Climate change mitigation potential of local use of harvest residues for bioenergy in Canada

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Abstract

We estimate the mitigation potential of local use of bioenergy from harvest residues for the 2.3×10^6 km^2 (232 Mha) of Canada's managed forests from 2017 to 2050 using three models: Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3), a harvested wood products (HWP) model that estimates bioenergy emissions, and a model of emission substitution benefits from the use of bioenergy. We compare the use of harvest residues for local heat and electricity production relative to a base case scenario and estimate the climate change mitigation potential at the forest management unit level. Results demonstrate large differences between and within provinces and territories across Canada. We identify regions with increasing benefits to the atmosphere for many decades into the future and regions where no net benefit would occur over the 33-year study horizon. The cumulative mitigation potential for regions with positive mitigation was predicted to be 429 Tg CO$_2$e in 2050, with 7.1 TgC yr^{-1} of harvest residues producing bioenergy that met 3.1% of the heat demand and 2.9% of the electricity demand for 32.1 million people living within these regions. Our results show that regions with positive mitigation produced bioenergy, mainly from combined heat and power facilities, with emissions intensities that ranged from roughly 90 to 500 kg CO$_2$e MWh^{-1}. Roughly 40% of the total captured harvest residue was associated with regions that were predicted to have a negative cumulative mitigation potential in 2050 of -152 Tg CO$_2$e. We conclude that the capture of harvest residues to produce local bioenergy can reduce GHG emissions in populated regions where bioenergy, mainly from combined heat and power facilities, offsets fossil fuel sources (fuel oil, coal and petcoke, and natural gas).

Keywords: bioenergy, Canada's managed forest, Carbon Budget Model of the Canadian Forest Sector, climate change mitigation, GHG emissions, harvest residues

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Introduction

Global efforts to reduce the rate of increase in atmospheric greenhouse gas (GHG) concentrations require both a reduction in GHG emissions and an increase in removals of carbon dioxide (CO$_2$) from the atmosphere. It is anticipated that global bioenergy production will increase (IPCC, 2011) and there is significant interest in promoting bioenergy use to meet national and international GHG emission reduction goals (e.g. DECC, 2012, O'Neill, 2012). In Canada, there are national and provincial/territorial emission reduction targets for 2020 and 2030 (Government of Canada 2013, 2015), to which bioenergy production could contribute.

In this analysis, we estimate the climate change mitigation potential of local (i.e. forest management unit) use of bioenergy in Canada from harvest residues.

Earlier bioenergy studies have used a variety of methodologies to examine the biophysical potential, generally related to specific activities at smaller scales (Valente *et al.*, 2011; Domke *et al.*, 2012; Repo *et al.*, 2012; Röder *et al.*, 2015), but few studies have attempted to determine national mitigation potential (Werner *et al.*, 2010; Whittaker *et al.*, 2011; Lundmark *et al.*, 2014). Determination of the mitigation potential of forest-derived products 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; Obersteiner *et al.*, 2010; White, 2010; Lemprière *et al.*, 2013). The assumption that bioenergy is 'carbon neutral' (i.e. that it has no net GHG emissions) must be avoided, and bioenergy emissions must be estimated quantitatively. We previously examined harvest of live trees for bioenergy (Smyth *et al.*, 2014), but did not find this strategy to be effective for mitigation, which is consistent with other studies (Colombo *et al.*, 2005; Ralevic *et al.*, 2010; McKechnie *et al.*, 2011;

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Ter-Mikaelian *et al.*, 2015), although it could have potential in remote communities where fossil fuels are transported over long distances. Harvest residues for bioenergy have also been examined previously, and this feedstock source had a higher mitigation potential than harvest of live trees because there is no forgone sequestration to consider. If residues are not used for bioenergy, they would progressively decay over time, or be burned for fuel hazard management.

In this analysis, we consider bioenergy from harvest residues using a systems approach to determine mitigation potential by considering the forest ecosystem, harvested wood products (HWP), bioenergy emissions, and displaced emissions when bioenergy is substituted for other energy sources. Displaced emissions considered the local jurisdictional-average heat and electricity fuel mix including, where available, the fuel mix of remote (off-grid) communities. The electricity infrastructures of Canadian off-grid remote communities are diverse and vary depending on access to energy resources, remoteness of location, and impact of climate. However, with the exception of a few local hydro grid-tied communities, the vast majority of remote communities across Canada rely on diesel generators for the production of electricity (Royer, 2011). We compared the emissions associated with capturing and burning harvest residues locally for bioenergy (converted to heat and/or electricity) to the alternate scenario of *in situ* decay and/or slashburning (Fig. 1) to determine whether the use of captured harvest residues resulted in a net reduction of GHG emissions from the forest and energy sector over the 2017-to-2050 period.

Recognizing that the use of harvest residues may not result in a decrease in GHG emissions in all locations, our first objective was to identify regions where local use of forest-derived bioenergy from harvest residues results in positive mitigation. The second objective was to determine the time it takes to reach the break-even point (*i.e.* the point at which the fossil and bioenergy sources have the same impact on the atmosphere) for regions where there is a reduction in GHG emissions. This is an important indicator because bioenergy does not have to be C neutral (*i.e.* C uptake in the forest offsets the emissions from burning the biomass for energy) to achieve a mitigation benefit; it just has to generate fewer emissions than the base case energy source. For example, emissions from bioenergy include the emissions from bioenergy burning [112 kg CO_2e GJ^{-1} based on the IPCC default value (Gómez *et al.*, 2006)] and the forgone release of C from decay and/or slashburning. These are compared to fossil fuel emissions which range from 56.1 to 94.6 kg CO_2e GJ^{-1} depending on the fossil fuel type (IPCC default values). The time at which the break-even point is reached is important, because early
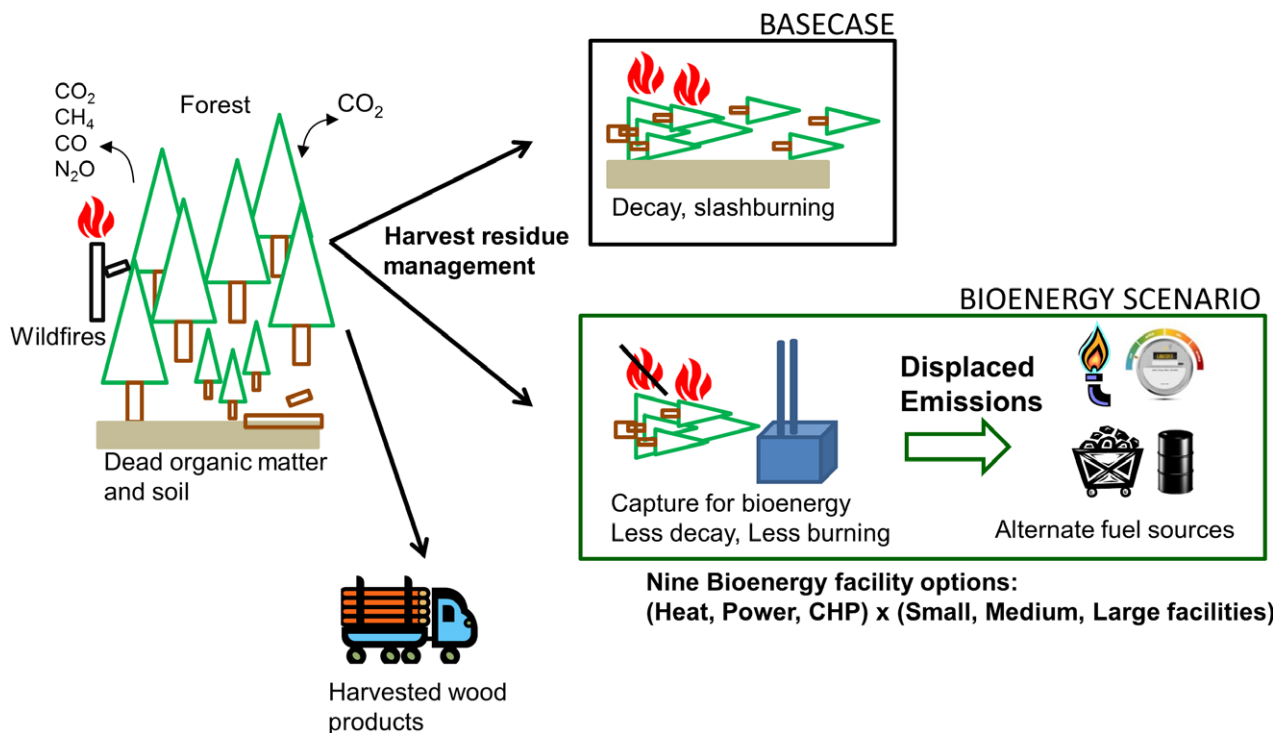

