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RESEARCH

Climate-driven changes in tree species dominance across Canada

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Abstract

Differential tree species response to a changing climate could serve to drive changes in tree species dominance that alter forest ecosystem dynamics and have cascading socio-ecological impacts. This study projected climate change–driven shifts in tree species dominance across Canada's forests by the end of the twenty-first century. To do this, we mapped predictions of dominant tree species under possible future climate conditions using remotely sensed data products and climate projections. We applied species distribution models incorporating spectral, structural, topographic, geographic, and climatic predictors to estimate dominant species and probability of occurrence across Canada's forested ecozones in both 2020 and 2100. While holding other predictors constant, we altered climatic model inputs (i.e., precipitation and temperature) to relate possible future conditions under a moderate climate change scenario (SSP2-4.5). Comparisons of the model outputs for 2020 and 2100 were analyzed to assess changes in species dominance across environmental gradients and ecozones. Results indicate that approximately 18.7% (68.2 Mha) of Canada's 367 Mha of treed area is projected to experience changes in dominant tree species by 2100. Of pixels projected to change, approximately 10.9% represented a transition from coniferous to broadleaf species, while approximately 7.8% reflect a shift from broadleaf to coniferous species. The greatest changes in species dominance were projected in areas of lower topographic wetness, high-elevation regions, and in ecozones near the southwestern and southeastern coasts, as these are expected to have relatively large climatic changes. By quantifying potential shifts in dominant species across ecological gradients, this study contributes to the broader understanding of climate-induced changes in forested ecosystems, enabling effective long-term silvicultural and conservation strategies.

Keywords Tree species distributions · Climate change · Open data · Landsat · Forest management

Introduction

Tree species abundance and distribution are mediated by characteristics such as latitude, topography, soil conditions, and climate (Boisvert-Marshet al. 2014; Kirschbaum 2000; Wang et al. 2017). Climate-induced changes—namely, rising temperatures and changes to precipitation regimes—are likely to alter current growing conditions and, subsequently, tree species abundance and distribution. Tree species must either adapt to their altered environment or migrate towards optimal growing conditions (assuming an ability to keep up with the pace of climate change; Aitken et al. 2008). Predicting the magnitude and extent of species changes across broad spatial extents represents a fundamental step in understanding potential shifts in ecosystem dynamics (Baltzer et al. 2021; Johnston et al. 2009; Mack et al. 2021), nutrient availability (Macdonald et al. 2010), and future wood supply (Wang et al. 2023)

Future climatic changes may drive shifts in resource availability and tree species will have unique responses to changes in available water, sunlight, and nutrients (Avolio et al. 2019). For example, dominant tree species traits can influence ecosystem resilience and resistance to disturbance, such as a tree's physical resistance to fire (Hengst and Dawson 1994) or from adaptations that drive regeneration success (Agne et al. 2022; Baltzer et al. 2021). Climate change

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is also expected to alter the frequency, severity, and extent of natural disturbances such as fire, thereby increasing the exposure of tree species to mortality events and potentially accelerating changes in composition (Seidl et al. 2017). Changes in precipitation and climate moisture regimes may also alter the resilience of individual species, as severe fires expose mineral soil and reduce seed availability for regeneration (Baltzer et al. 2021). Dominant species also determine forest ecosystem responses to disturbances such as insect outbreaks, disease epidemics, fires, or drought (Mack et al. 2021). For example, broadleaf forests produce higher volumes of leaf litter that is decomposed and leads to greater soil carbon concentrations (Macdonald et al. 2010). While shifts in species dominance will impact aboveground patterns of landscape-level C cycling in boreal forests, variations in soil C pools and forest properties like albedo must also be assessed to accurately determine implications for global and regional climate.

Tree species dominance refers to the extent to which a tree species exerts control over the composition, structure, and function of a forest ecosystem, often measured by relative abundance, basal area, or canopy cover (Avolio et al. 2019). Dominant species can influence light availability, nutrient cycling, and species diversity, and are controlled by many interacting biotic and abiotic factors such as historical climate, topography, dispersal, geology, competition, and available resources. Differential tree species responses to a changing climate could drive associated changes in tree species dominance that substantially alter forest ecosystem dynamics and have cascading socio-ecological impacts (Dyderski et al. 2018). Over time, future climate changes are likely to have marked impacts on forest structure, age class distributions, and future species composition (Johnston et al. 2009). Discerning the magnitude and extent of potential changes in dominant species is critical to informing sustainable forest management and understanding ecological function across broad spatial scales (Martinez del Castillo et al. 2022).

Models that project species responses to future climate trends use varied approaches such as climate niche models (Campbell et al. 2025; McKenney et al. 2007), ecological niche models (Drake 2014), and process-based models (Nenzén et al. 2023; Szewczyk et al. 2019). These various approaches project shifts in species abundances and altered forest species composition due to the direct effects of climate on trees and the indirect effects of climate-altered disturbance regimes, interspecific competition, and dispersal capabilities (Iverson et al. 2004). For example, drought-induced tree mortality is predicted to intensify in moisture-limited areas of western boreal forests (Liu et al. 2023), at northern latitudes, and in high-elevation forests (Buma et al. 2016). Several models indicate the decline of spruces (*Picea* spp.) in the southern limits of their geographic ranges across Canada (Searle and Chen 2017). Wang et al. (2012) also projects the expansion of climatically suitable habitat for commercially important Douglas-fir in western Canada. In the boreal and temperate hardwood transition zone of southern Canada, several studies project shifts from mixedwoods or conifer-dominated forests to forests increasingly dominated by broadleaf species such as birch (*Betula* spp.), aspen (*Populus tremuloides*), and maple (*Acer* spp.; Brice et al. 2020; Chaste et al. 2019; Nenzén et al. 2023).

Sustainable forest management aims to balance natural resource development with the maintenance of healthy and diverse forest ecosystems that are resilient to future changes in environmental conditions (Campbell et al. 2009; MacDicken et al. 2015). Knowledge of potential shifts in tree species dominance is critical to informing present-day forest management opportunities that promote sustainability goals. More generally, an understanding of the responses of dominant tree species to future climate is essential to determining the continued viability of a broad range of ecosystem services. This is particularly important in Canada, where forests occupy large areas and serve important functions ecologically and economically. However, because forest stewardship responsibilities that contribute to national forest sustainability goals reside with the provincial and territorial governments (Stinson et al. 2019), relationships between forest species composition and future climate characteristics are often explored at regional and provincial scales. National-scale knowledge about shifts in future tree species dominance across jurisdictional boundaries is needed.

Remotely sensed data are increasingly available at broader spatial scales and finer levels of spatial detail, enabling the characterization of forests in a spatially continuous manner. Time series of optical satellite data products can capture changes and long-term trends in forest environments (Wulder et al. 2022). Land cover characterization has long been of interest, particularly across large extents (Hansen and Loveland 2012). Using satellite data and appropriately trained models, maps can be generated across regional to national extents to characterize forest attributes such as tree biomass and volume (Nguyen et al. 2020), height (Potapov et al. 2021), species presence and distribution (Pu 2021), and forest change dynamics (Woodcock et al. 2020). Furthermore, combining the rich spatial and temporal detail of these data with information on the structure (e.g., from airborne lidar) and composition (e.g., forest inventory plots) can enable the generation of map products informing on a variety of forest attributes. Satellite time series have a demonstrated capacity to characterize forest changes in the past (White et al. 2017), and these data products in combination with future climate projections could also provide expectations regarding the extent and location of changes in species dominance across Canada's forests.

