Carbon sequestration and emission mitigation potential of afforestation and reforestation of unproductive territories

Isabelle Ménard[1], Evelyne Thiffault[1], Werner A. Kurz[2] and Jean-François Boucher[3]

[1]Research Centre on Renewable Materials, Department of wood and forest sciences,
Laval University, Québec City, QC, G1V 0A6, Canada

[2]Canadian Forest Service, Natural Resources Canada, Victoria, British-Columbia, V8Z
1M5, Canada

[3]Centre of Forest Research, Département des Sciences Fondamentales, Université du
Québec à Chicoutimi, Chicoutimi, Québec, G7H 2B1, Canada

Corresponding author: Isabelle Ménard (isabelle.menard.3@ulaval.ca)

ORCID:

Isabelle Ménard: 0000-0001-5036-1857
Evelyne Thiffault: 0000-0001-9586-3834
Werner A. Kurz: 0000-0003-4576-7849
Jean-François Boucher: 0000-0002-2918-8057

Abstract

Afforestation and reforestation can contribute to the mitigation of climate change by increasing forested areas that can actively sequester carbon dioxide from the atmosphere through photosynthesis. The purpose of this study was to assess the potential for carbon sequestration in the ecosystem and in harvested wood products, and associated greenhouse gas (GHG) emission mitigation, following the application of afforestation/reforestation strategies on unproductive lands in the Province of Quebec over an 80-year long period (2021-2101), using the *Carbon Budget Model of the Canadian Forester Sector 3.* Afforestation/reforestation scenarios without harvesting and scenarios based on establishment of fast-growing species such as hybrid poplar showed the greatest short-term (2020-2040) carbon sequestration potential. Over the 80-year simulation period, plantations without harvesting generated a greater potential for carbon sequestration in ecosystems; after each harvesting event, several decades were necessary to regain any ecosystem carbon loss, which could be compensated only if a proportion of the harvested wood is converted to long-lived wood products, with high substitution effects in other sectors. In the northern boreal zone of Quebec, significant mitigation potential can be expected from the afforestation of open woodlands and poorly regenerated burns, both with or without harvesting. In the southern zone, the need for better data on vegetation succession and carbon accumulation on abandoned farmlands in the absence of plantations was highlighted by this study. This study increases the understanding of carbon sequestration by plantations, and their role as a mitigation strategy to contribute to national GHG emission reduction targets and net-zero carbon objectives.

Keywords

Carbon dioxide removal; Open woodlands; Abandoned farmlands; Poorly regenerated burns; Harvested wood products; Displacement factor.

Statements and Declarations

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Author's contributions

Isabelle Ménard (IM), Evelyne Thiffault (ET), Jean-François Boucher (JFB) and Werner A. Kurz (WK) conceived the approach and methods. IM drafted the paper and ran the analyses. All authors contributed to the revision of the manuscript. All authors read and approved the final manuscript.

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Introduction

Anthropogenic climate change is mainly due to increased concentrations of greenhouse gases (GHG) in the atmosphere from the burning of fossil fuel and land-use change, especially the reduction in the area occupied by forest lands (IPCC 2014; Gillett et al. 2021). Afforestation, i.e. the human-induced conversion of land that has not been forested for a period of at least 50 years to forest land (Penman et al. 2003), and reforestation, i.e., the human-induced conversion of non-forested land to forested land through planting on land that was once forested but has been converted to non-forested land (Penman et al. 2003), are recognized as carbon dioxide removal (CDR) strategies by creating or increasing carbon sinks (United Nations 2015). They are part of the larger portfolio of forestry practices that can provide mitigation benefits by maintaining or increasing forest carbon stocks, while producing a sustainable flow of timber, fibre and energy (Nabuurs et al. 2007).

Forest management and the use of harvested wood products (HWPs) can increase the amount of carbon sequestered and stored in the long term. Moreover, wood processing requires less energy from fossil fuels than other materials such as steel and cement (Eriksson et al. 2007); therefore wood products can contribute to climate change mitigation by substituting more GHG-intensive products (Sathre and O’Connor 2010; Werner et al. 2010; Smyth et al. 2014). Wood residues can also be used to produce bioenergy to substitute fossil fuels (Eriksson et al. 2007), which can reduce net GHG emissions to the atmosphere (Laganière et al. 2017).

With its well-developed forest sector, Canada is assessing how forestry-based solutions, such as afforestation and reforestation (A/R), can be mobilized for climate change mitigation (Drever et al. 2021). As an example, the province of Quebec, in eastern Canada, according to the most recent forest inventory (Tremblay et al. 2013), contains approx. 1.3 million hectares of unproductive boreal open woodlands (OWs), within the limits of allowable territory for forest management. Once afforested, these lands may reach the yield of productive boreal spruce or pine plantations (Hébert et al. 2014; Dufour et al. 2016), and thus increase the surface area of forest carbon sinks (Gaboury et al. 2009; Boucher et al. 2012; Dufour et al. 2016). Boreal areas that are poorly regenerated after natural disturbance such as wildfire can also be candidates for reforestation. Moreover, in the temperate zone of the province, abandoned farmlands, situated in the St. Lawrence valley (part of the Atlantic maritime ecozone) and originating from forested lands cleared for agriculture purposes at the end of the 19th century (Bélanger and Grenier 2002), can represent a sizable share of the territory that can be converted to forested lands. Considering these three types of currently unproductive areas (from a forestry and GHG balance point of view), Quebec has a strong A/R potential to create new carbon sinks by increasing forested areas. These new forested areas can then be subjected to further forest management activities, and contribute to a new sustainable supply of wood products (Paradis et al. 2019). Furthermore, these areas are potential planting sites for Canada's 2 Billion Trees Program, and can contribute to the national path to net-zero emissions by 2050 (Government of Canada 2021).

The general aim of this study was to evaluate the carbon sequestration and GHG emission mitigation potential of A/R strategies, on three different types of unproductive lands, using the province of Quebec as a case study. This potential was assessed by simulating carbon fluxes and stocks in ecosystems and HWPs, including wood product displacement effects on markets, according to various scenarios of A/R, harvesting and wood products utilization. Three different types of unproductive sites were studied: open woodlands (OWs) and poorly regenerated burns in the boreal zone and abandoned farmlands in more temperate/southern regions. The model CBM-CFS3 was used to test a portfolio of A/R scenarios at the site-level (a one-hectare area), with and without harvesting. All A/R scenarios were compared to relevant reference baseline scenarios, to quantify the additional net effects of A/R activities on carbon fluxes.

Methods

Study areas

Open woodlands (OWs) are unforested lands on which the last major disturbance dates back more than 50 years. They result from regeneration failure following the succession of disturbances, among which fire plays a major role (Jasinski and Payette 2005). According to Quebec governmental definitions, OWs produce less than 30 m^3 of merchantable wood per hectare at 120 years old (Parcs 2015), which typically correspond to less than 600 trees per ha (Dufour et al. 2016). Poorly regenerated burns are lands for which the last major disturbance occurred less than 50 years ago, and on which tree density and regeneration stocking are not sufficient to meet the definition of productive forested lands (Parcs 2015). Abandoned farmlands are lands where agricultural activities have been abandoned, and where vegetation transits towards natural succession, with or without trees (Benjamin et al. 2005). In our study, the simulated OWs and poorly regenerated burns were assumed to be located in the spruce-moss bioclimatic domain (between the 49th and 52nd parallels), part of the boreal zone of northern Quebec; abandoned farmlands were assumed to be located in southeastern Quebec, in the Eastern balsam fir - yellow birch bioclimatic subdomain between latitude 47° and 48.5° N (Tremblay and Ouimet 2013).

Forest carbon model

We simulated a portfolio of forest management scenarios over a time scale of 80 years, corresponding to the 2021-2100 time horizon. This horizon was chosen to correspond to a climate policy-relevant timeframe. We used the operational-scale *Carbon Budget Model of the Canadian Forest Sector 3* (CBM-CFS3) (Kurz et al. 1995, 2009; Kull et al. 2014) to model carbon stocks and fluxes in the ecosystem. CBM-CFS3 is driven by empirical yield curves of merchantable wood volume which are converted in biomass of individual tree components as a function of diameter at breast height and tree height (Lambert et al. 2005; Kurz et al. 2009). A matrix describing the carbon transfers between forest pools and between the ecosystems and the forest products sector can be scheduled to reproduce natural and anthropic disturbances (Kurz et al. 2009). CBM-CFS3 was developed as part of the accounting tools needed to produce the national GHG inventory report in Canada, and is the core component of National Forest Carbon monitoring, Accounting and Reporting System (Kurz et al. 2009). It has been widely used in forest carbon science to identify mitigation strategies by the forest sector in Canada and other countries (Smyth et al. 2014; Drever et al. 2021; Forster et al. 2021).

