Supplementary Materials

for article

Can wood pellets from Canada's boreal forest reduce net greenhouse gas emissions from energy generation in the UK?

1. Forest biomass estimation

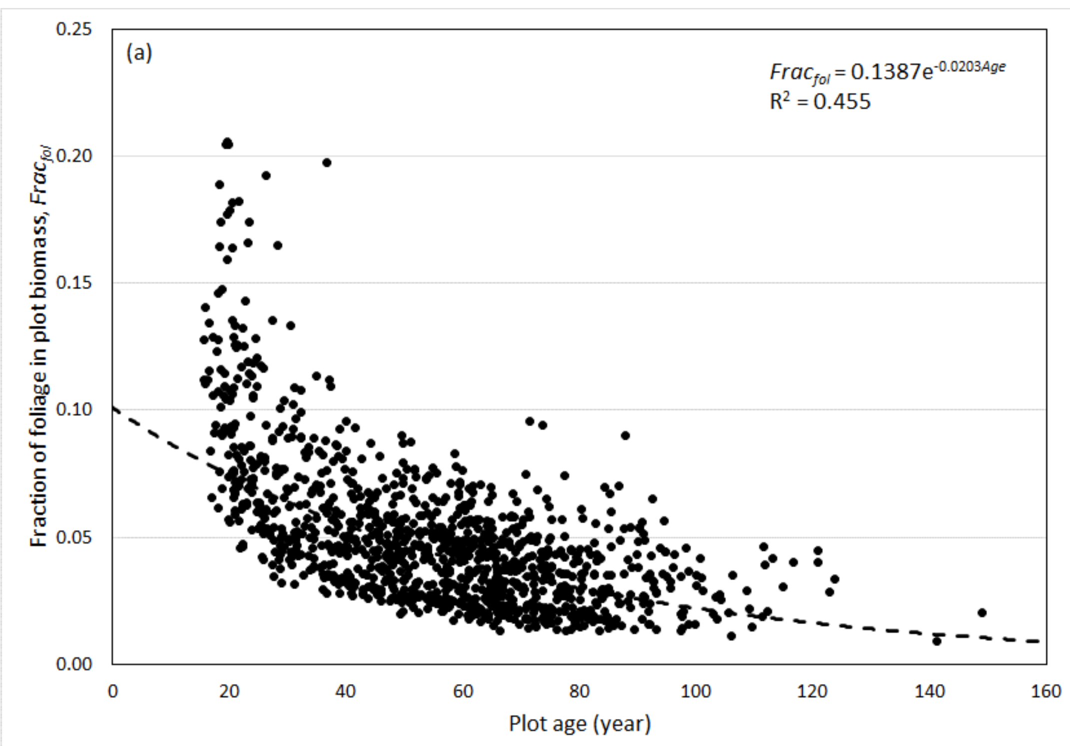
Biomass of each species included in the forest unit yield was calculated using stemwood densities, *Dens*, from [26] (Gonzalez 1990); see Equation (1) in the main text. Of the various estimates included in the latter review paper we used stemwood densities (average for the entire stem) for green volume (i.e., estimated in kg of oven-dried weight per m^3 of green volume) from Canada and northern US states (e.g., Minnesota, Wisconsin). Values in Table S1 are averages of the estimated stemwood density ranging from 2 to 20 estimates per tree species. Table S1 includes stemwood densities for tamarack and beech estimated in Ontario, although these species are not on the forest unit species composition list. Their densities were included in the calculation of average densities for conifers and hardwoods that were used to estimate the mass of "other conifers" and "other hardwoods" (two categories on the forest unit species composition list used for minor tree species).

Table S1. Mean stemwood density for major Ontario tree species.

Common name	Scientific name	Stemwood density ($t \cdot m^{-3}$)
Balsam fir	*Abies balsamea* (L.) Mill.	0.3335
Black spruce	*Picea mariana* (Mill) B.C.P.	0.4188
Eastern hemlock	*Tsuga canadensis* (L.) Com.	0.3861
Eastern white cedar	*Thuja occidentalis* L.	0.3068
Eastern white pine	*Pinus strobus* L.	0.3393
Jack pine	*Pinus banksiana* Lamb.	0.3914
Red pine	*Pinus resinosa* Ait.	0.3680
White spruce	*Picea glauca* (Moench) Voss.	0.3636
Tamarack	*Larix Laricina* (Du Roi) K.Koch	0.4625
All softwoods		0.3816
Balsam poplar	*Populus balsamifera* L.	0.3625
Red oak	*Quercus rubra* L.	0.5855
Sugar maple	*Acer saccharum* Marsh.	0.6065
Trembling aspen	*Populus tremuloides* Michx.	0.3930
White birch	*Betula papyrifera* Marsh.	0.5104
Yellow birch	*Betula alleghaniensis* Britt.	0.5683
Beech	*Fagus grandifolia* Ehrh.	0.5985
All hardwoods		0.4893

