada’s boreal forests, with the strongest mortality trends in western Canada (Peng et al., 2011; Liu et al., 2023).

Western boreal forest regions of Canada have been identified as vulnerable with respect to global climate change because of their above-average warming rates and observed impacts on ecosystems (Gauthier et al., 2015). The region will likely be among the first where large-scale management interventions are needed to mitigate the effects of climate change on forest ecosystems. One option is to modify reforestation practices by planting different species or different genotypes of the same species with higher drought tolerance (e.g., Depardieu et al., 2020). However, such prescriptions usually require long-term field testing, which is available for only a few species of commercial interest (e.g., Eilmann et al., 2013; Park and Rodgers, 2023; Sang et al., 2023). An alternative approach to evaluating the tolerance of species and populations to climatic stress is dendrochronology, taking advantage of historical records of tree growth contained in tree rings, as well as archival climate data. This approach can be used to monitor forest growth and health in response to climate trends (e.g., Girardin et al., 2016; Hogg et al., 2017), quantify drought sensitivity (e.g., D’Orangeville et al., 2018), and identify patterns consistent with population-level differences in drought tolerance traits (Isaac-Renton et al., 2018; Sebastian-Azcona et al., 2020; Depardieu et al., 2021). Recent Canada-wide tree-ring analyses have shown that many major tree species exhibit low post-drought resilience, with declining recovery and resilience especially evident in deciduous species, while evergreen conifers showed generally stable but low resilience (Marchand et al., 2025).

This study uses a regional dataset of western Canadian tree-ring chronologies to screen for geographic, species-level, and population-level patterns in drought response among seven common conifer tree species. Rather than testing a single a priori mechanism, we use regional climate-growth clusters to identify where drought resistance, recovery, and resilience are lowest, and then interpret these patterns in relation to historical moisture limitation, species distributions, and implications for climate-informed reforestation. Our specific objectives were (1) to identify regional drought events and associated tree-growth responses across western Canada; (2) to compare drought resistance, recovery, and resilience among species and regional populations within drought-sensitive clusters; and (3) to evaluate how these observed drought-response patterns can inform assisted migration and adaptive reforestation programs.

2. Methods

2.1. Tree-ring data and chronology selection

Tree-ring data for western Canada were obtained from a regional compilation by Hynes and Hamann (2020), which included conifer chronologies from Canadian Forest Service collections (Hogg et al., 2017) and the International Tree-Ring Data Bank (ITRDB; GrissinoMayer and Fritts, 1997; NOAA, 2023). Data sharing with the Canadian Forest Service occurred before the publication of the national CFS-TRenD database, but we note that many of these federal tree-ring records are now available through CFS-TRenD (Girardin et al., 2021).

Raw tree-ring data were detrended with the Friedman method (Friedman, 2001), a non-parametric regression based on a kernel smoothing algorithm that primarily preserves high-frequency variability. The method was chosen because we were specifically interested in tree responses to short-term drought events, rather than longer-term climate trends, in this analysis. Detrending was implemented with the dplR package (Bunn et al., 2025) for the R programming environment (R Core Team, 2025).

We calculated mean inter-series correlations (R-bar) and expressed population signal (EPS) statistics to evaluate the temporal coherence of individual site chronologies. We retained chronologies with R-bar values

above 0.2 and EPS values above 0.85. These thresholds were used to ensure that site chronologies showed sufficient common year-to-year growth variation for drought-response analysis, not as a test of cross-dating accuracy. Furthermore, chronologies were required to be 90% complete within the 1978–2010 period to capture major drought events in western Canada over a relatively recent period. Because most dendrochronology databases are assembled from increment cores collected during earlier sampling campaigns, only a limited number of samples extend to the present. Lastly, we required at least 15 site chronologies that met the above criteria for a species to be included in the analysis.

In total, these criteria yielded 392 site chronologies, including seven conifer species: three spruce species, three pine species, and Douglas-fir (Table 1). Across retained chronologies, the mean R-bar and EPS values were 0.4 and 0.95, indicating strong common growth signals within sites. Douglas-fir and limber pine showed the strongest inter-series correlations and expressed population signals. The average sample depth per site chronology was approximately 25 cores, typically with two cores per tree (Table 1).