Baseline scenarios

The baseline scenarios corresponded to the fluxes of carbon under the conditions of an OW, a poorly regenerated burn or an abandoned farmland, on which no harvest or other interventions. These baseline scenarios correspond to the most probable business-as-usual situations in each site type (Beauregard et al. 2019).

The selected yield curve for the OWs baseline scenario was that of a low-density stand, composed of 100% black spruce with site index (SI, at 50 years) of 9 m, which is the lowest yield curve for a mature black spruce cover (Pothier and Savard 1998). To reproduce the disturbance pattern of a regeneration failure that can create OWs, as described in the literature (Intergovernmental Panel on Climate Change 2007), we ran the simulation over 300 years to set the initial carbon stock values at time 0 of our simulation horizon: we first simulated a wildfire at stand age 70, followed by another wildfire 10 years after the first fire (i.e., the time between the two fires being less than 50 years, to create an OW (Jasinski and Payette 2005)), then an afforestation at year 200.

For poorly regenerated burns, we run a wildfire at year 1 of the simulation in a mature stand characterized by a medium density and composed of 100% black spruce with SI 12 (Pothier and Savard 1998) (i.e., representing the average stand in black spruce feather moss (Laflèche et al. 2013)). To simulate a low regeneration after wildfire, we selected a low-density stand composed of 100% black spruce with SI of 12 m (Pothier and Savard 1998). We modelled planting at year 10 or year 40 (after the wildfire) according to our assumptions: there can be variation in the age of the residual stand on poorly regenerated burns, we wanted to test the effect on the carbon balance of afforestation on different stand ages (10 years and 40 years). Afforestation took place in the residual stand to increase the stand density.

For abandoned farmlands, we used data of Tremblay et al. (2013) (Tremblay and Ouimet 2013) to estimate the baseline scenario. Natural succession started to grow 20 years after abandonment with an annual growth rate of 3.61 t C ha^{-1} yr^{-1} (13.25 t CO_2 ha^{-1} yr^{-1}) between year 20 to year 80. We then assumed a linear trajectory based on Hooker et al. (2003) (Hooker and Compton 2003) (i.e., an age-independent constant rate of carbon accumulation), until the end of the simulation. Due to the uncertainties and lack of data on ecological succession after abandonment of agricultural lands, and the multiple factors that determine their composition (Benjamin et al. 2005), we added a sensitivity analysis on the baseline scenario (Fig. 1). We created the BL0 (assuming the return of a tree cover as soon as it is abandoned) and BL40 (assuming the return of a tree cover after 40 years), with the same constant rate of accumulation of 3.61 t C ha^{-1} yr^{-1} starting at the moment of tree cover return (year 0 or year 40). Initial carbon stocks in the soil of abandoned farmlands were set at 100.00 t C ha^{-1} (367.00 t CO_2 ha^{-1} yr^{-1}) in CBM-CFS3, and litter and woody debris pools were initially set to 0.00 t C $ha^{-1.}$

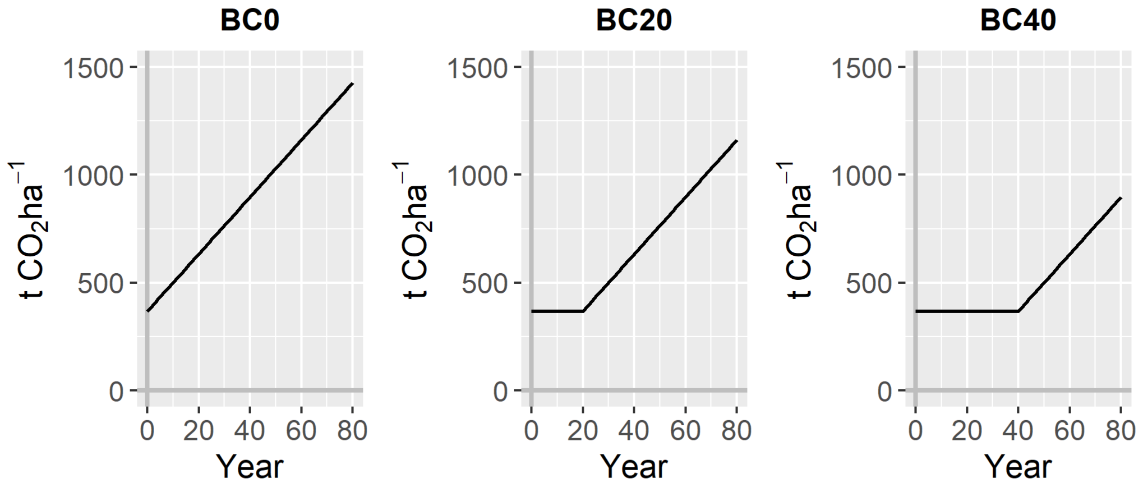

Fig. 1 Baseline scenarios of the return of natural succession after abandonment of the agricultural land. The growth rate of successional vegetation is based on data of Tremblay et al. (2013) and a linear trajectory of the rate of carbon accumulation over time was assumed according to a sensitivity analysis of the vegetation return start time (BL0 = 0 years, BL20 = 20 years, and BL40 = 40 years)

Alternative afforestation and reforestation scenarios

Simulation of plantation with several species was tested for each land type: black spruce (*Picea mariana* (Mill.) B.S.P.), white spruce (*Picea glauca* (Moench) Voss) and jack pine (*Pinus banksiana* Lamb.) were simulated for OWs and poorly regenerated burns, and white spruce, red pine (*Pinus resinosa* Ait.) and hybrid poplar (*Populus* spp.) for abandoned farmlands. For each species, we modelled two scenarios: i) a plantation at year one without any further human intervention, and ii) a plantation at year one followed by harvesting, based on recommended silvicultural strategies in Quebec (Larouche et al. 2013). Clearcutting was planned at the year when the afforested stand reaches merchantable volume at maturity (Bolghari and Bertrand 1984; Prégent et al. 1996; Pothier and Savard

1998). Commercial thinning was scheduled 15 years before clearcutting according to the Quebec annual allowable cut methodology (Poulin 2013a).

A sensitivity analysis was performed for each scenario of A/R and on each type of land to test a gradient of site index values (SI), i.e. the average height of the dominant trees in a stand at a reference age, i.e, 50 years for natural stands and 25 for planted stands (Ung et al. 2001; Laflèche et al. 2013; Larouche et al. 2013). Values for SI were chosen based on the productivity associated with the potential vegetation accross the spruce-moss and balsam fir-yellow birch domains (Poulin 2013b). The minimum value for SI of jack pine was based on Fradette et al. (2012) which calculated a SI of 4.5 in jack pine plantation on open woodlands. In total, 36 alternative scenarios were simulated for OWs and poorly regenerated burns (Table 1).

Table 1 Combinations of growth curves (Site Index or SI in height (m) at age 25) used to model afforestation scenarios on OWs and poorly regenerated burns and their forest management scenarios over 80 years

Afforestation/reforestation scenarios	Growth curve input for sensitivity analysis	Density (plant/ha)	Forest management scenarios	Sylvicultural treatment schedule in CBM-CFS3	Year
100% Black spruce	SI 6 and SI 8 (Prégent et al. 1996)	2000	Afforestation/reforestation	Plantation	1
			Afforestation/reforestation +harvesting	Plantation	1
				Commercial thinning (removing 30% of the cover)	55
				Clear cut (removing 97% of the cover)	70
				Plantation	71
100% White spruce	SI 6 and SI 10 (Bolghari and Bertrand 1984)	2000	Afforestation/reforestation	Plantation	1
			Afforestation/reforestation +harvesting	Plantation	1
				Commercial thinning (removing 30% of the cover)	55
				Clear cut (removing 97% of the cover)	70
				Plantation	71
100% Jack pine	SI 4.5 (Fradette 2012) and SI 6 (Pothier and Savard 1998)	2000	Afforestation/reforestation	Plantation	1
			Afforestation/reforestation +harvesting	Plantation	1
				Commercial thinning (removing 30% of the cover)	55

				Clear cut (removing 97% of the cover)	70
				Plantation	71

On both OWs and poorly regenerated burns, it was assumed that a residual stand was in place at the time of afforestation. For both OWs and poorly regenerated burns, this was simulated by creating an aggregate curve combining the yield of the residual stand and the yield of the plantation. For OWs, residual stand was based on a 100% black spruce stand with SI 9 and a low density (Pothier and Savard 1998); for poorly regenerated burns, the residual stand was based on a 100% black spruce stand with SI 12 and a low density.

The effect of site preparation on carbon stocks prior to plantation was manually added for OWs and poorly regenerated burns: we calculated a carbon loss of 10% in the soil dead organic matter in the form of carbon release to the atmosphere, which was assumed to be almost entirely recovered after 10 years (field validated in Dufour et al., in preparation).

