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Improving carbon storage and greenhouse gas emissions avoidance through harvested wood products use

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ABSTRACT

Afforestation can mitigate climate change by creating new carbon sinks and increasing wood supply. However, climate change can impact the growth of trees in afforested areas and affect their characteristics, and the harvested wood products that can be manufactured from them. This study aimed to quantify to what extent the quality of the wood supply directed to primary processing is influenced by climate change and alters the carbon storage of wood products. A multi-model approach was used to estimate the carbon stocks in harvested biomass resulting from plantations of black spruce on open woodlands and hybrid poplar on abandoned farmlands in Québec (Canada) under a gradient of climate forcing projections. Results suggest that increased climate forcing negatively impacts the quality of the harvested wood product basket and influences the relative amount of lumber vs. pulpwood. However, according to our assumptions, the decay of solid wood products in landfills produced more methane emissions than paper, which may constrain their climate change mitigation potential in the absence of methane capture or flaring. The cascading use of solid wood products in bioenergy at the end of their service life significantly reduced overall emissions. This study highlights how comprehensive afforestation strategies can, in the long term, be used to maximize the carbon storage potential of harvested wood products sourced from new plantations, as long as these strategies also include better use of pulp-quality wood, improved cascading use at the end-of-life of wood products and, most importantly, the avoidance of methane emissions from landfilled wood.

1. Introduction

The mitigation potential of greenhouse gas (GHG) emissions by the forest sector has been scrutinized in several studies (Nabuurs et al., 2017). The forests–products–markets value chain can sequester and store carbon in forest ecosystems and wood products, and reduce carbon emissions by displacing GHG-intensive materials and energy sources in markets (Kurz et al. 2013; Smyth et al. 2014). As such, afforestation and reforestation can play a crucial role by increasing terrestrial carbon sinks and by allowing the management of forest composition to increase the resilience of ecosystems to the future climate (Amichev et al. 2012; Boucher et al. 2012; Drever et al. 2021; Ménard et al. 2022a). The newly afforested/reforested areas can then be managed for wood supply (Forster et al. 2021) and provide wood products to meet the material and energy needs of societies.

Wood products act as temporary carbon storage for varying periods depending on the type of products, their end-use, their service life duration, and the disposal or recycling at their end-of-life (Donlan et al. 2012). The efficiency of carbon storage of harvested wood products (HWP) is primarily defined by the proportion of long-lived products, such as sawnwood and panels, that can be manufactured from the available feedstock. Although market variables (timber prices, exchange rates, fluctuating customer demand) influence the wood processing capacity of a given industrial network (Buongiorno et al. 1988), the characteristics of individual tree stems at the time of harvest, i.e., tree species, tree diameter at breast height (DBH), tree total height, and stem taper, also partly determine lumber recovery during sawmilling of a given wood supply (Liu and Zhang 2005; Zhang et al. 2009). Moreover,

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tree species and DBH are among the primary drivers determining the amount of sawn boards produced in a given stem (Auty et al. 2014). Wood-based products, such as wood panels, can also be manufactured from recovered residues from sawmilling activities or low-quality logs (Cai and Robert 2006; Barbuta et al. 2011).

At their end of service, and depending on existing laws and regulations, wood products are sometimes directed to landfills where they decompose for several decades, and a part of their carbon content is re-emitted to the atmosphere as carbon dioxide (CO_2) but also methane (CH_4) if the landfill is not equipped with a methane capture and a recovery system (Ximenes et al. 2015; Moreau et al. 2023). However, some wood products can be recovered at their end-of-life for particleboard manufacturing or bioenergy production, therefore contributing to the cascading use of wood (Kim and Song 2014; Vis et al. 2016; Suominen et al. 2017; Xie et al. 2024). Wood products (sourced from primary or recycled wood) can substitute more GHG-intensive materials and fossil energy sources, further avoiding GHG emissions (Smyth et al. 2017; Howard et al. 2021; Xie et al. 2021). This is especially true in the construction sector, in which sawn wood products and wood panels can be used instead of non-renewable materials (Churkina et al. 2020), and in the energy sector, in which woody biomass-based bioenergy can displace a variety of fossil fuels.

In a plantation context, forest tree breeding is also a factor driving tree growth (White et al. 2007; Desponts and Numainville 2013; Ruotsalainen 2014). Moreover, the average tree DBH of a given stand is the result of site characteristics and growing conditions, e.g., stand density and climate, and their influence on the physiology of tree species (Rohner et al. 2018; Chen et al. 2020). Climate warming is projected to impact the productivity of common species of Eastern Canada (D'Orangeville et al. 2018; Hember et al. 2019; Danneyrolles et al. 2023); the effects on tree growth should vary among species and will depend on the actual climate and environmental trends. These impacts on tree growth will affect the amounts and types of products that can be manufactured from future wood harvest. This could, in turn, influence the expected potential for GHG mitigation of commercial afforestation/reforestation activities and their associated wood supply under a changing climate.

This study aimed to estimate the net carbon storage of HWP sourced from newly afforested areas in the context of climate change and their potential for GHG emission avoidance (by substituting GHG-intensive materials and fossil-based energy sources). Using afforestation scenarios of boreal open woodlands and abandoned agricultural lands aimed at creating new forested lands under management in Québec (Canada) and considering a range of climate forcing projections, a multi-model approach was used to estimate wood volume, stem characteristics, wood product allocation and their effects on carbon storage and GHG emissions. The impact of an increasing climate forcing on the growth of tree species commonly used in plantations, and its associated impact on HWP manufactured from these plantations, was evaluated. The consequences of alternative wood use and product end-of-life scenarios on carbon storage and GHG emissions were also assessed.

2. Methods

2.1. Study areas

Two bioclimatic domains of the Province of Québec that are commercially important for the forest sector were chosen as case studies. They were selected based on the availability of currently non-forested sites that are likely candidates for increasing forested land areas in the province (Ménard et al. 2022b): the spruce-moss domain located between the 49th and 52nd northern parallels, in which boreal open woodlands are abundant within a matrix of closed crown stands (Jasinski and Payette 2005), and the balsam fir-yellow birch domain located between latitudes 47° and 48.5° N, which comprises large portions of abandoned farmlands (Tremblay and Ouimet 2013) (Fig. 1).

The mean annual temperature in the spruce-moss domain is −0.1 °C, and the mean annual precipitation is 989 mm; these values are

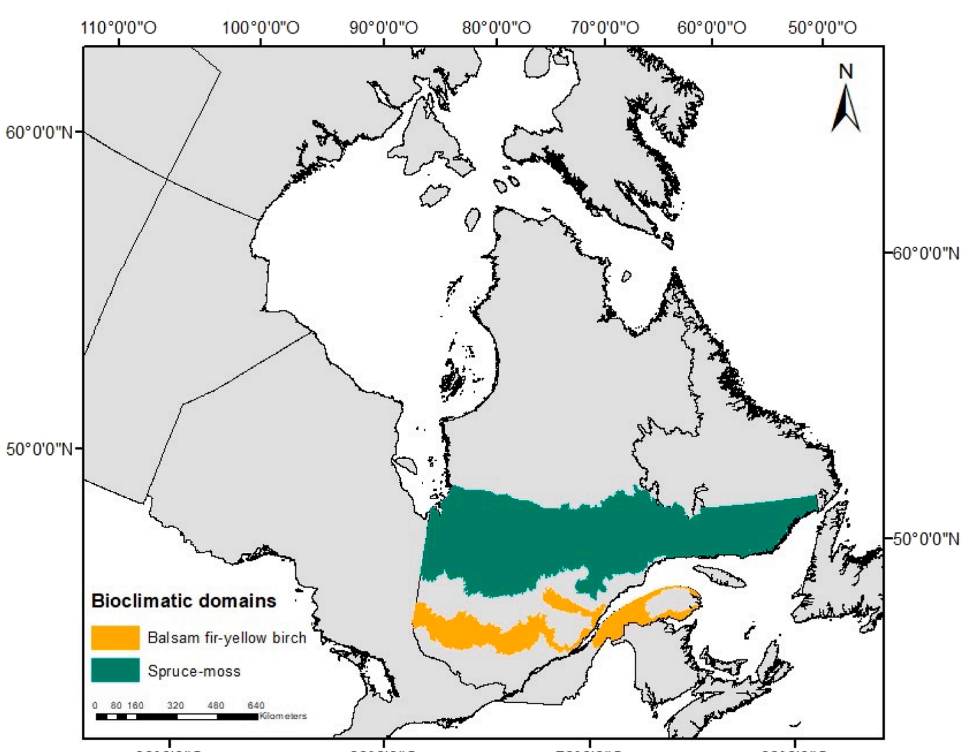

Fig. 1. Two bioclimatic domains in Quebec where open woodlands (spruce-feathermoss) and abandoned farmlands (balsam fir-yellow birch) are located, the two types of land assessed in this study.