2.2. Climate data and climatic drought indices

Monthly climate data for chronology sites for the period 1978–2010 were obtained with ClimateNA v6.40 (Wang et al., 2016). ClimateNA extracts monthly historical time series of interpolated climate data for specific locations and variables of interest. The interpolated climate grids are based on the Parameter Regression of Independent Slopes Model (PRISM) interpolation method for weather-station data (Daly et al., 2008). In the version of ClimateNA used here, historical anomaly data for average monthly temperature and monthly precipitation were obtained from CRU-TS 4.04 (Harris et al., 2020) and overlaid as deviations from the 1961–1990 PRISM baseline data. The software version used to query historical data and future projections is available for download at <http://tinyurl.com/ClimateNA>. The latest version of the software is maintained at <http://ClimateNA.ca>.

We used the Climate Moisture Index (CMI) to quantify drought and examine its influence on tree growth (Hogg, 1997). CMI was developed for western Canada and estimates climatic water balance from precipitation and potential evapotranspiration, using an empirically optimized method based on a modified Penman-Monteith equation. It is calibrated so that zero-CMI corresponds approximately to the boreal forest-grassland transition. Positive CMI values therefore indicate excess water, whereas negative values indicate water-deficit conditions for boreal forest trees, expressed in millimetres of precipitation. For each chronology site and year, we summed monthly CMI estimates provided by ClimateNA over a 15-month period from the previous June to the current August, to account for current-year growing-season moisture conditions as well as lagged effects of water stored in soils.

We evaluated this 15-month CMI water balance against remotely

Table 1
Species and chronology statistics included in the study. Number of site chronologies for each species, as well as mean inter-series correlations (R-bar), expressed population signal (EPS) and mean sample depth (S-Depth) are listed as averages across site chronologies.

Common Name	Scientific Name	Sites	R-bar	EPS	S-Depth
White spruce	<i>Picea glauca</i> (Moench) Voss	206	0.40	0.91	23.3
Engelmann spruce	<i>Picea engelmannii</i> Parry ex Engelm.	60	0.37	0.95	22.9
Black spruce	<i>Picea mariana</i> (Mill.) Britton	24	0.33	0.93	38.2
Jack pine	<i>Pinus banksiana</i> Lamb.	24	0.38	0.94	22.7
Whitebark pine	<i>Pinus albicaulis</i> Engelm.	15	0.33	0.96	29.9
Limber pine	<i>Pinus flexilis</i> E. James	15	0.44	0.97	22.3
Douglas-fir	<i>Pseudotsuga menziesii</i> (Mirbel) Franco	48	0.54	0.97	25.2

sensed soil moisture from the European Space Agency's Climate Change Initiative soil moisture database (ESA CCI) (Gruber et al., 2019). The ESA CCI data are available at a spatial resolution of approximately 0.25° and a temporal resolution of 1–3 days. We calculated monthly soil moisture values for each grid cell containing a chronology site and averaged those values for the current growing season, from May to August. The subsequent dendroclimatology analysis was carried out for both remotely sensed soil moisture and CMI-inferred water availability. While we include the remotely sensed soil moisture data in some figures, the CMI-inferred water availability generally had slightly stronger correlations with tree-ring chronologies. We therefore report statistics and main findings using CMI as the water-availability metric.

2.3. Regional clustering of drought and growth histories

For the assessment of drought-response metrics, the 392 site chronologies of all species were first clustered according to their similarity in historical climate conditions and growth response. Clustering was implemented with the k-means method, which can handle relatively high-dimensional datasets, in this case 64 variables: detrended ring-width index (RWI) values for 32 years and a 32-variable CMI or remotely sensed soil moisture dataset. Three transformations were carried out on the drought metric. First, a log transformation, fine-tuned with a constant, was used to improve the distribution of the water-availability metric across the full dataset. While not strictly necessary, this transformation makes subsequent multivariate ordinations easier to interpret. Second, rows corresponding to chronology sites were scaled so that the drought metric was expressed in standard deviations from a mean of zero, providing an index of relative drought conditions for each chronology site. Third, columns were scaled in the same way, so that each of the 64 variables had equal weight in subsequent clustering and ordinations. Clustering was implemented with the kmeans function of the stats package, which is part of the base R programming environment (R Core Team, 2025), using a Euclidean distance matrix. An optimal cluster number of 10 was determined with the help of silhouette width, gap statistics, and within-cluster sum of squares, obtained with the fviz_nbclust function of the factoextra library (Kassambara and Mundt, 2020).

