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ARTICLE
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Tree communities face rising soil water deficits exposure under projected climate change in northern temperate forests

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Abstract

Soil water deficits in temperate forests are projected to become more frequent, more severe, and longer in duration. This study aims to quantify the current (1981–2010) and projected (2041–2070) exposure of 17 tree communities to soil water deficit (severity and duration) in southwestern Quebec, Canada, using the Canadian Land Surface Scheme (CLASS) model. We classified these communities into clusters based on their current exposure to soil water deficit and examined interactions with species sensitivity to drought. Our results show that all tree communities will experience significant increases in both the severity (−0.11 to −0.21 MPa) and duration (4–8 days per year) of soil water deficits by 2041–2070. Despite these absolute increases, we expect the relative ranking of tree communities on the exposure scale to remain unchanged. *Quercus rubra* communities will continue to be the most exposed community type and face the highest soil water deficit. *Populus tremuloides* and *Larix laricina* communities will remain the least exposed; however, they are projected to face soil water deficits similar to those currently experienced by red oak communities. Forest tree communities often consist of species with diverse drought response strategies, as observed by trait values related to drought avoidance and drought tolerance. This study shows the importance of conducting localized assessments to identify tree species that are the most vulnerable, based on exposure and sensitivity, at a scale that can guide forest management strategies and silvicultural practices. The projected increase in exposure to soil water deficit could lead to shifts in community composition and species dominance, particularly in communities with species that have marked differences in drought sensitivity (e.g., where dominant species have high sensitivity and coexist with less sensitive tree species).

KEYWORDS
climate change, drought exposure, drought sensitivity, drought vulnerability, land surface model, soil water deficit, temperate forest, tree communities

INTRODUCTION

Climate change is increasingly impacting terrestrial ecosystems, with forests among the most vulnerable (Pörtner et al., 2022). Rising average global temperature and shifting precipitation patterns are projected to intensify the frequency, severity, and duration of extreme weather events such as droughts (Seidl et al., 2017), impacting forest health and resilience. Regionally, these climatic changes have profound implications for forest dynamics (Boccanfuso et al., 2018), such as changes in species' ranges and their within-range distributions (Boisvert-Marsh et al., 2014; Brice et al., 2019; Fei et al., 2017). Uncertainties remain around how forests will fare under changing conditions due to the complexity and adaptiveness of forest ecosystems (Deser et al., 2014; Kumar & Ganguly, 2018; Littell et al., 2011), especially at more local scales (Hanson & Weltzin, 2000).

Rising temperatures impact forest ecosystems in various ways, notably by increasing evapotranspiration and altering precipitation patterns (Kirschbaum, 2000; Mátyás & Sun, 2014; Price et al., 2013), including prolonged periods without precipitation (Buma & Livneh, 2015). Changes in the timing, intensity, and frequency of rainfall events can disrupt the water balance in forests, creating longer periods of water deficit (Davies, 2006). When faced with periods of water deficit, trees exhibit various coping strategies (Brunner et al., 2015) as supported by different traits (Choat et al., 2018), including: (1) maintaining water potential (drought avoidance) and (2) limiting damage to vascular systems (drought resistance). Several traits underlie these two strategies; one is the ability to close stomata, which reduces water loss through transpiration and limits the risk of embolism while reducing the intake of carbon dioxide needed for photosynthesis (Jones, 1998). Rooting depth is another key trait for mitigating water stress in trees (Phillips et al., 2016). Species with deeper root systems can access moisture reservoirs in deeper soil layers, providing a more stable water supply during periods of surficial soil dryness (Lindh et al., 2014; Tauc et al., 2020). Continued access to water sustains physiological functions, safeguarding the tree against the adverse effects of water scarcity (Pierret et al., 2016). Embolism resistance is another important trait for drought resistance that allows trees to maintain intact water transport systems, even under drought conditions (Lens et al., 2013; Zwieniecki & Secchi, 2015). Although these adaptations can confer some resilience to drought, they are not always, by themselves, reliable indicators of how a species will fare under water deficit (McDowell et al., 2022).

Indeed, tree vulnerability to water deficit as individuals and communities is multidimensional (Allen et al., 2015) and can be seen as the result of three factors: exposure, sensitivity, and adaptive capacity (Aubin et al., 2018; Lecina-Diaz et al., 2021). Exposure here refers to the degree of environmental change trees will experience. Sensitivity can be defined as the degree to which a species might be affected by fluctuations in water availability (Ruehr et al., 2016). At the individual tree level, properties such as deep root systems, efficient stomatal regulation, and resistance to embolism are typically associated with lower drought sensitivity (Aubin et al., 2016; Lloret et al., 2011). At the population level, sensitivity extends to a species' ability to persist on the landscape and includes factors like reproductive capacity, seedling establishment, and competitive ability (Aubin et al., 2016; Bennett et al., 2015). Adaptive capacity refers to the ability of a species to accommodate changes in the water regime. A comprehensive assessment of forest vulnerability to water stress requires an interdisciplinary exercise, in which physiological traits, ecological dynamics, and biophysical predictions are integrated with modeling.

While global studies on vegetation have shown contrasting tree responses to water deficit across biomes (Knapp & Smith, 2001; Vicente-Serrano et al., 2013), few studies have tested whether these responses persist at a regional scale outside drought-prone emblematic forest communities. In addition, at the local scale, exposure to water deficit is modulated by factors such as (micro) topography and soil type (McLaughlin et al., 2017; Tauc et al., 2020). Assessing local exposure to water deficit is an important way to refine predictions of drought-induced vegetation shifts under climate change, as exposure interacts with species-specific sensitivity to drought (Martínez-Vilalta et al., 2023).

Previous work by Cholet et al. (2022) in the temperate forests of southwestern Quebec (Canada) developed a working soil water balance model—the Canadian Land Surface Scheme (CLASS) model—and used it to describe projected changes in exposure to soil water deficit between 1981–2010 and 2100. They showed that the largest increase in the duration of water deficit will occur in areas currently found to be dry, while the largest increase in the severity of water deficit is projected for more humid areas. Soil water deficit refers to conditions where soil moisture limits transpiration, such that water availability becomes insufficient to meet plant demand. In the present study, we assess how exposure to soil water

deficit is projected to change over time at a finer scale and across different tree communities.