The overall goal of this study was to predict climate-driven changes in tree species dominance across Canada's forests by the year 2100, using remotely sensed data products characterizing contemporary (2020) tree species dominance (Hermosilla et al. 2022a, 2024) and projections for future climate data (Wang et al. 2016). Specific objectives included (i) identifying the spatial extent and location of conifer to broadleaf (or vice versa) transitions nationally, (ii) characterizing changes in dominant tree species among ecozones and along topographic and climatic gradients, and (iii) identifying shifts in the national distribution of dominant tree species under future climate scenarios. Our national analysis of future changes in tree species dominance provides a broad-scale understanding of forest change that transcends provincial and territorial jurisdictions and informs both regional forest management and national forest sustainability goals in the context of a changing climate.

Materials and methods

Study area

Canada's land area is comprised of 15 ecozones—ecological areas with relatively homogeneous climate and topographic conditions that support distinct assemblages of plants and animals. Of the 15 ecozones, 12 are dominated by forests (Frazier et al. 2015) and represent more than 650 Mha of Canada's terrestrial area (Wulder et al. 2008). Among these ecozones, 367 Mha is occupied by treed land cover (Hermosilla et al. 2018; Natural Resources Canada 2023). In the Atlantic Maritime ecozone, maritime climate and forest management legacies contribute to diverse mixtures of tree species including trembling aspen (*Populus tremuloides*), white spruce (*Picea glauca*), and balsam fir (*Abies balsamea*; Ecological Stratification Working Group 1996). In the northernmost forested ecozones of Canada (i.e., Taiga Plains, Taiga Shield West, Hudson Plains, Taiga Cordillera, and Taiga Shield East ecozones), forest landscapes are dominated by black spruce (*Picea mariana*), while more southern boreal forests of the Boreal Plains, Boreal Shield West, Boreal Cordillera, and Boreal Shield East ecozones, forest landscapes are dominated by white spruce, balsam fir, trembling aspen, and jack pine (*Pinus banksiana*). The southern extents of the boreal ecozones are dominated by trembling aspen, maples (*Acer* spp.), balsam fir, and jack pine. Large variations in elevation and precipitation patterns in southern parts of western Canada (e.g., Pacific Maritime, Montane Cordillera) support diverse mixtures of conifer species, with most forested land being dominated by Douglas-fir (*Pseudotsuga menziesii*) and hemlock (*Tsuga* spp.), with subalpine fir (*Abies lasiocarpa*) and lodgepole pine (*Pinus contorta*) forests at higher elevations. Forests dominated by black spruce occupy the greatest treed area in Canada (~57%) and occur in most ecozones (Hermosilla et al. 2022a). A list of species and the extent of their dominance is found in Table 1.

Future climate projections

Contemporary (2018–2022) and future (2080–2100) precipitation and temperature variables were generated using ClimateNA, which uses bilinear interpolation and dynamic local elevational adjustment to produce scale-free estimates of a suite of climate variables based on an input elevation model (Wang et al. 2016). The climate projections utilized the system of Shared Socioeconomic Pathways (SSPs), which estimate future global emissions based on social, political, and economic development scenarios. Climate variables were generated using SSP2-4.5 to represent a climate projection with moderate and an ensemble mean of eight global climate models included in the Intergovernmental Panel on Climate Change's Coupled Intermodel Comparison Project Phase 6 (Mahony et al. 2022). While more extreme climate scenarios (e.g., SSP3-7.0 or SSP5-8.5) would generate more dramatic changes in tree species dominance across Canada, we chose to implement a more moderate emissions scenario (SSP2-4.5) to demonstrate the utility of remotely sensed data for developing climate-sensitive models of species dominance, to which other climate scenarios could be compared. Additionally, the outcomes presented herein are the result of an ensemble of 8 climate models, meaning that there may be some overlap between this and other SSPs. Nevertheless, while beyond the scope of the current work, we foresee that future work could assess the sensitivity species dominance shifts to multiple climate change scenarios, including those representing more extreme climate change. We generated estimates of mean current and future precipitation, maximum temperature, and minimum temperature at a 30-m spatial resolution to match the resolution of other datasets used in this study. We mapped change in climate attributes across the study area summarized changes by ecozone (Fig. 1).

Modelling

We adapted the Landsat-driven methods and models introduced by Hermosilla et al. (2022a) and expanded upon in Hermosilla et al. (2024) to project future tree species dominance in pixels across Canada given estimates of climate variables for each pixel during the period 2080–2100. These models used a suite of Landsat-derived spectral values, imputed forest structural attributes, topographic data, geographic information, and climatic predictors to estimate the probability of dominant species occurrence within each pixel using a Random Forest classification

Table 1 Description and areal extent of dominant tree species across Canada circa 2020 (Hermosilla et al. 2024). Treed pixels dominated by each species were summed to calculate both absolute (ha) and relative (%) area. Non-native species and those with total area less than 1000 ha were not included in this table

Common name	Scientific Name	Forest type	Area (ha)	Relative area
Black spruce	*Picea mariana*	Coniferous	207,276,546	56.69%
Trembling aspen	*Populus tremuloides*	Broadleaf	39,378,059	10.77%
Lodgepole pine	*Pinus contorta*	Coniferous	19,932,615	5.45%
Subalpine fir	*Abies lasiocarpa*	Coniferous	19,547,722	5.35%
Jack pine	*Pinus banksiana*	Coniferous	15,909,478	4.35%
Balsam fir	*Abies balsamea*	Coniferous	12,268,217	3.36%
Sugar maple	*Acer saccharum*	Broadleaf	8,411,562	2.30%
White birch	*Betula papyrifera*	Broadleaf	7,697,746	2.11%
Engelmann spruce	*Picea engelmannii*	Coniferous	7,328,124	2.00%
Western hemlock	*Tsuga heterophylla*	Coniferous	7,184,639	1.97%
White spruce	*Picea glauca*	Coniferous	6,740,150	1.84%
Douglas-fir	*Pseudotsuga menziesii*	Coniferous	4,301,431	1.18%
Eastern white pine	*Pinus strobus*	Coniferous	2,362,418	0.65%
Mountain hemlock	*Tsuga mertensiana*	Coniferous	1,868,866	0.51%
Tamarack	*Larix laricina*	Coniferous	1,451,439	0.40%
Western redcedar	*Thuja plicata*	Coniferous	1,312,023	0.36%
Red maple	*Acer rubrum*	Broadleaf	1,143,735	0.31%
Largetooth aspen	*Populus grandidentata*	Broadleaf	408,913	0.11%
Amabilis fir	*Abies amabilis*	Coniferous	306,212	0.08%
Yellow birch	*Betula alleghaniensis*	Broadleaf	249,794	0.07%
Yellow-cedar	*Chamaecyparis nootkatensis*	Coniferous	237,978	0.07%
Red spruce	*Picea rubens*	Coniferous	131,769	0.04%
Eastern white-cedar	*Thuja occidentalis*	Coniferous	47,212	0.01%
Red oak	*Quercus rubra*	Broadleaf	34,383	0.01%
Red pine	*Pinus resinosa*	Coniferous	23,621	0.01%
Balsam poplar	*Populus balsamifera*	Broadleaf	18,798	0.01%
Gray alder	*Alnus incana*	Broadleaf	18,245	< 0.01%
Western larch	*Larix occidentalis*	Coniferous	9,304	< 0.01%
Sitka spruce	*Picea sitchensis*	Coniferous	3,490	< 0.01%
Ponderosa pine	*Pinus ponderosa*	Coniferous	1,734	< 0.01%

model (Hermosilla et al. 2022a). Species with the highest probability values for a pixel, as determined by votes from the classification algorithm, were assigned as the dominant species for that pixel. When two species had an equal probability of dominance, the pixel was assigned to one of the two classes at random. However, ties were rare, occurring in < 1% of pixels. Topographic data for the models were generated from the Advanced Spaceborne Thermal Emission and Reflection Radiometer global digital elevation model, version 3 (Abrams et al. 2020). The models were trained with NFI photo plots (between 1984 and 2019), which contain species composition information, based on manually interpreted aerial photography and very high spatial resolution (< 1 m) satellite imagery. Within each photo plot, tree species dominance is interpreted based on characteristics such as overstory cover or stem number. Plots where the leading tree species was ≥ 50% were selected as candidate samples for the model. In total, 37 species were determined to have a sufficient sample size to be modeled in previous work (Hermosilla et al. 2022a, 2024).

