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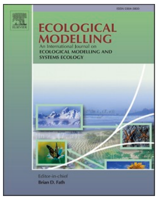

One century of carbon dynamics in the eastern Canadian boreal forest under various management strategies and climate change projections

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ABSTRACT

Partial cutting has lower canopy removal intensities than clearcutting and has been proposed as an alternative harvesting approach to enhance ecosystem services, including carbon sequestration and storage. However, the ideal partial cutting/clearcutting proportion that should be applied to managed areas of the eastern Canadian boreal forest to enhance long-term carbon sequestration and storage at the landscape scale remains uncertain. Our study projected carbon dynamics over 100 years (2010–2110) under a portfolio of management strategies and future climate scenarios within three boreal forest management units in Quebec, Canada, distributed along an east–west gradient. To model future carbon dynamics, we used LANDIS-II, its Forest Carbon Succession extension, and several extensions that account for natural disturbances in the boreal forest (wind, fire, spruce budworm). We simulated the effects of several management strategies on carbon dynamics, including a business-as-usual strategy (clearcutting applied to more than 95 % of the annually managed area), and compared these projections against a no-harvest natural dynamics scenario. We projected an overall increase in total ecosystem carbon storage, mostly because of increased productivity and broadleaf presence under limited climate change. The drier Western region under climate scenario RCP8.5 was an exception, as stocks decreased after 2090 because of the direct negative effects of extreme climate change on coniferous species' productivity. Under the natural dynamic scenario, our simulations suggest that the Quebec Forest in the Central and Western regions may act as a carbon sink, despite high fire-related carbon emissions, particularly under RCP4.5 and RCP8.5 Conversely, the eastern region periodically switched from carbon sink to source following SBW outbreaks, thus being a weak sink over the simulation period. Applying partial cutting to over 50 % of the managed forest area effectively mitigated the negative impacts of climate change on carbon balance, reducing differences in stand composition and carbon storage between naturally dynamic forests and those managed for timber. In contrast, clearcutting-based scenarios, including the business-as-usual approach, substantially reduced total ecosystem carbon storage— by approximately double (10 tC ha^{-1} yr^{-1}) compared to partial cutting scenarios (<5 tC ha^{-1} yr^{-1}). Clearcutting led to higher heterotrophic respiration due to the proliferation of fast-decomposing broadleaves, resulting in lower carbon accumulation compared to partial cuts. Our findings underscore the importance of balancing canopy removal intensities to increase carbon sequestration and storage while preserving other ecosystem qualities under climate change.

Abbreviations

AGB	Aboveground biomass
BAU	Business-as-usual
BGB	Belowground biomass
CanESM2	Second-generation Canadian earth system model
CC	Clear cutting
CLAAG	Careful logging around advanced growth
CPRS	Cutting with the protection of regeneration and soil
CRI	Canopy removal intensities
DOM	Dead organic matter
ForCS	Forest carbon succession extension

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maxAGB	Maximum aboveground biomass
maxANPP	Maximum aboveground NPP
MNRF	Ministry of Naturelle's resources and forest
MU	Management units
NBPa	Accumulated net biome productivity
NEPa	Accumulated net ecosystem productivity
NPP	Net primary productivity
PC	Partial cuts
PnET	Photosynthetic/Evapotranspiration model
RCP	Representative concentration pathway
R_h	Heterotrophic respiration
SBW	Spruce budworm outbreaks
SEP	Species establishment probability

1. Introduction

Forests store about 50 % of the world's terrestrial carbon, making these biomes important for climate change mitigation (Pan et al., 2011). Forest ecosystems remove nearly 2 Pg·yr^{-1} of carbon from the atmosphere through photosynthesis, absorbing about 30 % of anthropogenic CO_2 emissions (Bellassen & Luyssaert, 2014; Köhl et al., 2015). The boreal forest is the second-largest terrestrial biome, representing 27 % of the world's forests in 2020, and provides 7 % of the global wood supply (Dixon et al., 1994; Gauthier et al., 2015; Girona et al., 2023a; Grace, 2005). It stores 88 GtC in living biomass and 471 GtC in soils (Dixon et al., 1994), the latter corresponding to 60 % of the world's soil organic carbon (Pan et al., 2011). However, carbon sequestration and storage in the boreal forest are sensitive to climate change (direct climate effects on growth, mortality, decay rates, regeneration, and reproduction), natural disturbance (the frequency and severity of these events will be altered by climate change), and forest management practices, all of which could alter boreal forest composition and structure and switch areas of the boreal forest from carbon sinks to sources (Ameray et al., 2021; Boulanger et al., 2019; Girona et al., 2023b).

Forest management has the potential to alter the carbon pool and flux dynamics; the extent of this influence depends on the applied canopy removal intensity (CRI). Partial cutting (PC), having a low–moderate CRI, reduces competition and favors a gradual shift in stand structure from stands with many trees of low individual biomass toward stands having fewer but larger trees (Zhou et al. 2013; Moussaoui et al., 2020; Taylor et al., 2008). PC also maintains uneven age structures and continuous cover, thereby ensuring some degree of carbon storage; the actual amount depends on the CRI (Taylor et al., 2008). In contrast, clearcutting (CC) results in a long-term reduction in overall ecosystem carbon storage due to its potential to accelerate the decomposition process and heterotrophic respiration (R_h) during post-harvest (Ameray et al., 2021; Vestin et al., 2020). In addition to the pulse of dead organic materials following harvest, this acceleration could be explained by increasing surface temperatures and exposing of deadwood and litter to light, thereby enhancing microbial activity (Campbell et al., 2009). Moreover, at a stand scale, CC can temporarily shift forests from being carbon sinks to sources by increasing R_h and reducing the C uptake in the post-harvest period (Ameray et al., 2021). If regeneration occurs without any delays, these stands return to their carbon sink status generally 10 to 20 years after harvest (Goulden et al., 2011, Paradis et al., 2019). The effects of PC and CC on soil carbon stocks appear minor (Mayer et al., 2020). However, CC has been shown to reduce total soil organic carbon storage relative to PC, although the degree to which CC affects this carbon pool relates to site conditions, mainly temperature which may increase R_h, as well as carbon transfer from the litter (e.g., leaves, lifted branches post-cutting) to the soil (Goulden et al., 2011; Jandl et al., 2007).

The managed forests in Quebec's boreal zone, which represent 70 % of the total Quebec forest area, are harvested for wood production (NFD, 2023). These forests are subject to high-CRI silvicultural practices, such as CC and careful logging around advanced growth (CLAAG). The latter is also known as cutting with the protection of regeneration and soil (CPRS) and reduces the canopy by about 95 % while attempting to preserve advanced regeneration (Girona et al., 2023b; MRNF, 2010a). The even-aged management systems using CC and CPRS are currently used in more than 95 % of the annual harvested area (MRNF, 2010a). On the other hand, uneven-aged systems using PC are applied across less than 5 % of the annually harvested area. These PC treatments include shelterwood cutting and commercial thinning with the protection of small merchantable stems (MRNF, 2010a). In the Western management units of Quebec, the reforestation rate is approximately 10–15 %, whereas in the Eastern management units, it is less than 2 % (MRNF, 2010a).

Currently in Quebec, sustainable forest management is the primary goal of ecosystem-based forest management (ECM), which aims to minimize the differences between managed and natural forests with the underlying goal that the applied ECM approaches preserve biodiversity and ensure the supply of ecosystem goods and services (Girona et al., 2023a). ECM strategies must also be designed to offer the capacity for climate change mitigation (Girona et al., 2023a). Smyth et al. (2014) identified that reduced harvesting levels and an improved selection of trees to produce long-lived wood products could offer an optimal mitigation strategy for forests within Canada's Eastern Boreal Shield region. However, novel silvicultural approaches must be evaluated to address the challenges facing the eastern Canadian boreal forest under future environmental conditions, including warmer temperatures, altered natural disturbance regimes, greater forest fragmentation, and a reduced extent of old-growth forest (Girona et al., 2023b).

Quebec has set ambitious greenhouse gas reduction targets to achieve carbon neutrality by 2050. Achieving this goal may be facilitated by the presence of natural sinks that can be enhanced further by placing a particular emphasis on forest management (Krug, 2018). Therefore, it is crucial to understand the short- and long-term forest carbon dynamics at the landscape scale and include the effect of various forest management strategies and silvicultural practices within the context of climate change. Moreover, the short- and long-term impacts of fire, windthrow, and spruce budworm (SBW; *Choristoneura fumiferana*) outbreaks on carbon dynamics must be considered in eastern Canadian forests (Boulanger et al., 2012; MacLean, 2016). In these forests, climate change is expected to shorten fire-return intervals and heighten fire sizes and intensities (Boulanger et al., 2014). Additional studies are needed to fully understand the cumulative effects of natural and anthropogenic disturbances on carbon stocks and fluxes under climate change and how these vary along a longitudinal gradient.

This research expands upon our prior investigations (Ameray et al.; 2023a, 2023b), which identified both positive and negative climate change and disturbances effects in the same study area by simulating the carbon sequestration potential per species, evaluating regeneration/mortality, and projecting the cumulative effects of fires, wind, SBW, and harvest. In this study, however, we investigate all carbon pools and fluxes. Here, we ran a forest landscape model over one century (2010–2110) and examined forest carbon dynamics under various climate change (representative concentration pathway; RCP) and management scenarios. We varied the CRI and the annually harvested area per treatment to identify better strategies for increasing forest carbon sequestration and storage capacity at the landscape scale. Specifically, we aimed to i) quantify the isolated effects of climate change on carbon dynamics under natural dynamic scenarios (no-harvest, only natural disturbances were considered: wildfires, windthrows, SBW); and ii) investigate the effect of management strategies on carbon dynamics under different climate projections. This study should improve our understanding of carbon dynamics in Quebec's managed boreal forests. Our research may help find the most efficient ways to enhance the contribution of Quebec's forests to climate change mitigation efforts.

2. Material and methods

2.1. *Study area*

Our study area comprises three management units (MUs) located in several sensitive areas near the Quebec northern limit of commercial forestry (Jobidon et al., 2015). Beyond this northern limit, forests are not managed for timber production because of their lower productivity. The three management units —Nord-du-Quebec (Western region), Saguenay-Lac-Saint-Jean (central region), and Côte-Nord (Eastern region)—lie within the spruce–feathermoss and balsam fir–white birch bioclimatic domains of the Boreal Shield along an east–west gradient (Fig. 1). These landscapes are dominated by black spruce (*Picea mariana*), jack pine (*Pinus banksiana*), balsam fir (*Abies balsamea*), white birch (*Betula papyrifera*), and trembling aspen (*Populus tremuloides*) (MRNF, 2010b). The dominant age class is 20–40 years in the West, 80–120 years in the Center, and 120–200 in the East regions (MRNF, 2010b). Annual precipitation averages 800 mm to 1000 mm with a strong longitudinal gradient, with greater precipitation moving eastward (Wang et al., 2016). Each management unit has a marked north–south temperature gradient (Wang et al., 2016). The dominant soil texture is clay Western region, sandy-loam in the central and Eastern regions (Ameray et al., 2023a; Duchesne & Ouimet, 2021). We identified and excluded water bodies, wetlands, islands, and non-commercial species.

2.2. *Simulation models*

2.2.1. *LANDIS-II and extensions*

We simulated the forest dynamics using LANDIS-II, a stochastic and spatially explicit forest landscape model widely used to integrate forest succession, management, and natural disturbances and to simulate forest degenerative processes (senescence and mortality) at large spatial (~10^5–10^7 ha) and temporal (≥100 years) scales (Mladenoff & He, 1999; Scheller et al., 2007). LANDIS-II can project changes in species composition, biomass, carbon stocks, natural disturbances, etc. (Mladenoff & He, 1999). We conducted our simulations at a spatial resolution of 200 × 200 m (4 ha) and at a 1-year time step over 100 years (2010–2110). The simulated areas covered 0.62 Mha, 1.16 Mha, and 1.15 Mha for the Western, Central, and Eastern regions, respectively. LANDIS-II simulates forest succession and productivity at both the stand and landscape scales under different environmental conditions and disturbances using a variety of extensions. Each extension requires independent parameterization and calibration to reflect the current and future forest state. We used the extensions Forest Carbon Succession (ForCS) v 3.1 (Dymond et al., 2016), Base Fire V4.0 (Scheller & Domingo, 2018), Biomass Harvest V4.4 (Gustafson et al., 2000), Base Biological Disturbance Agent V4.0.1 (Sturtevant et al., 2004), and Base Wind V3.1 (Scheller et al., 2018).

2.2.2. *Initial landscape: climate, species, and ecoregions*

The 2010 spatial forest inventory data set maintained by the MRNF (Quebec's *Ministère des Resources naturelles et des Forêts*) provided the species and age information for the initial communities mapped at a 200 m resolution. Each species in the data set is associated with its life-history attributes collected from previous studies, including longevity, sexual maturity, shade tolerance, fire tolerance, seed dispersal distance, sprouting, and post-fire regeneration (Table A.1) (Ameray et al., 2023a; Boulanger et al., 2017; Molina et al., 2021). Each cell (4 ha) in the landscape is assigned to a single land type where soil and climate conditions are assumed to be homogeneous, and growth and reproduction functions are unique.