To estimate the amount of foliage and stem bark, we used individual tree measurements from the growth sample plots established within the framework of Ontario's Growth and Yield program [27] (Sharma et al. 2008). Each plot has a circular shape with an area of 400 m^2; all trees within each plot are measured for diameter (DBH) and their species identified. This allowed calculation of the biomass of foliage, branches, inside-bark stem wood, and stem bark for each tree using DBH-based allometric equations from [29] Lambert et al. (2005); the sum of the listed tree components provided an estimate of total aboveground tree biomass. These estimates were summarized for each sample plot for the plot-level totals; the latter was done because the data on harvest blocks contain no data on individual trees but only plot-level estimates. In addition, each plot included a limited sample of trees measured for age at the base (30 cm above the ground) or DBH age, with the trees' positions in the stand canopy identified. These data were used to estimate forest age for each plot by averaging age of all dominant and co-dominant trees within the plot. For more information about the growth plots see [27,28] (Sharma et al. 2008; Chen et al. 2020).

The ratios of foliage biomass to total aboveground biomass ($Frac_{fol}$) and of stem bark to stem wood biomass ($Frac_{bark}$) were estimated separately for conifer and hardwood-dominated plots; the plots were classified by estimating the prevailing total basal area of conifer and hardwood trees in each plot. Since some plots were measured more than once, only one measurement per plot was randomly selected for the analysis to avoid concerns about autocorrelation. This resulted in 4146 and 1114 conifer- and hardwood-dominated plots, respectively, each with a plot-level estimate of $Frac_{fol}$ and $Frac_{bark}$. The ratios were examined for a possible relationship with plot age by means of visual assessment, and linear and negative exponential regression. The most pronounced were the negative exponential $Frac_{fol}$-age and $Frac_{bark}$-age relationships for hardwood-dominated plots, with the coefficient of determination R^2 equal to 0.455 and 0.159, respectively (Fig. S1). The respective equations were used to estimate the fraction of foliage and the amount of bark in the hardwood-dominated stands available for harvest. For conifer-dominated plots there was no dependence of either ratio on plot age, with R^2 of 0.053 and 0.001 for negative exponential $Frac_{fol}$-age and $Frac_{bark}$-age relationships, respectively. Therefore, the values $Frac_{fol}$ = 0.0952 and $Frac_{bark}$ = 0.1366 averaged over plots older than 50 years were used to estimate the fraction of foliage and the amount of bark in conifer-dominated stands available for harvest.



