Contemporary Issues in Québec's Temperate Forest — Part 4: Climate Change

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ABSTRACT

This paper is the fourth in a series on the topic of contemporary issues in Québec's temperate forest. It focuses on the topic of climate change, beginning with a brief profile of climate history and changes, both contemporary and anticipated. It goes on to discuss the main impacts of climate change on forest ecosystems and the issues raised. Many studies have shown that rapidly rising temperatures since the mid-1970s have affected various aspects of forest ecosystems, including forest composition and productivity, natural disturbance regimes, the biogeochemical cycling of elements, wildlife populations and maple syrup production. Despite this, however, no major issues were identified for the three principal tree species in Québec's northern temperate zone (i.e., sugar maple [*Acer saccharum* Marsh.], red maple [*Acer rubrum* L.] and yellow birch [*Betula alleghaniensis* Britt.]) as a result of anticipated climate change between now and the end of the century. The climate in the current temperate zone is likely to remain within the conditions generally encountered in these species' range. Similarly, the natural disturbance regime in the zone is not expected to change significantly. However, we did identify some important socioeconomic and ecological issues arising from the impacts of climate change on forest ecosystems.

Keywords: northern hardwood, mixedwood, warming, climate, maple syrup

RÉSUMÉ

Cet article est le quatrième d'une série qui analyse les enjeux contemporains en forêt tempérée au Québec. Nous y abordons plus précisément les changements climatiques en traçant d'abord un bref portrait du climat historique ainsi que de ses changements contemporains et anticipés. Nous discutons ensuite de leurs principaux impacts sur les écosystèmes forestiers, de même que des enjeux qui en découlent. De nombreuses études révèlent que depuis le milieu des années 1970, la hausse rapide des températures a des répercussions sur les écosystèmes forestiers, notamment sur la composition et la productivité des forêts, le régime de perturbations naturelles, le cycle biogéochimique des éléments, les populations fauniques et la production acéricole. Malgré tout, nous n'avons pas relevé de grands enjeux pour les 3 principales essences de la zone tempérée nordique du Québec (soit l'érable à sucre [*Acer saccharum* Marsh.], l'érable rouge [*Acer rubrum* L.] et le bouleau jaune [*Betula alleghaniensis* Britt.]) en lien avec les changements climatiques anticipés d'ici la fin du siècle. En effet, le climat de la zone actuelle est susceptible de demeurer à l'intérieur des conditions généralement rencontrées dans l'aire de répartition de ces espèces. De même, on ne semble pas anticiper de grands changements au régime de perturbations naturelles dans cette zone. Nous identifions néanmoins certains enjeux socioéconomiques et écologiques d'importance qui découlent des impacts des changements climatiques sur les écosystèmes forestiers.

Mots-clés : érablière, forêt mixte, réchauffement, climat, acériculture

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Introduction

Climate change is defined as a persistent alteration (usually over at least several decades) of average and/or variability of climate properties. Climate change may be due to natural internal processes or climate drivers such as variations in the solar cycle, volcanic eruptions or persistent anthropogenic changes in atmospheric composition or land use (IPCC 2023a). Contemporary changes are attributed to greenhouse gases of human origin, mainly carbon dioxide (CO_2) and methane (CH_4). These gases are generated by combustion of fossil fuels such as coal, petroleum and natural gas for energy production. Agriculture, deforestation and industry also play a role in their production.

In this fourth paper in a series on the topic of contemporary issues in Québec's northern temperate forest (see Part 1 of the series: Duchesne *et al.* 2025), we present a brief profile of climate history in the temperate zone, along with contemporary and anticipated changes. We then summarize the existing literature on the main impacts of climate change on forest ecosystems and the issues raised. The area under study, which consists of the northern portion of the temperate forest in North America, was described in detail in the first paper of the series. In Québec, it falls mainly within the sugar maple-bitternut hickory, sugar maple-basswood and sugar maple-yellow birch bioclimatic domains, as well as in the balsam fir-yellow birch bioclimatic domain (for scientific tree names, see Part 1 of this series — Duchesne *et al.* 2025). Sugar maple, red maple and yellow birch are the three principal hardwood species in the northern temperate vegetation zone, but they are mixed with several other species in what is effectively a transitional zone between the temperate and boreal forests.

Although our analysis focuses specifically on Québec's forest due to province-specific data content and sources, it nevertheless provides relevant input for reflections pertaining to forests of the same type located in other Canadian provinces and the northeastern United States.

Climate history

Information on past changes to climate and forest composition is useful in situating the scope and pace of current climate change and in anticipating its potential impacts on forest vegetation. Long-term climate history can be reconstructed from comparisons of contemporary meteorological measurements and substitute climate variables, such as those measured from ice cores, tree rings, coral skeletal strips, pollen assemblages and so on. It can also be modelled using general circulation models (Jones *et al.* 1998; PAGES 2k Consortium 2017, 2019). These reconstructions and models show that global climate remained relatively stable during the Common Era pre-industrial period, with a long-term trend toward cooling during the last millennium (Mann and Jones 2003; PAGES 2k Consortium 2019). Cooling periods spanning several decades also coincided with volcanic eruptions, in both the reconstitutions and simulations (PAGES 2k Consortium 2019). A particularly pronounced cooling period known as the Little Ice Age occurred in the northern hemisphere from the early 15th century to the mid-18th century (Jones *et al.* 1998; Mann *et al.* 2009). Climate forcing due to orbital cycles, reduced solar activity and volcanic eruptions were all identified as factors that might have triggered this cooling period (Crowley 2000; Mann *et al.* 2009).

However, conclusions from longer-term climate reconstructions are not necessarily unanimous. Some recent analyses found that the average global temperature has warmed slightly but regularly by around 0.5 °C since the beginning of the Holocene (9000 years ago, Osman *et al.* 2021), whereas others concluded that Early Holocene warming (10 000 to 5000 years ago) was followed by cooling during the Middle and Late Holocene (less than 5000 years ago), culminating in the coldest Holocene temperatures during the Little Ice Age, roughly 200 years ago (Marcott *et al.* 2013; Kaufman *et al.* 2020). Postglacial climate reconstructions using pollen analysis of lake and peat bog sediments in Québec's maple bioclimatic domains have also suggested more pronounced warming at the beginning of the Holocene, culminating in maximum temperatures 6000 to 7500 years ago, followed by a more stable period characterized by a slight cooling of summer temperatures and a slight increase in winter temperatures starting 4500 years ago (Richard *et al.* 2025).

