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Quantifying the biophysical climate change mitigation potential of Canada's forest sector

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Abstract

The potential of forests and the forest sector to mitigate greenhouse gas (GHG) emissions is widely recognized, but challenging to quantify at a national scale. Forests and their carbon (C) sequestration potential are affected by management practices, where wood harvesting transfers C out of the forest into products, and subsequent regrowth allows further C sequestration. Here we determine the mitigation potential of the $2.3 \times 10^6\,\mathrm{km}^2$ of Canada's managed forests from 2015 to 2050 using the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3), a harvested wood products model that estimates emissions based on product half-life decay times, and an account of emission substitution benefits from the use of wood products and bioenergy. We examine several mitigation scenarios with different assumptions about forest management activity levels relative to a base-case scenario, including improved growth from silvicultural activities, increased harvest and residue management for bioenergy, and reduced harvest for conservation. We combine forest management options with two mitigation scenarios for harvested wood product use involving an increase in either long-lived products or bioenergy uses. Results demonstrate large differences among alternative scenarios, and we identify potential mitigation scenarios with increasing benefits to the atmosphere for many decades into the future, as well as scenarios with no net benefit over many decades. The greatest mitigation impact was achieved through a mix of strategies that varied across the country and had cumulative mitigation of $254\,\mathrm{Tg\,CO_2e}$ in 2030, and $1180\,\mathrm{Tg\,CO_2e}$ in 2050. We conclude that (i) national-scale forest sector mitigation options need to be assessed rigorously from a systems perspective to avoid the development of policies that deliver no net benefits to the atmosphere, (ii) a mix of strategies implemented across the country achieves the greatest mitigation impact, and (iii) because of the time delays in achieving carbon benefits for many forest-based mitigation activities, future contributions of the forest sector to climate mitigation can be maximized if implemented soon.

1 Introduction

Global efforts to reduce the rate of increase in the atmospheric carbon dioxide (CO_2) concentration require both a reduction of emissions and an increase of removals of CO_2 from the atmosphere. Forests not affected by land-use change are currently estimated to remove about 2.4 $\text{Pg}\,\text{C}\,\text{yr}^{-1}$ from the atmosphere (Pan et al., 2011) and together with carbon (C) sinks in oceans remove from the atmosphere about half of the annual anthropogenic emissions from the burning of fossil fuels and cement manufacturing (Le Quéré et al., 2012). The potential of forests and the forest sector to contribute to climate change mitigation has long been recognised (Cooper, 1983; Marland, 2003; Pacala and Socolow, 2004; Nabuurs et al., 2007) but estimates of this potential remain highly uncertain.

Mitigation is defined as a change in human behaviour or technology that increases sinks or reduces sources relative to a baseline. Forest sector mitigation can be achieved through management activities in the forest that increase landscape-level C density though forest conservation or silvicultural activities (Sathre et al., 2010; Werner et al., 2010). The design of a forest sector mitigation portfolio should consider the trade-offs between increasing forest ecosystem C stocks and increasing the sustainable rate of harvest to meet society's demands (Nabuurs et al., 2007).

Determination of the mitigation potential of forests is complex because the forest sector interacts with energy and industrial products sectors, and a systems approach to analysis is required (Nabuurs et al., 2007; White, 2010; Lemprière et al., 2013). A full account of emissions when and where they occur, accounting for emissions or removals from the forest ecosystem, from Harvested Wood Products (HWP), and product or energy substitution is needed to fully quantify mitigation impacts. Substitution benefits occur when wood is used in place of other emissions-intensive materials such as concrete, steel and plastics, and when biomass-derived energy is used in place of fossil fuels (Sathre and O'Connor, 2010; Böttcher et al., 2012). There is a need to avoid assumptions of C neutrality in bioenergy emissions (Johnson, 2009; Lemprière

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et al., 2013), and to avoid assumptions of instantaneous oxidation of HWPs' which can substantially overestimate C emissions from HWPs (Apps et al., 1999; Environment Canada, 2013a).

Our first objective in this analysis was to examine the biophysical mitigation potential of a suite of strategies for Canada's 2.3×10^6 km^2 managed forests. Our analysis included seven forest management strategies that (i) maintained or increased stand-level C density through silvicultural activities or a reduction in harvest levels, and (ii) used forest-derived biomass to displace the use of other energy sources. The analysis also included two HWP strategies that shifted the commodity mix towards either longer-lived products or bioenergy feedstock relative to the baseline. Finally, we examined two combination strategies that included a forest management strategy combined with the longer-lived products strategy.

Our second objective was to determine what portfolio mix of mitigation strategies in the forest sector could contribute towards short-term (2020), medium-term (2030), and long-term (2050) emissions reductions in Canada. Canada has committed to reduce its GHG emissions to 17 % below 2005 levels by 2020 (Envionment Canada, 2013b). International negotiations are now underway to establish post-2020 emission reduction targets (e.g. for 2030) (UNFCCC, 2012). For 2050, the G8 countries have supported a goal of developed countries reducing GHG emissions in aggregate by 80 % or more (G8, 2011).

2 Methods

2.1 Analytical framework

Our analysis examined how changes in Canada's forest sector activities could reduce GHG emissions or increase C removals relative to a *Base Case*. The system boundaries of the analysis included forest management (FM), HWPs and bioenergy, and emissions displaced in the energy and product sectors. Displaced emissions and HWP emissions that occur both nationally and internationally as a result of the export of Canadian HWPs and bioenergy are included.

The analysis was conducted at the spatial resolution of the spatial units that Canada uses in its national GHG inventory reporting to the United Nations Framework Convention on Climate Change (UNFCCC). These geographic regions were created from the intersection of Canada's terrestrial ecozones with provincial and territorial borders, and are referred to as reconciliation units in the national inventory report (Environment Canada, 2013a). In total, there were 39 spatial units for the managed forest, and of these, 32 included management activities and were used in estimating the impacts of one or more of the mitigation strategies. Characterization of the *Base Case* and individual strategies was based on assumptions made for each province and territory (Table S1), and then applied to each spatial unit within the province or territory. This meant that strategies had different implementation levels across the country, and not all strategies were implemented in every spatial unit.

Forest ecosystem C dynamics were analyzed using the National Forest Carbon Monitoring, Accounting and Reporting System (NFCMARS) datasets and its core modelling engine, the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3). See Stinson et al. (2011) for a description of NFCMARS datasets and Kurz et al. (2009) for a description of CBM-CFS3. Model simulations were conducted for Canada's managed forest, which included lands managed for sustainable harvest, lands under protection from natural disturbances, and areas managed to conserve forest ecological values. Forest inventory data were provided by provincial and territorial agencies or compiled from the Canadian National Forest Inventory (Power and Gillis, 2006). Inventory data included stand attributes (age, general location, species types) and merchantable volume yield tables for each of the hardwood and softwood components.