Our overall objective was to better understand the vulnerability of temperate forests to drought by assessing how changes in exposure interact with species' sensitivity to water deficit. In this regional case study (~30,000 km^2) in the temperate forests of southwestern Quebec, Canada, our specific objectives were to: (1) quantify the current (1981–2010) and projected (2041–2070) level of exposure (severity and duration) of tree communities to soil water deficit; and (2) explore changes in the relative rank and position of tree communities along a water deficit exposure scale. In other words, we evaluated whether a community currently experiencing low exposure to water deficit was projected to remain so in the future (based on rank), given nonlinear impacts of climate change on soil water availability.

METHODS

Study area

The study area is 33,442 km^2, located in the Outaouais region of southwestern Quebec, Canada. This region includes five bioclimatic vegetation zones (Robitaille & Saucier, 1998), characterized by the late successional species typically found on mesic sites (Figure 1 and Table 1). The three southern zones are dominated by deciduous forests (*Acer saccharum*, *Betula alleghaniensis*, *Fagus*

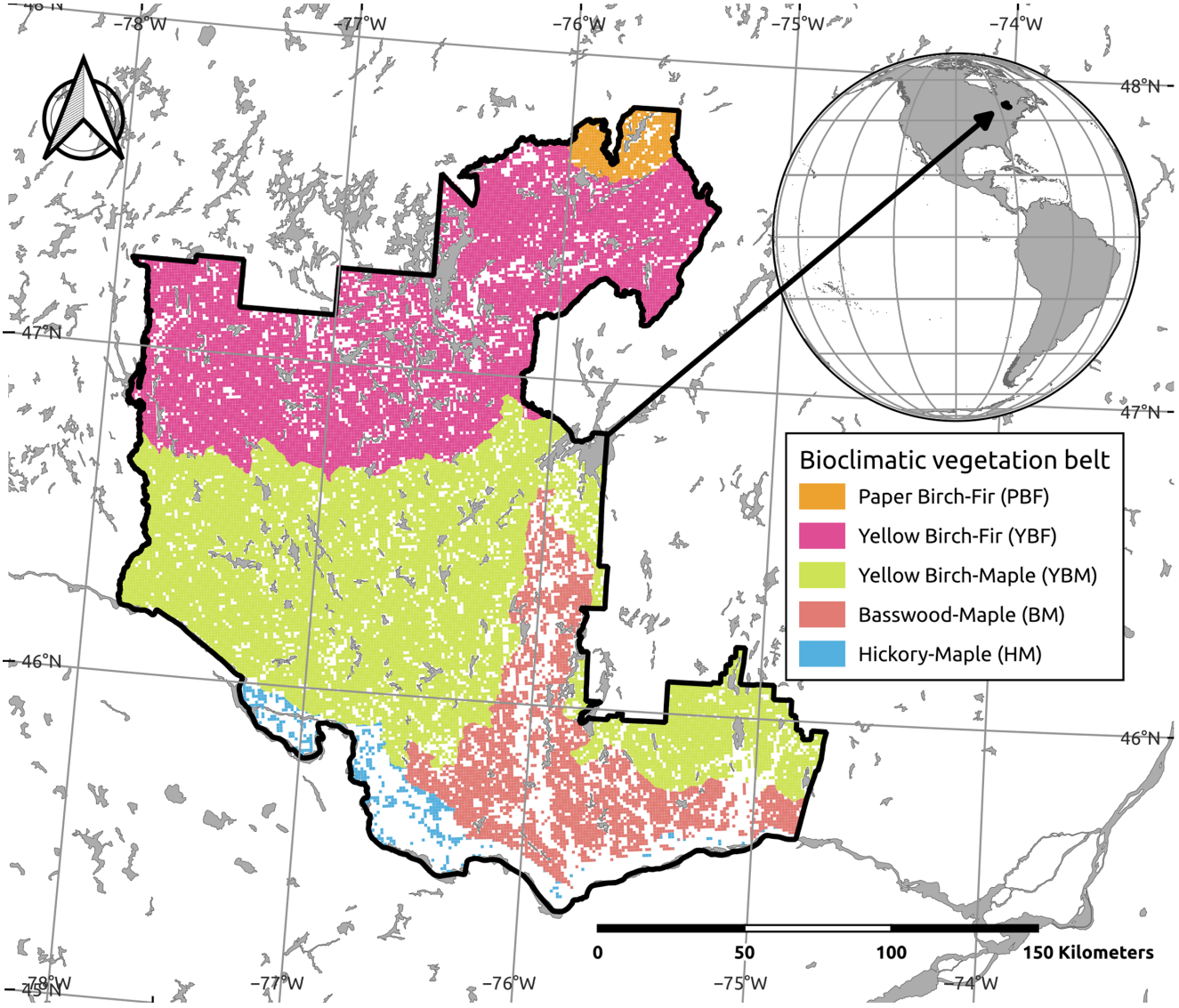

FIGURE 1 Bioclimatic vegetation belts within the study area (from Robitaille & Saucier, 1998). Gray (water) and white (nonforested) areas were not analyzed.

TABLE 1 Descriptions of tree communities within the study area (hereafter named for their dominant tree species and their species code).