Contemporary climate

Climate reconstructions using substitute variables, modelling and direct climate measurements during the last century are generally unanimous in finding that warming during the industrial era exceeded the pre-industrial variability range (PAGES 2k Consortium 2019). Two successive trends can be seen. The first covers the period of warming in the early 20th century, apparently triggered by a combination of increased greenhouse gases and natural forcing from solar radiation, compensated to some extent by aerosols. Warming of the Atlantic Ocean and other regional-level forcing also appear to have played a role (Brönnimann 2009; Hegerl 2018). The second trend covers the modern period from the mid-1970s to the present day and is associated with significant warming, mostly due to anthropogenic forcing (Christidis *et al.* 2007; PAGES 2k Consortium 2019). All trends derived from instrumental measurements since the mid-20th century exceed the 99th percentile for pre-industrial trends documented over comparable periods (PAGES 2k Consortium 2019). Thanks to exceptionally hot summer temperatures in the northern hemisphere, 2023 and 2024 were the hottest years on record, with summer temperatures more than 0.5 °C above the 95% confidence interval for natural climate variability in the northern hemisphere in the last two millennia (Esper *et al.* 2024; Global Temperature - Earth Indicator - NASA Science).

Climate index trends based on temperature and daily precipitation at weather stations in southern Canada, considered relevant because of their impacts on society, are consistent with global warming (Vincent *et al.* 2018. Table 1). In the case of southern Québec and the period 1948–2016 in particular (Table 1), temperature indices show an increase in the frequency and intensity of extreme cold in winter, longer growing seasons (the number of days with an average temperature > 5 °C) and an increase in the number of growing degree-days. Longer growing seasons are due mainly to later end dates (18.6 days later) and, to a lesser extent, earlier starts (7.4 days earlier). As for precipitation, the only significant trend observed in the precipitation index was for the number of days of intense rain (> 90th percentile).

Climate change scenarios

Climate change scenarios for the coming decades can be prepared by climate simulations. Simulations are performed using climate models representing climate system processes in equation form. They are therefore strongly influenced by scenarios for greenhouse gases, aerosol and other anthropogenic source gas emissions in the atmosphere (Mote *et al.* 2011; Charron 2016). The Coupled Model Intercomparison Project (CMIP) is an international collaborative climate modelling group initiative that facilitates the dissemination of simulation results from different models using different emission scenarios.

In 2011, scenarios for different climate indices and variables were prepared for Québec's forest by the regional climate and climate change adaptation consortium Ouranos (Logan *et al.* 2011). These scenarios were based on a set of 71 global simulations and 18 regional simulations. Three emission scenarios were considered for the global simulations (*Special Report on Emissions Scenarios*, IPCC 2000). It is important to note that these emission scenarios were those considered for the third and fourth assessment reports produced by the Intergovernmental Panel on Climate Change (IPCC), which were replaced by representative concentration pathways (RCP) and, more recently, by shared socioeconomic pathways (SSP). These scenarios range from more optimistic (eventual decline in CO_2 concentrations in the atmosphere) to more pessimistic (projected increase in CO_2 concentrations). The Ouranos consortium has posted and updated climate profiles on its web platform since 2018. The data now include a set of post-processed simulations (ESPO-G6-R2; Lavoie *et al.* 2024) from CMIP6 models (Eyring *et al.* 2016). Compilations are posted for three emission scenarios (moderate [SSP2-4.5], high [SSP3-7.0] and very high [SSP5-8.5]). Table 2 summarizes various climate indices (10th, 50th

Table 1. Climate indicator trends for weather stations in Québec during the period 1948–2016 (Vincent *et al.* 2018)

Climate indicator	Trend	Unit
Number of days with a MaxT of > 25 °C	6	Day
95th percentile of summer MaxT	1	°C
95th percentile of summer MinT	1.8	°C
Number of days with MinT of ≤ 0 °C	−16.7	Day
Maximum number of consecutive days with MinT of ≤ 0 °C	−16.4	Day
Number of days with MaxT of ≤ 0 °C	−13.5	Day
5th percentile of winter MaxT	2.2	°C
5th percentile of winter MinT	2.2	°C
5th percentile of summer MaxT	1.3	°C
5th percentile of summer MinT	1.5	°C
Maximum number of consecutive days with MaxT of > 0 °C	25.5	Day
Start date of frost-free season (consecutive days with MinT of > 0 °C)	−9.7	Day
End date of frost-free season (consecutive days with MinT of > 0 °C)	17.1	Day
Start date of growing season (6 consecutive days with AvT of > 5 °C)	−7.4	Day
End date of growing season (6 consecutive days with AvT of > 5 °C)	18.6	Day
Length of growing season (end day – start day)	25.6	Day
Growing degree-days (total of degrees when AvT is > 5 °C)	182.3	Degree-days
Cooling degree-days (total of degrees when AvT is > 18 °C)	31.6	Degree-days
Heating degree-days (total of degrees when AvT is < 18 °C)	−211.7	Degree-days
Number of freeze-thaw days (MinT ≤ 0 °C and MaxT > 0 °C)	−7.6	Day
Number of days of intense rain (> 90th percentile)	2.1	Day

Note: Only statistically significant trends with a probability threshold of 5% are counted. AvT = average temperature; MinT = minimum temperature; MaxT = maximum temperature and 90th percentiles) for southern Quebec during the reference period 1991–2020, as well as the anticipated changes for the 2041–2070 and 2071–2100-time horizons, using ESPO-G6-R2 post-processed simulations for the high emission scenario (SSP3-7.0). The area under consideration includes Québec's 12 southern administrative regions (excluding the Montréal-Laval region), roughly corresponding to Québec's northern temperate vegetation zone. Despite climate differences between the regions, the extent of the anticipated changes is more or less the same across the area. In addition, the climate indices presented include both average conditions and extreme events for which we analyzed frequency.

Regarding average annual temperatures, the anticipated changes are 2.5 °C for the 2041–2071 horizon and 4.3 °C for the 2071–2100 horizon (Table 2). For comparison, the same simulations showed that average annual temperatures increased by 1 °C between 1951–1980 and the reference period 1991–2020, reaching 3.7 °C. The projected temperature increase is greater in winter. Warming results from an increase in the number of growing degree-days, frost-free days and days of extreme heat, combined with a reduction in the number of heating degree-days. The number of freeze-thaw events is also expected to increase in winter and decrease in the other three seasons, contributing to the higher temperatures.

