Title: A regional integrated assessment of the impacts of climate change and of the potential adaptation avenues for Quebec's forests

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Abstract

Regional analyses assessing the vulnerabilities of forest ecosystems and the forest sector to climate change are key to consider the heterogeneity of climate change impacts but also the fact that risks, opportunities and adaptation capacities might differ regionally. Here we provide the Regional Integrated Assessment of climate change on Quebec's forests, a work that involved several research teams and that focused on climate change impacts on Quebec's commercial forests and on potential adaptation solutions. Our work showed that climate change will alter several ecological processes within Quebec's forests. These changes will result in important modifications in forest landscapes. Harvest will cumulate with climate change effects to further alter future forest landscapes which will also have consequences on wildlife habitat (including woodland caribou habitat), avian biodiversity, carbon budget and a variety of forest landscape values for Indigenous peoples. The adaptation of the forest sector, will be crucial to mitigate the impacts of climate change on forest ecosystem goods and services and improve their resilience. Moving forward, a broad range of adaptation measures, notably through reducing harvest levels, should be explored to help strike a balance among social, ecological and economic values. We conclude that without climate adaptation strong negative economical and ecological impacts will likely affect Quebec's forests.

Keywords: Québec, boreal forest, synthesis, ecosystem services, regional analyses

RÉSUMÉ

Les analyses régionales évaluant la vulnérabilité des écosystèmes forestiers et du secteur forestier aux changements climatiques sont essentielles pour prendre en compte l'hétérogénéité des impacts des changements climatiques, mais aussi le fait que les risques, les opportunités et les capacités d'adaptation peuvent différer d'une région à l'autre. Nous présentons ici l'évaluation régionale intégrée des changements climatiques sur les forêts du Québec, un travail qui a impliqué plusieurs équipes de recherche et qui s'est concentré sur les impacts des changements climatiques sur les forêts commerciales du Québec et sur les solutions d'adaptation à ces changements. Nos travaux montrent que les changements climatiques pourraient modifier plusieurs processus écologiques dans les forêts du Québec. Ces changements entraîneront d'importantes modifications des paysages forestiers. La récolte forestière pourrait s’additionner aux changements climatiques pour modifier davantage les futurs paysages forestiers, ce qui pourrait également avoir des conséquences sur les habitats fauniques (notamment ceux du caribou forestier), la biodiversité aviaire, le bilan carbone et les valeurs des paysages forestiers pour les Peuples autochtones. Nous préconisons que l'adaptation du secteur forestier sera essentielle afin d’atténuer les impacts des changements climatiques sur plusieurs biens et services écosystémiques forestiers. Ces stratégies devraient améliorer la résilience des services écosystémiques. Par exemple, la réduction de la récolte pourrait permettre de maintenir l'habitat du caribou, favoriser la biodiversité aviaire, bonifier la capacité de stockage du carbone et profiter aux activités traditionnelles autochtones. La réduction des taux de récolte du bois pourrait aussi aider à réduire les échecs de régénération après les feux dans les régions où ceux-ci sont actuellement communs, ou dans celles qui seront à risque dans le futur. Sur la base de nos travaux, nous concluons qu’omettre de mettre en œuvre des options d'adaptation aux changements climatiques pourrait représenter des impacts économiques et écologiques négatifs importants pour les forêts du Québec.

Mots-clés : Québec, forêt boréale, synthèse, services écosystémiques, analyses régionales

1. Introduction

The science is clear: human-caused climate change has been warming the planet by 1.1°C since 1880, with a recent rate of increase of 0.18°C per decade since 1981 (IPCC 2021, NOAA 2021). The 2011-2020 decade was the hottest ever recorded since 1880 and the six warmest years on record are all after 2015 (World Meteorological Organization 2021). In Canada, land surface temperatures have increased twice as fast as global rates (mean +1.7°C for Canada vs 0.8°C for the globe for the 1948-2012 period), with the largest increases recorded during winter and in the northernmost part of the country (Bush and Lemmen 2019). Projections of future temperature and precipitation for the upcoming decades are causes for concern (Bush and Lemmen 2019). Such an alteration of climate conditions by the end of this century is likely to strongly affect wildlife and ecosystems, as well as our economies, societies, and cultures (IPCC 2021).

Forests are one of the ecosystems that are most likely to be significantly impacted by climate change (Bernier and Schoene 2009, Gauthier et al. 2015a), either directly - through tree physiological changes - or indirectly through changes in natural disturbances. For instance, the significant increases in annual area burned observed in western Canada since the 1970s are strongly linked to the concurrent increase in temperatures (Gillett et al. 2004, Hanes et al. 2019). Similarly, several catastrophic fire-related events, like those that occurred in the last decade in Canada (e.g. the 2016 Fort McMurray Fire, the 2017 fire season in British Columbia, the 2021 heat wave that triggered massive wildfires in northwestern North America), were shown to be increasingly likely under stronger anthropogenic radiative forcing (Kirchmeier-Young et al. 2017, 2019, Philip et al. in review). Future climate-induced lengthening of the fire season as well as the increase in fire-prone weather conditions could further contribute to a 2- to 4-fold increase in annual area burned by the end of the century in most regions of Canada (Flannigan et al. 2005, Boulanger et al. 2014). Furthermore, alteration of climate conditions have already contributed to changing insect outbreak regimes (Pureswaran et al. 2015), increasing drought-related mortality of trees (Hogg and Bernier 2005, Michaelian et al. 2011, Peng et al. 2011, Hogg et al. 2017), and altering tree productivity over extensive regions of boreal Canada (Chen and Luo 2015, Girardin et al. 2016). As a result, forest composition and structure (Steenberg et al. 2013, Boulanger et al. 2016a, Searle and Chen 2017, Taylor et al. 2017) could be strongly modified with global warming, potentially leading to biome shifts (Boisvert-Marsh et al. 2014, Périé et al. 2014, Stralberg et al. 2018, Brice et al. 2019, Whitman et al. 2019).

Climate-induced changes in forest and northern ecosystems could strongly impact forest value and economy in the future (Williamson et al. 2009, Price et al. 2013, Gauthier et al. 2014, 2015b, Boucher et al. 2018) with tangible risks of ecological (e.g., species extinction, ecosystem collapse) and societal disruptions (Duerden 2004, Hope et al. 2016). The forest industry sector contributed $23.7 billion in 2019 Canada's GDP (NRCan 2021), placing the country first in the world's forest product trade balance (NRCan 2020). Forest contribution to the economy also arises from the variety of ecosystem services it provides to human populations, including food and material provision as well as sustaining cultures and knowledge. Although temporary climate-induced increase in forest productivity could benefit the industry (D'Orangeville et al.

2018), financial losses in the long term could be colossal, with many direct and indirect jobs at stake, including in remote and mono-industrial regions.

In this context, assessing the vulnerabilities of forest ecosystems and the forest sector to climate change is required. Such an analysis requires a holistic and integrated approach. Regional analyses are key as they take into account the heterogeneity of climate change impacts across broad spatial scales. They also factor in differences in risks, opportunities and adaptation capacities across regions (Williamson et al. 2008). As a result, regional analyses help develop local-scale adaptation solutions to mitigate the global-scale impacts of climate change on ecosystem services (Millar et al. 2007, Williamson et al. 2008, Edwards and Hirsch 2012, Gauthier et al. 2014, Nagel et al. 2017, Splawinski et al. 2019 a, c, Cyr et al. 2021).

Between 2017 and 2021, the Canadian Forest Service of Natural Resources Canada partnered with local, regional, provincial, and federal agencies, as well as academia, industrial stakeholders, and Indigenous communities to lead five Regional Integrated Assessments (RIA) across Canada. RIAs aimed to generate new models, monitor climate change, establish reference conditions and inform forest management in different regions in Canada. (Further information about RIAs can be found at https://ca.nfis.org/forestchange/StoryMap_EN/Regional.html). More specifically, one of these RIAs was to assess the impact of climate change on Quebec's forests, ecosystem services, and the forestry sector (Quebec's RIA). The objectives of this RIA was i) to identify vulnerabilities of Quebec's forests to climate change (e.g., productivity, natural disturbances, forest landscapes), ii) identify specific ecosystem services potentially at risk (e.g., biodiversity, carbon, timber supply, Indigenous provisioning and cultural values) as well as iii) to explore potential adaptation strategies to mitigate previously identified vulnerabilities. The great majority of individual projects within the RIA has been published (see Figure 1 for references). Here we summarize and, most importantly, integrate the work carried out under Quebec's RIA to provide readers a synthesis of the transdisciplinary studies that were carried out within this project. By doing so, we present how the assessment helped improve our understanding of climate change vulnerabilities of Quebec's forests and we present analyses of potential adaptive strategies to minimize these impacts. Although results are specific to Quebec, we believe that the general framework within which this project was carried out could be transposed to any forest regions around the globe that wish to develop climate change adaptation strategies.

1.2 Area covered by the study area

Areas covered by Quebec's RIA mostly lie within forests subject to industrial timber harvesting in Quebec (hereafter the commercial forest, Figure 1a). The broad study area covered a vast diversity of forest ecosystems. Temperate forest, dominated by diverse broadleaf species (e.g., *Acer* spp., *Fagus grandifolia* Ehrh., *Quercus* spp., *Betula alleghaniensis* Britt.), occurrs in the southern part of the region, whereas conifer-dominated (e.g., balsam fir [*Abies balsamea* (L.) Mill.], jack pine [*Pinus banksiana* Lamb.], spruces [*Picea* spp.]) boreal forests extended to the northern part. The study area covered wide latitudinal and longitudinal temperature and precipitation gradients, with mean annual temperatures ranging from 6.6°C (south) to -3.1°C (north) and total annual precipitation ranging from 600 mm (west) to 1200 mm (east) (Ouranos 2015).

The great majority of the climate projections conducted within the RIA were run under two different radiative forcing scenarios, known as Representative Concentration Pathways (RCP, e.g., van Vuuren et al. 2011), i.e., RCP 4.5 and RCP 8.5. The RCP 4.5 scenario involves a stabilization of radiative forcing at 4.5 W/m^2 after 2100, without any "overshoot" pathway. In contrast, the RCP 8.5 scenario involves a radiative forcing of 8.5 W/m^2 in 2100, which then continues to rise for an indefinite period of time. Although recent analyses suggested that the RCP 8.5 scenario is less likely than first anticipated (Hausfather and Peters 2020), we used these two projections to consider a range of potential outcomes (Schwalm et al., 2020). According to the CanESM2 model, mean annual temperatures are expected to increase on average by 3.5˚C (RCP 4.5) to 7.5˚C (RCP 8.5) and precipitations by 7% (RCP 8.5) to 10% (RCP 4.5) by 2100, compared to year 2000. Such alterations of climate regimes would suggest a 300-km northward displacement of ombrotrophic envelopes, i.e., zones defined by mean temperatures and precipitations, under RCP 8.5 (Périé et al. 2014, Grondin et al. 2022, Chalumeau et al. submitted).

The forest sector is currently one of the most important industries in Québec, representing $CAN 20.6 MM of domestic economic impact in 2020 (NRCan 2022). Managed forests covers 58.3 Mha from which 43.4 Mha are considered as productive. Approximately 92% of the managed forests are public. During the 2013-18 period, approximately 181 000 ha were harvested annually on average on public lands under management, representing a mean rate of 0.7%.yr^{-1} (MFFP 2019a). In the province, forest management in Quebec is guided by the principles of sustainable development and is intended to ensure the long-term productivity of the forest. This involves a range of activities, including the planning and implementation of harvesting operations, the regeneration of harvested areas and the protection of forests from pests and fires. In Quebec, the management of public forests is the responsibility of the Ministry of Natural Resources and Forests, while the management of private forests is the responsibility of the owners. In Québec, forest companies have contracts signed with the provincial government that guarantee the access to a given volume of wood and set ethical guidelines and regulations for the harvesting operations. The rate of timber harvest varies and tends to be higher with larger cutblocks and higher proportions of biomass harvested as one moves towards the higher latitudes. On public lands, the great majority of stands located in the southern part of the study area, within the temperate region, are partially harvested by means of single-tree and small-patch harvesting. In more northern locations, clearcuts, mostly those with protection of the regeneration and soils (which typically remove trees larger than 9 cm of diameter at breast height) might represent more than 90% of the prescriptions (MFFP 2019). In this area, clearcut patches reaching a maximum of 150 ha are frequently agglomerated in patches that could reach a maximum of 15 000 ha (*Loi sur l'aménagement durable du territoire forestier,* chap A-18.1, a. 38, 39 and 44). Natural regeneration is favored but planting is advocated in poorly regenerated stands following disturbances. A total of 64,868 ha was planted in 2020 within Québec's managed forests (NRCan 2022). Partial harvesting, notably shelterwood logging, also occur in a lesser proportion mainly within black spruce and balsam fir stands. Pre-commercial and commercial thinnings are frequently performed to reduce density and favor growth during stand development (Laplante 2009).

