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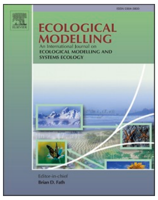

Multi-model approach to integrate climate change impact on carbon sequestration potential of afforestation scenarios in Quebec, Canada

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ABSTRACT

Afforestation of unproductive or currently non-forested territories can increase carbon land sinks and thus contribute to mitigate climate change. However, investments on large-scale afforestation could be risky because of the predicted effect of climate change on forest productivity of newly created plantations. The aim of this study was to assess the carbon sequestration and mitigation potential of afforestation scenarios with different species (*Picea mariana, Picea glauca, Pinus banksiana, Pinus resinosa* and *Populus* spp) on open woodlands and abandoned farmlands in the Province of Quebec (Canada) under different radiative forcing projections. We modelled carbon dynamics in these lands under three Representative Concentration Pathways projections (RCP 2.6, RCP 4.5, and RCP 8.5) over the 2021–2100 period. The forest gap model PICUS was used to model tree growth of afforested species as a function of the *Representative Concentration Pathways* 2.6, 4.5 and 8.5; these data were then used as input in the *Carbon Budget Model – Canadian Forest Sector 3* to simulate the evolution of ecosystem carbon stocks and fluxes as a function of forest management and climate. Carbon transfer to harvested wood products, and carbon fluxes associated with product life cycles and substitution effects on markets, were also included in the analyses. Results showed that *Pinus* species responded more strongly to variations in radiative forcing than for the other simulated species. Overall, aboveground biomass was particularly altered by increased radiative forcing, which in turn reduced harvesting yield and transfers to wood processing and products. At the end of the simulation, despite the expected impacts of radiative forcing on ecosystems, afforestation scenarios on open woodlands with black spruce, white spruce, and jack pine can deliver carbon mitigation of 32% – 70% over the baseline scenario and 4% – 12% for red pine on abandoned farmlands and, hence, contribute to efforts to reduce GHG emissions, especially over the long term. Although climate change is expected to impact the growth of newly planted areas as part of afforestation efforts, the results of our study suggest that the choice of species to plant and the selected forest management strategy have a greater impact on carbon stocks than climate change itself. This study provides a better understanding of the dynamics of afforestation under climate change and whether investments in plantation can contribute to GHG reduction targets.

1. Introduction

The anthropogenic emissions of greenhouse gases (GHG) are known to significantly modify the climate system, with consequences on ecosystems (Intergovernmental Panel on Climate Change, 2014). For instance, the global increase of mean temperature caused by GHG emissions over the last century has been accompanied by an increase in the frequency and intensity of droughts and precipitation events (Hoegh-Guldberg et al., 2018; Allen et al., 2015). There also has been documented evidence of the impacts of climate change on forest productivity (Boisvenue and Running, 2006), notably through effects on the physiology and phenology of individual tree species and their capacity to grow and regenerate (Boulanger et al., 2018).

Climate drivers, i.e., temperature, radiation, and water, are the main abiotic factors that drive primary production (Boisvenue and Running, 2006). A minor increase in temperature, i.e., 1 °C – 2 °C, can lead to an increase in forest growth rate, and thus forest productivity and carbon sequestration; on the other hand, a higher increase of temperature (>2 °C) can lead to an overall growth decline due to a higher mortality and a lower capacity to regenerate (Boulanger et al., 2018; D'Orangeville

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et al., 2018). Forest management and wood supply are dependent on forest productivity; anticipated changes in aboveground biomass can lead to a decrease in wood availability and thus impact the forest sector (Brecka et al., 2020).

Climate-induced changes in the dynamics of natural disturbances can also alter the capacity of carbon sinks of forests (Kurz et al., 2013; Anderegg et al., 2013). Maintaining or increasing carbon sequestration and storage in forests, as encouraged by the Paris Agreement, can therefore be challenging under a changing climate; in fact, forest areas previously known as sinks can become carbon sources, causing emissions that can thwart GHG reduction strategies in other sectors (Smith et al., 2011; Warren, 2011).

Afforestation and reforestation are recognized as a climate change mitigation tool that enhances carbon sinks since it creates or re-establishes forested areas. Forest management and the use of harvested wood products (HWPs) can also increase carbon sequestration and storage, especially when harvested biomass is transformed into long-lived wood products and substitute GHG-intensive materials or energy sources (Drever et al., 2021; Magnus et al., 2021; Ménard et al., 2022). For example, the carbon sequestration potential of afforestation has been estimated for non-forested boreal areas such as open woodlands, poorly regenerated burns and abandoned farmlands in Canada (Drever et al., 2021; Ménard et al., 2022; Boucher et al., 2012; Dufour et al., 2016). However, there may be uncertainties to implement such a strategy because of the rapidly changing climate that drives ecosystem dynamics (Hobbs et al., 2014;Intergovernmental Panel on Climate Change 2014), and the effects of these variations on forest carbon sinks (Kurz et al., 2013; Valade et al., 2017).

The aim of this study was to estimate the carbon sequestration and the mitigation effect potentials of afforestation of unproductive/non-forested lands, in the context of climate change. Boreal open woodlands and abandoned agricultural lands in Quebec (Canada) were used as case studies, and a multi-model approach was used to assess climate change mitigation potential of afforestation scenarios. First, the process-based and climate-sensitive PICUS model was used to produce yield curves according to a climate change gradient. The Carbon Budget Model of the Canadian Forest Sector v.3 (CBM-CFS3) was then used to model afforestation scenarios at a stand scale, and to test a portfolio of forest management and species choices for plantation relative to a baseline/reference scenario without afforestation. Carbon stored in harvested wood products was also taken into consideration using a modified version of the Carbon Budget Model – Harvested Wood Products (CBM-HWP) of the Canadian Forest Service, as well as the emission mitigation through product substitution on markets, following the conceptual framework of Smyth et al. (2014)).

2. Methods

2.1. Study areas, baseline scenarios and afforestation scenarios

Two types of land were used in this study as afforestation opportunities in Quebec (Fig. 1), i.e., boreal open woodlands and abandoned farmlands. The two types of land qualify for afforestation under the additionality criterion of climate change mitigation activities (Richards and Huebner, 2012). Open woodlands are lands that have been devoid of a productive forest stand for more than 50 years. In Quebec, most of the open woodlands are located in the boreal black spruce-feathermoss bioclimatic domain, and are mostly the result of regeneration accidents following successive wildfires (Jasinski and Payette, 2005). Open woodlands situated in this bioclimatic domain cover about 1.3 million ha of the continuous boreal forest in the province of Québec (according to the 4th Quebec's decennial forest inventory). There is presently no evidence of natural re-densification of open woodlands, and afforestation is the only known mechanism that can lead to a closed-crown forest structure (Boucher et al., 2012; Jasinski and Payette, 2005). According to the provincial ecological classification, open woodlands have less than 30 m^3 of merchantable wood per hectare at 120 years of age (Ministère des Forêts de la Faune et des Parcs 2015). The baseline scenario describing vegetation on open woodlands is based on Jasinski and Payette (2005). In this study, we assumed that the residual stand was composed of 100% black spruce. Non-merchantable vegetation such as dwarf birch (*Betula glandulosa*), ericoid shrubs and lichen ground cover (Jasinski and Payette, 2005) was not included in the initial carbon stocks of the site because of a lack of data. The boreal black spruce-feathermoss bioclimatic domain is characterized by a longitudinal climate contrast: the western part is subject to a continental and drier climate, while the