CBM-CFS3 outputs describing the quantities of C transferred to HWP and bioenergy were passed to the Carbon Budget Modelling Framework for Harvested Wood Products (CBM-FHWP), an analytical tool that tracks the fate of harvested C through manufacturing, use, and end-of-life use. All emissions associated with forest C harvested in Canada were tracked in the analysis, irrespective of whether the HWPs were exported, in keeping with internationally-agreed upon approaches for HWP C accounting (IPCC, 2013a). The framework has been used in a similar national-scale analysis (Environment Canada, 2013a), and in smaller-scale applications (Dymond, 2012). For this analysis, production and export of Canada's wood product commodities (sawnwood, panels, other solid wood, and pulp and paper) were estimated using national statistics from the UN Food and Agriculture Organization (FAO) (online forest products database http://www.fao.org/forestry/databases/29420/en/ accessed 18 March 2013). See Table S1 for more information. Product half-lives were assumed to be 35 yr for sawnwood and other solid wood, 25 yr for panels, and 2 yr for pulp and paper (IPCC, 2013a). Estimates of bioenergy emissions, milling efficiencies and mill residue capture were also tracked in the HWP framework. Product end-of-life handling was included, with 10 % of discarded product C assumed to be used for bioenergy, and the remainder directed to landfills. For products entering the landfill, 23 % of solid wood products were assumed to be degradable with a half-life of 29 yr, and 56 % of paper products were assumed to be degradable with a half-life of 14.5 yr. Landfill half-lives were estimated from the average of Intergovernmental Panel on Climate Change (IPCC) default values for dry and wet, boreal and temperate climates (IPCC, 2006). Landfill emissions were assumed to be 50 % CO_2 and 50 % CH_4, with no methane capture or flaring (Micales and Skog, 1997; Pingoud and Wagner, 2006).

Avoided or displaced emissions, defined as the emissions that would have occurred if the alternate energy sources or products had been used (Sathre and O'Connor, 2010), were included in the analysis by calculating displacement factors. Every unit of wood C used in the production of bioenergy was assumed to displace some alternative energy source that would otherwise have been used to produce the same quantity of useful energy (thermal or electrical). The bioenergy displacement factors derived for this study quantify the emissions that were avoided per unit of wood C converted to energy. We calculated energy displacement assuming that increased harvesting for bioenergy would displace heat or electricity production in the same province or territory where the additional wood was harvested. We consulted provincial and territorial government representatives and used information they provided to establish our assumptions about which substitutions would most likely occur in the event of increased forest bioenergy production. Domestic bioenergy displacement factors were estimated by comparing the emissions intensity of the original energy source (hydro, natural gas, diesel, oil or coal) to the comparable bioenergy facility (electricity generation, district heating, and combined heat and power). These estimates included emissions resulting from resource extraction and refinement, transportation, and combustion (Hondo, 2005; Statistics Canada, 2007; Canadian Energy Research Institute, 2008; Skone and Gerdes, 2008). Domestic bioenergy displacement factors varied between −0.08 and 0.79 Mg C avoided per Mg C used, while the international value was assumed to be 0.6 (Schlamadinger and Marland, 1996). The wide range of displacement factors occurs because bioenergy displaces different original energy sources in different regions of Canada. For example, some regions have low emission energy sources, such as hydro, while others have coal. The emission substitution effects of more (or less) bioenergy use were estimated by multiplying the displacement factors by the increase (or decrease) in biomass available for bioenergy harvest as a result of each strategy.

Product displacement factors were estimated by selecting a representative set of functionally equivalent comparable products (e.g. concrete, steel) and then allocating the substitution benefits to the primary wood products used to manufacture the end-use products. The difference in emissions needed to extract resources, manufacture primary products, assemble final products and operate the comparative functional units was estimated using various published emissions intensities for Canadian-specific raw materials extraction (wood and non-wood), transportation and manufacturing operations (Jönsson et al., 1996, 1997; Schmidt et al., 2004; Marceau et al., 2007; ASMI, 2008a, b, 2009a, b, c; Cha and Youn, 2008; NREL, 2008; Bala et al., 2010). For solid wood products, a set of end-use products (single-family homes, multi-family homes, flooring for residential upkeep, non-residential buildings, furniture, and other products) and their respective material lists was gathered from the literature (Jönsson et al., 1997;

Scheuer et al., 2003; Lippke et al., 2004; Gustavsson et al., 2006). Estimated displacement factors were 0.38 (Mg C avoided per Mg C used) for sawnwood and 0.77 (Mg C avoided per Mg C used) for panels. The emission substitution effects of more (or less) production and use of products were estimated by multiplying product displacement factors by the increase (or decrease) in products as a result of each strategy.

2.2 Base Case

The *Base Case* was defined as the scenario of FM activity levels that would occur in the absence of mitigation activity. In the historic time period (1990 to 2011) the *Base Case* matched the National Inventory Report (NIR) assumptions including those for harvests, wildfire, insects, deforestation and afforestation (Environment Canada, 2013a). In the future time period (2012 to 2050) the *Base Case* included harvest projections and an assumption of a constant area burned. Deforestation and afforestation were not included in the future projections because the areas affected are relatively small (Environment Canada, 2013a). Insects were not included because future affected areas and severity are highly uncertain. However, we did examine the sensitivity of the results to increased natural disturbance levels (Sect. 2.5).

For wildfire, future annual burned areas were set to the 1990 to 2011 average area-burned. Future harvest volumes, bioenergy harvest proportion, residue management, and salvage harvest proportion were set based on information provided by provincial and territorial government experts in response to detailed questionnaires (National Forest Sinks Committee, personal communications, May 2012); however the authors accept full responsibility for assumptions made.

Clearcut harvesting was implemented using a utilization rate of 85 % to 97 % of the merchantable stem biomass present at the time of harvest, and the remainder was assumed to be left on site as logging residue along with all tops, branches, stumps, foliage, roots and trees of submerchantable size. Partial harvesting had a utilization rate of 30 %, leaving 70 % of the merchantable stem biomass to continue growing.

More detailed information on the *Base Case* and strategy parameters can be found in the Supplement, Table S1.

2.3 Mitigation strategies

We analyzed seven FM strategies and two HWP strategies, Table 1. The first FM strategy, *Better Utilization*, included several concurrent activities: (i) increased utilization of wood from harvest cut blocks, (ii) increased salvage harvesting, (iii) stopping burning of harvest residue in situ (pile-burning of slash), and (iv) increased recovery of harvest residue for bioenergy to 50 % of the available residue. The second strategy, *Harvest Less*, reduced the harvest volume and restricted the forest area available for harvest. The third strategy, *Planting*, simulated faster regeneration after post-harvest planting, with no change the maximum attainable stand biomass (or volume). We set the treated stands to a later point of their yield table, thereby accelerating their transition through the early, slow stage of sigmoidal growth. In the fourth strategy, *Better Growth*, maximum attainable stand biomass was increased through various silvicultural activities including fertilization, use of improved tree stock or seed, and reduction of competing vegetation (release) through mechanical or manual control or herbicide application. The remaining three strategies increased harvest of live biomass relative to the *Base Case* to produce bioenergy feedstock from (i) *Clearcut Harvest*, (ii) *Commercial Thinning* (CT) *Harvest* and (iii) *Pre-Commercial Thinning* (PCT) *Harvest*. We assumed that increased harvest and thinning activities did not affect subsequent stand-level growth, but harvested wood was used for bioenergy feedstock instead of being transferred to HWPs or decaying in situ.