Fig. 1 Schematic of C flows in the *Base Case* and *Bioenergy Scenario*. The *Bioenergy Scenario* differs from the *Base Case* forest management assumptions by reducing slashburning (where applicable) and utilizing harvest residues for bioenergy.

emission reductions contribute to achieving emission reduction targets and limit future climate change. Our third objective was to determine what proportion of the national heat and electricity demand could be produced from bioenergy derived from harvest residue for regions with positive mitigation.

This study is the first comprehensive integrated analysis of the climate change mitigation potential for bioenergy from captured harvest residues for Canada's managed forest. It builds on the integrated analysis of the climate change mitigation potential for Canada's managed forest for seven forest management strategies and two harvested wood products strategies examined in Smyth *et al.* (2014). Comparisons are made to the results from the earlier analyses to assess the mitigation potential for bioenergy from harvest residues relative to three strategies: increasing the longevity of HWPs, better utilization that alters forest management practices, and harvesting less. Results from this national study can be used to inform bioenergy policy decisions. There are currently no federal regulations on minimum contributions from forest biomass and only two regulations for biofuels: fuel producers and importers must have an average renewable content of at least 5% based on the volume of gasoline and at least 2% of average renewable content based on the volume of diesel fuel and heating distillate oil (Environmental Protection Act Bill C-33, 2008).

Materials and methods

Greenhouse gas emissions from the forest ecosystem and HWP are based on the same models and data sets used to produce estimates for Canada's GHG National Inventory Report (NIR2014). We used the same forest management units (FMUs), Fig. S1, and the same historical (1990–2012) assumptions for harvests, wildfire, insects, deforestation and afforestation (Environment Canada, 2014). We chose these frameworks and data sets because they are well documented, the models and data sets have been peer-reviewed, and methods for estimating forest GHG emissions and removals have been reviewed, refined and revised as part of the annual National Inventory Reporting process since 2004.

Base case and bioenergy scenarios

Our analysis examined how changes in Canada's forest sector activities could reduce GHG emissions relative to a base case. The *Base Case* was defined as forest management (FM) activity levels and energy use that would occur in the absence of mitigation activity. In the *Bioenergy Scenario*, a proportion of the harvest residues (which varied by province and territory, Table 1) was recovered and used for bioenergy instead of decaying or being burned, starting in 2017.

In the rest of the time period, 2013–2050, both scenarios included the same wildfire and harvest projections for each

Table 1 Indicators for the *Base Case* and *Bioenergy Scenario*. Some parameters have ranges, indicating that implementation varied by jurisdiction

Scenario	Residue recovered* (%)	Residue recovered (Tg C yr^{-1})	Slashburning (% of harvested area)
Base Case	0–10	1.0	0–50
Bioenergy Scenario	25–60	11.9	0–30

*Per cent of harvest residues recovered for bioenergy feedstock.

FMU. Projected annual burned-areas for wildfire were estimated for each FMU from the historical burned area averaged from 1990 to 2012. Future harvest volumes were based on information provided by provincial and territorial government experts in response to detailed questionnaires (personal communications, February 2014). Future spatial allocation of projected harvesting within a jurisdiction was estimated from historical (2000–2011) disturbance change information in 250-m resolution remotely-sensed products (Guindon *et al.*, 2014) overlain with FMU boundaries. These estimates of harvest area were weighted by C harvest density to convert area allocations into the volume allocations required for modelling. The density factor took into account C density in the FMU and was estimated from average harvested merchantable C per hectare over the historical period (1990–2012), normalized to one for each jurisdiction. For the province of British Columbia, a different method was used because the impact of mountain pine beetle has significantly influenced the historical harvest allocation: future spatial harvest allocation was based on the forecast of future Allowable Annual Cut (AAC) levels (http://www.for.-gov.bc.ca/hts/aactsa.htm, Accessed May 2014).

Clearcut harvesting assumed utilization rates of 85–97% of the merchantable stem biomass present at the time of harvest, with the remainder left on site as logging residue along with trees below merchantable size. In the *Base Case*, most of harvest residues progressively decayed over time, but in some regions harvest residues are piled and burned for fuel hazard management or a small amount is captured for bioenergy. In the *Bioenergy Scenario*, up to 60% of harvest residues are captured for bioenergy (depending on the province/territory) and slashburning activities are reduced or stopped. Additional details on model assumptions are found in Table S2.

We assumed that emissions associated with local (within FMU) transportation of harvest residues were roughly the same as those associated with transportation of base case fuels. We did not consider global climate change impacts on forest growth, decomposition, or disturbance regimes.

Analytical frameworks

The system boundary of the analysis included FM, HWPs, bioenergy, and corresponding fossil emissions displaced in the energy sector. We assessed 634 FMUs and identified 502 where harvest activity could support bioenergy production.

Forest ecosystem C dynamics

Forest ecosystem C dynamics were analysed using the National Forest Carbon Monitoring, Accounting and Reporting System (NFCMARS) data sets 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 data sets 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 included stand attributes (age, species types) and merchantable volume yield tables for each of the hardwood (broadleaf) and softwood (coniferous) components. CBM-CFS3 tracks C stocks in ten biomass pools (hardwood and softwood versions of merchantable stemwood, foliage, coarse roots, fine roots, and 'other' which includes branches and non-merchantable-sized trees), 11 dead organic matter pools (which include woody litter, the soil organic horizon and mineral soil), and emissions of carbon dioxide (CO_2), methane (CH_4), carbon monoxide (CO) from slashburning and wildfires. Nitrous oxide (N_2O) is also included, using an emissions factor that is applied to the CO_2 emissions resulting from burning. Additional background information on forest ecosystem modelling is in the Supplementary Information.

Harvested wood-product emissions

Carbon Budget Model of the Canadian Forest Sector outputs describing the quantities of C transferred to HWPs and bioenergy were inputs to the Carbon Budget Modelling Framework for Harvested Wood Products (CBMF-HWP), an analytical tool that tracks the fate of harvested C through manufacturing, use, and end-of-life treatment. All emissions associated with forest C harvested in Canada were tracked in the analysis using the production approach, irrespective of whether the HWPs were exported, in keeping with internationally agreed upon approaches for HWP C accounting (IPCC, 2014), and are consistent with the 2014 National Inventory Report (Environment Canada, 2014). HWP commodity and postconsumer parameters (Table S2) were the same for both scenarios and therefore HWPs other than bioenergy had no impact on mitigation potential. Bioenergy production from captured harvest residues was also tracked in the CBMF-HWP, and these emissions were higher in the *Bioenergy Scenario*.

Displaced emissions

Displaced emissions are defined as emissions that would have occurred if *Base Case* energy sources had been used. Displaced emissions were estimated by multiplying the captured harvest residues by a regionally determined displacement factor for each FMU. The displacement factor was estimated for each FMU by selecting the type, size and number of bioenergy facilities that maximized displaced emissions based on the (1) available harvest residues, (2) regional energy consumption, and (3) *Base Case* fuel mix. See Smyth *et al.* (2016) for a complete description of the displacement factor estimates.