Species code	Tree communities	Percentage of all communities	Companion species (% occurrence)	Preferred habitat drainage	Median latitude
Cluster 1 – Highest exposure					
QR	*Quercus rubra* L. Red oak	4	*A. rubrum* (18%) *A. saccharum* (16%)	Good	46.08335
Cluster 2 – Intermediate exposure					
TC	*Tsuga canadensis* (L.) Carrière Eastern hemlock[a]	1	*P. strobus* (18%)	Good	46.02338
PS	*Pinus strobus* L. Eastern white pine[a]	7	*P. resinosa* (28%)	Good	46.46627
FG	*Fagus grandifolia* Ehrh. American beech	<1	*A. saccharum* (60%)	Moderate	46.23872
PR	*Pinus resinosa* Aiton Red pine[a]	<1	*P. strobus* (59%)	Good	46.46860
AS	*Acer saccharum* Marshall Sugar maple	17	*B. alleghaniensis* (16%)	Moderate	46.38019
FN	*Fraxinus nigra* Marshall Black ash	<1	*B. alleghaniensis* (13%)	Imperfect	46.33418
AR	*Acer rubrum* L. Red maple	3	*B. alleghaniensis* (31%) *B. papyrifera* (9%)	Moderate	46.66693
PG	*Picea glauca* (Moench) Voss White spruce[a]	<1	*A. balsamea* (56%)	Moderate	47.39190
TO	*Thuja occidentalis* L. Eastern white-cedar[a]	4	*A. balsamea* (46%)	Moderate	46.78355
BA	*Betula alleghaniensis* Britton Yellow birch	12	*A. rubrum* (29%) *B. papyrifera* (22%)	Moderate	46.75140
Cluster 3 – Lowest exposure					
BP	*Betula papyrifera* Marshall Paper birch	12	*A. rubrum* (28%) *B. alleghaniensis* (18%)	Moderate	47.44847
PB	*Pinus banksiana* Lamb. Jack pine[a]	2	*P. mariana* (63%)	Good	48.68865
PM	*Picea mariana* (Mill.) Britton, Sterns & Poggenb Black spruce[a]	17	*A. balsamea* (50%)	Moderate	48.86721
AB	*Abies balsamea* (L.) Mill. Balsam fir[a]	19	*P. mariana* (44%)	Moderate	47.48294
LL	*Larix laricina* (Du Roi) K. Koch Tamarack[a]	<1	*P. mariana* (79%)	Imperfect	48.56688
PT	*Populus tremuloides* Michx Trembling aspen	<1	*B. papyrifera* (97%)	Moderate	47.48307

Note: Species are ordered from the highest to the lowest soil water deficit exposure according to the 95th percentile of annual soil water deficit severity (S95) and grouped in three clusters. "% of all communities" indicates the percentage of area covered by stands of a given community, "Companion species" indicates the main companion species found in the tree community, with the percentage of occurrences for the companion species in the community, "Preferred habitat drainage" indicates the drainage class mode of the dominant species in the study area according to the forest inventory. Good drainage implies that water is primarily from rainfall and drains rapidly, moderate drainage indicates that the rainfall inputs drain more slowly, and imperfectly drained stands have very slow drainage of water from rainfall and groundwater sources. The median latitude was calculated from the provincial forest inventory permanent sample plots across Quebec (Boisvert-Marsh et al., 2014; Boisvert-Marsh & de Blois, 2021) to give an overview of the geographic distribution of the species found in the study region.
[a]Indicates that the dominant species is a gymnosperm.

grandifolia, *Quercus rubra* L., *Tilia americana*, *Tsuga canadensis*, *Picea rubens*, and *Pinus strobus*), while the two northern ones are dominated by mixed deciduous–conifer forests (*Acer rubrum*, *B. alleghaniensis*, *Betula papyrifera*, *Populus tremuloides*, *Abies balsamea*, *Picea glauca*, *Picea mariana*, and *Thuja occidentalis*). The climate is humid continental with warm summers and cold winters with average monthly temperatures below 0°C. Precipitation in the region is on the low end for the temperate forest biome, with mean annual precipitation for 1981–2010 ranging from 847 to 1088 mm, making the region a suitable location for investigating soil water deficit. Average annual temperature for 1981–2010 varied from 6.3°C in the south to 1.7°C in the north (McKenney et al., 2011).

Modeling current conditions and projected changes in soil water deficit

The soil water data used in the present study to describe exposure to water deficit are the modeled outputs from Cholet et al. (2022; where futher methodological details can be found). Briefly, to assess soil water deficit across the study area, an offline simulation of soil moisture was conducted using the CLASS version 3.6 (Verseghy, 2000), embedded within the MESH platform (Pietroniro et al., 2007). CLASS, a land surface model, simulates heat and moisture exchange between the land surface and the atmosphere. The model operates on a grid-based system, calculating energy and water budgets for each cell based on four subareas: canopy over snow, canopy over bare ground, bare ground, and snow. Vegetation characteristics are defined by four broad plant functional types (PFT): needleleaf trees, broadleaf trees, crops, and grass, with their fractional coverage within each cell specified. Each PFT is assigned values for physiological and structural properties representative of that type, and these values remain constant throughout the year, except for leaf area index (LAI), which varies seasonally. Nine soil layers were defined within the model, with soil texture data obtained from the SIIGSOL database (Sylvain et al., 2021). We implemented the model at a spatial resolution of 1 km^2 for cells with at least 75% forest cover. The model outputs volumetric soil water content, which was then converted to daily maximum absolute soil water potential (hereafter called soil water potential, units = MPa) using the Clapp and Hornberger water retention curve (Clapp & Hornberger, 1978) implemented in CLASS. We found soil water potential to be a more representative measure of plant water availability than volumetric water content as it considers the influence of soil texture; higher values of absolute soil water potential indicate that water becomes less available. We defined soil water deficit as occurring when soil water potential falls below −0.90 MPa, a threshold associated with moderate plant water stress. For comparison, Fu et al. (2022) reported that plant water stress in European forests began at −0.64 MPa. We selected a more negative threshold to capture conditions of moderate stress rather than the onset of stress while still remaining less negative than values typically associated with the risk of embolism. Although recent studies have shown that plant water stress thresholds vary with soil texture, with plant water stress occurring at less negative soil water potentials in coarse-textured soils compared to fine-textured soils (Wankmüller et al., 2024), we chose to define a single, broadly applicable threshold based on soil water availability. This decision recognizes that plant water stress results from complex interactions among atmospheric, plant, and soil variables. Importantly, by basing our analysis on soil water potential rather than volumetric soil water content, we largely reduce some of the texture-related differences that would otherwise arise.