The 10 clusters of similar climate histories and ring-width patterns were visualized with principal component analysis, implemented with the princomp function of the base R programming environment. Principal component loadings for the original variables were displayed as vectors in the ordination using the vf function of the ecodist library (Goslee and Urban, 2007). Vectors were flipped by multiplying by negative one, so that they point toward, rather than away from, clusters with small ring widths and high water deficits in a specific year. This provides a concise summary of which geographic regions experienced drought conditions in which years, and when a drought response, represented by small ring widths, was observed, typically in the same or subsequent year.

2.4. Drought-response metrics and statistical comparisons

Drought response of forest trees was assessed with three metrics calculated from ring-width patterns: resistance, recovery, and resilience, following Lloret et al. (2011). Resistance refers to a tree's ability to resist growth decreases during drought and was calculated as the ratio of drought-period to pre-drought ring-width index values. Recovery refers to post-drought growth improvement and was calculated as the ratio of post-drought to drought-period growth. Resilience refers to the ability to return to pre-drought growth levels and was calculated as the ratio of post-drought to pre-drought growth. The most straightforward interpretations are resistance as an indicator of short-term drought impact on growth and resilience as an indicator of longer-term growth impairment following drought.

Pre-drought and post-drought growth were defined as the average

ring-width index values for the two years before and after a drought event, respectively. If the drought extended over multiple years, or if two subsequent drought periods were too close to allow for a two-year intermediate reference period, ring-width index values for drought years were averaged, and the two years before the onset of the first drought year and the two years after the last drought year were used as reference periods. A relatively short two-year post-drought period was chosen to measure the capacity of trees to recover quickly, while allowing most drought events to be evaluated separately for comparisons among species and regions.

Least-squares means and 95% confidence intervals for resistance, recovery, and resilience were estimated by cluster and species with a linear fixed-effects model, implemented with the lm function of the base R package and the emmeans package (Lenth, 2016) for the R programming environment (R Core Team, 2025). We did not conduct separate null-hypothesis tests for all cluster-species combinations. Instead, confidence intervals were used to identify estimates that differed from the reference value of one. Confidence intervals not overlapping one were interpreted as evidence of drought-related growth reduction for resistance, post-drought growth improvement for recovery, or incomplete recovery to pre-drought growth for resilience.

3. Results

3.1. Regional clustering of drought and growth histories

Cluster analyses based on similarity of drought histories and tree growth responses revealed ten geographically distinct groups of chronologies (Figs. 1 and 2). Because the ordination in Fig. 1 summarizes a complex time series dataset, we first describe one example in detail to guide interpretation of the figure. The cluster of chronologies located primarily within the Northwest Territories (NWT, yellow) experienced a pronounced drought in 1995 that was most specific to this region (Fig. 2, NWT panel). Accordingly, the 1995 CMI vector points toward this cluster in the ordination (Fig. 1, black vector). The corresponding 1995 growth-response vector also points in the same direction, indicating reduced ring-width index values in the same region during that year (Fig. 1, grey vector, negated to point toward chronologies with small ring widths). To a lesser degree, the same drought also affected northern Alberta (Figs. 1 and 2, nAB, green, positioned similarly but closer to the center). Similarly, other drought years for other regions can be interpreted in the same way: black vectors identify regions with strong relative water deficits, while grey vectors identify regions with reduced growth in the same or subsequent years.

This two-dimensional ordination is necessarily an imperfect representation of a complex multivariate dataset, but it provides a useful summary of the major regional droughts and associated growth responses in western Canada. The most notable regional drought was the two-year event in 2001–2002, which affected central and southern Alberta and Saskatchewan (Fig. 1, vectors pointing toward the right). This drought caused agricultural crop failures and substantial tree mortality at the southern fringe of the boreal forest (Michaelian et al., 2011). The ordination also reveals delayed growth responses to drought. For example, the severe 2001–2002 drought was associated with pronounced growth reductions in 2002 and 2003, while the 1980–1982 drought had its strongest growth response in 1982, and the 1984–1985 drought showed responses in 1985 and 1986.