Base Case energy sources for electricity were from projected energy sources (Table S3) for each province/territory (National Energy Board, 2013) and sources of heat were from contemporary (2012) energy sources (Office of Energy Efficiency, 2015) because projections were not available. For FMUs that contained a remote community, the regional fuel mix was estimated from the provincial or territorial average and then adjusted to include the contemporary remote community fuel mix using to a weighted-proportion of the population of the remote community and regional population (Natural Resources Canada, 2014). Remote communities are defined as those that are not connected to an electricity grid and that therefore have a different fuel mix than the jurisdictional-average fuel mix.

Energy consumption for heat and electricity was estimated from each jurisdiction's per capita energy use and contemporary population estimates from census data (Statistics Canada, 2011).

We assumed that all captured harvest residues were first used within their FMU to produce heat and electricity to meet local demand, which was estimated from per capita use multiplied by the population within the FMU. Heat production was constrained to local demand, and any excess harvest residues (beyond that needed for local demand) were consumed to generate grid electricity which was assumed to displace the average electricity fuel mix.

The nine bioenergy facilities included three different types of facilities (heat, power, and combined heat and power) and three different sizes of facilities, ranging from 200 kW turbines to a 10 MWh steam cycle power facility, Table 2. These facilities were selected for analysis because they cover a wide range of heat and power production scales, and because information was available on annual fibre demand and operating and capital costs for these facilities.

Mitigation indicators

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

$$M = E_{Base} - E_{BioE}, \tag{1}$$

where M is the mitigation, E_{Base} is the *Base Case* emissions, and E_{BioE} is the *Bioenergy Scenario* emissions. Evaluating the mitigation scenario relative to the *Base Case* in this way and applying *Base Case* and the mitigation scenario to the same forest inventory data factors out age-class legacy effects (Böttcher *et al.*, 2008) on contemporary C dynamics. Simulating the same base level of natural disturbance in the *Base Case* and the *Bioenergy Scenario* also causes the impacts of natural disturbances assumed to occur from 2013 onward to be almost completely factored out, with slight differences caused by interactions between forest management and natural disturbance activities.

Total emissions in both the *Base Case* (E_{Base}) and the *Bioenergy Scenario* (E_{BioE}) were estimated as the sum of emissions from three components:

$$E = E_{Forest} + E_{HWP} - E_{Displaced}, \tag{2}$$

where E_{Forest} is GHG removals from the forest due to C uptake and the emissions from the forest due to heterotrophic decay

Table 2 Bioenergy facilities description adapted from Smyth *et al.* (2016)

Facility type	Facility description	Biomass delivered (odt)	Electrical conversion rate (kWh odt^{-1})	Thermal conversion rate (kWh odt^{-1})	Assumed electrical efficiency (%)	Assumed thermal efficiency (%)	Böttcher overall efficiency (%)
Heat	0.4 MWth boiler for district heating*	783	–	15.00	–	75	75
	2.3 MWth boiler for district heating*	3974	–	17.00	–	85	85
	6.62 MWth process heat via syngas†	11 576	–	16.80	–	84	84
Power	0.2 MWe gas turbine‡	1600	1020	–	18	–	18
	5 MWe steam cycle†	34 971	1167	–	21	–	21
	10 MWe steam cycle†	63 861	1278	–	23	–	23
CHP	0.2 MWe, 0.98 MWth organic rankine cycle§	2098	778	14.00	14	70	84
	1.8 MWe, 4.5MWth steam turbine¶	10 575	1389	10.80	25	54	79
	8 MWe CHP steam turbine†	46 870	1393	5.88	25	29	54

*RETScreen International (2015).
†Biopathways (2015).
‡Arena *et al.* (2010).
§Wood & Rowley (2011).
¶Pröll *et al.* (2011).

and disturbances; E_{HWP} is emissions from bioenergy produced from harvest residues, bioenergy from harvested roundwood, and postconsumer emissions; and $E_{Displaced}$ is the emissions displaced by substituting bioenergy for alternate fuel sources.

Indicators included projections of future harvest residue availability for bioenergy from 2017 to 2050 for each FMU, identification of FMUs where there is a positive mitigation benefit of using residues for bioenergy, and identification of the point in time at which this positive benefit begins to occur (i.e. the 'break-even' point). After the break-even point, continuing to displace the *Base Case* energy sources results in a net GHG emission reduction.

Break-even points were also estimated based on a cumulative radiative forcing indicator which considers the temporal dynamics of atmospheric CO_2. We use the method by Sathre & Gustavsson (2011), where the atmospheric decay of each annual pulse emissions is estimated as

$$(CO_2)_t = (CO_2)_0 \left[0.217 + 0.259e^{\frac{-t}{172.9}} + 0.338e^{\frac{-t}{18.51}} + 0.186e^{\frac{-t}{1.186}} \right], \quad (3)$$

where t is the number of years since the pulse emissions, $(CO_2)_0$ is the mass of CO_2 emitted at year 0 for the *Base Case* minus the *Bioenergy* scenario, and $(CO_2)_t$ is the mass of CO_2 remaining in the atmosphere at year t. The total change in atmospheric mass of CO_2 for each year of the study period is then determined by summing the emissions occurring during that year plus the emissions of all previous years minus their decay during the intervening years.

The change in atmospheric mass of CO_2 is then converted to change in atmospheric concentration, based on the molecular mass of CO_2 (44.0095 g mol^{-1}), the molecular mass of dry air

(28.95 g mol^{-1}), and the total mass of the atmosphere (5.148 × 10^{21} g). Annual changes in instantaneous radiative forcing due to the CO_2 concentration changes are then estimated using

$$F_{CO_2} = \frac{3.7}{\ln 2} \ln \left[1 + \frac{\Delta CO_2}{CO_{2R}} \right], \quad (4)$$

where F_{CO_2} is instantaneous radiative forcing in W m^{-2}, ΔCO_2 is the change in atmospheric concentration of CO_2 in units of ppmv, and the reference concentration, CO_{2R}, is 383 ppmv. Positive radiative forcing tends to warm the earth's surface, while negative radiative forcing tends to cool it. We then estimate the cumulative radiative forcing (CRF) occurring each year in units of W-s m^{-2}, by multiplying the instantaneous radiative forcing of each annual period by the number of seconds in a year and determine the break-even point, after which there is a net reduction in the cumulative radiative forcing.

Sensitivity analysis

A sensitivity analysis was performed to assess the change in cumulative mitigation potential by omitting the remote community fuel mix and assuming higher efficiencies in bioenergy conversion resulting in different displacement factors. These sensitivity runs were modelled using two different sets of displacement factors. In the first case, the remote community fuel mix was omitted, and the jurisdiction-average fuel mix was assumed in all FMUs. In the second case, a set of nine generic bioenergy facilities with higher energy conversion efficiencies and different facility sizes (Table S4) was used to determine displacement factors for the sensitivity analysis.

Results

Results are presented include (1) national-level stocks and flows that are spatially and temporally averaged, (2) national-level emissions time series that are spatially averaged, and (3) FMU-level mitigation indicators that are temporally averaged.

Averaged stocks and flows

National-scale estimates of average stocks and flows are shown in Fig. 2 for the *Base Case* and *Bioenergy Scenarios*.

Most of the C is stored in dead organic matter, with 71.8% of the total C stocks in litter, dead wood, and soil. Live biomass storage accounts for 27.1% of the total C stock, and 1.2% is contained within HWPs that have been harvested since 1990 and are in use.