For each ecoregion, we collected historical monthly weather data and RCP scenarios (RCP2.6, RCP4.5, RCP8.5) from the ClimateNA model (CanESM2 projections), a local downscaling model that facilitates extracting climate data for specific locations (longitude, latitude, elevation) in North America (Wang et al., 2016). In ClimateNA, multiple general circulation models (GCMs) were included for the paleoclimatic period, historical data (1901–2010), and future periods (Wang et al., 2016). To represent ecoregion climate conditions, we considered the average of every climate parameter using data from 10 randomly selected locations within each ecoregion. For the current baseline climate, we extrapolated the historical monthly climatic data from 1991 to 2010, including minimum and maximum temperatures and precipitation, on the basis of their Gaussian distribution around the mean so that the baseline climate would be constant (Ameray et al., 2023a). The CanESM2 projections have mean annual temperatures increasing respectively by about 2.5, 4, and 7 °C for RCP2.6, RCP4.5, and RCP8.5

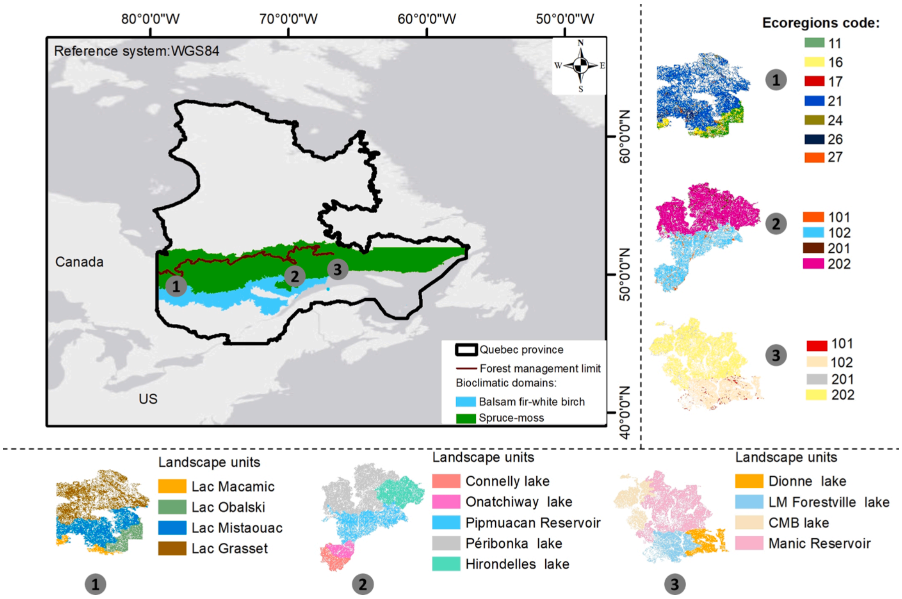

Fig. 1. Location of the three studied management units (MUs) in Quebec, Canada: Nord-du-Quebec (**1**: Western region), Saguenay-Lac-Saint-Jean (**2**: central region), and Côte-Nord (**3**: Eastern region)). For each management unit, we present the landscape units used as managed areas (MRNF, 2010a), and the ecoregion code used during the simulation.

by 2100 relative to the current baseline climate (Figure A.1). Furthermore, precipitation is projected to rise by approximately 40 mm for RCP2.6 and by over 100 mm for both RCP4.5 and RCP8.5. We used ecoregions from Ameray et al. (2023a), which are delimited according to the Duchesne and Ouimet (2021) soil map and the bioclimate regions of MRNF geodatabase (Fig. 1, Table A.2). Duchesne and Ouimet (2021) modeled and mapped particle size composition (clay, silt, and sand) for the entire managed forest in Quebec. Relying on a decision tree algorithm, Ameray et al. (2023a) applied these soil data to categorize the soil texture for all MUs using clay, silt, and sand percentages for each 4 ha cell.

2.2.3. ForCS calibration and parameterization

The ForCS (v3.1) extension for LANDIS-II calculates how cohorts of trees reproduce, age, grow, and die (Dymond et al., 2016). The accumulation of biomass carbon through growth and reproduction generally follows the Biomass Succession (v5.7) extension and the methods outlined in Scheller and Mladenoff (2004). This extension also tracks the evolution of forest stands and carbon dynamics, including carbon turnover, net growth, net primary production (NPP), heterotrophic respiration (R_h), net ecosystem productivity (NEP), net biome productivity (NBP), transfers between pools, losses from the ecosystem because of logging (carbon flux to forest product sector), and carbon emissions because of decay or combustion (Dymond et al., 2016; Hof et al., 2017). Moreover, as described in Dymond et al. (2016), the ForCS dead organic matter (DOM) and soil dynamics are built from the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3) model. CBM-CFS3 implements a Tier 3 approach of the Intergovernmental Panel on Climate Change (IPCC) good practice guidance for reporting on carbon stocks and changes resulting from land-use change and forestry. We used the updated decay rates by group (coniferous vs hardwood), obtained from Hararuk et al. (2017) (Table A.3). These values were calibrated for CBM-CFS3 using data from the National Forest Inventory across Canada. The model also accounted for the direct impact of temperature on DOM decay rates, with temperature inputs adjusted for each climate scenario and period.

ForCS requires species establishment probability (*SEP*), maximum aboveground NPP (*maxANPP*), and maximum aboveground biomass (*maxAGB*) as inputs (Fig. 2). Natural regeneration for each site (grid cell) in ForCS depends on neighboring species composition, seed dispersal distances, available light, and species' shade tolerance. For a species to seed a site or resprout on a site, sufficient light must be available, determined by comparing the species' shade tolerance with the shade at the site. ForCS model handles' species mixture and pure stands by

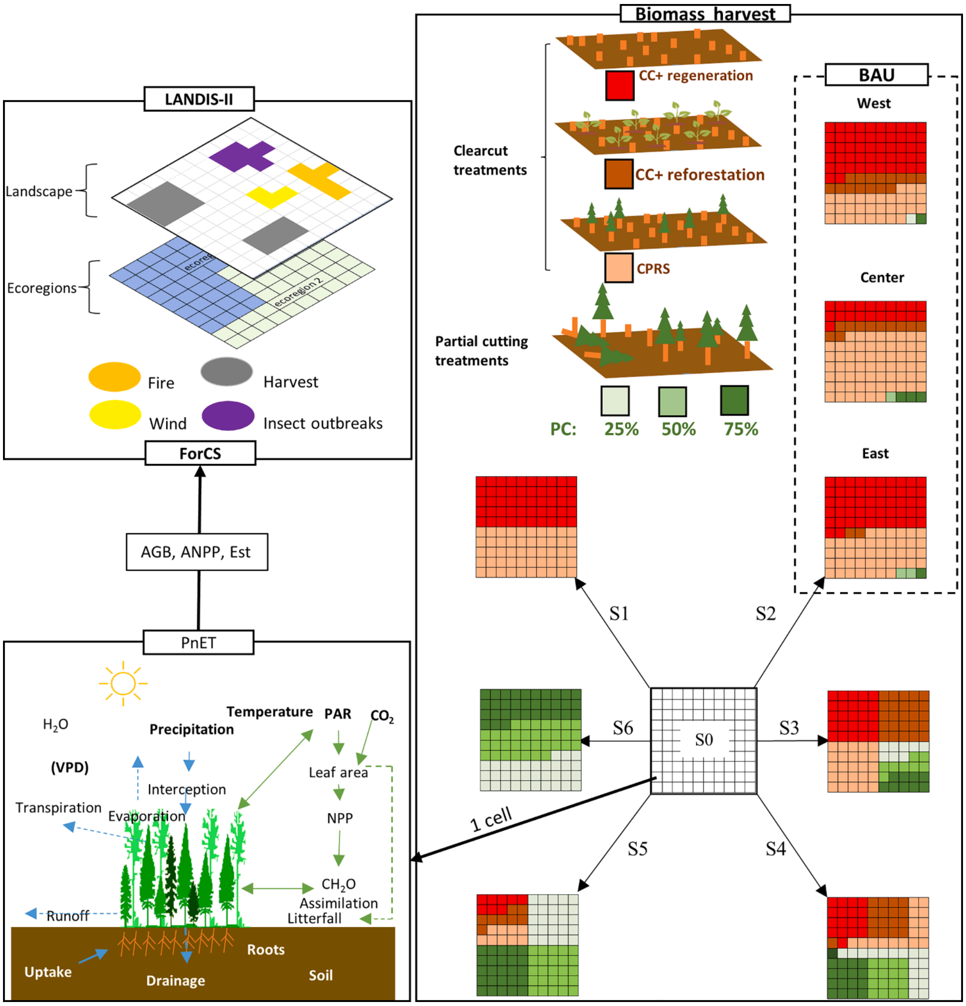

Fig. 2. General methodology framework. The PnET-Succession model used for succession simulates simultaneously water and carbon cycles and integrates environmental factors such as soil texture, precipitation temperature radiation (PAR), and vapor pressure deficit (VPD). The model estimated the above net primary productivity (ANPP), aboveground biomass (AGB), and establishment (Est). These parameters were then integrated into ForCS and other disturbance extensions [harvest, winds, biological disturbance agent (BDA), fire] within the LANDIS-II model, and management scenarios (Biomass harvest) were tested at the landscape scale (see Table 1 for more details). S2 reflects the BAU scenario derived from the 1970–2010 historic harvested geodatabase from the Quebec Forest inventory of each region (West, Center, and East).

incorporating species-specific parameters and rules based on shade tolerance class into its algorithms (Scheller et al. 2007). The *SEP, ANPP,* and *maxAGB* were derived directly from the PnET-Succession extension (V5). PnET-Succession includes many algorithms from the PnET-II forest ecophysiology model, which rely heavily on first principles of physiology, chemistry and physics (De Bruijn et al., 2014). This extension accurately simulates vegetation establishment, growth, competition, and mortality, employing physiological first principles to model cohort growth through competition for light and water (Gustafson et al. 2023a; 2023b). It centers on two fundamental relationships: 1) maximum photosynthetic rate is a function of foliar nitrogen concentration, and 2) stomatal conductance is a function of realized photosynthetic rate. The version (V4) of this extension was calibrated and validated in our previous work in the same study areas, using yield curves, and remote sensing (MODIS and Sentinel-2 images) (Ameray et al., 2023a). We recalibrated version (V5) using Pothier and Savard's (1998) yield curves for the historical climate (Figure A.2). The simulated biomasses generated by ForCS were compared with those simulated by the PnET extension (V5). This comparison involved calculating the coefficient of determination (R^2) and the root-mean-square error (RMSE) between the two model outputs. We obtained a strong correlation between the simulated biomasses in both models ($R^2 = 0.83$). However, on average, the simulated above biomass values from ForCS differ from those of the PnET extension by approximately 15 $t.ha^{-1}$ (Figure A.2).

For each climate change scenario, we used PnET-Succession version (V5) to estimate ForCS input parameters (*SEP, maxANPP, maxAGB*) for each monospecific stand per species for all land types (ecoregions) using a 10-year time step. The *SEP* is simulated in the PnET model as a function of light and water photosynthesis reduction factors for the species at the time of establishment. Establishment probabilities were adjusted for an annual time step using the properties of Bernoulli's trials, assuming that the species could establish at least one time or more [*SEP* ($X \geq 1$)] in 10 successive trials. All simulations were run in PnET-Succession on a single cell to drive each simulation for 140 years, starting from a single 20-year-old cohort on bare ground. According to Tremblay et al. (2018), most of the studied species' aboveground biomass reaches a plateau around 100–140 years.

For the baseline climate scenario, we estimated the parameters *SEP, maxANPP*, and *maxAGB* using the extrapolated annual weather stream from the historic monthly time series (1991–2010) at a constant CO_2 atmospheric concentration of 389 ppm (2010 value) (Ameray et al., 2023a). We applied the obtained values for the historic climate scenario (1991–2010) for the starting year 0 (2010). For all climate change scenarios (baseline, RCP2.6, RCP4.5, and RCP8.5), we modeled *SEP, maxANPP*, and *maxAGB* for each 20-year time series of climate data for five periods (2010–2030, 2030–2050, 2050–2070, 2070–2090, and 2090–2110). For each species and land type, we ran ten replicate runs to isolate the stochastic effect of PnET-Succession on the *SEP, maxANPP*, and *maxAGB* outputs. *MaxAGB* and *MaxANPP* and *SEP* parameters derived from PnET-Succession were updated every 20 years to account for climate change until 2110. Before starting the simulation at the landscape scale, successional pathways at stand scale (1 cell) were verified based on Tremblay et al. (2018), using LANDIS-Site.

2.2.4. Biomass and soil pool initialization

At the beginning of each scenario (time=0), the initial communities initiate with appropriate living values estimated for each cell, based on provided cohort information (species/age). The user does not need to provide initial biomass estimates; instead, the ForCS model autonomously calculates them using the three input parameters (*SEP, MaxANPP*, and *MaxAGB*) and the methodology outlined in Scheller and Mladenoff (2004). Beginning at time t-oldest cohort age, cohorts are added at each time step corresponding to the time when the existing cohorts were established. Thus, each cohort undergoes growth and mortality for the number of years equal to its current age, and its initial biomass value reflects competition among cohorts (Dymond et al., 2016). For the initial DOM carbon pool, ForCS implements the same approach as CBM-CFS3 (Kurz et al. 2009). We use a spin-up approach to initialize the soil pools, as described in Dymond et al. (2016). Using this approach, the model operates by growing the biomass pools to the largest age present on the site as defined in the 'initial communities' file. At this age, the model will then assume that all cohorts have been killed by a high severity (severity = 4) fire, and then will regrow exactly as before. This process repeats until the slow soil pools reach a stable state, which happens when the size of the slow soil pool at the end of one cycle matches that at the end of the previous cycle. The last cycle of the initialization procedure starts with a stand-replacing fire and then simulates growth and decay dynamics until all cohorts reach the age in the 'initial communities' file. The model will output the size of the soil pools by species and ecoregion at the end of the initialization: timestep 0 in the output file. Before starting the simulation, we compare the initial simulated soil carbon pool with literature values (60–131 $tC\ ha^{-1}$) (Paré et al. 2011).

