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Assessing future climate trends and implications for managed forests across Canadian ecozones

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Abstract

Climate change interacts with ecological processes leading to changes in tree and forest growth rate, biome shifts and species composition, all of which are influenced by disturbances. This study explores future overarching climate trends of eight of Canada's ecozones containing managed forests. For the 2071 to 2100 period, climate projections indicate a warming trend of up to an additional 5.5 °C and an overall increase in annual precipitation. Future trends suggest marked contrast between coastal and interior forests and polarization between western and eastern forests. Warmer temperatures, accumulating degree-days above 5 °C and frost-free days suggest longer and drier growing seasons and greater risk of drought particularly in moisture-limited areas such as montane cordillera, taiga shield and boreal shield ecozones. Warmer temperatures and rising precipitation combined with less snow suggest shorter and wetter future winters. This indicates greater risk of rain-on-snow and freeze-thaw events, flooding and landslides particularly in coastal ecozones. We discuss how these projections are likely to result in shifts in dominant species and abundance, which when coupled with the cumulative effects of future disturbances, is likely to alter future forest dynamics and impact harvestable wood volumes for Canada's forestry industry.

Key words: climate change, climate projections, forest management, forest dynamics, ecozones

1. Introduction

Canada's managed forests cover more than 225 million ha, and as one of the top global manufacturers of forest products, they contributed $34.8 billion (1.5%) to Canada's nominal GDP in 2021 (Natural Resources Canada 2022*a*). Managed forests are transforming rapidly due to climate change which is likely to impact harvestable wood volumes, carbon sequestration potential, and Canada's forestry industry. Current climate projections show warming of up to 5 °C by the end of the century with precipitation regimes expected to be spatially variable (Bush and Lemmen 2019). Climate interacts with ecological processes that vary depending on forest type. These interactions result in biome shifts, increases in biotic and abiotic disturbances, changes to tree and forest growth rates, and shifts in species abundance and composition (Gauthier et al. 2014, 2015; Brecka et al. 2018). Forests' susceptibility and response to one—or a combination of—these interactions will have significant implications for how Canadian forests will need to be managed under future climate change.

Warming across Canada suggests that forests' susceptibility to climate change will be heavily influenced by regional water availability (Girardin and et al. 2016; Vincent et al. 2018; Intergovernmental Panel on Climate Change 2022). In temperature-limited forests, where soil moisture is able to withstand greater evapotranspiration demand, gains in tree growth may be expected (Wang et al. 2023). Forests that receive relatively high annual precipitation will likely be able to take advantage of warmer annual temperatures, greater atmospheric carbon dioxide (CO_2), and longer growing seasons to promote growth due to greater water availability (Jobidon et al. 2015; D'Orangeville et al. 2016; Chagnon et al. 2022). However, greater productivity in response to temperature may also be transient, until a point in time where excessive temperatures may cause growth declines due to reduced water availability (D'Orangeville et al. 2018). Moisture-limited forests are likely to see reduced growth rates with warming temperatures, causing drought stress. Without adequate soil moisture, fewer carbohydrates for growth are produced and deplete reserves when drought conditions extend over multiple growing seasons (Peltier et al. 2023). Risk of drought-induced mortality is greater in moisture-limited forests when excessive evapotranspiration demand can cause xylem cavitation and tree death (Chaste et al. 2019). Research suggests that overall, warming-induced tree growth may promote some biomass accumulation (Wang et al. 2023) though this will be exceeded by biomass lost to drought-induced mortality, suggesting an overall net negative effect of climate change on harvestable wood volume and timber production in established forests across Canada (Seidl et al. 2017). It is projected that for every degree of annual temperature increase, a reduction of net annual aboveground biomass changes from 0.20 to 1.07 Mg ha^{-1} year^{-1} across four major forest types in western Canada. This is particularly true for older forests and late successional conifer forests, where mortality rates exceed growth gain (Chen et al. 2016). This reduce not only harvestable wood volumes for the forest industry but also the carbon sequestration potential of Canadian forests (Ma et al. 2012; Zhu et al. 2018). As climate changes, warmth, moisture availability, and disturbance drive changes in forest structure, vegetation change, and species composition to shift ecological biomes and create new ones (Rehfeldt et al. 2012). As these biome shifts occur, tree species will be forced to either adapt to new environmental conditions or migrate toward more optimal growing conditions (Aitken et al. 2008). Such shifts of boreal species have already been predicted for northeastern Canada whereby trees will likely shift toward northeastern North America to regions of greater annual precipitation (Housset et al. 2015; D'Orangeville et al. 2016). When rates of forest expansion are slower than that of changing climates, species within their current distribution range may be unable to adapt to changing conditions (Aitken et al. 2008; Boisvert-Marsh et al. 2014; Allen et al. 2015). This is already being predicted for the southern transition zone of the boreal and temperate hardwood forests across eastern Canada (Stralberg et al. 2018; Brice et al. 2020; Boulanger and Puigdevall 2021) suggesting greater interspecies competition resulting in a shift from softwood species such as spruce (*Picea* spp.) and fir (*Abies* spp.) toward hardwood species, such as birch (*Betula* spp.), poplar (*Populus* spp.), and maple (*Acer* spp.) (Chaste et al. 2019; Brice et al. 2020; Klesse et al. 2020).