In some projects, the study area covered most of the commercial forest study area (Boulanger and Pascual 2021, Boulanger et al. 2021, Leblond et al. 2022) whereas others focused on smaller regions projected to experience specific climate-induced vulnerabilities (e.g., Splawinski et al. 2019a, c, Cyr et al. 2021, Landry et al. 2021, Moreau et al. 2022).

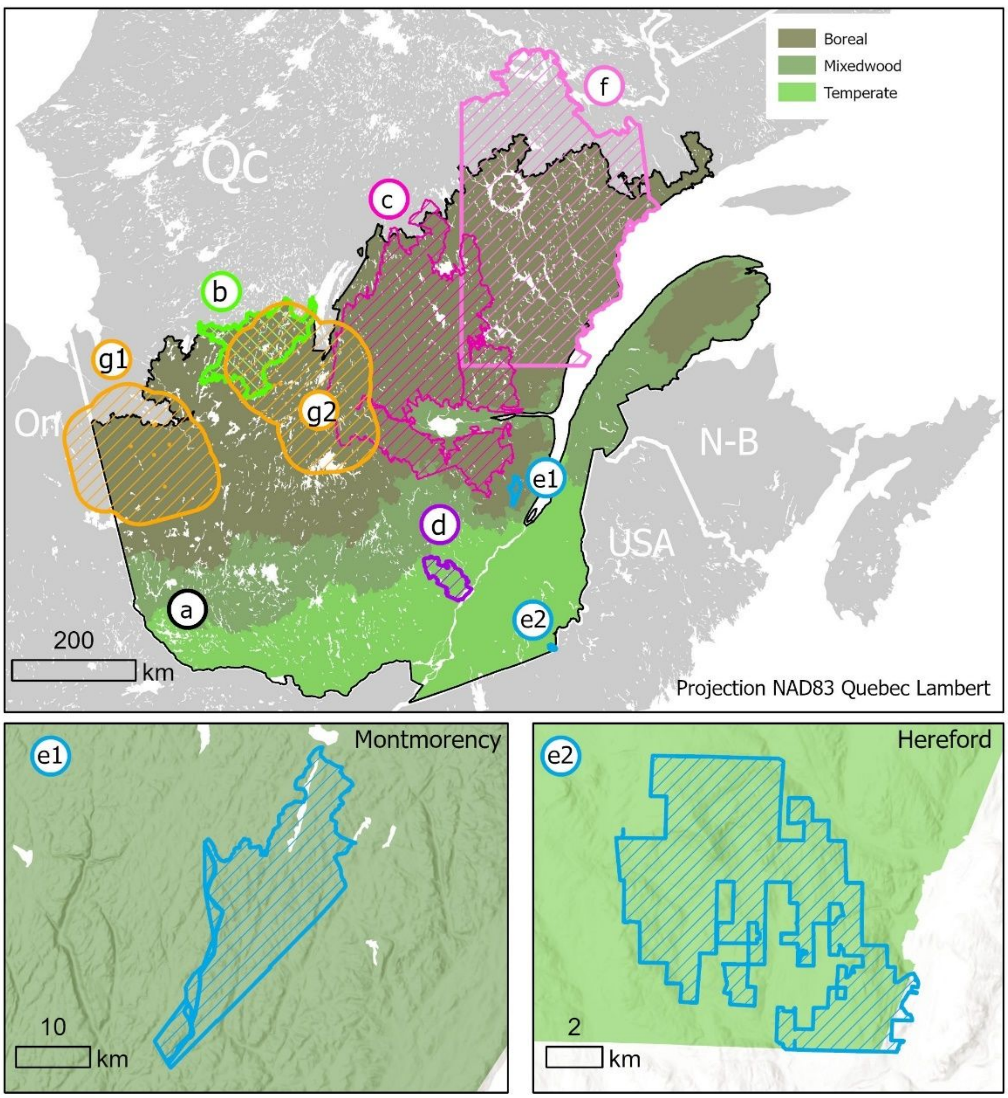

Figure 1. Location of each individual projects included in the RIA. Region a: De Grandpré et al. (2019), Boulanger and Pascual Puigdevall (2021), Boulanger et al.

(2021), Leblond et al. (2022). Also corresponds to the Quebec's managed forest as well as the intensive protection zone for fire suppression; Region b: Cyr et al. (2021); Region c: FEC (2021); Region d: Landry et al. (2021); Regions e1 and e2: Moreau et al. (2022), Labadie et al. (in prep.); Region f: Labadie (2022). Regions g1 (Abitibiwinni) and g2 (Ouje-Bougoumou): Bélisle (2022). Forest region (Boreal, Mixed, Temperate) shapefile available from https://www.foretouverte.gouv.qc.ca/ .

2. Assessing the vulnerability of Quebec's forests to climate change

2.1. Climate change will alter forest productivity and stand dynamics

Previous work conducted within Quebec's RIA (Girardin et al. 2016, Boakye et al. 2021, Marchand et al. 2021, Pau et al. 2022) area showed that warmer temperatures and increased drought severity can affect several tree physiological processes (e.g., photosynthesis, respiration). These could in turn alter tree productivity, regeneration, phenology, stem growth, and mortality rates. Such alterations will be highly contingent on the regional context, the level of anthropogenic radiative forcing (Huang et al. 2013, D'Orangeville et al. 2018, Pau et al. 2022), and species composition. For instance, climate change could be either detrimental (Girardin et al. 2016) or beneficial (Huang et al. 2013, D'Orangeville et al. 2018) for boreal conifer productivity. Locally, soil conditions (e.g., water holding capacity, soil depth, nitrogen conditions) are also likely to play a significant role in altering future tree's productivity (Taylor et al. 2017).

We conducted additional analyses within the RIA study area (Figure 1, region a) to better identify which tree species growth could be most altered by climate change. Analyses showed that in 2100, strong climate forcing could alter boreal species growth (mostly spruce, pine, larch and balsam fir) throughout the study area, but mostly in the southern part of our study area, i.e., within the mixedwood and temperate forests) (Figure 2i).

Conversely, thermophilous species, i.e., those associated with relatively warmer conditions (mostly *Acer rubrum*, *Quercus rubra*, *Tsuga canadensis*, *F. grandifolia*), are expected to experience increased potential productivity and growth (Figure 2i), notably at the leading edge of their current distribution and beyond under moderate anthropogenic radiative forcing. Such climate-induced decreases in boreal species productivity might trigger a “climatic debt” (Taylor et al. 2017): increased productivity in thermophilous species will be unable to compensate for productivity declines in co-occurring boreal species. As shown later in this paper, extensive productivity loss is likely to affect species competitive abilities leading to composition shifts (Fisichelli et al. 2014, Reich et al. 2015) as well as reduced timber volumes (Brecka et al. 2020).

2.2. Natural disturbance regimes will change: a review

Even though no additional research on projections of natural disturbances were conducted within the RIA, these need to be reviewed here in order to better understand future forest vulnerabilities. Indeed, natural disturbances, which many are stand-replacing, are strongly driving forest dynamics in boreal Quebec. As virtually all natural disturbances are partially or completely weather- or climate-driven, any changes in these conditions will affect their temporal and spatial distribution, as well as their severity regimes.

Here we focus on two major natural disturbances that are known to impact forest landscapes within the RIA’s study area: wildfires and spruce budworm (*Choristoneura fumiferana* [Clem.]; SBW) outbreaks. Since the last three decades, annual area burned averages 72 000 ha (0.12%.yr^{-1}) within Quebec’s managed forests (MFFP 2020).

Typically, wildfires are more common along a south-to-north and an east-to-west gradient, mostly following the precipitation gradient. Wildfires are most common within the westernmost Boreal region, especially within black spruce and jack pine stands, where the regional fire cycle is 120 years (Couillard et al. 2022). Stand-replacing, lightning-caused fires are responsible for most of the annual area burned within the boreal forest. The entirety of the RIA study area is under intensive forest fire suppression (MFFP 2019b) although suppression success is higher in the southern regions (Cardil et al. 2019). In this latter regions, annual area burned is rather low (fire cycle exceeding 800 years) and caused by small (<10 ha) and mostly anthropogenic fires. The entirety of the RIA study area is under intensive forest fire suppression. Severe impacts of spruce budworm outbreaks occur mostly within the mixed and the southern part of the boreal forest regions according to a 35-year recurrence cycle on average since the last 400 years (Boulanger et al. 2012). Most vulnerable host species are by a decreasing order balsam fir, white spruce, red spruce and black spruce, for which multi-year severe defoliation can cause important growth reduction and ultimately result in host mortality over extensive areas. A major outbreak covering more than 55 Mha affected mixed and conifer forests of northeastern North America (including 32.3 Mha in Quebec) between 1967 and 1992. The latest SBW outbreak in Quebec began in 2004 and is currently (as of 2022) affecting approximately 9.1 Mha of forest, decreasing from 13.5 Mha recorded in 2020 (MRNF 2022).

Previous analyses have shown that fire activity during the 20th century strongly decreased in Quebec when compared with the preindustrial era (Bergeron et al. 2006), which is consistent with a concomitant decrease in summer drought intensity (Girardin et al.

2009). Conversely, weather conditions in Quebec during recent decades are increasingly more conducive to fires (Wasneem et al. in prep.), although not as markedly as in western Canada (Jain et al. 2017, 2022, Chavardes et al 2022, Ellis et al. 2022). Future warming would further contribute to increased fire-conducive conditions through an increase in spread days (Wang et al. 2017), moisture deficit and fire season length. As a result, previous analyses (Boulanger et al. 2014, Gauthier et al. 2015b) have shown that fire activity would greatly increase under strong anthropogenic forcing (Boulanger et al. 2014, Gauthier et al. 2015b, Boulanger et al. 2018) but mainly within the boreal portion of the study area (Figures 2ii). Important alterations in fire regimes could occur as soon as in 2040, especially in northwest Quebec (Boulanger et al. 2014). Such an extreme scenario could result in fire cycles not experienced by forest during all the Holocene (Bergeron et al. 2010).

In addition, climate change is likely to change pest distribution ranges and severity (Régnière et al. 2012, Lehmann et al. 2020). Native species like the SBW are predicted to shift their distribution northward as climate warms, thus potentially impacting ecosystems that were previously spared from their effects (Régnière et al. 2012; Pureswaran et al. 2015). The primary SBW host, balsam fir, is abundant in its current distribution range, but is gradually being replaced at higher latitudes by black spruce (*Picea mariana* [Mill.] BSP), a secondary host. When considering the current vulnerability of these hosts as well as climate change, volumes at risk to SBW (Boucher et al. 2018) would strongly decrease throughout the RIA’s study area (Figure 2iii) because of a “mismatch” between host distribution and the future northward displacement of the SBW climate envelope (Boulanger et al. 2016b). Climate-induced reduction in SBW volume at risk could thus "relax" future SBW outbreak impacts on forest landscapes compared with those observed under historical climates although high uncertainty remains (Boulanger et al. 2016b).

The northward transition to less vulnerable forest composition was thought to represent a barrier preventing major SBW damages in northern forests. However, it was shown that future host vulnerability to SBW might be greatly altered (Pureswaran et al. 2015), which might completely modify the impacts this insect could have on future forest landscapes. For instance, there is a potential for increased phenological synchrony between larval emergence and budburst of black spruce (Pureswaran 2015; Pureswaran et al 2019). Climate warming could reduce the lag in budburst phenology between balsam fir and black spruce, thus increasing the vulnerability of black spruce to SBW defoliation (Correia et al. in prep.). Furthermore, larval winter survival in black-spruce dominated forests (Berthiaume et al. 2020) is expected to increase, as winters will become milder in the future. Altogether, these changes could help sustain defoliation events at levels in northern forest ecosystems that will result in tree mortality, with unknown consequences on regional forest composition. These SBW defoliation events could interact with drought stress with the potential of causing severe black spruce mortality (De Grandpré et al. 2019) as it is currently observed in the North-Shore region of Quebec. Such impacts have yet to be fully understood and included in models projecting changes in forest landscapes as well as on other ecosystem goods and services. Despite this relative uncertainty, recent examples (e.g., mountain pine beetle in western Canada [Safranyik et al. 2010], winter and autumnal moths in northern Fennoscandia [Jepsen et al. 2008, 2022] and hemlock looper in central Québec [Béland et al. 2022]) have shown that stakeholders must be ready for unexpected climate-induced impacts of insect pests on boreal forest landscapes.