The two HWP mitigation strategies altered the commodity proportions relative to the *Base Case*. In the first HWP strategy, *Longer-Lived Products (LLP)*, the harvest was used to produce a commodity mix shifted towards a greater proportion of long-lived sawn-wood and panel products, at the expense of pulp and paper production. In the second HWP strategy, *Bioenergy Feedstock*, a greater proportion of the harvested C was redirected toward bioenergy production, at the expense of the other commodities.

It was assumed that additional bioenergy production relative to the *Base Case* for this strategy and FM strategies was consumed domestically, while reductions in bioenergy production as a result of the *Harvest Less* strategy affected bioenergy production both domestically and abroad.

A ramp-up period was assumed for both HWP and FM strategies. HWP strategies were implemented with a linear increase in activity levels over three-years, starting in 2015 with one-third of the final implementation level, and full implementation in 2017. FM strategies were implemented in 2015 with one quarter of the final implementation level, and full implantation in 2021.

We analyzed FM and HWP strategies individually, but recognized that some of the strategies could be implemented at the same time and result in improved mitigation outcomes. We examined two combinations of FM and HWP strategies: *Better Utilization + LLP* and *Harvest Less + LLP*. We also recognized that improved mitigation outcomes at the national level could be feasible by developing portfolios of mitigation strategies that vary across spatial units. A long-term portfolio mix was derived by choosing the strategy in each spatial unit that maximized the cumulative mitigation in 2050. A short-term portfolio mix was derived by choosing the strategy in each spatial unit that maximized cumulative mitigation in 2020.

2.4 Mitigation indicators

Mitigation was defined as the difference between the *Base Case* emissions and the strategy emissions:

$$M = E_\mathrm{B} - E_\mathrm{S} \tag{1}$$

where M is the mitigation, E_B is the *Base Case* emissions, and E_S is the strategy emissions. Mitigation was estimated for each year in each spatial unit in which a strategy was simulated. Emissions were estimated as the sum of the emissions from three components:

$$E = F + P + D \tag{2}$$

where F is the net GHG emissions from the forest, P is the emissions from HWPs, including bioenergy, end-of-life treatment and decay, and D is the displaced emissions from substituting HWPs and bioenergy for alternatives.

Mitigation indicators presented at the national level included the cumulative mitigation timeseries for each strategy, and the cumulative component contributions (Eq. 2) in 2050. Estimates of cumulative mitigation are presented at the ecozone level for 2020, 2030 and 2050.

2.5 Sensitivity analysis

The effectiveness of a mitigation strategy can be impacted by natural disturbance, particularly if high levels of natural disturbance influence the harvestable area. A sensitivity analysis was performed to investigate the likely effects of natural disturbances being greater or less than the historic average (1990 to 2011). Annual burned area was increased by 20 % (high disturbance scenario) and decreased by 20 % (low disturbance scenario) for the *Base Case* and the *Better Utilization* strategy. The analysis assessed the impacts of changes in natural disturbance levels on the mitigation potential.

3 Results

3.1 Base Case

Emissions from the *Base Case* were estimated as the sum of emissions from the forest ecosystem and emissions from HWPs. A positive sign denotes release of GHGs to the atmosphere, and a negative sign denotes removals. Direct emissions from wildfires were highly variable for the 1990 to 2011 historic period, and large when large areas burned (Fig. 1a) up to a maximum of 234 Tg CO_2e yr^{-1}. Direct annual wildfire emissions for the future period (2012 to 2050) were based on an average annual burned-area assumption, and released an average of 97 Tg CO_2e yr^{-1}. Emissions from pile-burning of slash in the future period were 9.8 $\text{Tg CO}_2\text{e yr}^{-1}$ on average, and were similar to the direct emissions during the historic period of 7.3 $\text{Tg CO}_2\text{e yr}^{-1}$. Burning of residues was a means of fire hazard control, and was generally not used as a site preparation activity (e.g. broadcast burning). The net C balance of the forest was a strong C sink (Fig. 1b) for most of the timeseries, with strong impacts on inter-annual variability from natural disturbance emissions in the historic period. HWP emissions included emissions from bioenergy and mill residues, and landfill emissions from retired products. HWP emissions for the *Base Case* increased with time (Fig. 1c) because product pools started in 1990 in our accounting. Emissions from HWPs produced pre-1990 are not included, but this has no effect on the results because all emissions associated with HWPs produced before 2015 (whether calculated or not) would cancel out when strategy results are compared to the *Base Case*. Emissions from pulp and paper (not shown) were the largest contributor to HWP emissions because of this commodity's short life-time.

3.2 Forest Management (FM) mitigation

Cumulative mitigation timeseries from 2015 to 2050 were estimated for seven FM strategies. Positive values indicate that mitigation occurs; negative values indicate that a strategy increases emissions relative to the *Base Case*. National cumulative mitigation timeseries for the total, and three components (forest, HWP and displaced emissions) are shown in Fig. 2. Some of the strategies resulted in positive mitigation (a reduction in emissions to the atmosphere) while other strategies had negative mitigation (increased emissions) relative to the *Base Case*.

The *Better Utilization* strategy had positive mitigation (enhanced removals) in the forest ecosystem because higher utilization levels resulted in reduced harvest areas for the same amount of C harvested, and because of reductions in slashburning. However, this was partly offset by negative mitigation (increased emissions) from HWP. This was caused by larger emissions from the collection and use of harvest residues for bioenergy production, which has instantaneous emissions compared to delayed emissions from in situ decay. However, increased bioenergy use also displaced emissions from alternate domestic energy sources, such that the sum of all mitigation impacts resulted in an overall positive cumulative mitigation for the *Better Utilization* strategy after 2026. This strategy yielded the highest cumulative mitigation from 2015 to 2050 (511 Tg CO_2e) which was 2.4 times larger than the second-ranked strategy.

The *Harvest Less* strategy ranked second highest for national cumulative mitigation from 2015 to 2050 among the seven FM strategies. This strategy had enhanced removals in the forest because of C sinks from forests that were not harvested, and reduced HWP emissions because of the reduction in harvest levels, resulting in a positive mitigation from both of these components. However, the reduction in harvest levels relative to the *Base Case* accrued negative displaced emissions because more emissions-intensive non-wood products were required to cover the reduced availability of HWP and bioenergy. Overall, the cumulative mitigation was positive over the time period analyzed.