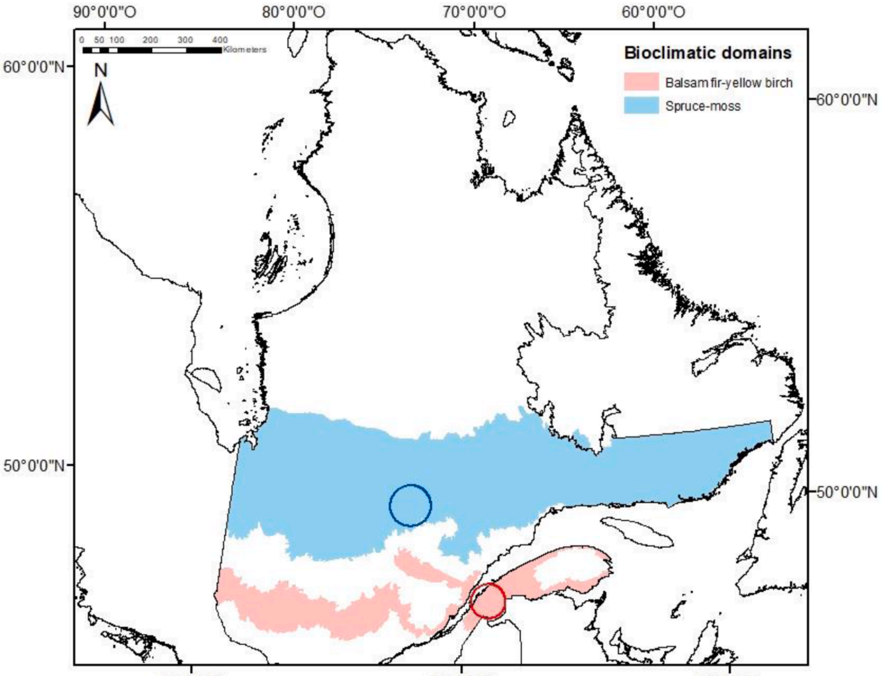

Fig. 1. Two target areas in Quebec tested in this study: open woodlands (blue circle) and the abandoned farmlands (red circle).

climate of the eastern part is maritime with higher relative humidity and cooler summers (Couillard et al., 2019). The mean annual temperature is -0.1 ^{o} C, with a mean maximum temperature during the growing season of 10.8 ^{o}C, and a mean annual precipitation of 989 mm.

Abandoned farmlands are lands where agricultural activities have been abandoned and where the type of vegetation transits between agriculture and forestry (Benjamin et al., 2005). In recent decades, and on a global scale, areas supporting extensive agriculture have been abandoned due to a shift towards intensive and industrial agriculture (Benayas et al., 2007; Tremblay and Ouimet, 2013). In the province of Quebec, there are 100,000 ha of abandoned farmlands, mostly located in the Lower St. Lawrence region (Tremblay and Ouimet, 2013). Abandoned agricultural lands have been widely discussed as candidate areas for implementing nature-based solutions such as afforestation in Canada and in Europe (Drever et al., 2021; Magnus et al., 2021; Forster et al., 2021). We selected abandoned farmlands located in the balsam fir-yellow birch bioclimatic domain due to their abundance in this area, and to the availability of field data for parameterization of the models. Prior to their clearing for agricultural use, farmlands of this bioclimatic domain were mostly forested lands (Bélanger and Grenier, 2002). The balsam fir-yellow birch bioclimatic domain is characterized by a mean annual temperature of 2.8 ^{o} C, with a mean maximum temperature during the growing season of 12.4 °C, and a mean annual of total precipitation of 1052 mm. The baseline scenario for abandoned farmlands predicted the return of the natural forest succession 20 years after agricultural abandonment (Tremblay and Ouimet, 2013), with a linear annual carbon accumulation rate of 3.61 t C ha^{-1} yr^{-1} (13.25 t CO_2 e ha^{-1} yr^{-1}) between year 20 and year 80 (Ménard et al., 2022). In this study, the baseline scenario was considered neutral to climate change. Carbon stocks from total ecosystem for each baseline scenario are shown in Appendix A.

For afforestation scenarios, we tested three species for each type of land determined according to the most promising species for each bioclimatic domain. Species were selected based on their distribution along the bioclimatic gradient and on recommended silvicultural strategies of Quebec (Larouche et al., 2013). The chosen species were black spruce (*Picea mariana* (Mill.) B.S.P), white spruce (*Picea glauca* (Moench) Voss) and jack pine (*Pinus banksiana* Lamb.) on open woodlands, and white spruce (*Picea glauca*), red pine (*Pinus resinosa* Ait.) and hybrid poplar (*Populus* spp.) on abandoned farmlands. Black spruce, white spruce and jack pine are softwood species commonly found across natural boreal landscapes of Canada; they are also routinely used in commercial forestry. The average yield of black spruce is 4.1 m^3 ha^{-1} $year^{-1}$ (Prégent et al., 1996). In comparison, white spruce can yield 4.6 m^3 ha^{-1} $year^{-1}$, jack pine 5.2 m^3 ha^{-1} $year^{-1}$, and red pine 9.1 m^3 ha^{-1} $year^{-1}$ (Bolghari and Bertrand, 1984). Hybrid poplar is a deciduous, fast-growing species; it usually reaches maturity at 20 years with a merchantable volume of 160 m^3 ha^{-1} (Pothier and Savard, 1998). Boreal softwood species are used to produce both (long-lived) sawn products and (short-lived) pulp and paper; the proportion of each product category varies according to the species and the harvested stem characteristics such as diameter at breast height, taper and total height (Auty et al., 2014). Wood from hybrid poplar is mostly sent to pulp mills to produce pulp and paper (Ministère des Forêts de la Faune et des Parcs 2019).

2.2. Climate change projections

We used three radiative forcing projections from the IPCC (2014), known as Representative Concentration Pathways (RCP) (van Vuuren et al., 2011): RCP 2.6, RCP 4.5, and RCP 8.5. These climate projections predict a temperature increase of about 1.7 ^{o} C to 6.3 ^{o} C throughout the province until 2100, while average precipitation is projected to increase by 7–23% (Boulanger et al., 2017). We first modelled a climate baseline projection with historical data (McKenney et al., 2013; Zhang et al., 2019), based on the methodology of Boulanger et al. (2017). We used the historical climate corresponding to the period from 1981 to 2010. Future climate projections came from the Canadian Earth System Model version 2 (CanESM2) using data downloaded from the World Climate Research Program (WRCP) Climate Intercomparison Project Phase 5 (CMIP5) archive (Boulanger et al., 2017, McKenney et al., 2013), and further downscaled at a 10 km resolution (McKenney et al., 2011).

2.3. Models

The existing growth curves for natural and planted forests in Quebec are not climate-sensitive. However, climate change can influence the physiological parameters of tree species within a given ecosystem. Therefore, the combination of PICUS, a 3D gap model linked to a process-based model, and CBM-CFS3, a forest carbon dynamics model allowing forest management analysis, allowed for in-depth analysis of interactions between species-specific responses to variations of the climate and forest carbon accounting, therefore adding a complex biological component to the results (Houghton et al., 2001).

2.4. PICUS calibration

To model changes in the physiological response of tree species and demographic attributes of tree stands over time under different climate change projections, we used PICUS, version 1.5 (Lexer and Hönninger, 2001), a spatially-explicit process-based model that simulates the dynamics of individual trees on a 1 ha x 1 ha grid. PICUS is a process-based model for the simulation of the growth of individual trees. In the model, tree growth potential is calibrated from empirical height growth curves and height-diameter relationships of open grown trees. Annual tree growth is then calculated as a fraction of potential growth and is constrained by available radiation as influenced by competition (estimated by a 3D light model that considers direct and diffuse radiation within the canopy (Lexer and Hönninger, 2001)). Thermal heat sum above a threshold of 5.5 °C growing degree days, minimum winter temperatures, soil moisture index (estimated with a water balance model), soil pH and soil available nitrogen also drive vegetation processes within the model (Taylor et al., 2017). In PICUS, climate projections influence vegetation growth through effects on temperature and precipitation (which influences soil water availability).