2.3. Cumulative impacts of climate-induced changes in stand dynamics and natural disturbance regimes will modify forest landscapes

The above-mentioned evidence suggests that climate change could alter Quebec's forest productivity, stand dynamics, and natural disturbance regimes. Because forest ecosystems are complex and highly dynamic (Messier et al. 2019), these climate-induced impacts are likely to strongly cumulate and interact. Therefore, these processes cannot be considered in isolation when assessing the vulnerabilities of future forest landscapes to climate change. For instance, climate-induced changes in forest productivity could modify species competitive ability and forest composition (Reich et al. 2015), which could in turn affect insect outbreak severity (Boulanger et al. 2016a) and landscape flammability (Dawe et al. 2022). Forest harvesting could also interact with climate change to further modify forest landscapes (Cyr et al. 2021, Splawinski et al. 2019a, Leblond et al. in 2022). Moreover, these processes are likely to interact across different spatial and temporal scales and are expected to differ regionally (Boucher et al. 2018) according to climate change amplitude and specific features of the biophysical environment such as soil, initial conditions, forest legacy, dispersal limitations, and physical barriers to fire spread.

We assessed the cumulative impacts of these agents of change on RIA's forests (Figure 1, region a) by running spatially explicit forest landscape simulations. Analyses showed that most boreal conifer species would experience strong decreases in aboveground biomass, particularly in the southern parts of the study area (Figure 2iv) (Boulanger et al. 2021, Boulanger and Pascual Puigdevall 2021). Such climate-induced declines in competitive ability by boreal species (Fisichelli et al. 2014, Reich et al. 2015) would favor deciduous species (Figure 2iv), many of which are thermophilous. Projected changes in tree species aboveground biomass reflect an acceleration of species turnover rate within the mixed and temperate forests (Boulanger and Pascual Puigdevall 2021), a trend already observed in Quebec (Brice et al. 2019, 2020). Although northern parts of the study area could become more suitable for deciduous species, dispersal limitations (Sittaro et al. 2017, Vissault et al. 2020), trophic interactions (Boulangeat et al. 2018), as well as increased disturbance rates will likely slow down the northward colonization by these species and prevent a full compensation for boreal species decline. Locally, unfavorable legacy soil conditions of conifer-dominated forests could also impede the northward migration of thermophilous tree species through the boreal forest (Lafleur et al. 2010, Carteron et al. 2020). The increase in fire activity, mostly within the northwestern part of the boreal forest, greatly contributes to boreal's reduction in aboveground biomass by decreasing mean stand age and productivity (Splawinski et al. 2019a, Cyr et al. 2021, Boulanger and Pascual Puigdevall 2021). Concomitantly, progressively shorter fire cycles will promote succession towards pioneer species, such as trembling aspen, that can take advantage of warmer soil conditions following fire and regenerate asexually (Greene et al. 1999).

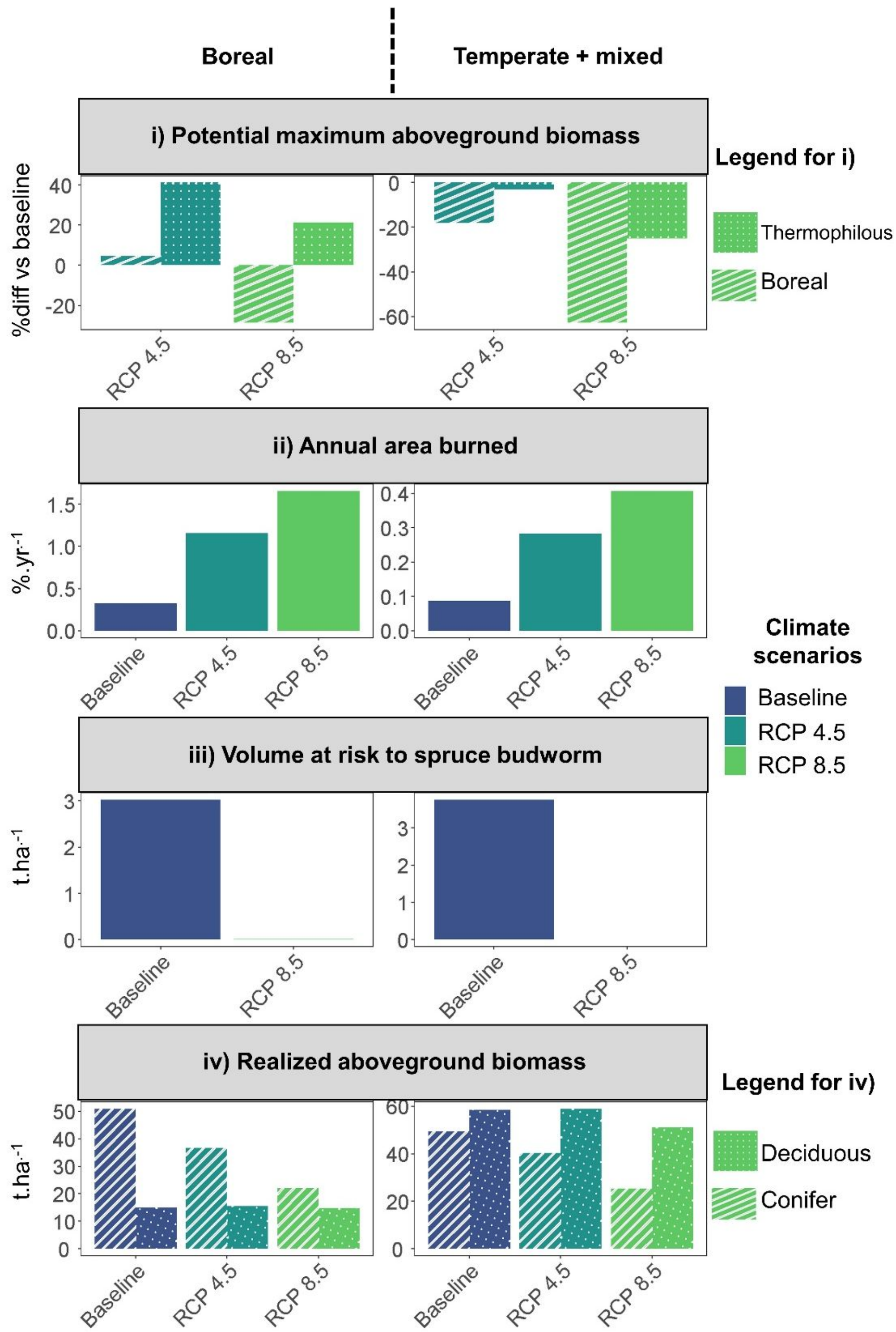

Figure 2. Impacts of climate scenarios (baseline, RCP 4.5 and RCP 8.5) on productivity (potential maximum aboveground biomass; i), on annual area burned (ii) and on volumes at risk to spruce budworm outbreaks (iii). Cumulative impacts on aboveground biomass of deciduous and conifer species are also shown in iv. Results are shown for either the

boreal (left column) or the temperate and mixed forest regions (right column). Note that in iii, volume at risk to SBW is virtually nil under RCP 8.5. i from Boulanger and Pascual Puigdevall (2021); ii from a modified version of Boulanger et al. (2014) models; iii from Boucher et al. (2018); iv from Boulanger and Pascual Puigdevall (2021). Readers can refer to figure 1 for forest regions.

The latter results were obtained through the use of one forest landscape model, namely LANDIS-II (Boulanger and Pascual Puigdevall 2021). However, many additional models have been developed to assess the impact of climate change. Examining a suite of model projections could benefit the RIA as it helps quantify uncertainty but also assess to what extent models are agreeing when projecting future forest conditions. Stakeholders faced with different model projections may hence find it more convenient to turn to multimodel assessments for decision-making and the development of strategies to adapt forest management. Following these results, we conducted a multimodel analysis in which seven models were used to assess the performance of several tree species under climate change in the RIA's study area (Boulanger et al. 2021). Despite a wide diversity of model types, we found a high level of agreement (in 73.1% of the area) in projected species' performance across regions, scenarios, and time periods (Boulanger et al. 2021). These models confirmed that the performance of boreal conifer species will be severely affected by strong climate change, especially in the temperate and mixed forest regions while deciduous thermophilous species, such as sugar maple, will perform better within its current range (Figure 3).

Despite the models' differing assumptions, strong agreement between models, predictors, and structure contributed to the development of a solid foundation on which projections of future impacts of climate change on forest ecosystem services were assessed in the RIA. For instance, these results helped emphasize that cumulative climate-induced changes will make boreal regions more vulnerable to climate change, especially in the central and northwestern part of the commercial forest in the province (Boulanger and Pascual Puigdevall 2021). As such, these results triggered further vulnerability assessments for specific ecosystem services in these areas (see sections 3.1, 3.3 and 3.4 for instance).

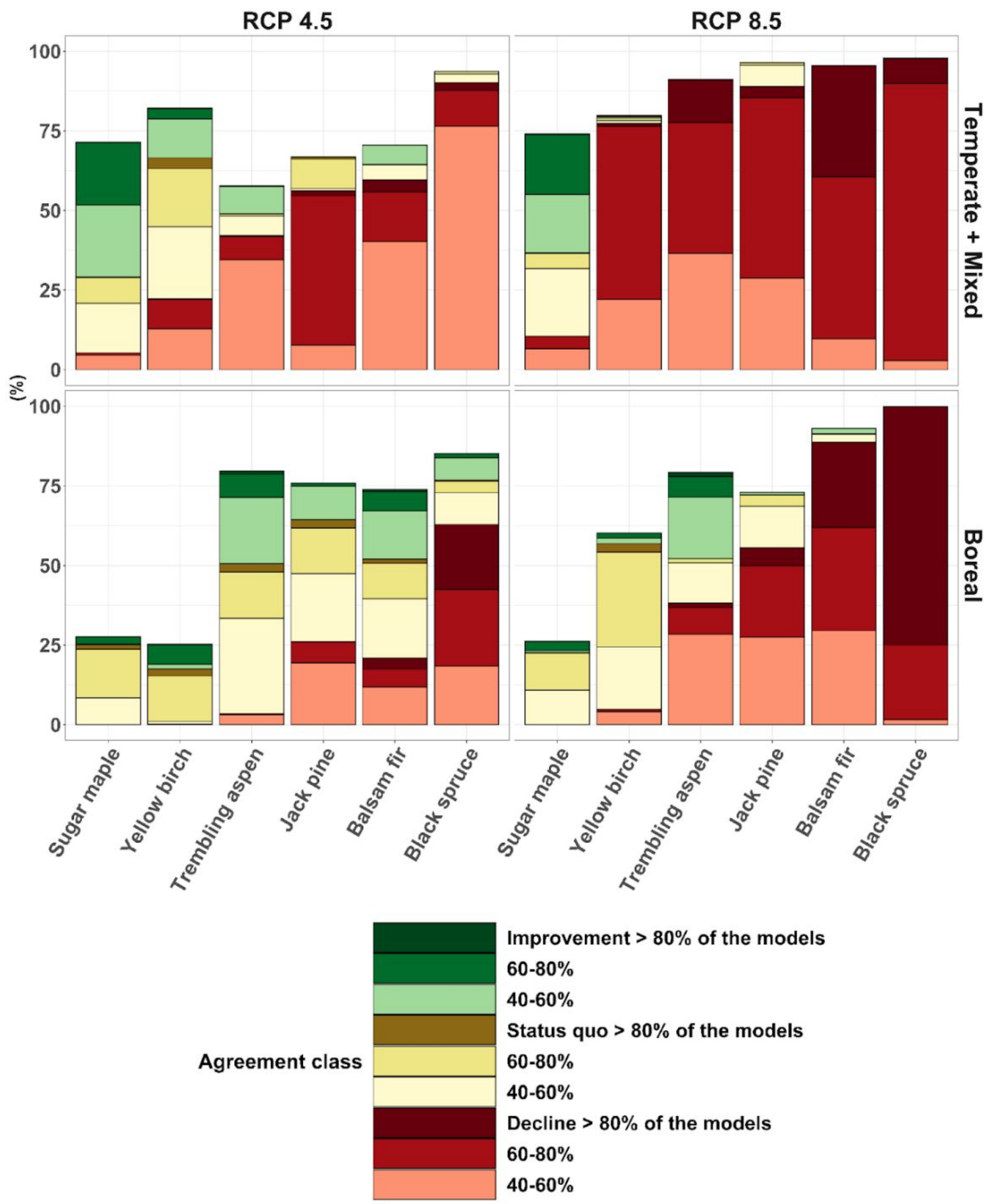

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Figure 3. Model ensemble agreement classes (%) per species, and forest region (Temperate + Mixed and Boreal). Green tones: Improvement; yellow tones: status quo; red tones: decline. Results are compiled under the RCP 4.5 and RCP 8.5 climate scenarios. Modified from Boulanger et al. (2021). Bars only show when at least 40% of the models agreed for a given species and cell. As such, overall agreement was low for sugar maple and yellow birch in the boreal region, especially under RCP 4.5.