Forest disturbances will also increase in frequency and severity with climate change, including insects (Kurz et al. 2008), pathogens (Flannigan et al. 2005; Sturrock et al. 2011), and fires (Flannigan et al. 2005). Canadian forests are expected to experience an increase in active fire spread days by 35%–400% by 2050, particularly in western coastal regions (Wang et al. 2015) while increasing post-fire regeneration failure in fire-adapted species (Baltzer et al. 2021). Insect infestations such as the mountain pine beetle (*Dendroctonus ponderosae*) and the spruce budworm (*Choristoneura fumiferana*) have amplified across Canada due to recent winter warming that is no longer cold enough to prevent larvae from over wintering (Bale and Hayward 2010; Pureswaran et al. 2018). Forests that are—or most likely to become—moisture limited are most susceptible to disturbances (Seidl et al. 2017) and more likely to undergo changes to forest age class structure post-disturbance to promote younger, faster growing pioneer species resulting in mixedwood or pure deciduous stands (Johnstone et al. 2010; Brecka et al. 2018). These interactions between climate change and ecological processes generate greater uncertainty about ecosystem-based forest management strategies and their ability to maintain both forest productivity and the current structure of its associated value chain (Millar et al. 2007).

For this reason, understanding how climate is expected to change across Canada in the upcoming century is vital to ensure forest managers in both provincial and federal governments, as well as industry, foresee potential changes in forest health and productivity, timber products, carbon sequestration, and climate mitigation potential (Moreau et al. 2022). While some studies have compared spatial climate projections for select Canadian species or forest types (McKenney et al. 2007, 2009; Price et al. 2013; Gauthier et al. 2014; Taylor et al. 2017), few studies in the last decade (Price et al. 2013) have yet to compare managed forests of all ecozones across the country. Climate model projections are the primary means to inform forest managers as to how climate may change over the next 80–100 years. General circulation models (GCMs), produced by the Intergovernmental Panel on Climate Change's Coupled Model Intercomparison Project (CMIP6) (Eyring et al. 2019), can be used to project changes of future climate and thus the environment in which future forests will be growing. Using empirical evidence of the effect of climate on forest growth, structure, and composition, future climate projections allow forest managers to explore potential changes to forest structure dynamics and future vulnerability in a changing climate (Torresan et al. 2021). The result is "climate-smart" approach to short- and long-term regional forest management decisions that impact both the harvestable wood volume for the Canadian forest industry and climate change mitigation and adaptation potential (UNFCCC 2015).

The focus of this study is to summarize overarching climate trends of climate projections across Canada's National Forest Inventory's 12 forested ecozones with a focus on managed forests within them. Therefore, the objectives are to (1) generate historical and future projections of multiple climate variables for the 12 forested ecozones in Canada, (2) identify overarching future climate trends and compare these across the eight forest ecozones that contain managed forests, and (3) discuss the implications of future forest dynamics including species composition and abundance. These results can then provide insight for researchers and forest managers to better understand the possibilities of future climate and the implications on forest dynamics for regional climate-smart management in different ecozones across Canada.

2. Methods

2.1. Study area

Of Canada's 15 terrestrial ecozones, 12 are identified by the National Forest Inventory for reporting on the status and development of Canada's forests (Natural Resources Canada 2022*b*). Excluding the Arctic ecozones, these ecozones contain unique geologic and climatic conditions, supporting various forms of vegetation and wildlife, and these conditions are influenced by different forms of human activity. Historical climate and future projections were generated for these 12 forested ecozones with an additional data subset for the eight ecozones that contain managed forests (excludes Hudson Plains, Taiga Cordillera, and the east and west Taiga shields ecozones) (Fig. 1; Table 1).

Fig. 1. The National Forest Inventory's 12 terrestrial ecozones. Eight ecozones contain managed forested areas that contribute to Canada's forestry industry (indicated by hatched lines) and four do not (indicated by an asterisk in the legend). This figure was created using ArcGIS (version 2.9.2).