For abandoned farmlands, 12 alternative scenarios were modelled. Scenarios were based on combinations of species (white spruce, red pine, and hybrid poplar), site productivity and further silvicultural/harvesting operations (with and without) (Table 2):

Table 2 Combinations of growth curves (Site Index or SI at age 25) used to model afforestation scenarios on abandoned farmlands and their forest management scenarios over 80 years on open wood land (OW) and poorly regenerated burns (PRB)

Afforestation/reforestation scenarios	Growth curve input for sensitivity analysis on OW and PRB	Density (plant/ha)	Forest management scenarios	Sylvicultural treatment schedule in CBM-CFS3	Year
100% White spruce		2000	Afforestation	Plantation	1
			Afforestation+harvesting	Plantation	1

	SI 6 and SI 12 (Bolghari and Bertrand 1984)				
				Commercial thinning (removing 30% of the cover)	40
				Clear cut (removing 97% of the cover)	55
				Plantation	56
100% Red pine	SI 3 and SI 8 (Pothier and Savard 1998)	2000	Afforestation	Plantation	1
			Afforestation+harvesting	Plantation	1
				Commercial thinning (removing 30% of the cover)	35
				Clear cut (removing 97% of the cover)	50
				Plantation	51
100% Hybrid poplar	SI hardwood and SI softwood (Pothier and Savard 1998)	2000	Afforestation	Plantation	1
			Afforestation+harvesting	Plantation	1
				Clear cut (removing 97% of the cover)	20
				Plantation	21
				Clear cut (removing 97% of the cover)	40
				Plantation	41
				Clear cut (removing 97% of the cover)	60
				Plantation	61
				Clear cut (removing 97% of the cover)	80

Harvested wood products

For each alternative scenario that included harvesting actions, we simulated carbon fluxes associated with wood procurement and processing, and end-of-life of resulting wood products (Smyth et al. 2014). To track carbon stocks and emissions from wood products, co-products and by-products over their service life and in landfills, we used a modified version of the Carbon Budget Model – Harvested Wood Products (CBM-HWP) which was run using the Abstract Network Simulation Engine (ANSE) of the Canadian Forest Service (Magnan 2013; Smyth et al. 2014) (Fig. 2).

For a given species, the basket of wood products associated with each simulated harvested cubic meter was estimated based on provincial data provided by the Quebec Wood Auction Bureau (*Bureau de la mise en marché des bois du Gouvernement du Québec*). Product end-of-life emissions were estimated based on a simple decay function using product half-life

(Smyth et al. 2014): half-life of sawn wood, panels and pulp and paper was estimated at 35, 25 and 2 years, respectively, and that of bioenergy was set to 0 (i.e., assuming an immediate release of carbon at the time of utilization).

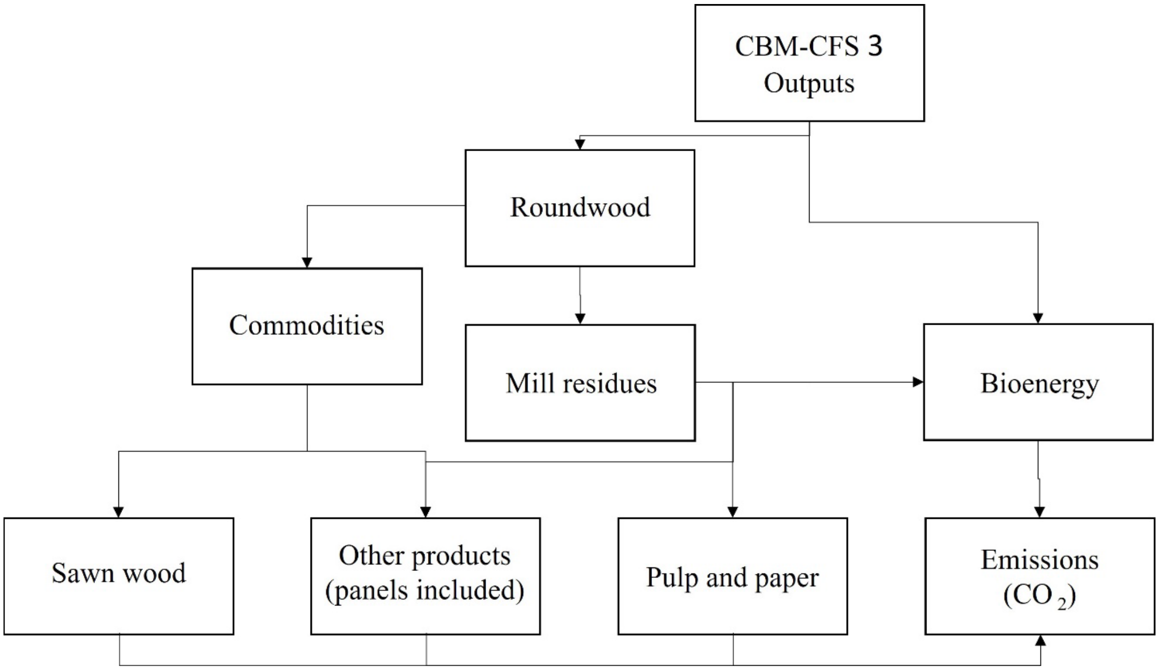

Fig. 2 Simplification of the wood products division of CBM-CFS 3 inputs in the framework of harvest wood products CBM-FHWP

Substitution

The substitution effect is assumed when the production and use of non-renewable products – such as concrete, steel, and fossil fuels – are avoided, and replaced by wood products for construction or energy production. The substitution effect of wood products resulting from harvesting was estimated with displacement factors for each type of product. Displacement factors are based on emissions from the production chain of both wood products and the displaced products. We used 0.54 tonne of CO_2 equivalent avoided per tonne of CO_2 stored in wood product (Smyth et al. 2014) for sawn wood, 0.45 (Smyth et al. 2014) for panel, and 0.47 for bioenergy (Smyth et al. 2017). No substitution effect was considered for pulp and paper. Substitution benefits were constant over time.

Net carbon balance of afforestation and reforestation activities

To determine the emission mitigation potential of afforestation/reforestation activities for the three types of unproductive land, we estimated the net changes in ecosystem carbon stocks (expressed in tonnes of C per hectare of afforested/reforested area (t C ha^{-1})) (SI 1), and the emissions of the various scenarios. Net emissions were calculated using the difference between total fluxes of the alternative and the baseline scenarios, considering carbon fluxes at the ecosystem level, and those associated with wood products and their substitution effect when relevant. Annual results were summed to obtain cumulative fluxes. Fluxes were expressed in tonnes of CO_2 equivalent per hectare of afforested/reforested area (t CO_2 ha^{-1}). A scenario was considered to generate a net mitigation when cumulative net carbon fluxes (difference between reference and afforestation/reforestation scenarios) were negative and a net source when net fluxes were positive. The results of this study show the benefit of afforestation/reforestation in terms of carbon, but it does not consider the albedo effect and the radiative forcing that could reduce the benefit of afforestation, especially in boreal regions (Bernier et al. 2011; Drever et al. 2021). All graphs presenting the results were made using the *ggplot2* package (Wickham 2016) in R (R Core Team 2020).

Results

The results showed that for all scenarios on OWs (Fig. 3), including those with or without harvesting, the system became a net carbon sink after 15 years and remained so until the end of the simulation period. Also, planting with jack pine appeared to be a better mitigation scenario, with a cumulative net balance (cumulative fluxes from ecosystem, wood products and displacement effect on markets) of 118.1 t CO_2 ha^{-1} ± 16.8 and 371.1 t CO_2 ha^{-1} ± 21.4 with and without harvesting, respectively. Overall, scenarios without harvesting yielded higher mitigation potentials, despite carbon storage in wood products and the GHG benefits of product substitution (Fig. 3).

In harvesting scenarios, wood products were first simulated to reach the markets at year 55, when a commercial thinning at 30% (tree removal) was assumed to be performed (Fig. 3, right handed panels). Cumulative ecosystem carbon loss was significant at the end of the simulation period (year 80), because of the clearcut at year 70. Nevertheless, the effects of carbon storage in wood products and displacement on markets resulted in net carbon mitigation potentials for all the scenarios.