2.2.5. Disturbance parameterization and simulated scenarios

The natural dynamics scenario (no-harvest) reflected forest succession under fire, windthrow, and spruce budworm (SBW) disturbances as the three major natural disturbances shaping the boreal forest in the study areas (Aakala et al., 2023). The extensions used for these disturbances were already calibrated and parameterized in our previous works (Ameray et al., 2023a, 2023b). Briefly, the Base Fire extension simulates fire regimes through stochastic fire events that depend on fire ignition, initiation, and spread by ecoregion, using the input data of ignition probability, map of fire regions, fire size (minimum, mean, and maximum), and fire severity (Scheller & Domingo, 2018). As the wildfire regime depends on climate, we calibrated the burn rate (% of land disturbed annually) per ecoregion (5a, 5d, 5 g, 6a, 6 h, 6i) for each climate change scenario, including the current baseline climate from the literature (Bergeron et al., 2006; Boulanger et al., 2014; Molina et al., 2021; Tremblay et al., 2018). Climate change is expected to increase the burn rate and fire return interval, particularly in Western and Central regions (Boulanger et al., 2014). The Base Wind extension was used to stochastically simulate windthrow disturbance on the basis of windthrow intensity, size, spread, severity, and rotation period (Scheller et al., 2018). Windthrow size and period per ecoregion were parameterized using the historical data from the forest inventory geodatabase (1970–2010). Similarly, the Biological Disturbance Agent (BDA) extension stochastically introduces periodic defoliation events parameterized solely by defoliation during SBW outbreaks (Sturtevant et al., 2019). SBW host species included, from most to least vulnerable, balsam fir, white spruce, and black spruce. The BDA extension parameters were calibrated and validated in other studies for similar landscapes in the Quebec boreal forest (Boulanger et al., 2017, 2019). We relied on a 400-year dendrochronological reconstruction of SBW outbreaks in southern Quebec to set an average of 32 years between outbreaks (Boulanger et al., 2012; Navarro et al., 2018). After the SBW event, we assumed that all biomass of the killed cohorts transferred to the DOM pool. This can produce an immediate increase in the DOM pool and a decrease in living biomass. Finally, salvage logging was not considered in this study.

We used the Biomass Harvest extension v4.4 to simulate harvest disturbance (Gustafson et al., 2000). First, for all scenarios, annually harvested area—expressed as a percentage (Table 1)—was calibrated to match as close as possible to the allowable annual cut determined for the current planning cycle (2023–2028), given that the model's target is area-based whereas the allowable annual cut is volume (biomass)-based (246 Gg in West, 512 Gg in center, and 406 Gg in East). This model requires dividing the landscape into management areas, specifying the order in which stands are to be harvested. Stands were deemed eligible for harvesting on the basis of their exploitability age and the species' economic importance. The Biomass Harvest extension modeled the various management scenarios described in Fig. 2 and Table 1 (Scheller

Table 1
Tested scenarios and their description. Used treatment at stand scale with different harvesting intensity and the percentage of annually managed area per treatment. CC+ reforestation reflects that clear-cut or CPRS is followed by replanting, due to a lower soil seed banks and regeneration rate.

Scenario	Description	Used treatment at stand scale and % of annual managed area per treatment						Annual managed area (%) per zone		
		CC+ regeneration	CC+ reforestation [a]	CPRS	PC75 %	PC50 %	PC25 %	West	Center	East
S0	No harvest scenario under natural disturbances	0	0	0	0	0	0	0.0	0.0	0.0
S1	All the annually harvested area (AHA) is managed using high CRI (CC and CPRS). The establishment is based only on regeneration.	50	0	50	0	0	0	1.4	2.2	1.9
S2	BAU. Currently used scenario, where CPRS and CC are used for more than 90 % of AHA, and 10 % of AHA is managed using PCs with 25 %, 50 %, 75 % of CRI.	Historic % per management unit from forest inventory geodatabase.						1.5	2.3	2.0
S3	we used 75 % of AHA for high CRI (CC and CPRS) and 25 % for low-removal ones (PC)	25	25	25	8.3	8.3	8.3	1.5	2.4	2.1
S4	we used 50 % of AHA for high-removal treatments and 50 % for low-removal ones.	16.7	16.7	16.7	16.7	16.7	16.7	1.6	2.6	2.2
S5	we used 25 % of AHA for high-removal treatments and 75 % for low-removal ones.	8.3	8.3	8.3	25	25	25	1.9	2.8	2.4
S6	Extreme use of PCs (100 % of AHA), the opposite of scenario 1	0	0	0	33.3	33.3	33.3	2.2	3.5	2.9

[a] The reforestation level (CC+ reforestation) is the percentage of the afforested area after harvest by CC and CPRS with a lower regeneration rate. From the historic 14.8 %, 8.9 %, and 1.4 % of AHA were reforested in Western, Central, and Eastern units respectively.

et al., 2019). We designed prescriptions on the basis of current silvicultural treatments and implemented them in varying proportions through different management scenarios (MRNF, 2010a). These scenarios included clearcutting (100 % CRI), CPRS (CRI fixed at 95 % and the cohorts of 1–20 years being avoided), and three forms of PC having 25 %, 50 %, and 75 % CRI (Table 1). For all management scenarios, we applied stem-only harvest processing (also known as short-wood or cut-to-length logging in North America), assuming that only merchantable wood was transferred to the forest industry, whereas foliage, branches, and coarse and fine roots were left on site and transferred to DOM. Moreover, all PCs were based on commercial thinning from above (only cohorts older than the economic age of operability were removed). In the Quebec boreal forest, reforestation/replanting generally occurs after CC or CPRS in areas having a poor soil seed bank and a low regeneration rate; our prescriptions ensured that the historic replanted ratio of each species was respected, at 70 % black spruce, 25 % jack pine, 3 % larch, and 2 % white spruce. In addition, our proposed scenarios featured varying levels of annual replanted area, as outlined in Table 1.

2.3. Data analysis

To account for the variability among simulations, we repeated each management scenario four times per climate change pathway, including the natural dynamics scenario (a total of 336 simulations in all MUs). This number of repetitions was sufficient to identify the stochastic effect of LANDIS-II on the outputs (Ameray et al., 2023a; Zhuo et al., 2020). We aimed to compare the BAU scenario in the selected MUs against other management scenarios under different climate scenarios (baseline, RCP2.6, RCP4.5, and RCP8.5) (Fig. 2). Firstly, for the natural dynamic scenario (S0: no harvest occurs, and only natural disturbances are considered), we assessed and visualized carbon pools (biomass and DOM) and fluxes (NPP, R_h, accumulated NEP, accumulated NBP), averages with their confidence intervals. Secondly, under S0, the direct effect of climate change on carbon dynamics was calculated as the difference ($\Delta_{i,j}$) between each RCP scenario ($V_{i,0}$) and baseline climate scenario ($V_{1,0}$) (Eq.1). Thirdly, to identify the effect of management, we also calculated the magnitude of change for each variable (pools and fluxes) as the difference ($\Delta'_{i,j}$) between each management scenario ($V_{i,j}$) relative to the reference S0 ($V_{i,0}$) for each climate projection (i) (Eq. 1). White et al. (2014) proposed that evaluating the magnitude of differences between simulations was a better approach than relying on statistical tests within the simulation models. The calculation of those variations allows us to compare CC-based scenarios (S1, S2, and S3)—in which high-CRI silvicultural practices (CC and CPRS) were applied to more than 50 % of the harvested area during the year—with PC-based scenarios (S4, S5, and S6) (Table 1, Fig. 2). Finally, to evaluate the harvested biomass across management scenarios, we visualized the carbon flux to the forest product sector. The data analysis and visualization were conducted within the *R* software environment.

$$\Delta_{i,j} = V_{i,0} - V_{1,0} \tag{Eq. 1}$$

$$\Delta'_{i,j} = V_{i,j} - V_{i,0} \tag{Eq. 2}$$

where i is the climate change scenario, i.e., baseline ($i = 1$), RCP2.6 ($i = 2$), RCP4.5 ($i = 3$), RCP8.5 ($i = 4$), and j is the management scenario, i.e., from 1 to 6 (Fig. 2).

3. Results

3.1. Effect of climate change on carbon dynamic under natural dynamic scenario

3.1.1. Carbon pools and fluxes under the current climate

The Simulations indicated that the DOM carbon pool stocks (including carbon in deadwood, litter, humus, and mineral soil) were higher than biomass carbon storage and that DOM variations considerably impacted total ecosystem carbon stocks at the landscape scale (Fig. 3). Under baseline climate scenario and S0, our simulations indicated an overall average increase in carbon stocks of biomass (AGB and BGB) and DOM for Western and Central regions. In fact, the living biomass (AGB + BGB) increased from 30 tC ha^{-1} to 43 tC ha^{-1} in the Western region and from 27 tC ha^{-1} to 42 tC ha^{-1} in the center. However, in the Eastern region, it was stable around 27 tC ha^{-1}. Regarding the DOM carbon pool, there was also a significant increase, reaching 85 tC ha^{-1} and 67 tC ha^{-1} in the Western and Central regions, respectively, by the end of the simulation in 2110. In the Eastern region, however, DOM stocks increased modestly from 50 to 56 tC ha^{-1} by the end of the simulation. The observed increase in biomass and soil carbon storage in the Western and Central management units can be attributed to the abundance of both young and mature stands (high productivity). In contrast, the Eastern unit showed only a slight increase in stocks due to the abundance of old-growth forests (lower productivity).

Under the baseline climate and S0 scenario, both the West and Center management units showed an increase in NPP and R_h, reaching approximately 2.5 and 2.7 tC ha^{-1} yr^{-1}, respectively (Fig. 3). The Western region acted as a significant carbon sink, accumulating around 38 tC ha^{-1}

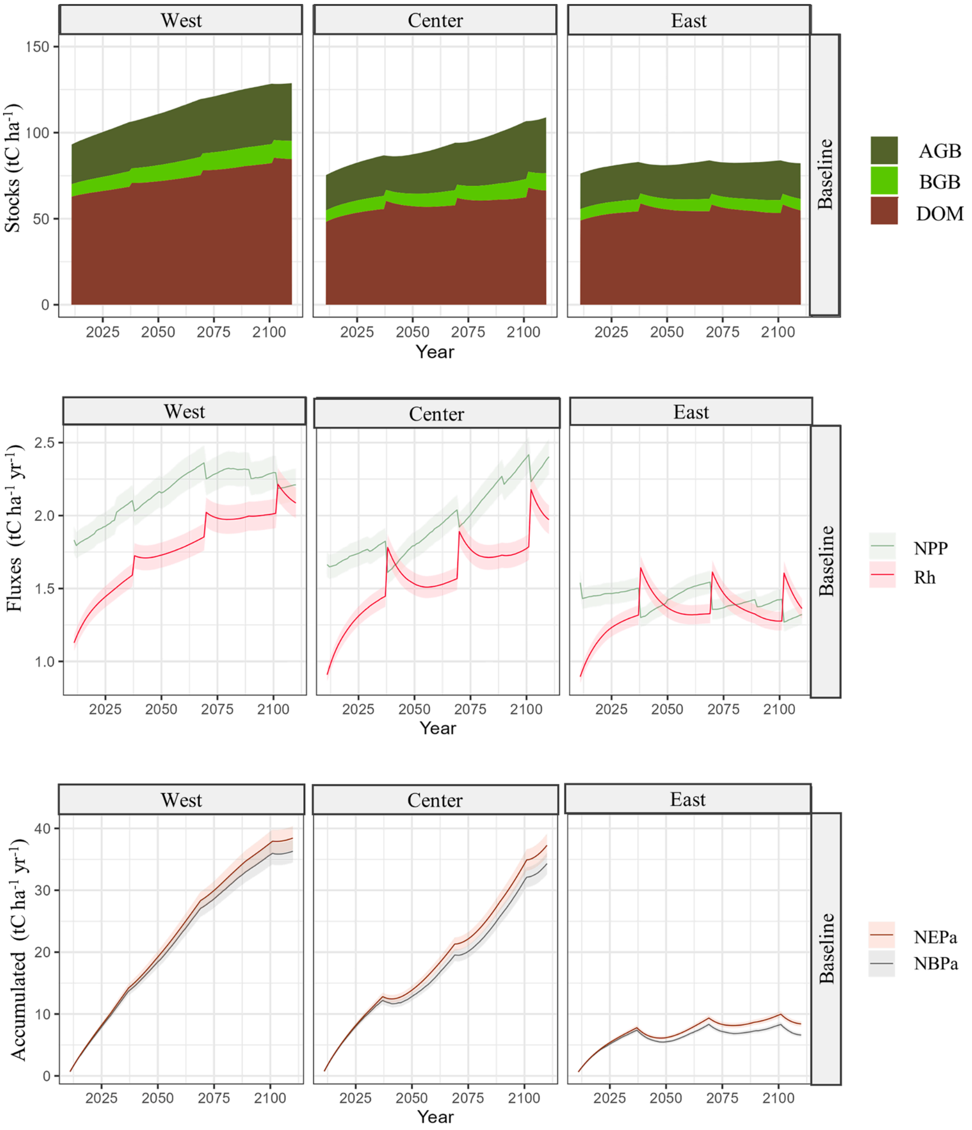

Fig. 3. Average carbon stock (tC ha^{-1}) for the S0 scenarios including aboveground biomass (AGB), belowground biomass (BGB), and dead organic matter (DOM: includes deadwood, litter, humus, and mineral soil). Average ecosystem carbon fluxes (tC ha^{-1} yr^{-1}) for the S0 scenarios, including net primary production (NPP), heterotrophic respiration (R_h), accumulated net ecosystem productivity (NEPa), and accumulated net biome productivity (NBPa) in three management units within the Quebec boreal forest (West, Center, and East) under baseline scenarios from 2010 to 2110. The average carbon stocks and fluxes and their confident interval were calculated from four replicates.

of NEPa and 36 tC ha^{-1} of NBPa by the end of the simulation in 2110. Similarly, the Central region also performed as a carbon sink, with NEPa and NBPa values of about 35 tC ha^{-1} and 32 tC ha^{-1}, respectively. These findings highlight the effectiveness of these regions in capturing and storing carbon, thus contributing positively to the overall carbon balance despite periodic SBW outbreaks occurring every 32 years (2028, 2060, 2092).