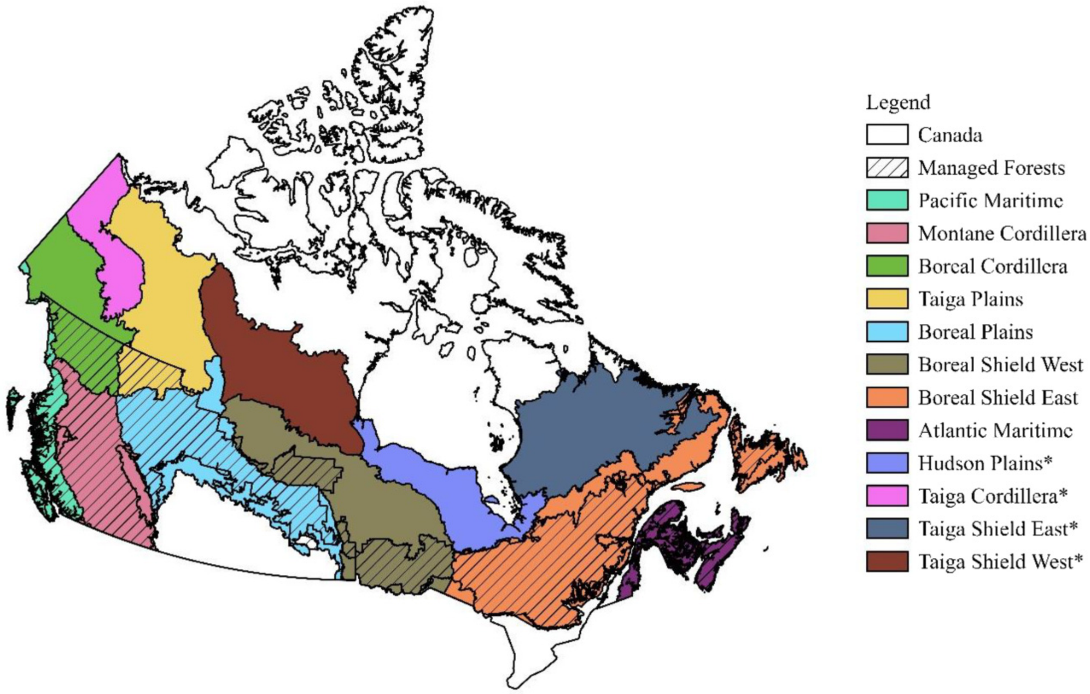


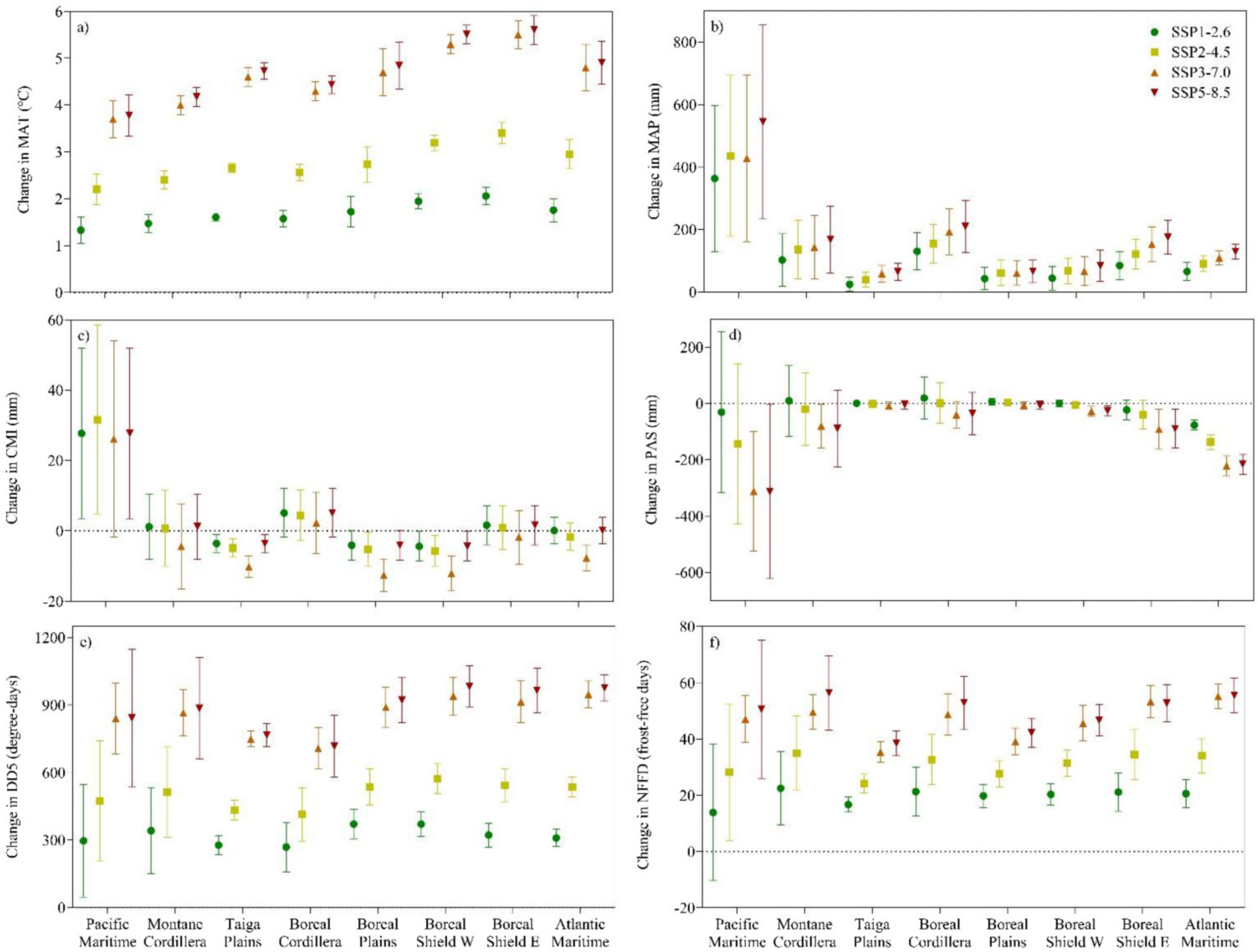
Table 1. Canada's eight forest regions, their locations, and the National Forest Inventory's corresponding ecozones that contain managed forested areas, as well as predominant tree species. Adapted from Natural Resources Canada (2022*b*).

Forest region	Location	Corresponding ecozones	Predominant tree species
Coastal	British Columbia	Pacific Maritime	Western red cedar (*Thuja plicata*), western hemlock (*Tsuga heterophylla*), Sitka spruce (*Picea sitchensis*), and Douglas-fir (*Pseudotsuga mensiesii*)
Montane	British Columbia and Alberta	Montane Cordillera Boreal Cordillera	Douglas-fir, lodgepole pine (*Pinus contorta*), ponderosa pine (*Pinus ponderosa*), and trembling aspen
Subalpine			Engelmann spruce (*Picea engelmannii*), subalpine fir (*Abies lasiocarpa*), and lodgepole pine
Columbia			Western red cedar, western hemlock, Stika spruce, and Douglas-fir
Boreal	Western and central Canada	Taiga Plains Boreal Plains Boreal Shield West	White spruce (*Picea glauca*), black spruce (*Picea nigra*), balsam fir, Jack pine (*Pinus banksiana*), white birch (*Betula papyrifera*), trembling aspen (*Populus tremuloides*), tamarack (*Larix larcina*), and willow (*Salix* spp.)
Great Lakes-St Lawrence	Central and southwestern Canada	Boreal Shield East	Red pine (*Pinus resinosa*), eastern white pine (*Pinus strobus*), eastern hemlock (*Tsuga canadensis*), yellow birch, maple, and oak
Carolinian/deciduous			Beech (*Fagus* spp.), maple (*Acer* spp.), black walnut (*Juglans nigra*), hickory (*Carya* spp.), and oak (*Quercus* spp.)
Acadian	Maritimes	Atlantic Maritime	Red spruce (*Picea rubens*), balsam fir (*Abies balsamea*), and yellow birch (*Betula alleghaniensis*)