We extracted the maximum absolute value of daily soil water potential during the growing season only (May to October) for (1) current conditions, that is, simulations for the 1981–2010 period using ERA5 reanalysis (Hersbach et al., 2020) as forcing data, and (2) projected conditions, that is, simulations for the current period and a future period (2041–2070) associated with a high-emission scenario (RCP8.5) using simulations from the fifth-generation Canadian Regional Climate Model (CRCM5) as forcing data. In total, we used eight simulations from CRCM5, which was driven by four global climate models (GCMs) from the fifth Coupled Model Intercomparison Project (CMIP5) ensemble (CRCM5-CANESM2, CRMC5-CNRM-CM5, CRCM5-GFDL-ESM2M, and CRCM5-MPI-ESM-LR) for two different representative concentration pathways (RCP4.5 and RCP8.5). For this study, we chose to focus on RCP8.5 as it represents a high-emission scenario often used to assess potential upper-range impacts of climate change. We used a high-emission scenario to illustrate the maximum potential changes in water deficit exposure. More details on forcing data can be found in Cholet et al. (2022).

We computed soil water deficit duration (D) as the mean number of days per year where absolute soil water potential exceeded 0.90 MPa (−0.90 MPa), a threshold that characterizes moderate to severe water stress in trees. In this study, D refers to the mean of the accumulated number of days per year in the simulations and it is serving as a metric of seasonal prevalence rather than consecutive persistence. We calculated two indices of prevalence for each of the cells in the model: the 95th percentile of the annual D over the entire period (D95)

and the annual average of D (Dmean). D95 can therefore be used to determine the value close to the maximum number of days of moderate to severe water stress for each 30-year period, while Dmean reflects the average annual number of days of water deficit periods. We calculated soil water deficit severity (S) as the 95th percentile of the daily maximum absolute soil water potential (S95). S95 refers to the severity of soil water deficits over a 30-year period.

We used the anomaly method (Deque, 2007) to assess projected changes in the duration and severity of soil water deficit between the current (1981–2010) and future (2041–2070) periods. We computed three indices of projected change—ΔD95, ΔDmean, and ΔS95—from simulations using CRCM5 forcing data for the current and future periods. Since the CRCM5 forcing data were not bias corrected, we could only assess relative changes in the duration and severity of soil water deficit. We used simulations using ERA5 reanalysis as forcing data to describe soil water deficit in absolute terms in the present. Simulations using ERA5 reanalysis as forcing data were not directly compared to simulations of soil water potential using CRCM5 simulations as forcing data.

Characterizing tree communities

We obtained data on tree species composition from the Quebec provincial forest inventory (4th provincial forest inventory, Ministère des Forêts, de la Faune et des Parcs, 2018), in which forest stands are classified according to the dominant and subdominant species identified from aerial photos (1:15,000) taken in 2007. As per the methodology used to produce the forest inventory, stand composition is based on the species or class that occupies at least 50% of the stand basal area (i.e., dominant) (Berger, 2015). Stands with codes referring to unspecified mixed species or species groups as the dominant class were not used in this study (38% of the stands). For each tree community dominated by a particular species, we assessed both the number of stands and cumulative percent area in the study region. We retained those communities that represented more than 0.1% of the total study area (Table 1). Soil layering (depth = 0.5, 1, ≥2 m) was performed as in Cholet et al. (2022) to extract data on surficial deposits from the inventory.

We used a comparative approach to identify groups of tree communities showing similar soil water deficit indices under current conditions (ERA5 data). To do so, we performed a dissimilarity analysis based on a maximum distance (also referred to as Chebyshev distance in the literature) clustering, implemented using the package factoextra (v1.0.7). Specifically, we used the function get_dist with the maximum method (Kassambara & Mundt, 2020) in R 4.1.2 (R Core Team, 2023). The maximum distance measure will treat a species community as dissimilar if any delta variables deviate strongly. This measure was chosen because it can separate communities based on the amplitude of the largest change in the three indices (the similarity within a cluster means that the largest difference across the three indices is small enough that they are close). The number of clusters was chosen visually by plotting the distances obtained from the function. The use of statistical tests to assess significant differences between tree communities was not considered appropriate given the large number of stands included in the analysis (n = 526,183 for 17 tree communities). In this situation, significant differences are often detected although effect sizes are not necessarily meaningful (Lantz, 2013).

To explore differences in drought sensitivity among dominant tree species in our study area, we adapted the framework of Laughlin et al. (2023), which positions species drought sensitivity strategies within a two-dimensional space defined by drought avoidance and drought resistance. Laughlin et al. (2023) used rooting depth to characterize drought avoidance and xylem resistance to embolism (Psi50, the potential value at which there is a 50% loss of hydraulic conductance in the xylem) to characterize drought resistance. As a proxy of those strategies, we used relative trait values of rooting depth and xylem resistance for each species (five classes, from sensitive to tolerant) from Boisvert-Marsh et al. (2020). Based on the relative trait values of the dominant species, we positioned the studied communities (based on the dominant species) within this framework.

RESULTS

Tree communities' current exposure to soil water deficit

Figure 2 presents the current exposure (1981–2010) to soil water deficit of the different tree communities (i.e., stands dominated by a given tree species) in the region in terms of severity and duration. Tree communities were grouped into three clusters (Table 1): *Q. rubra* communities (Cluster 1 [C1], high exposure) represented 4% of the number of forest stands in the study area and are the most exposed to soil water deficit under current conditions (Figure 2 and left sides of Figure 3). Cluster 2 (C2, intermediate exposure) consisted of communities dominated by *Ac. rubrum*, *Ac. saccharum*, *B. alleghaniensis*, *Fa. grandifolia*, *Fraxinus nigra*, *Pic. glauca*, *Pinus resinosa*, *Pin. strobus*, *Ts. canadensis*, and