respectively 2.8 °C and 1 052 mm for the balsam fir-yellow birch bioclimatic domain.

2.2. Radiative forcing projections

Representative Concentration Pathways (RCP) 2.6, 4.5 and 8.5 were selected for this study (van Vuuren et al. 2011): these scenarios forecast an increase in mean annual temperature in Quebec ranging from 1.7 °C to 6.3 °C by 2100, while average precipitation is expected to increase by 7–23 % (Boulanger et al. 2017). A historical climate projection (based on McKenney et al. 2013; Zhang et al. 2019) was also used as a reference. The Canadian Earth System Model version 2 (CanESM2) and the World Climate Research Program (WRCP) Climate Intercomparison Project Phase 5 (CMIP5) archive (McKenney et al. 2013; Boulanger et al. 2017) were used to make future climate projections, which were then downscaled to a 10 km resolution (McKenney et al. 2011). Extreme climate events were not included in this study.

2.3. Multi-model approach

We used PICUS version 1.5 (Lexer and Hönninger 2001) to model how tree species will physiologically respond, and how the demographic attributes of newly afforested stands will evolve over time, under different climate change scenarios. The PICUS model is spatially explicit and simulates the dynamics of individual trees on a 1 ha x 1 ha grid. It combines a 3D light model for estimating radiation within the canopy (Lexer and Hönninger 2001) and the environment conditions represented by available radiation, a thermal heat sum above a threshold of 5.5 growing degree days, the minimum winter temperatures (the coldest month of the year), a proxy of drought based on soil moisture index derived from a water balance model, and a site nutrient status (soil pH and available nitrogen) (Taylor et al. 2017).

Simulations were conducted for black spruce plantations in open woodlands and hybrid poplar plantations in abandoned farmlands as they are two contrasting cases in terms of species physiology, site conditions and harvested wood products. They are respectively the most planted softwood and hardwood species in Quebec. PICUS operates with fixed parameters related to species autecology, which were previously calibrated for the species considered in our study (Taylor et al. 2017; Boulanger et al. 2018). Since the model is currently parameterized only for native species, trembling aspen was selected as a proxy for hybrid poplar (Ménard et al. 2022a).

Simulations in PICUS were performed using soil physical and chemical characteristics averaged across the two land types simulated based on Mansuy et al. (2014). For open woodlands, the average soil nitrogen (N) concentration was 49.4 g kg^{-1}, the pH was 4.5 and the water-holding capacity averaged 53.3 cm. For abandoned farmlands, the average soil N concentration was 74.4 g kg^{-1}, the pH was 5.1, and the water-holding capacity averaged 65.8 cm. See Taylor et al. (2017) for a detailed description of the model. Note that PICUS does not take atmospheric CO_2 fertilization into consideration.

For the two combinations of afforested species x site type, tree growth within monospecific stands was modelled for 80 years starting from bare ground, according to the changing climate and fixed soil properties associated with each site type (open woodlands and abandoned farmlands). The 80-year period was selected to be consistent with international GHG emissions reduction targets 2030, 2050 and 2100. For each afforested stand, PICUS provided stem volume curves (in m^3) that were then used as input to the Carbon Budget Model of the Canadian Forest Sector v.3 (CBM-CFS3) (Kurz et al. 2009) (see below). The density of each stand modelled in PICUS was equivalent to a plantation of 2000 stems per hectare based on current practices in Quebec (Bolghari and Bertrand 1984; Prégent et al. 1996; Pothier and Savard 1998).

2.4. Forest carbon dynamics

The yearly dynamics of aboveground and belowground carbon stocks of each afforestation scenario over the 2022–2101 period was constructed using CBM-CFS3. In this model, we used an initial soil carbon stock (i.e., at the year of plantation) of 57.0 t C ha^{-1} for open woodlands according to previous simulations done in Ménard et al. (2022a) and 100.0 t C ha^{-1} for abandoned farmlands based on Tremblay and Ouimet (2013). All parameters used to calibrate the model before simulations are explained in Ménard et al. (2022a) and are based on previous simulations and field data (Tremblay and Ouimet 2013).

The harvesting scenarios for each newly afforested stand were based on the best practices used in Quebec (Larouche et al. 2013; Ménard et al. 2022b) (see Supplementary Material 1). The total annual amount of carbon harvested and transferred to wood products was estimated with CBM-CFS3 assuming the clearcutting, i.e., harvesting 97 % of the merchantable stems, of the afforested stand at the age of maturity. Clearcutting is the process of harvesting all trees in an area while ensuring the protection of existing regeneration and soil; it is the most common approach in Quebec's boreal forests. The 97 % value was based on the default value for Quebec in the National Forest Carbon Monitoring, Accounting and Reporting System of Canada. Clearcutting was scheduled at year 70 on open woodlands for black spruce. On abandoned farmlands, we scheduled the clearcutting at years 20, 40, 60, and 80 followed by a replanting after each harvest for hybrid poplar. For hybrid poplar, we used the total harvested biomass of the 4 harvest rotations over 80 years. Harvest residues such as branches and stumps were assumed to be left on the site as dead organic matter, which gradually decomposes.

In Quebec, the diameter at breast height (DBH) is measured in 2 cm classes (Ministère des Forêts de la Faune et des Parcs, 2016). For each afforestation scenario, we assumed that the average DBH given by PICUS for each monospecific and even-aged stand was applied to all stems of the stand (Table 1).

2.5. Carbon storage in harvested wood products

A model developed by the Quebec government for the evaluation of the profitability of silvicultural investments, i.e., the MÉRIS model (*Modèle d'évaluation de rentabilité des investissements sylvicoles* (Bureau de la mise en marché des bois 2018)) was used to calculate the wood product allocation of the harvested wood from the simulated plantations. Based on statistical information collected from forest inventories and supply chains across the province, MÉRIS provides allocation matrices that break down the total volume of a standing tree into harvested logs of the following wood qualities according to the tree species and DBH (using 2-cm classes): sawnwood, pulpwood, merchantable branches, decayed wood, and loss. The "loss" category corresponds to the kerf (1 % of the volume) and inventory adjustment, i.e., the relative difference in gross merchantable volume between the inventory definition and the minimum diameter of use measurement; it was therefore removed from further analyses.

Decayed wood was assumed to be directed to industrial bioheat production within sawmills. The volume of harvested stems or logs suitable for sawing was directed to the sawnwood category. All the harvested wood categorized as pulpwood was sent to the pulp and paper category (Bureau de la mise en marché des bois 2018). In the baseline scenario, it was assumed that there was no wood panel production.