2.2. Climate data

Climate projections for the 12 forested ecozones (Fig. 1; Table 1) were generated using ClimateNA (Version 7.3) (Wang et al. 2016), a software that downscales PRISM (Daly et al. 2008) monthly climate data to scale-free point locations at 800 m × 800 m resolution. Historical climate data were generated for 30-year climate normals (means) using 1991–2020 as the reference period. Future climate data were generated for 2071–2100 under scenario SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5 using an eight-GCM ensemble (Mahony et al. 2022). Projections under SSP3-7.0 scenario were used as the main dataset for consideration of climate change on forest impact and adaptation research. This accounts for the "business-as-usual" scenario instead of SSP5-8.5, which assumes coal-

Fig. 2. Projected changes for 2071–2100 in mean annual (*a*) temperature (MAT), (*b*) precipitation (MAP), (*c*) climate moisture index (CMI), (*d*) precipitation falling as snow (PAS), (*e*) degree-days above 5 °C (DD5), and (*f*) number of frost-free days (NFFD) compared to the 1991–2020 reference period for eight forested ecozones that contain managed forests. Projections were generated at 800 m resolution using an eight-global circulation model (GCM) ensemble. Shapes and colors indicate means of four shared socioeconomic pathways (SSPs), and vertical lines denote standard deviation within scenarios generated by the ensemble.



energy dependence and is highly unlikely considering future socioeconomic trends (van Vuuren et al. 2011; Ritchie and Dowlatabadi 2017).

Future mean annual values were generated for temperature (MAT; °C), precipitation (MAP; mm), degree-days above 5 °C (DD5; degree-days), the number of frost-free days (NFFD; days), precipitation falling as snow (PAS; mm), and Hogg's climate moisture index (CMI; mm) for Canada's forested forest ecozones. CMI is calculated by subtracting the potential evapotranspiration (PET) from annual precipitation (CMI = MAP – PET) indicating the ability of a landscape to maintain adequate soil moisture (Hogg 1997). Larger CMI indicates wet conditions, while smaller CMI indicates drought conditions.

Mean values for each ecozone were extracted based on the values of each input raster for both total forested area and the area found within the boundaries of Canada's managed forests. Change in projected values was calculated as the difference between each projection value and the historical mean of the reference period. Climate projections and calculation of the resulting differences were performed using R Studio (Version 4.2.1) (R Core Team 2022).

3. Results

Projections of future climate change for managed forests within eight of the 12 ecozones under four SSP scenarios for the period of 2071–2100 are shown in Fig. 2. Scenarios SSP1-2.6 and SSP2-4.5 show more moderate projections with the greatest variation between means in MAT, DD5, and NFFD. Scenarios SSP3-7.0 and SP5-8.5 show more extreme projections but with less variation between them compared to the other two SSP scenarios. Because SSP5-8.5 assumes the highly unlikely dependence on coal-energy in future socioeconomic trends, SSP3-7.0 was chosen as the main scenario for the interpretation of projected change in climate for the eight ecozones containing managed forests. The variation within these projections is indicated by standard deviation from the mean of the eight GCMs within the ensemble (Tables 2 and 3). Projected changes are relative to the 30-year mean of 1991–2020,

Table 2. Projected mean annual climate for 12 forested ecozones across Canada for 2071–2100 under SSP3-7.0 scenario at 800 m resolution.

	Mean annual temperature (°C)	Mean annual precipitation (mm)	Hogg's climate moisture index (mm)	Precipitation falling as snow (mm)	Degree-days above 5 °C	Number of frost-free days
Pacific Maritime	8.1 (3.8)	3104 (1491)	261 (155)	606 (1024)	1902 (690)	252 (67)
Montane Cordillera	6.2 (2.1)	1002 (437)	45 (54)	335 (242)	1740 (456)	196 (23)
Boreal Cordillera	2.2 (1.7)	814 (637)	38 (7)	331 (423)	1310 (306)	155 (20)
Taiga Cordillera	−0.7 (1.3)	702 (227)	33 (24)	301 (126)	1112 (243)	133 (13)
Taiga Plains	0.9 (2.0)	428 (119)	−0.06 (11)	149 (41)	1580 (298)	157 (14)
Boreal Plains	5.8 (1.1)	524 (71)	−8.7 (9)	117 (18)	2216 (224)	189 (6)
Taiga Shield West	−0.6 (1.7)	408 (71)	7.0 (7)	147 (19)	1380 (236)	147 (14)
Taiga Shield East	2.1 (1.1)	909 (171)	59 (15)	329 (75)	1290 (201)	145 (15)
Boreal Shield West	4.9 (1.7)	640 (125)	10 (11)	157 (33)	2181 (269)	179 (8)
Boreal Shield East	6.7 (2.1)	1132 (158)	60 (24)	261 (105)	2131 (437)	184 (17)
Hudson Plains	4.1 (1.7)	690 (123)	23 (7)	196 (22)	1877 (259)	165 (18)
Atlantic Maritime	9.7 (1.3)	1301 (126)	67 (16)	133 (73)	2593 (268)	211 (20)

Numbers in parentheses indicate standard deviation from the mean. Shaded rows indicate ecozones that do not contain managed forests.