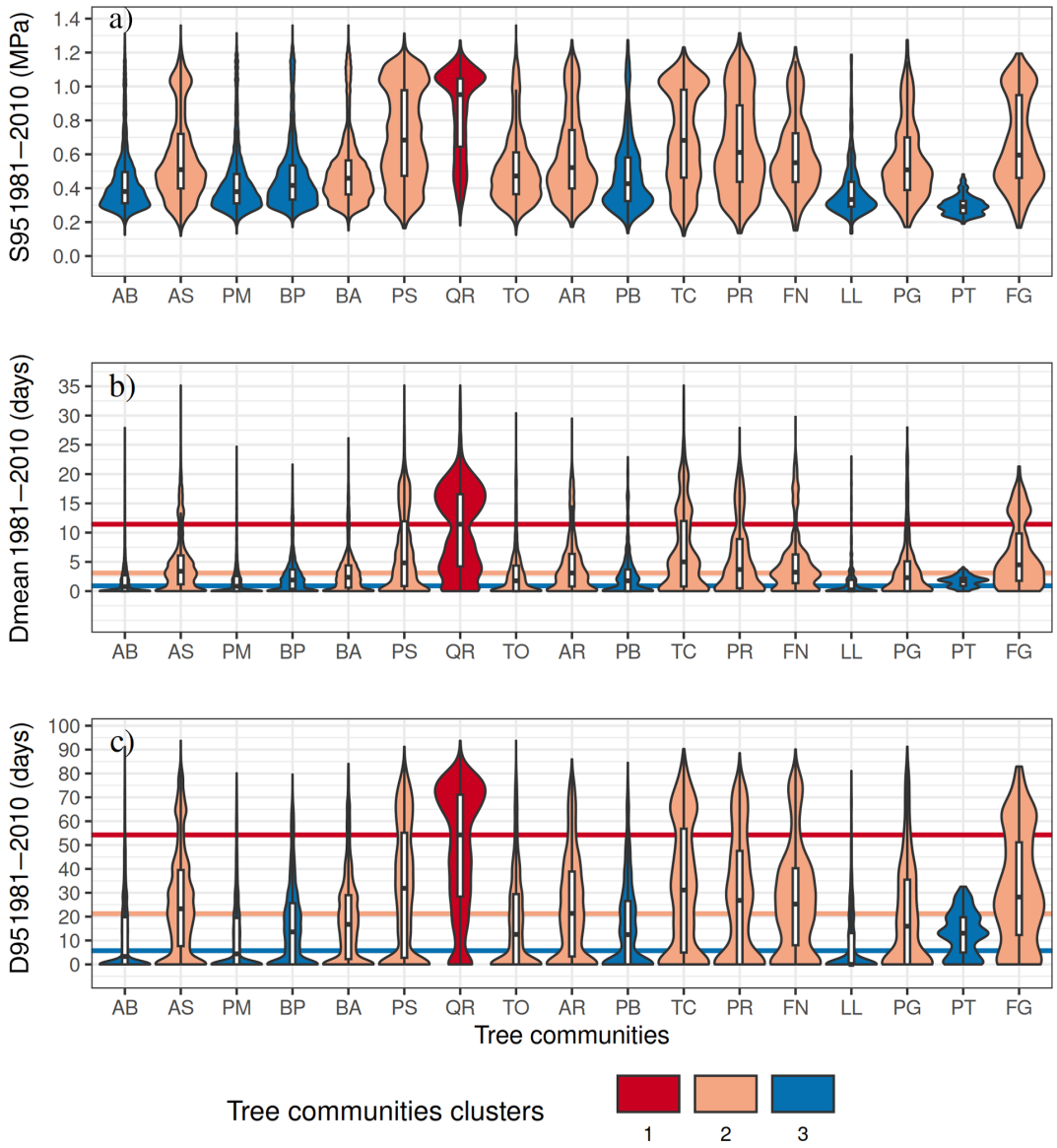

FIGURE 2 Current exposure (1981–2010) to soil water deficit, as quantified using three indices: (a) the 95th percentile of annual soil water deficit severity (S95), (b) mean annual soil water deficit duration, calculated as the annual average number of days where absolute soil water potential is greater than 0.90 MPa (Dmean), and (c) the 95th percentile of annual soil water deficit duration (D95). Colors refer to community clusters. The tree communities are ranked according to their abundance within the study area and the line represents the cluster-wide community median. See Table 1 for species codes.

Th. occidentalis and represented 51% of the total number of stands. These tree communities experience less water deficit than *Quercus* communities and exhibit a wide range of index values. Under the current climate, they generally show higher values for S95, D95, or Dmean compared to the third cluster (Figure 2 and left sides of Figure 3). Cluster 3 (C3, low exposure) consisted of tree communities dominated by *Ab. balsamea*, *B. papyrifera*, *Larix laricina*, *Pinus banksiana* Lamb., *Po. tremuloides*, and *Pic. mariana* (Table 1) and represented 45% of the total number of stands. Except for *Q. rubra* communities, most communities experienced only short-duration soil water deficits under the current climate, either on an annual basis (low Dmean values) or over the 30-year period (low D95 values; Figure 3).

Projected changes in exposure to soil water deficit

Compared to current conditions (1981–2010), projected (2041–2070) changes showed an increase in soil water deficit severity (ΔS95) from −0.11 to −0.21 MPa for the tree communities in the study area on average (Figure 3).