For each combination of afforestation scenarios (2 scenarios) and climate projections (1 historical and 3 projections) (8 combinations in total), we used the average DBH estimated by PICUS for the simulated monospecific stand at the time of harvest as input for MÉRIS, along with the species and harvested volume. This allowed for the estimation, for each combination, of the proportions of the harvested carbon associated with each wood product category.

The carbon stocks and emissions from wood products, co-products

Table 1
Average simulated stem DBH (cm), harvested biomass (t C ha^{-1}), and proportion per type of wood product (%) for each afforestation scenario and climate projection.

Type of land	Planted species	RCP scenarios			Proportion of harvested biomass per type of wood product		
			Average stand DBH (cm)	Harvested biomass (t C ha^{-1})	Sawnwood (%)	Pulpwood (%)	Bioenergy (%)
Open woodlands	Black spruce	Historical	18.5	60.4	59.8	38.1	2.1
		RCP 2.6	18.3	55.7	59.8	38.1	2.1
		RCP 4.5	15.1	55.5	40.0	57.9	2.1
		RCP 8.5	14.5	46.4	3.2	94.6	2.2
Abandoned farmlands	**Hybrid poplar**	Historical	18.5	160.5	0.0	95.7	4.3
		RCP 2.6	16.5	121.2	0.0	95.7	4.3
		RCP 4.5	16.1	123.9	0.0	95.7	4.3
		RCP 8.5	16.2	119.5	0.0	95.7	4.3

and by-products, both throughout their service life and in landfills (Head et al. 2021), were then tracked with the Quebec Stem-Level Harvested Wood Products model 2022 (QSL-HWP 2022) (Fig. 2), using the total amount of harvested biomass (t C ha^{-1}) over the 80 years per wood product category as input. QSL-HWP 2022 was created by parametrizing the *Carbon Budget Model – Harvested Wood Products* (CBM-HWP) model (Smyth et al. 2014), which was run using the Abstract Network Simulation Engine (ANSE) of the Canadian Forest Service.

Carbon stocks and emissions were tracked over 100 years following harvest. For hybrid poplar, the total harvested biomass over the four harvest events was assumed to all be sent to wood processing and markets at the same time after the fourth harvest. In this study, we used national statistics from the UN Food and Agriculture Organization (FAO) to estimate the proportion of exported and imported HWP produced in Quebec (McKenney et al. 2013; Smyth et al. 2014): 61 % of sawnwood, 44 % of pulp and paper, and 58 % of panels were assumed to be used locally within Québec, while the rest was assumed to be exported outside Canada. Carbon storage and substitution of exported HWP were not included in the results of our study. We assumed that 100 % of the bioenergy produced was used in Quebec as industrial bioheat within mills that would otherwise use fossil fuels.

Carbon emissions related to the degradation of harvested wood products in QSL-HWP 2022 were estimated using the default half-life values for each product type: 35 years for sawnwood products, 2 years for pulp and paper products and 25 years for panels (Penman et al. 2003). The carbon fraction remaining in HWP at the end of their service life in sawn products, panels and pulp and paper was calculated using the following equation (Rüter et al. 2019):

$$\text{Fraction remaining in HWP at the end of service life} = 1 - \ln(2)/\text{half-life} \quad (1)$$

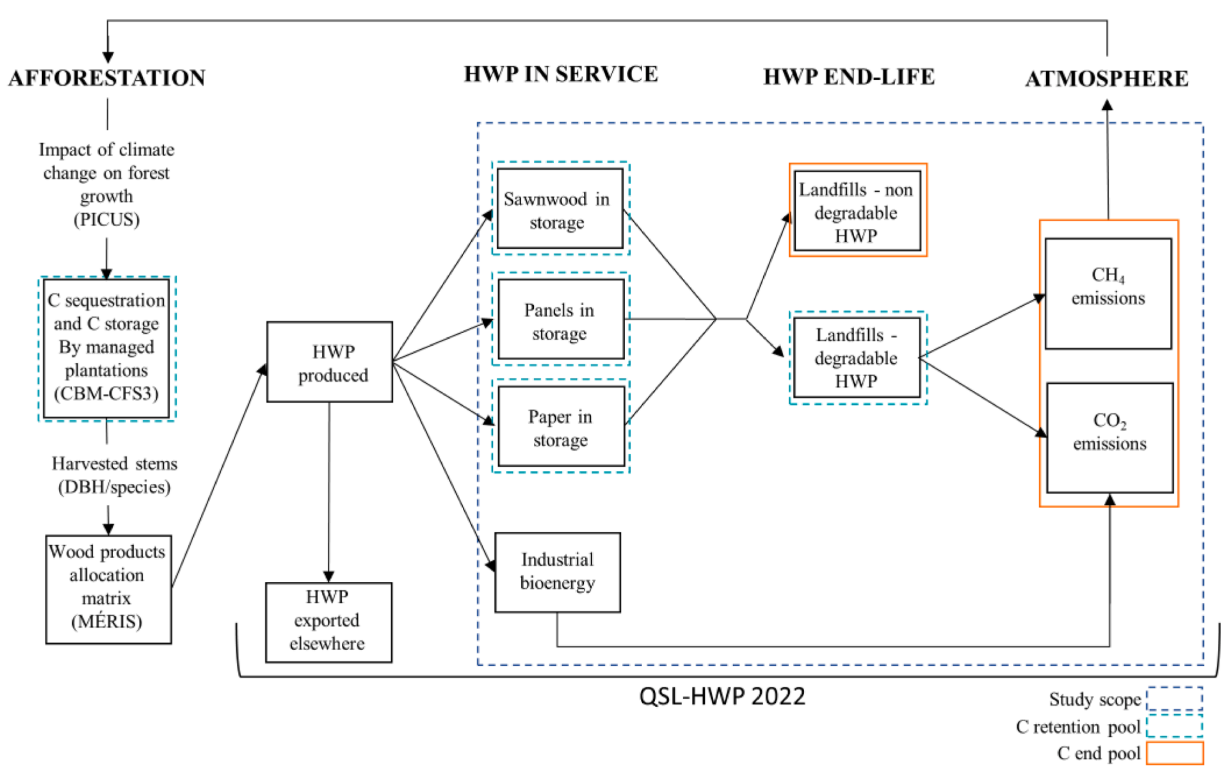

Fig. 2. Conceptual framework for this study: Simplification of the Quebec Stem-Level Harvested Wood Products model 2022 (QSL-HWP 2022) and the pathways from harvested stems to harvested wood products and GHG emissions resulting from decay in the landfills or combustion (bioenergy). Exports are defined as outside Canada.

In QSL-HWP 2022, this carbon fraction is assumed to enter landfills, where it is allocated to degradable and non-degradable fractions. Default values from the IPCC (2006) were used for this partitioning: the degradable fraction was assumed to correspond to 23 % of solid wood products (sawnwood and panels) with a half-life of 29 years, and 56 % for paper with a half-life of 14.5 years (Smyth et al. 2014).

A first-order decay equation was also used to estimate changes in the carbon stocks of the degradable fraction of wood products sent to landfills (Intergovernmental Panel on Climate Change 2006):

$$DDOCm = DDOCM_0 \cdot e^{-kt} \quad (2)$$

Where: t is time in years, $DDOCm$ is the mass of the degradable organic carbon in the wood product that will decompose under anaerobic conditions in landfill at time t, $DDOCm_0$ is the mass of $DDOC$ at time 0, k is the decay rate constant ($years^{-1}$). In this study, the k value was set to 0.03 $years^{-1}$, representing Canada's average decay rate of landfilled wood (Head et al. 2021). Carbon lost through decomposition in landfills was assumed to be emitted as 50 % CO_2 and 50 % CH_4. We assumed no methane capture or flaring (Smyth et al. 2014) as this practice is still marginal in Quebec; nevertheless, this assumption can underestimate the benefits of wood products. Total CO_2 and CH_4 emissions from the decay process of harvested wood products during their service life and in landfills were tracked separately.