3.2. Drought-event selection and retained clusters

Only the most important drought events and corresponding growth-response vectors could be included in Fig. 1. All drought events considered for subsequent analysis of drought-response traits are listed in Table 2. Measured in standard deviations of 15-month CMI values, the highest relative drought severity occurred during the 2001–2002 drought, with average CMI values 1.42 and 2.08 standard deviations

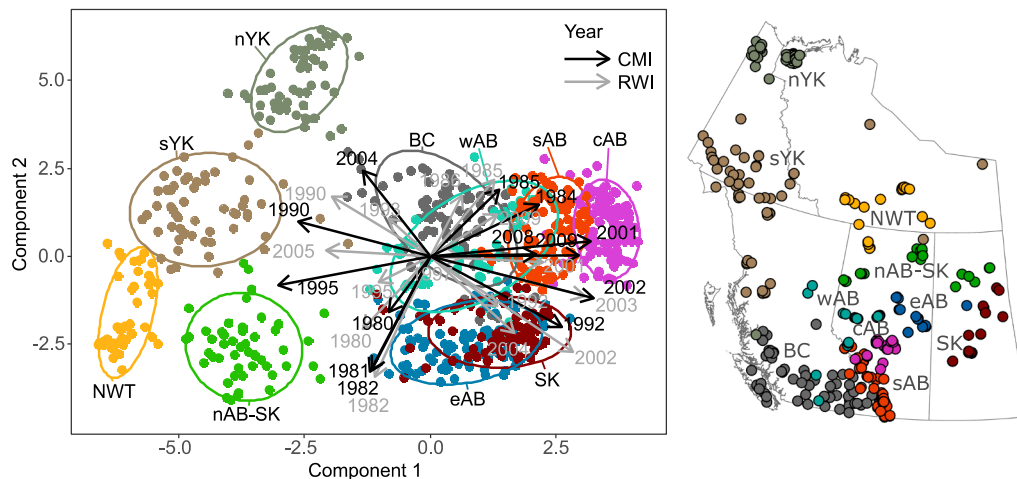


Fig. 1. Principal component ordination and geographic distribution of k-means clusters for tree-ring chronologies, based on similarities in drought timing and growth response. Variables included a scaled and negated climate moisture index (CMI; black vectors) and a detrended and negated ring-width index (RWI; grey vectors). Vectors point toward groups of chronologies that experienced the strongest drought conditions or growth reductions in the corresponding years. Ellipses indicate 90% confidence regions for each cluster. Cluster labels refer to approximate geographic locations: northern Yukon (nYK), southern Yukon (sYK), British Columbia (BC), western Alberta (wAB), Northwest Territories (NWT), northern Alberta and Saskatchewan (nAB-SK), central Alberta (cAB), southern Alberta (sAB), eastern Alberta (eAB), and Saskatchewan (SK).

below normal. Other prolonged drought periods affecting Alberta and Saskatchewan occurred in the early and mid-1980s, with relative water deficits as low as 1.28 standard deviations below normal conditions. The drought with the highest absolute water deficit was a single-year event in 2004, with an average 15-month CMI value of -23.3 mm, which affected the Northwest Territories cluster. In some cases, absolute CMI values were positive, indicating a positive water balance despite a negative relative drought score. This occurred in relatively moist regions such as the southern Alberta foothills (Table 3, sAB), which receive relatively high precipitation but nevertheless contain species that responded strongly to moderate water limitations.

To compare drought-response traits among species, we restricted the analysis to clusters where growth response was primarily associated with water availability. This excluded the western regions of British Columbia and the Yukon Territory (BC, nYK, sYK), where ring-width index was not strongly correlated with either water availability inferred from average 15-month CMI (Fig. 2, black line) or remotely sensed soil moisture during the growing season (Fig. 2, dark grey line). These regions either had high precipitation and a positive evapotranspirative balance (Table 3, high MAP and CMI values for BC and sYK), or, in the case of the northern Yukon cluster, appeared to be limited primarily by cold rather than drought (Table 3, low MAT value for nYK). In all other regional clusters, drought periods were consistently associated with growth reductions. A drought period was evaluated in subsequent analyses if it was associated with a ring-width index below 0.8 in at least 50% of chronologies of at least one species in a cluster in the same or subsequent year (Fig. 2, circles).

3.3. Species differences in regional drought response

Drought responses varied considerably among species and clusters (Fig. 3). In interpreting Fig. 3, the reference value of 1 has a different meaning for each metric. Resistance < 1 indicates growth reduction during drought; recovery > 1 indicates increased growth after drought relative to the drought period; and resilience $= 1$ indicates return to pre-drought growth levels. Thus, low resistance with resilience near 1 indicates drought impact followed by recovery, whereas low resistance with resilience < 1 indicates incomplete post-drought recovery.