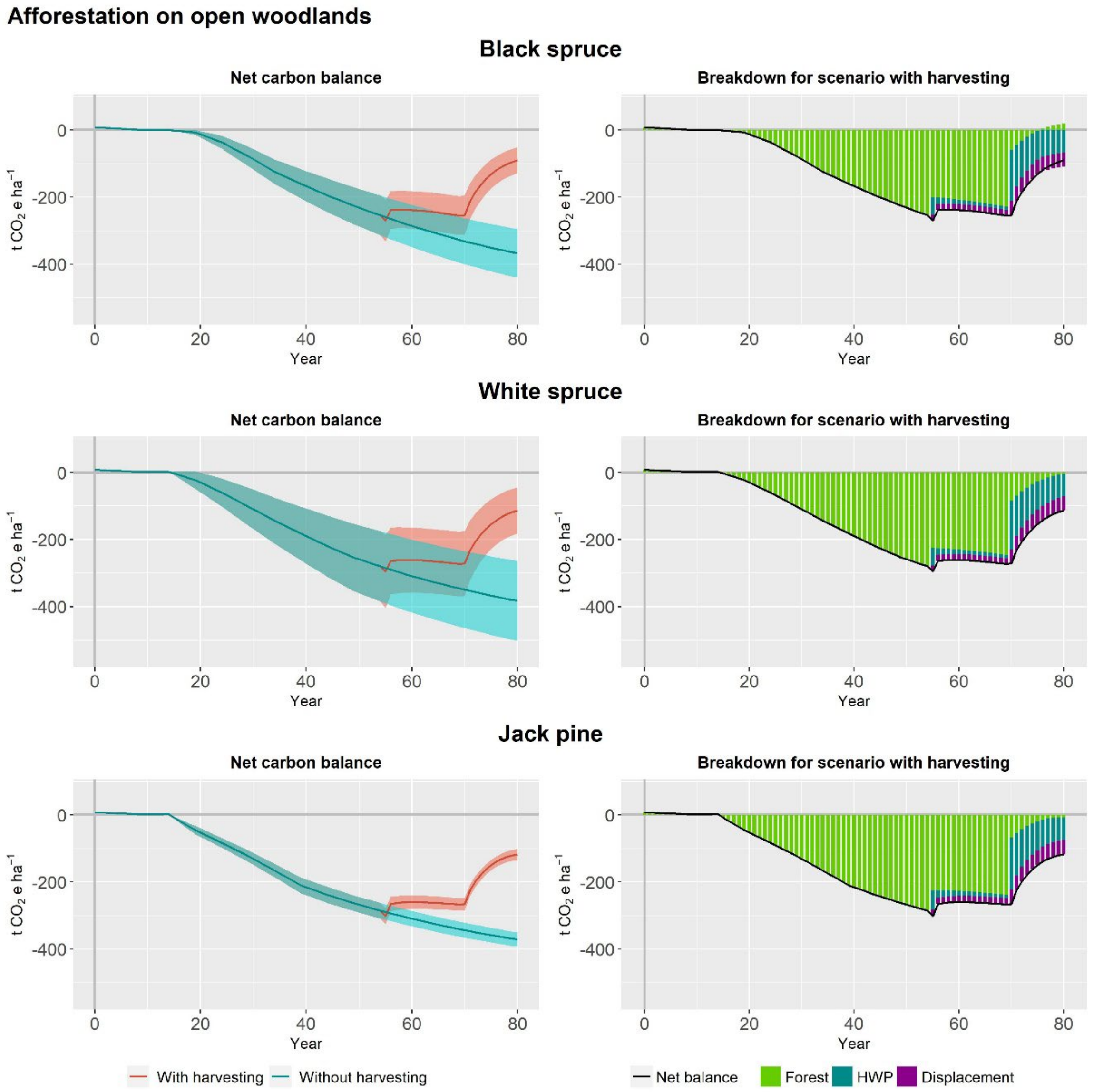

Fig. 3 Cumulative net carbon balance (relative to the baseline) of afforestation scenarios on OWs for each planted species: black spruce, white spruce, and jack pine. The left panel presents the cumulative net carbon balance including the range of values generated by the sensitivity analysis of plantation productivity. The right panel presents the breakdown of the cumulative net carbon balance for scenarios with harvesting, for the following components: ecosystem, harvested wood products (HWP) and displacement (substitution)

The best scenario of reforestation on 10-year old poorly regenerated burns gave a cumulative net balance of 369.0 t CO_2 ha^{-1} ± 72.3 for the no harvesting scenario using black spruce, and 93.4 t CO_2 ha^{-1} ± 16.9 the for harvesting scenario using jack pine (Fig. 4). Reforestation on 40-year old poorly (Fig. 5) regenerated burns generated greater mitigation benefits than afforestation on OWs and on 10-year old poorly regenerated burns, with a cumulative net balance of 400.7 t CO_2 ha^{-1} ± 63.0 for the no harvesting scenario using white spruce. The difference between OWs and poorly regenerated burns can be explained by the difference in initial carbon stock contained in the ecosystem when A/R occurred. Another major difference was the faster sequestration rate after reforestation on poorly regenerated burns, compared to afforestation on OWs: plantations on poorly regenerated burns was compared to a baseline in which the ecosystem was a net carbon emitter until year 20 (because of the recent fire) and a lower growth rate of the restored forest; afforestation on OWs was compared to a baseline scenario that included a more stable ecosystem characterized by a positive sequestration rate (see supplementary information).

Reforestation scenarios on 10-year old poorly regenerated burns sequestered carbon from year 4 for jack pine and year 5 for black spruce and white spruce, up to year 80 for all species (Fig. 4). For reforestation scenarios on 40-year old poorly regenerated burns (Fig. 5), net sequestration began at year 5 for jack pine, year 6 for black spruce and year 7 for white spruce; for all scenarios, the system acted as a sink until year 80. Reforestation with no harvesting generated greater mitigation benefits for all poorly regenerated burns; nevertheless, reforestation+harvesting scenarios still acted as C sinks at year 80, thanks to the carbon storage in HWPs and their mitigation benefits from substitution.

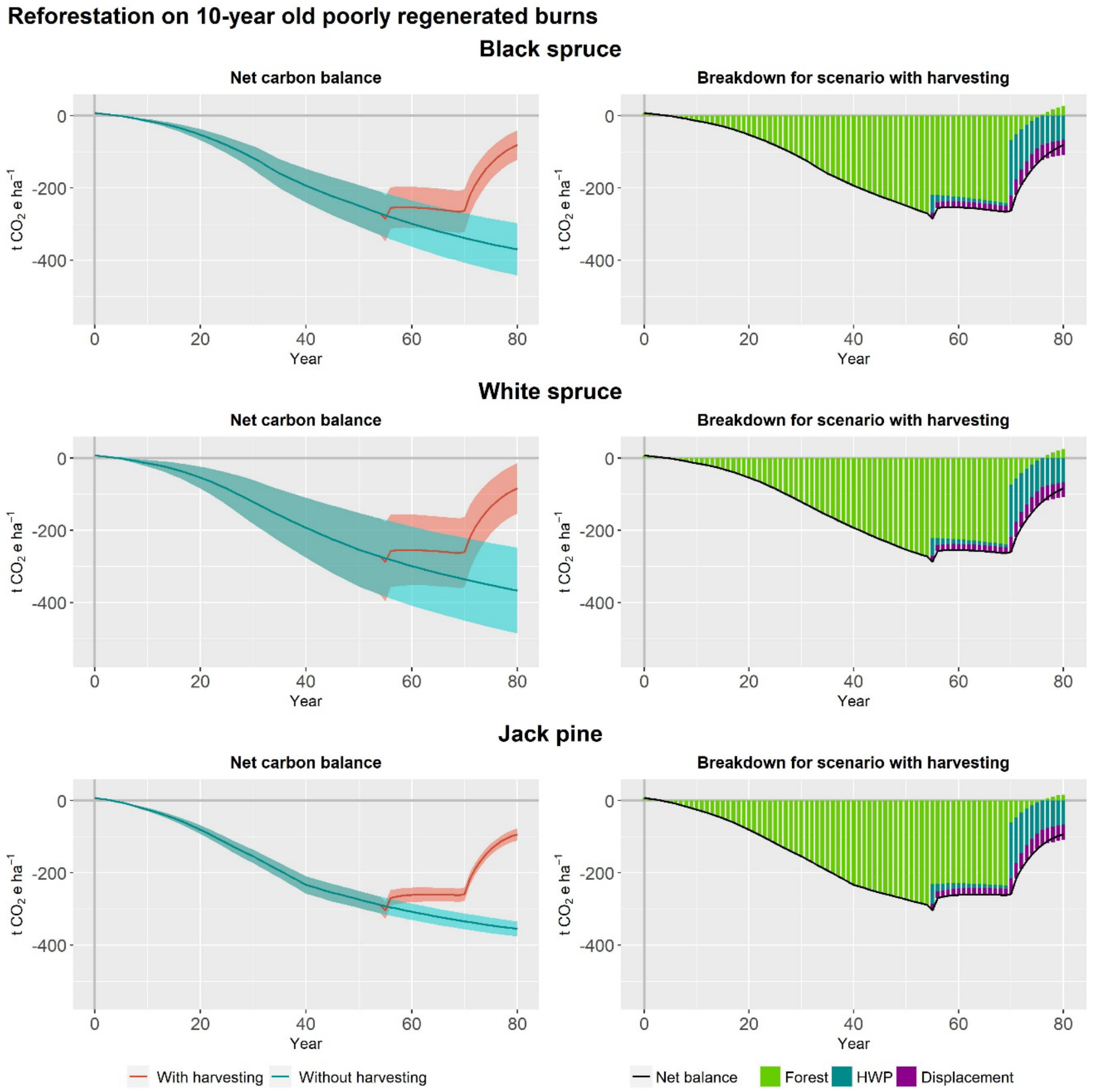

Fig. 4 Cumulative net carbon balance of afforestation scenarios on poorly regenerated burns 10 years after wildfire for each planted species: black spruce, white spruce, and jack pine. The left panel presents the cumulative net carbon balance including the range of values generated by the sensitivity analysis of plantation productivity. The right panel presents the breakdown of the cumulative net carbon balance for scenarios with harvesting, for the following components: ecosystem, harvested wood products (HWP) and displacement (substitution)