Fossil fuel emissions from extraction, transport, and manufacturing were calculated for products when no substitution effect was estimated (see next section) to avoid double accounting. For all types of products, we used an average emission rate of 9.9 kg of CO_2 equivalent (CO_2e) per m^3 for extraction and 8.68 kg CO_2e per m^3 for transportation (Athena Sustainable Materials Institute 2018a). For manufacturing, we used an emission factor of 20.48 kg CO_2e per m^3 for sawnwood (Athena Sustainable Materials Institute 2018a), 64.04 kg CO_2e per m^3 for panels (average of plywood and oriented strand board) (Athena Sustainable Materials Institute, 2018b, 2018c) and 250 kg CO_2e per tonne of paper, based on values calculated for Nordic countries (Sun et al. 2018). Those emissions were included in the “products” emissions category.

2.6. Substitution

The substitution of non-renewable products by wood was assessed using displacement factors. Displacement factors are calculated as the difference in fossil fuel emissions needed to extract resources, manufacture primary products, assemble final products and operate comparative functional units (wood-based vs. non-wood/fossil-based units); they are expressed as an emission avoidance in t of avoided C per t of C in the wood product (Sathre & O'Connor 2010). Such an effect was assumed for sawnwood products, wood panels and bioenergy, which are thought to replace fossil-based/non-renewable materials and energy sources (Cardinal et al. 2024). Following other North American studies, no substitution effect was assumed for pulp and paper products to avoid overestimating the climate benefits of wood products (Smyth et al. 2014; Dugan et al. 2018; Xu et al. 2018). The displacement factors used in our study were based on average values calculated for the Quebec and Canadian contexts: 0.54 t of C avoided per t of C in wood product for sawnwood (Smyth et al. 2014), 0.45 for panels (Smyth et al. 2014), and 0.47 for bioenergy (Smyth et al. 2017).

2.7. Carbon and emission estimation

Carbon fluxes from wood product degradation during their lifetime and in landfills were converted into units of CO_2e (1 t of C = 44/12 tonnes of CO_2e). Based on IPCC estimates (Intergovernmental Panel on Climate Change 2006), the conversion of CH_4 into CO_2e was calculated as 1 t CH_4 = 25 t CO_2e, using the 100-year global warming potential of methane. Carbon storage in HWP and fluxes from wood extraction, transport and manufacturing (when included), wood product degradation and substitution were expressed in tonnes of CO_2e per hectare of afforested land (t CO_2e ha^{-1}) and were tracked over 100 years. When cumulative net carbon fluxes were negative, the scenario was considered to contribute to net mitigation, whereas it was deemed a net source when the cumulative net carbon fluxes were positive.

2.8. Sensitivity analysis

A sensitivity analysis was performed to estimate carbon storage and emissions resulting from three alternative HWP scenarios compared to a baseline: one assumed a different product allocation for harvested wood, and two assumed greater recycling and cascading use of wood products. In this study, the *Baseline* scenario referred to the original HWP breakdown obtained with the MÉRIS allocation matrix. The *Panels+* scenario directed all pulpwood to wood panel production in the form of particle and fiberboards (instead of pulp and paper products). The *Paper+* scenario assumed an extension of the half-life of paper from 2 to 4 years to simulate the effect of increased recycling or extension of service life for pulp and paper products. Finally, the scenario *Bioenergy+* assumed that all sawnwood and paper products would be recovered at their end-of-life to produce bioenergy instead of being sent to landfills; this scenario involved the combustion of biomass for bioenergy of the remaining carbon fraction at the end of the product service life. For the *Bioenergy+* scenario, a range of displacement factors from 0.47 to 0.89 t C t C^{-1} based on Canadian and Quebec values was also tested (Smyth et al. 2017) based on the assumption that bioenergy can displace a suite of fossil fuel sources for different uses. *Bioenergy+* scenario assumed the complete combustion of biomass and emissions of CO_2. and no emissions of CH_4 or N_2O.

3. Results

Increased climate forcing reduced the amount of wood harvested and the average diameter of the harvested stems in both three species (Table 1). The average DBH reached by a given stand at the time of harvest was found to be critical to the amount of sawnwood that could be sourced from the stand (Table 1). First, increased climate forcing had an impact on the tree growth of afforested stands, affecting the DBH of the stems at the time of clearcutting, with consequences for the basket of wood products that could be sourced from harvested wood (Table 1). Second, the amount of harvested carbon on afforested sites, which was transferred to wood products, was also affected by the combination of climate forcing scenarios and the planted tree species (Table 1). Indeed, an increased climate forcing caused a decrease in the overall amount of carbon processed and stored into products for black spruce on open woodlands and for hybrid poplar on abandoned farmlands.

Afforestation with black spruce allowed the production of roundwood with a high share of sawnwood quality logs, which could be processed into sawn products storing carbon over a long period (Fig. 3). Conversely, hybrid poplar produced a much smaller share of sawn products and a high share of short-lived paper, which quickly degraded over time (Fig. 4). Note that for simplification, it was assumed that all biomass harvested over the four harvest events was sent to wood processing and markets at the same time, i.e., after the fourth harvest; in practice, carbon storage and emissions would therefore start earlier and be spread over a longer period of time.

The impact of climate forcing on stem DBH (Table 1), in turn, impacted landfill carbon storage and GHG emissions (Fig. 3 and Fig. 4). For black spruce (Fig. 3), the carbon accumulation rate in landfills was constant over 100 years and correlated with the long service life of solid wood products. For aspen, the high proportion of paper caused a rapid decrease of carbon in products still in service and a fast transfer to landfill sites (Fig. 4).

For black spruce stands from afforested open woodlands (Fig. 3), harvested volume decreased from RCP 2.6 to 8.5, directly reducing wood product emissions. Reduction in processed volumes means that