The largest C flows in the system are part of the annual cycle of uptake of C from the atmosphere, turnover of biomass stocks, and release of C through heterotrophic respiration (consistent with Stinson *et al.*, 2011). Smaller disturbance emissions are found for wildfires and slashburning. HWP flows release C to the atmosphere from instant oxidation of postconsumer products
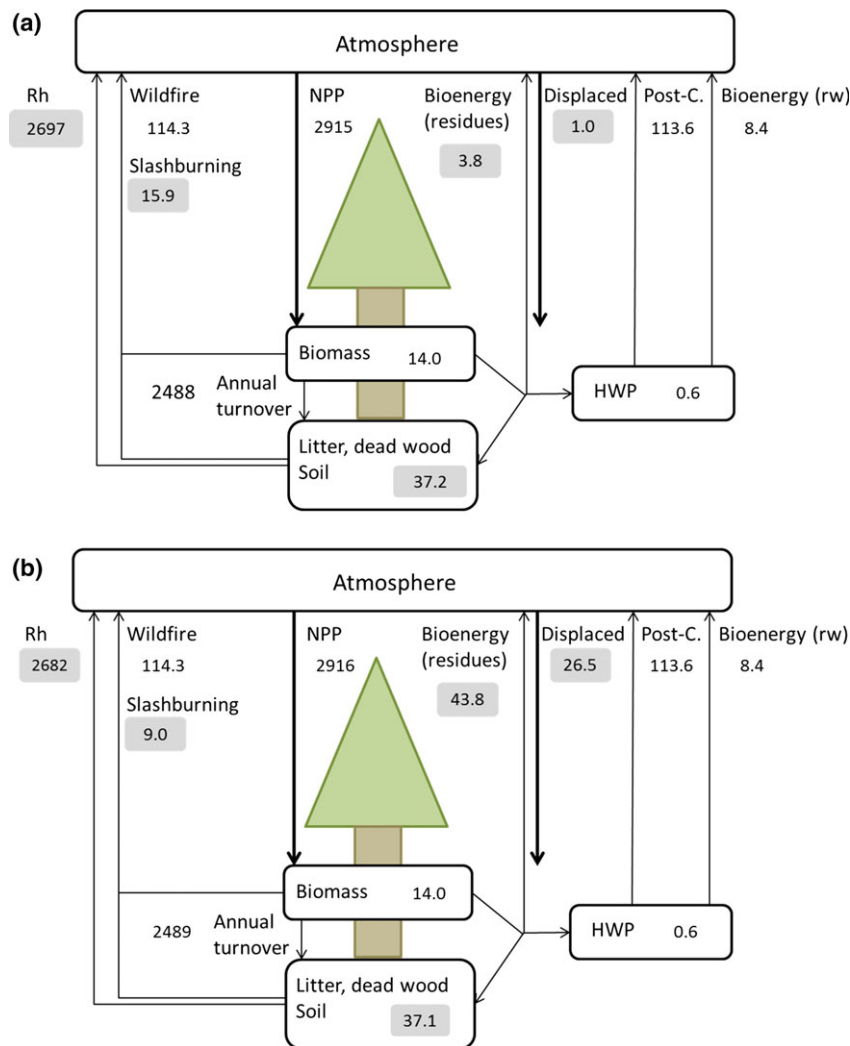

Fig. 2 Stocks and flows temporally averaged over 2017–2050 for Canada's 2.3×10^6 km^2 managed forest in the (a) *Base Case* and (b) *Bioenergy Scenario*. Changes in forest management activities affect certain stocks and flows (grey boxes). Stocks for biomass, dead organic matter (litter, dead wood, and soil), and in-use harvested wood products (HWP) are in PgC. Annual flows, in TgCO$_2$e yr^{-1}, show uptake of C through net primary productivity (NPP), transfer of C through annual turnover, and release of C through heterotrophic respiration (Rh). Release of C also occurs as a result of disturbances and through release of C from postconsumer HWP (Post C.) and bioenergy from roundwood (rw). Emissions from wood harvested before 1990 are not included. Harvest transfers an average of 41.5 TgC yr^{-1} (152.2 TgCO$_2$ yr^{-1}) from live biomass and dead organic matter to harvested wood products.

and mill residues, and bioenergy production from harvest residues and roundwood.

The *Base Case* and *Bioenergy Scenarios* differ in the treatment of harvest residues which affects emissions related to bioenergy and slashburning, heterotrophic respiration, and dead organic matter stocks. In the *Base Case*, harvest residues are either (1) piled and burned, and most of the C is instantly released to the atmosphere, or (2) left in the forest to progressively decompose, and most of the C is released to the atmosphere more slowly over time or incorporated into the soil as more stable C compounds. In the *Bioenergy Scenario*, harvest residues are used to produce bioenergy, and carbon that would have been gradually released from the dead wood and litter pools or stored in the soil is released immediately to the atmosphere. The *Bioenergy Scenario* has lower heterotrophic respiration, lower dead organic matter stocks (dead wood, litter and soil), and lower slashburning emissions relative to the *Base Case*, for regions where slashburning is present (Table S2).

Harvest transfers an average of 41.5 TgC yr^{-1} (152.2 $TgCO_2$ yr^{-1}) from live biomass and dead organic matter from 2017 to 2050. In the *Bioenergy Scenario*, an average of 11.9 TgC yr^{-1} of harvest residues are used for bioenergy, and the displaced emissions from using bioenergy in place of another energy source are 28.6 $TgCO_2e$ yr^{-1}.

The *Base Case* includes a small amount of harvest residues used for bioenergy and small associated displaced emissions, but these emissions are also contained in the *Bioenergy Scenario* and therefore cancel out of the mitigation estimate.

Mitigation timeseries

Timeseries of emissions/removals associated with forest, HWP, and displaced emissions components are shown in Fig. 3a for both scenarios. Emissions/removals associated with growth, transfer, decay, and disturbances (including wildfires and slashburning) are contained within the forest component.

During the historical period, the forest ecosystem shows large fluctuations in emissions and removals due to the impacts of natural disturbances (large and intermittent wildfire activity and mountain pine beetle epidemic from 2000 to 2010 (Kurz *et al.*, 2008; Stinson *et al.*, 2011)).

For the future period, forest ecosystem removals are enhanced in the *Bioenergy Scenario* relative to the *Base Case* due to lower slashburning emissions and lower heterotrophic respiration. Bioenergy emissions, product emissions, and postconsumer product emissions are included in the HWP component. HWP emissions are
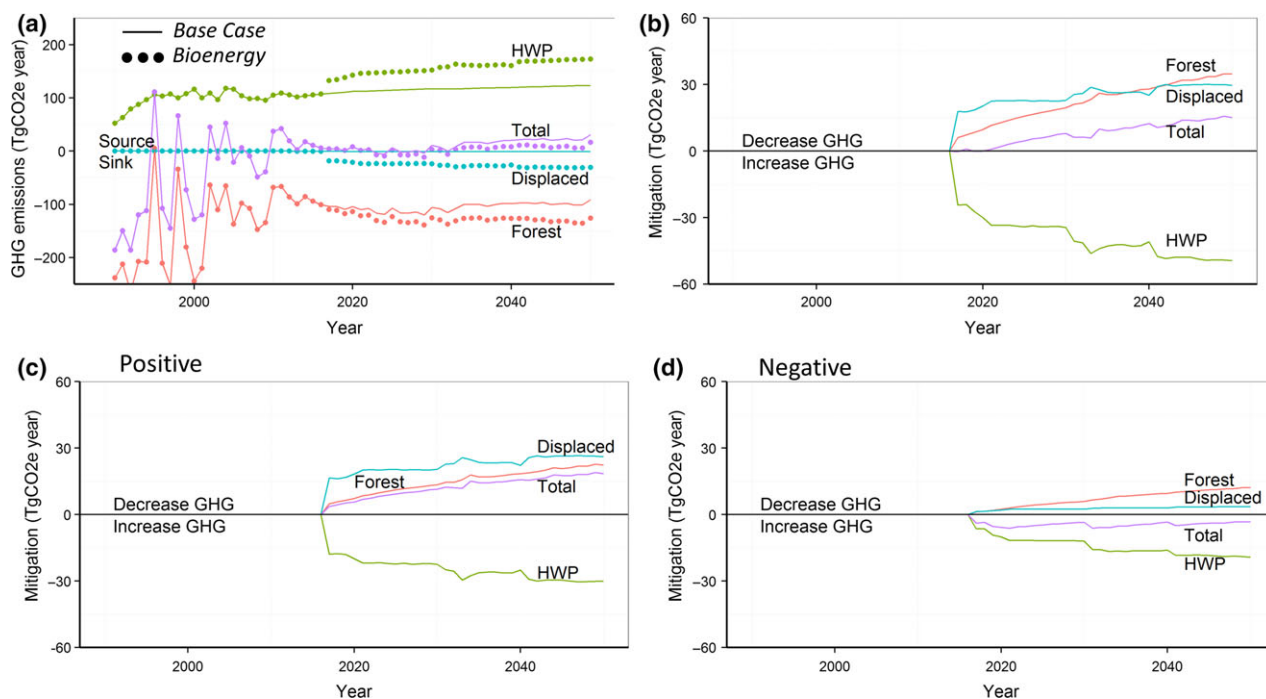