The simulations also show an increase in liquid and total precipitation, combined with a reduction in solid precipitation. They project a slight increase in the number of heavy precipitation days (≥ 20 mm), but little to no change in the number of precipitation-free sequences (≥ 6 days with less than 1 mm) and freezing rain episodes (≥ 10 mm).

Impacts on forest ecosystems

Climate has a major impact on species range, forest composition, dynamics and productivity, and the processes that govern forest ecosystem functions (IPCC 2023a). It also has an indirect impact on forest ecosystems via its effect on disturbances, including wildfires, insect populations, diseases, wildlife populations and extreme climate events such as wind gusts and ice storms. It is, therefore, responsible for numerous issues affecting those ecosystems, and which have attracted a significant amount of research funding in Québec and elsewhere in recent decades. Although many questions still remain, there is nevertheless a growing body of information on the impacts of climate and climate change on forest ecosystems. In Québec, however, research has focused mostly on the boreal zone and much less on the northern temperate zone.

Forest composition

Historical evolution

The temperate forest's long-term history was reconstructed through taxonomic identification of pollen accumulated in lacustrine sediments and peat bogs and from charcoal contained in mineral soils. Several studies indicate that climate and fire regimes have had a significant influence on forest composition over the past millennia, particularly on the historical proportion of hardwood and conifer species in forests

Table 2. Climate indicators (50th percentile) for the reference period (1991–2020) in southern Québec (10th and 90th percentiles in brackets), and anticipated changes for the 2041–2070 and 2071–2100-time horizons, calculated using the ESPO-G6-R2 post-processed simulations for the high emission scenario (SSP3-7.0)

Climate indicator	1991–2020	2041–2070	2071–2100	Unit
Average of temperatures	3.7 (3.6; 3.7)	2.5 (1.9; 3.2)	4.3 (3.9; 5.5)	°C
Average of temperatures — winter	−10.2 (−10.5; −10.1)	3.5 (2.3; 4.3)	5.7 (4.5; 7)	°C
Average of temperatures — spring	1.7 (1.5; 1.8)	2.2 (1.7; 2.9)	4.2 (3.4; 4.7)	°C
Average of temperatures — summer	17.1 (17.1; 17.2)	2.2 (1.7; 3.1)	4 (3; 5.3)	°C
Average of temperatures — fall	5.8 (5.7; 5.9)	2.1 (1.7; 3)	3.9 (3.2; 4.8)	°C
Growing degree-days — base 4 °C	1785 (1766; 1797)	418 (334; 569)	769 (666; 1 019)	Degree-days
Number of frost-free days	175.3 (168.7; 182)	18.9 (13.6; 24.6)	35.7 (29; 44.2)	Day
Number of days with MinT of < −25 °C	12.3 (10.2; 14.6)	−9.1 (−8.5; −8.8)	−11.5 (−9.9; −13.1)	Day
Number of days with MaxT of > 30 °C	3 (2.8; 3.4)	7.7 (4; 14)	20.1 (10.8; 37.3)	Day
Number of days with MaxT of > 32 °C	0.7 (0.6; 0.9)	2.8 (1.4; 6.3)	9.4 (4.3; 20.6)	Day
Frost degree-days	1 258 (1 237; 1 280)	−420 (−518; −287)	−664 (−773; −552)	Degree-days
Number of freeze-thaw days— winter	17.7 (16.3; 19)	7.1 (5; 9.7)	13.7 (9.4; 16.9)	Day
Number of freeze-thaw days — spring	45.1 (42.3; 47.1)	−4.2 (−4.1; −1.7)	−8.3 (−8.2; −5.8)	Day
Number of freeze-thaw days — fall	31.5 (29; 33.9)	−4.8 (−5.5; −4.5)	−8.8 (−10.3; −8.3)	Day
Total precipitation	1 137 (1 126; 1 149)	90 (69; 126)	150 (106; 211)	mm
Total liquid precipitation	830 (816; 848)	109 (85; 131)	195 (179; 271)	mm
Total solid precipitation	305 (287; 322)	−11 (−45; 1)	−61 (−75; −35)	mm
Sequence ≥ 6 precipitation-free days (< 1 mm)	9.9 (9.1; 10.7)	0.04 (0.1; −0.21)	−0.02 (0.11; −0.03)	Number
Number of days with precipitation of ≥ 20 mm	10.7 (10.5; 10.9)	2.1 (1.7; 2.9)	3.6 (2.2; 5)	Day
Freezing rain episodes of > 10 mm	0.3 (0.1; 0.4)	−0.04 (0.01; −0.06)	−0.06 (0.02; −0.08)	Number

Note: The values are the average values from the regional summaries of the 12 southern administrative regions (excluding the Montréal/Laval region) as displayed on the Ouranos consortium's web platform (https://portraits.ouranos.ca). With regard to seasonal data, winter comprises the months of December, January and February; spring comprises the months of March, April and May; summer comprises the months of June, July and August; and fall comprises the months of September, October and November. Intense freezing rain episodes are calculated using regional MRCC5 model simulations, piloted by the global CMIP5 models for the RCP8.5 emission scenario.

that are now dominated by sugar maple (Richard 1978; Houle *et al.* 2012a; Payette *et al.* 2021; Richard *et al.* 2025). In Québec's maple bioclimatic domains, post-deglaciation afforestation (roughly from 11 500 to 10 000 years) came in the form of aspen, spruce and fir forests, followed by closed fir and pine groves (jack pine) (Richard *et al.* 2025). The maple forests appear to have been formed 9500 to 8000 years ago, with typical companion species from the current temperate vegetation zone, i.e., red oak, white pine, yellow birch, eastern hemlock and American beech (Richard *et al.* 2025).

During the last century, however, anthropological disturbances appear to have had a more predominant impact on forest dynamics than higher temperatures (≤ 2 °C). The changes caused by these disturbances may slow down or speed up future transformations of communities in response to climate change (Danneyrolles *et al.* 2019).