3. Cumulative climate-induced changes in forest landscapes may impact ecosystem services

3.1. Impacts on forest harvesting

Previous assessments performed at the country scale (e.g., Gauthier et al. 2015b, Boulanger et al. 2017, Boucher et al. 2018) have suggested that ecosystems may be unable to sustain current harvesting rates within many forest management units (FMU) as a result of climate-induced increases in fire activity. Further investigations were conducted in the northwestern part of the commercial forest in Quebec to better quantify climate-induced impacts on harvested volumes. In this area, black spruce and jack pine dominate the landscape (Payette 1992). These species are well-adapted to frequent fires, typically following a self-replacement dynamic over time (Viereck and Johnson 1990). However, their resilience, i.e., their ability to recover pre-disturbance forest attributes after forest disturbance, is limited by the frequency and severity of fire events (Pinno et al. 2013, Splawinski et al. 2019a,c, Baltzer et al. 2021), which are projected to increase over the next century (Flannigan et al. 2005, Boulanger et al. 2014). Analyses conducted within the northwest (Figure 1, region b) and central RIA study area (Figure 1, region c) revealed that regions that are already characterized by a relatively short fire interval and low productivity will be increasingly vulnerable to regeneration failure with changes in burn rate (Splawinski et al. 2019a,c, Cyr et al. 2021, Forestier en Chef 2021a), with regeneration failures that could cover more than 30% of the territory by 2100 under RCP 8.5 (Figures 4i and 4ii). Such changes will promote an important switch from boreal forest landscapes to unproductive open woodlands (Splawinski et al. 2019a, Cyr et al. 2021), hindering the recruitment of trees and maintaining low stand density over time (Splawinski et al. 2018) that could in turn alter future timber harvesting. In this context, we assessed the joint impact of climate-induced increases in burn rates as well as harvest on various productivity variables in these two regions.

In the study area located in northwestern Quebec, the results showed a loss of landscape productivity mostly due to post-fire regeneration failure over the course of the 150-year simulation period. Landscape vulnerability to future regeneration failure was defined as the proportion of productive forest that would shift to a non-productive state (<30m^3/ha of merchantable volume at 120 years of age) in the event of a fire that would burn the entire simulated area. With no intervention to mitigate these regeneration failures, future fire regimes were predicted to considerably increase the cumulative loss of productive forest area compared to the current fire regime, with only a negligible additional impact of harvesting and salvage logging. As most harvesting activities occur in mature productive forests, the result was a decline in the average stand potential productivity, ranging from 65.6 to 50.1 m^3/ha under the current fire regime and from 65.6 to 34.9 m^3/ha under the future fire regime (Figure 4iii, Cyr et al. 2021). Similar results were obtained in central Quebec where increased fire activity was also predicted to result in a sharp increase in non-regenerating areas (Forestier en Chef 2021). Under a business-as-usual harvest strategy, short-term climate-induced gains in productivity, notably for deciduous species (D'Orangeville et al. 2018), did not compensate for the fire-induced losses in wood volume. Indeed, maximum sustained yields under RCP 4.5 and RCP 8.5 were, respectively, 33% and 60% below baseline sustained yield harvest rates (Figure 4iv).

Taken together, these climate-induced impacts will considerably reduce forest landscape productivity and, consequently, the ability to maintain current harvesting levels if no further interventions or adaptive actions are undertaken. As a result, timber volume and quality in the boreal forest are expected to negatively influence the wood supply chain (Irland et al. 2001, Williamson et al. 2009, Gauthier et al. 2015b), with potential timber supply shortages becoming more common due to decreasing harvestable volumes (e.g., McKenney et al. 2016, Daniel et al. 2017, Yemshanov et al. 2018, Brecka et al. 2020). A transition towards the harvesting of more broadleaf species or salvaged wood will require technical innovations and the upgrading of existing facilities to efficiently handle greater volumes of lower-quality wood. Climate-induced decreases in quality and quantity of wood supply, particularly from coniferous stands, are likely to influence forest product market prices and consumer preferences, which in turn may impact both the economic welfare of consumers and producers (McCarl et al. 2000, Albrecht et al. 2010, Brecka et al. 2018). Recent sharp increases in sawn timber prices during the COVID-19 pandemic is a reminder that high demand can induce volatility on the markets.

3.2. Impacts on carbon sequestration and storage in forests and wood products

Climate change may affect the overall carbon (C) balance of the forest sector in several ways. Climate change has the potential to alter spatiotemporal patterns in net ecosystem productivity (NEP). More frequent and severe wildfires will likely increase the amount of transient emissions due to combustion of organic matter and therefore influence total net ecosystem exchanges (NEE). Furthermore, climate change will induce changes in forest composition, which will in turn affect industrial supply chains, with a cascade of effects on the life cycle of harvested wood products (HWP) and substitution benefits. Finally – and this goes beyond the carbon cycle *per se* – direct and indirect climate-related drivers will impact forest covers in such ways that they may modify biophysical processes such as surface albedo and evapotranspiration, which impact net radiative forcing.

The current estimates show that Canada's forest sector, ecosystems and harvested wood products combined, have switched from being a net sink of greenhouse gas up to 2001 (except in years of extreme fire activity like 1995 and 1998), to a consistent net source in 2002 and onward (NRCan 2021). Increasing amounts of areas affected by natural disturbances in the last decades (e.g., insect outbreaks, wildfires) have tremendous impacts on the overall carbon balance of the Canadian forest. Concurrently, forest management also contributed to reducing the ability of Canada's forests to act as a carbon sink as net removals from the anthropogenic component of the managed forest lands declined from 200 megatons in 1990 to 130 megatons in 2020 (ECCC 2022). However, there is still a significant level of uncertainty around those estimates (Wulder et al. 2020, Deng et al. 2022). Yet, recent observed trends and prospective studies conducted as part of this RIA suggest that this ecosystem service might be at risk.

Indeed, all carbon-focussed simulation experiments performed as part of this RIA (Landry et al. 2021, Figure 1, region d; Moreau et al. 2022, Figure 1, regions e1 and e2) suggest that radiative forcing itself is likely to substantially reduce the capacity of Quebec's forests to act as carbon sinks (Figure 3v) as the mean NEP is projected to be considerably reduced under increased climate forcing. As a result, cumulative C balance (which is considering C substitution in wood products as well as carbon stocks within the ecosystem) would considerably decrease with increasing anthropogenic climate forcing in both boreal (Figure 1, region e1; Figure 4vi) and in temperate (Figure 1, region b2; Figure 4vii) forests. In fire-prone areas, more specifically in black spruce-dominated forests, the most direct consequence of increasing fire frequency and severity (Boulanger et al. 2014, Gauthier et al. 2015b, Boulanger et al. 2018) are going to be higher C emissions through the combustion of vegetation and soil organic matter. However, the consequences will be further reaching as post-fire regeneration failures will indirectly affect the net biome productivity of the most widespread forest type in Quebec and Canada (Walker et al. 2019), both by lowering mean stand productivity and by eroding the very amount of productive forests due to poor or failed regeneration as shown above (Cyr et al. 2021). Whether or not the net effect of that process on radiative forcing is a negative one is uncertain. Indeed, the transition from closed-canopy black spruce forests to open-crown lichen woodlands, as difficult to revert as it might be, is also associated with an increased surface albedo that triggers negative feedback (Bernier et al. 2011).

3.3. Climate change in forest landscapes will affect biodiversity and wildlife habitat

Projected changes in forest structure and composition could directly affect wildlife habitat, potentially inducing shifts, contractions or expansions of species distribution ranges (Chen et al. 2011, D'Orangeville et al. 2022) and modifying biodiversity patterns (Parmesan 2007). Impacts are likely to strongly differ across taxa: species associated with landscape features that are projected to be vulnerable to climate change might be more at risk, whereas others may thrive and benefit from newly available resources and emerging features. Combined effects of harvesting and climate-induced changes in fire regime are projected to exacerbate the loss of old-growth stands within the boreal forest to proportions outside of their natural range of variability (Bergeron et al. 2017, Tremblay et al. 2018). Understanding climate-induced changes on wildlife habitat is of tremendous importance for conservation planning (Stralberg et al. 2019), especially for species at risk for which critical habitat could be strongly altered (Cadieux et al. 2019). For the purposes of the RIA, we assessed potential vulnerabilities to climate for boreal populations of woodland caribou (*Rangifer tarandus caribou*) and avian biodiversity.

Boreal populations of woodland caribou (hereafter boreal caribou), a cultural keystone species for many Indigenous communities (Herrmann et al. 2014) as well as an umbrella species for old-growth forest specialists (Bichet et al. 2016), is designated as *Threatened* under the Canadian Species at Risk Act since 2002 (Species at Risk Act; S.C. 2002, c.29), and as *Vulnerable* under Quebec's *Loi sur les espèces menacées ou vulnérables* since 2005 (RLRQ c E-12.01 r2). Landscape-level planning of resource extraction activities (e.g., Rudolph et al. 2017), local habitat restoration of disturbed areas (e.g., Lacerte et al. 2021, 2022) and various population management measures (e.g., predator control, Hervieux et al. 2014; maternity penning, Lamb et al. 2022) were identified among the essential tools for the successful recovery of the species (Johnson et al. 2019). In Quebec, the southern limit of boreal caribou's distribution has gradually retreated northward in the last century due to increased anthropogenic pressures, with southern remnant populations currently hovering at the brink of extinction (D'Orangeville et al. 2022; Morineau et al. in prep). Climate change will likely pose an additional threat to the long-term persistence of boreal caribou throughout Canada (e.g., Murray et al. 2015; Barber et al. 2018; Neilson et al. 2022) and Québec (Leblond et al. 2022; St-Laurent et al. 2022).

By combining previously modeled forest landscapes in the commercial forest of Quebec (Boulanger and Pascual Puigdevall 2021) with a habitat suitability model for boreal caribou (Leblond et al. 2014), we projected boreal caribou habitat suitability across the RIA study area (Figure 1, region a) for the 2020-2100 period under various climate and harvesting scenarios. We found that climate change was predicted to decrease boreal caribou habitat suitability, especially under RCP 8.5 (Figure 4viii), mostly as a result of increased wildfires at the expense of old conifer stands preferred by caribou (Leblond et al. 2022). As a result, climate change led to a significant decrease in habitat suitability, but mostly after 2070. Such changes in habitat are likely to impact trophic interactions notably by increasing moose populations, which could in turn support greater predator numbers, thereby increasing predation risk for caribou (Seip 1991; Wittmer et al. 2007; Frenette et al. 2020). A similar conclusion was found by Labadie (2022) in their simulations of forest dynamics and movements of interacting large mammal species (Figure 1, region f). In this study, the increase in caribou mortalities was exacerbated by the cumulative effects of land-use over the short term and climate change impacts over the long-term, with higher impact from land-use (Labadie 2022; Figure 4ix). Intensification of fire activity with increased radiative forcing could endanger currently stable caribou populations, notably those located in the central and northwestern parts of the study area. Other areas, notably in the northeast as well as at the extreme northwest, are predicted to remain highly suitable even under increased radiative forcing, and could serve as potential climate refugia (Stralberg et al. 2015) for the species. That being said, climate-induced northward shift of the closed boreal forest is highly uncertain in the next decades because of dispersal limitation of the tree species, natural disturbances and physical landscape barriers (Price et al. 2013, Pau 2023). The northern margin of high-quality boreal caribou habitat is thus unlikely to progress poleward. Climate change should exacerbate, however, the ongoing northward contraction of caribou range due to anthropogenic disturbances (Morineau 2022).