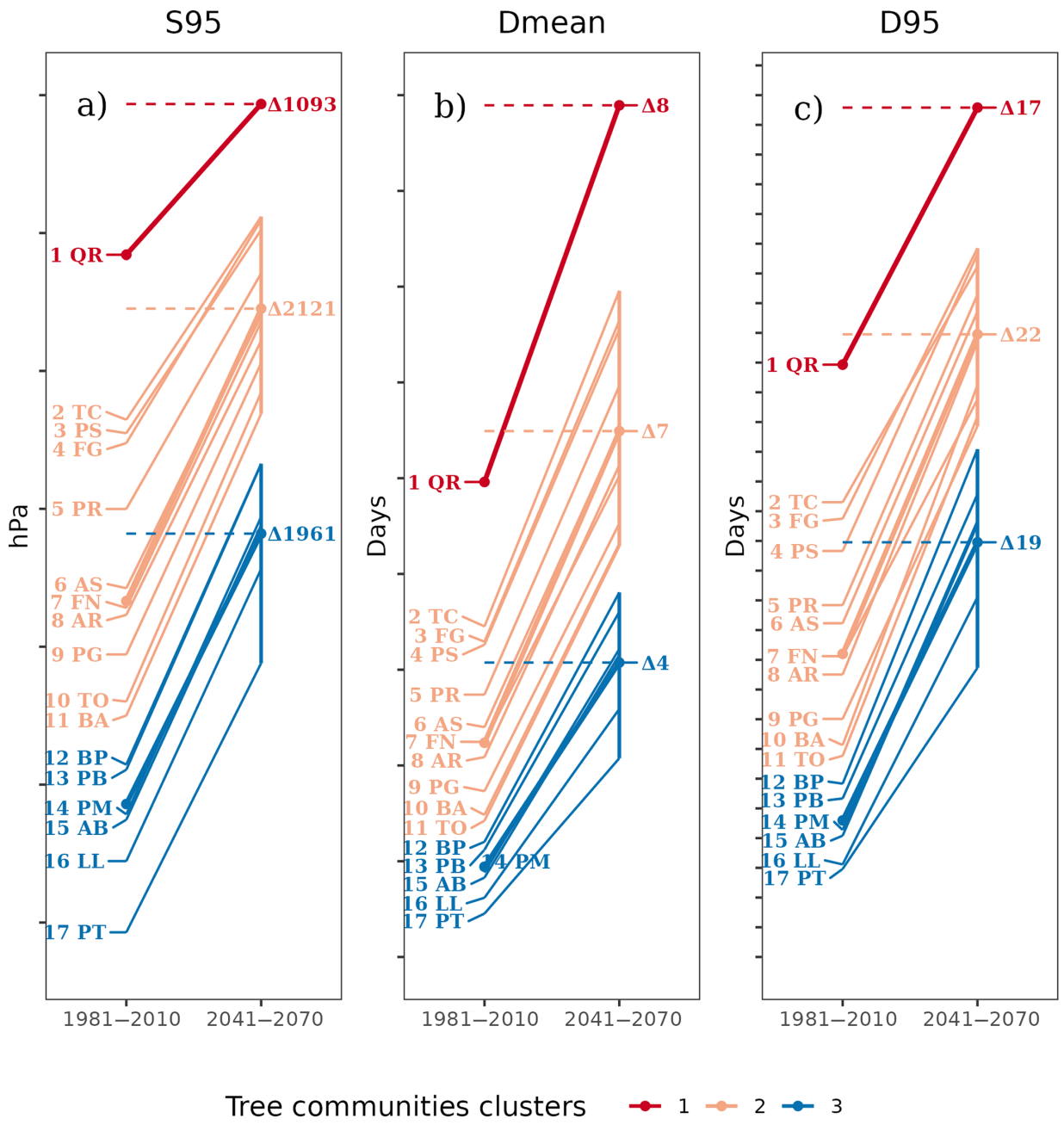

FIGURE 3 Changes in values of three soil water deficit indices between the current (1981–2010) period and the future (2041–2070) period under a high-emissions scenario (RCP8.5): (a) the 95th percentile of annual soil water deficit severity (S95), (b) mean annual soil water deficit duration, calculated as the annual average number of days where absolute soil water potential is greater than 0.90 MPa (Dmean), and (c) the 95th percentile of annual soil water deficit duration (D95). Position on the *y*-axis denotes relative values between tree communities. Clusters defined based on current climate conditions are displayed in color in each panel (from least to most exposed): Cluster 1 (C1) is in red, cluster 2 (C2) in orange, and cluster 3 (C3) in blue. The communities are ranked according to their mean value in the reference period in each panel. The dotted lines indicate the mean value of a community cluster in the future period. The bold line for each communities indicates the mean vector of change. See Table 1 for species codes.

The duration of mean annual water deficit (ΔDmean) increased on average by 4–8 days, and the 95th percentile of water deficit duration (ΔD95) increased by 17–22 days. We observe that the largest increases in severity were projected for the tree communities currently experiencing intermediate levels of soil water deficit (C2). For each soil water deficit index, tree communities in C2 had projected values of severity comparable to the *Q. rubra* community under the current climate. While values of all three indices are projected to change considerably, the relative positions of most tree communities on the exposure scale are expected to remain unchanged (15 communities out

of 17 retain their rank for ΔS95, 15 for Dmean, and 9 for ΔD95). In other words, all tree communities will experience an increase in the severity and duration of soil water deficit to such an extent that the least and most exposed communities in the current period remain so in the future. For instance, *Po. tremuloides* (PT) and *L. laricina* (LL) communities are currently the least exposed, while the *Q. rubra* (QR) communities are the most exposed. These positions are projected to remain unchanged for the period 2041–2070.

Differences in tree sensitivity to soil water deficit

Figure 4 presents the drought response strategies of each tree community based on the trait values of the dominant species. Tree communities in the study area showed a variety of trait values for rooting depth and xylem resistance to embolism, which can then be used to explain their associated response strategy. *Q. rubra* (QR, C1) and *Pin. strobus* communities (PS, C2) (top-left quadrat) are categorized as the most drought avoidant (deep roots) and drought resistant (low Psi50); in contrast, *B. papyrifera* communities (BP, C3) are categorized as the least drought avoidant (shallow roots) and resistant (high Psi50). Other tree communities exhibited some overlap in drought response strategies within two-dimensional space (Figure 4).

DISCUSSION

This study provides an assessment of the current and projected exposure of 17 tree communities to soil water deficit in the northern temperate forest of southwestern Quebec, as modeled by the CLASS (Cholet et al., 2022). The studied communities were ranked according to their current (1981–2010) exposure levels to soil water deficit.