Table 3. Projected mean annual climate for managed forests within eight of the ecozones across Canada for 2071–2100 under SSP3-7.0 scenario at 800 m resolution.

	Mean annual temperature (°C)	Mean annual precipitation (mm)	Hogg's climate moisture index (mm)	Precipitation falling as snow (mm)	Degree-days above 5 °C	Number of frost-free days
Pacific Maritime	8.2 (3.0)	2991 (1290)	249 (132)	487 (573)	1902 (615)	253 (58)
Montane Cordillera	6.4 (2.0)	980 (435)	42 (54)	322 (237)	1776 (454)	198 (22)
Boreal Cordillera	3.2 (1.0)	891 (331)	47 (39)	350 (210)	1262 (297)	164 (11)
Taiga Plains	4.0 (0.9)	545 (77)	−1.5 (9)	145 (14)	1925 (145)	177 (6)
Boreal Plains	5.8 (0.9)	537 (69)	−7.0 (8)	120 (17)	2184 (201)	189 (5)
Boreal Shield West	6.0 (1.5)	699 (140)	11 (12)	158 (41)	2347 (248)	182 (7)
Boreal Shield East	7.1 (1.8)	1092 (130)	51 (19)	255 (89)	2284 (342)	187 (13)
Atlantic Maritime	9.7 (1.5)	1342 (128)	72 (15)	129 (82)	2557 (279)	213 (22)

Numbers in parentheses indicate standard deviation from the mean.

which is shown in Fig. 2 for all 12 forested ecozones. Historical climate means for managed forests can be found in Table S1.

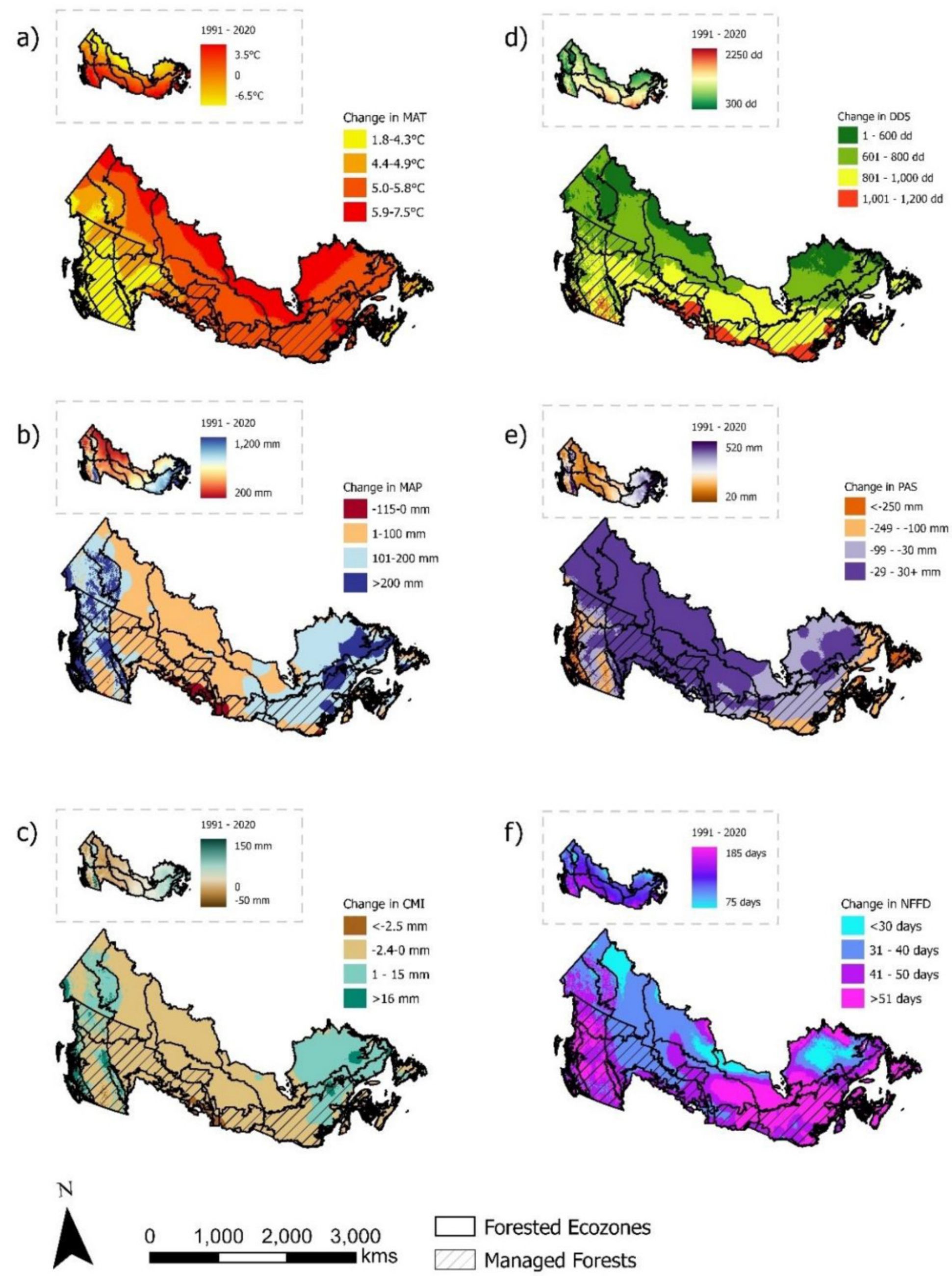
Projected changes in climate across Canada's forest ecozones are shown in Fig. 3. Future projected values for the 12 forested ecozones are shown in Table 2, and managed forested areas are shown in Table 3. In ecozones that contain both managed and unmanaged forests, areas of managed forests show greater indications of warming, particularly for the boreal and taiga plains, which are 2.8 and 2.0 °C warmer in the managed forests, respectively, compared to the rest of the ecozone area.