Although there is a large body of literature in North America about the effects of forest management on wildlife habitat and biodiversity (Drapeau et al. 2000, Venier and Pearce 2004; Schieck and Song 2006), current knowledge about the impact of climate change on avian community dynamics is limited (but see Langham et al. 2015, Stralberg et al. 2015, Tremblay et al. 2018, Cadieux et al. 2020, Micheletti et al. 2021). Birds are a diverse taxonomic group occupying a large variety of niches in forest landscapes and, as such, could serve as a useful proxy to assess the vulnerability of biodiversity to climate change and forest management over the RIA's study area. Therefore, we also projected changes in avian species abundance for the 2020-2100 period under various climate and management scenarios in two contrasting forest landscapes located within the boreal (Montmorency Forest, Figure 1, region e1) and temperate (Hereford Forest, Figure 1, region b2) forests.

Under RCP 8.5, generalist avian species and those associated with young hardwood stands were projected to increase in abundance, particularly within the temperate study area (increases of 8% and 24%, respectively, Figure 4xi). Conversely, bird species associated with closed and mature softwood stands were projected to decrease in abundance by ~24%. Within the boreal forest study area, the abundance of generalist avian species and those associated with closed deciduous stands were projected to increase by ~12% and 13%, respectively, under RCP 8.5 (Figure 4x). One species (Black-backed Woodpecker) was projected to decline by 39%, while other avian species groups remained relatively stable (Labadie et al. in prep.). Avian species were projected to be most impacted by climate change effects within the temperate forest study area (Labadie et al. in prep.). Our simulations highlighted that eight avian species were likely to be vulnerable to the effects of climate change in the temperate forest study area, with declines exceeding 25%; the steepest declines were observed for the Northern Parula (*Setophaga americana* [L.]; 46%), Blue-headed Vireo (*Vireo solitarius* [Wilson]; 40%), and Golden-crowned Kinglet (*Regulus satrapa* Licht.; 35%) (Labadie et al. , in prep). This study improves our understanding of how avian communities in the boreal and hemiboreal forests in eastern boreal region of North America are likely to be differently vulnerable by changes in forest composition resulting from climate change.

3.4. Climate- and forestry-induced changes could severely affect First Nations forest values

Indigenous livelihoods, cultures, and identities are strongly tied to the land (Saint-Arnaud et al. 2009, Bélisle et al. 2021). Climate change, forestry practices, and other industrial disturbances have been driving major changes in boreal landscapes (Gauthier et al.

2015a, Belisle et al. in press) with the potential for significant consequences for the well-being of Indigenous peoples (Parlee et al. 2012, Fuentes et al. 2020). For instance, Erni et al. (2021) showed that Indigenous communities are and would be most exposed in the future to climate-induced increases in wildfires. Changes in forest landscapes and wildlife habitats, notably those identified in the previous section, could strongly threaten cultural and subsistence practices that are important for Indigenous people, including hunting, trapping and knowledge transmission (Bélisle et al. 2021). Examples include climate-induced changes in specific cover types of significant economic, cultural and spiritual values for Indigenous communities (e.g., pine stands, Uprety et al. 2013, 2017) as well as damages to caribou habitat (see section 3.3), which is a cultural keystone species for several First Nations (Herrmann et al. 2014). In this context, developing partnerships between research institutions and Indigenous communities allows the assessment of impacts of environmental changes on forests from a perspective that is consistent with both Indigenous knowledge and western science (Barber and Jackson 2015, Bélisle et al. 2022).

With the collaboration of Université du Québec en Abitibi-Témiscamingue, University of Saskatchewan, Abitibiwinni First Nation Council, Ouje-Bougoumou Cree Nation, and Natural Resources Canada, a study was conducted as part of this RIA to assess how climate change and timber harvesting could affect Indigenous landscape values (e.g., moose abundance, fish quality, land access) within the Oujé-Bougoumou and Pikogan hunting grounds (Bélisle 2022, Figure 1, region g). As shown above, the area where these First Nations are located will be exposed to rapid and marked changes in forest landscape structure and composition, with mature and coniferous stands progressively transitioning to young stands with increasing proportions of hardwoods, mostly as a result of increased fire activity. By combining insights from local land-use experts as well as forest landscape simulations, we found that climate change will have a strong influence on values associated with mature coniferous forests, such as some species important to Indigenous trappers, e.g. American marten (*Martes americana*) (Figures 4xii and 4xiii). A loss in marten abundance affects many aspects of Indigenous livelihood. A loss in marten abundance affects many aspects of Indigenous livelihood since marten trapping is important for both Indigenous cultures and economies. Moreover, trapping requires traditional skills and knowledge that is passed down from one generation to the next and is a key cultural practice (Ohmagari and Berkes 1997, Radu et al. 2014).

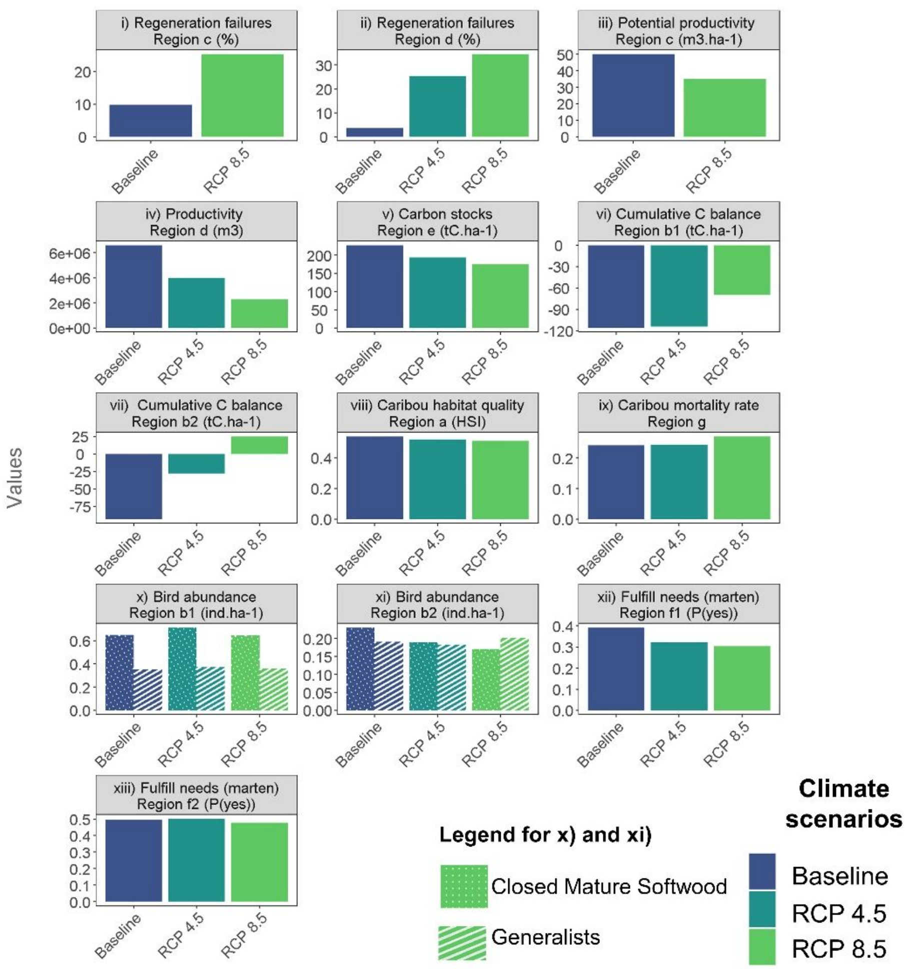

Figure 4. Impacts of climate scenarios (baseline, RCP 4.5 and RCP 8.5) on various ecosystem services as assessed in the RIA. All results considered the cumulative effects of climate change and business-as-usual forest management strategy. Analyses in i and iii were not conducted under RCP 4.5. Results in vi and vii are plotted relative to a reference scenario, i.e., under baseline climate conditions without forest management ("conservation"). For x and xi, bird abundance is expressed for species either associated with closed mature softwood forests and generalists. HSI: Habitat suitability index, unitless; P(yes): Probability to fulfill family's needs (with no need to adapt). Readers can refer to figure 1 for study locations. i) and iii) from Cyr et al. (2021); ii) and iv) from Forestier en Chef (2021a); v) from Landry et al. (2021); vi) and vii) from Moreau et al. (2021); viii) from Leblond et al. (2022); ix) from Labadie (2022); x) and xi) from Labadie et al. in prep.; xii) and xiii) from Belisle (2022).

4. The necessity of adapting forest management

Collectively, the results presented herein suggest that virtually every sphere of forest management and planning we studied will likely face several challenges in the context of climate change. Moreover, forest operations, the development and implementation of forest management strategies, the management of natural disturbances, and biodiversity conservation are likely to all be impacted by climate change. Forest managers must therefore take this new reality into account and prepare today's forests for tomorrow's climate (Gustafson et al. 2020) by adapting their practices and their visions of future forests. Forest management practices have been developed based on the premise of a stable climate. Climate change thus challenges the very essence of many forestry concepts and practices (Périé and De Blois, 2016). Achieving sustainable forest management objectives will be challenging, as forest managers will have to deal with increasing uncertainty (Ogden and Innes 2009). In this context, it seems clear that *status quo* is no longer an option (Drever et al. 2021).

The ecosystem-based forest management (EBFM) strategy is used to manage forests on public lands in Quebec, which represents nearly 90% of commercial forest landscapes (RLRQ, chapter A-18.1). This strategy aims at maintaining a disturbance regime close to the historical range of natural variability, and was initially proposed to reduce differences with presettlement forests (Landres et al. 1999) and help promote healthy ecosystems and conserve biodiversity while maintaining sustainable timber supply. Considering these characteristics, EBFM was therefore deemed by many to be suitable to mitigate climate change impacts on forests by enhancing their resilience (*Comité d'experts sur l'aménagement écosystémique des forêts et les changements climatiques* 2017). Indeed, initial analyses conducted within the RIA indicated that EBFM would be less likely than intensive strategies to increase the gap between current forest composition and the one prevailing during the pre-industrial era (Boulanger et al. 2019).

Yet, these current strategies are far from being a panacea in the context of climate change (Dhital et al. 2015, Landry et al. 2021), as they are still expected to result, for example, in carbon loss in the boreal forest, a hastening of climate-induced forest transition, a decrease in biodiversity and wildlife habitat, and a long-term reduction in harvested volumes (Figure 4). Adaptation beyond the current implementation of EBFM is therefore key to mitigating the impacts of climate change on several forest ecosystem services (Bergeron et al. 2010, Gauthier et al. 2014). Several options for the forest sector can be envisioned, from favoring persistence (resistance, resilience) to managing change (transition; Gauthier et al. 2014, Nagel et al. 2017, Peterson St-Laurent et al. 2021). Some of the adaptive solutions may directly come from current management practices and could be used as levers of action. Other solutions may require new developments in order to meet specific objectives.

In the following sections, we summarize analyses that were conducted as part of Quebec's RIA to assess the effects of various adaptation solutions to some of the vulnerabilities that were identified. These strategies were various between study areas but could be summarized according to a gradient of management intensity as follow: i) "Conservation" (e.g., no harvest), ii) "Reduction" (e.g., create conservation areas, lengthening harvest rotation, reduce harvesting rates, increase partial harvesting); iii) "business-as-usual" (e.g., current forest management strategies), iv) "Intensification" (e.g., increased plantation efforts, higher harvesting rates) , and v) "Mixed" (e.g., strategies that mix both "reduction" and "intensification" strategies). These solutions do not represent a comprehensive assessment of all potential strategies that could be tested and implemented to adapt forest management to specific regional vulnerabilities, but are rather a representative subset of strategies that could be implemented given the vulnerabilities identified above.