It is important to note that the NFI photo plots used for training are only found in Canada. For species with ranges spanning across the Canada and US border, the training data may not capture the full breadth of their climatic niche, particularly at the more diverse and warmer southern border. Conversely, this training data is well suited to ensure that model projections are well grounded in the realized niche of contemporary populations as one moves north. This calibration minimizes the risk of over-predicting suitability based on southern populations that may be adapted to different photoperiods or soil conditions, although it implies that the full physiological climatic tolerance of these species may be broader than modeled in this study.

To ensure a locally representative set of training data, models were generated using a network of 150 × 150-km tiles. For each tile, sampling units came from a 5 × 5-tile neighborhood and an inverse distance weighted approach,

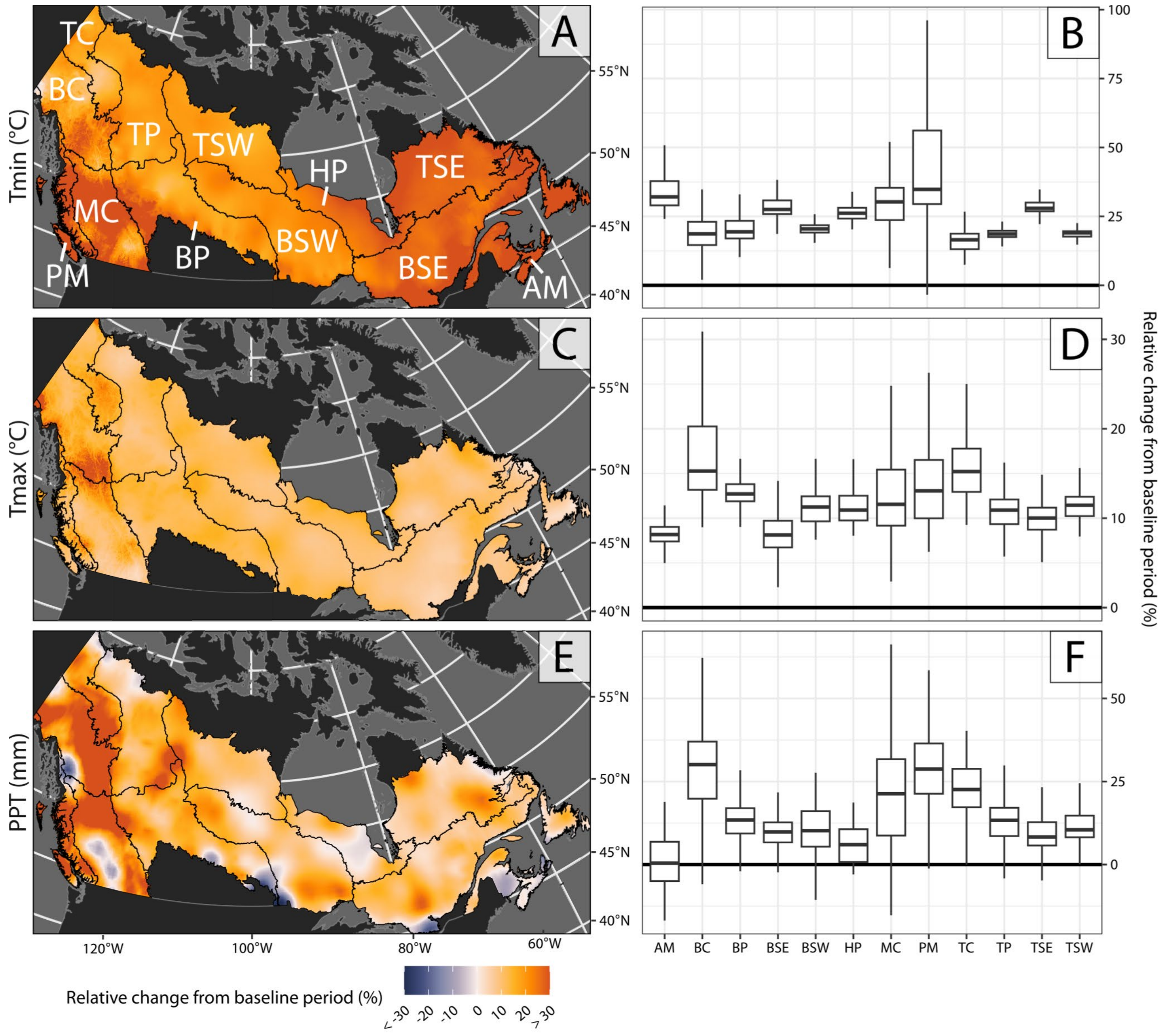

Fig. 1 Changes in climate variables across the study area. Changes were calculated relative to baseline (2018–2022) values of minimum temperature (Tmin), maximum temperature (Tmax), and precipitation (PPT). Panel **A** abbreviations refer to the names of Canada's forest-dominated ecozones: Atlantic Maritime (AM), Boreal Cordillera (BC), Boreal Plains (BP), Boreal Shield East (BSE), Boreal Shield West (BSW), Hudson Plains (HP), Montane Cordillera (MC), Pacific Maritime (PM), Taiga Cordillera (TC), Taiga Plains (TP), Taiga Shield East (TSE), and Taiga Shield West (TSW)

wherein 40% of training samples came from the center tile, 40% of samples came from tiles immediately adjacent, and 20% of samples came from the outermost tiles (Hermosilla et al. 2022b). Accuracy assessment of dominant species using a single time step showed an overall accuracy of approximately 93.1% when compared to independent validation samples of photointerpreted NFI data (Hermosilla et al. 2024). Additionally, models were assessed at an interannual time step based on changes in historic climate and biotic variables, and overall accuracy was found to be approximately 86.1% (Hermosilla et al. 2024). Of the 26 predictor variables assessed, three climatic variables were among the six most important predictors of species dominance; latitude, longitude, and elevation were the other three. To project species dominance under a future climate change scenario, we replaced current minimum and maximum temperature and precipitation used in the original models with projected mean values for these variables for the period 2080–2100. Values for all other predictor variables (e.g., topographic and geographic predictors) used in the original models remained constant. For brevity, hereafter we refer to historical (2018–2022) and future (2080–2100) epochs as "2020" and "2100," respectively, and a projected change in species dominance refers to a projected change under future climate conditions, given contemporary abiotic (e.g., topography) and biotic (e.g., land cover) conditions.