The Eastern region initially behaved as a carbon sink until the first SBW outbreak in 2028. Following this outbreak, this region shifted to a carbon source with a negative carbon balance (NEP < 0 and NBP < 0) (Figure A.3). During the year of the outbreak, the DOM pool experienced a slight increase due to a considerable expansion in deadwood caused by SBW. This was followed by a gradual decrease in the DOM pool due to high R_h until the next outbreak (Fig. 3). In the post-outbreak period, NPP increased, eventually surpassing R_h, causing the landscape to revert to a carbon sink (Figure A.3). The forest progressively recovered lost carbon, turning NEP and NBP positive in this region (~0.3 tC ha^{-1} yr^{-1}) (Figure A.3), with a net positive accumulation (Fig. 3). However, during each post-outbreak, the Eastern region consistently turned into a carbon source before recovering after 20 years. Despite these fluctuations, total carbon stocks increased due to positive NEPa and NBPa, reaching around 10 tC ha^{-1} yr^{-1} and 8 tC ha^{-1} yr^{-1}, respectively, by the end of the simulation.

3.1.2. *Climate change effect on carbon pools and fluxes*

Relatively to S0 under the baseline climate scenario, RCP2.6 produced an increase of 5 tC ha^{-1} (10 %) in average biomass carbon storage (AGB and BGB) over the 100-year simulation in Western and Center regions, and by 7.5 tC ha^{-1} (25 %) in Eastern region (Fig. 4). RCP4.5 resulted in even higher increases in biomass carbon storage, doubling those observed for RCP2.6, with increments of 20 %, 15 %, and 40 % in Western, Central, and Eastern regions, respectively. In the Western region under RCP8.5, it initially increased by 10 % until 2090, followed by a subsequent decrease of -5 %, meanwhile, in Central and Eastern regions, it experienced increments of 20 % and 43 %, respectively. Also, climate change has reduced the DOM carbon pool during the period of simulation (2010–2110), mainly under RCP8.5 and RCP4.5. By the end of the simulation, DOM stocks decreased by an average of −2 %, -8 %,

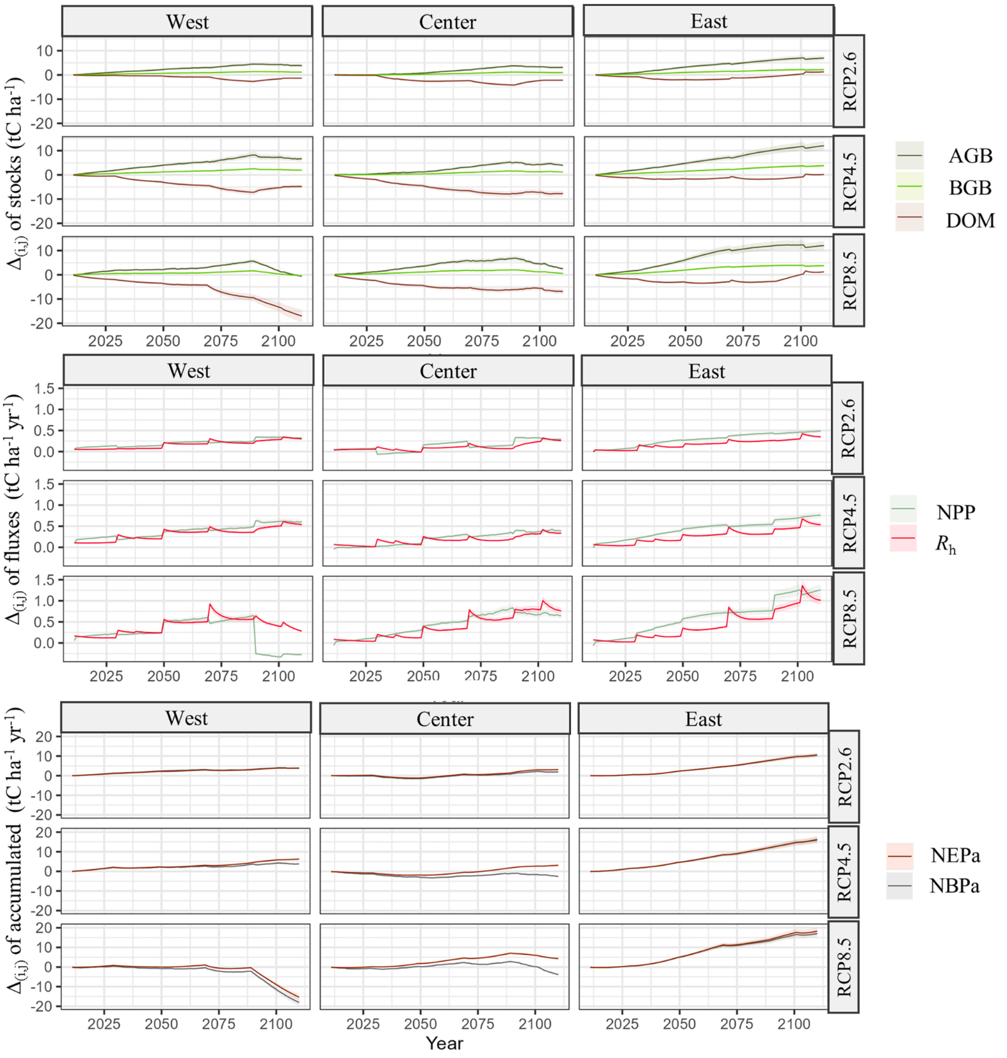

Fig. 4. Carbon stocks and fluxes in the next century (2010–2110) under climate change scenarios, including aboveground biomass (AGB), belowground biomass (BGB), dead organic matter (DOM: includes deadwood, litter, humus, and mineral soil), net primary production (NPP), heterotrophic respiration (R_h), accumulated net ecosystem productivity (NEPa), and accumulated net biome productivity (NBPa). The magnitude of change ($\Delta_{i,j}$) (tC·ha^{-1}·yr^{-1}) was calculated between each RCP scenario and baseline under the S0 scenario. The averages of $\Delta_{i,j}$ were determined by four simulation runs for three management units in the Quebec boreal forest (West, Center, and East).

and −20 % in the Western region for RCP2.6, RCP4.5, and RCP8.5, respectively. Similarly, reductions of −3 %, −11 %, and −13 % were observed in the center, and increases of 2 %, 3 %, and 5 % in the Eastern unit for the respective climate scenarios. Those reduction rates in the West and Center of Quebec, mainly under RCP4.5 and RCP8.5, could be attributed to the increased abundance of broadleaves (Figure A.4), which decompose at a faster rate compared to coniferous species (Table A.3), as well as to the annual carbon turnover which increased to reach around 2.5 tC·ha^{-1}·yr^{-1} mainly under RCP8.5 in both management units (Figure A.5).

Regarding the effect of climate change on carbon fluxes under S0, both NPP and R_h exhibited an increase across all climate change scenarios compared to the baseline (Fig. 4). In the Western region, the differences ($\Delta_{i,j}$) in NPP and R_h may reach 0.25 tC ha^{-1} yr^{-1} for RCP2.6 and 0.5 tC ha^{-1} yr^{-1} for RCP4.5. However, under RCP8.5, the differences in NPP decreased from +0.6 to -0.2 tC ha^{-1} yr^{-1} after 2090. These findings explained the constant pattern of accumulated NEP and NBP in the Western region under RCP 2.6 and RCP4.5 and their decline under RCP8.5 after 2090. As a result, this zone may become a carbon source after 2090 under the extreme climate change scenario (RCP8.5) (Figure A.3).

Similarly, in the Central zone, both NPP and R_h are projected to increase by 0.25, 0.5, and 0.8 tC ha^{-1} yr^{-1} under RCP2.6, RCP4.5, and RCP8.5, respectively, compared to the baseline climate scenario at the end of the simulations (Fig. 4). Our results also indicated that the differences ($\Delta_{i,j}$) in NEPa and NBPa could be relatively high (+2.5 tC ha^{-1} at 2110) under RCP2.6 compared to the baseline climate scenario (Fig. 4). Also, the $\Delta_{i,j}$ values of NEPa were positive at the end of the simulation, reaching approximately 3 tC ha^{-1} and 5 tC ha^{-1} for RCP4.5 and RCP8.5, respectively. However, the $\Delta_{i,j}$ values of NBPa may turn negative under RCP4.5 and RCP8.5 compared to the baseline climate scenarios, reaching around -2 tC ha^{-1} yr^{-1}. This reduction could be attributed to fires in this zone, which caused significant fluctuations in NBP fluxes under RCP4.5 and RCP8.5 (Figure A.3, Figure A.6). Based on NBP fluxes, this unit became a carbon source only after the SBW outbreak but recovered the carbon losses to become a carbon sink 10 years after the outbreak, despite the fluctuations in NBP values caused by fires (Figure A.3).

In the Eastern territory, Climate change effects are anticipated to be beneficial in this unit, as they lead to an increase in NPP relative to R_h, except during the post-outbreak periods when Rh exceeds NPP (Fig. 4). Consequently, the accumulated NEPa and NBPa exhibit positive changes compared to the baseline ($\Delta_{i,j}$>0), potentially exceeding 10, 15, and 18 tC ha^{-1} yr^{-1} under RCP2.6, RCP4.5, and RCP8.5, respectively (Fig. 4). However, despite this positive impact of climate change, the Eastern region may continue to act as a carbon source due to high R_h during the SBW outbreaks, which considerably increases deadwood amounts (Figure A.5).

In all regions and under different climate scenarios, SBW outbreaks (2028, 2060, 2092) are responsible for the temporary increase in R_h, which surpasses NPP (Figure A.3, Figure A.7), leading to negative NEP values (mainly in the East) and an instantaneous increase in post-outbreak DOM carbon storage (Fig. 4). After each outbreak, the NBP increases with more pronounced fluctuations under RCP4.5 and RCP8.5 (Figure A.3), primarily due to the increased burned areas (Figure A.6), especially in the central region.

3.2. Additional effects of forest management on carbon dynamics

3.2.1. Carbon stocks

Our simulations at the landscape scale for all climate scenarios showed that total ecosystem carbon storage (Biomass+ DOM) decreased ($\Delta'_{i,j}<0$), regardless of the applied management approach; compared to the S0 scenario (Fig. 5). In all regions independently of climate scenario, PC-based scenarios (S4, S5, S6) led to an approximate reduction of 5 tC ha^{-1} yr^{-1} (5 %) in total ecosystem carbon storage relative to S0, whereas CC-based scenarios (S1, S2, and S3) resulted in a greater reduction of approximately 10 tC ha^{-1} yr^{-1} (10 %) (Fig. 5). These losses were mainly from reductions in the biomass pool, indeed, the average of differences (over the entire simulation period) in biomass carbon storage varied between 3 and 4 tC ha^{-1} yr^{-1} under CC-based scenarios, whereas it ranged from 1 to 3 tC ha^{-1} yr^{-1} for PC-based scenarios. Conversely, the effect of management on the DOM soil carbon pool was relatively minor. CC-based scenarios reduced the DOM carbon storage by around 2.5 tC ha^{-1} yr^{-1}, while PC-based scenarios led to a reduction of 1 tC ha^{-1} yr^{-1}.

3.2.2. Carbon fluxes

To assess carbon sequestration under different management scenarios, we examined the accumulated NEPa (Fig. 6), which reflects the accumulated balance between NPP and R_h (Figure A.8). In the Western unit, PC-based scenarios initially showed negative deviations in NEPa compared to S0, averaging around -0.85 tC ha^{-1} yr^{-1} across all climate scenarios. However, from 2070 to 2110, these deviations became positive, reaching +1.25 tC ha^{-1} yr^{-1}, indicating a potential improvement in NEPa over time. In contrast, CC-based scenarios consistently displayed negative deviations, with accumulated NEPa reaching as low as -2.5 tC ha^{-1} yr^{-1}, more than double the negative impact observed in PC-based scenarios. In the central and Eastern management units, PC-based strategies enhanced NEPa compared to S0, with positive differences

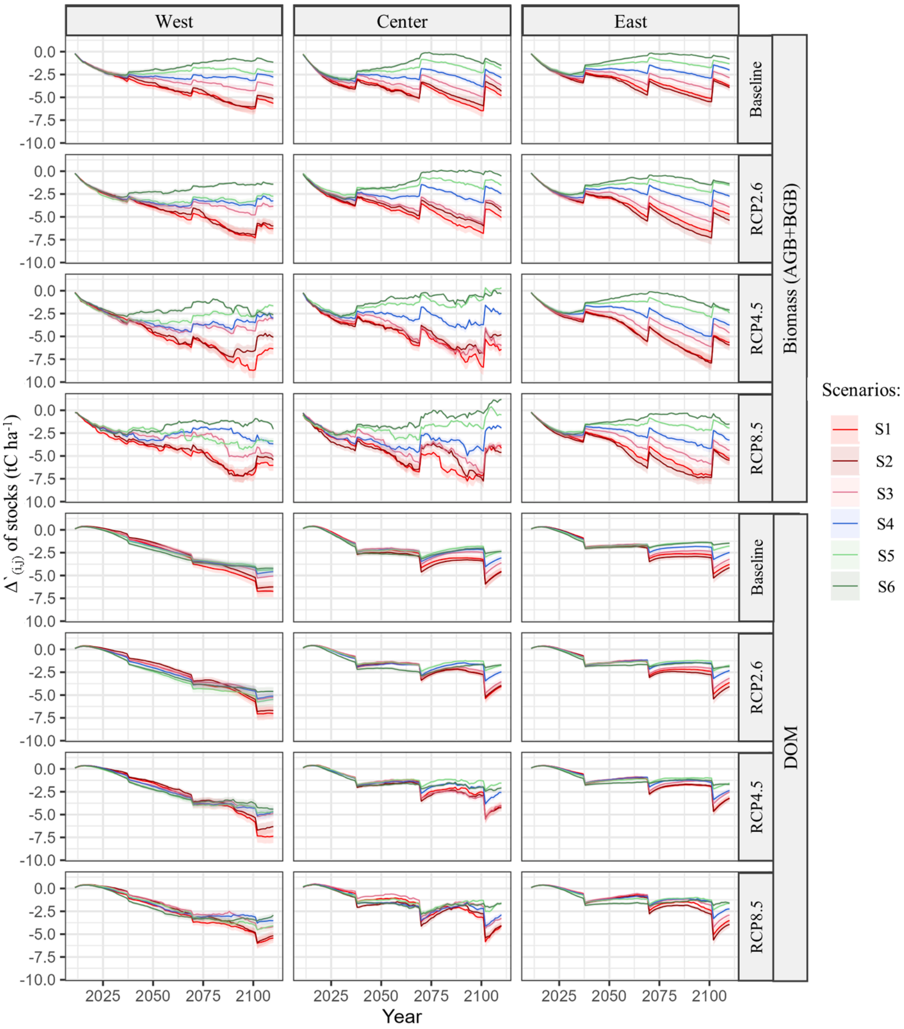

Fig. 5. Averages of the differences ($\Delta'_{i,j}$) between management scenarios S1, S2, S3, S4, S5, and S6) and S0 (see Fig. 2 for details) under climate change scenarios (baseline, RCP2.6, RCP4.5, and RCP8.5) for both biomass and DOM carbon storage (includes deadwood, litter, humus, and mineral soil) (tC ha^{-1}), visualized with their corresponding confidence intervals. Data was derived from four simulation runs for three management units (West, Center, East) of the Quebec boreal forest over 100 years (2010–2110).