Contemporary changes

Analysis of contemporary changes in forest composition based on Québec's forest inventory networks reveals that some dominant hardwood species in the northern temperate zone (sugar maple, red maple and American beech) have migrated northwards in recent decades at a rate of a few hundred metres per year (Boisvert-Marsh *et al.* 2014, 2019; DRF 2017; Sittaro *et al.* 2017). This migration is reflected by a greater increase in the frequency and occurrence of saplings of these species in the northern regions than in the southern regions. These contemporary changes appear to be explained mostly by changes to climate conditions at the beginning or end of the growing season and by the impacts of disturbances, that are generally less significant than the impacts of climate change (Boisvert-Marsh *et al.* 2019). Moderate disturbances such as partial cuts, by reducing competition, appear to speed up these species' migration toward the northern limit of their range, creating conditions in which mixed forests may be converted into forests dominated by temperate species (Brice *et al.* 2019, 2020). In the boreal zone, where forests are usually less diversified than in the northern temperate zone, these contemporary changes to composition appear to have been a factor in the slight increase in biodiversity observed in recent decades (Crockett *et al.* 2022). As far as the southern portion of Québec's northern temperate zone is concerned, we found no evidence to show that species associated with forests further south had begun to migrate into the zone.

Climate change, in addition to fostering northward expansion of the northern temperate zone, may also play a role in altering forest composition at the local and regional levels. For example, warming may foster regeneration of temperate species in adjacent stands dominated by boreal species (Fisichelli *et al.* 2014). In the temperate zone, climate change may also foster increases in the abundance of certain species better adapted to the new conditions at the expense of others that are less well adapted (Bose *et al.* 2017; DRF 2017; Jain *et al.* 2021).

Projected changes

Potential habitat projections and the relative abundance of forest species suggest that, from now to the end of the century, the future climate of Québec's forest under management will be almost entirely favourable to the hardwood species that currently dominate the northern temperate zone (sugar maple, red maple and yellow birch), regardless of which climate change scenario is used (McKenney *et al.* 2007, 2011; Périé *et al.* 2014; Périé and de Blois 2016; Prasad *et al.* 2020; Périé and Lambert 2023). Climate change would therefore trigger an increase in biodiversity in the northern regions where diversity is currently weaker because of the many species that are limited by the low temperatures (Berteaux *et al.* 2010. 2018). For a number of reasons, however, these species are unlikely to colonize these regions in the short and medium term.

The main obstacle to colonization is the limited migratory potential of the species. Fossilized pollen analysis suggests that, in North America, the range of many temperate zone species expanded at a rate of 100 to 1 000 metres per year at the beginning of the Holocene. On the other hand, molecular analysis of chloroplast DNA suggests that migration speed was, in fact, below 100 metres per year (McLachlan *et al.* 2005). Forecasts based on an optimistic migratory potential of 50 kilometres per century for North American tree species, including sugar maple, suggest that only a small portion of the climate habitat generated by the current changes would be colonized naturally by the end of this century (Prasad *et al.* 2020, 2025).

Abiotic and biotic soil properties may also prevent colonization of new, climatically appropriate habitats and hinder the migration of temperate species toward the boreal zone (Lafleur *et al.* 2010; Brown and Vellend 2014; Collin *et al.* 2018; Solarik *et al.* 2018; Carteron *et al.* 2020; Ni and Vellend 2024). At the local and regional levels, species distribution is linked more to edaphic factors than to climate-related factors. Some researchers have, in fact, found that tree species distribution in temperate forests in Europe is influenced more by soil properties, including the availability of nutrients, than by climate (Walthert and Meier 2017). Moreover, given that tree species react differently to climate variables and soil properties, new tree communities are likely to be created in response to climate change (Lafleur *et al.* 2010). The spatial analysis scales of habitat models developed in North America (e.g., 400 km^2; Iverson *et al.* 2008; Périé and de Blois 2016; Prasad *et al.* 2020) do not allow for local soil properties to be treated as habitat variables.

In Québec's northern temperate zone, habitat models predict the *status quo*, or a more favourable habitat, or a habitat gain for the main temperate hardwood species (sugar maple, red maple, yellow birch and American beech) by the end of the century, over almost the entire area they currently dominate.

More specifically, by the end of the century and based on the moderate greenhouse gas emission scenario, the *status quo* is predicted for the sugar maple and red maple habitat over 88% and 100% of the deciduous forest subzone, respectively, (maple-bitternut hickory, maple-linden and maple-yellow birch bioclimatic domains; MFFP 2020; Périé and Lambert 2023). Based on the high emission scenario, these percentages are 73% for sugar maple and 100% for red maple. For sugar maple, based on the moderate emission scenario, habitat loss is predicted over 7% of the total area, and a less favourable habitat over 2% of the area (16% and 8% for the high emission scenario). In the case of red maple, the models do not show any habitat loss or less favourable habitat regardless of the scenario used.

Using the moderate emission scenario for American beech, whose range is currently located further south, the *status quo* is anticipated for 59% of the area and a more favourable habitat for 25%, with a habitat gain for 12% of the deciduous forest subzone (these percentages are 50%, 15% and 11%, respectively, with the high emission scenario). Habitat loss is expected for 1% of the area, and a less favourable habitat for 4% of the area (13% and 10% using the high emission scenario). American beech could, therefore, benefit from global warming in Québec, but two exotic diseases may hinder its progression (see Parts 1 (Duchesne *et al.* 2025) and 2 (Guillemette *et al.* 2025) of this series of papers).

Under the moderate emission scenario for yellow birch, the *status quo* is anticipated for 82% of the maple-yellow birch and fir-yellow birch bioclimatic domains, a more favourable habitat for 14% of the area, and a habitat gain for 1% of the area (28%, 4% and 1%, respectively, with the high emission scenario). No habitat loss is anticipated, but a less favourable habitat is expected to exist over 4% of the area under this scenario. The percentages would increase to 4% and 63%, respectively, under the high emission scenario.

Habitat loss and less favourable habitats tend to be located on the southern boundary of these species' range in Québec. In the northern temperate vegetation zone, less favourable habitats and habitat losses are anticipated mainly for dominant species typical of the boreal zone. For balsam fir and black spruce, by the end of the century and under the moderate emissions scenario, habitat loss is projected for 32% and 18% of the northern temperate vegetation zone, respectively, and less favourable habitat for 60% and 80% of the area (habitat loss for 99% and 81%, and less favorable habitat for 1% and 16% under the high emissions scenario).

In addition to analysis scale limitations, the validity of the habitat model approach in anticipating climate change impacts has also been criticized because these models do not account for biotic interactions (competition, mutualism, predation, pathogens) or the species' genetic capacity to adapt to environmental change (Hampe 2004; Sinclair *et al.* 2010; Van der Putten *et al.* 2010). The fact that biotic interactions are not considered makes it especially hard to interpret the southern boundaries of species' ranges, which are usually thought to be limited more by competition than by climate (Brown *et al.* 1996; Hampe 2004). In addition, habitat models predict the potential locations of proper climate conditions for a given species, but do not include information on the species' performance or potential abundance in the new environments. Modelling the future abundance of forest species using climatic, edaphic and topographic variables, therefore, remains a challenge (Chambers *et al.* 2013), especially if we cannot consider the numerous biological interactions that come into play.