The two FM strategies that included silvicultural activities (*Planting* and *Better Growth*) had modest positive cumulative mitigation from enhanced sinks in the forest ecosystem. There was no change in HWP emissions or displaced emissions for these forest management strategies because harvest levels did not change relative to the *Base Case*.

National cumulative mitigation was negative for all three FM strategies in which harvesting levels were increased for the purpose of bioenergy. For these strategies, the displaced emissions from bioenergy production did not compensate for the increased emissions from bioenergy (accounted as HWP emissions) and the reduced carbon stocks the forest ecosystem.

3.3 Harvested Wood Product (HWP) mitigation

Cumulative mitigation timeseries from 2015 to 2050 were estimated for two HWP strategies. These strategies did not affect forest ecosystem C stock, but altered the

HWP commodity proportions to produce (1) more longer-lived products or (2) more bioenergy feedstock relative to the *Base Case*.

Cumulative mitigation for the *LLP* strategy was 435 Tg CO_2e, because of reduced emissions from HWPs (positive mitigation) and increased displaced emissions (positive mitigation) from using more wood products relative to the *Base Case* (Fig. 3). Shifting the commodity mix to longer-lived products increased the product lifetimes, which delayed end-of-life emissions from retired products which were used for bioenergy production or put into landfills. It also increased product displacement because there was an increase in sawnwood and panels relative to *Base Case* which resulted in greater avoided emissions. The cumulative mitigation for the HWP *LLP* strategy was comparable, but slightly smaller in 2050 than the *Better Utilization* strategy.

The strategy to increase the proportion of bioenergy feedstock from the harvest resulted in increased emissions (negative mitigation) relative to the *Base Case*. The net effect was an increase in emissions because increased HWP emissions resulting from shortening product lifetimes were not compensated by the emissions avoided by using bioenergy in place of other energy sources.

3.4 Combined strategies and portfolio mix

Combining the two FM strategies with the greatest mitigation potential (*Better Utilization* and *Harvest Less*) with the HWP *LLP* strategy resulted in greater cumulative mitigation (Fig. 3). Adding the *LLP* strategy to the *Better Utilization* strategy increased the 2050 cumulative mitigation to 946 Tg CO_2e and resulted in a shorter delay before the cumulative mitigation became positive (2019 vs. 2026 for the FM strategy alone).

The long-term portfolio mix, derived by choosing the strategy in each spatial unit that maximized the cumulative mitigation in 2050, resulted in the highest cumulative mitigation (Fig. 3c). Cumulative mitigation was modest during the ramp-up period from 2015 to 2020 at 25 Tg CO_2e, but increased to 254 Tg CO_2e for the 2015 to 2030 period, and 1180 Tg CO_2e for the 2015 to 2050 period. Annual mitigation increments grew substantially over time (Table 2): the average annual mitigation for the long-term portfolio mix more than doubled in 20 yr, increasing from 22.9 Tg CO_2e yr^{-1} (average from 2021 to 2030), to 51.0 Tg CO_2e yr^{-1} from 2041 to 2050.

The short-term portfolio mix, derived by choosing the strategy in each spatial unit that maximized the cumulative mitigation in 2020, had greater mitigation in 2015 to 2020 (31 Tg CO_2e) relative to the long-term portfolio mix, but 6 % lower cumulative mitigation in 2030 (238 Tg CO2e), and 15 % lower cumulative mitigation in 2050 (1002 Tg CO_2e). The difference between the short-term and the long-term mitigation portfolios resulted from the finding that the maximizing strategy choice in a spatial unit can change over time.

The long-term portfolio mix selected one of the two combination strategies in every participating spatial unit. The *Better Utilization* and *LLP* combination strategy was selected in most ecozones (Fig. 4).

3.5 Foreign and domestic partitioning

Consumption of Canadian HWP was considered for both foreign and domestic markets because Canada exports a substantial portion of many of its wood commodities. Figure 5 shows the partitioning in 2050 of the cumulative HWP and displacement for foreign and domestic components, and for product and energy components. Also shown are Canada's forest component and the total cumulative mitigation for all strategies, the two strategy combinations, and the two portfolios, in 2050. HWP emissions were reduced relative to the *Base Case* for the *Harvest Less* and *LLP* strategies (Fig. 5b). The reduction in harvest and a shift away from pulp and paper products for the *LLP* strategy reduced the emissions associated with pulp and paper products, which are mainly used in foreign markets.

The *Better Utilization* strategy and the three bioenergy strategies had greater domestic energy HWP emissions because we assumed that bioenergy was used domestically to replace other energy sources. These strategies also had the highest domestic displaced emissions from energy sources, which compensated for the greater HWP emissions (Fig. 5c). Positive displaced emissions also resulted from the *LLP* strategy, for both domestic and foreign product sectors. Foreign product displacement was larger than domestic displacement for this strategy because of the high export proportion for sawnwood and panels.

4 Discussion

Forest sector mitigation potential in countries like Canada could be high because the forest area is large and even modest per hectare impacts would add up to substantial values when applied over large areas. However, Canadian forests are relatively slow growing and sufficiently diverse that no mitigation strategy can be expected to be effective everywhere, and only those mitigation activities that are both technically feasible and economically attractive may be undertaken. Moreover, changes in human activities with the highest global mitigation potential identified by Nabuurs et al. (2007), are associated with reductions in emissions from deforestation, i.e. the conversion from forest to non-forest land uses. Reduction in deforestation rates were not addressed in our study because only ~ 0.02 % of the forest area is annually affected by deforestation in Canada (Environment Canada, 2013a; Kurz et al., 2013); afforestation and reforestation were not examined in our study, because several studies have already examined their economic feasibility (e.g. McKenney et al., 2004, 2006; Yemshanov et al., 2005; Boyland, 2006; Yemshanov and McKenney, 2008).

We examined a range of mitigation strategies that have not previously been evaluated in detail for all of Canada from a broad systems perspective. Increasingly, studies are using this perspective to fully quantify the impacts of mitigation activities undertaken by the forest sector on overall GHG emissions and removals (Lemprière et al., 2013). A broader systems approach includes not only the C in the forest and forest products, but also the interaction among land-use demands and the potential for forest fibre to substitute for fossil fuel energy and emission-intensive products like concrete, metals and plastics. It is now widely acknowledged amongst policymakers that the C in HWP pools must be accounted for, rather than treated as if it was instantaneously emitted at the time of harvest (IPCC, 2013a). Similarly, it is increasingly understood that bioenergy should not be assumed to be C neutral (Johnson, 2009; Agostini et al., 2013; Bracmort, 2013). This study tracked the emissions in HWPs where and when they occurred, and considered the substitution benefits, which provides a more accurate assessment of mitigation opportunities.