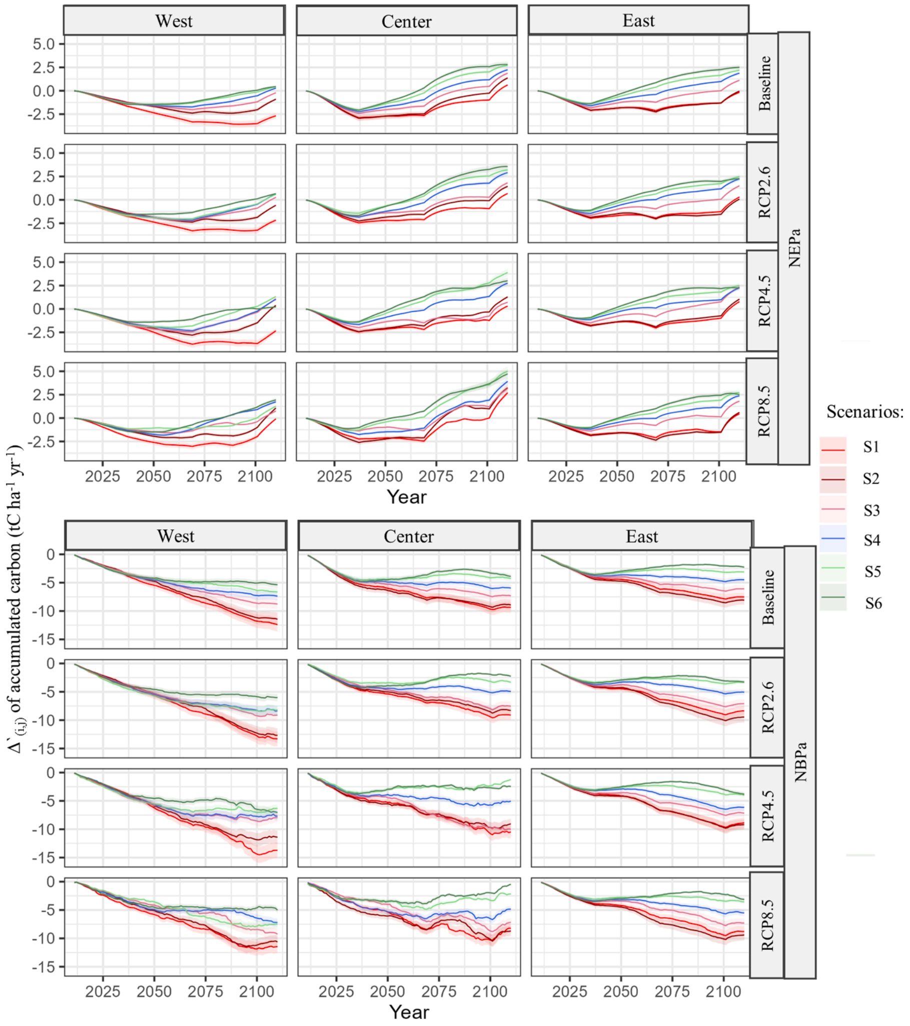

Fig. 6. Average differences ($\Delta'_{i,j}$) between management scenarios (S1, S2, S3, S4, S5, and S6) and S0 under various climate change scenarios (baseline, RCP2.6, RCP4.5, and RCP8.5) for the accumulated net ecosystem productivity (NEP) and net biome productivity (NBP) (tC ha^{-1} yr^{-1}), depicted with their corresponding confidence intervals. NEPa and NBPa reflect the carbon accumulation capacity of each management scenario compared to S0 (total conservation). Data was derived from four simulation runs for three management units (West, Center, and East) of the Quebec boreal forest over 100 years (2010–2110).

averaging +0.5 tC ha^{-1} yr^{-1} across all climate scenarios. Conversely, CC-based scenarios resulted in lower NEPa than S0, with values declining to -2 tC ha^{-1} yr^{-1}. These findings suggest that PC may better maintain or improve NEPa compared to both CC and conservation scenarios.

The consideration of harvest could result in a net reduction in cumulative NBPa between S0 and management scenarios (Fig. 6). However, the differences were more pronounced under CC-based scenarios compared to PC-based ones. Regardless of climate scenarios, the magnitude of changes relative to S0 at the end of simulation under PC-based scenarios could reach -7, -5, and -3 tC ha^{-1} yr^{-1} in Western, Central, and Eastern management units respectively. On the contrary, under CC-based scenarios, these values were doubled, reaching -15, -12, and -10 tC ha^{-1} yr^{-1} in the corresponding management units. Consequently, S0 (conservation) had the greatest NBP accumulation across the three management units, followed by the PC-based scenarios and then the CC-based ones. This can be attributed to the fact that CC-based scenarios export a significant amount of carbon to wood products, whereas the PC-based scenarios produced higher carbon emissions to the atmosphere because more areas are affected by windthrow and SBW outbreaks (Figure A.7), and less carbon is transferred to wood products (Fig. 7).

3.3. *Carbon transfer to wood products*

At the landscape level, annual carbon transfer to wood products rates (*H*) for all management scenarios remained constant in the central region and declined in the other regions until around 2030, after which they increased again in all regions (Fig. 7). For all regions, those rates were generally higher under the RCP scenarios than the current baseline scenario. As with other indicators, The *H* values differed among all management scenarios across all units and climate change scenarios (Fig. 7). The amount of carbon transferred to harvested wood products was lower in PC-based scenarios. For instance, in the Western region under the current baseline climate scenario, S1 and S2 transferred around 2 tC ha^{-1} yr^{-1}, whereas S6 transferred less than 1 tC ha^{-1} yr^{-1}. However, when comparing CC and PC management scenarios, we observed that PC-based scenarios harvested a larger area while transferring less carbon to harvested wood products (Fig. 7). The variation in *H* could be linked to the changes in species abundance across different scenarios.

4. Discussion

The boreal forests of Canada are currently experiencing climate change, including altered precipitation patterns, increased

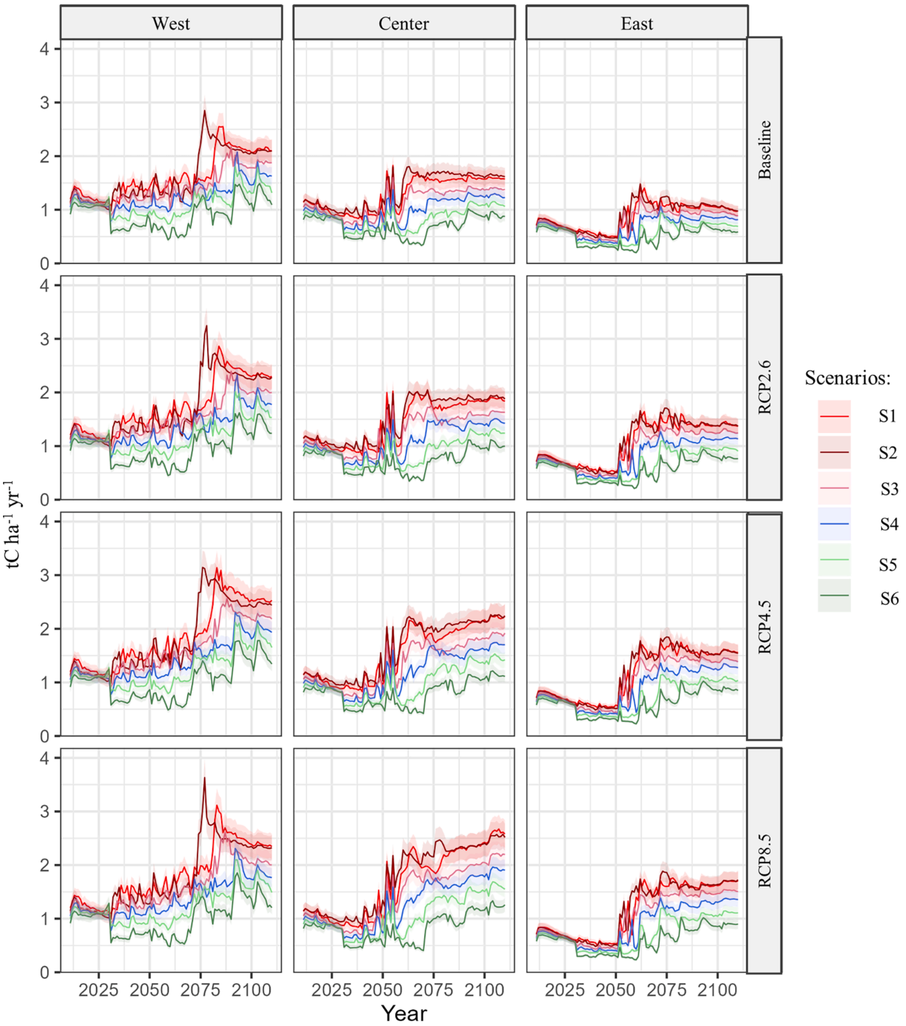

Fig. 7. Average amount of carbon transferred to harvested wood products (H; tC ha^{-1} yr^{-1}), including confidence intervals, per management (S0, S1, S2, S3, S4, S5, and S6) and climate change scenario (baseline, RCP2.6, RCP4.5, and RCP8.5) for three management units in the Quebec boreal forest (West, Center, and East) over 200 years (2010–2110).

temperatures, and changes in the frequency and severity of climate-influenced natural disturbances, such as forest fires and insect outbreaks (SBW) (Achim et al., 2022; Boulanger et al., 2019; Molina et al., 2021; Tremblay et al., 2018; Wang et al., 2016). Our study aimed to improve our understanding of carbon dynamics in the Quebec boreal forest ecosystem near the northern limit of the commercial forest under various climate change and management scenarios. This region's forests are currently characterized by relatively low productivity and severe natural disturbances, mainly wildfires in Quebec's central zones and SBW in Eastern regions. Our study supports previous ones that indicated that future climate change, natural disturbances, and management will affect forest ecosystem carbon fluxes and stocks considerably (Gauthier et al., 2023; Boulanger et al., 2023; Molina et al., 2021). Our study provides additional insights on how the direction and magnitude of the responses of carbon fluxes and stocks depend on the particular climate and management scenario.

4.1. *Impacts of natural disturbances*

Natural disturbances, including wildfires, SBW outbreaks, and windthrow, substantially impact carbon dynamics in boreal forests. Our simulations indicate that wildfires are primarily influenced by climate change, with increasing burn rates under RCP8.5 (Figure A.6). This increase results in significant biomass carbon losses, particularly in the Western and Central regions, where shorter fire cycles exacerbate these effects (Bergeron et al., 2006; Boulanger et al., 2014; Gauthier et al., 2015). SBW outbreaks also contribute to carbon dynamics, with affected areas projected to increase under current climate conditions (Figure A.7), but decrease under RCP4.5 and RCP8.5 due to a rise in broadleaf species that are less susceptible to SBW (Ameray et al., 2023b). The ecosystem carbon losses from SBW are substantial, particularly in the Eastern region, where it may decrease by 2–10 % during 14 years of the outbreak (Dymond et al., 2010). Windthrow, while less impactful than fire and SBW (Bouchard et al., 2009), still contributes to carbon losses, especially under PC-based scenarios that maintain a vulnerable age class of trees. These scenarios may thus increase areas affected by windthrow and, as well as SBW due to the promotion of host tree species (Ameray et al., 2023b).