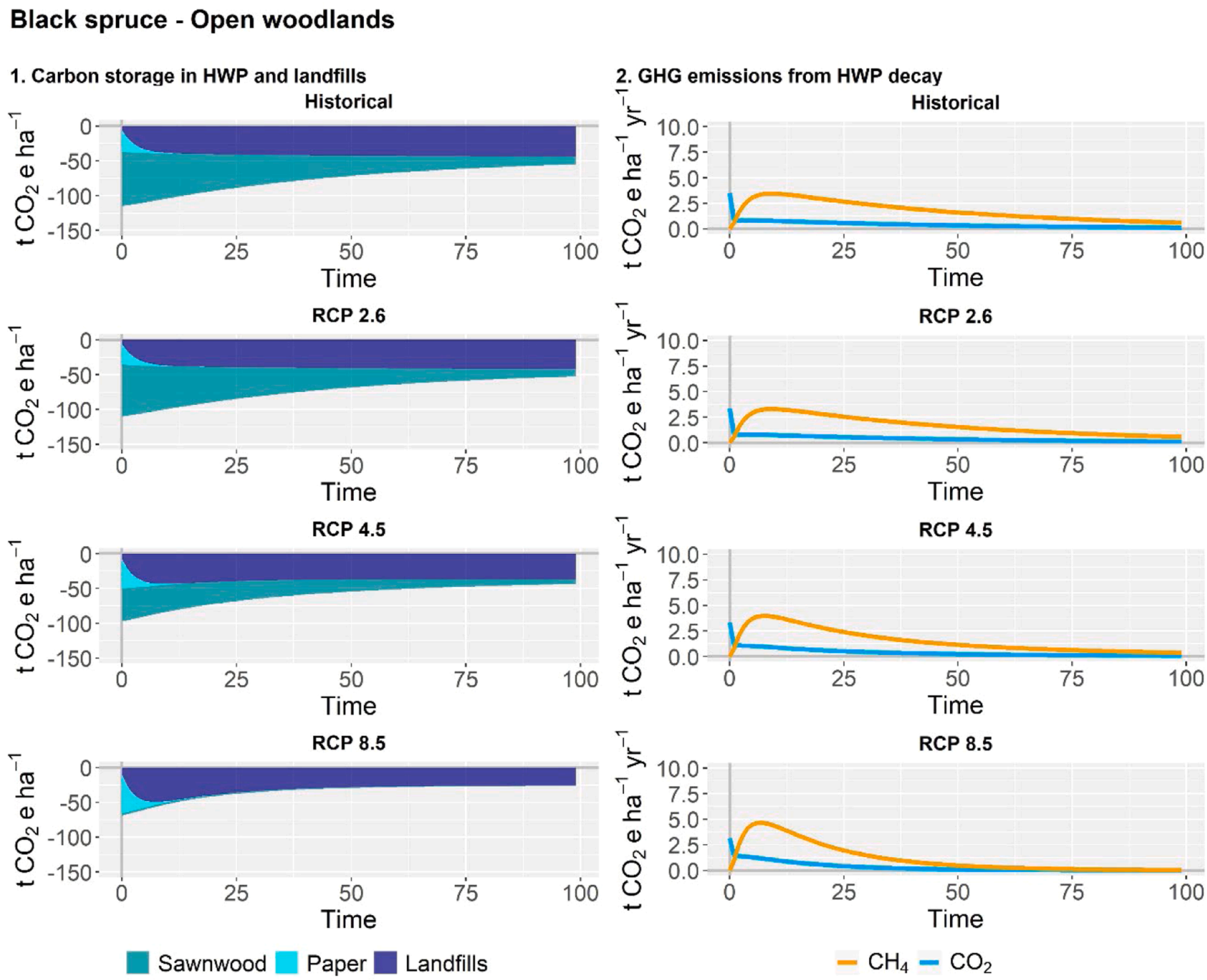

Fig. 3. Evolution of carbon storage in HWP in service and in landfills over time in Quebec (t CO_2e ha^{-1}) (left panel) and evolution of annual emissions resulting from HWP decay (t CO_2e ha^{-1} yr^{-1}) (right panel) under different radiative forcing projections for black spruce plantations on open woodlands. Time 0 corresponds to the moment when carbon harvested from afforested areas is transferred to wood products. Bioenergy is assumed to cause instant emissions by combustion and therefore does not appear as C storage (left panel), but those emissions are included in the right panel. Negative values correspond to carbon storage, and positive values to emitted carbon.

the carbon sink generated during the growth of afforested stands was also smaller. Hybrid poplar plantations on agricultural lands (Fig. 4) also experienced a decrease in harvested and processed volumes due to climate change, compared to the historical climate. Since black spruce produced more sawn products, scenarios for this species continued to emit even after 100 years. Compared to CO_2 emissions, CH_4 emissions had a greater share in total annual emissions from harvested wood products due to its higher global warming potential (see right panel in Figs. 3 and 4).

3.1. Alternative HWP scenarios

A sensitivity analysis using three alternative HWP scenarios (*Panels+*, *Paper+* and *Bioenergy+*) compared to the *Baseline* HWP scenario (presented in the previous section) showed that the emission trajectories varied according to the assortment of wood products and HWP recycling at their end-of-life (Fig. 5). For black spruce and hybrid poplar, total cumulative emissions, i.e., total of CO_2 and CH_4 emissions over a 100-yr period expressed in t CO_2e ha^{-1} resulting from HWP degradation during their service life and in landfills, were delayed in the *Panels+* scenario compared to the other scenarios. This was due to the increase in carbon storage associated with a larger proportion of long-lived wood products. On the other hand, at year 100, total emissions released by the *Panels+* scenario were higher than for the other scenarios because solid wood products sent to landfills caused larger emissions of CH_4 due to the anaerobic conditions. Cumulative emissions in the *Paper+* scenario, for which increased paper recycling was assumed, were only briefly delayed compared to the *Baseline* scenario. Finally, cumulative emissions from the *Bioenergy+* scenario grew faster in the first years than for all other scenarios. However, since this scenario did not send wood products to the landfills and, thus, no CH_4 was emitted, overall emissions decreased.

3.2. Substitution effect

CO_2 emissions avoided by product substitution for the *Baseline* HWP scenario decreased for both species as a function of radiative forcing projections. The increase in long-lived wood products and bioenergy simulated in the *Panels+* and *Bioenergy+* scenarios avoided more emissions through displacement than the baseline scenarios (Table 2). For the *Panels+* scenario, the increase of long-lived wood products associated with using pulpwood for fibre- and particleboard panels (instead of pulp and paper) increased displaced emissions for both species and all climate projections compared to the *Baseline* scenario. Paper recycling did not affect displaced emissions since we assigned no displacement factor to this product. The *Bioenergy+* scenario, which assumed that all HWP at the end of their service would be used for bioenergy (with