Analysis of model outcomes

Projected changes in tree species dominance across environmental gradients and ecozones

To characterize projected changes in tree species dominance across the study area, changes in the species dominating each pixel were classed into one of four types of transitions: (1) no change in dominant species, (2) change in dominant species, (3) shift from conifer to broadleaf species dominance, and (4) shift from broadleaf to conifer dominance. "Species change" represented pixels where the dominant species changed but the forest type (i.e., coniferous or broadleaf) remained the same. "Conifer-Broadleaf" and "Broadleaf-Conifer" comprised those pixels that changed both tree species and forest type, respectively from dominance by a coniferous to broadleaf species and vice versa. The number of pixels in each transition class was summed and expressed as a percentage of total treed area by ecozone, and binned values for three other variables: elevation (m above sea level), topographic wetness index (TWI; Beven and Kirkby 1979), and latitude (degrees north). Elevation influences factors such as climate, soil, competition, biotic interactions, and physiological adaptations (Körner 2007). TWI characterizes soil moisture availability, which can influence tree growth, regeneration success, and survival (Kopecký et al. 2021). Latitude likewise provides an important control on tree species presence through factors such as sunlight availability, temperature, and precipitation (Gillman et al. 2015; Qian and Ricklefs 2011), and thus is often used to model tree species distributions (e.g., Breidenbach et al. 2021). Additionally, transition classes were summed for each ecozone, addressing the second objective of understanding the projected spatial distribution of species dominance.

Geographic distribution of projected shifts in tree species dominance

The geographic distribution of shifts in tree species dominance was assessed by comparing the spatial distribution of pixels dominated by a particular species in 2020 with the distribution in 2100 (for species with a cumulative pixel area > 1,000 ha). Pixels were categorized in three groups: stable, increase and decrease. "Stable" pixels represented those where the dominant species of interest was the same in 2020 and 2100. A pixel was categorized as "Increase" if a species was dominant in 2100 but not 2020, and a pixel was categorized as "Decrease" if a species was dominant in 2020 but not 2100. The total area for each class was summed for each species and mapped using a kernel density approach to remove the effects of spatially disconnected pixels and capture the generalized area of species dominance. Using this approach, the location (latitude and longitude) of dominant pixels for a given species and year was entered into a kernel density function. The output of this function was an estimate for the 99% kernel density, or polygons encapsulating 99% of the spatial extent of pixels dominated by a given species. Kernel density analysis was conducted using the "eks" package (Duong 2024) in the R programming environment (R Core Team 2024). Default parameters for the package were used, which included a SAMSE (sum of asymptotic mean squared error) function to dynamically calculate the kernel bandwidth (Duong and Hazelton 2003). While kernel density analysis has been used to understand the spatial patterns of species presence and suitability (Zhang et al. 2018), it can smooth over spatially disjointed populations and fine-scale heterogeneity. However, as this study intended to demonstrate broad trends of species dominance, we believe its use in this context is effective in characterizing the spatially contiguous distribution of future species dominance.

Results

Conifer-broadleaf forest transitions

Of the 367 Mha of treed land across Canada reported for 2020, 68.2 Mha (18.7%) was projected to undergo a change in dominant species by 2100. Of the changing pixels, 10.9% (7.5 Mha) transitioned from a conifer to broadleaf species dominance, 7.8% (5.3 Mha) from broadleaf to conifer, and the remaining 81.3% (55.4 Mha) represented a species change but within the same coniferous or broadleaf forest type. A spatial representation of the pixel-based changes within each 150 × 150-km tile is shown in Fig. 2. Transition from conifer- to broadleaf-dominated forest was widespread in Atlantic Canada, while more localized transitions occurred in central Canada, and along the northwest coast. Transitions from broadleaf to conifer forests were less extensive, occurring mostly in southern regions of central Canada.

Projected changes in tree species dominance along environmental gradients and ecozones

We found distinct patterns of change in tree species dominance along environmental gradients and across Canadian ecozones. Projected changes in tree species dominance occurred frequently in high-elevation forests (Fig. 3A); ~35% pixels > 1000 m had a shift in species dominance. The distribution of changes by latitude had a multimodal distribution, with ~49% and ~32% of pixels showing a shift in species

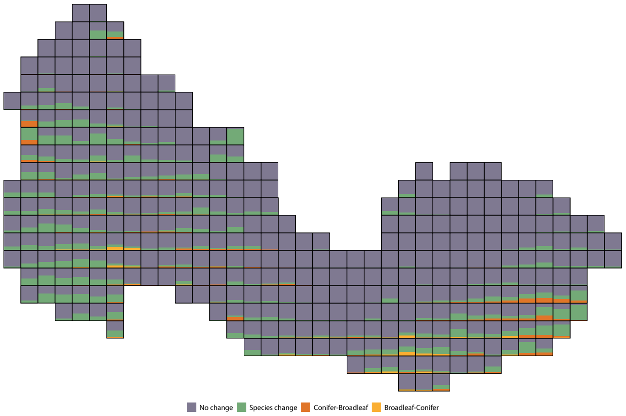

Fig. 2 Spatial distribution of the percent change in tree species dominance within each 150 × 150-km analysis tile. "Species change" refers to pixels where the dominant species changed but remained the same forest type (i.e., conifer or broadleaf), while "Conifer-Broadleaf" and "Broadleaf-Conifer" refer to species changes where the dominant species changed from a conifer to broadleaf forest type, or from a broadleaf to conifer forest type, respectively

dominance near 44°N and 61°N, respectively (Fig. 3B). There was an inverse relationship between the frequency of shifts in species dominance and TWI with more frequent transitions on dry sites (i.e., lowest TWI values) than wet sites (high TWI values). Additionally, there were large differences in species dominance shifts among ecozones. They were most frequent in the Atlantic Maritime (43.2%), Montane Cordillera (37.5%), and Pacific Maritime (35.4%) ecozones. The Taiga Shield East and Hudson Plains had the lowest amount of change, with 1% and 2.8%, respectively, of pixels with a shift in dominant species.

Species-specific patterns of change

Sankey diagrams illustrated important trends in species dominance state changes in pixels, both within and among ecozones (Fig. 4). Some of the largest shifts in species dominance occurred within the Atlantic Maritime ecozone, where nearly half of all pixels dominated by balsam fir in 2020 shifted to pixels dominated by deciduous species, mostly trembling aspen, by the end of the century. In western Canada, ecozones with diverse mountainous terrain also had marked shifts in species dominance. In high-elevation forests of the Montane Cordillera, approximately one quarter of subalpine fir-dominated pixels and one quarter of Engelmann spruce–dominated pixels shifted to dominance by lower elevation species, namely Douglas-fir and lodgepole pine. In the Boreal Cordillera, where Douglas-fir is absent, approximately a quarter of the pixels dominated by subalpine fir and Engelmann spruce were projected to shift to dominance by lodgepole pine, replacing black spruce as the most extensive species in this ecozone by the end of the century. Shifts in species dominance among ecozones of northern regions dominated by black spruce—Hudson Plains, Taiga Plains, Taiga Shield East, Taiga Shield West, Taiga Cordillera—were relatively uncommon.

While species dominance remained relatively stable over much of Canada by the end of the century, some forests were more vulnerable to change in species dominance than others (Table 2). Of the 30 native tree species included in Table 2, we projected an increase in the area of climatically suitable habitat for 17 species by 2100, while forests dominated by 13 species were projected to decrease in area. Some of the most extensive changes to Canada's forests involve species that dominated large areas in 2020. We projected a net decrease (5%) of climatically suitable habitat for black spruce–dominated forests, the most extensive forests in Canada. Similarly, there was a net decrease (30–43%) in climatically suitable habitat for other extensive forest types, including those dominated by subalpine fir, white birch, and Engelmann spruce. Conversely, the area of climatically suitable habitat dominated by sugar maple, western hemlock, Douglas-fir, and eastern white pine increased substantially (40–120%). The area of increase represents new, additional area of species dominance beyond the existing stable area and therefore is indicative of a change in the spatial location and/or extent of a given species' dominance.