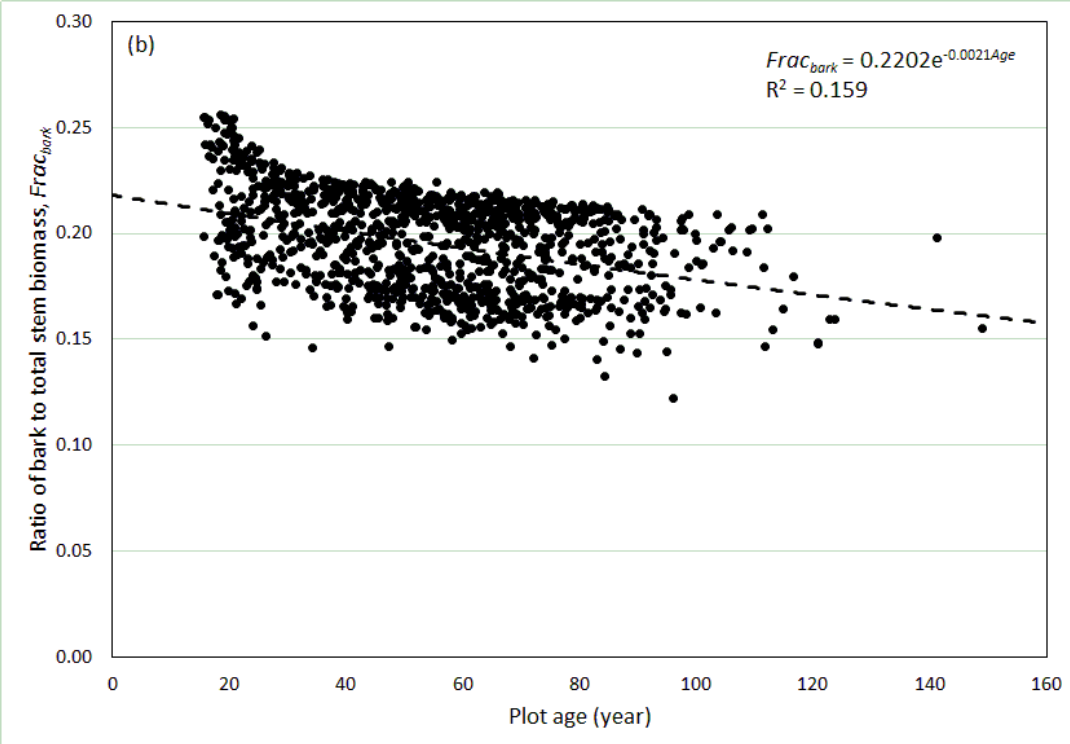


Figure S1. Scatterplots of plot level ratios of (a) foliage biomass to total aboveground biomass of live trees and (b) stem bark biomass to inside-bark stem biomass for hardwood-dominated growth plots in Ontario, Canada. Dashed lines indicate fitted negative exponential equations.

2. Parameter estimation

Several parameter estimates used in the analysis warrant discussion. First, we estimated bark-to-stemwood ratios using data from Ontario's network of growth plots rather than values from [53] (Chen et al. 2013) that were based on a literature review of 11 sources on "bark expansion factors." The latter expansion factors were estimated for individual trees while we needed bark-to-stemwood biomass ratios to apply them to plot-level volumes composed of trees differing in species and age. However, the average ratios used in this study (0.1366 and 0.1901 for conifer- and hardwood-dominated stands, respectively), are similar to those by [53] (Chen et al. 2013) who reported bark expansion factors ranging from 0.08 to 0.18 and from 0.06 to 0.27 for conifer and hardwood species, respectively; the averages for conifers and hardwoods used by [53] (Chen et al. 2013) were 0.119 and 0.189, respectively. Note that for hardwood-dominated stands we used an age-dependent equation (see Fig. 2b in the main text) and the above-quoted average value of 0.1901 was calculated (for 50+ year old stands) only for comparison with the values from [53] (Chen et al. 2013).

Second, calculating the amount of energy produced from one odt of biomass taken out of the forest, P_{Bio}, required estimating biomass losses along the pellet production-transportation chain and the efficiency of a biomass-fired power plant (see Equation (5) in the main text). Losses during biomass transport and wood pellet production, $Loss_{Bio}$, assumed in this study (15%) were consistent with estimates reported in other studies on pellet production in Canada (e.g., 15% by [54] (Laschi et al. 2016); 17.5% by [55] (Ghafghazi et al. 2017)). The median efficiency of electricity producing biomass-powered plants in Canada is about 31% [56] (Dymond and Kamp 2014), calculated as the ratio of the median operational net calorific value of electricity-producing power plants, 5.6 GJ·odt^{-1}, to the average heat value of wood, 18 GJ·odt-1. Slightly lower efficiency (29%) was reported by [57] (Wiltsee 2000) for the Williams Lake Generating

Station (BC, Canada), the largest single-unit biomass-fired power plant in North America. However, the Williams Lake Station has operated since 1993 and uses wood chips as feedstock. In this study, we used the efficiency of the Drax plant (38%) as representative of modern biomass-powered plants in Europe (note that the efficiency of the Drax plant would be around 36% if recalculated based on the high heating value used for estimating efficiency of Canadian plants). The resulting energy output per unit of biomass removed from the forest estimated in this study, P_{Bio} = 1.715 MWh·odt^{-1}, was within the range of estimates, 1.520–1.736 MWh·odt^{-1}, used by [8] (Ter-Mikaelian et al. 2015).