To supplement the information from habitat models, spatially explicit mathematical models at the landscape scale have been designed to simulate the spatial dynamics of ecosystems (e.g., Bouchard *et al.* 2019). These models are used to predict potential changes to species composition, biomass, carbon stocks and so on. They translate the processes that govern ecosystem dynamics into equations, and allow the simulation of disturbances (fire, wind, logging), seed dispersal, succession, growth, mortality and competition between trees according to soil characteristics and different climate scenarios (Scheller and Mladenoff 2004). LANDIS-II, with its various extensions, is the model used most to study the anticipated impacts of climate change on forest ecosystems in Québec and in the northeastern United States (Boulanger *et al.* 2017, 2019; Boulanger and Puigdevall 2021; Landry *et al.* 2021; Mina *et al.* 2021, 2022; Molina *et al.* 2021; Nevins *et al.* 2021; Moreau *et al.* 2022; Ameray *et al.* 2023, 2024). Although useful to explore scenarios, these models are nevertheless simplified representations based largely on logical hypotheses, given the limited availability of empirical data. They must also be configured using available knowledge of the characteristics of the area in which they will be applied (Scheller and Mladenoff 2004). There are other spatially explicit, individual-based forest stand models that simulate tree growth, regeneration and mortality. Models such as these have also been used to assess persistence potential among northern temperate zone dominant species when introduced into stands typical of Québec's boreal zone (Soubeyrand *et al.* 2023).

A recent study compared the results of seven different models, including a habitat model and LANDIS-II, to provide an assessment of uncertainty and consensus on the future performance of six tree species in Québec (Boulanger *et al.* 2022). The study found that, despite the diversity of model types, projections of species performance were largely consistent across species, regions, emission scenarios, and time periods. Disagreements among models were generally small. Model agreement was highest for cold-tolerant species like balsam fir and black spruce, particularly in southern forest regions, suggesting that these species are highly sensitive to stronger climate forcing in the southern part of their range. In contrast, lower agreement was observed for warm-adapted species like sugar maple and yellow birch in boreal regions, mainly due to differences in how models represent natural disturbances (e.g., wildfires) and the lag in species responses to climate change (e.g., migration limits or forest inertia).

Forest productivity

Alongside human activity, forest ecosystems play a major role in the atmospheric CO_2 balance. Globally, terrestrial ecosystems, within which forests play a predominant role, have stored roughly 30% of all anthropogenic C generated by fossil fuel combustion, cement production and land use changes since the 1960s (Friedlingstein *et al.* 2023). The amount of C captured by terrestrial ecosystems is greater than that sequestered by the oceans and is, therefore, important in mitigating climate change (Friedlingstein *et al.* 2023). On average, roughly 42% of the forest's C stocks are stored in living plant biomass, 9% in deadwood and the remainder (49%) in litter and soils (Pan *et al.* 2011, 2024). The geographical distribution of the forest's C stocks is determined mainly by the areas in which different forest types grow: roughly 55% of C is stored in tropical forest soils and vegetation, 30% in boreal forests and 15% in temperate forests (Pan *et al.* 2011, 2024).

Some studies have shown that the rates at which forests absorb C have remained stable or have declined in recent decades (Piao *et al.* 2008; Zhao and Running 2010; Pan *et al.* 2011, 2024). In spite of this, global C budget accounting from mass balances and dynamic global vegetation models show that the amount of C sequestered by terrestrial ecosystems, of which forest ecosystems account for the vast majority, has more than doubled since the 1960s. This is probably due to the combined impacts on tree growth of nitrogen inputs and fertilization through increased atmospheric CO_2, and the impacts of climate changes, including longer growing seasons in temperate and boreal zones (Ballantyne *et al.* 2012; Forkel *et al.* 2016; Zhu *et al.* 2016; Friedlingstein *et al.* 2023). In all forest biomes across all climate zones, total C stock density ($Mg{\cdot}C{\cdot}ha^{-1}$) has increased since the 1990s, suggesting that one or more factors play a role in increased forest productivity (Pan *et al.* 2024). These factors have apparently outweighed the negative impacts of climate warming, rainfall regime alterations and changes in the frequency and severity of natural disturbances (Pan *et al.* 2024). In the 1990s, boreal and temperate forests represented similar C sinks, but during the 2010s, the contribution of boreal forests declined to less than half that of temperate forests (Pan *et al.* 2024). Specifically, Canada's forests had a virtually neutral carbon balance in the 1990s but became a weak source of C in the 2000s and 2010s, mainly due to an increase in disturbances (insect infestations and wildfires), climate warming and drought (Pan *et al.* 2024).

To see whether these observations regarding the beneficial impacts of global changes on forest productivity hold true in Québec, a growing number of retrospective studies have examined temporal trends in tree growth, mortality and forest productivity over recent decades, and the possible connections to climate change (Table 3). Most of this work involves analysis of data from permanent forest inventory sample plots, tree ring measurements or vegetation indices derived from satellite observations. However, literature reviews have shown that trend estimates for forest growth and productivity in Canada differ from one study to the next, probably due to bias and methodological uncertainty (Marchand *et al.* 2018; Loehle and Solarik 2019).

Numerous studies have also considered the impact of spatial and temporal climate variability on tree growth, phenology and physiology, and for forest productivity in Québec (Table 3). For dominant northern temperate zone species, retrospective studies have also specifically examined the impact of climate and extreme weather events on sugar maple growth within the context of this species current decline in Québec (Table 3). Species sensitivity to climate has also been assessed in experiments carried out in forests or controlled environments, or based on functional traits of species (morphological, physiological and phenological attributes) (Table 3). Prospective studies have also considered the links between tree growth, forest productivity and contemporary climate, or have used species-specific sensitivity indices, to estimate future trends for different climate change scenarios (Table 3).