We mapped the spatial patterns of stable, decreasing, and increasing area of species dominance for exemplar forests—those dominated by those dominated by Douglas-fir (Fig. 5a), which occur in western Canada; trembling aspen (Fig. 5b)—which extend across Canada; and those dominated by sugar maple (Fig. 5c), which occur in eastern Canada. Relative to 2020, climatically suitable habitat for dominance by Douglas-fir and sugar maple expanded northward. The expansion of habitat for aspen-dominated forests was proportionately less but occurred across Canada. Habitat for sugar maple– and trembling aspen–dominated forests decreased substantially in eastern Canada. Projected decreases in suitable habitat for Douglas-fir in Canada were relatively small.

Discussion

Our analysis sought to characterize potential shifts in tree species dominance across Canada under a moderate climate warming scenario (SSP2-4.5). We found that approximately 18.7% of Canada's treed area was projected to experience a change in dominant species by 2100, with considerable spatial variation in projected shifts in tree species dominance. Shifts in tree species dominance were most common in the Atlantic Maritime, Montane Cordillera, and Pacific Maritime ecozones, while the Taiga Shield East and Hudson Plains had the lowest amount of change. Ecozones with

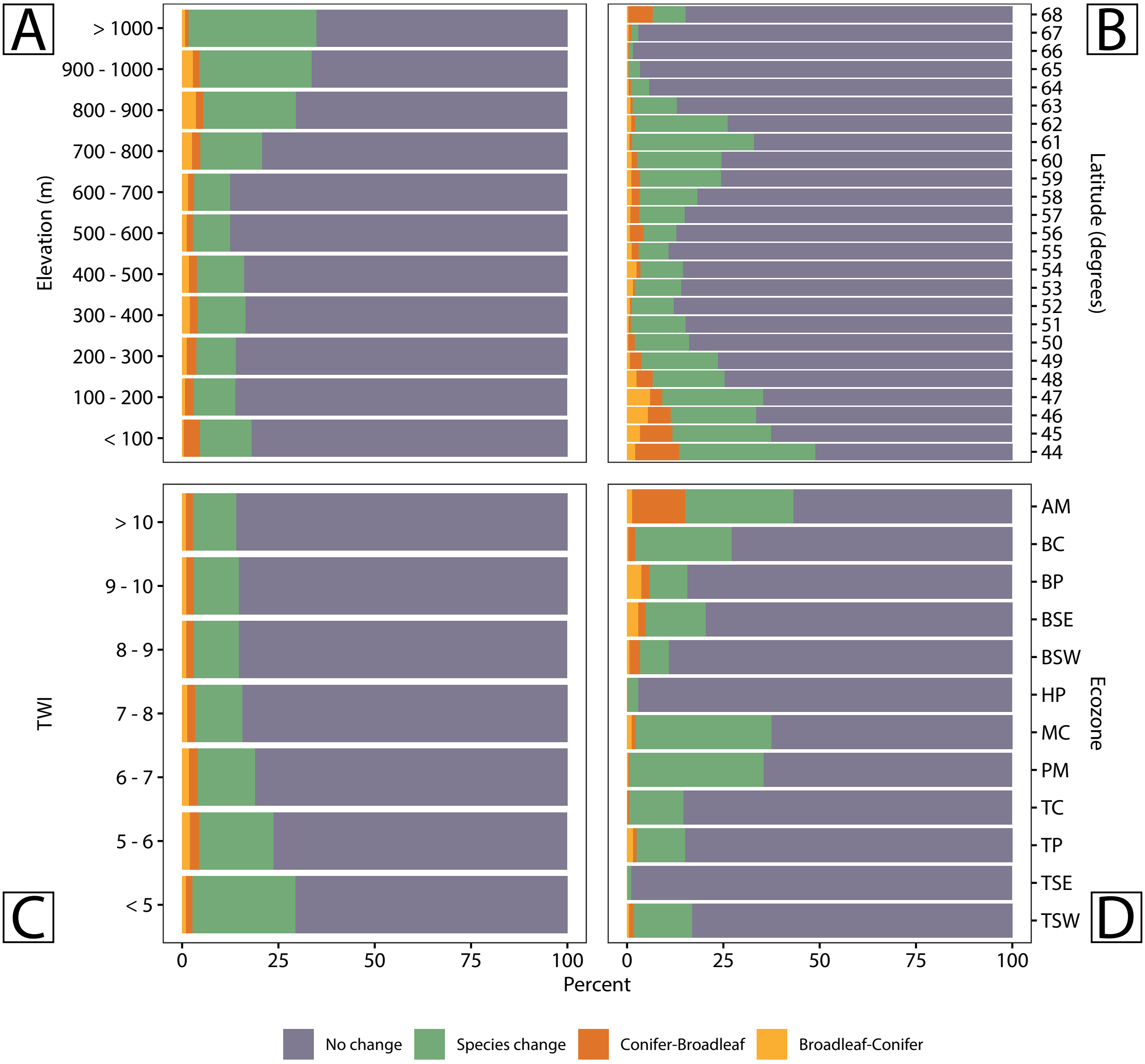

Fig. 3 Distribution of projected changes in species dominance along gradients of **A** elevation, **B** latitude, **C** topographic wetness index (TWI), and **D** by ecozone. The ecosystem acronyms in Panel **D** refer to the names of Canada's forest-dominated ecozones and can be found in Fig. 1

strong environmental gradients, like the Montane Cordillera and the Atlantic Maritime, support a diverse array of tree species and therefore more opportunities for shifts in tree species dominance compared to ecozones of the northernmost regions of Canada (e.g., Hudson Plains), which are dominated by black spruce.

Conifer-broadleaf forest transitions

One of the most notable projected changes in dominant species was a widespread and marked increase in broadleaf-dominated forests by 2100 in southeastern Canada (i.e., the Atlantic Maritime and Boreal Shield East ecozones). These conifer to broadleaf forest transitions are driven by a decrease in climatically suitable habitat supporting the dominance of balsam fir and spruce (*Picea* spp.) and an increase in climatically suitable habitat supporting broadleaf species, particularly sugar maple (Fig. 2). This finding is consistent with previous studies in this region that used ground plot data to project shifts from conifer to broadleaf forests dominated by birch (*Betula* spp.), aspen (*Populus tremuloides*), and maple (*Acer* spp.) as a function of warming temperatures and changing precipitation patterns creating unfavorable habitat for balsam