4.2. *Effect of climate change on forest productivity*

We observed that future climate change is projected to increase forest productivity (as estimated by NPP and biomass) in the Quebec boreal forest. These results are similar to those obtained previously in the same management units (Ameray et al., 2023a; Boulanger et al., 2019; Molina et al., 2021). Furthermore, D'Orangeville et al. (2018) found that a 2 °C increase (~RCP2.6) would cause an increase in forest productivity of up to 13 %. This increased productivity arises from warmer conditions extending the vegetative season and reducing the potential for cold-temperature injuries, thereby promoting greater tree growth (Ameray et al., 2023a). However, warmer conditions also create more favorable fire conditions, increasing disturbance frequency (Pau et al., 2023). Additionally, Marchand et al. (2021) utilized dendrochronological data to demonstrate that during periods of extreme drought, black spruce productivity experiences a significant decline to lower values. In the current climate scenario, Western and Central regions are characterized by the domination of young and mature stands (40–100 years old), likely contributing to the observed increase in NPP, while in Eastern zones, the age structure is predominantly composed of old forests (>120 years), potentially explaining the relative stability of NPP, as well as the high R_h because of senescence-related mortality. Under climate change RCP scenarios, the observed increase in NPP in Western and Central regions could be also attributed to the increase in trembling aspen and white birch abundance (Figure A.4) (Ameray et al., 2023b). Conversely, the Eastern unit exhibits a lower abundance of trembling aspen and white birch under RCP scenarios compared to other management units, consequently, the increase in NPP in Eastern zone is associated with the coniferous species' adaptation to climate change (Ameray et al. 2023a).

Other studies using CBM-CFS3 (Taylor et al., 2008) and LANDIS-II (Boulanger et al., 2017; Boulanger & Puigdevall, 2021; Landry et al., 2021) found that productivity in the Quebec boreal forest will benefit from increased temperatures in northern zones (including our study area), whereas lower coniferous productivity is expected in the more southern regions and transition zones (boreal–temperate forest) (). Our results suggest an exception to this pattern in the western region under RCP8.5, where productivity will be reduced after 2090; similar results have also been reported (Boulanger et al. 2023; Molina et al., 2021). This reduction is linked to climatic stress impacting the growing season of coniferous species, particularly black spruce, white spruce, and jack pine. Under the extreme climate change scenario RCP8.5, the growing season duration may decrease from 140 to approximately 100 days (Ameray et al., 2023a). Moreover, the increased NPP in the central region and NPP recovery in the Western region after 2090 appear to be related to a greater abundance of broadleaf trees (trembling aspen and white birch) in these areas and to the expansions in their growing season from 100 to 160 days (Ameray et al., 2023a).

Under the current baseline climate (1991–2010 historical averages), our estimated aboveground biomass (AGB) at the beginning of the simulation in 2010 was approximately 20 tC ha^{-1}, consistent with literature findings (Boudreau et al., 2008; Duchesne et al., 2016). Duchesne et al. (2016) reported AGB carbon storage in the Quebec boreal forest ranging from 10 to 30 tC·ha^{-1} based on the third forest inventory (1990–2002). Additionally, Boudreau et al. (2008) utilized airborne and spaceborne LiDAR, Landsat ETM, and land cover maps to estimate AGB carbon stocks between 10 and 30 tC ha^{-1} in 2008 in the same regions. Initial DOM carbon storage was 68, 60, and 54 tC ha^{-1} in the West, center, and East management units, respectively, aligning with Paré et al. (2011)'s lower range estimates (60–131 tC ha^{-1}) in the same region. Our model assumed high-severity fires, which kill all oldest cohorts, explaining why DOM initial values align with Paré et al. (2011)'s lower limit. In our model, fire size was updated for each climate change scenario and is projected to increase under global change (Boulanger et al., 2014). Bergeron et al. (2002) stated that a shorter fire return interval may increase young forests and reduce the abundance and extent of mature and old-growth forests (Bergeron et al., 2001); this change was indeed observed under RCP8.5, particularly in the Central region (Figure A.6).

The species' AGB can explain DOM carbon storage dynamics over time. Indeed, under the current baseline climate and natural dynamics scenario, all the studied species increase markedly in AGB over the landscape, particularly in Central region (Figure A.4). Empirical data from Laganière et al. (2015) showed that DOM carbon storage is higher under coniferous cover than under broadleaf trees, whereas broadleaf DOM decay rates are higher than for coniferous trees (Hüblová & Frouz, 2021). Our results show that the DOM carbon pool dropped particularly in Western and central regions, where there is a higher abundance of broadleaves, particularly under RCP4.5 and RCP8.5 climate change scenarios. Clearcutting exacerbates this situation by further increasing the abundance of broadleaves and, consequently, the carbon emissions from their decomposition. For instance, the total AGB of coniferous increased continually under RCP2.6 and RCP4.5 in all regions, except for the Western unit under RCP8.5, which established the largest reductions of coniferous AGB after 2090. Also, a slight decrease in coniferous species biomass was observed at the end of the simulation under RCP8.5 in the central zone. Relative to the initial conditions in the Western unit, the total AGB of black spruce under RCP8.5 decreased by 63 % at the end of the simulation, whereas trembling aspen and white birch stands increased by 263 % and 241 %, respectively. Similar results from Boulanger et al. (2017) and Molina et al. (2021) indicated that the AGB for black spruce significantly declined in this region.

4.3. *Effect of management on carbon dynamics: proposed strategies to mitigate climate change*

Our simulations were designed to compare the effects of partial cut (PC)-based management, clear-cut (CC)-based management, and conservation (S0) strategies on carbon dynamics in the Quebec boreal forest (Table 2). The findings reveal significant differences in how each strategy impacts carbon fluxes and stocks over time.

Clear-Cut (CC)-Based Management: At the stand scale, CC-based strategies tend to induce net emissions immediately following harvest due to higher decomposition rates surpassing carbon sequestration through photosynthesis (Taylor et al., 2008; Paradis et al., 2019). At the landscape scale in our study, CC-based scenarios lead to an increase in the relative abundance of trembling aspen and white birch, which, while increasing NPP in the short term, also results in higher R_h and lower NEP compared to PC-based scenarios (Table 2). This strategy increases the abundance of broadleaf species as well as young forests (Ameray et al., 2023b). This could explain the higher R_h and the reduction of the DOM carbon pool under CC-based management (Hararuk et al., 2017), particularly under RCP4.5 and RCP8.5 where the temperature was increased by 4, and 7 °C respectively. The CC-based scenarios, despite their increased reforestation efforts, could not fully offset the carbon losses resulting from clear-cutting, as seen in scenario S3 (Table 1), which implemented a 25 % annual reforestation rate but still underperformed in carbon sequestration. Also, Laganière et al. (2010) state that the increased rate of decomposition and the release of stored soil carbon following clear-cutting often outweigh the carbon sequestration gains from newly planted trees. On the other hand, the increased harvest volume under CC-based scenarios, though potentially leading to greater carbon storage beyond the ecosystem boundary depending on the life cycle of wood products (Smyth et al. 2014), comes at the cost of reducing old-growth forests and the associated ecosystem services (Zhou et al. 2013), including biodiversity conservation (Martin et al., 2022; Tremblay et al., 2018).

Partial Cut (PC)-Based Management: In contrast, PC-based scenarios maintain tree cover, accruing less carbon debt and ensuring a more consistent turnover of organic matter. Our simulations align with findings by other studies (Daigneault et al., 2024; Giasson et al., 2023; Taylor et al., 2008), showing that PC-based management leads to higher NPP and lower R_h compared to CC-based management, resulting in enhanced NEP and better overall carbon retention within the ecosystem. PC-based scenarios also preserve a higher proportion of coniferous cover and old-growth forests (Table 2), which play a critical role in enhancing long-term carbon sequestration and storage (Robinson et al., 2022). However, the potential expansion of older stands under PC-based management can lead to an increase in deadwood inputs to the DOM pool, which, although slower to decompose, still contributes to R_h over time. The overall benefits of PC-based management include maintaining

Table 2
A summary of advantages and disadvantages of conservation, partial cutting (PC)–based scenarios, and clearcutting (CC)-based scenarios in terms of age structure, composition, carbon sequestration and carbon storage, and disturbance (+++: high, ++: medium, +: low) under current climate and the additional effect of future climate scenarios (RCP): positive (+ increase) or negative (- decrease) or minimal change (∼) relative to the baseline conditions. The effect of each strategy on age structure and composition are outlined in Ameray et al., (2023b).

Component		Strategy under current climate			Additional effects of climate change		
		Conservation	PC-based scenarios	CC-based scenarios	RCP2.6	RCP4.5	RCP8.5
Age structure abundance	**Old**	+++	++	+	∼	-	-
	Mature	++	+++	+	∼	∼	-
	Young	+	++	+++	∼	+	+
Composition abundance	**Broadleaf**	+	++	+++	+	+	+
	Coniferous	+++	++	+	+	+	-
Carbon sequestration and storage	**NEP**	++	+++	+	+	+	+
	Biomass	+++	++	+	+	+	+ except in Western region
	DOM	+++	++	+	∼	-	-
	HWP	No-harvest	++	+++	+	+	+
Disturbances	**Fire**	+++	+++	+++	+	+	+
	SBW	+++	++	+	∼	∼	-
	Winds	+++	++	+	∼	-	-

a diverse age structure and enhancing long-term carbon storage, potentially making it a preferable option under changing climate conditions (Harmon & Campbell, 2017; Moussaoui et al., 2020). Furthermore, PC has the advantage of producing larger stems compared to CC, which can increase carbon sequestration and substitution benefits in longer-lived wood products (Auty et al., 2014; Smyth et al. 2014).

Conservation: Our simulation showed that this strategy generally stores more carbon in both DOM and biomass across various future climate scenarios. This finding is supported by studies from Keith et al. (2009) and Luyssaert et al. (2008), all of which highlight the role of conservation in maintaining high levels of carbon storage, particularly in old-growth forests. However, in the Eastern region, where coniferous species are expected to dominate, the accumulated NEP may be higher under PC-based scenarios compared to conservation in the long term, due to sustained NPP and lower decomposition rate (R_h). This indicates that while conservation remains a critical strategy for maintaining carbon stocks, integrating PC-based management can enhance carbon sequestration (Luyssaert et al., 2008; Zhou et al. 2013).

Balanced approach: Given the findings above, a balanced approach that integrates both PC and CC treatments may offer the best outcomes for carbon sequestration and ecosystem sustainability. PC-based scenarios (S4, S5, S6) demonstrated superior carbon sequestration and storage compared to CC-based ones (S1, S2, S3). However, scenarios with extreme PC-based (S6) mimicked natural dynamics and achieved the highest total ecosystem carbon storage, yet they posed challenges in meeting industrial needs (harvested biomass lower than the allowed annual cut). In contrast, Scenarios S4 (50% PC/50 % CC) and S5 (75% PC/25 % CC) emerged as optimal for maximizing carbon sequestration, conserving biodiversity, and fulfilling industrial demands. The TRIAD approach, which divides landscapes into zones for conservation, intensive management, and extensive management, aligns well with these strategies and supports diverse forest composition and age structure at various scales (Seymour & Hunter, 1992). To effectively implement S4 and S5, coniferous reforestation rates must be increased to 8 % and 17 % of the annually harvested area in the Eastern regions, with appropriate rates already applied in the Western and central regions (Table 1). While these strategies have demonstrated greater efficacy in climate change mitigation, they require improved infrastructure, presenting future logistical and financial challenges (Cyr et al., 2021).

Innovative products: the wood industry in Quebec faces significant challenges due to climate change, necessitating a proactive approach to forest management. Our simulations forecast an increase in broadleaf species abundance, mainly under CC-based scenarios and RCP scenarios (Table 2), consequently the transition towards innovative products that focus on broadleaf species rather than coniferous is essential (McKenney et al., 2016). For instance, broadleaf species, such as aspen and birch, are increasingly recognized for their potential in producing high-value products like bioenergy, and biochemicals (Laganière et al., 2015; Paradis et al., 2019). This shift not only addresses the challenges posed by climate change but could also create economic opportunities, ensuring the continuity of industrial operations and contributing to the preservation of forest resources.

4.4. *Model improvements and limitations*

The ForCS model, an extension of LANDIS-II, exhibits several limitations that affect its accuracy in simulating forest carbon dynamics. One significant issue is the model's sensitivity to input parameters, particularly those related to growth and establishment probabilities. These parameters, calibrated using growth and yield curves, are critical to the model's projections, but their variability can lead to inconsistent results (Dymond et al., 2016; Hof et al., 2017). Moreover, the modeling of dead organic matter (DOM) in mineral soils, based on CBM-CFS3, is a significant source of uncertainty, largely due to the current omission of lignin content representation (Metsaranta et al., 2017; Hararuk et al., 2017). The model also excludes several processes crucial for carbon storage, such as the chemical composition of litter and microclimate regulation (Feng et al., 2006). Furthermore, LANDIS-II is limited in how it represents the regeneration of broadleaf species, particularly in regions with organic soils and nutrient deficiencies (Ameray et al., 2023a). This limitation could affect the model's ability to accurately predict changes in forest composition and productivity. Another key limitation is the model's inability to properly account for the effect of light availability, which restricts its capacity to represent certain stand types, such as the paludified stands of western Quebec, where establishment and growth are not light-dependent. Lastly, we point out that the harvest model uses annual harvested areas per treatment instead of volumes (or biomass), which explains the variation in harvested biomass across different scenarios.

From the user's perspective, there are additional limitations related to how certain interactions are considered in the model. Notably, we did not account for salvage harvesting following disturbances such as SBW outbreaks. This omission could lead to an overestimation of carbon losses due to increased respiration rates (R_h) observed under partial cutting (PC) scenarios, as salvage harvesting might mitigate some of these losses. Moreover, the model does not incorporate the interactions between partial harvesting and subsequent disturbances like windthrow. This exclusion is significant because partial harvesting can alter stand age structure and composition, which in turn affects the forest's vulnerability to disturbances like windthrow and the associated carbon dynamics (Girona et al., 2019; Lavoie et al., 2021). By not including these interactions, the model may underestimate the potential impact of partial harvesting on the overall carbon balance. Despite the limitations, our study demonstrates the potential of a forest landscape model to simulate and reduce uncertainty around climate-adaptive silvicultural practices. These results can help managers make better-informed decisions for sustainable forest management in the face of global change.