PICUS uses fixed parameters related to species autecology as well as climate- and soil-sensitive dynamic parameters for tree growth; it has been previously calibrated for species used in our study (Boulanger et al., 2018; Taylor et al., 2017). Soil conditions were assumed to be constant over all the simulation period. Only climate variables were altered. Stochasticity was not included in this study since the objective of the study was to compare specific afforestation and management scenarios. The growth of each species was dynamically modelled during an 80-year period according to climate projections, starting from bare ground and fixed soil properties of the simulated open woodlands and abandoned farmlands. Other environmental parameters that may evolve as a function of climate change such as CO_2 fertilization were not implemented in PICUS. A complete description of the model, parameterization and validation can be found in Taylor et al. (2017).

Initial soil conditions were taken from Mansuy et al. (2014), and were averaged for both types of simulated lands. For open woodlands, the soil was classified as ferro-humic podzol and we used a mean concentration of soil nitrogen (N) of 49.4 g kg^{-1}, a mean pH of 4.5 and a mean water-holding capacity of 53.3 cm. For abandoned farmlands, the soil was classified as humo-ferric podzol (Tremblay and Ouimet, 2013) and we used a mean concentration of soil N of 74.4 g kg^{-1}, a mean pH of 5.1 and a mean water-holding capacity of 65.8 cm.

We simulated changes in biophysical processes under different radiative forcing projections starting in 2021, using monthly variations in specific climatic parameters: temperature, precipitation, radiation, and vapor pressure deficit. Simulations in PICUS were then done on an annual basis over the 80-year period (2021–2101 period).

PICUS outputs for each simulated stand included the total stand volume over bark (m^3), based on Pollanschütz volume functions. Since PICUS was parameterized for native species only, trembling aspen was used as a proxy for hybrid poplar. The trembling aspen curve simulated in PICUS gave a target volume of 185.99 m^3 at 20 years, which is comparable to the hybrid poplar yield curves at the same age in Pothier and Savard (1998).

2.5. *Initialization of parameters in CBM-CFS3*

To estimate forest carbon dynamics under forest management practices, CBM-CFS3, an empirical yield data-driven model which is the core component of the National Forest Carbon monitoring, Accounting and Reporting System, was used (Kurz et al., 2009). CBM-CFS3 tracks forest carbon stocks, carbon transfers between pools and GHG emissions. Data of merchantable wood volume as a function of stand type and age is required to estimate the carbon dynamics in each carbon pool (Boudewyn et al., 2007). Merchantable volume is converted in biomass of individual tree components as a function of diameter at breast height and tree height (Lambert et al., 2005). Harvesting can be scheduled using a matrix describing the proportion of carbon transferred between forest pools and to the forest products sector (Kurz et al., 2009).

CBM-CFS3 was used to simulate the evolution of carbon stocks of monospecific stands for 80 annual time steps corresponding to the 2021–2101 simulation period (Fig. 2). In CBM-CFS3, a decay rate associated with different pools of dead organic matter (DOM) drives decomposition on an annual basis and the decay rate is only modified by a temperature-dependent function (Kurz et al., 2009). The decay rate was thus adjusted yearly based on climatic assumptions of each scenario for mean annual temperature over the simulation period (2021–2100).

For each simulation, stocks were tracked for the four main carbon pools: aboveground biomass (stem wood, branches, stumps, and foliage of live trees), belowground biomass (fine and coarse roots of live trees), aboveground dead organic matter (DOM) (standing dead trees, downed woody debris, litter and humus) and belowground DOM (soil organic matter including dead roots), each expressed in t C ha^{-1}.

Initial soil carbon pools were calibrated for both types of land. For open woodlands, no field data was available for initial site conditions. Therefore, a spin-up simulation reproducing the historical disturbances leading to the creation of an open woodlands of 120 years old was done. We reproduced the disturbance pattern of a regeneration failure in CBM-CFS3: starting 200 years (200 annual time steps) before afforestation with a regenerating black spruce stand, we simulated a fire 70 years later, (i.e. 130 years before afforestation), followed by another fire 10 years later (i.e. 120 years before afforestation). Following these disturbances, the site was allowed to grow up to the year of afforestation (2021) according to a low-density growth curve of 100% of black spruce with site index (SI), (i.e., an indicator of site productivity represented by the average height of the dominant trees of a stand at a reference age (Laflèche et al., 2013)), of 9 m at age 50 (Pothier and Savard, 1998). This resulted in a soil carbon stock of 57.0 t C ha^{-1} in 2021, immediately prior to afforestation. Upon afforestation, 10% of the initial soil organic matter stock was assumed to be lost to the atmosphere following site preparation prior to plantation (preliminary results, Dufour et al., unpublished data).

For abandoned farmlands, soil carbon stocks were set to 100 t C ha^{-1} (367 t CO_2 e ha^{-1}) in CBM-CFS3, based on field data (Tremblay and Ouimet, 2013); litter and woody debris pools were initially set to 0 t C ha^{-1} (Thibault et al., 2021). No site preparation was simulated for plantation on abandoned farmlands.

We used the evolution of total stem volume (m^3) for each monospecific stand simulated by PICUS, as the input for CBM-CFS3 (Fig. 2). CBM-CFS3 converts volume tables into carbon increments for each biomass pool as a function of stand age (Fig. 2) (Kurz et al., 2009).

2.6. *Forest management scenarios*

Simulations in CBM-CFS3 were done on a time horizon of 80 years, starting in 2021 to cover the 21st century period. We simulated two distinct forest management scenarios for each afforested species: one including harvesting after afforestation and another without harvesting (Table 1). All scenarios were scheduled according to the recommended forest management practices (Larouche et al., 2013), with age at maturity respective to each species in its bioclimatic domain (Table 1). Following these guidelines, clearcut harvest rotations varied between 20 years (hybrid poplar on abandoned farmlands) and 70 years (black spruce, white spruce and jack pine on open woodlands). Clearcutting refers to clearcut harvesting with protection of advance regeneration and soils, which is the prescribed practice in the boreal forest of Quebec.

2.7. *Harvested wood products and substitution on markets*

For forest management scenarios that included harvesting (Table 1), we simulated carbon fluxes associated with harvested wood products (HWPs) using a modified version of the *Carbon Budget Model – Harvested Wood products* (CBM-HWP) model, which was run using the Abstract Network Simulation Engine (ANSE) of the Canadian Forest Service (Fig. 2) (Smyth et al., 2014; Magnan, 2013). CBM-HWP allows to track carbon stocks and emissions from wood products, co-products and by-products over their service life and in landfills (Smyth et al., 2014; Head et al., 2021). After a clearcutting simulated in CBM-CFS3, a portion of the aboveground biomass, more specifically the merchantable biomass, is removed from the ecosystem at the year of harvest; in CBM-HWP, this biomass is assumed to be instantly manufactured into different wood products according to a user-specified allocation (Appendix B).

The basket of wood products assumed to be sourced from each species is described in Ménard et al. (2022) (see also Appendix B). Carbon emissions associated with the degradation of harvested wood products during their life-time was estimated using the half-life value for each type of product suggested by the IPCC (Penman et al., 2003): 35 years for sawn wood, 25 years for panels, 2 years for pulp and paper and 0 for bioenergy (i.e., bioenergy is assumed to cause an immediate release of carbon upon utilization). Dynamics of emissions in landfills were

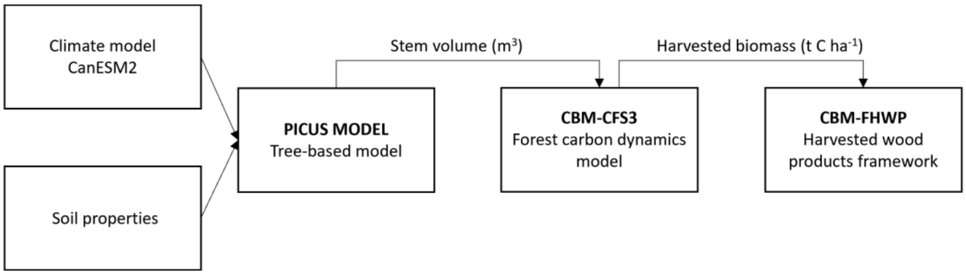

Fig. 2. Multi-model approach used to simulate on a 80-year period the impact of climate change under different radiative forcing projections on tree growth and forest carbon dynamics at a stand level.