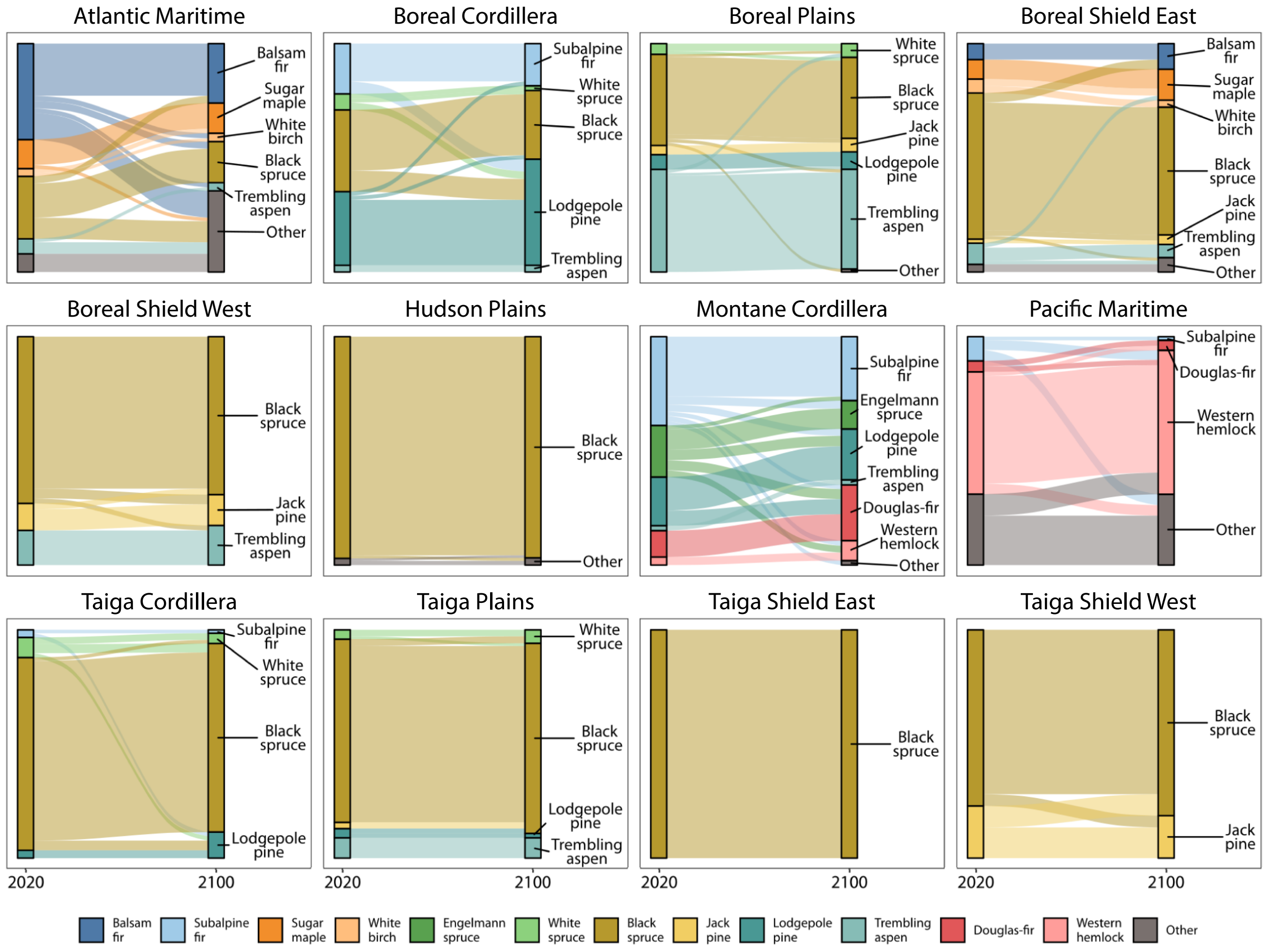

Fig. 4 Sankey diagrams showing changes in dominant species between 2020 and 2100. For simplified visualization, changes in species dominance that represented less than 1% of pixels in each ecozone were excluded, and species covering < 1% of the total study area are grouped into an "Other" category

fir and spruce (Joyce and Rehfeldt 2017; Price et al. 2013; Taylor et al. 2017). While some studies have proposed significant increases in broadleaf-dominated forests in the boreal zone due to increasing wildfire (e.g., Nenzén et al. 2023), particularly along the southern boreal forest transition zone (Boulanger et al. 2017), our projections indicate much less frequent conifer to broadleaf forest transitions in the Boreal Shield East relative to changes in species dominance involving conifers. Studies using Landsat time series data to map changes in dominant species composition retrospectively for the period 2000–2015 (Massey et al. 2023) and 1984–2022. Hermosilla et al. (2024) found relatively minor increases in broadleaf-dominated forests in the boreal region. In a separate retrospective investigation, forest area in Canada was found to have increased 7.2% (or 24 Mha) over the 1984–2022 period (Hermosilla et al. 2025). The largest increases in treed area were observed in post-disturbance landscapes and northern regions, including from wetlands. Nationally, balsam fir and trembling aspen exhibited the greatest area increases (Hermosilla et al. 2024).

Transitions from conifer-dominated to broadleaf-dominated forests constitute major ecosystem state shifts that come with significant socio-ecological consequences. Tree species dominance shifts like these impact forest vulnerability to subsequent disturbance, biological diversity, the regulation of water cycles, both above- and belowground carbon cycling, and forest albedo, which in turn has implications for both regional and global climate (Alexander et al. 2012; Baltzer et al. 2021; Parisien et al. 2023). In the Atlantic Maritime ecozone, projected increases in broadleaf-dominated forests across landscapes would likely reduce the impacts of future spruce budworm outbreaks (Campbell et al. 2008) and, given the comparatively low flammability of deciduous forests (Shinneman et al. 2013), broadleaf increases might also mitigate the impacts of increasing future wildfires

Table 2 Contemporary (2020) and future (2100) areas of native species dominance, with overall trend indcated, as well as the stable, decreasing, and increasing areas. The overall trend incorperates both increases and decreases in species area. Decreases in species area are taken from the stable area; increases in area or unique to the stable area

Species	2020 Area (ha)	2100 Area (ha)	Overall area trend	Area stable (ha)	Area decreasing (ha)	Area increasing (ha)
Black spruce	207,276,546	196,241,232	↓	186,344,349	20,932,197	9,896,883
Trembling aspen	39,378,059	38,361,404	↓	32,612,653	6,765,406	5,748,751
Lodgepole pine	19,932,615	23,939,146	↑	14,707,519	5,225,097	9,231,628
Subalpine fir	19,547,722	13,661,752	↓	12,168,400	7,379,322	1,493,352
Jack pine	15,909,478	16,309,058	↑	10,309,203	5,600,275	5,999,855
Balsam fir	12,268,217	12,682,023	↑	8,474,628	3,793,589	4,207,395
Sugar maple	8,411,562	12,295,750	↑	7,745,309	666,253	4,550,442
White birch	7,697,746	4,410,448	↓	2,905,255	4,792,491	1,505,193
Engelmann spruce	7,328,124	4,650,705	↓	2,767,102	4,561,022	1,883,604
Western hemlock	7,184,639	10,250,599	↑	6,342,639	842,001	3,907,960
White spruce	6,740,150	6,034,671	↓	2,904,840	3,835,310	3,129,831
Douglas-fir	4,301,431	8,424,421	↑	3,761,028	540,403	4,663,393
Eastern white pine	2,362,418	5,188,977	↑	2,153,002	209,416	3,035,975
Mountain hemlock	1,868,866	1,704,923	↓	594,301	1,274,565	1,110,623
Tamarack	1,451,439	1,890,414	↑	696,831	754,608	1,193,583
Western redcedar	1,312,023	2,361,177	↑	1,212,016	100,007	1,149,161
Red maple	1,143,735	3,672,570	↑	1,085,908	57,826	2,586,662
Largetooth aspen	408,913	346,875	↓	266,637	142,276	80,238
Amabilis fir	306,212	79,544	↓	11,818	294,394	67,726
Yellow birch	249,794	215,985	↓	23,808	225,986	192,176
Yellow-cedar	237,978	450,544	↑	100,483	137,495	350,060
Red spruce	131,769	1,951,177	↑	115,427	16,342	1,835,750
Eastern white-cedar	47,212	65,635	↑	18,550	28,662	47,085
Red oak	34,383	27,972	↓	14,921	19,462	13,051
Red pine	23,621	23,539	↓	9,578	14,043	13,961
Balsam poplar	18,798	9,691	↓	5,595	13,203	4,096
Gray alder	18,245	24,868	↑	9,479	8767	15,389
Western larch	9,304	178,934	↑	6,094	3210	172,840
Sitka spruce	3,490	18,882	↑	2,787	703	16,095
Ponderosa pine	1,734	2,154	↑	1,075	660	1,079

in this region (Taylor and MacLean 2025). However, an increase in broadleaf-dominated forests accompanied by a loss of commercially valuable conifers would have profound economic implications on forest resource-dependent communities in this region (Wang et al. 2023). Adapting forest management to resist or slow projected changes in forest species composition could lessen the economic impact (Moreau et al. 2022).

