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Greenhouse gas emissions of local wood pellet heat from northeastern US forests

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ABSTRACT

We explored greenhouse gas (GHG) implications of locally-sourced and produced wood pellets to heat homes in the US Northern Forest region. Using data from regional pellet industries, forest inventories and harvests, we analyzed pellet GHG emissions across a range of harvest and forest product market scenarios over 50 years. We expanded an existing life cycle assessment (LCA) tool, the Forest Sector Greenhouse Gas Assessment Tool for Maine (ForGATE) to calculate GHG balances associated with the harvest, processing, and use of wood pellets for residential heating vs. alternative heating fuels. Market assumptions and feedstock mix can create diverging GHG emission profiles for pellet heat. Outcomes are predominantly influenced by biogenic carbon fluxes in the forest carbon pool. An industry-average pellet feedstock mix (50% sawmill residues, 50% pulpwood) appeared to generate heat that was at least at parity with fossil-fuel heating alternatives when harvest levels remain unchanged due to pellet production. If harvest levels increase due to pellet production, using pellet heat increased GHG emissions. If baseline harvest levels drop (e.g., following the loss of low-grade markets), GHG emissions from pellet heat would at least remain stable relative to fossil alternatives.

1. Introduction

1.1. Rationale

Wood pellet heat is a new and growing heating alternative in the US and has been proposed as a climate-beneficial energy source to replace fossil-fuels. However, little work has been done to assess this claim. The opportunity for switching to wood pellet heat is particularly great for the Northern Forest region of northern Maine, New Hampshire, Vermont and New York which is home to more than 2 million people who live in rural communities, larger towns, and small cities surrounded by the largest intact forest in the eastern US (1). Around 42% of all energy consumed is for space heating [1] and the predominance is derived from fossil-fuels [2]. New York and the five New England states comprise 88% of the entire US consumption of home heating oil [3], which is a distillate fuel similar to diesel fuel. Though natural gas is used widely for heat throughout the northeastern US, the northern states of Maine, New Hampshire, Vermont, and the northern portion of New York still rely on home heating oil as a heat source (62%, 45%, 43%, and 50% of homes respectively; [4]. Propane and electricity account for the majority of the balance of heating fuel sources in the region.

Use of wood for heat is variable throughout the region, ranging from 17% of homes in Vermont to 8% in New Hampshire and northern New York [4]. Though the use of wood pellets is increasing, cord wood represents almost 82% of wood use for heat in the five-state New England region [5]. Wood pellet heating systems are up to 15% more efficient than non-catalytic cord wood stoves [6] and prices per Gigajoule of energy for pellets are competitive or better than split wood. For instance, pellet fuel for home heating was 12% less expensive than split wood for the same energy generation in Maine as of December 2016 [7].

GHG emissions from residential energy consumption in the New England states are responsible for 18% of the total GHG emissions for the region [8]. The widespread use of home heating oil contributes disproportionately to these emissions because of the low efficiency of heat conversion and high GHG emissions rates per

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thermal unit relative to other fossil-fuels [9]. In 2014, about 14.8 billion liters of heating oil were sold to residential consumers in New York and the five New England states [3]. An estimate for the broader northeastern US (Maine to Pennsylvania), suggests enough wood is economically available to replace 16% of the liquid fossil-fuels (i.e., home heating oil) used in the residential heating sector [10]. Though some are encouraging movement towards technology such as air-source heat pumps to meet heating needs and GHG reduction goals [11], others are advocating the conversion to modern wood heat systems such as wood pellet stoves and boilers that rely on locally-derived fuel (i.e., wood) and can support forest-based economies hit hard by recent solid wood and pulp and paper mill closures [12]. While forest-based bioenergy can be renewable if harvest does not exceed growth, these systems can also provide GHG benefits compared to fossil-fuel alternatives under specific conditions [13,14].

A declining marketplace for low-grade wood in the Northern Forest region creates a sense of urgency for local forest sector economies to replace these markets or face the further loss of jobs and logging infrastructure that have been essential elements of the economy. In Maine alone, paper mill and biomass electric facility closures since 2014 have resulted in the loss of more than 3.6 million green metric tonnes (MT) of the low-grade wood market for landowners and loggers [15]. Wood pellet manufacturing represents one growing aspect of the forest sector that could be developed to replace a portion of the lost low-grade marketplace. In early 2015, ten pellet manufacturing facilities were in operation within the Northern Forest region, though low oil prices and the warm winter of 2015–2016 forced many to curtail operations or temporarily shut down [16]. To create incentives for converting to wood pellet heating systems, states such as New Hampshire are offering rebates to homeowners of 40% of the installed cost of qualifying new residential bulk-fed, wood-pellet central heating boilers or furnaces [17]. Similar programs exist in Maine, Vermont, and New York [18]. One underlying assumption of these incentive programs, since funding typically comes from the Regional Greenhouse Gas Initiative carbon auction proceeds, is that the conversion to modern wood heat systems results in GHG reductions.