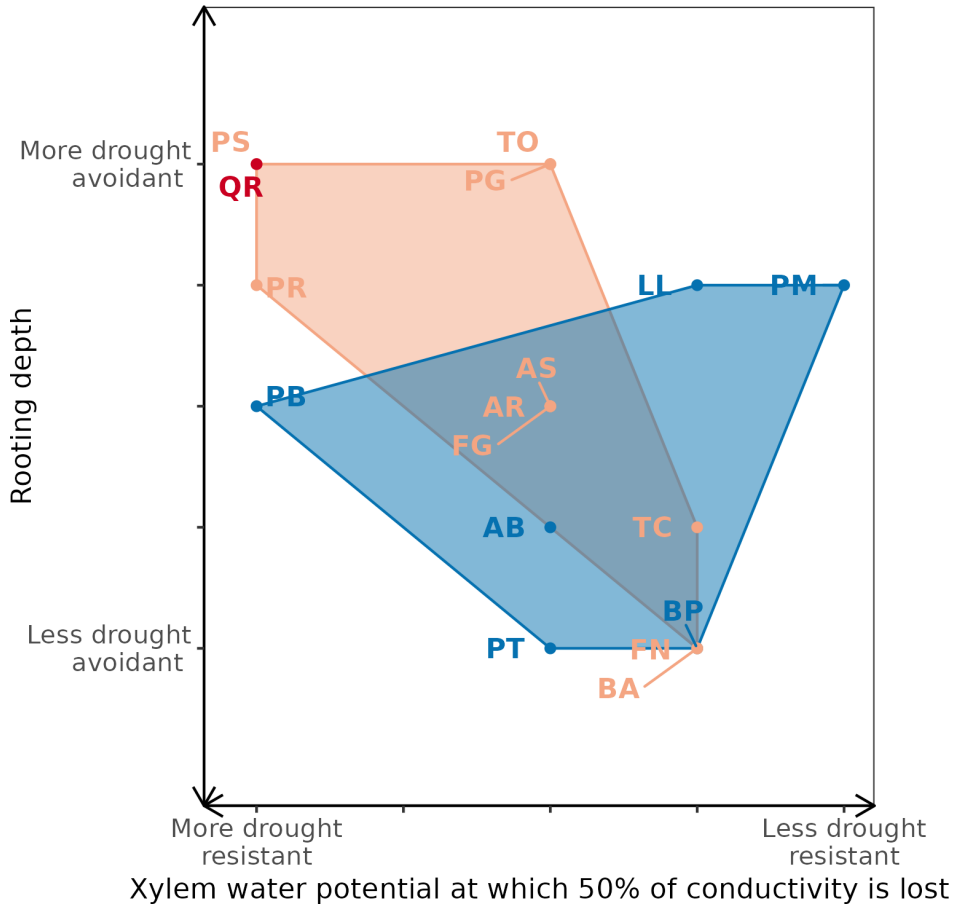

FIGURE 4 Relative position of dominant species of the studied tree communities in two-dimensional space that underlie drought response, following Laughlin et al. (2023) and using ranking data from Boisvert-Marsh et al. (2020). The *x*-axis represents the drought resistance strategy, as characterized by xylem resistance to embolism; species on the right are less resistant. The *y*-axis represents the drought avoidance strategy, as characterized by rooting depth, species on the top are more avoidant. Hull and species code colors indicate the identity and coverage of tree communities in the two-dimensional space: Cluster 1 is in red, cluster 2 in orange and cluster 3 in blue. See Table 1 for species codes.

When comparing current and projected (2041–2070) conditions under a high-emissions scenario (RCP8.5), we showed that all tree communities are projected to experience a substantial increase in exposure to soil water deficit. Both the severity and duration of soil water deficit are projected to increase for all tree communities: severity increases from −0.11 to −0.21 MPa, mean annual duration lengthens by 4–8 days, and the 95th percentile of duration extends by 17–22 days. While the magnitude of the projected changes differed among the tree communities, their relative positions and ranking in terms of exposure to soil water deficit remained unchanged. Most tree communities are projected to maintain their relative position and ranking within each cluster, in terms of soil water deficit exposure, with the least exposed community in the current period remaining so in 2041–2070.

While no change is expected in water deficit exposure rankings, the exposure magnitude is projected to increase substantially across all tree communities within our study area. Absolute changes suggest that communities will be regularly exposed in the future to conditions that are currently considered exceptional and likely outside their historical range of exposure (sensu Turner & Seidl, 2023). Similar trends in soil water deficit are projected elsewhere. For instance, Costanza et al. (2023) projected a threefold increase in meteorological drought exposure in US forests by 2070. At the global scale, Spinoni et al. (2021) also predicted an increase in drought exposure for several land cover categories, including forests. These studies describe projected changes on continental and global scales. The present study complements these findings by describing changes in water deficit exposure at a finer spatial scale to assess if regional changes in exposure vary among tree communities. Overall, we found relatively linear changes in soil water deficit exposure among various tree communities. As in Cholet et al. (2022), we found that the largest increases in severity (−0.20 MPa) were associated with communities that are currently the least exposed to soil water deficit (clusters C2, C3), while a smaller increase in severity (−0.10 MPa) was projected for *Q. rubra* communities, currently the most exposed to soil water deficit (Figure 2).

Tree communities' response to changes in soil water deficit exposure

Historically, climate variations have driven species distributions and migration in North America (Ordonez & Williams, 2013; Oswald et al., 2018). As tree species have different and complex responses to drought stress, it remains unclear how community dynamics will change with increased drought exposure (Bréda et al., 2006). One possible outcome is shifts in forest community composition. Many tree species considered here, for example, *Ab. balsamea*, *Pic. mariana*, *B. papyrifera*, *B. alleghaniensis*, and *Th. occidentalis*, are projected to be outside their current climatic niche within our study area by the end of the century (McKenney et al., 2007; Périé et al., 2014; Périé & de Blois, 2016), resulting in trees growing in novel environmental conditions. Projections from our modeling using the extreme climate scenario support this finding, highlighting that some communities might be confronted by soil water deficits beyond their tolerance threshold. In such situations, increased exposure to soil water deficit could impact stand productivity (D'Orangeville et al., 2018), result in increased mortality, and compromise reproductive success (Allen et al., 2010; Clark et al., 2016). Moderate disturbances could accelerate species turnover and community shifts at the temperate–boreal forest ecotone (Boisvert-Marsh & de Blois, 2021; Brice et al., 2019), though the velocity of climate change in Canada is projected to outpace migration capacity for many species (Boisvert-Marsh et al., 2022). In extreme cases, these changes could trigger a shift towards a more open, parkland structure (Boulanger et al., 2017; Seidl & Turner, 2022). Yet, the climatic threshold at which such regime shifts might occur remains unknown.