Of the eight ecozones that contain managed forests, future projections revealed rising MAT to be the most extreme in the boreal shield west (Fig. 3*a*), increasing by a factor of 10 and projected to reach 6.0 °C by 2100. By that time, the Pacific and Atlantic maritime ecozones will have the warmest annual temperatures of all ecozones after a twofold increase in MAT, reaching 8.2 (±3.0) °C and 9.7 (±1.5) °C, respectively. Managed forests in the boreal cordillera ecozone will remain the coldest with a future MAT of 3.2 (±1.0) °C by 2100, up from a 30-year mean of −0.6 °C.

Future patterns of MAP are anticipated to be variable across ecozones (Fig. 3*b*) with an average projected increase of 14% across all managed forests by 2100: the equivalent of an additional 141 mm per year. Within managed forests, MAP in the taiga plains is projected to decrease by 21%, the equivalent to 153 mm less, for a MAP of 545 (±77) mm. By comparison, MAP in the boreal cordillera is projected to increase by 80%, the equivalent of an additional 404 mm, for an annual total of 891 (±331) mm. Of total MAP, projections show an overarching trend of reductions in the proportion of precipitation falling as snow across all ecozones (Fig. 3*e*). The Atlantic maritime ecozone can expect a 63% reduction, or 222 mm, for an annual total 129 (±82) mm of snow, whereas the boreal and taiga plains ecozones are expected to maintain relatively consistent PAS with a slight reduction of 5% for an annual 120 (±17) and 145 (±14) mm of snow, respectively. The montane cordillera ecozone, which historically has received almost equal amounts of annual snow and rain (48% PAS), is projected to see PAS making up only 33% of annual precipitation by 2100 for a total of 322 (±237) mm of snow.

Changes in MAT and MAP are accompanied in corresponding shifts of CMI (Fig. 3*c*). The boreal plains eco-

Fig. 3. Future projections for six climate variables relative to their 30-year historic normals from 1991 to 2020 (gray box inserts) across Canada's forested ecozones (colored area) and managed forests (colored and hatched area). Projections are for future mean annual temperature (MAT; °C) (*a*), mean annual precipitation (MAP; mm) (*b*), mean annual climate moisture index (CMI; mm) (*c*), degree-days (dd) above 5 °C (*d*), precipitation falling as snow (PAS; mm) (*e*), and number of frost-free days (NFFD; days) (*f*) for 2071–2100 under SSP3-7.0 scenario at 800 m resolution. Figures were created using ArcGIS (version 2.9.2).



zone is expected to experience the most substantial drying with a projected 217% decrease from an annual 6.0 mm to −7.0 (±8) mm. There, along with the taiga plains (−1.5 [±9] mm by 2100), will be two ecozones with annual CMI values below zero by the end of the century. The Pacific maritime ecozone, historically the wettest region in Canada, is projected to have a 12% increase, the equivalent of an additional 26 mm for a mean annual CMI of 223 mm.

Projections reveal a consistent increase in the number of degree-days and frost-free days across all ecozones (Fig. 3*d* and 3*f*). On average, across Canada, an additional 879 degree-days and 47 frost-free days are projected by 2100 for an annual total of 2071 degree-days and 192 frost-free days per year. The most significant relative changes in degree-days will occur in the boreal cordillera ecozone, with a 130% increase (from 548 to 1262 degree-days) with a corresponding 42% increase of frost-free days (from 115 to 164). By comparison, the

Atlantic maritime ecozone will experience the smallest relative changes to degree-days, with a 59% increase (from 1608 to 2557 degree-days) and 35% increase in frost-free days (from 158 to 213).

4. Discussion

Canada's managed forests are projected to face rising MAT, which has been commonly reported in the literature (Vincent et al. 2018; Intergovernmental Panel on Climate Change 2022). In conjunction with rising number of degree-days and frost-free days, this suggests longer summers and shorter winters, supported by previous research that has found an additional 15 days have been added to the growing season since the 1948–2016 period (Vincent et al. 2018). An overall increase in MAP is expected across the country, though remains heterogeneous by region. Warmer temperatures, when combined with additional MAP, result in a reduced proportion of annual precipitation falling as snow. Managed forests that are currently temperature-limited may see gains in forest productivity from warmer temperatures and CO_2 fertilization (Jobidon et al. 2015), though perhaps only temporarily (D'Orangeville et al. 2018). By comparison, managed forests that are currently—or likely to become—moisture limited are likely to face reduced growth rates (Chagnon et al. 2022) in addition to the rising risk of drought and drought-induced mortality (Boucher et al. 2018). Greater MAP suggests a potential opportunity to provide additional spring moisture but may also increase rain-on-snow risks throughout the winter (Daniels et al. 2011).