Table 1
Species used to model afforestation scenarios in open woodlands and abandoned farmlands, and their forest management scenarios (afforestation+no harvesting (NH) and afforestation+clearcutting (CC)) according to an 80-year time scale.

Type of land	Species	Afforestation+NH	Year	Afforestation+CC	Year
Open woodlands	Black spruce	Afforestation	1	Afforestation	1
				Commercial thinning (30%)	55
				Clearcut (97%)	70
				Afforestation	71
	White spruce	Afforestation	1	Afforestation	1
				Commercial thinning (30%)	55
				Clearcut (97%)	70
				Afforestation	71
	Jack pine	Afforestation	1	Afforestation	1
				Commercial thinning (30%)	55
				Clearcut (97%)	70
				Afforestation	71
Abandoned farmlands	White spruce	Afforestation	1	Afforestation	1
				Commercial thinning (30%)	40
				Clearcut (97%)	55
				Afforestation	56
	Red pine	Afforestation	1	Afforestation	1
				Commercial thinning (30%)	35
				Clearcut (97%)	50
				Afforestation	51
	Hybrid poplar	Afforestation	1	Afforestation	1
				Clearcut (97%)	20
				Afforestation	21
				Clearcut (97%)	40
				Afforestation	41
				Clearcut (97%)	60
				Afforestation	61
				Clearcut (97%)	80

simulated according to parameters in Smyth et al. (2014).

The substitution effect that wood products can have on markets by displacing GHG-intensive products was simulated as an emission avoidance (Smyth et al., 2014). Displacement factors were used to calculate the substitution effect; these factors are expressed as the amount of C emissions avoided (in t of C) per t of C contained in the wood products. The displacement factors were: 0.54 t of C avoided per t of C in wood product for sawn wood (Smyth et al., 2014), 0.45 for panels (Smyth et al., 2014), and 0.47 for bioenergy (Smyth et al., 2017). No substitution effect was considered for pulp and paper. These are average values adapted to the Quebec and Canadian contexts; assumptions are also similar to those made in other North American studies and aim to avoid any over-estimation of climate benefits of wood products (Smyth et al., 2014; Dugan et al., 2018; Xu et al., 2018).

2.8. Net carbon balance of afforestation activities

To determine the emission mitigation potential of afforestation activities, net emissions were calculated using the difference between total fluxes of the baseline scenarios and the alternative scenarios, considering carbon fluxes at the ecosystem level, and those associated with wood products and their substitution effect on markets, when relevant. Carbon fluxes were converted into units of CO_2 equivalent considering that 1 tonne of C = 44/12 tonnes of CO_2 equivalent. The net carbon balance was compiled on a cumulative basis (i.e., sum of annual fluxes) over the 2021–2100 period. Cumulative fluxes were expressed in tonnes of CO_2 equivalent per hectare of afforested land (t CO_2 e ha^{-1}). A scenario was considered to cause a net mitigation when cumulative net carbon fluxes (difference between baseline and afforestation scenarios) were negative, and to be a net source when net fluxes were positive.

3. Results

3.1. Impacts of climate change on the forest carbon sequestration and storage in the ecosystem

Under a warmer climate, total ecosystem carbon stocks decreased by 19% for black spruce, 15% for white spruce, and stayed stable for jack pine for the afforestation+no harvesting on open woodlands (Figs. 3 and 5); for abandoned farmlands, climate warming caused total carbon stocks to decrease by 34% for white spruce, 2% for red pine and 24% for hybrid poplar (Figs. 4 and 6). For both type of lands, the saturation of C sink, i.e., when the annual carbon accumulation rate decreases, arrived earlier as a function of radiative forcing. On open woodlands (Figs. 3 and 5), the annual carbon accumulation rate reached saturation at time step 66 (RCP 8.5) and time step 75 (RCP 2.6 and 4.5) for black spruce, and at time step 66 (RCP 8.5) and 73 (RCP 2.6 and 4.5) for white spruce. For jack pine, it reached saturation at time steps 58 for the historical climate projection, 47 for RCP 8.5. On abandoned farmlands (Figs. 4 and 6), annual carbon accumulation rate reached saturation at time steps 46 (historical and RCP 2.6) and 35 (RCP 4.5 and RCP 8.5) for white spruce, at time steps 45 (historical and RCP 2.6) and 40 (RCP 4.5 and RCP 8.5) for red pine and at time steps 25 (historical, RCP 2.6 and RCP 4.5), and time step 20 (RCP 8.5) for hybrid poplar.

For both type of lands, aboveground DOM pools were stable for the first 20 years but decreased afterwards under RCP 8.5 for all three species relative to the historical climate projection. According to our simulations, aboveground biomass and aboveground DOM were the carbon pools that were the most affected by increased climatic forcing, while belowground DOM pool appeared to be rather stable.

The growth of tree species used in plantations was subject to significant variability due to climate change, with consequences for the carbon sequestration potential of afforestation. For plantations on open woodlands (Figs. 3 and 5), there was a gain in aboveground biomass under RCP 2.6 and RCP 4.5 of 7% and 9% for black spruce for the first 46 years, 11% and 12% for white spruce for the first 60 years, and 13% and 17% for jack pine for the first 45 years relative to the historical climate

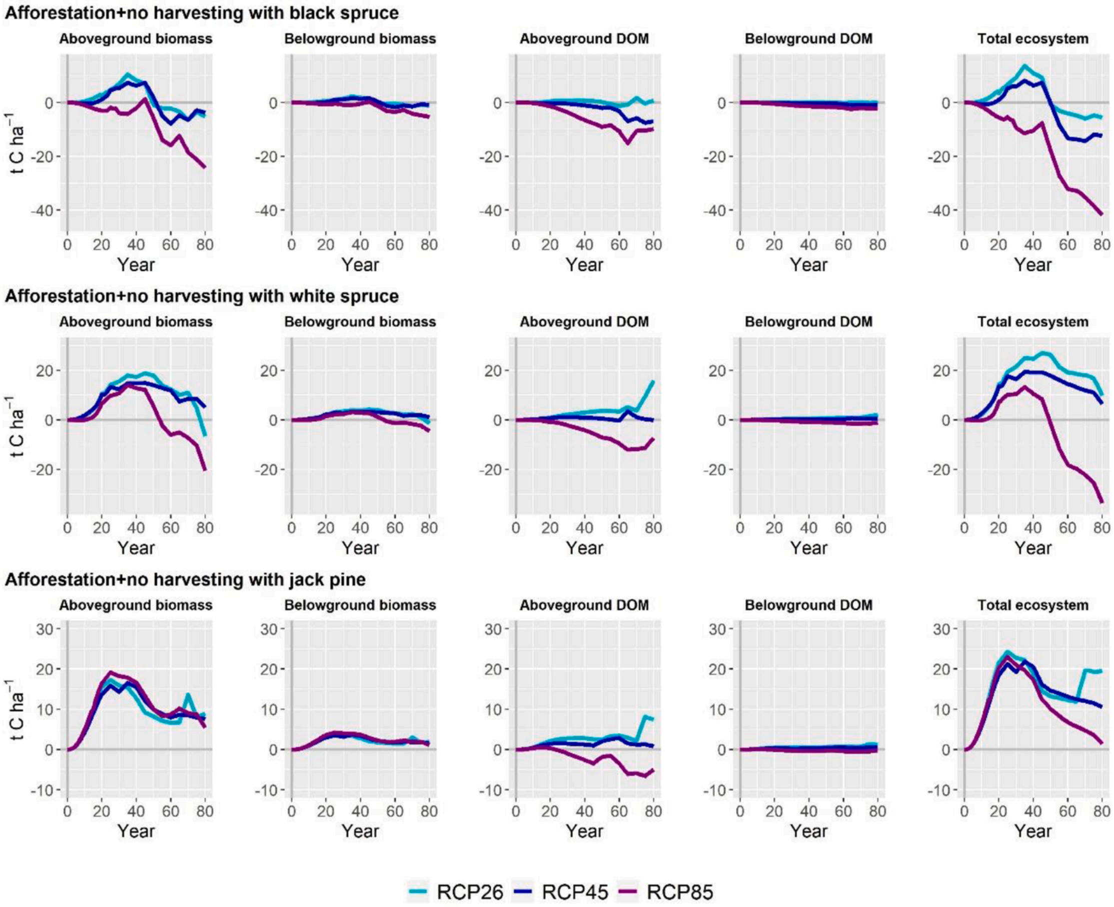

Fig. 3. Afforestation in the absence of harvesting on open woodlands - difference in carbon stocks between each RCP projection and historical climate projection for each ecosystem carbon pool including total ecosystem: demonstration of the variations of carbon stocks (t C ha^{-1}). Negative values indicate a negative impact of the radiative forcing projections on carbon stocks, comparing to historical values.