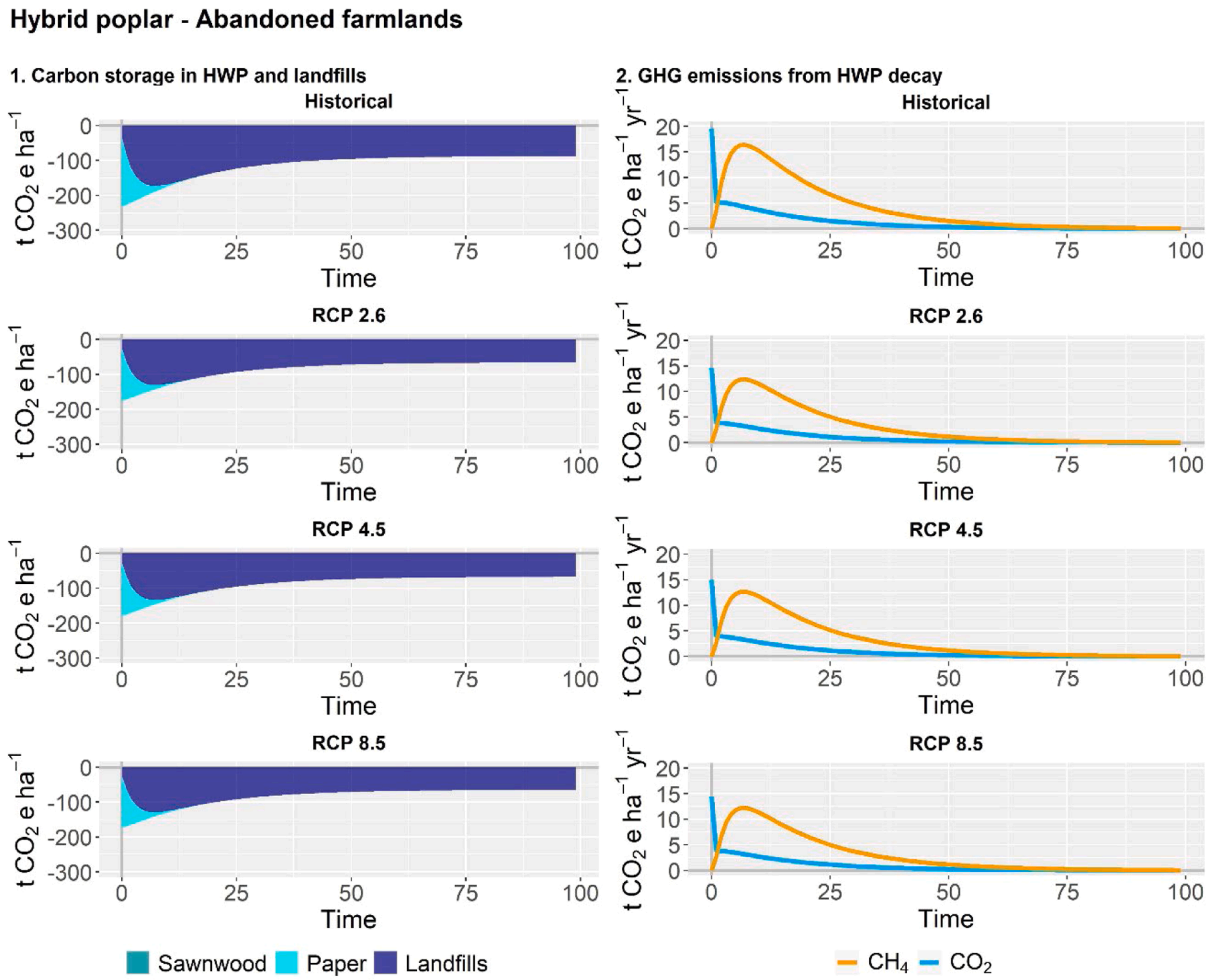

Fig. 4. Evolution of carbon storage in HWP in service and in landfills over time in Quebec (t CO_2e ha^{-1}) (left panel) and evolution of annual emissions (t CO_2e ha^{-1} yr^{-1}) (right panel) under different radiative forcing projections for hybrid poplar plantation on abandoned farmlands. Time 0 corresponds to the moment when carbon harvested from afforested areas is transferred to wood products (assuming that all harvested volume over the 4 clearcut events enters markets at the same time after the fourth harvest). Bioenergy is assumed to cause instant emissions by combustion and therefore does not appear as C storage (left panel), but those emissions are included in the right panel. Negative values correspond to carbon storage, and positive values to emitted carbon.

displacement factors ranging from 0.47 to 0.89 t C t C^{-1}), displaced more overall emissions than the *Baseline, Panels+* and *Paper+* scenarios.

When considering total GHG fluxes from the wood supply, processing and manufacturing, wood product degradation and product substitution effect on markets, all the alternative HWP scenarios showed a decrease in cumulative GHG emissions compared to the *Baseline* HWP scenario. The *Panels+* and *Bioenergy+* scenarios showed the greatest improvement compared to the *Baseline* HWP scenario for both species (Table 3). After 25 years, the scenario with the greatest improvement was the *Panels+* scenario. For the *Paper+* scenario, the difference caused by increased paper recycling disappeared over time (Table 3). After 75 years, Bioenergy+ was the scenario with the greatest benefits but caused more emissions than the *Baseline* in the first 4–5 years (Fig. 5); there was a decrease in emissions compared to the *Baseline* until the end of the simulation due to the accounting of two substitution effects, one for the first product life and one for its recycling as bioenergy.

4. Discussion

Our study has shown that the effect of climate change on stem diameter size and harvested volume of newly afforested stands can have direct consequences for carbon storage and GHG emissions associated with wood products derived from the harvest of afforested stands. Our study was based on the results of Ménard et al. (2022b) that highlighted the potential of plantation in climate change mitigation. We based our methodology and results on Ménard et al. (2022a) in which an approach combining tree physiology and forest carbon accounting was used to integrate the impact of climate change on forest productivity. In the present study, we assessed improved wood processing scenarios to highlight the role of carbon storage and GHG emissions avoidance in harvest wood products.

Our results suggested that although using fast-growing species such as hybrid poplar increases the carbon sequestration rate on afforested sites, this species mainly produces pulp-quality wood currently used for pulp and paper products, at least in the current wood industrial network of Quebec (Ministère des Forêts de la Faune et des Parcs 2019). As shown by the improved scenario *Panel+*, diverting pulpwood to panel manufacturing can significantly improve carbon storage and GHG emission avoidance. Accumulating long-lived wood products in landfills contributed to extend carbon storage; however, this helped reduce total emissions only over the first 50 years as methane (CH_4) emissions from landfills increased. On the other hand, the cascading use of wood products at their end-of-life, illustrated by the alternative scenario *Bioenergy+*, produced the lowest cumulative amount of emissions: it diverted biomass from landfills, thus also reducing CH_4 emissions, and caused additional substitution benefits. Overall, the length of carbon

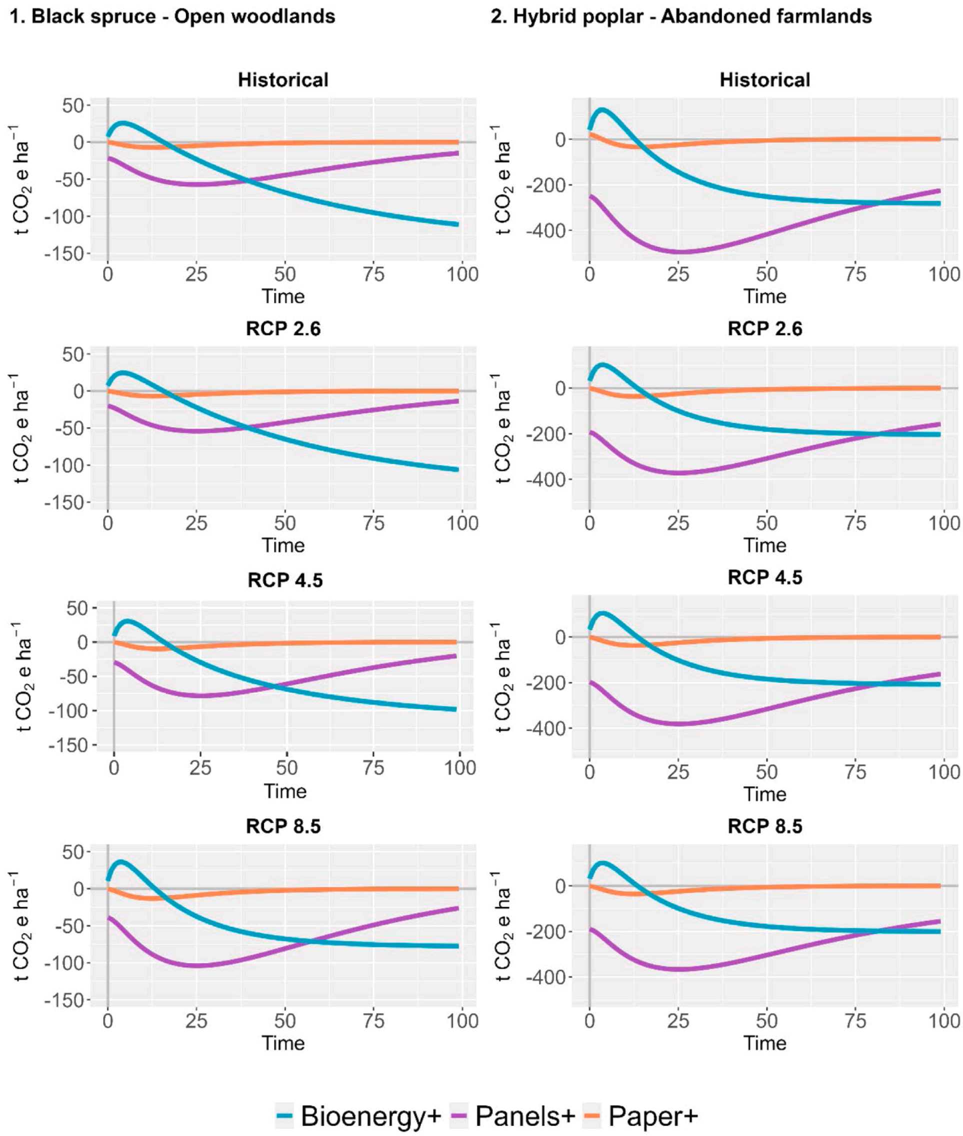

Fig. 5. Evolution of total net cumulative emissions (t CO_2e ha^{-1}), including emissions from extraction, transport, and manufacturing, HWP degradation during their service life and in landfills, for the three alternative HWP scenarios for two species (left panel for black spruce and right panel for hybrid poplar) under historical climate and three radiative forcing projections. Net cumulative emissions represented the difference between the three alternative HWP scenarios and the baseline scenario. Substitution benefits are not included. Time 0 corresponds to the moment when the carbon harvested from afforested areas is transferred to wood products (assuming that all harvested volume over the 4 clearcut events for hybrid poplar enters markets at the same time after the fourth harvest).

storage, the expected substitution effect on markets and CH_4 emission in landfills largely determined the cumulative net benefits of wood supply from afforestation for mitigation purposes.