Third, we used more conservative estimates when calculating the amount of harvest residue available from harvest operations than those in a previous study on biomass collection in northern Ontario [8] (Ter-Mikaelian et al. 2015). The fraction of unmerchantable biomass left on site (50%) is within the range (albeit closer to the upper end) of the minimum harvest residue retention values recommended in forest biomass harvesting guidelines (see the review of residue harvesting guidelines by [58]). This estimate is higher than the 30% value used by [8] (Ter-Mikaelian et al. 2015). Also, the estimated fraction of unmerchantable biomass in slash piles at roadside that can be recovered for wood pellet production (75%) is lower than that (85%) used by [8] (Ter-Mikaelian et al. 2015); in both cases, Ter-Mikaelian et al. [8] used the estimates generated by a harvesting model, while we use estimates based on field measurements reported by [23] (Ralevic et al. 2010).

Fourth, to estimate emissions from combustion of slash piles we used factors calculated as the average of two sets of emission factors reported in [46] (IPCC 2003) for boreal forest fires and generic forest fires, respectively. The latter factors accounted for emissions from both the flaming and smoldering emissions phases of forest fires. Studies estimating emissions for combustion of slash piles indicate lower emissions than those reported in [46] (IPCC 2003). For example, Aurell et al. (2017) [59] reported CH_4 emissions factors of 0.0057 and 0.0011 tonnes·odt^{-1} for wet and dry slash piles, respectively, in a clearcut of Douglas-fir stand in Oregon, USA. Ward et al. (1992) [60] estimated emissions of CH_4 ranging from 0.0043 to 0.0052 tonnes·odt^{-1} during combustion of slash in 15-year-old secondary forest cleared for pasture in Brazil (the study also included higher emission factors for combustion of slash after clearing primary forest; however, as noted by the study authors, the latter sites included many uncut trees making the respective estimates unsuitable for comparison with emissions from slash pile burning). Springsteen et al (2011) [61] reported a 0.001–0.011 tonnes·odt^{-1} range of CH_4 emissions factors based on the review of 12 studies on slash pile burning, with only two of them resulting in emission factors higher than the value used in our study (0.00805 tonnes·odt^{-1} range of CH_4). Fourth, we used conservatively high emission factors to estimate emissions from combustion of slash piles. Given the wide spread of emission factors from slash pile burning reported in the literature we decided to use the conservatively high factors from [46].

3. LCI emissions

Emissions for most LCI phases were based on estimates derived in [50] (Zhang et al. 2010). They assumed that emissions from forest harvest, forest road construction and maintenance, and forest renewal were due mainly to harvesting for traditional HWP and therefore allocated 0.35 of total emissions to biomass for energy; we re-calculated these emissions back to the full value. Emissions from collecting harvest residue were taken from [49] (McCloy 2009); since in the residue scenario, biomass for wood pellets was a by-product of ongoing harvesting operations, no emissions were assigned to forest road construction and maintenance or forest renewal. Emissions from transportation by ocean vessel were from [48] (Magelli et al. 2009). Emissions from transportation by truck, train, and ocean vessel were adjusted for distances specific to this study: 100 km on average from the harvesting sites to wood pelletization plants; 2,800 km and 3,800 km by train from wood pelletization plants to the Halifax port from Hearst and Kenora FMUs, respectively; 4,550 by ocean vessel from Halifax to Liverpool; and 160 km from Liverpool to the power plant. Where needed, conversion from units of harvested biomass to units of wood pellets and units of generated electricity was made using net calorific value of wood pellets (5.31 MWh·odt^{-1} from [36] (Tarasov (2014)) and plant efficiency (0.38) from [38] (European Commission 2016)).

Since there is no current production of wood pellets in either FMU, we assumed that pelletization plants are built in Hearst and Kenora (one plant per FMU) to process biomass collected in the respective FMU. The LCI emissions from construction of pelletization plants with a life span of 40 years were from [8] (Ter-Mikaelian et al. 2015) and were all assumed to occur in the first year of biomass collection for bioenergy. Thus, for continuous harvest operations, emissions from construction of pelletization plant were simulated in years 1, 41, and 81 from the beginning of collecting biomass for energy. With the exception of the harvest residue scenario in Kenora FMU (in which biomass was assumed to be burned both in bioenergy and baseline scenarios), LCI for wood pellets also included non-CO_2 emissions from biomass combustion using emission factors from [51] (IPCC 2006); CO_2 combustion emissions were not included to avoid double-counting, since these emissions are already accounted for as carbon losses in the forest during harvesting and slash pile collection.