4.1 Reduce the negative impacts of regeneration failures in the boreal forest

As shown earlier, climate-induced increases in fire activity, notably in the central and northwestern parts of Quebec's commercial forest, could trigger extensive regeneration failures and productivity loss (Figures 4i and 4iii), requiring prompt and extensive adaptive measures to maintain forest productivity (Cyr et al. 2021, Forestier en Chef 2021). Based on these impacts, we assessed the efficiency of several strategies, from total conservation, business-as-usual harvest as well as two main mitigation strategies against regeneration failures (variable retention and planting), to mitigate climate-induced loss in forest productivity. Variable retention harvesting is a proactive treatment and is used as a means to improve post-fire regeneration success whereas planting is a reactive strategy, in which reforestation is used to restore productivity in burned areas affected by regeneration failure. Several reforestation scenarios were considered but for the sake of the analysis here, we focus on i) a scenario involving variable retention and the plantation of jack pine using the existing road network ("Mixed") and ii) another scenario where business-as-usual harvesting rates are used and in which roads are extensively built to restore post-disturbance stands with jack pine plantation ("Intensification"). Planting jack pine is assessed in order to take advantage of its greater resilience to fire (Baltzer et al. 2021), largely based on its earlier age at reproductive maturity relative to that of black spruce (Viglas et al. 2013, Briand et al. 2015). We quantified their respective capacity to maintain landscape productivity and post-fire resilience, as well as associated financial returns under current and projected (RCP 8.5) fire regimes. While post-fire reforestation with jack pine was shown to be the most effective strategy in maintaining potential productivity (Figure 5i, "Mixed"), associated costs quickly became prohibitive regardless of planted species when applied over extensive areas, particularly under future fire regimes (Figure 5ii, "Intensification"). The proactive strategy employing variable retention harvesting, combined with replanting of fire-adapted jack pine in easily accessible areas (in close proximity to the existing road network), appeared as a promising strategy to maintain productivity at lower costs (Figure 5i and 5ii, "Mixed"). These results also highlighted the important role that forestry road networks play in our ability to effectively respond to regeneration failure events, since plantation establishment and the application of other silvicultural strategies are limited by accessibility and operational constraints.

This benefit will need to be weighed against the negative impacts of road networks on other valued components of the ecosystem, most notably caribou distribution and survival (e.g., Leblond et al. 2013). Indeed, roads are known to cause habitat fragmentation and favor the movements of wolves (Dickie et al. 2017), increase the encounter rates between predators and prey (Whittington et al. 2011), and intensify predation pressure on caribou (Mumma et al. 2017). Consequently, roads can jeopardize the sustainability of caribou populations via functional (or indirect) habitat loss (Polfus et al. 2011). In this context, forest zoning aiming at intensifying silviculture together while concurrently increasing habitat protection and restoration conservation in other areas, might constitute a valuable compromise (Royer-Tardif et al. 2021).

Promoting the establishment of broadleaf species could also help mitigate fire-induced losses in productive forests. An increased broadleaf component in the landscape would decrease its flammability, partially mitigating climate-induced increases in severe fire-weather conditions through negative fire-vegetation feedbacks (Krawchuk and Cumming 2011, Girardin et al. 2013, Boulanger et al. 2018, Chaste et al. 2019). Simulations involving different levels of post-disturbance establishment of either broadleaf or conifer species were conducted in central Québec (Figure 1, region c) (Forestier en Chef 2021a). These simulations considered both climate-induced changes in productivity and fire activity. Under RCP 8.5, doubling the post-disturbance area planted with conifer and broadleaf species as well as the creation of intensive management zones on 25% of the managed landbase (“Intensification”) was shown to almost double harvested volumes as compared to a business-as-usual approach under the same climate forcing scenario (Figure 5iii). Despite the implementation of this adaptation measure, a 31% decrease in harvested volumes relative to current levels (Figure 5iii) would still be required to stabilize harvest levels and avoid recurring timber shortages (Forestier en chef 2021a).

From both of these RIA studies (Cyr et al. 2021, Forestier en chef 2021a), it appears that post-disturbance plantation efforts in projected fire-prone landscapes may not entirely compensate for the projected climate-induced erosion of forest productivity and may prove to be prohibitively costly. In this context, integrating fire *a priori* and hence reducing annual allowable cut accordingly in strategic forest management planning may be beneficial. Several studies have already shown that reducing harvest levels *a priori* or considering a buffer stock would help stabilize long-term timber supply and avoid shortages in fire-prone regions (Boychuk and Martell 1996, Raulier et al. 2014, Leduc et al. 2015, Forestier en chef 2022), including under climate change (Daniel et al. 2017, Forestier en chef 2021a). Currently, the *Bureau du Forestier en Chef* (BFEC) applies a 20% buffer on annual allowable cuts for specific forest management units located in northwestern Québec as a result of high historical fire activity within these areas (Forestier en Chef 2021b). Our results suggest that the application of allowable cut buffers, in conjunction with measures enhancing post-disturbance productivity, may be required elsewhere in the boreal to help stabilize timber supply over time.

4.2 Maintain the potential for carbon sequestration and storage in forests and products under climate change

People and organizations who advocate in favor of conservation will often stress the importance of accumulating the largest carbon stocks possible at the ecosystem level, while on the opposite side of the spectrum, those biased towards the industry systematically plead in favor of increasing average net growth through more intensive silviculture so that more carbon can be transferred to long-lived wood products. Our RIA provides evidence that there is no simple answer to that debate and that the most beneficial strategy, from a climate change mitigation perspective, may vary from one forest landscape to another (Figure 5iv and 5v). For instance, conservation strategies that maintain or increase the abundance of mature and old-growth forests might be more at risk of carbon inversion in landscapes that are more prone to natural disturbances (Sharma et al. 2013). Moreover, there are still uncertainties regarding the ability of these stands to act as carbon sinks in the long term (Gao et al. 2018, Smyth et al. 2020, Gundersen et al. 2021) as conservation after age 70 does not result in significant carbon uptake or emission in Quebec's boreal forests (Harel et al. 2021). That being said, we advocate that these uncertainties should not overshadow the role of old-growth forests to act as carbon sinks (Harel et al. 2021).

On the other hand, while increasing harvesting may reduce the risk of ecosystem-level carbon pools being release in the atmosphere by reducing exposure time to the risk of natural disturbances, it also tends to shift forested landscapes to a younger state, which may in turn reduce its resilience and adaptive capacity in face of more frequent fires (Splawinski et al. 2019b; Cyr et al. 2021). However, silviculture can be used to increase ecosystem carbon sinks in some landscapes (Figure 5v), but emissions associated with the procurement and manufacturing of wood products and their decay during their lifetime must also be taken into a consideration as they heavily influence the net carbon balance (Moreau et al. 2022) and must be taken into consideration. Increasing the material use of wood as long-lived, durable products and encouraging their recycling and cascading at their end-of-life, both for material and energy uses can reduce annual product emissions while increasing the substitution effect, with a strong and direct impact on the forestry sector's carbon budget (Smyth et al. 2014, Chen et al. 2018, Dugan et al. 2018). Then again, some challenges are to be expected. For instance, our RIA suggests that climate change will be unfavorable to some species that are currently highly valued by the timber industry, such as *Picea spp*. (Figure 3, see also Brecka et al. 2018), and that it will be beneficial to other ones that are currently mostly dedicated to pulp and paper (e.g., deciduous species, Figure 3), i.e. products with a short lifespan and virtually no substitution effect on markets. It will be crucial, therefore, not only to focus on the supply-side actions (i.e., increasing carbon pools at the ecosystem level) but also on the demand-side (i.e., harvested wood products) to make sure that climate change mitigation potential is maximized.

Even if they achieve to maximize pools of non-atmospheric carbon, either within the ecosystem or in long-lived wood products, both types of strategies are usually associated with very different sets of co-benefits, which may also not be distributed in time the same way. Consequently, blanket statements about whether conservation or intensification is best should be avoided. There is still a lot of uncertainty surrounding our results and about the best course of action from a climate change mitigation perspective. Multiple factors such as initial conditions of forest landscape, current and future stand productivity, disturbance rates, adaptability of industrial supply chains, only to name a few, are at play. Our capacity to represent those factors within an integrative modeling framework is also still very limited, especially considering how much they vary in space and time and how poorly those variations are documented.

4.3 Using adaptation strategies to help biodiversity conservation under climate change

We previously illustrated that current harvest strategies had the potential to strongly impact avian diversity and caribou habitats as proxies of representative boreal wildlife diversity. Natural resource managers and conservation authorities are thus faced with the difficult task of defining and planning long-term habitat conservation strategies under a changing climate, notably for species at risk. Developing adaptive measures represents a valuable yet challenging goal in this context. Indeed, forest management and habitat recovery plans have great potential to influence how future forest landscapes and biodiversity will respond to climate change (Ravenscroft et al. 2010, Steenberg et al. 2013) and limit climate change impacts on recovery efforts for threatened species (Cadieux et al. 2019, St-Laurent et al. 2022).

As suggested from previous analyses, one of the biggest challenges to biodiversity conservation under a changing climate in eastern Canada will be to develop strategies to cope with increasing disturbance rates accruing from both harvesting and projected climate-induced increases in natural disturbances (St-Laurent et al. 2022). Of particular importance, increased disturbance rates could hasten the conversion of forest cover types and the strong decline in old-growth age classes (Bergeron et al. 2017), with detrimental impacts on caribou and other specialist species associated with these forest types

(Tremblay et al. 2018, Barber et al. 2018, Cadieux et al. 2020, Nenzen et al. 2020, Micheletti et al. 2021). Our analyses showed that ceasing harvest (Figure 5vi, "Conservation") could help mitigate alterations in boreal caribou habitat for the entire RIA study area (Leblond et al. 2022). Halting harvest activities in areas where habitat suitability is currently high could help maintain high quality habitat even under the most intense climate change scenarios as opposed to business-as-usual harvest (Figure 5vi, "BaU"). Reducing harvest levels was also shown to mitigate climate-induced decreases in the probability of occurrence for caribou in central Quebec (St-Laurent et al. 2022). Likewise, Labadie (2022) found that a management scenario aiming at creating exclusive zones for conservation while other zones would experience alternative management strategies to increase the proportion of old-growth stands would help decrease caribou predation and mortality regardless of radiative forcing.

These studies demonstrated that forest harvesting is a key driving force in a caribou-moose-wolf assemblage. Substantially reducing harvest rates or protecting specific areas mitigated the loss of old conifer and mixed forests favored by caribou, irrespective of climate-induced increases in fire activity. Conversely, high harvest levels coupled with increased fire activity would increase young, nutrient-rich stands for other ungulates (Potvin et al. 2005), exacerbating the vegetation-driven apparent competition dynamic between moose and caribou (Seip 1991; Frenette et al. 2020, Wittmer et al. 2007, Labadie 2022).

Lower harvesting levels (obtained either by increasing conservation area, reducing harvest levels, increasing partial harvesting, or implementing longer harvest rotation periods) would not only benefit caribou, but also avian abundance. Indeed, stopping or lowering harvest levels would partially mitigate the climate-induced loss in closed and mature mixed and coniferous forests, which would benefit overall avian abundance in both boreal and temperate forest regions (Figures 5vii and 5viii, "Conservation" and "Reduction"). Some species (e.g., Magnolia Warbler [*Setophaga magnolia*], Northern Parula [*Setophaga americana*], or Golden-crowned Kinglet [*Regulus satrapa*]), however, would still be highly vulnerable to climate change as they showed strong declines under all management scenarios simulated (Labadie et al., in prep.). Similarly, in the boreal forest study area, stopping or lowering harvest levels would benefit species associated with mature mixedwood and coniferous forest stands (e.g., the Brown Creeper *Certhia americana* and the Black-backed Woodpecker).

Hence, results obtained within Quebec's RIA illustrate that modulating harvest levels is effective when developing biodiversity conservation strategies under climate change. This is especially important as harvest was shown to be the most important agent of change explaining future caribou habitat and boreal bird abundance over the short- to medium-term, regardless of projected anthropogenic radiative forcing scenarios (St-Laurent et al. 2022, Leblond et al. 2022, Labadie et al., in prep.). Lowering harvest levels also constitutes one of the few management levers on which we have control in this context (in stark contrast with global GHG emissions). Resulting increased habitat protection in this context would benefit a plethora of species, notably those associated with old-growth coniferous forests in the boreal forest (Bichet et al. 2016, Drever et al. 2019, Labadie 2022).