4.1. Impacts of climate change on HWP, carbon storage and GHG emissions

In our study, changes in radiative forcing impacted predicted tree growth and resulted in variations in harvested volume from afforested sites. According to species growth simulations conducted with PICUS, black spruce and hybrid poplar showed a decrease in stand volume from RCP 2.6 to RCP 8.5 for specific site conditions. These results are consistent with Boulanger et al. (2022) that found a high level of model ensemble agreement in projected black spruce and trembling aspen performance under a changing climate. Other studies observed that black spruce growth response to climate change depends on several parameters such as site climatic and edaphic conditions and interannual climate variability (Girardin et al. 2016; D'Orangeville et al. 2018; Moreau et al. 2020).

Several environmental drivers can explain the impact of climate change on forest productivity. Extreme climate events could also have a large negative impact on forest growth. Yet, their integration in modelling processes can be complex and depends on scientific knowledge and data availability. PICUS does not include a CO_2 fertilization effect. If this where to occur, then the negative impacts of climate forcing could be reduced. However, forest growth in Quebec is limited by both moisture and nitrogen availability and there is no clear evidence of a CO_2 fertilization effect (e.g., Girardin et al. 2016).

The amount of manufactured wood products is a function of the volume of harvested wood. However, our study also showed that the impact of climate change on stem DBH influences the type of HWP that can be produced if there are no accompanying changes in wood processing methods (smaller average DBH resulting in a lower proportion of sawn products), with consequences on carbon storage in wood products, emissions in landfills and substitution effects. This suggests a need to refine the GHG emission estimation related to HWP. First, based on

Table 2
Total substitution effect (expressed in t CO_2e ha^{-1}) calculated for each HWP basket scenario of the sensitivity analysis for the two types of plantations and the four climate projections. For Bioenergy+, values in parentheses correspond to minimum and maximum values assuming a displacement factor of 0.47 (minimum) or 0.89 (maximum) t C t C^{-1}. Negative values indicate decreased emissions due to the substitution effect. Time 0 corresponds to the moment when carbon harvested from afforested areas is transferred to wood products.

Plantations	Climate Projections	Baseline	Panels+	Paper+	Bioenergy+
Black spruce on open woodlands	Historical	−44.4	−65.7	−44.4	(−93.5, −139.2)
	RCP 2.6	−42.4	−62.8	−42.4	(−89.3, −133.0)
	RCP 4.5	−27.4	−56.5	−27.4	(−70.0, −109.7)
	RCP 8.5	−3.3	−42.2	−3.3	(−35.8, −66.3)
Hybrid poplar on abandoned farmlands	Historical	−22.1	−159.9	−22.1	(−132.6, −251.1)
	RCP 2.6	−14.6	−118.7	−14.6	(−98.1, −185.68)
	RCP 4.5	−15.0	−121.3	−14.95	(−100.2, −189.8)
	RCP 8.5	−14.4	−117.0	−14.4	(−98.7, −183.1)

empirical data collected from forest inventories and supply chains across Quebec, large differences exist between species regarding wood product allocation, even among seemingly similar species (e.g., conifers). Second, projections of future dynamics of carbon storage and GHG emissions of forest ecosystems and HWP would need to include climatic feedback on HWP. At the very least, clear assumptions are necessary for the innovations required in wood processing, HWP manufacturing practices, HWP cascading uses and landfill management, including the capture of methane emissions. Given the large impact of methane emissions on future climate change, it is highly likely that methane management in landfills will be more strongly regulated. For example, using captured methane to replace fossil fuels can contribute additional substitution benefits (Scharff et al. 2023).

The amount and rate of GHG emissions to the atmosphere resulting from the degradation of wood products is a function of the amount and the nature of HWP and the conditions under which decay occurs. Long-lived wood products show delayed emissions over time, while ephemeral products such as paper and bioenergy exhibit rapid atmospheric GHG emissions. There are several ways to increase the proportion of long-lived wood products in the HWP basket. In our study, a black spruce plantation on open woodlands was harvested at year 70. Given the slower growth rate on these territories, increasing the time before harvesting could generate larger DBH stems. On the other hand, this also increases the exposure of the plantation to natural disturbance risks (e.g., wildfires). Integrating optimization tools to facilitate forest management and wood production planning at the tactical and operational level (Dumetz et al. 2021) and novel tools, such as Radio frequency identification (RFID) traceability systems, that can automatically calibrate sawmills with stems' information and avoid downgrading of wood, can help create more valuable products (Björk et al. 2011). Also, the results of our study suggest that efforts should be made to find opportunities for pulpwood to be processed into long-lived wood products, such as wood panels (Padilla-Rivera et al. 2018). Panels can be manufactured using small-diameter and low-quality logs (Barbuta et al. 2011), or using wood waste originating from solid wood products at their end-of-life (Vis et al. 2016). Lastly, many of the HWP emissions will be removed from the atmosphere by tree growth during the second rotation of the afforested stand, which we did not quantify in this study.

4.2. *Wood product end-of-life and cascading use*

The carbon emissions from landfills are directly proportional to the amount of degradable materials within discarded wood products, i.e., the cellulose and hemicellulose contained in the lignin matrix (O'Dwyer et al. 2018; Head et al. 2021). Under anaerobic conditions, degradation mainly releases CH_4, which can be captured for energy or flared to convert CH_4 to CO_2, thus reducing the radiative forcing. However, studies reported that landfill decomposition rates, such as those used in this study, likely overestimate methane emissions (Ximenes et al. 2015; O'Dwyer et al. 2018). Landfills may therefore store carbon longer and thus be a larger carbon reservoir than what was simulated here. In Quebec, larger landfills, i.e., landfills that have a maximum capacity of >1 500 000 m^3 or that receive 50 000 tonnes or more of waste per year, have been subject since 2009 to a methane destruction obligation, which converts methane into CO_2 and water under the Environment Quality Act and the Regulation respecting the landfilling and incineration of residual materials (Gouvernement du Québec 2021). However, capture efficiency depends on site configuration and other uncertainties, leading to an efficiency in the range of 35–70 % (Intergovernmental Panel on Climate Change 2006). Canada is working on adding a protocol for landfill methane recovery and destruction under its GHG Offset Credit System Regulations (Environment and Climate Change Canada 2022). The results of this and other studies (e.g., Moreau et al. 2023) suggest that this can be an effective climate change mitigation measure.

Alternative scenarios that include recycling and cascading use of wood products at the end of their service life (*Paper+* and *Bioenergy+*) showed that improved waste management helps avoid the onset of anaerobic decomposition processes in landfills. By definition, the cascading use of wood allows for the efficient utilization of resources and extends total biomass availability within a given system (Vis et al. 2016). In this study, we only tested the extension of the paper half-life as

Table 3
Difference between total GHG fluxes (t CO_2e ha^{-1}), including emissions from HWP degradation during their service life and in landfills, extraction, transport, and manufacturing emissions for pulp and paper products, and substitution benefits for sawn wood, panels and bioenergy, for the three alternative HWP scenarios (Panels+, Paper+ and Bioenergy+) and the baseline HWP scenario for the two types of plantations and the four climate projections at three time steps (25, 50 and 75). Negative values indicate lower emissions for the alternative scenarios compared to the baseline scenario. Time 0 corresponds to the moment when carbon harvested from afforested areas is transferred to wood products.