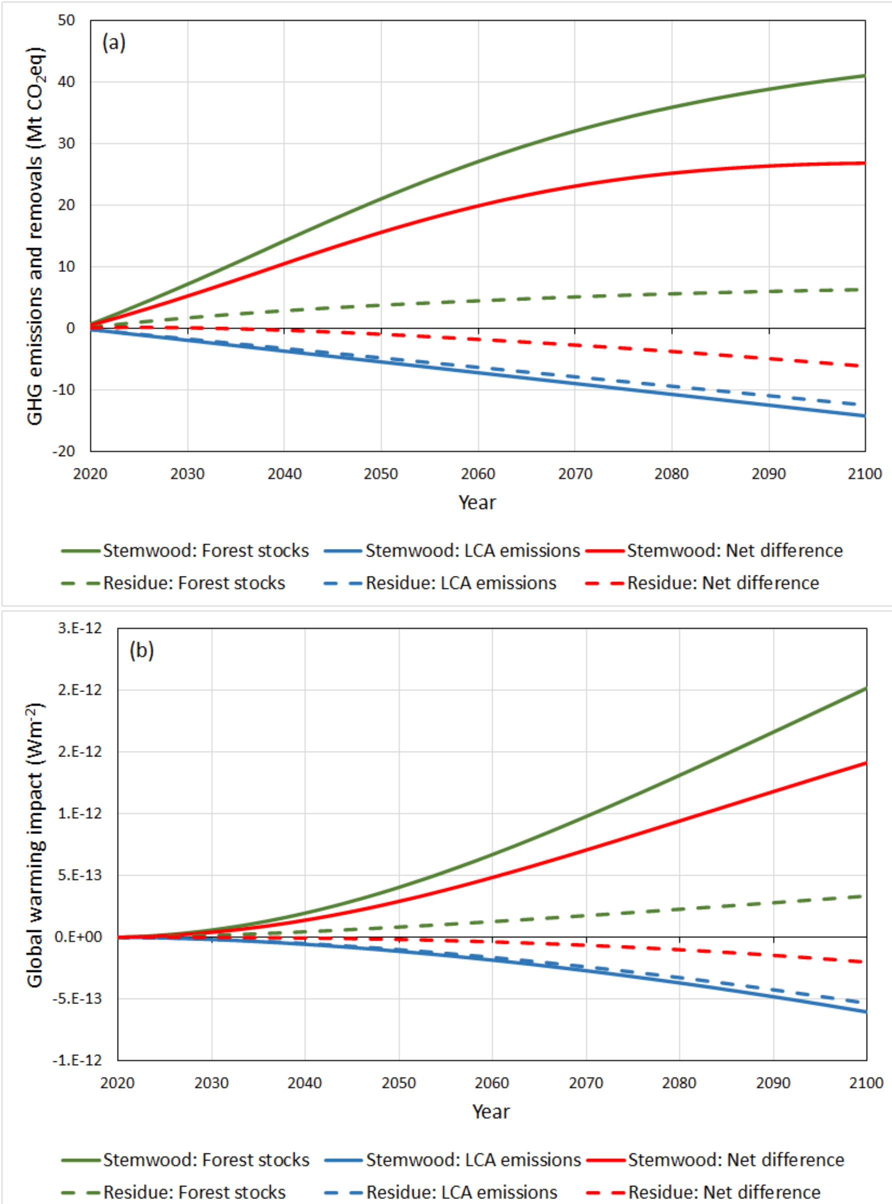
Table S2. LCI emissions for bioenergy scenarios.