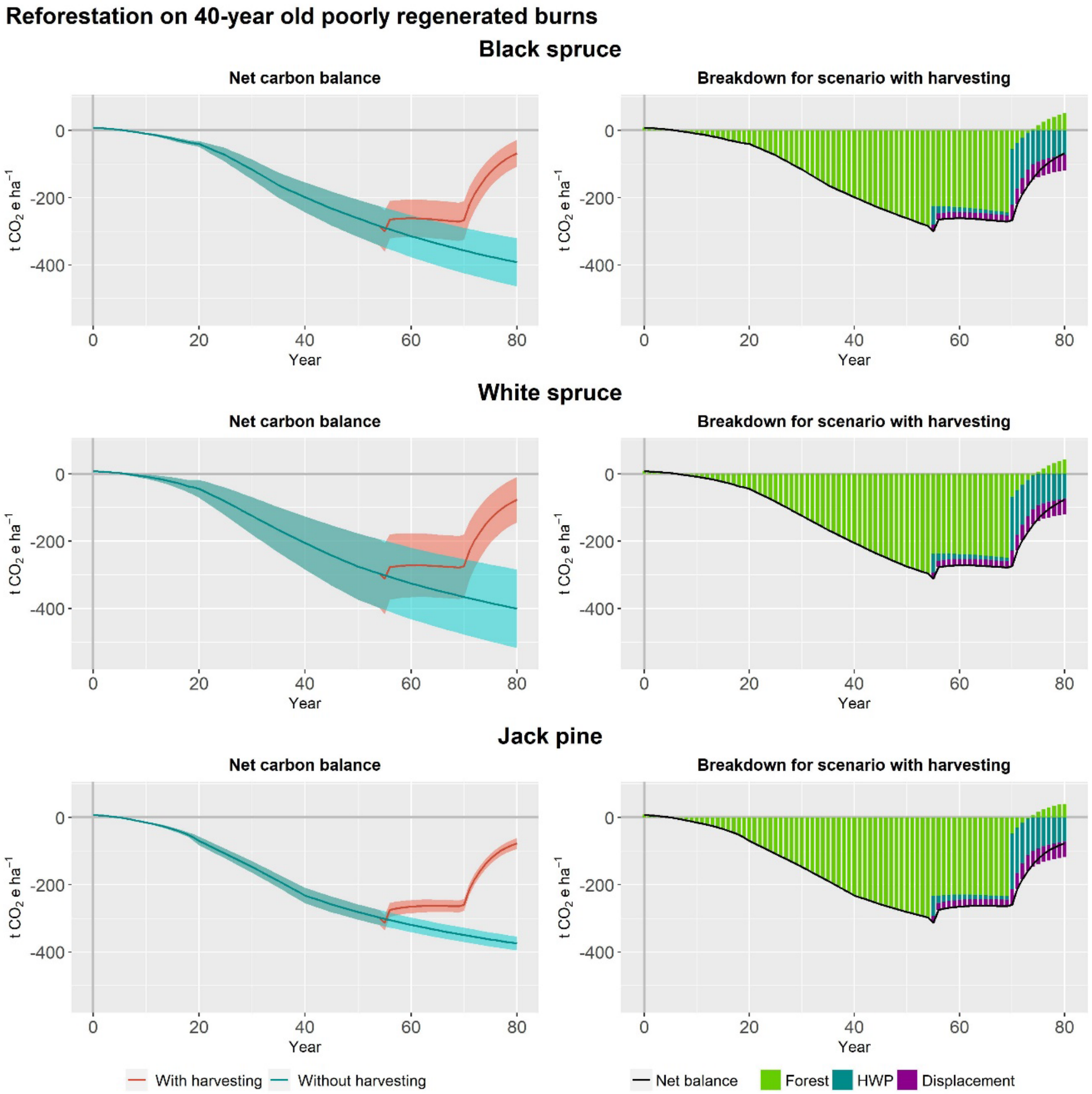

Fig. 5 Cumulative net carbon balance of afforestation scenarios on poorly regenerated burns 40 years after wildfire for each planted species: black spruce, white spruce, and jack pine. The left panel presents the cumulative net carbon balance including the range of values generated by the sensitivity analysis on plantation productivity. The right panel presents the breakdown of the cumulative net carbon balance for scenarios with harvesting, for the following components: ecosystem, harvested wood products (HWP) and displacement (substitution)

For scenarios of afforestation on abandoned farmlands with white spruce, we compared three different baseline scenarios that varied according to the rate of recovery and growth of natural vegetation in the absence of afforestation (Fig. 1). Yet, in all cases, natural vegetation accumulated more carbon than the white spruce plantations at the end of the simulation period; the difference between afforestation and baseline ranged from 357.0 t CO_2 ha^{-1} to 887.0 t CO_2 ha^{-1} (Fig. 6). As with the other site types, ecosystem carbon loss following harvest was not offset by carbon storage and displacement effect of wood products (Fig. 6, right handed panels).

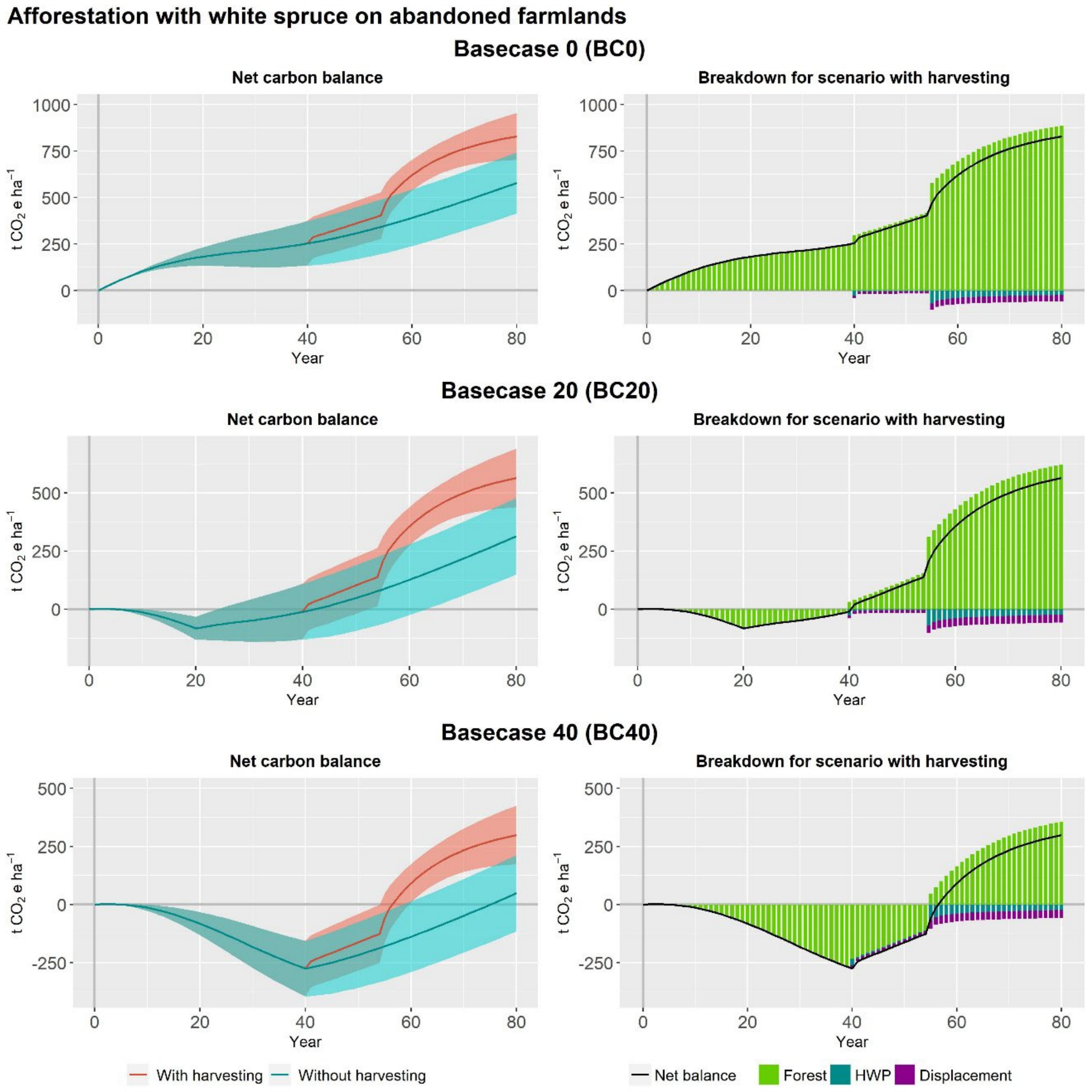

Fig. 6 Cumulative net carbon balance of afforestation scenarios with white spruce on abandoned farmlands relative to the baseline: BL0, i.e., the baseline assumes that natural forest vegetation returns immediately upon land abandonment, BL20 i.e., the baseline assumes that natural forest vegetation returns 20 years after abandonment and BL40 i.e., the baseline assumes that natural forest vegetation returns 40 years after abandonment. The left panel presents the cumulative net carbon balance including the range of values generated by the sensitivity analysis on plantation

productivity. The right panel presents the breakdown of the cumulative net carbon balance for scenarios with harvesting, for the following components: ecosystem, harvested wood products (HWP) and displacement (substitution)