Mitigation potential can be assessed in a number of ways (Lemprière et al., 2013). Biophysical potential is the upper limit to the potential because it ignores economic considerations and any regulatory or other constraints. Technical potential is the potential once constraints have been reflected, but still ignoring economic considerations. Our study quantified the biophysical potential but included some of the constraints that would define the technical potential, because we implemented the mitigation strategies at levels considered to be currently feasible. However our estimates are higher than the technical potential because there are uncertainties about technical feasibility, regulatory barriers and marketing barriers that we did not consider. Forests provide a range of services and co-benefits and forest managers are required to manage for multiple objectives, some of which could come into conflict with mitigation objectives (Golden et al., 2011).

Other Canadian studies have used a variety of methodologies to examine the biophysical potential of specific activities or to investigate the implications of including C as an objective in FM at various scales (e.g. Kurz and Apps, 1995; Chen et al., 2000; Meng et al., 2003; Colombo et al., 2005; Bourque et al., 2007; Hennigar et al., 2008; Taylor et al., 2008); however few studies have attempted to determine national mitigation potential. Nabuurs et al. (2007) estimated that the technical mitigation potential for Canada's forest sector could be 10 % of the biophysical potential estimated for Canada at that time (Chen et al., 2000), or 50 to 70 Tg CO_2 yr^{-1}. If this were realized annually from 2015 through 2050, it would yield a cumulative mitigation benefit of 1800 Tg CO_2 to 2520 Tg CO_2, or less if the mitigation benefits were ramped up gradually over the first few years. Kurz and Apps (1995) provided estimates of similar magnitude. Our estimates of 1180 Tg CO_2e cumulative mitigation for the best-performing long-term portfolio mix (Fig. 3) were smaller than these estimates, and we consider them to be more realistic than the earlier national-scale analyses.

While some studies, such as Karjalainen et al. (2003) and ours, prescribe mitigation as incremental activities relative to a baseline, others use methodologies that solve for forest sector mitigation activity given different economic stimuli, such as C prices. Sjølie et al. (2013) described why this latter method can result in a greater mitigation potential. Rather than letting a carbon price drive forest sector mitigation activity levels, we set activity levels based on the advice of provincial and territorial government experts, on the presumption that policy levers could be used to promote or stimulate these actions.

Our findings are generally similar to those of Werner et al. (2010) and Sjølie et al. (2013) who also took a broad systems perspective. Like Werner et al., we found that a strategy of reduced harvesting provides strong short-term mitigation benefit but was not the strongest long-term strategy. The *Harvest Less* strategy examined in our study provided the greatest benefits in the short term (Fig. 2d), but over time the *Better-Utilization* strategy became more effective. Initially, reduced harvesting allowed forest C stocks to accumulate relative to the *Base Case*, but this was offset by increased emissions from non-forest sectors which were assumed to increase production to satisfy the demand for materials and energy that was no longer satisfied by the forest sector. We assumed that the demand for the services provided for sawnwood, panels and bioenergy were not influenced by the level of forest sector production (Gan and McCarl, 2007); reducing harvest to maximize forest ecosystem C storage leads to negative displacement (see Fig. 5), expressed as increased emissions from other sectors.

Our results agree with findings by Werner et al. (2010), who found that wood-use strategies focused on manufacture and use of long-lived products perform better than strategies focused on bioenergy. Our HWP strategy aimed at shifting wood commodities to longer-lived products (at the expense of short-lived pulp and paper products) produced a cumulative mitigation benefit of 435 Tg CO_2e in 2050. The reduced emissions were the result of reduced HWP emissions because of a shift toward longer product lifetimes, and reduced emissions from substituting wood for other emissions-intensive products. However, we did not consider whether there is a demand for larger quantities of long-lived products or upper limits on wood substitution levels. For example, foreign demand for Canadian HWP exports is important for Canada's forest sector, and has major influence on the HWP product mix, but this is determined by complex supply and demand conditions. In addition, there could be technological and wood-quality constraints that reduce the mitigation potential of the combination strategy of *Better Utilization* and *LLP* because the increased utilization harvest utilization rate (with the harvest volume assumed to be unchanged) may not be able to produce biomass suitable for production of a greater proportion of longer-lived products.

Our results found no mitigation benefit achieved within the 36 yr time frame of our analysis when accounting for the impacts of bioenergy-related harvest on forest carbon stocks, and for the net emissions balance associated with bioenergy use and the avoided emissions from the fossil fuel alternatives. This is consistent with a series of recent studies examining the potential use of increased harvest for the production of bioenergy (Colombo et al., 2005; Ralevic et al., 2010; McKechnie et al., 2011; Ter-Mikaelian et al., 2011). This is in part a consequence of the slow growth rates of Canada's forests, and because displaced emissions from substituting bioenergy for fossil fuels were not able to compensate for increased bioenergy emissions. While some bioenergy options may not contribute to mitigation objectives when displacing emissions from the average energy profile within a province, we emphasize that this does not preclude significant mitigation benefits through bioenergy use in some regions. Our coarse-scale analysis across 32 spatial units for the entire Canadian managed forest could not capture this level of detail. For example, a positive mitigation benefit from bioenergy-related harvesting might occur in remote communities that are not connected to the electricity grid and where local electricity is produced from fossil fuels that have been transported over long distances. The pre-commercial and commercial thinning for bioenergy strategies (*Bioenergy PCT* and *Bioenergy CT*) that we explored also produced no mitigation benefit at the national scale. Undertaking these strategies for mitigation purposes alone would be expensive, but where thinning is being undertaken already for other purposes, such as wildfire fuel management, it may be worthwhile to collect the biomass from thinning for bioenergy (White, 2010).

The *Base Case* and mitigation strategies were applied to the same forest inventory data, which causes age-class legacy effects on contemporary C dynamics to be factored out when a mitigation strategy is compared to the *Base Case*. Similarly, the emissions associated with HWPs produced prior to 2015 are factored out. We also assumed the same base level of natural disturbance in the *Base Case* and all mitigation strategies, which caused natural disturbance effects on the forest C budget to be almost entirely factored out. The impacts of natural disturbance assumed to occur from 2015 onward were almost completely factored out, with slight differences caused from the interaction between forest management and natural disturbance activities. Over the 2015–2050 period, the cumulative differences in natural disturbance impacts ranged from zero to 2 Tg C, depending on the strategy, or well under 1 % of the estimated cumulative effects of each strategy by 2050. The impact of changing the area-burned by ±20 % in the *Base Case* and *Better Utilization* FM strategy was negligible. Cumulative mitigation timeseries for both high and low disturbance scenarios were within 1 % of the original cumulative mitigation estimate in 2050.