5. Conclusions

Our study indicates that climate change will likely increase future forest NPP, R_h, and carbon emissions in Quebec's boreal forests, mainly due to wildfires and SBW outbreaks. Over the next century, the combined effects of climate change and clearcutting are expected to increase the abundance of young forests and pioneer species, leading to greater carbon sequestration in vegetation, yet this increase may not fully counterbalance the carbon emissions from decomposition. We assessed the impact of various forest management strategies under different climate change scenarios, finding that the conservation scenario is projected to maintain the highest levels of carbon in both soil and living biomass pools. PC-based scenarios, on the other hand, produce conditions similar to conservation scenario, preserving coniferous species abundance and more old-growth and mature forests, thereby enhancing long-term ecosystem carbon sequestration and storage. In contrast, CC-based scenarios are associated with reduced carbon storage and lower carbon sequestration capacity than PC-based scenarios. Although clearcutting promotes the abundance of young forest and broadleaf species, it results in lower NEP, due to the higher decay rates associated with these species. To achieve a balance between carbon sequestration, industrial needs, and ecosystem sustainability, a combination of clearcutting and partial-cutting approaches is essential. Our study identifies strategies like S5 (75% PC/25 % CC) and S4 (50% PC/50 % CC) as the most effective, as they successfully integrate the advantages of both harvesting methods. However, further studies are required to explore necessary industrial adaptations and the socioeconomic implications of these strategies under future climate conditions.

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CRediT authorship contribution statement

Abderrahmane Ameray: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Xavier Cavard:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Dominic Cyr:** Writing – review & editing, Validation, Resources, Methodology. **Osvaldo Valeria:** Writing – review & editing, Investigation. **Miguel Montoro Girona:** Writing – review & editing, Investigation. **Yves Bergeron:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors have no conflict of interest to declare.

Data availability

Data will be made available on request.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.ecolmodel.2024.110894.

References

Aakala, T., Remy, C.C., Arseneault, D., Morin, H., Girardin, M.P., Gennaretti, F., Navarro, L., Kuosmanen, N., Ali, A.A., Boucher, É., 2023. Millennial-scale disturbance history of the boreal zone. Boreal Forests in the Face of Climate change: Sustainable Management. Springer, pp. 53–87.

Achim, A., Moreau, G., Coops, N.C., Axelson, J.N., Barrette, J., Bédard, S., Byrne, K.E., Caspersen, J., Dick, A.R., D'Orangeville, L., Drolet, G., Eskelson, B.N.I., Filipescu, C. N., Flamand-Hubert, M., Goodbody, T.R.H., Griess, V.C., Hagerman, S.M., Keys, K., Lafleur, B., White, J.C, 2022. The changing culture of silviculture. Forestry: An Int. J. For. Res. 95 (2), 143–152. https://doi.org/10.1093/forestry/cpab047.

Ameray, A., Bergeron, Y., Cavard, X., 2023b. Modelling the potential of forest management to mitigate climate change in Eastern Canadian forests. Sci. Rep. 13 (1), 14506. https://doi.org/10.1038/s41598-023-41790-2.

Ameray, A., Bergeron, Y., Cavard, X., 2023a. Climate change may increase Quebec boreal forest productivity in high latitudes by shifting its current composition. Front. For. Glob. Change 6 (20). https://doi.org/10.3389/ffgc.2023.1020305.

Ameray, A., Bergeron, Y., Valeria, O., Girona, M., Cavard, X., 2021. Forest carbon management: a review of silvicultural practices and management strategies across boreal, tropical, and temperate forests. Curr. For. Rep.

Auty, D., Achim, A., Bédard, P., Pothier, D., 2014. StatSAW: modelling lumber product assortment using zero-inflated Poisson regression. Can. J. For. Res. 44 (6), 638–647. https://doi.org/10.1139/cjfr-2013-0500.

Bellassen, V., Luyssaert, S., 2014. Carbon sequestration: managing forests in uncertain times. Nature 506 (7487), 153–155.

Bergeron, Y., Cyr, D., Drever, C., Flannigan, M., Gauthier, S., Kneeshaw, D., Lauzon, È., Leduc, A., Goff, H., Lesieur, D., Logan, K., 2006. Past, current, and future fire frequencies in Quebec's commercial forests: Implications for the cumulative effects of harvesting and fire on age-class structure and natural disturbance-based management. Can. J. For. Res. 36, 2737–2744. https://doi.org/10.1139/X06-177.

Bergeron, Y., Gauthier, S., Kafka, V., Lefort, P., Lesieur, D., 2001. Natural fire frequency for the eastern Canadian boreal forest: consequences for sustainable forestry. Can. J. For. Res. 31 (3), 384–391.

Bergeron, Y., Leduc, A., Harvey, B.D., Gauthier, S., 2002. Natural fire regime: a guide for sustainable management of the Canadian boreal forest. Silva Fennica 36 (1), 81–95.

Bouchard, M., Pothier, D., Ruel, J.-C, 2009. Stand-replacing windthrow in the boreal forests of eastern Quebec. Can. J. For. Res. 39, 481–487.

Boudreau, J., Nelson, R.F., Margolis, H.A., Beaudoin, A., Guindon, L., Kimes, D.S., 2008. Regional aboveground forest biomass using airborne and spaceborne LiDAR in Québec. Remote Sens. Environ. 112 (10), 3876–3890.

Boulanger, Y., Arseneault, D., Boucher, Y., Gauthier, S., Cyr, D., Taylor, A.R., Price, D.T., Dupuis, S., 2019. Climate change will affect the ability of forest management to reduce gaps between current and presettlement forest composition in southeastern Canada. Landsc. Ecol. 34 (1), 159–174. https://doi.org/10.1007/s10980-018-0761-6.

Boulanger, Y., Arseneault, D., Morin, H., Jardon, Y., Bertrand, P., Dagneau, C., 2012. Dendrochronological reconstruction of spruce budworm (Choristoneura fumiferana) outbreaks in southern Quebec for the last 400 years1This article is one of a selection of papers from the 7th international conference on disturbance dynamics in boreal forest. Can. J. For. Res. 42 (7), 1264–1276. https://doi.org/10.1139/x2012-069.

Boulanger, Y., Gauthier, S., Burton, P.J., 2014. A refinement of models projecting future Canadian fire regimes using homogeneous fire regime zones. Can. J. For. Res. 44 (4), 365–376.

Boulanger, Y., Puigdevall, J.P., Bélisle, A.C., Bergeron, Y., Brice, M.-H., Cyr, D., De Grandpré, L., Fortin, D., Gauthier, S., Grondin, P., Labadie, G., Leblond, M., Marchand, M., Splawinski, T.B., St-Laurent, M.-H., Thiffault, E., Tremblay, J.A., Yamasaki, S.H., 2023. A regional integrated assessment of the impacts of climate change and of the potential adaptation avenues for Quebec's forests. Can. J. For. Res. https://doi.org/10.1139/cjfr-2022-0282.

Boulanger, Y., Puigdevall, P.J., 2021. Boreal forests will be more severely affected by projected anthropogenic climate forcing than mixedwood and northern hardwood forests in eastern Canada. Landsc. Ecol. 36 (6), 1725–1740. https://doi.org/10.1007/s10980-021-01241-7.

Boulanger, Y., Taylor, A.R., Price, D.T., Cyr, D., McGarrigle, E., Rammer, W., Sainte-Marie, G., Beaudoin, A., Guindon, L., Mansuy, N., 2017. Climate change impacts on forest landscapes along the Canadian southern boreal forest transition zone. Landsc. Ecol. 32 (7), 1415–1431. https://doi.org/10.1007/s10980-016-0421-7.

Campbell, J., Alberti, G., Martin, J., Law, B.E., 2009. Carbon dynamics of a ponderosa pine plantation following a thinning treatment in the northern Sierra Nevada. For. Ecol. Manage 257 (2), 453–463.

Cyr, D., Splawinski, T.B., Pascual Puigdevall, J., Valeria, O., Leduc, A., Thiffault, N., Bergeron, Y., Gauthier, S, 2021. Mitigating post-fire regeneration failure in boreal landscapes with reforestation and variable retention harvesting: At what cost? Can. J. For. Res. 52 (4), 568–581. https://doi.org/10.1139/cjfr-2021-0180.

Daigneault, A., Simons-Legaard, E., Weiskittel, A., 2024. Tradeoffs and synergies of optimized management for maximizing carbon sequestration across complex landscapes and diverse ecosystem services. For. Policy. Econ. 161, 103178.

De Bruijn, A., Gustafson, E.J., Sturtevant, B.R., Foster, J.R., Miranda, B.R., Lichti, N.I., Jacobs, D.F., 2014. Toward more robust projections of forest landscape dynamics under novel environmental conditions: embedding PnET within LANDIS-II. Ecol. Modell. 287, 44–57.

Dixon, R.K., Solomon, A.M., Brown, S., Houghton, R.A., Trexier, M.C., Wisniewski, J., 1994. Carbon pools and flux of global forest ecosystems. Science (1979) 263 (5144), 185. LP –190. http://science.sciencemag.org/content/263/5144/185.abstract.

D'Orangeville, L., Houle, D., Duchesne, L., Phillips, R.P., Bergeron, Y., Kneeshaw, D., 2018. Beneficial effects of climate warming on boreal tree growth may be transitory. Nat. Commun. 9 (1), 3213. https://doi.org/10.1038/s41467-018-05705-4.

Duchesne, L., Houle, D., Ouimet, R., Lambert, M.-C., Logan, T., 2016. Aboveground carbon in Quebec forests: stock quantification at the provincial scale and assessment of temperature, precipitation and edaphic properties effects on the potential stand-level stocking. PeerJ. 4, e1767.

Duchesne, L., Ouimet, R., 2021. Digital mapping of soil texture in ecoforest polygons in Quebec, Canada. PeerJ. 9, e11685. https://doi.org/10.7717/peerj.11685.

Dymond, C., Beukema, S., Nitschke, C.R., Coates, K.D., Scheller, R.M., 2016. Carbon sequestration in managed temperate coniferous forests under climate change. Biogeosciences.

Dymond, C.C., Neilson, E.T., Stinson, G., Porter, K., MacLean, D.A., Gray, D.R., Kurz, W. A., 2010. Future spruce budworm outbreak may create a carbon source in eastern Canadian forests. Ecosystems. 13, 917–931.

Feng, R.-F., Yang, W.-Q., Zhang, J., 2006. Artificial forest management for global change mitigation. Acta Ecologica Sinica 11 (26), 3870–3877.

Gauthier, S., Bernier, P., Kuuluvainen, T., Shvidenko, A.Z., Schepaschenko, D.G., 2015. Boreal forest health and global change. Science (1979) 349 (6250), 819–822.

Gauthier, S., Kuuluvainen, T., Macdonald, S.E., Shorohova, E., Shvidenko, A., Bélisle, A.-C., Vaillancourt, M.-A., Leduc, A., Grosbois, G., Bergeron, Y., 2023. Ecosystem management of the boreal forest in the era of global change. Boreal Forests in the Face of Climate Change: Sustainable Management. Springer, pp. 3–49.

Giasson, L.A., Thiffault, E., Lebel, L., Carle, J.F., 2023. Carbon balance of forest management and wood production in the boreal forest of Quebec (Canada). Front. For. Glob. Change 6, 1242218.

Girona, M., Aakala, T., Aquilué, N., Bélisle, A., Chaste, E., Danneyrolles, V., Díaz-Yáñez, O., D'Orangeville, L., Grosbois, G., Hester, A., Kim, S., Kulha, N., Martin, M., Moussaoui, L., Pappas, C., Portier, J., Teitelbaum, S., Tremblay, J.-P., Svensson, J., Gauthier, S, 2023a. Challenges for the sustainable management of the boreal forest under climate change bt - boreal forests in the face of climate change: sustainable management. In: Girona, H, Morin, S.Gauthier, Bergeron, Y. (Eds.). Springer International Publishing, pp. 773–837. https://doi.org/10.1007/978-3-031-15988-6_31.

Girona, M.M., Morin, H., Lussier, J.-M., Ruel, J.-C., 2019. Post-cutting mortality following experimental silvicultural treatments in unmanaged boreal forest stands. In: Frontiers in Forests and Global Change, 2. https://www.frontiersin.org/article/10.3389/ffgc.2019.00004.

Girona, M.M., Moussaoui, L., Morin, H., Thiffault, N., Leduc, A., Raymond, P., Bosé, A., Bergeron, Y., Lussier, J.-M., 2023b. Innovative silviculture to achieve sustainable forest management in boreal forests: lessons from two large-scale experiments. Boreal Forests in the Face of Climate Change: Sustainable Management. Springer, pp. 417–440.

Goulden, M.L., McMillan, A.M.S., Winston, G.C., Rocha, A.V, Manies, K.L., Harden, J.W., Bond-Lamberty, B.P., 2011. Patterns of NPP, GPP, respiration, and NEP during boreal forest succession. Glob. Chang. Biol. 17 (2), 855–871.

Grace, J., 2005. Role of forest biomes in the global carbon balance. The Carbon Balance of Forest Biomes. Taylor & Francis, pp. 19–45.

Gustafson, E.J., Kern, C.C., Kabrick, J.M., 2023b. Can assisted tree migration today sustain forest ecosystem goods and services for the future? For. Ecol. Manage 529, 120723. https://doi.org/10.1016/j.foreco.2022.120723.

Gustafson, E.J., Miranda, B.R., Sturtevant, B.R., Zhou, Z., 2023a. PnET-Succession v 5.1: comprehensive description of an ecophysiological succession extension within the LANDIS-II forest landscape model. Published by The LANDIS-II Foundation. URL. https://github.com/LANDIS-II-Foundation/Foundation-Publications/blob/main.