Conversely, afforestation on abandoned farmlands with red pine (Fig. 7) was a net sink compared to the baseline when forest vegetation was assumed to return 20 to 40 years after land abandonment. On the other hand, if natural forest vegetation was assumed to recover immediately upon abandonment of agriculture (BL0), afforestation did not provide any net sequestration benefits. Again, all scenarios that included harvesting would be a net cumulative source at year 80. However, the cumulative source would be smaller with red pine afforestation+harvesting scenarios, than with white spruce, due to the higher proportion of long-lived sawn wood that can be sourced from red pine.

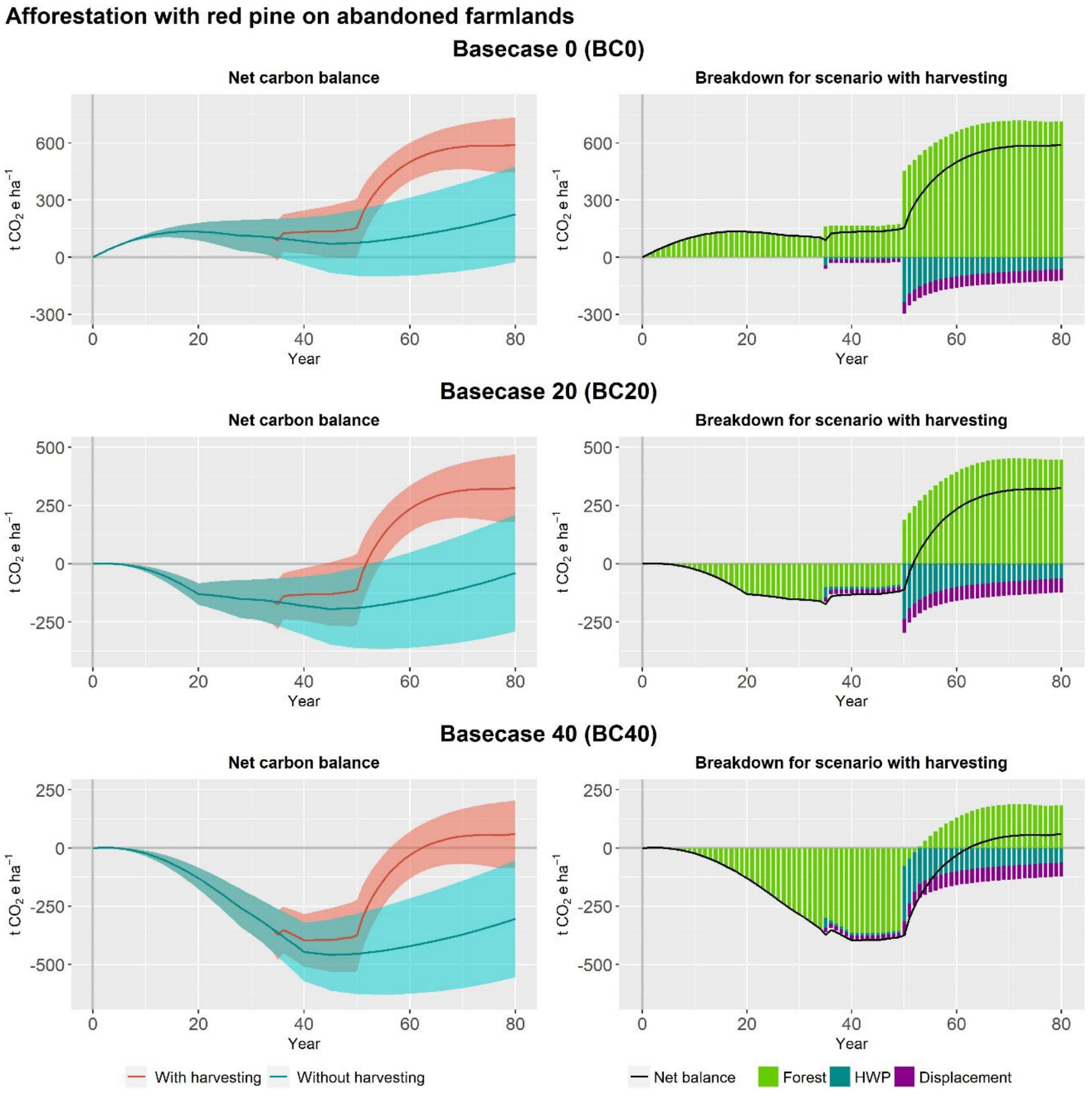

Fig. 7 Cumulative net carbon balance of afforestation scenarios with red pine on abandoned farmlands relative to the baseline: BL0, i.e., the baseline assumes that natural forest vegetation returns immediately upon land abandonment, BL20 i.e., the baseline assumes that natural forest vegetation returns 20 years after abandonment and BL40 i.e., the baseline assumes that natural forest vegetation returns 40 years after abandonment. The left panel presents the cumulative net carbon balance including the range of values generated by the sensitivity analysis on plantation

productivity. The right panel presents the breakdown of the cumulative net carbon balance for scenarios with harvesting, for the following components: ecosystem, harvested wood products (HWP) and displacement (substitution)

Afforestation scenarios on abandoned farmlands with hybrid poplar also suggest that assumptions related to the rate of natural forest vegetation recovery determine strongly whether afforested lands would be net cumulative sources or sinks at year 80 (Fig. 8). When establishment of natural vegetation upon abandonment was assumed to take 2 to 4 decades, planting provided carbon sequestration benefits. Afforestation followed by harvesting also caused scenarios to be net cumulative sources at year 80. The shorter harvesting rotations associated with fast-growing hybrid poplar allowed the transfer of a higher amount of carbon towards wood products. However, as the wood from hybrid poplar is currently processed mainly into short-lived wood products such as pulp, with no substitution effect, this did not translate into an important carbon storage or displacement effect on markets.