Fig. 3 Time series of (a) net GHG emissions/removals from the forest ecosystem, HWP emissions including bioenergy, displaced emissions and the total emissions for the *Base Case* and *Bioenergy Scenarios*, and (b) total climate change mitigation potential for all FMUs and the contribution from each component. Time series of the total and components for (c) FMUs with positive mitigation in 2050, and (d) FMUs with negative mitigation in 2050.

higher in the *Bioenergy Scenario* relative to the *Base Case* because of the capture and burning of harvest residues for bioenergy. The timeseries show a stepwise increase in HWP emissions due to a stepwise increase in proportion of harvest residues captured. Displaced emissions also show a stepwise increase over time and represent a reduction in emissions to the atmosphere. Total emissions are a small source of GHG emissions to the atmosphere of 11.5 TgCO$_2$e yr^{-1} for the *Base Case* and a smaller source of 3.4 TgCO$_2$e yr^{-1} for the *Bioenergy Scenario*, on average from 2017 to 2050.

The potential mitigation time series was obtained by subtracting the *Bioenergy* emissions/removals from the *Base Case*, Fig. 3b. The increase in emissions associated with production of bioenergy from harvest residues was offset by enhanced removals in the forest ecosystem and displaced emissions, resulting in an overall positive mitigation potential which increased over time. Of the 502 FMUs contained in the overall mitigation estimate, 278 had a positive cumulative mitigation (reduction in emissions relative to the *Base Case*) in 2050 and 224 FMUs had an increase in emissions (negative mitigation), resulting from increased use of harvest residues for bioenergy, Fig. 3c, d and Table 3.

Mitigation indicators for FMUs

We examined patterns of captured harvest residues, energy demand, displacement factors, and total cumulative mitigation potential to understand the spatial distribution of FMUs with positive and negative mitigation (Fig. 4). Captured harvest residues depend on assumptions about the proportion of harvest residues that can be extracted for bioenergy for each province or territory (See Supplementary Information), the allocation of future harvest within each jurisdiction, and the characteristics of the forest. For most jurisdictions, captured harvest residues are found in the northern and central regions of the managed forest (Fig. 4a), whereas energy demand, using population density as a proxy, is concentrated in the southern part of the jurisdictions (Fig. 4b). Results show that captured harvest residues and energy demand are not always co-located and the potential for bioenergy production exceeds local heat and electricity demand in many FMUs with small populations. Displacement factors (Fig. 4c) estimated from the displaced emissions resulting from the substitution of the suite of bioenergy facilities varied widely between 0 and 1.8 tonnes of C displaced per tonne of biogenic C utilized (tC/tC), with an average value of 0.5. Displacement factors

Table 3 Summary information for forest management units (FMUs) with positive and negative cumulative mitigation in 2050

Description	Positive mitigation		Negative mitigation	
Number of included FMUs	278		224	
Residues captured for bioenergy (Tg C yr^{-1})	7.1		4.8	
Total population (millions)	32.1		0.2	
Remote community population (thousands)	103.9		0	
Forest area ($\times 10^6$ km^2)	1.4		0.8	
Cumulative mitigation (TgCO$_2$e)	2020: 21.2			
			2020: −20.5	
	2030: 115.7			
			2030: −67.1	
	2040: 255.1			
			2040: −114.2	
	2050: 429.1			
			2050: −152.5	
Average break-even time (years)	6.2		−	
Heat demand met by bioenergy (% of local demand)	3.1		77.8	
Power demand met by bioenergy (% of local demand)	2.9		308.6	
Displaced energy fuel mix (total 100%)	Heat		Heat	
	Fuel Oil	23	Fuel Oil	3.6
	Coal and Petcoke	18.1	Coal and Petcoke	4.8
	Natural Gas	17.1	Natural Gas	17.1
	Electricity	9.4	Electricity	3.9
	Electricity		Electricity	
	Grid	12.6	Grid	63.8
	Natural Gas	8.7	Natural Gas	1.8
	Coal	7.7	Coal	0.7
	Diesel	1.7	Diesel	0.3

(a)
Average captured residues
(m³ yr⁻¹)

(b)
**Population density as
proxy for energy demand**
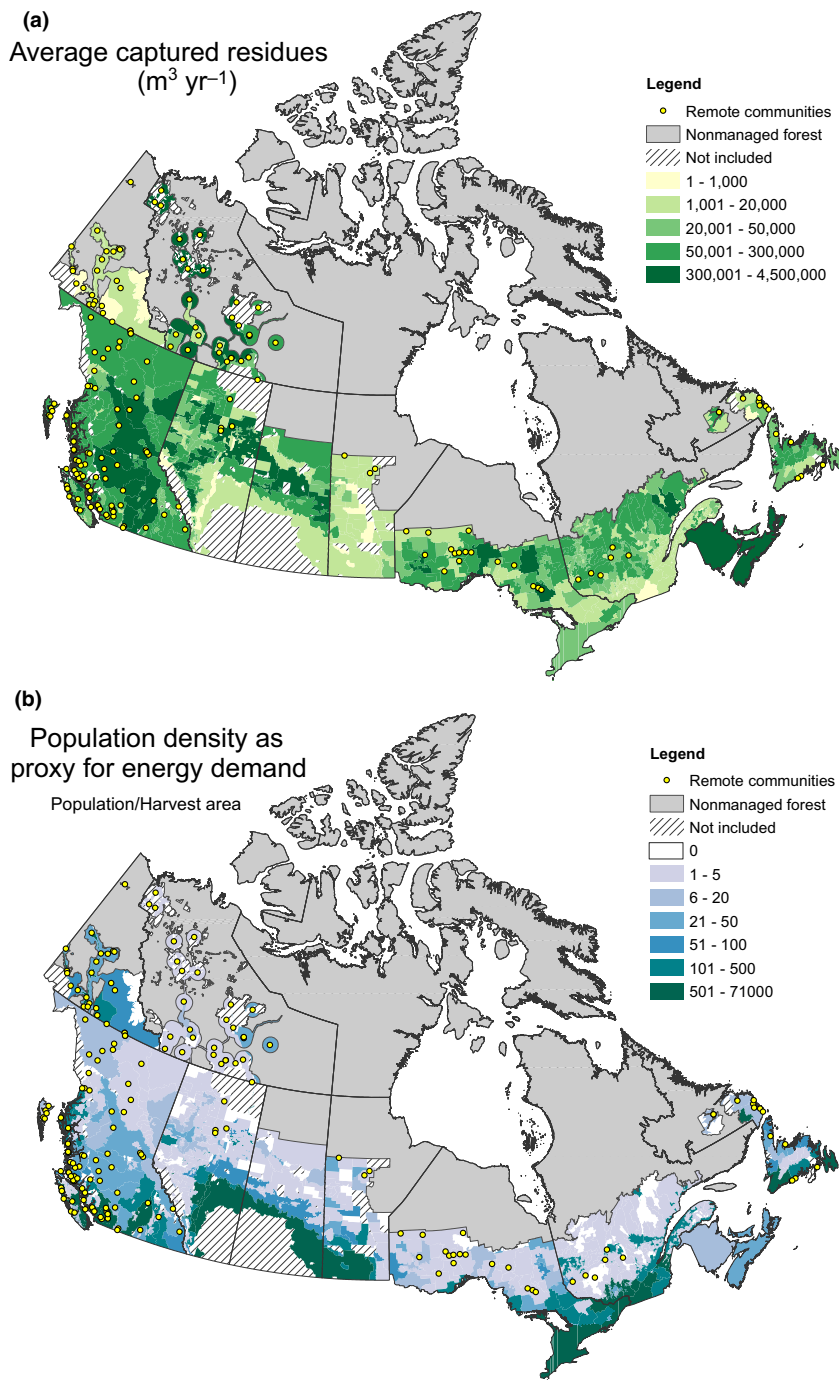Population/Harvest area