All these studies highlight the many different factors that impact forest productivity in Québec. The forest's vulnerability to climate change depends, among other things, on the scope of the change, the synchronization, scope and frequency of climate events, local climate, the species functional attributes, the source of a species and its adaptation to local conditions, pedological characteristics, the social position of the trees and their competitors, tree age, stand structure and competition, and so on. The task of quantifying the many dif-

Table 3. Examples of studies of the impact of climate and global changes on tree growth, mortality, phenology and physiology and on forest productivity and carbon storage capacity in Québec

Main topic of interest	Studies
Historical time-related trends	Peng *et al.* 2011; Girardin *et al.* 2011, 2012, 2014, 2016a; Ma *et al.* 2012; Hember *et al.* 2017a, 2017b, 2019; Sulla-Menash *et al.* 2018; Mirabel *et al.* 2023
Impact of climate on tree growth	Deslauriers *et al.* 2003; Huang *et al.* 2010; Duchesne and Houle 2011; Duchesne *et al.* 2012. 2020; Périé *et al.* 2012; D'Orangeville *et al.* 2018b; Ols *et al.* 2018; Babst *et al.* 2019; Itter *et al.* 2019; Brienen *et al.* 2020; Buttò *et al.* 2021; Girardin *et al.* 2022, 2024; Oogathoo *et al.* 2024; Soubeyrand *et al.* 2024; Sylvain *et al.* 2024
Impact of climate on tree phenology and physiology	Rossi *et al.* 2006, 2008; Krause *et al.* 2010; Boulouf Lugo *et al.* 2012; Dufour and Morin 2013; Rasheed and Delagrange, 2016; Delpierre *et al.* 2019; Guo *et al.* 2020. 2023; Oogathoo *et al.* 2020, 2022, 2023; Ren *et al.* 2020, 2021; Huang *et al.* 2020; Gu *et al.* 2022; André-Alphonse *et al.* 2023; Buttò *et al.* 2023; Gao *et al.* 2023; Qiao *et al.* 2023; Zhang *et al.* 2023, 2024; Zhou *et al.* 2023; Podadera *et al.* 2024
Impact of climate on forest productivity	Dupont-Leduc *et al.* 2024
Impact of climate and extreme climate events on sugar maple growth	Payette *et al.* 1996; Nolet and Kneeshaw, 2018; Moreau *et al.* 2019; Boakye *et al.* 2023
Tree sensitivity to climate based on experiments in the forest or in controlled environments	Rossi *et al.* 2009; Belien *et al.* 2012; Lupi *et al.* 2012a, 2012b; Balducci *et al.* 2013, 2015, 2021; D'Orangeville *et al.* 2013a, 2013b; Dao *et al.* 2015; Marty *et al.* 2020; Tauc *et al.* 2020; Ribeyre *et al.* 2022; Urli *et al.* 2023
Tree sensitivity to climate based on functional traits	Aubin *et al.* 2018; Boisvert-Marsh *et al.* 2020
Anticipated trends for different climate change scenarios	D'Orangeville *et al.* 2016, 2018a; Duchesne *et al.* 2016; Girardin *et al.* 2016b; Boulanger *et al.* 2022; Pau *et al.* 2022; Danneyrolles *et al.* 2023; Wang *et al.* 2023a, 2023b; Soubeyrand *et al.* 2024

ferent effects of climate change on tree growth and forest productivity is extremely challenging, among other things, because of the uncertainty surrounding all these factors and their interactions (Price *et al.* 2013). Nevertheless, a better understanding of the impacts of climate change on forest productivity is vital, given the preponderant role played by forest ecosystems in the global atmospheric CO_2 budget (Friedlingstein *et al.* 2023; Pan *et al.* 2024) and the importance of productivity for allowable cut assessments. Despite the variability in projections of changes in tree growth, productivity and forest composition in response to climate change, comparative studies reveal that performance projections for the main tree species in Quebec are generally consistent, regardless of the methodological approach used (Boulanger *et al.* 2022). This makes it possible to identify general trends in anticipated changes.

Furthermore, a positive correlation between the percentage of better-quality sugar maple stems and annual average temperature has also been shown (Guillemette and Bédard 2019). If climate change leads to improved growth conditions at the northern limit of the sugar maple range, stem quality may also improve after several decades. However, this possibility remains uncertain because other factors such as insects, which cause more damage to trees, may counterbalance any future gain.

Natural disturbances

Several studies have shown that climate change will alter the forest disturbance regime in Québec and throughout the world (Seidl *et al.* 2017, 2020; Boucher *et al.* 2018). For example, extreme climate events, whose frequency or scope may be exacerbated by climate change (IPCC 2023b), could trigger or constitute natural disturbances. However, the disturbance regime in Québec's northern temperate zone should be less affected by climate change than the boreal zone's regime (Seidl *et al.* 2017). Among other things, climate change is likely to create conditions favourable to more intense, more frequent, more severe and more extensive wildfires in Québec (Girardin and Mudelsee 2008; Terrier *et al.* 2013; Boucher *et al.* 2018; Augustin *et al.* 2022; Pau *et al.* 2023), but this is expected to occur only in the boreal zone.

Climate change may also impact disturbances caused by insect pests through changes to host trees, insect populations and their natural enemies (Pureswaran *et al.* 2015). Warming will apparently encourage some insect populations to move into more northerly latitudes and higher altitudes, especially in temperate regions (Régnière *et al.* 2012). Some studies have examined the impact of climate and climate change on insect populations and diseases, including spruce budworm (*Choristoneura fumiferana* Clem.), which is by far the most prevalent tree defoliator in Québec. The insect attacks balsam fir and spruce. Longer, more intense infestations are anticipated in the coming decades, but they are also likely to be less frequent (Gray 2008; Candau and Fleming 2011). Analysis has shown that unfavourable climate periods precede and amplify mortality among trees attacked by spruce budworm (De Grandpré *et al.* 2018). Increased frequency of extreme climate events may therefore amplify the consequences of infestations and cause more severe mortality. These projections are of concern because spruce budworm can have a significant impact on wood supplies and the C budget at the landscape level (Dymond *et al.* 2010; Liu *et al.* 2019). On the other hand, climate envelope modelling of spruce budworm spatial distribution within a moderate climate change scenario suggests that the areas most favourable to spruce budworm are likely to be concentrated mostly in the boreal forest, and even more so in its northern portion (Forestier en chef 2024).