4.4 Adapting forest management to sustain Indigenous values

The collaborative research work with the Abitibiwinni and Ouje-Bougoumou First Nations (Figure 1f) highlighted the benefits that could be achieved from lowering harvest rates. Major changes in forest structure and composition are expected in the coming decades and developing adaptation and mitigation strategies could limit the effects of climate change on Indigenous livelihoods and cultures. Indeed, we showed that increasing harvest levels could accelerate the climate-induced loss in good trapping habitats for marten (Figures 5ix and 5x, "Intensification") in the northwestern part of our study area whereas opposite effects would be reached under strict conservation (Figures 5ix and 5x, "Conservation"). The capacity of Indigenous communities to adapt to changing environmental conditions has been demonstrated numerous times in the past. However, there are limits on adaptive capacity, and the factors that maintain it still need to be investigated and documented. Strategies could include the valorisation of traditional knowledge associated with the forest types that will be more present in the future. Strategies to limit fire hazard on cultural keystone locations, species, and infrastructure, should also be considered. Moreover, diversifying landscape values that guide forest management to take into account Indigenous values is advised. More generally, a step towards collaboration with Indigenous peoples in land management to face the challenges of environmental change needs to happen. Collaborations between First Nation and provincial/territorial departments aiming at adapting forest management to community's values already exist in Canada (e.g., *Conseil Cris-Québec sur la foresterie* in Quebec [http://www.ccqf-cqfb.ca/fr/accueil/], Gwich'in Forest management plan in the Northwest Territories [https://www.gwichinplanning.nt.ca/landUsePlan.html]), and can be cited as successful examples that need to be repeated.

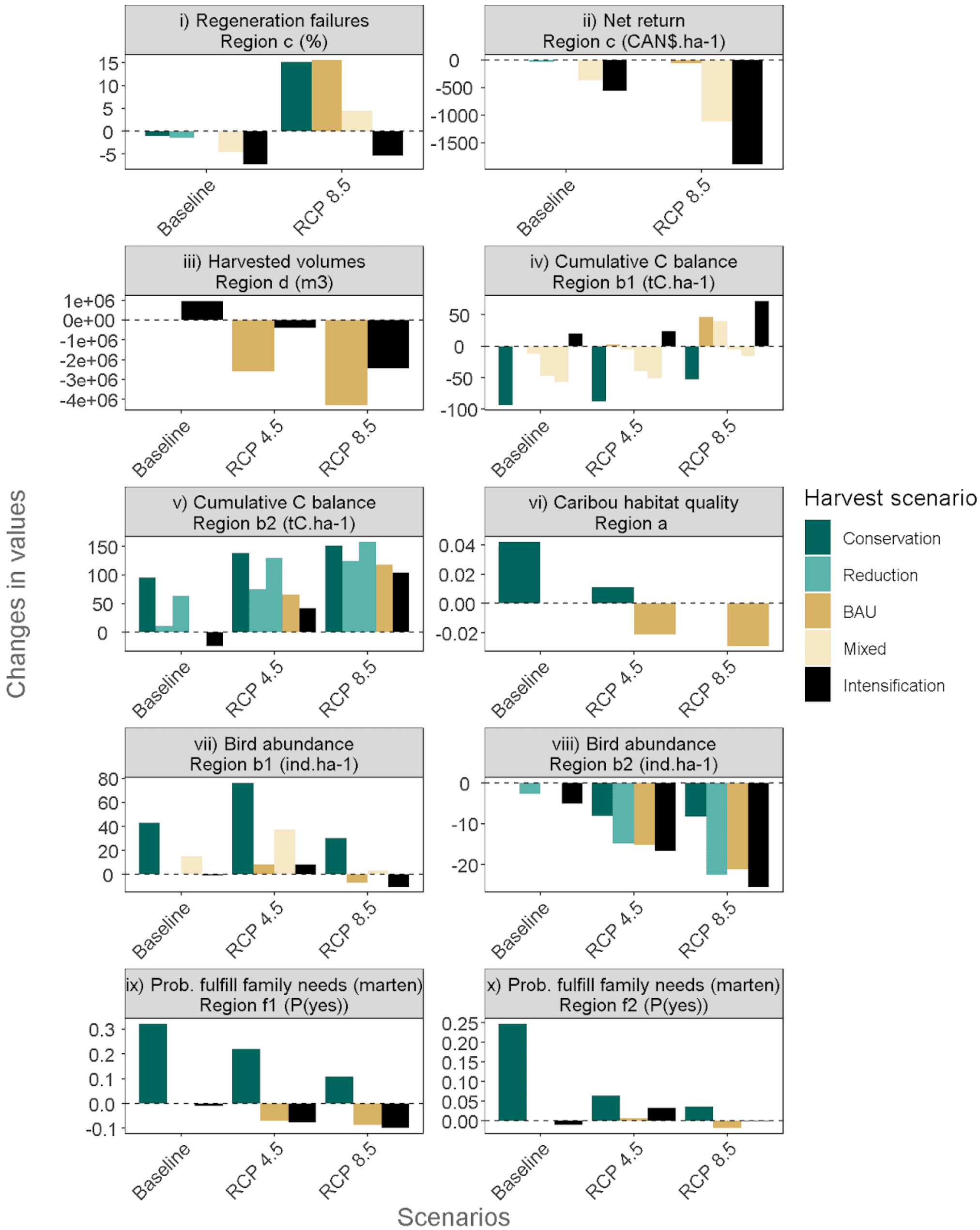

Figure 5. Impacts of forest management adaptation strategies on various ecosystem services as assessed in the RIA under baseline, RCP 4.5 and RCP 8.5 climates. The simulated forest management scenarios were classified as "Conservation" (e.g., stopping harvest), "Reduction" (e.g., create conservation areas, lengthening harvest rotation, reduce harvesting rates, increase partial harvesting); "business-as-usual" (e.g., current forest management strategies), "Intensification" (e.g., increased plantation efforts, higher harvesting rates), and "Mixed" (e.g., strategies that mix both "Reduction" and "Intensification" strategies). Not all studies included all scenarios. Results are plotted relative to a reference scenario, i.e., under baseline climate conditions and business-as-

usual forest management. P(yes): Probability to fulfill a family's needs (with no need to adapt). Readers can refer to figure 1 for study locations. i) and ii) from Cyr et al. (2021); iii) from FEC (2021); iv) and v) from Moreau et al. (2021); vi) from Leblond et al. (2022); vii) and viii) from Labadie et al., in prep.; ix) and x) from Belisle (2022).

5. Concluding remarks

Regional solutions to climate change impacts on forests require partnership and collaboration between experts working in various fields. The RIA process highlighted the necessity of integrating the expertise and perspectives of diverse knowledge-holders, as climate change impacts were revealed to also be diverse. Indeed, although we did not intend to develop standard practices for regional assessments, our framework could be well adapted across northern forest ecosystems. Regional integrated assessments such as this one are useful to better support decision-making at the regional level. We learned that a bottom-up approach, where problems are identified by local and regional partners including Indigenous peoples, was key to identify vulnerabilities and test adaptation measures. We believe that such collaborations and commitments should be set up early in the process and maintained over time. In our example, early and repeated consultations with regional partners and stakeholders played an integral role in the success of the RIA. Bilateral discussions greatly helped to work in a complementary fashion, for instance completing projects that were already undertaken by the province to identify climate vulnerability or test for adaptive strategies. Decade-long collaborations between research scientists and analysts belonging to different organizations was an additional asset and this project likely contributed to tightening these connections. Communicating RIA results to stakeholders was of first importance. However, sanitary restrictions caused by the COVID-19 pandemic prevented in-person workshops from being held. Instead, the work was presented in the form of webinars (in French) that took place between January and March 2021 (available online at https://www.youtube.com/playlist?list=PL9Sro7G6My3oM1QlW37fokxQLtstAW9hY). Between 80 and 150 people, from a diverse audience composed of local and regional stakeholders, academia, Indigenous organizations, and provincial and federal agencies, attended each of the seven webinars.

Our assessment helped confirm that Quebec's forests and forest sector will be highly impacted by climate change in the following decades. Strong agreement between models as well as the breadth of predicted impacts make a strong case for swift and meaningful action. Climate-induced impacts are already perceptible, and even stronger alterations could occur within the next few decades, even under moderate climate forcing. In this context, there is an urgent need to critically review management objectives and strategies to mitigate risk.

There is still uncertainty in how today's forest management strategies and proposed adaptation approaches in such an ecosystem with long-lived organisms will be able to cope with rapid climate change. As a consequence, our analyses suggest that we should aim to strengthen our capacity to detect changes, and take advantage of current monitoring systems, notably regarding tree regeneration, growth, mortality, and pests. From this perspective, Quebec is rather well positioned considering its extensive permanent and temporary sample plot network as well as the Canadian National Forest Inventory monitoring system (https://nfi.nfis.org/en/). Regional concertation tables (such as the *Tables locales de gestion intégrée des ressources et du territoire*) could be involved in the periodic review of successful and ineffective climate adaptation strategies based on its effectiveness in a regional context. Concurrently, continuous scientific, technical and financial support of large-scale climate adaptation initiatives (such as the Adaptive silviculture for Climate Change network in North America, Nagel et al. 2017), Research and Teaching Forests or Model Forests (e.g., https://www.modelforest.net/index_lang_en.html) will also be paramount to develop and maintain our ability to predict and prevent bad surprises. The development of such adaptive strategies will be integral in enhancing the resilience of forest ecosystems and the forestry sector to climate change.

We showed that business-as-usual strategies are likely to result in a deterioration of several ecosystems goods and services. Whether conservation, reduction, intensification or mixed strategies should be applied highly depends on the vulnerability identified, as well as the regional context. In this respect, it is difficult to determine a “one-size-fits-all” strategy. Wall-to-wall strategies are equally likely to fail as seen, for instance, from different regional impacts of harvest levels on carbon sequestration. Regional and infra-regional analyses and solutions are therefore imperative to fulfill stakeholder objectives.

Our analyses suggest that reducing harvesting could benefit several ecosystem services by mitigating climate-induced changes on caribou habitat, avian biodiversity, carbon storage (in the boreal forest), and Indigenous subsistence and cultural practices. In addition, we illustrated that, under the range of adaptive strategies tested, reducing harvest levels would help to stabilize timber harvest rates and reduce post-fire regeneration failures within current or future fire-prone regions. As demonstrated from several of our analyses, maintaining current harvest rates while applying status quo management strategies could lead to a supply of timber that is unstable and, by extension, have important economic impacts. Thus, our results suggest that a strategy aiming at reducing harvest levels may benefit both the health of forest ecosystems as well as the sustainability of the forest sector and forest dependent communities.

Although "Reduction" strategies did perform well under climate change conditions, we also showed that "Mixed" and "Intensification" strategies could also benefit certain values. Furthermore, it is important to note that we did not model all possible adaptation measures in response to the vulnerabilities identified. Other strategies seeking to balance timber supply and other forest values under climate change should be explored, such as the triad concept (Royer-Tardif et al. 2021). Strategies aiming to improve functional redundancy in complex ecosystems also show promise (Messier et al. 2019, Mina et al. 2022). Transition strategies based on assisted migration of climate-adapted species or populations have also demonstrated the potential to provide benefits under climate change (e.g., Pedlar et al. 2012). We advocate that testing a diversity of approaches will be paramount to better document trade-offs under uncertain future conditions.

Furthermore, documenting the overall risks to important aspects of forest ecosystems and the forestry sector will be necessary in this endeavor (Gauthier et al. 2014). For example, although developing the road network helps lower climate-induced regeneration failures by providing easier access for post-disturbance plantation, its negative impacts on other valued components of the ecosystem, most notably caribou (e.g., Leblond et al. 2013, 2014, 2022), have to be considered. The development of solutions that are sustainable, socially acceptable, and respectful of regulations and agreements in place will require compromise.

Although our assessment aimed at identifying major vulnerabilities to the forests of Quebec as well as to identify proper adaptation solutions, some aspects, though potentially important, could have not been covered by the work synthesized in this assessment. For instance, we did not explicitly explore the impact of climate change on soil properties and functions, including soil biodiversity. Climate change will alter plant-soil feedbacks, influencing plant performance and diversity that will ultimately drive ecosystem processes (Pugnaire et al. 2019). In the boreal forest, interactions between changes in climate conditions as well as in the disturbance regime could influence nutrient foliar content and insect outbreak (De Grandpré et al. 2022). Soil biota, which is known to play key roles in ecological responses of forest ecosystems to climate change (Bardgett and van der Putten 2014), could also be altered by climate change-induced soil warming, changes in precipitation and increased CO_2 concentration (Blankanship et al. 2011). Further work in this field is warranted.