Fig. 4 Maps of average captured residues between 2017 and 2050, population density as a proxy for energy demand, displacement factor, and national cumulative mitigation from 2017 to 2050. Only local use of bioenergy was considered, with heat production constrained by local demand, and excess bioenergy exported to the electricity grid.

varied between and within jurisdictions, and depended upon the *Base case* fuel mix, the energy conversion efficiency, and the local energy demand. Low displacement factors were found in regions where bioenergy exceeded local demand, and excess residues were converted to electricity and subsequently used to displace grid electricity produced by low-emission sources (predominantly hydro-electricity). High-displacement factors were found in regions (such as the Atlantic maritime and Boreal plains ecozones) where bioenergy displaced high-emissions fossil fuel sources (coal and fuel oil).
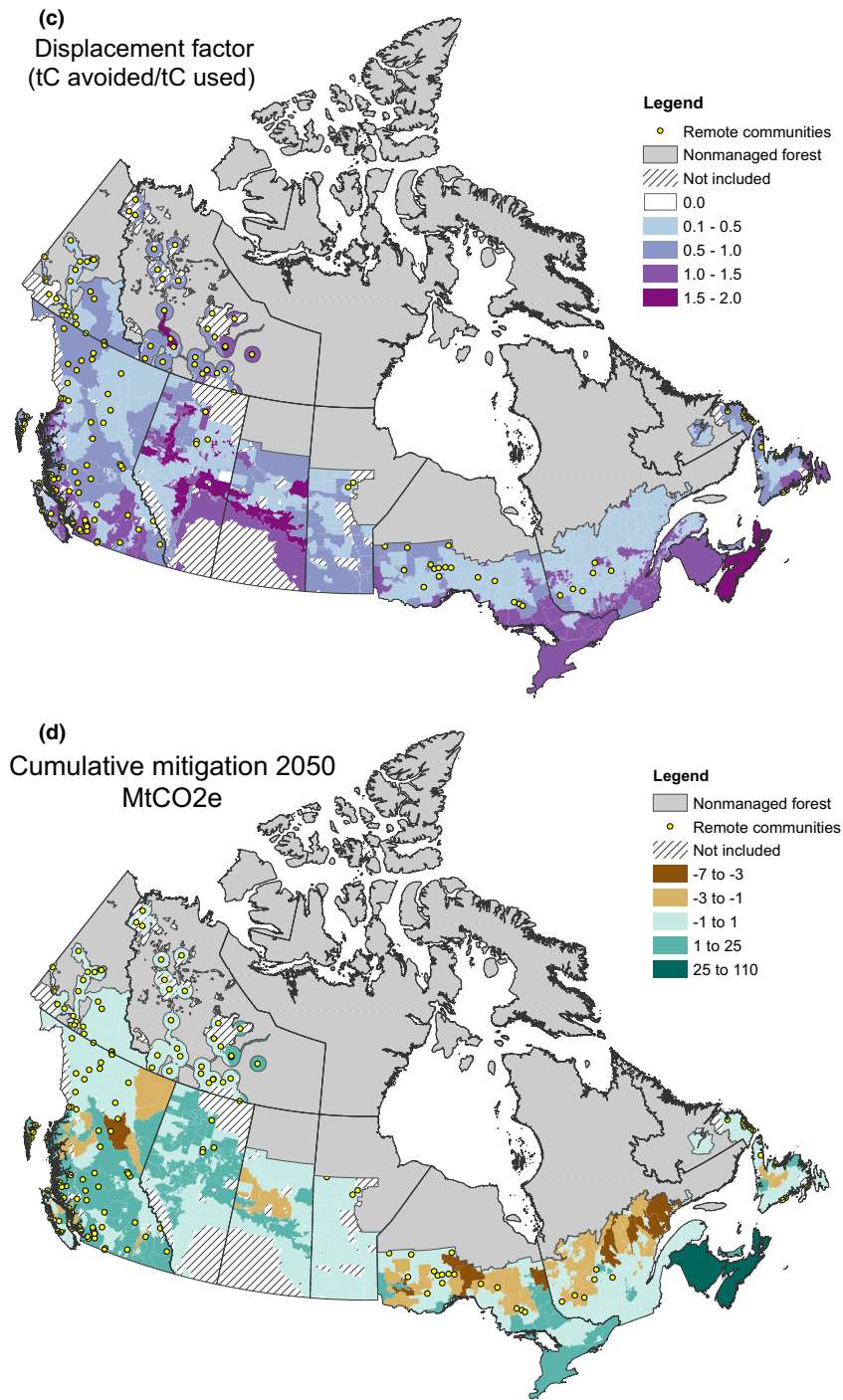
(c)
Displacement factor
(tC avoided/tC used)

Legend
- Remote communities
- Nonmanaged forest
- Not included
- 0.0
- 0.1 - 0.5
- 0.5 - 1.0
- 1.0 - 1.5
- 1.5 - 2.0

(d)
Cumulative mitigation 2050
MtCO2e

Legend
- Nonmanaged forest
- Remote communities
- Not included
- -7 to -3
- -3 to -1
- -1 to 1
- 1 to 25
- 25 to 110

Fig. 4 Continued.

The cumulative mitigation from 2017 to 2050 is shown in Fig. 4d. Regions with positive cumulative mitigation (*i.e.* net reduction in GHG emissions to the atmosphere) generally produced less bioenergy than local energy demand and displaced high-emissions fossil fuels. There are many regions where the cumulative mitigation was negative, indicating the use of harvest residues for bioenergy increased GHG emissions to the atmosphere. These regions corresponded to regions where bioenergy production exceeded local demand and displaced emissions were low because excess bioenergy displaced a low-emission electricity-grid mix. The

total national cumulative mitigation from 2017 to 2050 was 429 TgCO$_2$e for the 278 regions with positive mitigation potential (Table 3). This contribution came from 1.4×10^6 km^2 of managed forest in which 7.1 TgC yr^{-1} of harvest residues (27 Mm^3 yr^{-1}) produced bioenergy that met 3.1% of the heat demand and 2.9% of the electricity demand for 32.1 million people living within these regions. The average break-even time for regions with positive mitigation was 6.2 years, with a standard deviation of 8.6 years. Many regions had break-even times of zero (43% of all regions), and the majority of regions (63%) had break-even times less than 10 years. However, 25% of the regions with positive mitigation had break-even times between 10 and 20 years.

When the timing-adjusted emissions were considered, the number of regions with positive mitigation potential dropped to 210, and the break-even times increased to 9.6 years (SD 9.5 year). However, the cumulative mitigation potential from the 210 regions was very similar to the previous estimate at 428.5 TgCO$_2$e. For many regions, the break-even time was zero, and for these regions the timing-adjusted emissions had no impact.