In the northern temperate zone, the main indigenous defoliating insect attacking dominant hardwood species is the forest tent caterpillar (*Malacosoma disstria* Hübner). It can defoliate sugar maple, usually leading to a slight increase in mortality (Cooke and Lorenzetti 2006; Wood *et al.* 2009), although damage is associated more with lower forest productivity than with high mortality (Forestier en chef 2024). The task of anticipating the impacts of climate change on the forest tent caterpillar and other insect pests is challenging, in particular due to the lack of information on these organisms and because they depend on complex, relatively unknown and unstable interconnections (Dukes *et al.* 2009). Spatial distribution models of the forest tent caterpillar climate envelope within a moderate emission scenario suggest that major changes are unlikely (Forestier en chef 2024). The insect is already present in the temperate and boreal zones, where it defoliates trembling aspen and paper birch. The contemporary increasing risks associated with biological invasions have been documented in detail in Part 2 of this series of articles (Guillemette *et al.* 2025). We conclude that the most vulnerable species do not include Québec's three most abundant temperate hardwood species, namely sugar maple, red maple and yellow birch.

There are also some concerns regarding the impacts of climate change on disturbances such as windthrow associated with windstorms and ice storms. However, these disturbances are much less frequent than wildfires and insect infestations in Québec's forests (see Part 1 of this series of papers — Duchesne *et al.* 2025), and the anticipated increase in these disturbances in North America is much less than for wildfires and insect infestations (Seidl *et al.* 2017). Very little change is expected in the occurrence of ice storm episodes (≥ 10 mm) in the northern temperate zone by the end of the century (Table 2).

Concerns have also been raised about the impacts of climate change on tree and forest dieback following extreme climate events such as droughts or freeze-thaw episodes, which could interact with insect infestations or diseases, under the influence of acid rain, nutrient availability and succession dynamics (Auclair *et al.* 1996; Payette *et al.* 1996; Coble *et al.* 2017). Research has highlighted several influential factors for which the effect of climate change is not yet known. It is not a simple task to study the effects of extreme climate events because they are rare by definition. In southern Québec, historical climate data show an increase in the number of days with abnormally high temperatures (> 25 °C) and the number of days with abundant precipitation since the middle of the last century (Table 1). By the end of this century, the number of days with abnormally high temperatures is also expected to increase, the number of days with abnormally low temperatures (< −25 °C) to decrease, and the number of days with abundant precipitation (≥ 20 mm) to increase slightly, but little change is expected in the number of precipitation-free sequences (≥ 6 days with less than 1 mm) (Table 2). It is, however, difficult to anticipate the extent to which an increase in the intensity and frequency of these extreme climate events is likely to cause more forest dieback episodes in the area under consideration.

Biogeochemical cycle of elements

Studies have examined the impacts of climate and climate change on forest ecosystem functions in Québec. For example, droughts have been shown to have a definite impact on nutrient cycling in forest ecosystems, and to potentially play a role in reducing soil fertility (Houle *et al.* 2016). According to certain projections, climate change will warm forest soils and reduce their moisture content, with possibly significant repercussions for forest growth and biogeochemical cycles (Houle *et al.* 2012b; Cholet *et al.* 2022). Soil warming can increase humus decomposition rates and hence alter CO_2 emissions into the atmosphere as well as nutrient flows into soils (D'Orangeville *et al.* 2013b, 2014; Tremblay *et al.* 2018; Marty *et al.* 2019; Borah and Parmar 2024; Pan *et al.* 2024; Wang *et al.* 2024). An increase in the percentage of hardwood species in conifer forests would also generate a more labile litter, potentially reducing organic C storage in ecosystem soils (Boilard *et al.* 2023). Rising temperatures may also increase the rate of chemical alteration of minerals in forest soils, thereby accelerating the release of mineral nutrients contained in the soil's mineral matrix. These nutrients then become available in dissolved ionic forms, usable by plants and microorganisms. This could raise soil fertility and, indirectly, forest productivity and the quality of water in neighbouring lakes and watercourses (Houle *et al.* 2010, 2020; Marty *et al.* 2021). Climate also impacts concentrations of organic matter in soil solutions and ultimately in neighbouring lakes and watercourses (Jeljli *et al.* 2022).

Wildlife populations

Anticipated climate warming, along with its effects on forest structure, composition, and disturbance regimes, is expected to influence wildlife habitats and populations, including soil fauna, birds, and mammals (Moore *et al.* 2018; Boulanger *et al.* 2023). Changes in wildlife populations might in turn affect forests, for example, through excessive browsing of regeneration. A well-documented example of this is the white-tailed deer (*Odocoileus virginianus* Zimmermann), which feeds mainly on young shoots of certain tree species. There is broad consensus that deer populations are affected by winter rigour and that climate change is likely to result in larger deer populations and a northward expansion of their range (Kennedy-Slaney *et al.* 2018). It is, however, difficult to anticipate the long-term impact of climate change on wildlife populations, since other variables such as predation also play a role. In-depth research is still needed (Rodenhouse *et al.* 2009). It is worth noting that, according to some historical sources, the white-tailed deer was well-established in Québec's temperate zone when the first Europeans arrived (McCabe and McCabe 1984). As was the case in the United States, excessive harvesting was probably the reason for the collapse of deer populations. The species was subsequently able to recover, and its populations were able to grow as a result of hunting controls imposed during the 20th century, combined with declining populations of natural predators and alterations to the forest landscape (Rooney 2001). Because there is no information on the size of white-tailed deer populations during the pre-colonial period (Webb 2024) however, it is difficult to affect a comparison with the size of contemporary populations subjected to the impacts of climate change.

Maple syrup production

Maple syrup accounts for a growing share of Québec's economy, especially in rural areas. The number of production taps increased from 14.7 million in 1980 to 51 million in 2023. At the same time, annual production increased from 31.9 million to 124.1 million pounds of syrup (PPAQ 2023). In 2020, the economic spinoffs from all maple syrup activities in Québec (including production, processing and restoration) were estimated at nearly 10 000 full-time jobs, and they contributed $825 million to the province's gross domestic product (Doyon *et al.* 2022).

However, just like the number of productive taps, climate has a significant impact on maple syrup production because average tap yields can be doubled or halved from one year to the next, depending on weather. For example, the average provincial yield was 4.26 pounds per tap in 2022 (a record year), and just 2.43 pounds per tap in 2023 (PPAQ 2023), most likely due to the early warming of temperatures in spring which abruptly ended the season.