The best long-term mitigation FM strategy was the *Better-Utilization* strategy. This complex strategy involved concurrent implementation of four different mitigation activities. Increasing utilization levels while holding the absolute amount of wood to be harvested constant resulted in reduced harvest area and reduced the quantity of harvest residue. Both of these outcomes, along with an increase in salvage harvest, increased emissions reduction and an accumulation of C in the forest, but these impacts are difficult to differentiate because of the large impacts resulting from the elimination of slash burning in this strategy. The combined impact of reduced harvest area, elimination of slash burning, and reduced emissions from in situ residue decay, enhanced the forest sink significantly (Fig. 2a). HWP emissions increased significantly because of bioenergy production from harvest residues (Fig. 2b). We did not take the impacts of increased harvest residue removal on forest productivity into consideration (we assumed removal of 50 % of the residue). Removal of nutrients in harvest residue can lead to reduced soil and foliar nutrients, and hence sometimes reduced tree growth (Thiffault et al., 2011; Wall, 2012). However, the growth reductions sometimes found in Europe (Egnell, 2011; Mason et al., 2011) have not yet been reported in Canada. We therefore did not reduce tree growth because of harvest residue removals, but acknowledge that these reductions could arise over successive rotations in the future if Canadian forests are not managed using ecological rotation lengths (sensu Kimmins, 1974). The *Planting* strategy that we examined did not produce substantial mitigation benefit at the national scale by 2050. This accelerated regeneration does not translate into substantial landscape-scale C uptake in the short term when applied to small areas, as in our study. However, the impact may become substantial over time, when planted stands reach the more productive stages of their growth trajectories and the number of treated stands accumulates, or if planted stock from tree selection programs has higher growth rates or reduced vulnerability to diseases. Benefits may also be greater in situations where planting enables such regrowth, for example where natural or anthropogenic disturbances resulted in regeneration failure.

The *Better Growth* strategy involved treatment of 120 $\mathrm{kha\,yr^{-1}}$ using various combinations of improved seed, chemical and mechanical release and fertilization in different provinces and territories. The C uptake gains associated with the adoption of more intensive silviculture have generally been found to more than compensate for the increased fossil C emissions from forestry operations (Markewitz, 2006; Jassal et al., 2008) which we did not take into account. For this study, we simulated a multiplicative increase of the annual volume increment ranging from 6 % to 20 %, depending on the region, for a period of 10 yr to 35 yr without considering the activity-specific processes involved. Although greater understanding of these processes and their stand-level effect on C is needed, our results are more sensitive to the scale of application. Our conclusions about silvicultural activities and intensive forest management are thus appropriate in the context of our coarse-scale analysis but there may be high mitigation potential in specific regions, and this possibility should be examined more closely.

In all of our strategies, we examined only the impacts on greenhouse gas emissions and removals and we did not consider other impacts on the Earth's energy balance. Biogeophysical contributions of forests and forestry to the Earth's energy balance, such as alterations to surface albedo, may be important and could change our understanding of the effectiveness of climate change mitigation strategies (Foley et al., 2003; Bonan, 2008; Jackson et al., 2008; Thompson et al., 2009; Lemprière et al., 2013). We also ignored the effect of climate change on mitigation efforts. Climate change impacts could undermine or augment the mitigation effectiveness of forest management strategies or alter their relative effectiveness; for example, where a reduced harvesting or forest conservation strategy appears optimal, care should be taken to evaluate the risk of accidental carbon release by natural disturbance. Many Canadian forest ecosystems currently have short fire-return intervals and are affected by periodic large-scale insect outbreaks (Kurz et al., 2008; Sharma et al., 2013), but substantial increases in disturbance rates are anticipated (Flannigan et al., 2005; Balshi et al., 2009; Podur and Wotton, 2010) and are expected to have a major impact on forest C budgets (Metsaranta et al., 2010, 2011; Kurz et al., 2013).

The best performing scenario examined in our study was the long-term portfolio mix (Fig. 3c). This was a simplified portfolio that we constructed by re-assembling the modelling results ex post by identifying the best-performing long-term strategy in each spatial unit, and then summing these across the country. We repeated the exercise with the best-performing scenarios in the short-term (to 2020) to calculate the forest sector's highest potential contribution to Canada's 2020 GHG emissions reduction target of 17 % below 2005 levels. However, the best short-term portfolio did not perform as well over the period to 2030, or in the long-term to 2050. There is a trade-off between short-term and long-term goals, in that maximizing short-term emissions reduction can reduce the forest sector's ability to contribute to longer-term objectives. This finding is consistent with previous analyses (Werner et al., 2010; Sedjo, 2011; Cowie et al., 2013).

We found very large and clear differences in mitigation levels resulting from different strategies, and while there are uncertainties in our estimates, we demonstrate the broad differences between strategies that clearly contribute to mitigation objectives and those that do not. With limited financial resources, and scientific assessments that highlight the urgency of early emission reductions (IPCC, 2013b), analysis is needed to ensure that strategies implemented are not counter-productive to achieving emission reductions goals. Quantitative analyses contribute to evidence-based assessment of climate change mitigation options in the forest sector. A companion study on the associated costs per tonne of GHG emission reductions as a result of the strategies discussed in this paper will allow the cost effectiveness of forest sector mitigation options to be compared with those of options in other sectors.

5 Conclusions

Canada's forests and forest products can contribute to mitigating climate change, and several mitigation options are available for forest management and wood-product use. We first emphasize the importance of a sound analytical framework for mitigation assessment, and an integrated assessment of the various mitigation possibilities within the context of a systems approach. Our approach examined C pools in the forest ecosystem, C use and storage in HWPs and landfills, and substitutions of wood for other products and energy sources. From seven FM strategies and two HWP strategies, we identified activities that had the greatest impact, and estimated the mitigation associated with incremental activities relative to a *Base Case*.

In the FM strategies, there were clear differences in the long-term rankings of the seven strategies. The *Better-Utilization* strategy was found to provide the greatest climate change mitigation, for most locations. The strategy of maximizing the C in forests through the *Harvest Less* strategy generally ranked lower than the *Better Utilization* strategy, which supports the conclusion of IPCC AR4 WG III that, "[i]n the long term, [a] sustainable forest management strategy aimed at maintaining or increasing forest C stocks, while producing an annual yield of timber, fibre, or energy from the forest, will generate the largest sustained mitigation benefit." (Nabuurs et al., 2007).

Some bioenergy strategies were found to be effective, while others were not. Additional harvest for bioenergy was counter-productive from a climate change mitigation standpoint, while capturing more harvest residue in place of slash pile-burning was highly effective. While some bioenergy options may not contribute to mitigation objectives when displacing emissions from the average energy profile within a region, we emphasize that our coarse-scale analysis could not capture the possibility of significant mitigation benefits through harvests for bioenergy in regions with specific fossil energy use characteristics. More opportunities may be identified if examined at finer spatial scales and if emissions displacement is not determined relative to the average energy profile within a region, for example in the case of remote communities that are not connected to the electricity grid.

Of the two HWP strategies examined, using wood for long-lived products was a better mitigation strategy than using wood for bioenergy. To achieve the mitigation benefits from the production of longer-lived products, effective mitigation portfolios need to integrate forest management with wood use strategies. Potential avenues for shifting the commodity mix to longer-lived products include increasing the types of buildings that could be constructed with wood, and reducing the proportion of short-lived pulp and paper that is produced.