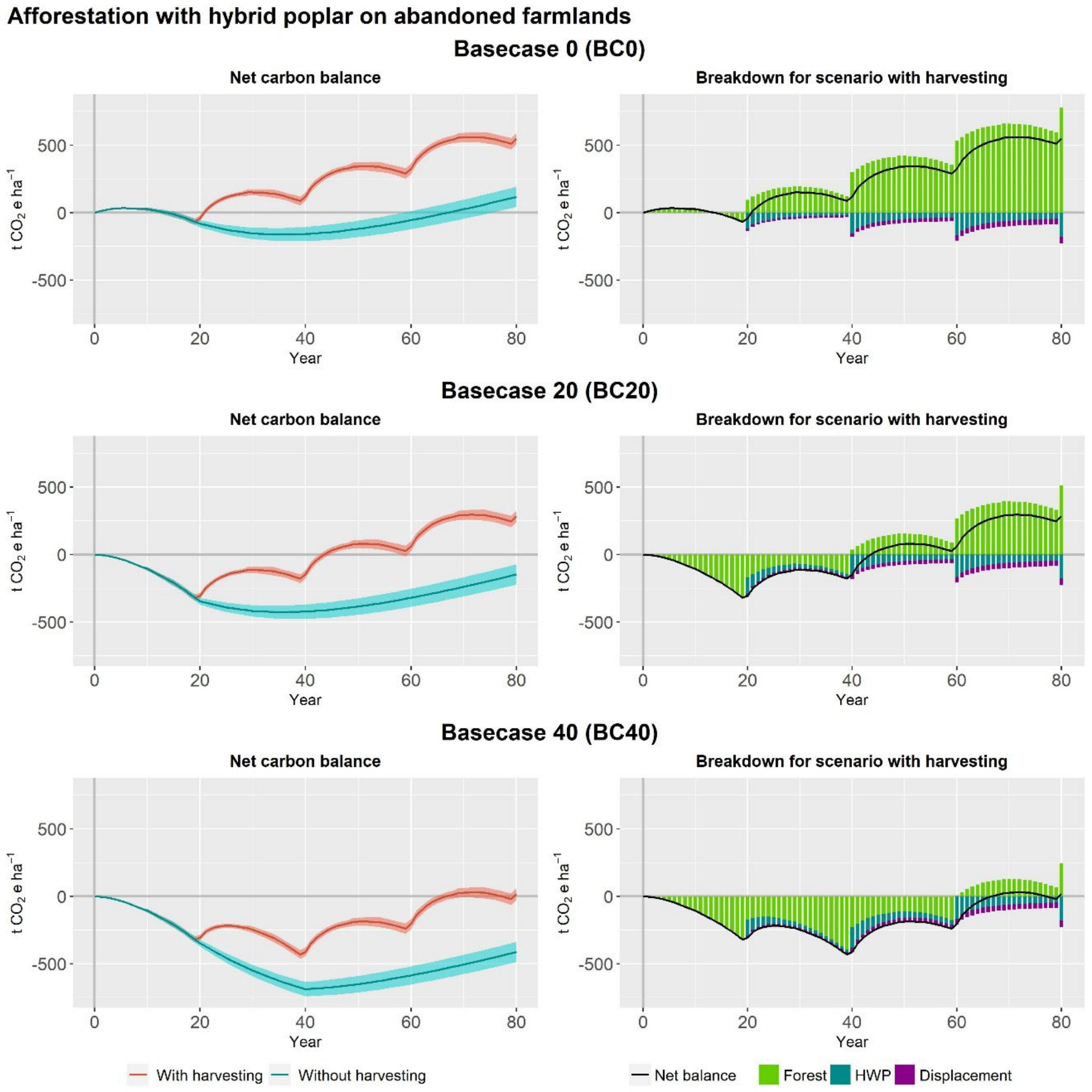

Fig. 8 Cumulative net carbon balance of afforestation scenarios with hybrid poplar on abandoned farmlands relative to the baseline: BL0, i.e., the baseline assumes that natural forest vegetation returns immediately upon land abandonment, BL20 i.e., the baseline assumes that natural forest vegetation returns 20 years after abandonment and BL40 i.e., the baseline assumes that natural forest vegetation returns 40 years after abandonment. The left panel presents the cumulative net carbon balance including the range of values generated by the sensitivity analysis on plantation

productivity. The right panel presents the breakdown of the cumulative net carbon balance for scenarios with harvesting, for the following components: ecosystem, harvested wood products (HWP) and displacement (substitution)

Discussion

In this study, we explored the potential of afforestation/reforestation of unproductive lands for GHG emission mitigation. For boreal unproductive lands, i.e., open woodlands (OWs) and poorly regenerated burnt sites, our results highlight the carbon benefits of such afforestation efforts. However, over an 80 year-period, afforestation/reforestation without harvesting on these lands should result in higher net mitigation potentials than scenarios with harvesting, even when considering carbon stored in wood products and the displacement effect of wood products on markets. This is due to the relatively long rotation periods of plantations in these boreal areas, i.e., 70 years; the emissions following harvesting take some time to be recaptured through photosynthesis, causing the harvested site to be a net source for some years, i.e., beyond the end of the 80-year simulation horizon in 2100. These results are similar to those found in other studies, for which scenarios without harvesting were the most effective for net carbon sequestration over one rotation (Paradis et al. 2019). Other sylvicultural scenarios, such as partial cutting, can improve the mitigation potentials of afforestation scenarios (Paradis et al. 2019). Significantly improving the yield of long-lived wood products and/or the efficiency at which wood products can displace highly carbon-intensive products might also be an option to increase the carbon benefits of afforestation+harvesting (Smyth et al. 2014; Valade et al. 2017). However, given the importance of the cumulative carbon debt created by ecosystem emissions following harvesting, it remains to be seen if and how realistic solutions for wood processing and use can offset this carbon debt. The time horizon used for assessments must be carefully considered: indeed, in such boreal ecosystems, harvesting does not seem to cause decline in forest productivity and carbon sequestration over time (Paradis et al. 2019) and if we want to maintain and enhance carbon sinks into the next century, then conservation strategies alone cannot fulfill this role. Besides, a more systemic analysis approach – where management scenarios with less harvesting activities and wood procurement are compared, at the whole system level and on the long term, against the impact of using more carbon intensive products, like concrete and steel – may also produce higher mitigation benefits, when the consequences of not using wood products are evaluated (Gustavsson et al. 2021).

Unsurprisingly, our results showed that, generally, faster-growing species sequester more carbon in the ecosystem. According to our study, afforestation without harvesting, using white spruce and black spruce, produces higher C stocking rates than using jack pine on both OWs and poorly regenerated burns. We used a gradient of SI values to perform the sensitivity analysis which may explain this difference. Based on results of the carbon sequestration of each species at their minimum SI, jack pine sequestered more carbon than white spruce and black spruce for A/R on OWs and poorly regenerated burns. Conversely, because jack pine logs generate more long-lived wood products with a higher substitution benefit, afforestation+harvesting of OWs and reforestation of poorly regenerated burns with jack pine show a higher sequestration potential than with spruce species. For afforestation on abandoned farmlands, fast-growing hybrid poplar appears to be a better choice for sequestering carbon in the ecosystem, especially if natural succession is expected to be productive in the absence of afforestation (i.e., in the counterfactual scenario). Moreover, the choice of deciduous species could have a lower warming effect than evergreen conifers if we consider the surface albedo effect of plantations on global warming (Bright et al. 2015).

However, results were highly sensitive to assumptions related to the baseline scenarios used in simulations. Based on the literature, we chose relatively conservative values of stand site index for simulations of plantation on OWs. More optimistic yields are also possible, and could be similar to that of dense stands from the black spruce feather moss (Dufour et al. 2016). Careful selection of candidate sites according to existing vegetation and anticipated rate of regrowth for the natural forest could increase the mitigation success of the plantation.

The importance of selecting realistic baseline scenarios was also highlighted in our study with afforestation scenarios on abandoned farmlands. For example, the somewhat pessimistic emission mitigation outcomes of white spruce plantations on abandoned farmlands are related to the choice of our baseline assumptions for natural succession recovery rate; they were based on field data from Tremblay and Ouimet (2013) and assumed a fairly high growth rate. It would be possible to assume that plantations on highly productive sites (that can otherwise support high natural succession growth rates) would also reach very high yields, contrarily to the somewhat conservative site index and yield assumptions used in our simulations. This study highlights the need to use realistic and coherent assumptions of productivity for both natural succession and plantation scenarios. There is especially a need to better document the trajectories of natural vegetation strata over time on these types of land, to better assess and quantify their afforestation potential and to better target sites suitable for climate change mitigation.

Several studies have shown the complexity of factors that influence the composition and the timing of natural vegetation return dynamics, making them difficult to predict (Inouye et al. 1987; Benjamin et al. 2005). There can be variability in the carbon accumulation rate in vegetation on abandoned farmlands depending of abiotic and biotic factors such as climatic ecozones and soil productivity (Post and Kwon 2000; Hooker and Compton 2003; Foote and Grogan 2010; Voicu et al. 2017). In our study, the mean annual carbon accumulation rates for each baseline scenarios, when calculated over the 80-years horizon (year 0 being the time of land abandonment) were 3.61 t C ha^{-1} yr^{-1} for BL0, 2.71 t C ha^{-1} yr^{-1} for BL20 and 1.81 t C ha^{-1} yr^{-1} for BL40 (the variation between scenarios being caused by the assumed year of onset of tree growth). These values are similar in range as those reported by Hooker et al. (2003) for developing forests on abandoned agricultural lands in eastern United States, which varied between 1.27 to 5.24 t C ha^{-1} yr^{-1}. Abandoned farmlands located in the St. Lawrence valley in the Atlantic Maritime ecozone mostly originated from cleared forests (Bélanger and Grenier 2002), and, it is possible that natural succession will create vegetated conditions similar to pre-agricultural sites (Yang et al. 2020). Ground plots from Canada's National Forest Inventory located in natural stands of Quebec and part of the Atlantic Maritime ecozone display an average total ecosystem C of 105.00 t C ha^{-1} for early successional stands (based on the average of 3 plots), 223.00 t C ha^{-1} for mid-successional stands (5 plots) and 588.00 t C ha^{-1} for late-successional and mature stands (3 plots). These values are similar in range to those simulated in our baseline scenarios, which can then thus be considered realistic. As anticipating the yield of natural succession can be quite difficult, selecting for restoration of forest cover older abandoned farmlands for which natural succession has not been successful may be a pragmatic solution. Similarly, planting fast-growing species and ensuring careful plantation tending so that trees can fully meet their growth potential is paramount, especially in the context of high uncertainty for the baseline scenario.

Nevertheless, our study suggests that plantations are likely to be more predictable in terms of carbon sequestration over time, in comparison with the (current) uncertainty associated with the carbon sequestration yield of natural vegetation on abandoned farmlands. Plantations on abandoned farmlands can in fact generate a net carbon sink, for example in Ontario (Canada) where afforestation on degraded croplands and abandoned agricultural lands has been operationally implemented (Magnus et al. 2021). Besides, afforestation on abandoned farmlands offers an opportunity to revitalize forestry on private lands, and allow landowners to increase the value of their land (Benjamin et al. 2008), possibly preventing change to other, non-agricultural or forestry-related use (Bellassen and Luyssaert 2014).