projection. However, black spruce growth dropped after 50 years under all three RCP projections. With all climate projections showing an increase in growth rates compared with the historical climate projection, even under RCP 8.5 at time step 80, jack pine was rather positively impacted by the radiative forcing projections, except when harvesting was included (Figs. 3 and 5). For white spruce, simulations under RCP projections 2.6 and 4.5 showed an increase in growth compared with the historical climate projection; under RCP 8.5, a decrease was noticeable at time step 50 (Figs. 3 and 5). For afforestation with white spruce and jack pine, there was an increase of the belowground biomass and aboveground DOM pools under RCP 2.6 and RCP 4.5 (Figs. 3 and 5).

Similarly to open woodlands, results of afforestation on abandoned farmlands showed that there were species-specific responses to climate projections. White spruce and hybrid poplar decreased in growth over the entire simulation period relative to the historical climate projection (Figs. 4 and 6). Red pine growth increased and reached a maximum of carbon stock of 35.0 t C ha^{-1} at time step 31 (RCP 2.6), of 28.2 t C ha^{-1} at time step 29 (RCP 4.5), and of 23.5 t C ha^{-1} at time step 28 (RCP 8.5). Red pine plantations sequestered carbon until time step 50 for RCP 8.5, time step 64 for RCP 4.5, and was still sequestering at time step 80 for RCP 2.6 relative to historical climate projection (Figs. 4 and 6). White spruce plantations had a different growth response depending on the type of land, with carbon sequestration relative to historical climate projection being higher on afforested open woodlands than on abandoned farmlands (Figs. 4 and 6).

3.2. *Harvested wood products*

On both type of lands, afforestation+clearcutting scenarios transferred carbon stocks to HWPs (Table 2). The total biomass harvested during clearcutting is taken from the aboveground biomass pool. The total amount of harvested biomass was therefore correlated to the responses of forest growth to the different radiative forcing projections. Afforestation+clearcutting with hybrid poplar illustrated the effect of multiple harvesting rotations and the accumulation of carbon in HWPs (see Appendix C for open woodlands and Appendix D for abandoned farmlands). Because of the small proportion of long-lived wood products manufactured from hybrid poplar, carbon stocks in wood products were ephemeral relative to the softwood species.

3.3. *Carbon sequestration and mitigation potential of scenarios*

The total net cumulative carbon balance of afforestation scenarios was calculated by adding carbon storage from wood products and the emission avoidance caused by product substitution effect on markets to net cumulative carbon fluxes from forest ecosystems (Fig. 7). Mitigation potential of each scenario (Fig. 7) is presented in t CO_2 e ha^{-1} while previous figures (Figs.3–6) were presented in t C ha^{-1}.

For open woodlands, afforestation scenarios acted as a net cumulative carbon sink at the end of the simulation, under all radiative forcing projections (Fig. 7). Black spruce scenarios acted as a cumulative carbon sink from time step 11 for the historical climate and time step 14 for RCP 8.5. White spruce and jack pine started to sequester carbon between time step 5 and 9 for all climate projections; for those two species, RCP

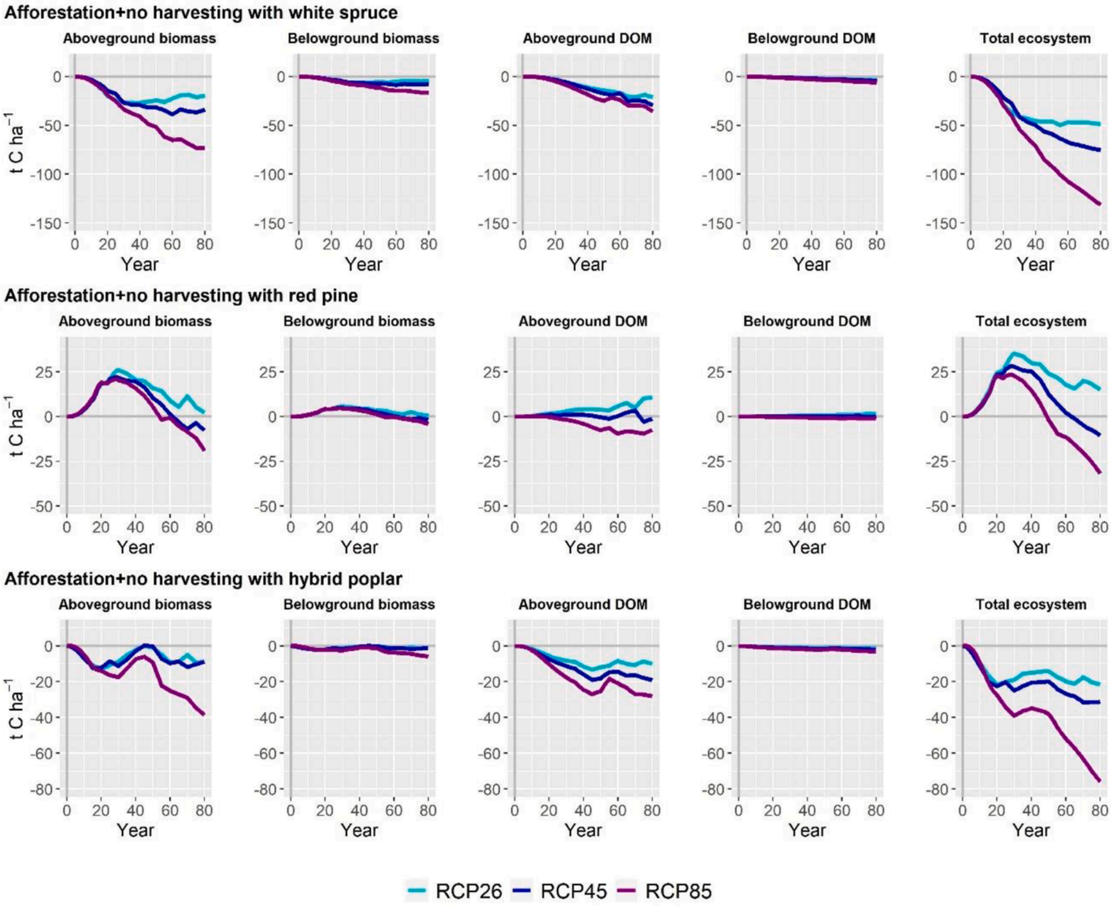

Fig. 4. Afforestation in the absence of harvesting on abandoned farmlands - difference in carbon stocks between each RCP projection and historical climate projection for each ecosystem carbon pool including total ecosystem: demonstration of the variations of carbon stocks (t C ha^{-1}). Negative values indicate a negative impact of the radiative forcing projections on carbon stocks, comparing to historical values.