We found that substantial gains could be realized through a portfolio of strategies, both in contributing to Canada's emission reduction targets and in reducing global emissions. The long-term portfolio strategy was constructed by selecting the strategy in each spatial unit which had the highest mitigation potential, and then summing all spatial units. However, the development of a mitigation portfolio requires understanding of the timelines of mitigation activities. We found that the ranking of mitigation strategies could change over time, and a portfolio mix which selected strategies based on the best short-term mitigation fell short of the cumulative mitigation achieved in 2050 in the long-term portfolio mix.

Key uncertainties that can be addressed in future analyses include examination of mitigation strategies at finer spatial scales to identify locally relevant options, and to identify how mitigation related to increasing forest C stocks may interact with the impacts of different climate change scenarios. In addition, the biogeophysical effects of FM strategies on climate, e.g. through changes in albedo, could affect both the magnitude of the mitigation and the relative ranking of the strategies, and should therefore also be examined.

Supplementary material related to this article is available online at http://www.biogeosciences-discuss.net/11/441/2014/bgd-11-441-2014-supplement.zip.

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Table 1. Indicators for the seven forest management and two harvested wood product strategies.

Strategy type	Strategy name	Description	Parameter changed	Parameter Value[a]
FM	Better Utilization	Increased harvest utilization levels and utilize residues	Utilization rate increase[b] (percentage points)	+5 to +12
			Salvage harvest increase[c] (percentage points)	+2 to +4
			Residue recovered[d] (%)	10 to 50
			Residue recovered ($\mathrm{Tg\,C\,yr^{-1}}$)	9.9
	Harvest Less	Reduce harvest levels and restrict harvest area	Harvest reduction (%)	2 to 5
			Harvest reduction ($\mathrm{Tg\,C\,yr^{-1}}$)	1.41
	Planting	Faster regeneration from post-harvest planting	Yield table shift[e] (years)	+5 to +6
			Affected area (kha)	3.2
	Better Growth release.	Increased growth from fertilization, use of improved seed, or stand	Young stands: growth multiplier[f] (%)	6 to 20
			Mature stands: growth multiplier (%)	20
			Young stands: affected area (kha)	49.5
			Mature stands: affected area (kha)	70.0
	Bioenergy Harvest	Clearcut harvest for bioenergy feedstock	Additional harvest (%)	2 to 5
			Additional harvest ($\mathrm{Tg\,C\,yr^{-1}}$)	1.42
	Bioenergy CT	Commercial thinning for bioenergy feedstock	Additional harvest ($\mathrm{Tg\,C\,yr^{-1}}$)	0.62
	Bioenergy PCT	Pre-commercial thinning for bioenergy feedstock	Additional harvest ($\mathrm{Tg\,C\,yr^{-1}}$)	0.029
HWP	Longer-Lived Products (LLP)	Increased proportion of harvest wood for longer-lived products	HWP component changes[g] (percentage points)	
			Sawnwood (%)	+4.2
			Panels (%)	+1.7
			Other solid wood (%)	+0.3
			Pulp and paper (%)	−6.2
	Bioenergy Feedstock	Increased proportion of harvested wood for bioenergy feedstock	Bioenergy harvest change[g] (percentage points)	+5 to +20
			HWPs change (percentage points)	−20 to −5

[a] Some parameter values have ranges, indicating that implementation varied according to the province or territory. Individual values were estimated as the average from 2015 to 2050.

[b] Increase was added to the *Base Case* utilization rate assumption.

[c] Increase was added to the *Base Case* assumption of percent of total harvest from salvage.

[d] Percent of clear cut area over which residues were collected.

[e] Faster regeneration was modeled by shifting forward in the yield table.

[f] Increased growth was modeled by multiplying the volume increment.

[g] Increases or decreases in percent of total harvest were relative to the *Base Case*.

Table 2. Average annual mitigation (in $\mathrm{Tg\,CO_2e\,yr^{-1}}$) for each decadal range for the strategy combination and strategy portfolios.

Strategy Combination	2021 to 2030	2031 to 2040	2041 to 2050
Better Utilization + LLP	14.5	34.2	45.1
Harvest Less + LLP	12.8	21.4	26.5
Short-term portfolio	20.7	34.8	41.5
Long-term portfolio	22.9	41.5	51.0

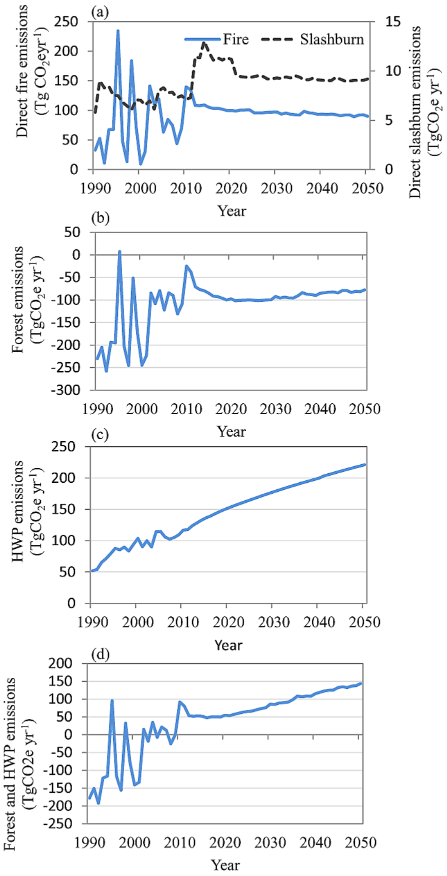

Fig. 1. Timeseries of **(a)** direct GHG emissions from fire, and slashburning (secondary y-axis), **(b)** net GHG emissions from the forest, **(c)** HWP emissions including bioenergy (excluding emissions from HWP manufactured from pre-1990 harvests), and **(d)** forest and HWP emissions. A positive sign denotes release of GHGs to the atmosphere.

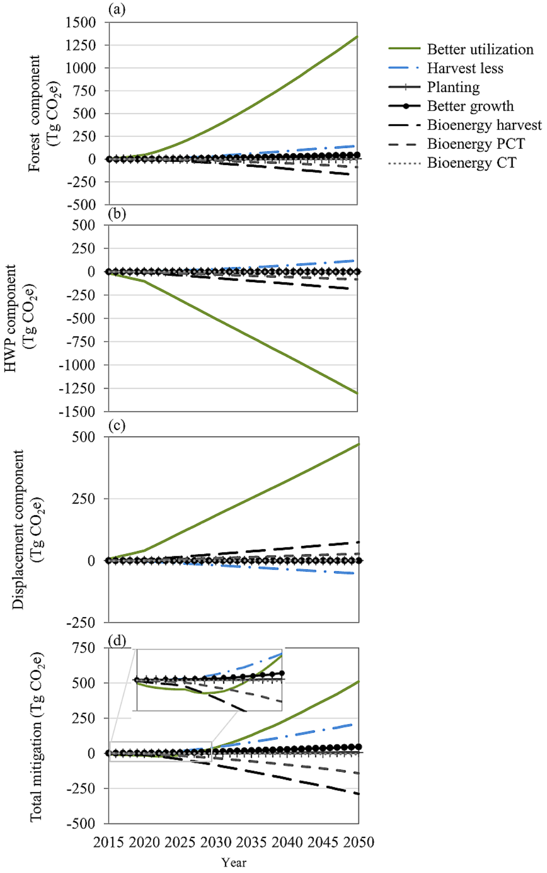

Fig. 2. National cumulative mitigation timeseries for seven forest management strategies for the **(a)** forest component, **(b)** HWP component, **(c)** displacement, and **(d)** total cumulative mitigation. The inset in **(d)** shows the 2015–2030 timeseries expanded with a ±50 Tg CO$_2$e scale. Positive mitigation denotes a reduction in emissions.