Projected changes in tree species dominance along environmental gradients

In mountainous regions of western Canada (i.e., Pacific Maritime, Montane Cordillera, and Boreal Cordillera ecozones), we projected widespread shifts in forest composition, tree species distribution, and abundance that varied strongly along topo-edaphic gradients. We found that projected changes in species dominance occurred mostly at high elevations or at sites with low TWI, suggesting increasing drought stress and warming temperatures at high elevations are important drivers of the shifts in species dominance we observed. Consistent with this pattern, our results indicated that forests dominated by high-elevation species (i.e., subalpine fir and Engelmann spruce) are projected to decrease in abundance, while forests dominated by low-elevation species (i.e., lodgepole pine and Douglas-fir) are projected to increase substantially across the landscape (Fig. 4). The elevational limits of Douglas-fir and lodgepole pine are delineated by cold temperatures that limit tree growth and survivorship, although lodgepole pine can tolerate much colder environments than Douglas-fir (Bansal et al. 2016; Campbell and Antos 2003), so a future upward migration of

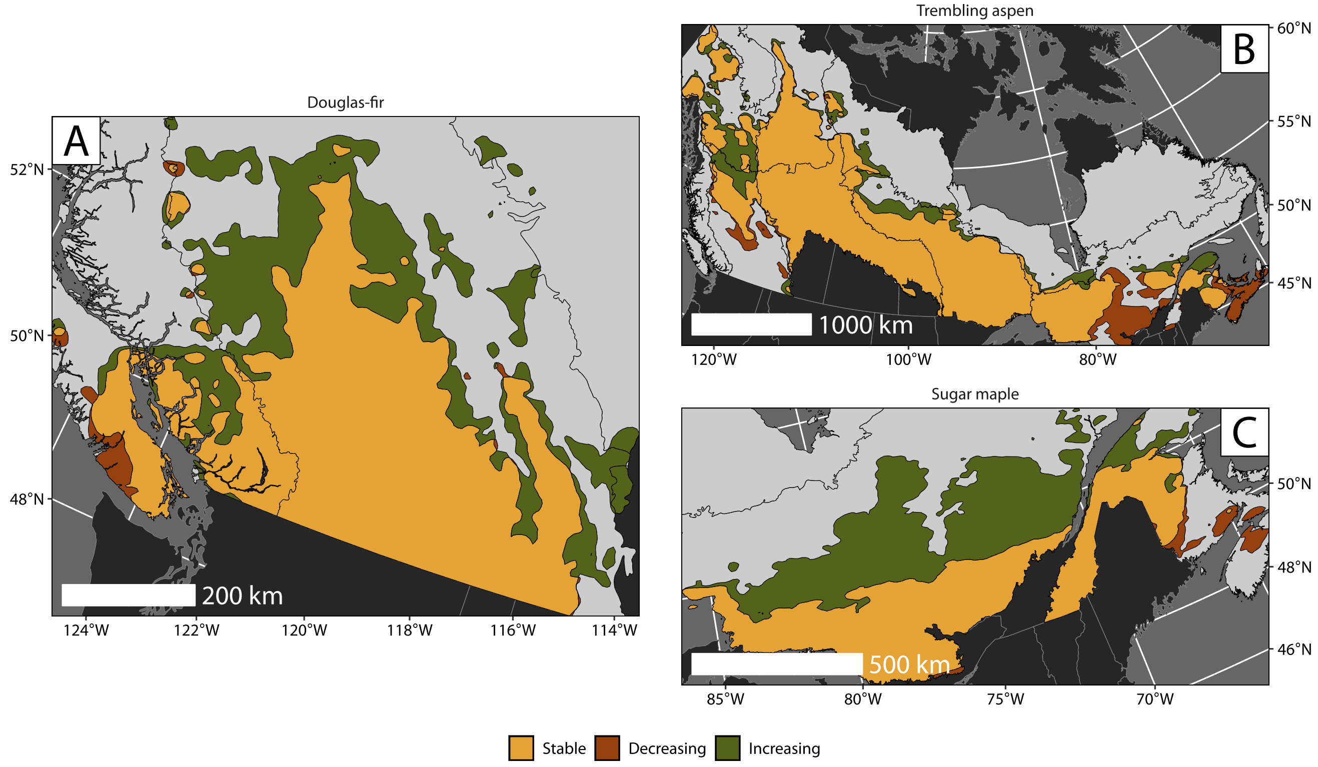

Fig. 5 Change in the distribution of pixels dominated by three exemplar species - Douglas-fir (*Pseudotsuga menziesii*; panel A), trembling aspen (*Populus tremuloides*; panel B), and sugar maple (*Acer saccharum*; panel C) between 2020 and 2100. "Stable" refers to areas with dominant pixels in both 2020 and 2100, while "Decreasing" and "Increasing" refer to those only present in 2020 and 2100, respectively

climatically suitable habitat for Douglas-fir and lodgepole pine-dominated forests is expected. This is supported by several other model projections indicating upward migrations of climatically suitable habitat for these species, and other low-elevation tree species, in mountainous regions (Pepin et al. 2022; Wang et al. 2012). However, the realization of this range expansion will depend on seed source availability, species-specific dispersal capacity and the presence of suitable seedbeds.

Our finding that projected changes in dominant species were most abundant on the driest sites (TWI < 5) is consistent with the increasing effects of drought stress (Allen et al. 2010). As the climate continues to warm, species on dry sites are likely to become increasingly vulnerable to prolonged drought and—because many may already be at, or near, their physiological limits—further stress may lead to hydraulic failure and mortality (Allen et al. 2010; Ryan 2011). While the specific nature of these projected shifts in species dominance on the driest of sites is difficult to determine, our analysis suggests it may largely involve the expansion of climatically suitable habitat for Douglas-fir and lodgepole pine-dominated forests in western Canada; as both species are highly tolerant to drought (Fig. 4). Overall, the widespread shifts in species dominance we projected for western Canada are consistent with other studies showing western boreal and mountainous forest regions are particularly susceptible to climate-driven shifts in species composition (Coops and Waring 2011; Mathys et al. 2017).

Projected geographic changes in species dominance

The impact that projected changes in dominance have on Canada's forests varied by species. Even though a relatively small proportion of the extensive black spruce–dominated forests in Canada (207 Mha) were vulnerable to the effects of climate change, the total area affected was greater than any other species, which is consistent with similar model projections showing major decreases in suitable habitat for spruce along the southern extent of the range of this species (Boulanger et al. 2022; Campbell et al. 2025; Joyce and Rehfeldt 2017). Black spruce is a shallow-rooted species that is sensitive to water stress, and the effects of future drought would substantially alter forest species composition in these regions (Girardin et al. 2016; Lesven et al. 2024).