Our assessment encourages us to think about forest management and adaptation to climate change in terms of a plurality of values, notably by taking into account the knowledge and perspectives of Indigenous peoples. Varied silvicultural toolboxes to manage climate risk to forests will be necessary, as will be the need to raise awareness and mobilize regional stakeholders. Furthermore, as knowledge about climate change impacts and adaptation strategies evolves, and as climate change severity unfolds, forest management strategies will have to be highly adaptive to better cope with current and emergent risks (Gauthier et al. 2014, Achim et al. 2021). Some of the solutions will likely necessitate extensive actions and require increased resources that will have to be considered upfront. No-regret actions will have to be prioritized. In any case, dedicated adaptive resources and approaches will be necessary to prevent potentially significant and severe alterations of forest ecosystem processes and forestry sector activities in Quebec in the coming decades.

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Data generated or analyzed during this study are available upon request from authors of each individual project included in this synthesis (see Figure 1).

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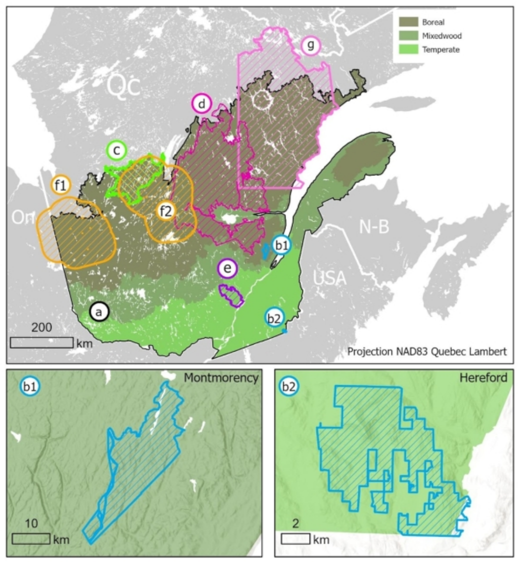

Figure 1. Location of each individual projects included in the RIA. Region a: De Grandpré et al. (2019), Boulanger and Pascual Puigdevall (2021), Boulanger et al. (2021), Leblond et al. (2022). Also corresponds to the Quebec's managed forest as well as the intensive protection zone for fire suppression; Region b: Cyr et al. (2021); Region c: FEC (2021); Region d: Landry et al. (2021); Regions e1 and e2: Moreau et al. (2022), Labadie et al. (in prep.); Region f: Labadie (2022). Regions g1 (Abitibiwinni) and g2 (Ouje-Bougoumou): Bélisle (2022). Forest region (Boreal, Mixed, Temperate) shapefile available from https://www.foretouverte.gouv.qc.ca/ .

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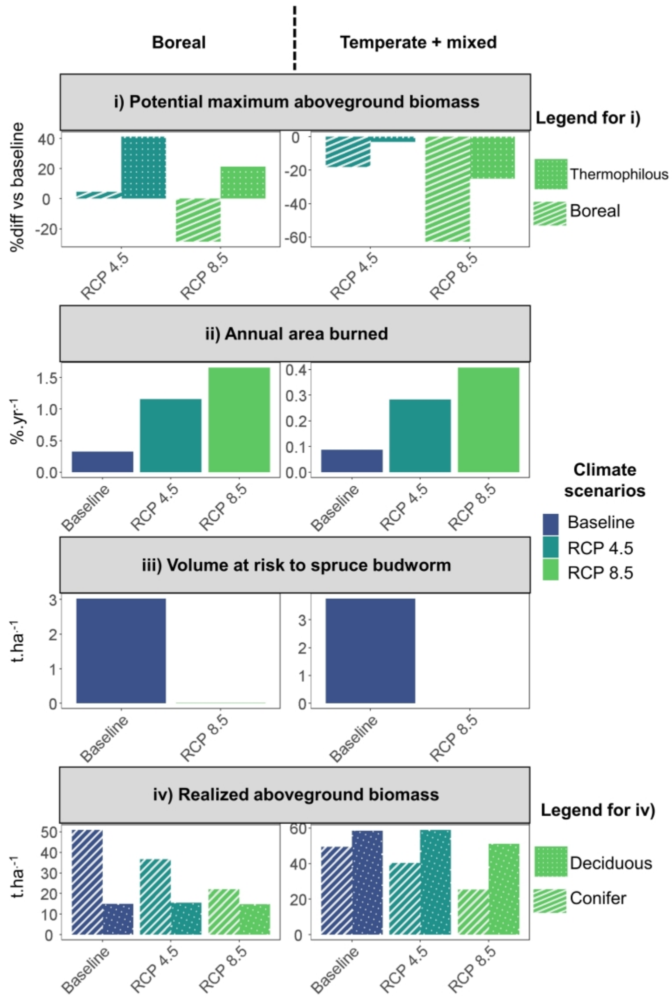

Figure 2. Impacts of climate scenarios (baseline, RCP 4.5 and RCP 8.5) on productivity (potential maximum aboveground biomass; i), on annual area burned (ii) and on volumes at risk to spruce budworm outbreaks (iii). Cumulative impacts on aboveground biomass of deciduous and conifer species are also shown in iv. Results are shown for either the boreal (left column) or the temperate and mixed forest regions (right column). Note that in iii, volume at risk to SBW is virtually nil under RCP 8.5. i from Boulanger and Pascual Puigdevall (2021); ii from a modified version of Boulanger et al. (2014) models; iii from Boucher et al. (2018); iv from Boulanger and Pascual Puigdevall (2021). Readers can refer to figure 1 for forest regions.

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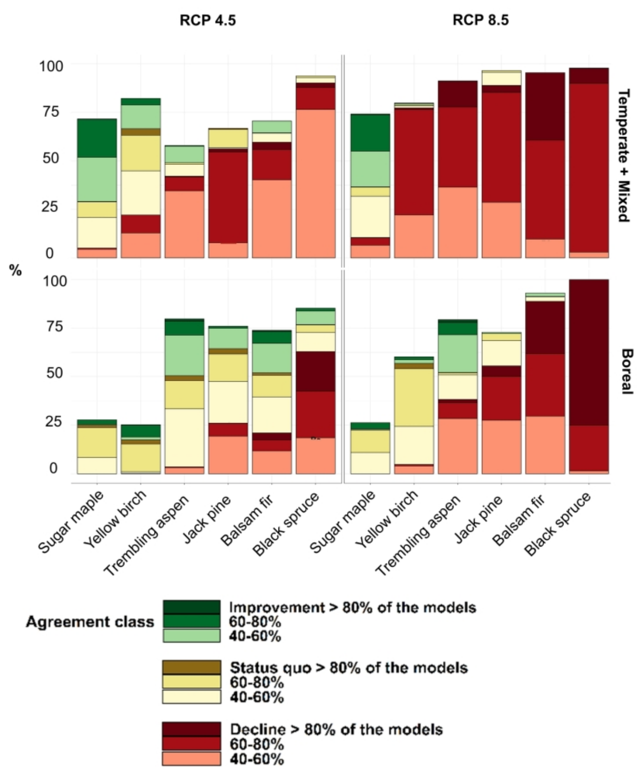

Figure 3. Model ensemble agreement classes (%) per species, and forest region (Temperate + Mixed and Boreal). Green tones: Improvement; yellow tones: status quo; red tones: decline. Results are compiled under the RCP 4.5 and RCP 8.5 climate scenarios. Modified from Boulanger et al. (2021). Bars only show when at least 40% of the models agreed for a given species and cell. As such, overall agreement was low for sugar maple and yellow birch in the boreal region, especially under RCP 4.5.

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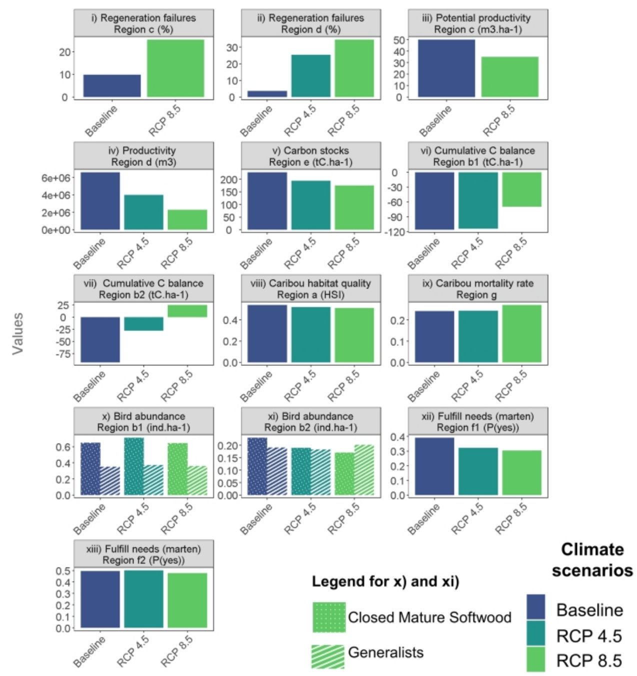

Figure 4. Impacts of climate scenarios (baseline, RCP 4.5 and RCP 8.5) on various ecosystem services as assessed in the RIA. All results considered the cumulative effects of climate change and business-as-usual forest management strategy. Analyses in i and iii were not conducted under RCP 4.5. Results in vi and vii are plotted relative to a reference scenario, i.e., under baseline climate conditions without forest management ("conservation"). For x and xi, bird abundance is expressed for species either associated with closed mature softwood forests and generalists. HSI: Habitat suitability index, unitless; P(yes): Probability to fulfill family's needs (with no need to adapt). Readers can refer to figure 1 for study locations. i) and iii) from Cyr et al. (2021); ii) and iv) from Forestier en Chef (2021a); v) from Landry et al. (2021); vi) and vii) from Moreau et al. (2021); viii) from Leblond et al. (2022); ix) from Labadie (2022); x) and xi) from Labadie et al. in prep.; xii) and xiii) from Belisle (2022).

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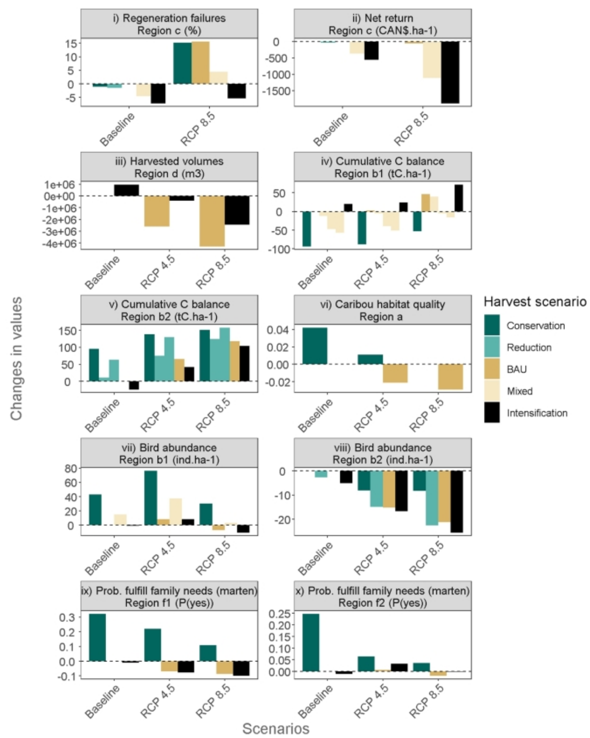

Figure 5. Impacts of forest management adaptation strategies on various ecosystem services as assessed in the RIA under baseline, RCP 4.5 and RCP 8.5 climates. The simulated forest management scenarios were classified as “Conservation” (e.g., stopping harvest), “Reduction” (e.g., create conservation areas, lengthening harvest rotation, reduce harvesting rates, increase partial harvesting); “business-as-usual” (e.g., current forest management strategies), “Intensification” (e.g., increased plantation efforts, higher harvesting rates), and “Mixed” (e.g., strategies that mix both “Reduction” and “Intensification” strategies). Not all studies included all scenarios. Results are plotted relative to a reference scenario, i.e., under baseline climate conditions and business-as-usual forest management. P(yes): Probability to fulfill a family's needs (with no need to adapt). Readers can refer to figure 1 for study locations. i) and ii) from Cyr et al. (2021); iii) from FEC (2021); iv) and v) from Moreau et al. (2021); vi) from Leblond et al. (2022); vii) and viii) from Labadie et al., in prep.; ix) and x) from Belisle (2022).

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