Resistance was generally lowest for Douglas-fir, jack pine, and white spruce (Fig. 3, *Pseudotsuga menziesii*, *Pinus banksiana*, and *Picea glauca*), corresponding to relatively large growth reductions during drought.

Recovery largely mirrored resistance, but with some exceptions that led to resilience values that deviated from complete recovery within two years (Fig. 3, 95% confidence intervals not overlapping the reference line). Complete recovery to pre-drought growth levels, indicated by resilience values near 1, was prevalent in the southern Alberta and Saskatchewan clusters that border prairie grassland ecosystems (sAB and SK in Figs. 1 and 3). Despite these clusters having different climatologies, with moister foothill forests in southern Alberta and drier southern boreal forests in Saskatchewan (Table 3), all species in these groups recovered to pre-drought growth levels within two years.

Notable deviations from complete recovery within two years were observed for Douglas-fir, jack pine, and white spruce in dry boreal and sub-boreal ecosystems. Low resilience for both jack pine and white spruce was most pronounced in the Northwest Territories cluster (Fig. 3, NWT, *Pinus banksiana*, *Picea glauca*), followed by the northern Alberta and Saskatchewan cluster (nAB-SK), with resilience approaching full recovery in the central and eastern Alberta clusters (cAB and eAB). For white spruce and jack pine, resilience therefore followed a geographic cline from full recovery near the forest-grassland transition zones to lower resilience in northern boreal forests.

Other notable within-cluster species differences included Douglas-fir, which showed the lowest resilience value across all species and regional groups in the western Alberta cluster (Fig. 3, wAB, *Pseudotsuga menziesii*), corresponding to sub-boreal ecosystems near the northern range limit of the interior Douglas-fir subspecies. Douglas-fir was also the most sensitive species to drought at its northeastern range limit in the southern Alberta foothills (Fig. 3, sAB, resilience values). Lastly, black spruce differed substantially from white spruce and jack pine in the Northwest Territories cluster, with higher resistance values and resilience values not significantly different from full recovery (Fig. 3, NWT, *Picea mariana*).

4. Discussion

The main result of this study is that drought vulnerability in western Canadian forests was not confined to the southern boreal fringe, where current moisture deficits are greatest. Instead, low post-drought resilience was observed further north in dry boreal mixedwood regions, especially for white spruce and jack pine. Although this pattern emerged from a regional screening of drought-response metrics rather than from a sampling design intended to test genetic adaptation directly, we