Mitigation sign and magnitude were significantly affected by the magnitude of the displaced emissions and was predominantly affected by the jurisdiction-average fuel mix. The emissions intensity range of the displaced energy sources ranged from 0 for hydro-, solar-, and wind-generated electricity to 1000 kg CO$_2$e MWh^{-1} for coal-generated electricity. The emissions intensity for bioenergy from residues (estimated as the bioenergy and forest mitigation potential divided by the energy produced) is compared to the displaced emissions intensity in Fig. 5. There was a wide range of emissions intensities for the harvest residues, reflecting differences in energy conversion efficiencies, number and types of facilities selected for substitution, and the alternate fate of residues in the forest (decay and/or slashburning in the *Base Case*). Regions with positive mitigation were associated with *Base Case* emissions intensities that ranged from ~200 kg CO$_2$e MWh^{-1} to 1000 kg CO$_2$e MWh^{-1}; these were displaced with *Bioenergy Scenario* emissions intensities (taking into account bioenergy and forest emissions) ranging from ~90 to 500 kg CO$_2$e MWh^{-1}. Regions with negative mitigation were associated with displaced emissions generally less than 220 kg CO$_2$e MWh^{-1}. Most of the projected electricity-grid emissions intensities (Table S3) are below this level, thus explaining why many regions have a negative mitigation when excess fibre was converted to electricity and used to displace the average grid fuel mix.

Sensitivity: impact of remote communities

The total population in remote communities was estimated at 109 366 people. Of these, the fuel mix was different from their jurisdiction average for 72 394 people in remote communities in 54 FMUs (Table S3). The impact of the remote community fuel mix was assessed
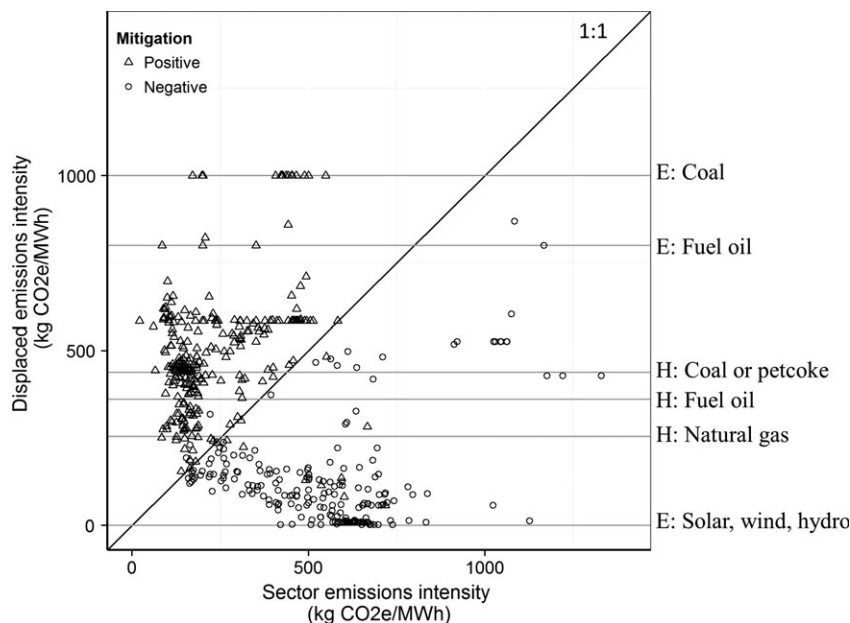

Fig. 5 Displaced emissions intensity versus the sector (Forest + HWP mitigation) emissions intensity for regions with positive mitigation and negative mitigation. Emissions intensities for alternate fuels are shown for reference.

by re-estimating the mitigation potential without the remote community fuel mix and comparing it to the previous results. Removing the fuel mix associated with remote communities decreased the total cumulative mitigation from 429 $TgCO_2e$ to 397 $TgCO_2e$ for the 278 FMUs originally estimated to have positive mitigation in 2050. Including only FMUs with positive mitigation when the remote community fuel mix was removed reduced the number of FMUs from 278 to 259 and decreased the total cumulative mitigation to 413 $TgCO_2e$.

Overall, taking remote community fuel mix into consideration increased the national mitigation potential because the fuel mix for a significant number of remote communities contained a larger proportion of higher emission fuels than the fuel mix for grid-connected communities. These results suggest that using residues for bioenergy in remote communities would result in a cumulative mitigation of 16 $TgCO_2e$, which is high considering that these communities only represent 0.3% of Canada's population.

Sensitivity: impact of bioenergy facility selection

The magnitude of the cumulative mitigation is expected to increase if energy conversion efficiency increases due to technological advances (Gustavsson *et al.*, 2015). The nine bioenergy facilities used in this analysis were selected because associated information on capital and operating costs was available that allowed us to estimate mitigation cost efficiency (Rampley *et al.*, 2016). Switching to a different set of nine types of bioenergy facilities (Table S4) with a higher conversion efficiency decreased the number of FMUs with positive mitigation from 278 to 268, which seems contradictory, but the bioenergy facilities have different fibre demands, and different sizes or types of bioenergy facilities with different conversion efficiencies were selected in some cases. A comparison of the displacement factors in the two cases revealed much lower displacement factors in regions with small residue availability when the alternate facilities were used. The alternate facilities had a higher annual fibre demands for heat and small CHP facilities than the generic facilities, and in some cases only small electricity facilities were selected. Total cumulative mitigation in 2050 increased from 429 to 552 $TgCO_2e$ using the nine generic facilities. The largest difference between the nine selected facilities and the generic facilities was for the medium-sized CHP (1.8 MWe/4.5 MWth selected, 1.0 MWe/5 MWth generic) which produced most of the heat (67% and 85% for the selected and generic facilities, respectively) and much of the electricity (40% and 34%). The total heat produced from the nine generic facilities was 35% larger

than that produced by the selected facilities, while the total electricity production was roughly the same (i.e. within 0.5% of each other).

Mitigation potential comparisons

Results of this study cannot be compared directly to strategies examined in an earlier study (Smyth *et al.*, 2014) because of slight differences in the modelling assumptions made regarding projected harvest levels, start dates for the mitigation activities, and differences in displacement factors for bioenergy. However, these studies are similar enough that general comparisons of the magnitudes of the cumulative mitigation potential by 2050 can be made at the ecozone level. Figure 6 shows the present estimates of the cumulative mitigation potential in comparison with four of the nine strategies previously examined (Smyth *et al.*, 2014). The present results have much higher mitigation potential than a green harvest for bioenergy strategy because we found in the previous study that green harvest resulted in a negative mitigation potential. Compared to a strategy of using more of the stem harvest for longer-lived wood products, the national-level mitigation estimates were similar to results from this study (435 $TgCO_2e$ vs. 429 $TgCO_2e$) but the allocation by ecozone was different: roughly half of the cumulative mitigation potential in this study was concentrated in one ecozone (Atlantic Maritimes), whereas the contribution from longer-lived wood products was
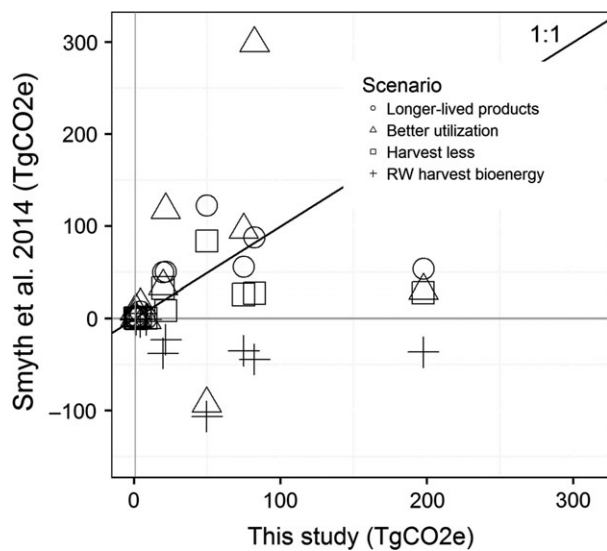

Fig. 6 Comparison of mitigation strategies from Smyth *et al.* (2014) to results from this study. Ecozones with higher mitigation potential from production of bioenergy from harvest residues (present results) are below the 1 : 1 line.

distributed over many ecozones. Overall, the longer-lived wood products strategy had a higher mitigation potential than capturing residues for bioenergy in all but two ecozones. Similarly, the better utilization strategy (involving increasing the harvest utilization rate of merchantable-sized trees, increasing the proportion of salvage harvest, capturing residues for bioenergy and omitting or reducing slashburning) had a higher mitigation potential than this study in all but two ecozones. As in the previous analysis, it would be possible to combine mitigation activities by creating a portfolio and selecting the best combination of activities to maximize the mitigation potential in each region.