The projected absolute increase in soil water deficit duration and severity experienced by all tree communities could trigger changes in their dynamics, particularly in mixed stands where species with differences in drought sensitivity coexist. Extreme water stress events can alter species competitive dominance within stands (Cavin et al., 2013). Species with greater drought tolerance may outcompete their less tolerant counterparts, leading to shifts in species dominance and community assemblages (Falk et al., 2022). For example, both *Acer* species are actually co-occurring close to the same frequency in *Q. rubra* communities (Table 1) but *Ac. rubrum* may take over *Ac. saccharum* under the drier soil conditions expected for this community type. *B. alleghaniensis* and *B. papyrifera* are commonly observed as co-occurring species in many other tree communities. However, their low drought avoidance and resistance range (Figure 4) suggest they will be outcompeted under future water availability conditions by less sensitive species that exhibit deeper roots and greater resistance to embolism, leading to a loss in stand diversity. Even when dominating, the two *Betula*-dominated communities, representing altogether 24% of the tree communities within the study area, may shift towards *Ac. rubrum*-dominated communities as it co-occurs in nearly 30% of those stands. For the two most important gymnosperm-dominated communities (*Ab. balsamea* and *Pic. mariana*), it is unclear what shift in composition might prevail in the future as both species are co-occurring with the other one with about

the same proportion (~50%, Table 1). Consequently, the biotic composition and functional diversity of mixed forest stands in the study area could undergo profound transformations in the future (Iverson & Prasad, 2001; Wieczynski et al., 2019; Zhang et al., 2018).

Limitations and the way forward

When conducting vulnerability assessments at the regional scale, some simplifications are inevitable due to practical constraints and limited data on species abundance, traits, and other factors. Here, we ranked tree communities according to current levels of exposure to soil water deficit, but this ranking also reflects the latitudinal distribution of dominant tree species. For example, *Pic. mariana* communities are generally found at higher latitudes (Table 1), while *Q. rubra* communities are found at lower latitudes. Overall, more detailed stand composition data and the inclusion of additional physiographic variables could have led to more precise rankings.

Additionally, we assumed that tree communities remained static over time when assessing future exposure to soil water deficit. However, ecosystem dynamics generate a shifting mosaic that changes spatial distributions of forest communities over time (Bormann & Likens, 1979), though slow tree growth may limit these changes. This is particularly true in the southern portion of our study area where large-scale disturbances are rare and colonization is difficult under closed canopy (Fischer et al., 2013; Lorimer & Halpin, 2014). Climate change may further interact with successional processes (e.g., species-specific mortality, growth and recruitment rates) and disturbance regimes, making our static vegetation assumption uncertain. Such feedback loops between exposure to climate change and vegetation response complicate sensitivity analysis of future tree communities.

Data on tree communities need to be improved. The forest inventory used in this study assigns a dominant species to a stand if it covers at least 50% of the polygon, excluding companion species that can modulate community response to soil water deficit through interactions (e.g., complementarity and facilitation, Larocque et al., 2012). Stands with unspecified mixed species or species groupings (e.g., genus-level identification) were also excluded, potentially skewing community definitions and ignoring some regional heterogeneity. For example, stands dominated by *Ac. rubrum* are often identified to species when they occur on mesic sites; on xeric sites, they only tend to be interpreted to genus and thus were not considered in this study. As a result, some communities with bimodal exposure to soil water deficit were not captured in this study.

In addition, high-quality trait data are still scarce for North American tree species, especially for less abundant ones. Low data availability and biases in sampling coverage affect the representativeness of "average" data typically used in trait-based analysis (Aubin et al., 2024). Intraspecific trait variability (ITV) is also rarely taken into account but is crucial for understanding tree drought response (Aubin et al., 2018; Martínez-Vilalta et al., 2023; Westerband et al., 2021). Our study relied on categorical trait values with some species poorly documented (e.g., *Ac. rubrum*) and considered only two traits, despite drought sensitivity being multidimensional, which may have influenced sensitivity rankings (Figure 4). Furthermore, within ITV, ontogeny influences trait values and young individuals are more susceptible to stresses and extreme climate conditions (Niinemets, 2010; Walck et al., 2011). Field trait measurements are costly and time-consuming, highlighting the need for collaborative efforts to collect robust trait data across environmental gradients (e.g., Kumordzi et al., 2019). Finally, a trait-based approach requires theory-driven trait selection (Chacón-Labella et al., 2023). However, trait coordination and variation across species and environments in tree drought responses often remain unclear, which complicates the selection process (e.g., Augustine & McCulloh, 2024). This highlights the need for further studies to better understand these relationships.

CONCLUSION

Bridging the gap between research and forest management scales is essential. This study shows the value of local vulnerability assessments that consider species sensitivity and exposure to tailor area-specific forest management strategies. Vulnerability assessments can be a key decision support tool for forest management (Lecina-Diaz et al., 2021), especially when tailored to a regional context. However, most of the research supporting these regional assessments is conducted at the stand or global scale. For a comprehensive assessment of forest vulnerability at the regional level to be carried out, key limitations must be addressed, namely, (1) data availability and quality and (2) alignment between forest management and research scales. It is crucial to undertake studies at the scale at which actions are taken. To better predict species' community responses to drought, species interactions, often overlooked in distribution models, must be better understood and validated at the regional scale (Maynard et al., 2022; Sanczuk et al., 2024).

AUTHOR CONTRIBUTIONS

Jean-Francois Senecal, Audrey Maheu, Laura Boisvert-Marsh, Frédérik Doyon, and Isabelle Aubin conceived

the paper idea. Jean-Francois Senecal and Laura Boisvert-Marsh analyzed the data. Jean-Francois Senecal, Laura Boisvert-Marsh, and Morgane Dendoncker wrote the paper. All authors reviewed and edited the manuscript.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

Data used in this study are openly available from the following sources: soil water data (Cholet et al., 2022) are available on Zenodo: https://doi.org/10.5281/zenodo.6059351; trait data are available from Natural Resources Canada: https://natural-resources.canada.ca/science-data/science-research/research-centres/topic-network-traits-plants-canada-database-topic-canadian-repository-invertebrate-traits-trait-ecological-records-critter; and tree species composition data are available on Données Québec: https://www.donneesquebec.ca/recherche/dataset/resultats-d-inventaire-et-carte-ecoforestiere_4eme.

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