4.1. Wetter coasts may maintain growth rates but with more rain-on-snow events

On Canadian coasts, Pacific and Atlantic maritime are the two wettest forest regions, with a previous average of 2566 and 1232 mm of MAP, respectively. In both ecozones, rising MAP will help to meet greater evapotranspiration demand of warmer temperatures, allowing trees to increase growth and stands to maintain regional productivity (Vaughn and Taylor 2022). However, gain in growth could be outweighed by tree mortality caused by warmer temperatures in older, more vulnerable forests and growth declines due to reduced snow cover (Daniels et al. 2011). Reduced snow cover and a greater number of rain-on-snow and freeze-thaw events can have large implications for tree growth (Moreau et al. 2020). Loss of snow cover has been found to reduce the protective insulation layer that protects fine root dynamics, promotes nutrient exchange, and maintains overwintering survival, particularly for conifers (Girardin and et al. 2016). A lack of snow cover can also result in soil freezing and subsequent loss in aboveground biomass (Reinmann et al. 2019) and lower overwintering survival (Yang et al. 2020). Reduced snow cover may also exacerbate the effects of freeze-thaw events, which are expected to increase in both frequency and duration across Canada in the upcoming century (Solomon et al. 2007) and can cause freezing injuries to both roots and emerging buds in early spring (Inouye 2008). Such risks are greater at high-altitude and mountainous forests and more severe in areas that have recently undergone other forms of disturbance, such as fire (Bergeron et al. 2010; Jordan 2015). Greater rain-on-snow events can also generate greater runoff than rain alone, and when combined with greater winter precipitation will increase the risk of flood events (Marks et al. 1998). Shifts in snowpack runoff to rain pack runoff can also increase landslide risk, as well as debris flow (Guthrie et al. 2010). This can also lead to the flooding and conversion of forested land area to wetlands, which is also threatened in conjunction with thawing of permafrost present in the boreal cordillera ecozone (Carpino et al. 2018). Runoff, flooding, and landslides in British Columbia have been found to have a direct loss of productive forested land at an estimated amount of \$16–\$48 million year^{-1} (Porter et al. 2019). Species most at risk are likely to be those at northern latitudes and higher elevations such as Jack pine (*Pinus banksiana*), lodgepole pine (*Pinus contorta*), alpine larch (*Larix lyallii*), Pacific silver fir (*Abies amabilis*), subalpine fir (*Abies lasiocarpa*), and yellow-cedar (*Callitropis nootkatensis*) (Buma et al. 2016).

4.2. Western Canada can expect the greatest relative drying

Further to the interior, the montane cordillera, taiga plains, and boreal plains ecozones are expected to see the largest relative reductions in CMI across Canada (Fig. 3*c*). Annual CMI in the montane cordillera will remain positive at 42 mm annually, though the taiga and boreal plains are projected to have annual CMI fall below zero (Table 3). This region has been previously identified at high risk of moisture deficits that could significantly slow growth rates and increase the risk of drought-induced mortality (Hogg and Bernier 2005). Although the taiga plains contain only a small area of managed forests, slower growth of white spruce (*Picea glauca*) (Aubin et al. 2018) and western red cedar (*Thuja plicata*) in the interior of British Columbia has been observed across the montane cordillera and boreal plains (Andrus et al. 2023) and could continue in these three ecozones. Across Canada, 43% of the boreal forest has already experienced drought-induced mortality from 1970 to 2020, 71% of which was from the western boreal forests (Liu et al. 2023). As climate becomes warmer and drier in boreal zones, a greater proportion is likely to experience drought with a shift toward more drought-tolerant species composition. This has already been seen in the greater abundance of interior Douglas fir (*Pseudotsuga menziesii*) and Ponderosa pine (*Pinus ponderosa*) in the boreal shield west and which are likely to continue to expand into the interior plateau (Searle and Chen 2017). Species that are unable to successfully compete for soil water are likely to attempt a northern migration toward regions of greater moisture availability. For this reason, the potential climate niche of tree species in British Columbia is projected to gain an additional 100 km per decade, leading to a significant shift of sub-boreal and montane climate regions (Hamann and Wang 2006). This includes the potential shift away from commercially important conifer species (such as subalpine fir, white spruce, and black spruce ([*Picea mariana*]) that are likely to be outcompeted by southern species such as Douglas fir and lodgepole pine (Searle and Chen 2017).

Though moderate winter warming has been found to be temporarily beneficial for the growth of pines and high-elevation hardwoods such as trembling aspen (*Populus tremuloides*) and paper birch (Girardin et al. 2022), gains in productivity are likely not be enough to offset the loss that occurs at higher elevations where loss of mountainous habitat of white bark pine, cypress, and mountain hemlock occurs at a faster rate (Hamann and Wang 2006).

4.3. Contrasting projections for east and west boreal shields

The boreal shield west is likely to undergo similar changes to the boreal plains, though it contains a smaller area of managed forests. The boreal shield east is expected to see the largest relative warming (an increase of 5.5 °C by 2100) but in addition to greater MAP, allowing annual CMI to remain relatively unchanged (at 51 mm annually) by the end of the century. Species within this ecozone that were previously temperature limited are therefore likely to see greater growth in the future, which has been predicted for yellow birch (*Betula alleghaniensis*), white pine (*Pinus strobus*), eastern hemlock (*Tsuga canadensis*), red maple (*Acer rubrum*.), sugar maple (*Acer saccharum*), red oak (*Quercus rubra*), and American beech (*Fagus grandifolia*) (Taylor et al. 2017). However, any gain in productivity may be transitory until these forests too become moisture limited (D'Orangeville et al. 2018). Still, to seek out a relatively cooler and wetter refugium, it is expected that boreal species will begin migrating to northeast (D'Orangeville et al. 2016). Tree species along the southern boreal-temperate hardwood transition line, particularly in Ontario and Quebec, are likely to be outcompeted by more drought-tolerant species leading to a potential deborealization in the region and a shift from softwood to hardwood species (Taylor et al. 2020). Managed forests in Atlantic maritime ecozones have also been found to be increasing abundance of warm-adapted temperate species and replacing cold-adapted boreal conifers including greater competition from American beech and red maple and lower abundance of sugar maple (Taylor et al. 2017). This potential gain of growth and carbon sequestration by species in the boreal shield east is still unlikely to counteract the loss of older forest to drought-induced mortality in other parts of the country (Seidl et al. 2017).