Gas	CO_2 (kg·MWh^{-1})	CH_4 (kg·MWh^{-1})	N_2O (kg·MWh^{-1})	Source
Hearst FMU: Stemwood scenario				
Forest harvest	40.31545	0.058087	0.014168	[50] Zhang et al. (2010)
Forest road construction and maintenance	1.494686	0.002125	0.000425	[50] Zhang et al. (2010)
Forest renewal	1.98347	0.002834	0.000567	[50] Zhang et al. (2010)
Transportation by truck	10.85562	0.015523	0.000862	[50] Zhang et al. (2010)
Pelletization	16.54115	0.020876	0.000012	[50] Zhang et al. (2010)
Transportation by train	18.73498	0.016529	0.006612	[50] Zhang et al. (2010)
Transportation by ocean vessel	30.04964	0.003348	0.000728	[48] Magelli et al. (2010)
Wood pellet combustion	0	0.107914	0.014388	[51] IPCC (2006)
Sub-total (without emissions from construction of pelletization plant)	119.975	0.227235	0.037761867	
Construction of pelletization plant: total for the plant life span, kg of gas per 40 years)	22183.98	1.934259	0.311448	[8] Ter-Mikaelian et al. (2015)
Hearst FMU: Residue scenario				
Collection of harvest residue	2.294875	0.038033	0.004214874	[49] McCloy (2009)
Forest road construction and maintenance	0	0	0	N/A
Forest renewal	0	0	0	N/A
Truck	10.85562	0.015523	0.000862378	[50] Zhang et al. (2010)
Pelletization	16.54115	0.020876	0.00001225	[50] Zhang et al. (2010)
Train	18.73498	0.016529	0.006611567	[50] Zhang et al. (2010)
Ocean	30.04964	0.003348	0.000727806	[48] Magelli et al. (2009)
Wood pellet combustion	0	0.107914	0.014388489	[51] IPCC (2006)
Sub-total (without emissions from construction of pelletization plant)	78.47626	0.094309	0.012428873	
Construction of pelletization plant: total for the plant life span, kg of gas per 40 years)	22183.98	1.934259	0.311448	[8] Ter-Mikaelian et al. (2015)
Kenora FMU: Stemwood scenario				
Forest harvest	40.31545	0.058087	0.014168	[50] Zhang et al. (2010)

Forest road construction and maintenance	1.494686	0.002125	0.000425	[50] Zhang et al. (2010)
Forest renewal	1.98347	0.002834	0.000567	[50] Zhang et al. (2010)
Transportation by truck	10.85562	0.015523	0.000862	[50] Zhang et al. (2010)
Pelletization	16.54115	0.020876	1.22E-05	[50] Zhang et al. (2010)
Transportation by train	24.97997	0.022039	0.008815	[50] Zhang et al. (2010)
Transportation by ocean vessel	30.04964	0.003348	0.000728	[48] Magelli et al. (2009)
Wood pellet combustion	0	0.107914	0.014388	[51] IPCC (2006)
Sub-total (without emissions from construction of pelletization plant)	126.22	0.232745	0.039966	
Construction of pelletization plant: total for the plant life span, kg of gas per 40 years)	22183.98	1.934259	0.311448	[8] Ter-Mikaelian et al. (2015)
Kenora FMU: Residue scenario				
Collection of harvest residue	2.294875	0.038033	0.004215	[49] McCloy (2009)
Forest road construction and maintenance	0	0	0	N/A
Forest renewal	0	0	0	N/A
Truck	10.85562	0.015523	0.000862	[50] Zhang et al. (2010)
Pelletization	16.54115	0.020876	1.22E-05	[50] Zhang et al. (2010)
Train	24.97997	0.022039	0.008815	[50] Zhang et al. (2010)
Ocean	30.04964	0.003348	0.000728	[48] Magelli et al. (2009)
Wood pellet combustion	0	0	0	N/A
Sub-total (without emissions from construction of pelletization plant)	84.72125	0.099818	0.014633	
Construction of pelletization plant: total for the plant life span, kg of gas per 40 years)	22183.98	1.934259	0.311448	[8] Ter-Mikaelian et al. (2015)

4. Comparison of GHG emissions and removals and global climate impacts

Results of scenario comparisons are shown in Fig. S2. These differ from Fig. 2 in the main text only by grouping of emissions/removals and climate impacts: green lines reflect the difference in forest carbon stock changes between bioenergy and respective baseline scenarios, while blue lines correspond to the difference in all other LCI emissions. Red lines represent cumulative net differences between bioenergy and baseline scenarios and are identical to the red lines in Fig. 2. Results for the stemwood (solid lines) and residue (dashed lines) scenarios in Hearst FMU and Kenora FMU are shown in Figs. 2a and 2c, respectively. Positive values are GHG emissions and negative values are removals. Cumulative global warming impacts for both bioenergy scenarios and their baseline scenarios are shown for both FMUs in Figs. 2b and 2d using the same grouping of the effects as for GHG emissions. Positive values of global warming impacts indicate no climate change benefit of the bioenergy scenario, with negative values showing the opposite.