Plantations	Climate projections	Alternative scenarios at time 25, 50 and 75 (t CO_2e ha^{-1})								
		Panels+			Paper+			Bioenergy+		
		25	50	75	25	50	75	25	50	75
Black spruce on open woodlands	Historical	−88.04	−75.39	−57.96	−4.89	−1.22	−0.28	−70.13	−127.68	−162.63
	RCP 2.6	−83.47	−71.38	−54.73	−4.67	−1.17	−0.27	−67.0	−122.0	−155.4
	RCP 4.5	−120.4	−103.1	−79.3	−6.69	−1.67	−0.38	−77.0	−123.9	−147.8
	RCP 8.5	−159.8	−136.7	−104.8	−8.94	−2.23	−0.51	−84.0	−115.0	−122.9
Hybrid poplar on abandoned farmlands	Historical	−632.53	−555.02	−443.2	−24.53	−5.21	−0.13	−308.5	−416.6	−441.4
	RCP 2.6	−479.8	−415.9	−328.0	−24.66	−6.16	−1.41	−228.2	−309.0	−327.5
	RCP 4.5	−491.4	−426.1	−336.3	−25.21	−6.30	−1.45	−233.2	−315.9	−334.8
	RCP 8.5	−472.4	−409.5	−322.8	−24.31	−6.07	−1.39	−225.0	−304.7	−322.9

a proxy for increased paper recycling and the instantaneous combustion of all HWP at the end of their first service for bioenergy. Nevertheless, other opportunities exist; for instance, wood products can be recycled into other material forms before further recovery for energy purposes. Recovered wood from sawn products can be recycled as particleboard, extending carbon storage and creating a new occasion for substituting fossil-based materials. However, only a small amount of wood coming from certain types of panels, such as oriented strand board (OSB), particleboard, fibreboard and plywood, can be further recycled as particleboard; under current industrial practices, the major part of panels at end-of-life can only be directed to energy purposes (Vis et al. 2016). Nevertheless, cascading use of wood has been found to generate a higher potential for mitigating climate change than only increasing the lifetime of HWP (Budzinski et al. 2020; Xie et al. 2024).

4.3. Substitution on markets

In this study, we used conservative displacement factors from the literature to calculate the substitution effect of HWP. Sawn products and panels yield higher values in carbon storage and substitution than ephemeral products such as paper (Zabalza Bribián et al. 2011; Cobut et al. 2013; Smyth et al. 2014). For the *Bioenergy+* scenario, the addition of the substitution by long-lived wood products during their service life, with the benefits of recovering these products as feedstock for bioenergy, showed the greatest potential for emission reduction through diversion of wood from landfills and product displacement on markets. This was especially true for species that yield a large share of long-lived wood products, such as black spruce. The results support that while the quantity of GHG emissions avoided through substitution is a function of the amount of long-lived wood products and bioenergy, the cascading use allows for the same quantity of harvested stems to have a greater GHG mitigation potential. However, our study suggested that variations in the quantity and quality of forest supply due to the impact of climate change on forest growth can lead to a decrease in the capacity of forests to provide long-lived wood products under the current industrial structure. Therefore, substitution should not be seen as an independent component but complementary and interdependent on carbon sequestration in ecosystems, carbon storage in HWP, and managing methane emissions from landfills.

4.4. The role of plantations in the production of long-lived wood products

As shown by our results, the choice of an afforestation strategy (i.e., type of land and planted species) impacts the quantities of carbon sequestered in the ecosystem (Valade et al. 2017). Once harvested biomass stocks are transferred to primary wood processing, the wood product allocation of the logs influences carbon storage (Ramage et al. 2017). Forest management strategies should, therefore, aim to better capture the importance of carbon storage in wood products. Part of the global demand for wood products comes from plantations, and this trend is likely to increase over time (Ramage et al. 2017). Since the economic value of long-lived wood products typically is greater than that of short-lived products, a greater value to afforestation can be predicted as it can contribute to increasing carbon sinks and facing the increasing global demand for timber (Ramage et al. 2017). Novel bioproducts can also be expected in the future to displace fossil-based products and meet material needs (Hassegawa et al. 2022). In the long term, the carbon sink of unmanaged plantations (in the absence of further harvesting) would eventually saturate (Taylor et al. 2014). Natural disturbances, e.g. wildfire, can also terminate carbon sequestration and release carbon (Gauthier et al. 2015). Afforestation for harvesting is a process that takes decades to achieve. Moreover, the MÉRIS wood product allocation matrix was used to define the proportion of HWP for each species, even though there may be regional variations in stem processing capacity. Yet, the current diameter limits for sawn wood and pulpwood may change in the future depending, for example, on the adaptation of mills to future wood supplies.

Our analysis assumed that no mitigation benefits would be achieved from wood that was exported from Canada. While difficult to quantify, some mitigation benefits will be achieved in the country that imported the HWP exported. Thus, global mitigation benefits from the use of wood product derived from afforestation efforts in Quebec are higher than estimated here.

5. Conclusion

Climate change will impact forest growth, with consequences for the quantity and quality of forest supply and harvested wood products. In two contrasting afforestation scenarios, species such as black spruce and hybrid poplar showed with increasing climate forcing a decrease in total harvest volume and average DBH, which directly reduced the proportion of long-lived wood products manufactured from their wood. Under a changing climate, the potential basket of wood products from future harvests, including the prospect of novel bioproducts, should be considered at the outset of planning mitigation actions such as afforestation. The avoidance of GHG emissions, especially CH_4, from landfilled wood products also appeared as an important aspect of the GHG balance of the forest value chain. Developing longer-lived materials from pulp-quality wood and cascading use of wood were highlighted by this study as important means to increase carbon storage in HWP and reduce overall GHG emissions. Recovering wood products at the end of their service life for bioenergy production was also particularly efficient, as it reduces CH_4 emissions from landfilled materials and provides additional substitution benefits. Taken together, these conclusions make it possible to improve the contributions of afforestation to climate change mitigation by increasing land carbon sinks, the storage of carbon in the initial wood products and the re-use of wood products in panels and bioenergy, the displacement of GHG-intensive materials and energy sources, and, most notably, the avoidance of methane emissions from landfilled wood.

List of abbreviations

GHG: greenhouse gas; CBM-CFS3: Carbon Budget Model of the Canadian Forest Sector v.3; CBM-HWP: Carbon Budget Model for Harvested Wood Products 2018; QSL–HWP 2022: Quebec Stem-Level Harvested Wood Products model 2022; ANSE: Abstract Network Simulation Engine; HWP: harvested wood products; DBH: diameter at breast height

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CRediT authorship contribution statement

Isabelle Ménard: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Formal analysis, Conceptualization. **Evelyne Thiffault:** Writing – review & editing, Supervision, Resources, Methodology, Funding acquisition, Conceptualization. **Michael Magnan:** Writing – review & editing, Software, Methodology, Conceptualization. **Werner A. Kurz:** Writing – review & editing, Validation, Software, Methodology, Conceptualization. **François Hébert:** Writing – review & editing. **Jean-François Boucher:** Writing – review & editing, Supervision, Resources, Methodology, Funding acquisition, Conceptualization.

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.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.tfp.2024.100757.

Data availability

The datasets supporting the conclusions of this article are available in the Figshare repository at: https://doi.org/10.6084/m9.figshare.26738245.v1.

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