Improvements to the earlier analyses (Smyth *et al.*, 2014) include higher spatial resolution in the harvest allocation and improvements to the displaced emissions estimates. The bioenergy facilities and displaced fuel sources in the earlier analysis were selected based on expert judgement, but in this study we considerably refined displaced emissions estimates based on an optimized selection of the type, number and size of bioenergy facilities (see Smyth *et al.*, 2016) that would maximize displaced emissions.

Discussion

Our results demonstrate a significant potential for climate change mitigation from Canada's forest sector through use of harvest residues for bioenergy. This type of quantitative analysis has never been carried out at the national level for Canada, in particular for displaced emissions based on multiple fuel sources and optimized facility selection.

These results should be interpreted as an upper limit in some regions because we have not included economic considerations, or regulatory or market barriers (Roach & Berch, 2014). 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 and may limit the level of mitigation strategy implementation (Golden *et al.*, 2011). We assumed that harvest occurred primarily for the production of wood commodities, but 6% of harvest in 2050 was for the production of bioenergy where it may be less likely to capture harvest residues.

Results of the study found that 278 of the 502 regions investigated had a positive mitigation, in which 7.1 TgC yr^{-1} of harvest residues produced bioenergy that displaced a higher-emitting fossil fuel. For the other regions, there were significant volumes of residues (roughly 40%) that would not reduce GHG emissions if captured for bioenergy. In many of these regions,

captured residues exceeded local demand for heat and power, and excess residues were used to generate electricity. This is not to say that these regions could not produce positive mitigation benefits because each region has an optimal amount of captured residues that would maximize displaced emissions. The optimal amount of captured residues would depend on local heat demand and regional fuel mix, and we anticipate amount of residues necessary to meet demand would be a small proportion of the 4.8 Tg C yr^{-1} captured residues because the population within the negative mitigation regions is small (0.2 million people, Table 3). Dynamically capturing enough harvest residues to meet local demand and displacing only high-emissions fuels would give a greater mitigation potential, but this is beyond the scope of our study.

Break-even point, or C payback period, is the principal metric identified in a recent meta-analysis of forest bioenergy GHG accounting studies (Buchholz *et al.*, 2016), and hence comparisons were made to other studies of GHG mitigation from use of harvest residues for bioenergy. The average payback period in our study was 6.2 ± 8.6 years, with forest residues from bioenergy predominantly producing heat and replacing fuel oil, coal and petcoke, and natural gas. This compares favourably with the range of values found in the literature, as described below.

An immediate carbon benefit has been found in regions where slash-burning treatment to reduce fuel loads is common practice and is replaced using this material as bioenergy feedstock (Jones *et al.*, 2010). A payback time of 16 years was found in a study by McKechnie *et al.* (2011) where residues were co-fired in a coal facility to generate electricity. Zanchi *et al.* (2012) found the break-even time for use of harvest residues ranged from 0 for when they displaced coal, 7 years for oil, and 16 years for natural gas. Guest *et al.* (2013) found payback times of 13–36 years for natural gas (heat) and 0–12 years for coal (electricity).

Differences in payback times between studies can result from different assumptions about displaced fossil fuels, facility efficiencies, and residue feedstocks. The effectiveness with which fossil C is displaced has a major influence on net GHG balances, and faster climate benefits have been found when bioenergy displaced coal rather than natural gas (Cintas *et al.*, 2015). Shorter break-even times have been found for heat or combined heat and power technologies due to the increased conversion efficiency of woody biomass combustion (Richter *et al.*, 2009). Payback times are also affected by differences in decomposition rates due to biomass type (e.g. capture of stumps) and the overall rate of decomposition (Repo *et al.*, 2011).

Residue extraction can sometimes affect subsequent growth rates of forests and hence C sequestration rate in Europe, but there is little evidence for this in North America (Thiffault *et al.*, 2011) where there is only one known long-term study with growth reductions following nutrient removals in harvest residue (Ponder *et al.*, 2012), and this is on a poor phosphorus-deficient site in the south-eastern United States (Scott & Dean, 2006). On the other hand, residue extraction can assist with site preparation before planting and reduce the fuel hazard (Saarinen, 2006; Helmisaari *et al.*, 2011). In the absence of long-term data to the contrary, we have therefore assumed that there is no reduction in growth rates following harvest residue removal from sites in Canada. Additionally, climate change impacts on forest growth, decomposition, or disturbance regimes were not considered in this analysis.

Future analysis will consider additional impacts on the national mitigation potential, beyond the sensitivity of bioenergy facilities and remote community fuel mix. Refining the spatial allocation of fossil fuel usage to account for the fuel mix used locally could increase the mitigation potential in regions with high fossil fuel emissions intensities. An additional assessment could consider alternate future energy demands, with different trajectories of fossil fuel elimination by decade. The mitigation potential could decrease, relative to the present results, if fossil fuels are more quickly replaced by hydro-electricity, solar, tidal, geothermal, or nuclear energy sources. On the other hand if the current fossil fuel mix is maintained, the mitigation potential would be higher. We did not address the option to transfer residues across FMU boundaries where communities are nearby, but outside the FMU, because these simulations are not spatially explicit. Future analyses could address these issues.

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. The results of this study provide estimates of the mitigation potential to 2050 of using the residues for bioenergy that will be useful to strategic decision-makers and planners at regional, provincial, or national scales.

We emphasize the importance of a sound analytical framework for mitigation assessment associated with incremental activities relative to a *Base Case*, and an integrated assessment of harvest residues for bioenergy using a systems approach, and hence we examined C pools in the forest ecosystem, C use and storage in

HWPs, and substitution of wood for other energy sources.

The local use of harvest residues for local production of bioenergy was found to be effective in some locations but counter-productive from a climate change mitigation standpoint in other locations. The total national mitigation potential of 429 $MtCO_2e$ was comparable to some of the other mitigation strategies examined in an earlier analysis (Smyth *et al.*, 2014), but the mitigation potential from this analysis is concentrated in two ecozones, whereas the other strategies had higher mitigation potential in many ecozones for a longer-lived products strategy and a better utilization strategy. Substantial gains could be realized through a portfolio of strategies, both in contributing to Canada's emission reduction targets and in reducing global emissions.

This national-level study estimated the displaced emissions from using bioenergy in place of another energy source by multiplying the captured residue by a displacement factor for each forest management unit. Displacement factors (from Smyth *et al.*, 2016) were based on the local energy demand, strategic displacement of the highest emitting fuels in the fuel mix for heat and electricity, and a selection of the set (size, type and number) of bioenergy facilities that maximized the displaced emissions. Our results show that the use of harvest residues for bioenergy resulted in a reduction in GHG emissions in regions where high-emitting fossil fuels were displaced, mainly from heat production in combined heat and power facilities. Negative mitigation potential was found in regions where harvest residues were used to generate electricity and displace low-emission hydroelectricity. We conclude that national-scale forest sector mitigation options need to be assessed rigorously from a systems perspective to distinguish policies that deliver net benefits to the atmosphere from those policies that do not contribute to climate change mitigation.

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Supporting Information

Additional Supporting Information may be found online in the supporting information tab for this article:

Fig. S1. Forest management units within the managed forest.

Fig. S2. Carbon pools and transfers simulated by the CBM-CFS3.

Fig. S3. Disturbance matrix simulating the C transfer associated with a historic clearcut and salvage harvest.

Table S1. Historic harvest methods as simulated in CBM-CFS3 parameterization for each harvest method

Table S2. Parameters for *Base Case* and the *Bioenergy* strategies

Table S3. Projected electricity emissions intensities and fuel mix percentages for electricity (E) and heat (H)

Table S4. Bioenergy facilities for (a) the nine selected facilities, and (b) the 9 generic facilities used to assess the sensitivity to bioenergy facility type