2.6 and 4.5 resulted in an increased mitigation potential for afforestation (Fig. 7). Clearcutting created a carbon debt in the ecosystem. A part of the carbon was transferred to the wood products;carbon stored in harvested wood products and the substitution effect did not fully offset this debt. On the other hand, the annual rate of carbon sequestration in the no harvesting scenarios reached saturation at the end of the simulation unlike clearcutting scenarios which allowed a comeback of growing forest regeneration. Although scenarios of afforestation+no harvesting sequestered more carbon than afforestation+clearcutting scenarios, the scenarios with harvesting still showed net cumulative mitigation after 80 years.

Afforestation scenarios on abandoned farmlands displayed a more variable carbon sequestration efficiency according to the gradient of radiative forcing and returned more quickly to emission under RCP 8.5. Indeed, afforestation+no harvesting scenarios sequestered over a longer time horizon, returning to emissions in the last years of the simulation. Under the historical climate projection, white spruce started to sequester carbon between time step 5 and 8 depending on the RCP projections up until the end of the simulation. For RCPs 2.6, 4.5 and 8.5, afforestation scenarios sequestered less carbon than baseline scenarios. Red pine started to sequester carbon 4 to 5 years after afforestation and remained a carbon sink until time steps 77 – 80 depending on the climate projection. Hybrid poplar started to sequester carbon right from the start, but mitigation benefits decreased near the end of the simulation period.

4. Discussion

The combination of models on tree physiology, ecosystem carbon accounting and wood processing and use made it possible to estimate the mitigation benefits of afforestation under a changing climate. Although climate change is expected to impact the growth of newly planted areas as part of afforestation efforts, the results of our study suggest that the choice of species to plant and the selected forest management strategy have a greater impact on carbon stocks than climate change itself. Efforts to reduce GHG emissions and to increase carbon sinks such as afforestation of unproductive lands can help to reduce the gap between present and predicted future climate while ensuring a supply of renewable products for future generations. The multi-model approach presented in this study has demonstrated the importance of land and species selection in implementing nature-based solutions and could be applied to other areas where afforestation has additional carbon sequestration potential.

4.1. *Impacts of climate change on carbon storage*

Changes in the abiotic factors, such as temperature and precipitation, can impact aboveground biomass growth (Boulanger et al., 2018; D'Orangeville et al., 2018). In our study, under a light or moderate increase in anthropogenic radiative forcing (RCP 2.6 and RCP 4.5), some species such as white spruce (on open woodlands only), jack pine and red pine showed an increase in yield compared to a historical climate.

Belowground DOM pool was shown to be the most stable pool under warmer climate, even though the rate of DOM decay was somewhat increased with increased temperature. This could be due to the small amount of decomposing dead wood in newly afforested ecosystems, which are young forests with no legacy of debris from previous stand

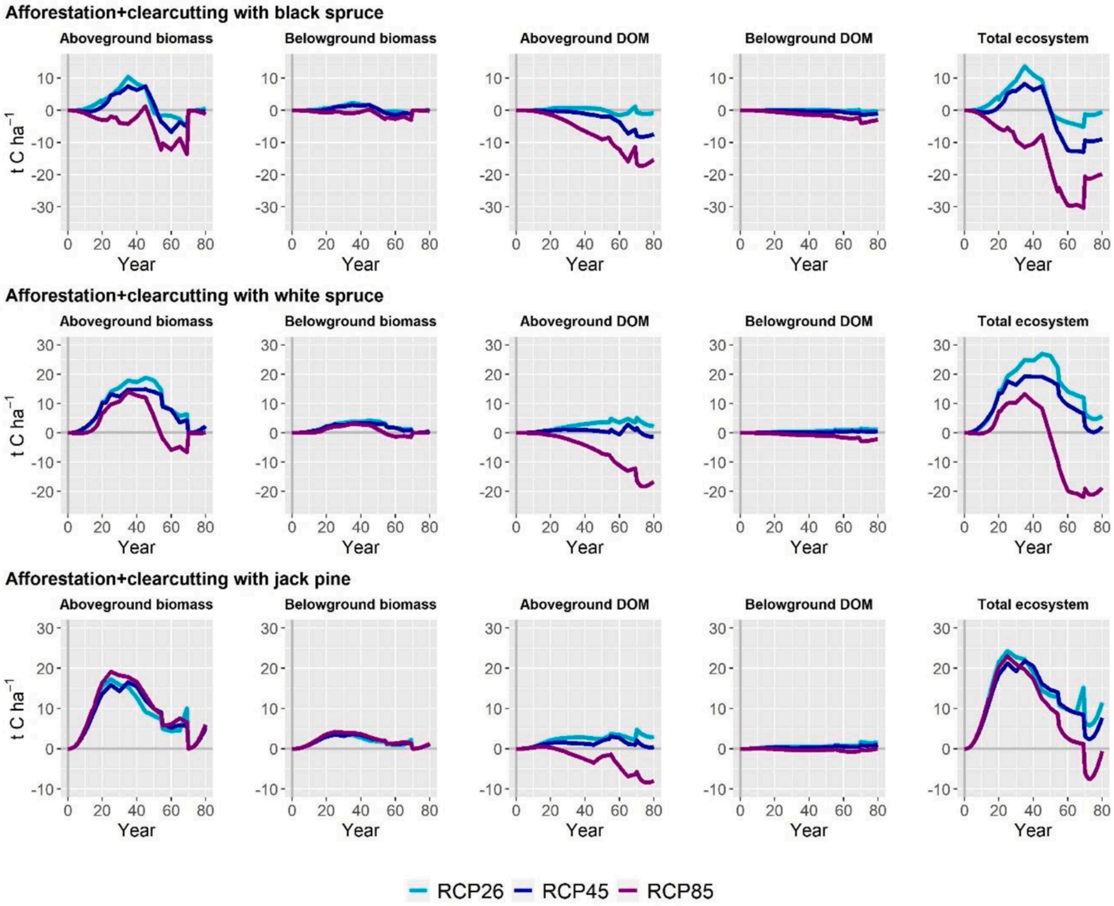

Fig. 5. Afforestation and clearcutting on open woodlands - difference in carbon stocks for each RCP projection and historical climate projection for each ecosystem carbon pool including total ecosystem: demonstration of the variations of carbon stocks (t C ha^{-1}). Negative values indicate a negative impact of the radiative forcing projections on carbon stocks, comparing to historical values.

rotations. Nevertheless, our modelling suggests that DOM inputs can decrease considerably with a warmer temperature as a result of decreased forest productivity.

4.2. Species-specific responses to climate change

Under a changing climate, several species could see their climate envelope move northwards (Boulanger et al., 2018), and other species would not be able to acclimate to changing conditions, especially at the limit of their current distribution. Indeed, in the northern portions of our study area where open woodlands are located, the growth of white spruce was increased by climate warming, suggesting that temperature is a limiting factor for this species at those higher latitudes. Conversely, white spruce planted on the more southerly abandoned farmlands showed a decrease in growth with increasing radiative forcing. On the other hand, jack pine appears better adapted to temperature change, probably due to its higher tolerance to drought stress compared to other boreal species (Hébert et al., 2006). The choice of the species used to afforest is thus very important and should consider both the regional context as well as specific functional traits such as drought tolerance (Thom et al., 2021; Royer-Tardif et al., 2021).

A combination of several environmental drivers can explain the impact of climate warming on forest productivity, but several uncertainties in the scientific literature remain. Net primary production can decrease due to drought, as water availability could become a limiting factor (Kurz et al., 2013; Flannigan et al., 2009). Increased temperatures could also increase the capacity of carbon assimilation by trees and may lead to an increase in autotrophic respiration, which altogether can negatively impact aboveground biomass (Girardin et al., 2016; Zhang et al., 2008). Evidence in the literature suggests that other factors than temperature and precipitation can also play a role in tree growth. For example, warmer temperature can increase tree mortality risk as it increases stress (Mcdowell et al., 2008; Adams et al., 2009) or increases risks from pests and pathogen infestations. Conversely, trees can benefit from climate change as it can increase nutrient availability through a faster nitrogen mineralization rate (which was not included in the model), and increase the pace of the organic matter decomposition rate in the boreal zone (Melillo et al., 2011). Increases in CO_2 concentrations (which was also not included in the model) can have a fertilizing effect on forest growth and on increasing water use efficiency by plants (Huang et al., 2007; Sperlich et al., 2020). However, the interaction of this parameter with the other biophysical variables remains unclear (Girardin et al., 2016). The impact of increased CO_2 concentrations on forest growth was not considered in our simulations, which can add uncertainties to the predictions of reduced forest growth.