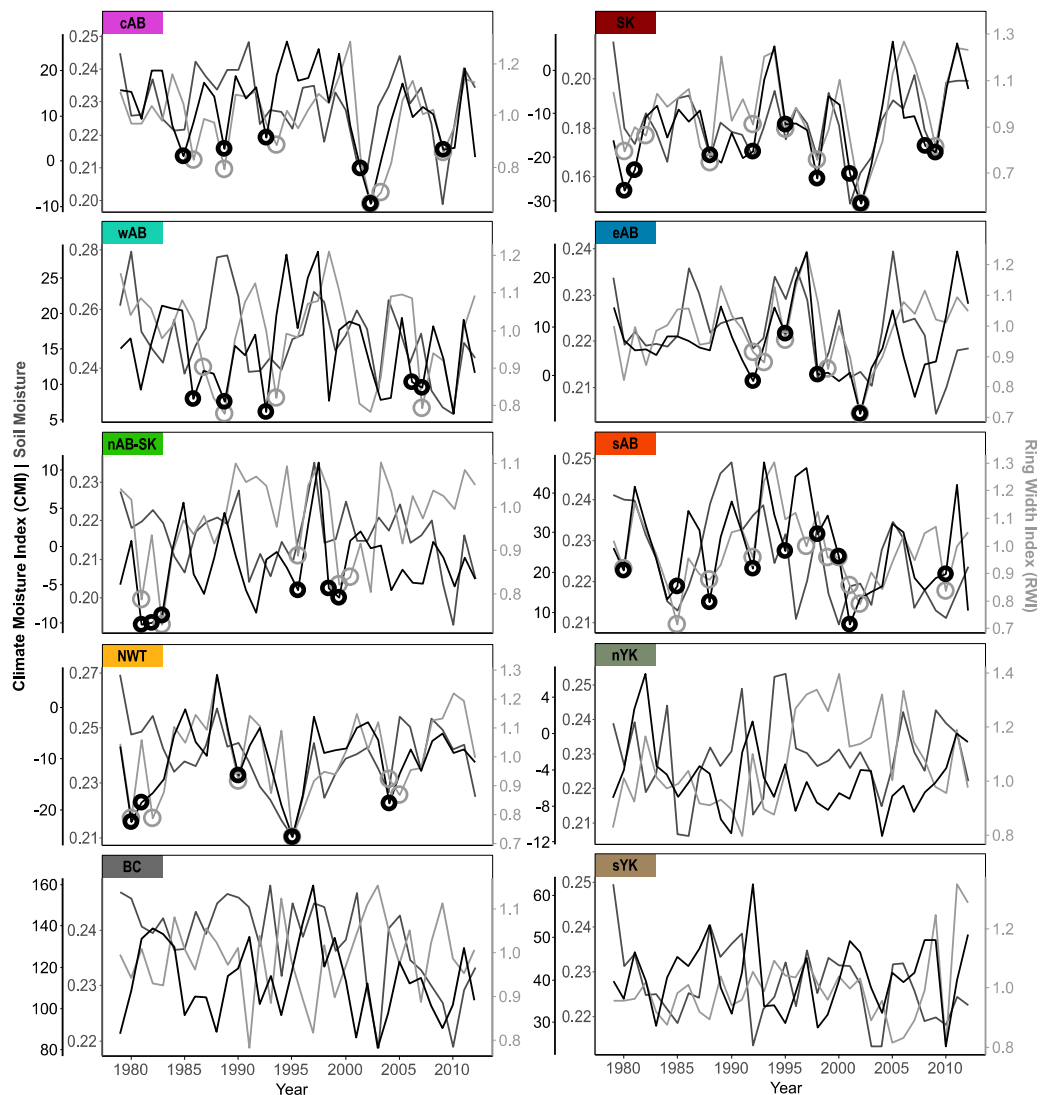


Fig. 2. Regional time series used to identify drought-response events for subsequent resistance, recovery, and resilience analyses. Lines show cluster means for climate moisture index (CMI; black), remotely sensed growing-season soil moisture (dark grey), and detrended ring-width index (RWI; light grey). Cluster colours and abbreviations correspond to Fig. 1. Circles indicate drought-response events retained for analysis, defined as years with low relative CMI and an associated growth reduction, where mean RWI fell below 0.8 in at least 50% of chronologies of at least one species within the cluster in the same or subsequent year.

Table 2

Drought events ordered chronologically, and clusters (as in Fig. 1) affected by each drought period. Response years refer to years with a low detrended ring width index value. Drought severity was measured as absolute water deficits of a 15-month CMI value (mm), and the relative drought severity is the same CMI value expressed in standard deviations from chronology means of zero for the study period, averaged across all chronologies within the affected clusters.

Drought years	Response years	Relative drought severity (stdev)	Absolute drought severity (mm)	Regional clusters affected by the drought					
1980-82	1980-82	-1.28, -1.18, -1.15	-12.5, -21.4, -11.3	sAB	SK			nAB-SK	NWT
1984-85	1985-86	-1.19, -0.90	1.5, 15.2	sAB		cAB	wAB		
1988	1988	-0.99	1.0	sAB	SK	cAB	wAB		
1990	1990	-0.46	-16.6						NWT
1992	1992-93	-0.8	3.1	sAB	SK	cAB	wAB	eAB	
1995	1995-97	-0.44	-2.3	sAB	SK			eAB	nAB-SK NWT
1998-99	1998-99	-0.58, -0.72	-0.2, -8.5	sAB	SK			cAB	nAB-SK
2001-02	2001-03	-1.42, -2.08	-7.7, -19.9	sAB	SK	cAB		eAB	
2004	2004-05	-1.23	-23.3						NWT
2006-07	2007	-0.58, -0.78	12.8, 11.9				wAB		
2008-09	2009	-0.43, -0.81	-21.8, -10.1		SK	cAB			
2010	2010	-0.66	24.5	sAB					

Table 3
Long-term climate normal conditions for regional clusters as shown in Fig. 1. Regional clusters are ordered from left to right based on to their water balance according to Hogg’s (1997) climate moisture index, where a value near zero is calibrated for the boreal forest to grassland transition zone in western Canada (last row).