4.4. Impacts of climate change–disturbance interactions on forest composition

Climate change could affect both the ecology and the harvestable wood volume of forests across Canada with altered tree growth rates, biome shifts, and the rising frequency and intensity of biotic and abiotic disturbances. The cumulative effect of such future disturbance- and drought-induced tree mortality is said to be Canada's largest threat to harvestable wood volumes by the end of the century (Seidl et al. 2017; Boucher et al. 2018; Brecka et al. 2018). Overarching trends of longer and drier summers, as well as warmer and wetter summers, indicate a rising risk of drought (Chaste et al. 2019), fires (Flannigan et al. 2005), forest pests (Kurz et al. 2008; Zhang et al. 2014), wind throw (Saad et al. 2017), and land slides (Porter et al. 2019). Cumulative loss of biomass to disturbance threatens to reduce harvestable wood volumes by as much as 50% by 2150 (Boulanger and Puigdevall 2021).

Stand-replacing disturbances not only result in the loss of aboveground harvestable biomass but also the loss of mature and oldest forests such as spruce, eastern hemlock, and American beech to younger regenerating stands such as poplar, paper birch (*Betula papyrifera*), maple, and balsam fir. Such shifts have already been noticed in eastern Canada with reduced abundance of trembling aspen, red maple, and white pine (Saad et al. 2017; Danneyrolles et al. 2019; Boulanger and Puigdevall 2021). These species have been found to be more abundant in areas after disturbance and result in a shift toward greater mixedwood composition that contains less harvestable biomass than their pure stand counterparts (Saad et al. 2017; Danneyrolles et al. 2019; Boulanger and Puigdevall 2021). This is particularly true after a pest infestation where a single species is mostly removed from the landscape (Amoroso et al. 2013; Ministère des Forêts de la Faune et des Parcs 2015). The resulting younger forests are composed of less biomass unable to compensate for the loss of older forests (Ma et al. 2012; Dymond et al. 2016; Seidl et al. 2017). Future post-disturbance stands may also be composed of fewer commercially relevant tree species making it difficult for forest managers to supply mills with mature and harvestable wood (NRTEE 2011; Gauthier et al. 2015; McKenney et al. 2016). This could be particularly problematic in boreal forests, for example, where later-successional conifers such as spruce and fir are preferred for paper and lumber (Searle and Chen 2017; Brecka et al. 2018). Though mixedwood stands may be less vulnerable to future disturbances such as pest infestations by reducing dominant host abundance (Bouchard et al. 2006) and limiting fire spread (Girardin et al. 2013; Marchal et al. 2017, 2020), the consequential species composition may be problematic for industries that rely on single species harvesting, particularly if their forests are in transition zones or are highly susceptible to disturbance. Consequently, an uncertain future arises whereby younger post-disturbance stands could become a net carbon source with a net loss of biomass and timber production by 2100 (Ma et al. 2012; Zhu et al. 2018).

5. Conclusion

Here, we present overarching climate trends across Canada's forested ecozones containing managed forests. Across Canada, warming and rising annual precipitation can be seen alongside an overall reduction of precipitation falling as snow and the increase in the number of degree-days above 5 °C and frost-free days. Marked contrasts were observed across several ecozones, particularly between dry coastal and interior forests and the polarization between western and eastern forests. Temperature-limited forests found in ecozones such as the boreal shield east and Atlantic maritime have the potential to temporarily increase forest growth rates while promoting northeastern migration toward greater resource availability. However, this is likely to concur with and greater risk of pest overwintering success and windthrow. This is true for forests in wetter than average ecozones such as those in the Pacific maritime, the boreal cordillera, and the Atlantic ecozones though with the additional risk of rain-on-snow events that increase vulnerability to flooding, landslides, and windthrow due to greater annual precipitation. In moisture-limited forests, such as those in the montane cordillera, boreal plains and taiga plains ecozones of western Canada, warmer future temperatures are likely to reduce growth rates and promote species compositional shifts toward more drought-tolerant species. These climate conditions are likely to increase drought events (and thus drought-induced mortality), as well as forest fires. Of course, projections that are further into the future coincide with reduced accuracy and limits to adaptation (Dessai et al. 2009). However, the cumulative risk of drought, fire, and forest pests is undoubtedly to be the largest challenge in maintaining forest productivity against Canada (Boulanger and Puigdevall 2021). Though not all land area indicated in managed forests regions is actively managed, changes to forest health and composition limit potential forest operation expansion opportunities and increases the risk of disturbance to nearby managed areas. As biomass of future forests lost to disturbances will outweigh any beneficial growth as a result of climate change (Ma et al. 2012; Dymond et al. 2016; Seidl et al. 2017), adaptive forest management practices that promote forest resistance and resilience will be key to sustainable forestry practices as well as a continued contribution to Canada's GDP. Overarching climate trends should be considered in future regional forest management planning and in conjunction with bioclimatic models to map ongoing changes to species distribution (Rehfeldt et al. 2015; Schneider et al. 2016) and growth and yield models (Boulanger et al. 2017) for projections of future wood volumes.

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Data availability

Data generated and analyzed within this study are available from ClimateNA (https://climatena.ca/spatialData). Derivatives of this data, and other, are available from the corresponding author upon reasonable request.

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The authors declare there are no competing interests.

Supplementary material

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