(a)
GHG emissions and removals (Mt CO2eq)
50
40
30
20
10
0
-10
-20
2020
2030
2040
2050
2060
2070
2080
2090
2100
Year
Stemwood: Forest stocks
Stemwood: LCA emissions
Stemwood: Net difference
Residue: Forest stocks
Residue: LCA emissions
Residue: Net difference
(b)
Global warming impact (Wm-2)
3.E-12
2.E-12
2.E-12
1.E-12
5.E-13
0.E+00
-5.E-13
-1.E-12
2020
2030
2040
2050
2060
2070
2080
2090
2100
Year
Stemwood: Forest stocks
Stemwood: LCA emissions
Stemwood: Net difference
Residue: Forest stocks
Residue: LCA emissions
Residue: Net difference

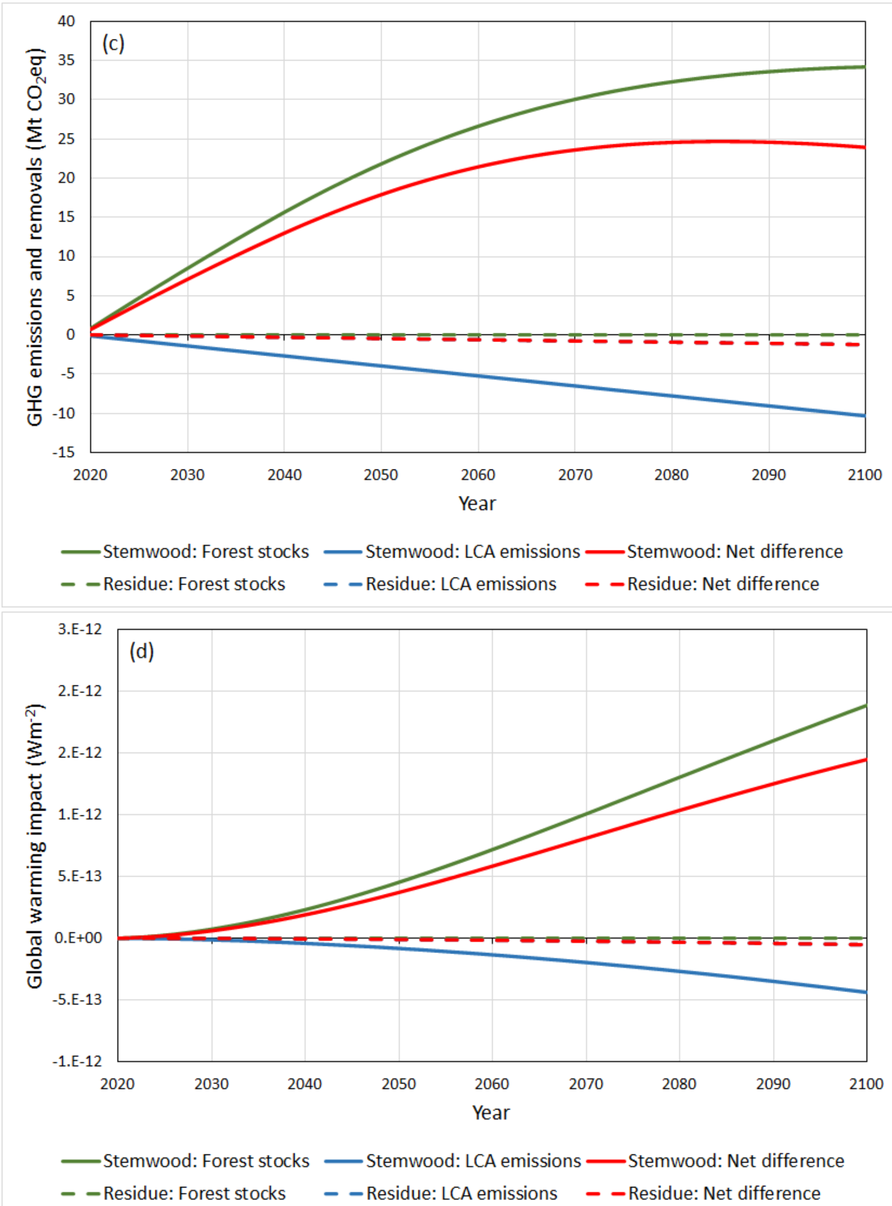


Figure S2. Cumulative GHG emissions and removals (a,c) and cumulative global warming impacts (b,d) in the bioenergy and baseline scenarios in the (a,b) Hearst and (c,d) Kenora forest management units. Stemwood and residue scenarios are shown using solid and dashed lines, respectively. Positive values indicate emissions and negative values are removals.

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Reference numbers correspond to those in the main text.

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