Climate normals (1978–2010)	SK	NWT	nAB-SK	nYK	eAB	cAB	wAB	sAB	sYK	BC
Mean annual temperature (°C)	1.7	-2.4	0.0	-7.8	1.4	2.7	2.7	1.4	-1.6	2.1
Mean coldest month temp. (°C)	-17.8	-23.9	-19.5	-27.8	-17.0	-13.4	-12.5	-12.5	-17.1	-8.8
Mean warmest month temp. (°C)	17.7	16.3	15.6	14.1	15.9	15.6	14.9	13.3	11.8	12.7
Mean annual precipitation (mm)	424	358	435	260	490	555	585	671	693	1456
Climate moisture index (mm/yr)	-6.1	0.0	3.4	3.8	6.4	8.6	15.3	27.8	42.0	112.0

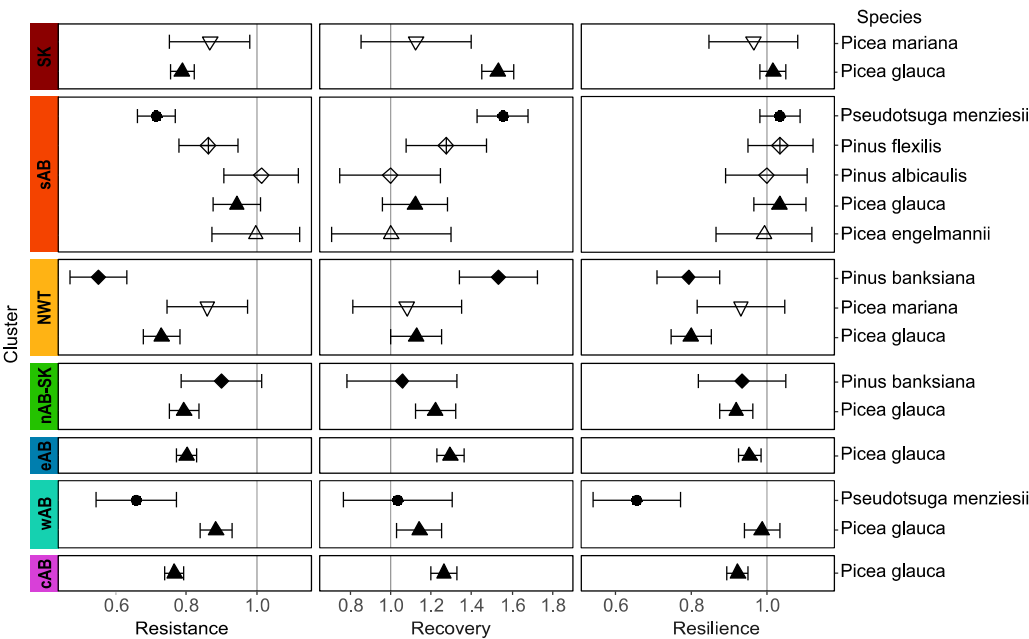


Fig. 3. Drought resistance, recovery, and resilience metrics according to Lloret et al. (2011) for each species and cluster. Clusters where growth was not primarily limited by water availability were omitted (BC, nYK, and sYK), as were species with fewer than five sample locations within a cluster. Error bars represent 95% confidence intervals. Estimates whose confidence intervals do not overlap 1 were interpreted as individually significant departures from the reference line. For resistance, values below 1 indicate growth reduction during drought. For recovery, values above 1 indicate increased growth after drought. For resilience, values below 1 indicate incomplete recovery to pre-drought growth levels.

interpret it as evidence that warming may expose drought limitation in regions where forest growth has historically been supported by low evapotranspirative demand. Regional drought vulnerabilities observed in this study therefore generally conform to geographic patterns expected from observed warming trends and historical moisture balances (Zhang et al., 2019; Levesque and Hamann, 2022), but they also show that drought vulnerability may be more widespread than expected from current moisture deficits alone.

Observed climate trends provide one explanation for the northward increase in drought vulnerability observed for white spruce and jack pine. Across western Canada, temperature increases over recent decades have generally been larger at higher latitudes, while precipitation increases have been smaller and regionally variable (Zhang et al., 2019; Levesque and Hamann, 2022). These climate analyses suggest that northern boreal regions may be especially vulnerable to emerging moisture limitation because normal precipitation is low and warming increases evaporative demand. This climate gradient is consistent with the lower post-drought resilience we observed in northern white spruce and jack pine chronologies.