Gustafson, E.J., Shifley, S.R., Mladenoff, D.J., Nimerfro, K.K., He, H.S., 2000. Spatial simulation of forest succession and timber harvesting using LANDIS. Can. J. For. Res. 30 (1), 32–43.

Hararuk, O., Shaw, C., Kurz, W.A., 2017. Constraining the organic matter decay parameters in the CBM-CFS3 using Canadian national forest inventory data and a bayesian inversion technique. Ecol. Modell. 364, 1–12.

Harmon, M.E., & Campbell, J.L. (2017). c. People, Forests, and Change: Lessons from the Pacific Northwest, 161–173.

Hof, A.R., Dymond, C.C., Mladenoff, D.J., 2017. Climate change mitigation through adaptation: the effectiveness of forest diversification by novel tree planting regimes. Ecosphere 8 (11), e01981.

Hüblová, L., Frouz, J., 2021. Contrasting effect of coniferous and broadleaf trees on soil carbon storage during reforestation of forest soils and afforestation of agricultural and post-mining soils. J. Environ. Manage. 290, 112567. https://doi.org/10.1016/j.jenvman.2021.112567.

Jandl, R., Lindner, M., Vesterdal, L., Bauwens, B., Baritz, R., Hagedorn, F., Johnson, D. W., Minkkinen, K., Byrne, K.A., 2007. How strongly can forest management influence soil carbon sequestration? Geoderma 137 (3), 253–268. https://doi.org/10.1016/j.geoderma.2006.09.003.

Jobidon, R., Bergeron, Y., Robitaille, A., Raulier, F., Gauthier, S., Imbeau, L., Saucier, J.-P., Boudreault, C., 2015. A biophysical approach to delineate a northern limit to commercial forestry: the case of Quebec's boreal forest. Can. J. For. Res. 45 (5), 515–528.

Keith, H., Mackey, B.G., Lindenmayer, D.B., 2009. Re-evaluation of forest biomass carbon stocks and lessons from the world's most carbon-dense forests. Proc. Natl. Acad. Sci. 106 (28), 11635–11640.

Köhl, M., Lasco, R., Cifuentes, M., Jonsson, Ö., Korhonen, K.T., Mundhenk, P., de Jesus Navar, J., Stinson, G., 2015. Changes in forest production, biomass and carbon: results from the 2015 UN FAO global forest resource assessment. For. Ecol. Manage. 352, 21–34.

Krug, J.H.A., 2018. Accounting of GHG emissions and removals from forest management: a long road from Kyoto to Paris. Carbon. Balance Manage. 13 (1), 1. https://doi.org/10.1186/s13021-017-0089-6.

Kurz, W.A., Dymond, C.C., White, T.M., Stinson, G., Shaw, C.H., Rampley, G.J., Smyth, C., Simpson, B.N., Neilson, E.T., Trofymow, J.A., 2009. CBM-CFS3: a model of carbon-dynamics in forestry and land-use change implementing IPCC standards. Ecol. Modell. 220 (4), 480–504.

Laganière, J., Angers, D.A., Paré, D., 2010. Carbon accumulation in agricultural soils after afforestation: a meta-analysis. Glob. Chang. Biol. 16 (1), 439–453.

Laganière, J., Cavard, X., Brassard, B.W., Paré, D., Bergeron, Y., Chen, H.Y.H., 2015. The influence of boreal tree species mixtures on ecosystem carbon storage and fluxes. For. Ecol. Manage. 354, 119–129. https://doi.org/10.1016/j.foreco.2015.06.029.

Landry, G., Thiffault, E., Cyr, D., Moreau, L., Boulanger, Y., & Dymond, C. (2021). Mitigation potential of ecosystem-based forest management under climate change: a case study in the boreal-temperate forest ecotone. In Forests.(Vol. 12, Issue 12). https://doi.org/10.3390/f12121667.

Lavoie, J., Montoro Girona, M., Grosbois, G., Morin, H., 2021. Does the Type of Silvicultural Practice Influence Spruce Budworm Defoliation of Seedlings?, 12. Ecosphere, p. e03506.

Luyssaert, S., Schulze, E.D., Börner, A., Knohl, A., Hessenmöller, D., Law, B.E., Ciais, P., Grace, J., 2008. Old-growth forests as global carbon sinks. Nature 455 (7210), 213–215. https://doi.org/10.1038/nature07276.

MacLean, D.A., 2016. Impacts of insect outbreaks on tree mortality, productivity, and stand development. Can. Entomol. 148 (S1), S138–S159. https://doi.org/10.4039/tce.2015.24.

Marchand, W., Girardin, M.P., Hartmann, H., Lévesque, M., Gauthier, S., Bergeron, Y., 2021. Contrasting life-history traits of black spruce and jack pine influence their physiological response to drought and growth recovery in northeastern boreal Canada. Sci. Total Environ. 794, 148514.

Martin, M., Leduc, A., Fenton, N.J., Montoro Girona, M., Bergeron, Y., Valeria, O., 2022. Irregular forest structures originating after fire: an opportunity to promote alternatives to even-aged management in boreal forests. J. Appl. Ecol. 59 (7), 1792–1803. https://doi.org/10.1111/1365-2664.14186.

Mayer, M., Prescott, C.E., Abaker, W.E.A., Augusto, L., Cécillon, L., Ferreira, G.W.D., James, J., Jandl, R., Katzensteiner, K., Laclau, J.-P., Laganière, J., Nouvellon, Y., Paré, D., Stanturf, J.A., Vanguelova, E.I., Vesterdal, L., 2020. Tamm review: influence of forest management activities on soil organic carbon stocks: a knowledge synthesis. For. Ecol. Manage. 466, 118127. https://doi.org/10.1016/j.foreco.2020.118127.

McKenney, D.W., 2016. Canada's Timber Supply: Current status and Future Prospects Under A Changing Climate. Natural Resources Canada, Canadian Forest Service, Great Lakes Forestry Centre.

Metsaranta, J.M., Shaw, C.H., Kurz, W.A., Boisvenue, C., Morken, S., 2017. Uncertainty of inventory-based estimates of the carbon dynamics of Canada's managed forest (1990–2014). Can. J. For. Res. 47 (8), 1082–1094.

Mladenoff, D.J., He, H.S., 1999. Design, behavior and application of LANDIS, an object-oriented model of forest landscape disturbance and succession. Spatial Modeling of Forest Landscape Change: Approaches and Applications. Cambridge University Press, Cambridge, UK, pp. 125–162.

Molina, E., Valeria, O., De Grandpre, L., Ramirez, J.A., Cyr, D., Boulanger, Y., 2021. Projecting future aboveground biomass and productivity of managed eastern canadian mixedwood boreal forest in response to climate change. For. Ecol. Manag. 487, 119016.

Moussaoui, L., Leduc, A., Girona, M.M., Bélisle, A.C., Lafleur, B., Fenton, N.J., Bergeron, Y., 2020. Success factors for experimental partial harvesting in unmanaged boreal forest: 10-year stand yield results. Forests. 11 (11), 1199.

MRNF, 2010b. b Système hiérarchique de classification écologique du territoire. https://mffp.gouv.qc.ca/forets/inventaire/inventaire-systeme.jsp.

MRNF, 2010a. a Forêt ouverte: inventaire forestier national. https://www.foretouverte.gouv.qc.ca/?context=_catalogue_complet&zoom=6&center=-73,51&invisiblelayers=*&visiblelayers=pee_index_pdf_mai2015,fond&llcv=1.

Navarro, L., Morin, H., Bergeron, Y., Girona, M.M., 2018. Changes in spatiotemporal patterns of 20th century spruce budworm outbreaks in Eastern Canadian Boreal forests. In: Frontiers in Plant Science, 9, p. 1905. https://www.frontiersin.org/article/10.3389/fpls.2018.01905.

NFD. (2023). *Forestry highlights | national forestry database*. http://nfdp.ccfm.org/en/highlights.php.

Pan, Y., Birdsey, R.A., Fang, J., Houghton, R., Kauppi, P.E., Kurz, W.A., Phillips, O.L., Shvidenko, A., Lewis, S.L., Canadell, J.G., Ciais, P., Jackson, R.B., Pacala, S.W., McGuire, A.D., Piao, S., Rautiainen, A., Sitch, S., Hayes, D., 2011. A large and persistent carbon sink in the world's forests. Science (1979) 333 (6045), 988. https://doi.org/10.1126/science.1201609. LP –993.

Paradis, L., Thiffault, E., Achim, A., 2019. Comparison of carbon balance and climate change mitigation potential of forest management strategies in the boreal forest of Quebec (Canada). Forestry: An Int. J. For. Res. 92 (3), 264–277. https://doi.org/10.1093/forestry/cpz004.

Paré, D., Banville, J.L., Garneau, M., Bergeron, Y., 2011. Soil carbon stocks and soil carbon quality in the upland portion of a boreal landscape, James Bay, Quebec. Ecosystems. 14 (4), 533–546. https://doi.org/10.1007/s10021-011-9429-7.

Pau, M., Gauthier, S., Boulanger, Y., Ouzennou, H., Girardin, M.P., Bergeron, Y., 2023. Response of forest productivity to changes in growth and fire regime due to climate change. Can. J. For. Res. https://doi.org/10.1139/cjfr-2022-0207.

Pothier, D., Savard, F., 1998. Actualisation des tables de production pour les principales espèces du Québec. Gouvernement Du Québec, Ministère Des Ressources Naturelles, Bibliothèque Nationale Du Québec RN98–3054.

Robinson, A.J., Defrenne, C.E., Roach, W.J., Dymond, C.C., Pickles, B.J., Simard, S.W., 2022. Harvesting intensity and aridity are more important than climate change in affecting future carbon stocks of Douglas-fir forests. Front. For. Glob. Change 5, 934067.

Scheller, R.M., & Domingo, J.B. (2018). LANDIS-II base fire v4.0 extension user guide. In Reproduction. (pp. 0–9).

Scheller, R.M., Domingo, J.B., Sturtevant, B.R., Williams, J.S., Rudy, A., Gustafson, E.J., Mladenoff, D.J., 2007. Design, development, and application of LANDIS-II, a spatial landscape simulation model with flexible temporal and spatial resolution. Ecol. Modell. 201 (3–4), 409–419.

Scheller, R.M., Mladenoff, D.J., 2004. A forest growth and biomass module for a landscape simulation model, LANDIS: design, validation, and application. Ecol. Modell. 180 (1), 211–229. https://doi.org/10.1016/j.ecolmodel.2004.01.022.

Scheller, R.M., Sturtevant, B.R., Gustafson, E.J., Miranda, B.R., & Zollner, P.A. (2019). Biomass harvest v4.3 LANDIS-II extension user guide. 0–9.

Scheller, R.M., Sturtevant, B.R., Gustafson, E.J., Miranda, B.R., Zollner, P.A., Mladenoff, D.J., & Domingo, J.B. (2018). LANDIS-II base wind v3.0 extension user guide (pp. 1–11).

Seymour, R.S., Hunter, M.L., 1992. New Forestry in Eastern Spruce-Fir Forests: Principles and Applications to Maine, 716. College of Forest Resources, University of Maine Orono, ME, USA.

Smyth, C.E., Stinson, G., Neilson, E., Lemprière, T.C., Hafer, M., Rampley, G.J., Kurz, W. A., 2014. Quantifying the biophysical climate change mitigation potential of Canada's forest sector. Biogeosciences. 11 (13), 3515–3529.

Sturtevant, B.R., Gustafson, E.J., Li, W., He, H.S., 2004. Modeling biological disturbances in LANDIS: a module description and demonstration using spruce budworm. Ecol. Modell. 180 (1), 153–174. https://doi.org/10.1016/j.ecolmodel.2004.01.021.

Sturtevant, B.R., He, H.S., Scheller, R.M., & Miranda, B.R. (2019). LANDIS-II biological disturbance agent v2. 0 extension user guide. 0–19.

Taylor, A.R., Wang, J.R., Kurz, W.A., 2008. Effects of harvesting intensity on carbon stocks in eastern Canadian red spruce (Picea rubens) forests: an exploratory analysis using the CBM-CFS3 simulation model. For. Ecol. Manage. 255 (10), 3632–3641. https://doi.org/10.1016/j.foreco.2008.02.052.

Tremblay, J.A., Boulanger, Y., Cyr, D., Taylor, A.R., Price, D.T., St-Laurent, M.-H., 2018. Harvesting interacts with climate change to affect future habitat quality of a focal species in eastern Canada's boreal forest. PLoS. One 13 (2), e0191645.

Vestin, P., Mölder, M., Kljun, N., Cai, Z., Hasan, A., Holst, J., Lindroth, A., 2020. Impacts of clear-cutting of a boreal forest on carbon dioxide, methane and nitrous oxide fluxes. Forests. 11 (9), 961.

Wang, T., Hamann, A., Spittlehouse, D., Carroll, C., 2016. Locally downscaled and spatially customizable climate data for historical and future periods for North America. PLoS. One 11 (6), e0156720. https://doi.org/10.1371/journal.pone.0156720.

White, J.W., Rassweiler, A., Samhouri, J.F., Stier, A.C., White, C., 2014. Ecologists should not use statistical significance tests to interpret simulation model results. Oikos. 123 (4), 385–388.

Zhou, D., Zhao, S.Q., Liu, S., Oeding, J., 2013. A meta-analysis on the impacts of partial cutting on forest structure and carbon storage. Biogeosciences. 10 (6), 3691–3703.

Zhuo, W., Dai, E., Wu, Z., Lin, M., 2020. Assessing differences in the response of forest aboveground biomass and composition under climate change in subtropical forest transition zone. Sci. Total Environ. 706, 135746.