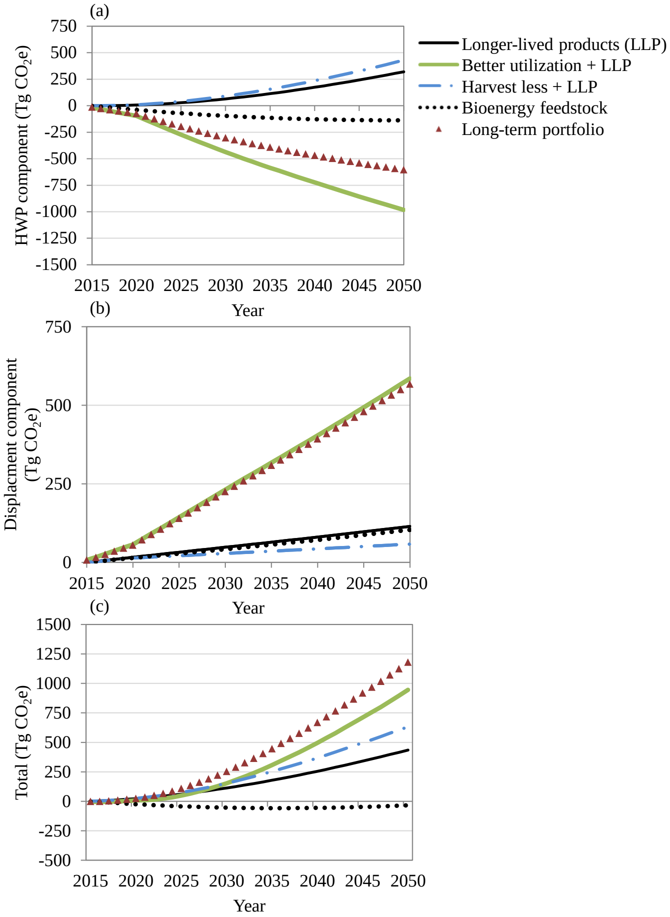

Fig. 3. National cumulative mitigation components for **(a)** HWP, **(b)** displacement and the total cumulative mitigation for two HWP strategies, two combined strategies and the portfolio mix. The forest component has already been presented in Fig. 2.

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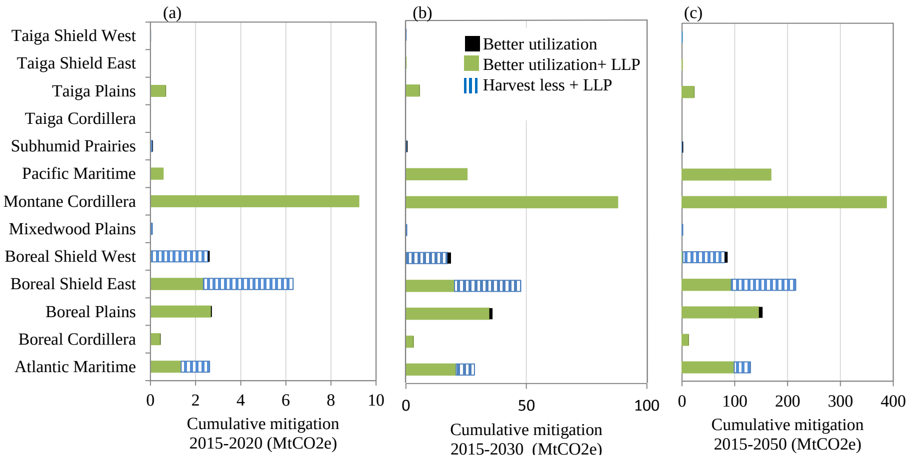

Fig. 4. Cumulative mitigation for long-term portfolio strategy mix by ecozone for **(a)** 2015 to 2020 and **(b)** 2015 to 2030, and **(c)** 2015 to 2050.

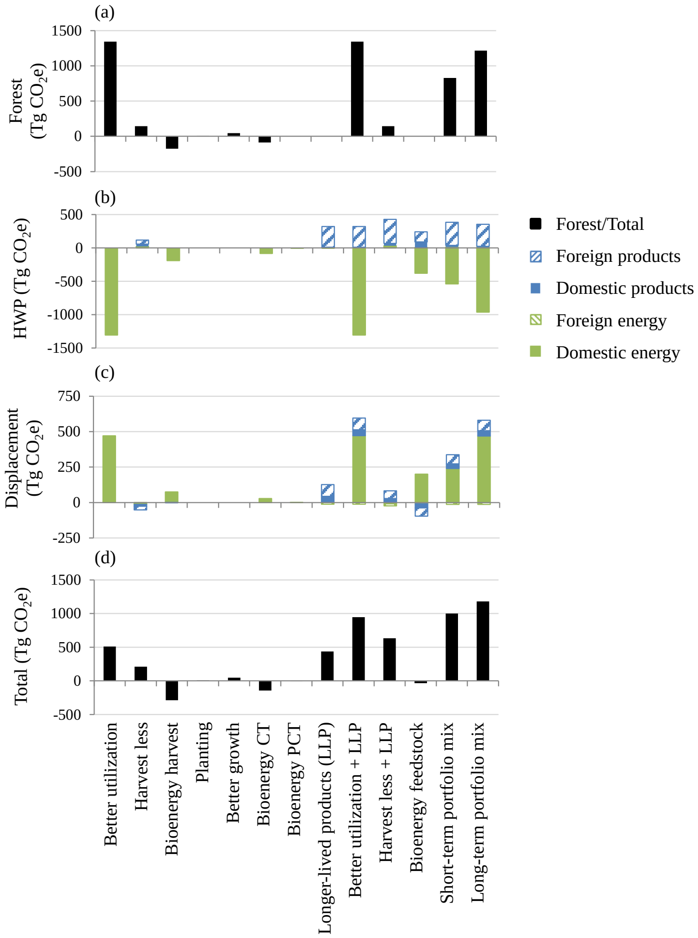

Fig. 5. Cumulative mitigation for all FM, HWP and combination strategies in 2050 by component for **(a)** forest, **(b)** HP, **(c)** displacement, and **(d)** total (sum of components).