Maple syrup producers are well aware of the impact of climate on syrup production and are concerned about the direct and indirect effects of climate change (Legault *et al.* 2019; Caughron *et al.* 2021; Ahmed *et al.* 2023). Recent quantitative studies have shown the impact of climate on temporal and spatial variability of per-tap yields in Québec and the United States. Maple sap production is closely aligned with freeze/thaw circadian cycles, since most sap is produced when temperatures fall below freezing at night and rise above 0 °C during the day (Pothier 1995; Kurokawa *et al.* 2023). The production season generally occurs during the period when average daily temperatures warm to between −2 °C and 2 °C (Kurokawa *et al.* 2023). Maple syrup production therefore varies significantly, both annually and regionally, according to climate fluctuations. Analysis of historical provincial and regional per-tap statistics has shown the main climate factors influencing yields (Duchesne *et al.* 2009; Duchesne and Houle 2014; Houle *et al.* 2015). Yields are likely to be better in the season following a year with a large number of degree-days and abundant rainfall in summer, as well as cold temperatures in winter. Similarly, climate conditions conducive to long production periods (early spring and gradual warming) are associated with better yields. The best yields are therefore associated with the length of production season as opposed to intensity.

Projections using mathematical models linking yields to climate conditions suggest that the maple syrup production season will occur between two and three weeks earlier by the end of the century, depending on the climate change scenario used (Duchesne *et al.* 2009; Houle *et al.* 2015). However, climate change is not expected to have a major impact on annual yields in most regions of Québec, except for those located further south where the season may be shortened exceptionally due to rising temperatures. Some projections have, however, suggested significantly lower yields and more frequent adverse production years throughout the maple range in the United States (Rapp *et al.* 2019), although these conclusions have been criticized (Houle and Duchesne 2020).

The main issues for forest ecosystems

We did not identify major issues arising from climate change during this century for Québec's three principal temperate hardwood species (sugar maple, red maple, and yellow birch). The climate in the current zone is likely to remain within the conditions generally encountered in these species' range. There may be some local adaptation failures, but we found no strong trend indications of this. The concerns are more with conifers, which nevertheless represents a major anticipated issue for northern temperate forests across North America. Similarly, the natural disturbance regime in Québec's northern temperate zone is not expected to change significantly, although further study is required to confirm this hypothesis.

Despite uncertainties with mathematical models used to predict future states, a number of issues can be associated with the ongoing northward expansion of the northern temperate zone and changes to the composition of Québec's forests in response to climate change. The expansion of temperate hardwood species into the boreal forest may be an issue for softwood species processors targeting specific markets, whose logging equipment and processing infrastructures are currently adapted to small-diameter softwood species. On the other hand, an increase in the abundance of temperate hardwood species in the boreal zone may eventually reduce the impact of climate change on wildfire frequency within the zone (Terrier *et al.* 2013). Northward migration of sugar maple may, in the long term, offer a development opportunity for Québec's maple syrup industry, but for this to occur in many places, suitable soils would have to be identified, and maple trees would have to be planted and maintained. However, increased abundance of some lower-value temperate species that are more sensitive to specific insects and pathogens (e.g., American beech), at the expense of sugar maple, could also be a challenge for processors and for the maple syrup industry.

From an ecological standpoint, the development of plant communities can result in habitat loss for organisms adapted specifically to existing communities. Conversely, other organisms might benefit from new habitats. However, biodiversity loss resulting from climate change on tree communities in Québec's temperate and boreal forests does not appear to be an issue (Crockett *et al.* 2022). Given that stands dominated by temperate hardwoods are usually more productive and store more C because the trees are larger, any change in composition could enhance forest productivity and C storage (Duchesne *et al.* 2016; Ameray *et al.* 2023). On the other hand, the increase in temperate species may not keep pace with the rapid reduction in boreal species, thereby causing a temporary reduction in both productivity and biomass storage (Taylor *et al.* 2017; Chaste *et al.* 2019). Aerial biomass may, in fact, decline as a result of climate change, despite anticipated changes to composition (Landry *et al.* 2021). In addition, an increase in the production of short life-cycle wood products with virtually no substitution effect (more pulp and pulpwood and less lumber), from landscapes dominated increasingly by temperate hardwood species, may reduce the forest sector's effectiveness as a climate change mitigator (Landry *et al.* 2021; Moreau *et al.* 2022).

The direct impacts of climate change on tree growth and forest productivity, like its indirect impacts on disturbances and forest ecosystem functions, nevertheless raise issues with respect to the forests' role in the carbon cycle. Among other things, reduced tree growth and productivity would also reduce carbon capture, thereby enhancing the effects of anthropological emissions on atmospheric greenhouse gas concentrations and speeding up climate change. Mortality may also increase when trees fail to adapt to new climate conditions. More frequent or intense extreme climate events such as droughts or heatwaves (Allen *et al.* 2010) may also lead to increased mortality. In addition, increased mortality may be associated with greater growth in response to global changes due to the inverse relationship between tree growth and longevity (Brienen *et al.* 2020). Another major issue is increased decomposition of organic matter in soils, and hence increased C emissions (Pan *et al.* 2024). Rising temperatures may, nevertheless, be beneficial for soil fertility and, indirectly, for forest productivity.

Sustainable development criteria for forests include conservation of biological diversity, maintenance and improvement of the condition and productivity of forest ecosystems, conservation of soils and water, maintenance of the ecosystem contribution to major ecological cycles, and maintenance of the numerous socioeconomic benefits that forests provide. Forest managers and scientists must show ingenuity to address the major challenges created by climate change and prepare effective strategies aimed at adapting sustainable forest management practices (Price *et al.* 2013; Messier *et al.* 2019; Royer-Tardif *et al.* 2021; Boulanger *et al.* 2023). These strategies include consideration of climate and environmental variables in the growth and yield models used to plan forest development (Metsaranta *et al.* 2024), and preparation and application of silvicultural treatments to mitigate the impacts of climate change on forest ecosystems (Thiffault *et al.* 2021, 2024; Wotherspoon *et al.* 2022; Royo *et al.* 2023; Guignabert *et al.* 2024). These adaptation strategies must be based on information on the potential impacts of climate change on forest ecosystems, along with a monitoring system for indicators relevant to climate change (Gauthier *et al.* 2014a). The perceptions, concerns and expectations of communities, forest owners and the forest industry should be taken into consideration (Morin *et al.* 2015; Bissonnette *et al.* 2017). Although their implementation may be limited by current economic conditions and uncertainties remain regarding their effectiveness, several adaptation strategies have been proposed. These include measures aimed at reducing non-climatic stressors and sensitivity to climate change, and at maintaining or enhancing the adaptive capacity of the biophysical and human components of forest management systems (Gauthier *et al.* 2014b; Messier *et al.* 2019; Boulanger *et al.* 2023). However, a detailed review of adaptation strategies to reduce the vulnerability of northern temperate forests to climate change is beyond the scope of this article.

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