Nevertheless, as showed by our results with red and jack pines, the increase in tree growth under light and moderate (RCP 2.6 and 4.5) radiative forcing can be a positive ecosystem response to climate change, as it can sequester carbon more rapidly in the ecosystem. This can also help shorten rotations, increase the availability of merchantable wood for harvest and increase the carbon transfer towards wood products. Even if afforestation+clearcutting scenarios created a carbon loss in the ecosystem, the consideration of carbon fluxes from wood products and markets allowed them to become a cumulative net sink. The proportion of long-lived wood products is critical in increasing the mitigation potential of afforestation. If plantations can reach maturity, i.e., if

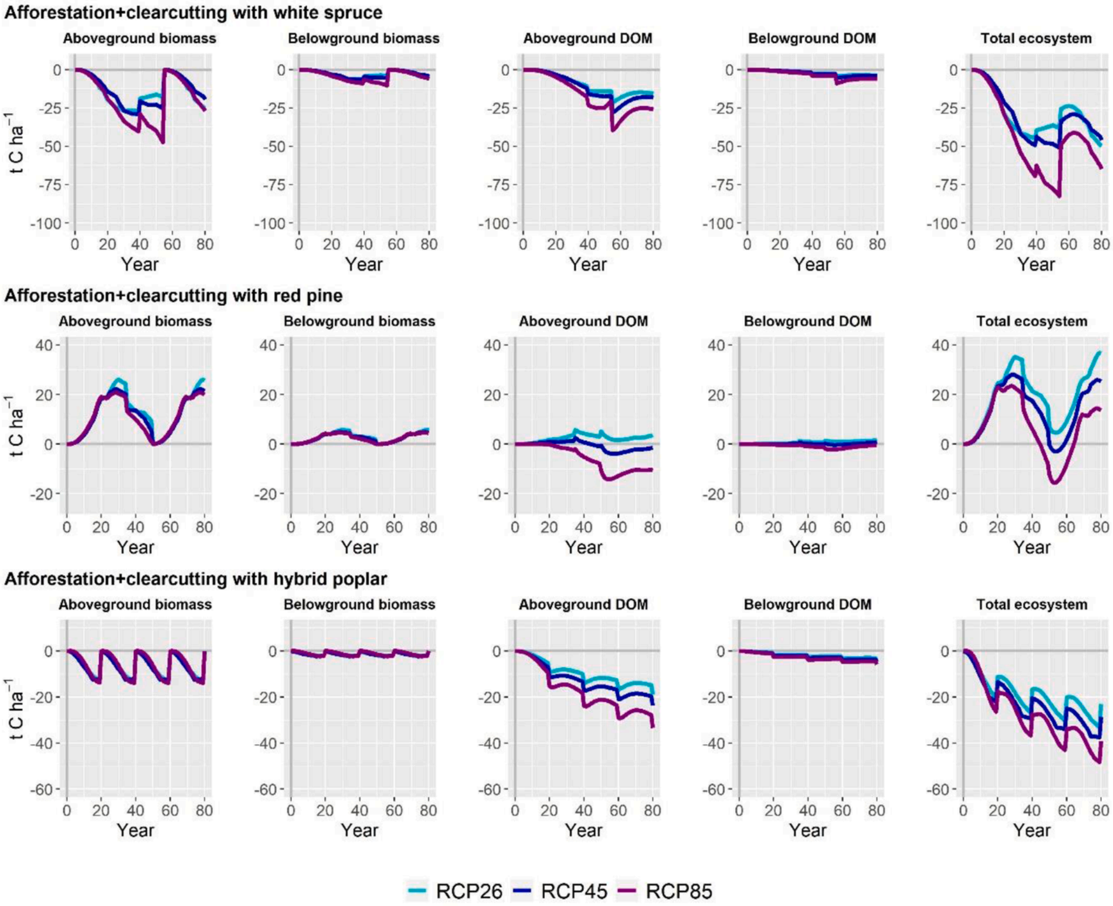

Fig. 6. Afforestation and clearcutting on abandoned farmlands - difference in carbon stocks for each RCP projection and historical climate projection for each ecosystem carbon pool including total ecosystem: demonstration of the variations of carbon stocks (t C ha^{-1}). Negative values indicate a negative impact of the radiative forcing projections on carbon stocks, comparing to historical values.

Table 2
Total harvested biomass (t C ha^{-1}) for afforestation+clearcutting scenarios. The total includes all harvesting treatments over the 80 years of modelling.

Type of land	Species	Total harvested biomass (t C ha^{-1})			
		Historical	RCP 2.6	RCP 4.5	RCP 8.5
Open woodlands	Black spruce	60.4	55.7	55.5	46.4
	White spruce	73.9	81.81	80.0	69.0
	Jack pine	46.5	56.3	53.4	54.0
Abandoned farmlands	White spruce	90.5	72.8	67.2	48.0
	Red pine	104.2	117.0	113.2	109.4
	Hybrid poplar	160.5	121.2	123.9	119.5

they can escape stand-replacing natural disturbances, long-lived wood products can be a way to secure carbon storage out of the forest ecosystem (Valade et al., 2017). Moreover, such products can displace non-renewable materials with high GHG footprints, leading to emission avoidance through substitution. The wood manufacturing industry varies in its capacity to turn different species into long-lived wood products (as opposed to short-lived products that degrade quickly and release their C content back to the atmosphere, and usually have no or little substitution effect on markets); careful consideration should be given to the choice of species to be planted (Ménard et al., 2022). For example, hybrid poplar allows for several clearcutting rotations over a 80-year period. However, under current industrial conditions, the harvested wood from poplar only yields a very small proportion of long-lived wood products compared to softwood species (white spruce and pine) that can generate more sawn wood products.

4.3. *Carbon sequestration and mitigation potential of afforestation*

Results of total net carbon balance and emission mitigation scenarios support the role of plantations established through afforestation in the context of climate change mitigation and adaptation. Climate change mitigation and wood supply benefits have been shown in stands where regeneration failures occur after wildfires (Menard et al. Submitted). Reforestation on poorly regenerated burns showed a net carbon sequestration ranging between 297.6 t CO_2 e ha^{-1} and 517.4 t CO_2 e ha^{-1} after 80 years of simulation for afforestation+no harvesting scenario, depending on the choice of species and the time of planting after wildfire. However, wildfires pose a risk for plantations implemented in vulnerable areas such as northwestern Quebec (Boulanger et al., 2013), which can potentially reverse any carbon benefit, cause a loss of financial investments and impede expected wood supplies. The choice of sites is crucial and targeting less fire-prone areas could help secure ecosystem carbon storage. Other strategies that can decrease risk of fire at the stand level could also be envisioned, such as management of tree composition and density and ground cover (Cavard et al., 2015).