To evaluate the success of a plantation, our results showed that we must consider the carbon sequestered by the ecosystem, but also the carbon dynamics of wood products resulting from harvesting. On abandoned farmlands, the choice of fast-growing hybrid species allows more ecosystem carbon sequestration than the baseline scenarios. In that case, the inclusion of wood products in the analysis is not significant because processing and market opportunities for producing long-lived wood products have yet to be developed for such species. In the current wood-processing industrial network in Quebec, planting scenarios with species that can yield a significant share of long-lived products for each harvested cubic meter of wood, such as *Pinus* (red pine, jack pine) and *Picea* (white spruce, black spruce) species, can thus present a significant advantage, particularly if these products can displace highly carbon-intensive products, like steel and concrete (Smyth et al. 2014; Valade et al. 2017). Nevertheless, one should consider the possibility of future improvement in wood-processing capacities and development of novel engineered wood products for currently-undervalued species, as well as the possibility that the displacement effect of wood might decrease over time as other non-forest products could reduce their own carbon footprints (Valade et al. 2017). This thus warrants the need for a more detailed and nuanced look into the role of wood products from various species for climate change mitigation.

Silvicultural treatments that can improve tree growth and planting success should be considered when planning afforestation projects, especially in OWs. It has been shown that control of competing vegetation, especially ericaceous shrubs, prior to planting is crucial for successful plant growth in boreal OWs (Nilsson and Wardle 2005). In addition, site preparation and plant size selection can increase the yield success of the plantations in the context of a pesticide-free forest management regime such as the one in Quebec (Thiffault et al. 2003; Thiffault and Roy 2011). Studies will have to be carried out to more precisely determine the quantities of carbon emitted by site preparation and plantation tending operations, in order to better quantify their net impact on the forest carbon balance. Also, the financial investments that are needed for afforestation/reforestation and plantation tending of unproductive lands need to be compared with the expected economic returns, including the consideration of economic costs (dollars per tonne of CO_2) of other mitigation actions (Fuss et al. 2018).

The success of each A/R scenario depends of the time scale of the mitigation goals (Smyth et al. 2014; Xu et al. 2018). A period of carbon loss in the ecosystem seems inevitable following harvesting operations, which tend to disadvantage afforestation+harvesting scenarios, especially when considering the short time frame of a few decades. Most of the time, the addition of carbon storage in wood products and their substitution effect on markets is not enough to offset the ecosystem carbon debt compared to no-harvest planting scenarios. However, one could assume that a longer time period than the one used here (80 years) would allow ecosystem carbon to be re-sequestered by plantation growth over the decades following clearcut harvest (Gustavsson et al. 2021). Forest management strategies are usually planned and assessed over long time horizons: for example, annual allowable cut in Quebec is calculated over 150 years (Bureau du forestier en chef 2018). Over such a period, the co-benefits of ecosystem carbon sequestration and wood procurement and use could become more obvious. A longer time horizon would allow to demonstrate the effect of multiple harvest rotations and the accumulation of carbon stockage in the HWPs, which could have significantly increased the mitigation effect of afforestation+harvesting scenarios (Forster et al. 2021). However, whether such long horizons are relevant or not in the context of the (urgent) need for climate change mitigation, can be questioned (Fearnside et al. 2000). Nevertheless, actions that increase forest areas under active management can still be envisioned as part of a longer-term economic transition towards renewable resources, or even for carbon-neutral national objectives later in this century, as laid out in the Paris agreement (United Nations Framework Convention on Climate Change 2020).

Also related to the time horizon, the permanence of plantations (and their ecosystem carbon store) over long periods of time needs to be examined. Natural disturbances were not considered in this study; yet carbon sequestration of newly afforested sites can quickly be reversed with the occurrence of e.g., wildfire. The risks of afforestation in areas that are particularly prone to wildfire disturbances, or are expected to see an increase in their fire activity in the future (Boulanger et al. 2016), should be assessed carefully. Acceleration of climatic change has already altered ecosystem structure, ecological processes and the rate and severity of natural disturbances that shape the forest landscape (Gauthier et al. 2015). This can negatively affect carbon sequestration gains resulting from afforestation/reforestation efforts. Actively increasing resilience of forest landscapes through targeted afforestation and silvicultural actions should be considered (McKinley et al. 2011). On the other hand, carbon stored in wood products is protected from natural disturbances; as such, harvesting for wood procurement and use can somewhat help to manage risks on forest carbon losses from natural disturbances.

The results of this study show the benefit of A/R, without considering radiative forcing dynamics nor albedo effect. Surface albedo can reduce or overwhelm the climate cooling effect of carbon storage, especially in the boreal zone (Williams et al. 2021). Large-scale restoration of forest cover in Canada, with site and species selection taking albedo impacts into consideration, was shown to contribute climate mitigation benefits even after subtracting the radiative forcing contribution of albedo changes (Drever et al. 2021). At the moment, policy-makers evaluate concrete land management actions based on their contribution to improving GHG balances, sometimes also taking the radiative forcing effect into consideration (Drever et al. 2021). Further research will be required to operationalise the assessment of land-use change impacts on concomitant biophysical effects of albedo and aerosols (Kalliokoski et al. 2020).

Operational constraints will also have to be considered from an economic point of view. OWs and poorly regenerated burns are located in the northern part of the province, for which the road network and the need of workers can be constraining or may require investments for new roads. Also, afforestation of abandoned farmlands might require regulatory/legislative adjustments since it might be considered a change in land-use (from agriculture to forestry). The associated costs should be quantified, and balanced against the new bio-economic opportunities for rural and remote regions (Nabuurs et al. 2017).

As pointed out by the IPCC (2017), although carbon benefits from afforestation and afforestation might take time to materialize, these practices can also provide multiple ecological co-benefits that can increase their appeal from a societal perspective. Nevertheless, these practices alone will be insufficient to meet national and global targets of atmospheric CO_2 removal; or they would require a deployment at a scale that would likely cause possible land conversion issues (Fady et al. 2021; Suryaningrum et al. 2021).

For example, full afforestation/reforestation of 1.6 million ha of suitable land in Quebec would yield an annual sequestration of up to 14.8 Mt of CO_2 year^{-1} in 2050 (Table 3). This approximately corresponds to 18 % of Quebec's current annual GHG emissions. For 2100, full afforestation/reforestation would yield an annual sequestration of 2.1 Mt of CO_2 year^{-1}. Lower benefits can be explained by the age-dependent saturation of carbon sinks. Thus, reduction of fossil fuel emissions has to remain the primary pathway towards net zero emission targets.

Table 3 Estimates of GHG emissions mitigation in 2050 for Quebec per type of territory assuming the best mitigation scenario (i.e. without harvest) for each type of territory, using the maximum area available. Data for the area (ha) of OWs and poorly regenerated burns were provided by the Direction des inventaires Forestiers from Minister of Forests, Wildfire and Parks of Quebec

Territories	Area (ha)	Mitigation with afforestation/reforestation (Mt of CO_2 year^{-1} in 2050)	Mitigation with afforestation/reforestation (Mt of CO_2 year^{-1} in 2100)
OWs	1 300 000	10.9	2.3
Poorly regenerated burns	185 000	2.1	0.7
Abandoned farmlands	100 000	1.8	-1.0
Total	1 585 000	14.8	2.1

Conclusions

The analysis of carbon sequestration through afforestation and reforestation on unproductive lands suggests that, in specific instances and at the stand level, these practices can provide benefits in terms of carbon sequestration over an 80 year long period. In the case of afforestation of open woodlands, the results suggest that all scenarios, irrespective of planted species, would act as carbon sinks at year 80, even when harvesting is included.

Similar results were obtained for the reforestation of poorly regenerated burns that gave faster and greater mitigation benefits than afforestation on open woodlands. Results with these sites suggest that mitigation benefits can be achieved with afforestation performed between 10 to 40 years following wildfire. For afforestation on abandoned farmlands, the carbon benefits of planting largely depend on (currently poorly quantified) assumptions related the rate of return of natural vegetation, under a baseline scenario in the absence of planting. Careful integration of afforestation/reforestation at appropriate scales within sustainably managed landscapes and as part of a larger portfolio of mitigation actions will likely produce the greatest benefits.

List of abbreviations

A/R: afforestation/reforestation; CBM-CFS3: Carbon Budget Model of the Canadian Forest Sector; CBM-FHWP: Carbon Budget Modelling Framework of Harvested Wood Products; OWs: Open woodlands; HWPs: harvested wood products

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_et_al_Afforestation_Quebec/14879700

Conflict of interest statement

The authors have no conflict of interest to declare. All co-authors have seen and agree with the contents of the manuscript and there is no financial interest to report.

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