We projected the largest net increases in climatically suitable habitat (~2 Mha) for Douglas-fir-, sugar maple–, and western hemlock–dominated forests. These findings are consistent with several other model projections (Boulanger et al. 2022; Campbell et al. 2025; Hanberry 2024; Wang et al. 2012). Douglas-fir is a major timber species in western Canada and the expansion of climatically suitable habitat for abundant Douglas-fir generates novel opportunities for this valued species provided sufficient seed is available (Wang et al. 2012). Habitat for sugar maple expanded substantially northward but declined substantially in the Atlantic Maritime. While many other models produce similar results, other studies suggest climate change may not favor extensive northward expansion of sugar maple forests (Boakye et al. 2023). Sugar maple is highly valued for the production of maple syrup and high-grade lumber for flooring and furniture (Carteron et al. 2020) and despite potential for the expansion of suitable habitat in some regions of Canada, losses in the dominance of sugar maple in the Atlantic Maritime region have great socio-economic implications. In western Canada, we projected a substantial expansion of climatically suitable habitat for western hemlock-dominated forests that contributed to the decline of climatically suitable habitat for Englemann spruce and subalpine fir-dominated forests. Such transitions are expected in mountainous regions with warmer climates that become more suitable for low-elevation species previously limited by cold and declines of subalpine species at their lower limits due to climate stress and increased competition (Conlisk et al. 2017; Coops and Waring 2011).

For some species such as trembling aspen–dominated forests, decreases in suitable habitat in central British Columbia and eastern Canada were offset by the northward expansion of habitat across Canada. Drought and drought-linked disturbances are already contributing to the decline of aspen across Canada and are expected to drive future aspen forest decline (Boulanger et al. 2022; Rehfeldt et al. 2012). Our projections indicated that the northward expansion of climatically suitable habitat for aspen forests across much of Canada's boreal forest is in part at the expense of a decline in climatically suitable habitat for black spruce and jack pine forests. Similar reports of aspen forest expansion and forest transitions are reported in other studies (Nénzen et al. 2023; Boulanger et al. 2022). As the climate warms and spruce becomes increasingly drought stressed, aspen may be better positioned to capitalize on limited site resources (Cortini et al. 2012).

Limitations and future directions

While holding non-climatic predictors (e.g., spatial location, topography, stand structure) constant allows for isolation of the effects of climate change on species distributions, this approach may limit the realism of long-term projections. In reality, forest attributes—such as canopy height, stand age, and composition—are dynamic and influenced by processes like succession, natural disturbance (e.g., fire, windthrow, pests), and forest management. By assuming these variables remain static, the model may underestimate species turnover or misrepresent the pace and pathways of change, particularly in regions where disturbance regimes are intensifying or management practices are shifting. Acknowledging this simplification is important for contextualizing projections and highlights the need for future work to incorporate dynamic landscape processes into species distribution modeling frameworks.

Furthermore, our analysis focused exclusively on shifts in dominance within the current extent of Canada's forests and does not consider potential future state transitions from forest to non-forest ecosystems (e.g., shrubland or grassland). Climate-induced stress and disturbances can drive forests towards alternative stable states, particularly in ecotones such as the Aspen Parklands where drought-induced mortality has been documented (Hogg et al. 2008; Michaelian et al. 2011). As a result, projected dominance changes will not capture locations where climate change could lead to forest loss rather than compositional shifts (Seidl & Turner 2022). Extending this framework to integrate dynamic vegetation models that consider state transitions could enable future assessments to capture a broader range of ecosystem responses. Like many other studies, we assumed current plant-climate relationships to remain valid throughout the period of analysis. We acknowledge, however, that projections of future vegetation under novel climate conditions can be challenging and prone to extrapolation errors. While the current structure of our study using remotely sensed data cannot yet account for changes in vegetation associated with novel climate conditions, we are aware of other studies that undertook this task (Mahony et al. 2017, 2018; Rehfeldt et al. 2012). They report that projected future novel climate conditions are geographically limited in Canada, with the emergence of novel climates largely restricted to a few disparate locations across the country. Understanding, modeling, and projecting vegetation associated with novel future climates remains a challenging and active area of research.

Our modeling approach characterizes spatial relationships between contemporary climate and species dominance and projects these relationships onto future climate scenarios. This approach assumes that temporal shifts in species dominance will mirror current spatial gradients. However, forests exhibit substantial ecological inertia; established individuals may persist in climates unsuitable for regeneration, delaying compositional changes (Aitken et al. 2008). Common to such modeling, our projections represent potential habitat suitability rather than immediate or observed changes. Recognizing this limitation underscores the importance of continuous, long-term monitoring to compare observed changes with projections and refine model assumptions over time. Unlike joint species distribution models which account for species co-occurrence and abundance directly (e.g., Clark et al. 2017), our approach models dominance as a categorical outcome based on the most probable species. While this provides a robust characterization of the leading species, it may oversimplify complex ecological dynamics where species codominance is present.

In addition to statistics used to assess the accuracy of the RF algorithm used to model relationships between species dominance, we compared the outcomes of our projected futures to vegetation changes projected by other models (e.g., Gray and Hamann 2013; McKenney et al. 2007). Akin to the International Panel on Climate Change (IPCC) model intercomparison project, which includes the outcomes of several different global circulation models (GCMs) to project future climate, comparisons of outcomes from different plant-climate models provide information about a range of possible futures. As noted above, we found that the major trends in vegetation changes we projected were consistent with the outcomes of many other future projections (Boulanger et al. 2022; Campbell et al. 2025; Coops and Waring 2011; Hanberry 2024; Joyce and Rehfeldt 2017; Mathys et al. 2017; Nenzén et al. 2023; Price et al. 2013; Rehfeldt et al. 2012; Taylor et al. 2017; Wang et al. 2012), despite differing modeling approaches, which lends confidence to the robustness of our projections. Nonetheless, variation in projected outcomes due to methods, input data, and model structure are inevitable, underscoring the importance of multi-model comparisons, continued monitoring to evaluate forest conditions and continuously improve projection model accuracy, and flexible natural resource management to deal with inherent uncertainties in projections about future forests.

Conclusion

Knowledge of tree species dominance and potential changes in their spatial distribution and extent under a changing climate is important information for a wide range of management and policy applications. Future changes in climate are likely to reshape tree species distributions in Canada's forest ecosystems. Using predictive models of dominant species informed by remotely sensed data and climate projections, we estimated that approximately 18.7% of Canada's treed area will undergo a change in dominant species by the year 2100 under a moderate climate change scenario (SSP2-4.5). Overall, our analysis also indicated considerable stability in tree species dominance nationally, with shifts expected to be most pronounced in the Atlantic Maritime, Montane Cordillera, and Pacific Maritime ecozones, where changes in temperature and precipitation patterns will drive marked changes in tree species dominance. We also projected marked state transitions from conifer to broadleaf dominance, which has widespread implications for ecosystem function, forest fire occurrence, nutrient cycling, and carbon storage (Baltzer et al. 2021; Black et al., 2026). Finally, our results indicate that despite differences in data and modeling approaches, the trends in changes in tree species dominance that we observed are similar to those reported in other studies, contributing to a confluence of evidence regarding the impact of climate change on dominant tree species. Unique to our approach is the integration of site-level climate effects into our modeling, which is often not incorporated into tree species niche models. The use of spatially explicit, fine resolution, remotely sensed data products to support investigations of changes to future species dominance offers additional, complementary information to support forest management and policy development.

Our projected shifts in species dominance suggest that certain species may become more prevalent, thereby influencing changes in light availability, nutrient cycling, and species diversity, among other factors in those forest ecosystems. Conversely, other species may experience a loss of dominance, particularly in higher elevations and along the southern portions of current species dominance. Our results highlight the importance of flexible forest management and silviculture strategies that can adapt to shifts in tree species dominance and the resulting changes in ecosystem dynamics, supporting forest resilience under changing climatic conditions.

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Data Availability The projected dominant tree species maps described herein for Canada's forested ecosystems are open access and are available at https://opendata.nfis.org/mapserver/nfis-change_eng.html.

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