Values other than wood yield and carbon accumulation should also be considered when implementing climate change mitigation strategies such as afforestation (Nabuurs et al., 2017). First, the temporality of emission/sequestration of a given forest management scenario can greatly influence its climatic effect; for example, emissions that occur

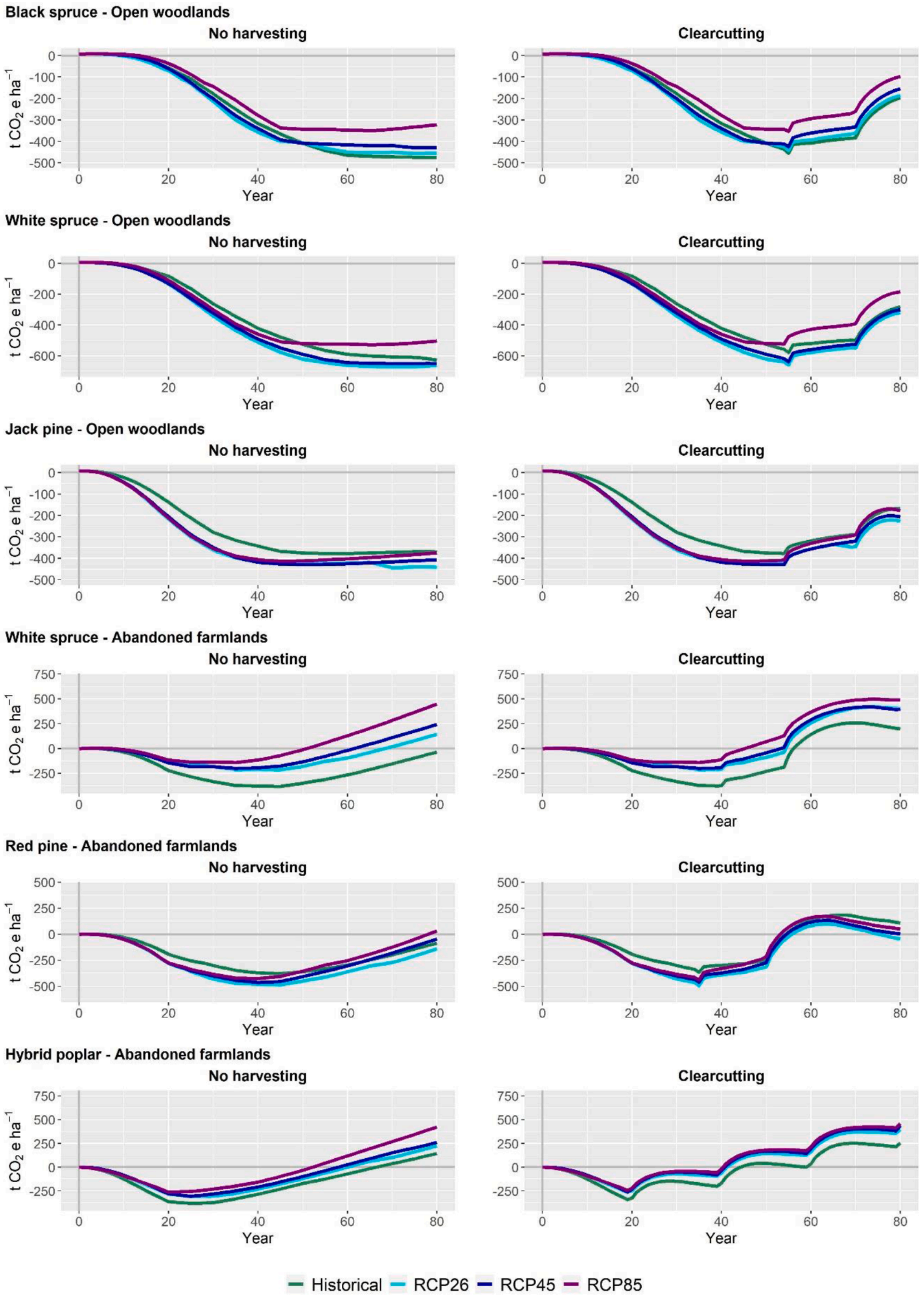

Fig. 7. Cumulative net carbon balance of afforestation scenarios (i.e., difference in carbon fluxes between afforestation and baseline scenarios) on open woodlands and abandoned farmlands according to the planted species and radiative forcing projections. The net carbon balance includes net fluxes from ecosystems, products and substitution. A negative value indicates a net emission mitigation; a positive value indicates a net emission source.

early over a given period cause an overall higher radiative forcing than emissions occurring later and cannot be simply compensated by later sequestration (Paradis et al., 2019). In our case, scenarios that would cause the most sequestration early in the simulation period should lead to a more beneficial climatic effect. Moreover, the change in albedo caused by afforestation can also affect the global radiative forcing effect of a forest management practice; for example, converting open woodlands to close conifer stands could decrease surface albedo with consequences for the long wave radiation budget (Bernier et al., 2011). How this effect compares and contrasts with the radiative forcing effect of carbon management, along with the effect of any other climate feedback mechanism that may occur in forest ecosystems (Yli-Juuti et al., 2021), would need to be carefully quantified in order to provide more complete estimates of the mitigation potential of afforestation.

Finally, solutions such as afforestation can deliver co-benefits beside climate change mitigation. Plantations could fill a need for connectivity between forest ecosystems in fragmented landscapes such as those impacted by agriculture; afforestation efforts could be designed with such objectives in mind. Moreover, diverse planted forests that ensure multifunctionality, resilience and productivity at the stand and landscape scales could be considered (Messier et al., 2021). Complexification of age structure and forest composition has been shown to increase the resilience of ecosystems, and allow better adaptation to climate change as well as increase carbon storage in the ecosystem (Messier et al., 2021;

Paquette and Messier, 2010).

5. Conclusion

This study assessed the vulnerability of afforestation scenarios in Quebec (Canada) to estimate their GHG mitigation potential under a changing climate. The growth of some species was shown to be climate-sensitive, which affected the mitigation benefit of the afforestation scenarios. Compared to the historical climate projection, a slight-to moderate increase in temperature (RCP 2.6 and RCP 4.5) can increase the mitigation potential of certain species such as jack pine (6–11%) and white spruce (3–4%) in the boreal zone of the province, and red pine (1–7%) in its southeastern part. It was shown that the most pessimistic radiative forcing projections (RCP 8.5) may adversely decrease the capacity of new plantations for carbon sequestration and emission reduction by 19% for black spruce and 15% for white spruce on open woodlands, and by 34% for white spruce, 2% for red pine, and 24% for hybrid poplar on abandoned farmlands.

However, even with a drop in forest productivity, afforestation on boreal open woodlands with common species remains a valid option for GHG mitigation under all radiative forcing projections; for abandoned farmlands located under more temperate conditions, plantation with species more adapted to an increase of temperature can also be beneficial. Assisted migration could be used to improve forest growth and maintain carbon sinks (Etterson et al., 2020). Some studies emphasize the importance of bringing species to their northernmost limits to compensate for the lag that climate change will cause in their environment, as seeds from more southern regions may do well in more northern regions (Prud'Homme et al., 2018). The use of species with genetic modifications or more adapted to a larger set of environmental conditions should also be considered. Closely monitoring the planted trees and measuring their evolution over time is crucial to ensure the success of plantations (Sebastian-Azcona et al., 2020).

Modelling allows to draw general lines for the future of forests under changing climatic conditions. Uncertainties in modelling increase when considering a more distant future, especially since climate trajectories can be different from those currently predicted. Nevertheless, using a longer time horizon for simulations and projections could reveal further patterns of carbon recovery and accumulation in harvested wood products, but also expose future risks to ecosystem productivity. The projected drop in plantation productivity under a changing climate, especially on abandoned farmlands, emphasizes the need for better wood processing to secure carbon in long-lived wood products as a way to manage risks.

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Availability of data and materials

The datasets supporting the conclusions of this article are available in the Figshare repository at: https://figshare.com/articles/dataset/Menard_Afforestation_CC_data/17,202,488

CRediT authorship contribution statement

Isabelle Ménard: Conceptualization, Methodology, Formal analysis, Writing – original draft, Writing – review & editing. **Evelyne Thiffault:** Supervision, Conceptualization, Methodology, Funding acquisition, Writing – review & editing. **Yan Boulanger:** Conceptualization, Methodology, Software, Validation, Writing – review & editing. **Jean-François Boucher:** Supervision, Conceptualization, Methodology, Funding acquisition, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

The datasets supporting the conclusions of this article are available in the Figshare repository at: https://figshare.com/articles/dataset/Menard_Afforestation_CC_data/17,202,488

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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.2022.110144.

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