In addition to gradients of environmental change, prior exposure to drought may help explain regional differences in drought response within species. The Saskatchewan cluster had the highest water deficit under normal conditions, yet chronologies from this region near the forest-grassland transition suggested rapid recovery from drought impacts. One explanation is local adaptation to drought, meaning genetic

population differences shaped by historical moisture limitation. This interpretation is supported by provenance and common-garden studies showing higher drought tolerance or resilience in populations from drier environments (Montwe et al., 2016; Isaac-Renton et al., 2018; Depardieu et al., 2020). However, our chronology data alone cannot distinguish genetic adaptation from non-genetic explanations such as ecological filtering, whereby drought-sensitive individuals, stand types, or site conditions are underrepresented in chronologies from historically dry regions.

The same link between reduced cold limitation and emerging drought limitation is also relevant for interior Douglas-fir, although the pattern was species-specific rather than a broad north-south trend. In the southern Alberta cluster, Douglas-fir showed low resistance but resilience near 1, indicating drought impact followed by recovery. In contrast, in the western Alberta cluster, Douglas-fir showed both low resistance and resilience below 1, indicating growth reduction during drought and incomplete recovery within two years. We therefore interpret the western Alberta result as evidence that interior Douglas-fir may be vulnerable to drought limitation in parts of its sub-boreal distribution. This interpretation is consistent with previous work showing that water availability can limit Douglas-fir growth in interior environments (Griesbauer and Green, 2010), even though northern and high-elevation range limits of interior Douglas-fir are often assumed to be governed primarily by growing-season length and cold tolerance (Burns et al., 1990).

These results have implications for assisted migration and climate-informed reforestation programs. Northward planting of interior Douglas-fir should not be based solely on regional warming trends, because the same warming that reduces cold limitation may also increase drought limitation in relatively dry sub-boreal forest ecosystems. For white spruce and jack pine, the geographic cline of increasing resilience toward southern boreal populations suggests that seed sources from regions with a history of stronger moisture limitation may be useful candidates for improving drought resilience in central and northern boreal forests. This interpretation should not replace the testing of planting stock, but it identifies populations that warrant consideration in provenance testing and seed-transfer decisions that are based on climate matching alone.

Several limitations follow from the regional screening design. Chronology locations were not sampled according to a balanced experimental design, species were unevenly represented among regions and site types, and drought events differed among clusters. As a result, regional differences in resistance, recovery, and resilience cannot be attributed solely to species identity or population-level adaptation. Site conditions also likely contributed to some observed differences. For example, black spruce showed higher resistance and resilience than white spruce and jack pine in the Northwest Territories cluster, likely reflecting its association with wetter peatland sites. In addition, ring-width chronologies indicate growth responses to drought but do not identify the underlying physiological mechanisms. The results are therefore best interpreted as a regional screening of drought-response patterns and a source of testable hypotheses for provenance trials, rather than a direct test of genetic adaptation or planting performance.

5. Conclusions

Climate-informed reforestation is often framed around release from cold constraints, with warming expected to favor northward or upslope movement of tree species and seed sources. Our results suggest that this expectation is incomplete for western Canadian boreal and sub-boreal forests. In regions where forest growth has historically depended on low evapotranspirative demand, warming may simultaneously reduce cold limitation and expose drought limitation. As a result, species or local populations that appear climatically favored by warming may still be vulnerable if they have limited capacity to recover from drought.

This has two practical implications. First, drought vulnerability should not be treated as a problem restricted to the southern boreal fringe. Central and northern boreal forests may also require adaptive reforestation strategies as warming increases moisture stress. Second, assisted migration should consider population histories of drought exposure and recovery, not only projected temperature suitability. Southern boreal populations of white spruce and jack pine may be useful seed sources for improving drought resilience farther north, whereas northward planting of interior Douglas-fir should be approached cautiously because warming may increase drought limitation even as it reduces cold limitation.

Tree-ring-based resistance, recovery, and resilience metrics do not replace provenance trials or operational testing, but they provide a practical regional screening tool for identifying vulnerable populations and candidate drought-resilient seed sources. Integrating these drought-response histories into seed-transfer and reforestation planning would help avoid treating assisted migration prescriptions as simple expansions of species ranges, and instead support adaptation strategies that account for both temperature release and emerging moisture limitation where applicable.

CRedit authorship contribution statement

Benjamin Panes: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Andreas Hamann:** Writing – original draft, Supervision, Resources,

Project administration, Methodology, Funding acquisition, Data curation, Conceptualization. **Charles A. Nock:** Writing – review & editing, Supervision, Resources, Funding acquisition, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

All tree ring and climate data used in this study are already available via open access repositories as cited in the article

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