1.2. Wood energy emissions and study purpose

Much of the research conducted to date to study the potential GHG impacts of switching from fossil-fuel derived energy to woody biomass energy has focused on the electricity sector and has not addressed comprehensively the thermal uses of wood [14]. Greenhouse gas emissions implications are often expressed in terms of the carbon "payback period", which is the time required by the forest sequester an equivalent amount of carbon dioxide from woody biomass energy combustion. Modeling has shown that payback periods for electricity uses can be long (e.g., 45–75 years) when harvest rates must be increased to meet the demand of a new wood-consuming facility [13]. But models also show the payback period can be relatively short, especially when the new market creates incentives for landowners to plant trees in previously unforested areas [19]. When modern thermal uses of wood were evaluated, carbon payback times were generally shorter than when wood is used for electricity [13,14]. Greater efficiency of wood for thermal uses compared to electricity as an end use is the key factor in this difference.

To date, only one study we are aware of has looked at the atmospheric implications of switching from fossil-fuel heat sources to wood heat in the northeastern US [13]. This study was focused on one state (Massachusetts) and only looked at wood chips used for industrial thermal and combined heat-and-power outputs and did not evaluate wood pellet systems.

The goal of the study presented below was to explore the GHG impacts of locally sourced, produced, and consumed wood pellets (referred to hereafter as "pellets") for heating applications including both the biogenic and fossil-fuel carbon cycle. The approach included a rigorous LCA framework that considered a range of plausible forest market scenarios to capture an uncertain future.

We focus on a case study area in Maine and discuss the relevance to the broader region through an analysis of survey data from pellet manufacturing facilities throughout Maine, New Hampshire, Vermont, and northern New York.

2. Materials and methods

2.1. Study area

One representative softwood dominated wood supply area in Maine was chosen to evaluate the impacts of adding a pellet manufacturing facility to the forest landscape. The wood supply areas each were defined by an 83 km (50 mile) radius centered on an existing wood pellet manufacturing facility. We queried USDA Forest Service Forest Inventory and Assessment (FIA) data to categorize the current acreage within the radius based on forest cover type, tree diameter size class, and stand density. FIA data also allowed us to categorize forest acreage as available or unavailable for harvest. We categorized the delta between "forest land" total acreage minus "timberland" acreage as "reserve".

Baseline forest sector and alternative future pellet sector silvicultural regimes need to be designated for each forest cover type

Table 1
Harvest acreage allocation to silvicultural regimes as a percentage of total harvestable land base (excluding reserve acreage). The total study area forested landscape was 504,081 ha (1,245,612 acre).

Harvest regime	Reserve (% of total landscape)[a]	Partial harvest[b]	Heavy harvest[c]	Selection harvest[d]	Shelterwood harvest[e]	Clearcut harvest[f]
Current harvest Level	3%	16%	16%	16%	41%	7%
Increased harvest	3%	5%	78%	8%	0%	7%
Low demand	9%	15%	11%	11%	9%	46%

See Hennigar et al. [9] for more details on the silvicultural regimes described below. Totals do not equal 100% due to rounding.

[a] Baseline reserve percentage of total forested land base was determined from USFS FIA acreage summary of study areas.

[b] Partial Harvest regime involves a thin from above (remove trees with a larger diameter at breast height first) harvest entry every 30 years or more when stands reach 23 m^2/ha of Basal Area (BA). Target BA removal was ≤30%.

[c] Heavy Harvest regime is a thin from above harvest of ≥60% of BA every 50 years or more. Harvest entry threshold was 175 m^2/ha of merchantable volume.

[d] Selection Harvest regime is a thin from below (remove trees with a smaller but still merchantable diameter at breast height small first) harvest to create uneven-aged stands with entries every 30 years or more that reduce no more than 30% of the BA.

[e] Shelterwood Harvest regime is two stage process that involves an initial thin from below every 70 years or more that removes ≤60% of the BA. The second harvest entry is a 100% overstory removal 10 years after the first entry.

[f] Clearcut Harvest regime is a 100% removal when merchantable volume reaches 175 m^2/ha (generally every 60 years).

Table 2
Baseline forest sector and alternative future pellet forest sector harvest scenario combinations and harvest volume changes.

Scenario# and Title	Change in harvest volume between baseline and alternative future										
			Softwood			Hardwood					
	Baseline Forest Sector	Alternative Future Pellet Forest Sector	Sawlog	Pulpwood	Residues	Sawlog	Pulpwood	Residues	Total Annual Harvest Volume Change	Total Volume Change (MT)	Pellet feedstock Volume Change (MT)
1: New Harvests	Current Harvest	Increased Harvest	18%	8%	8%	76%	−2%	−7%	10%	27,323	47,002
2: Market Shift	Current Harvest	Current Harvest	–	–		–	–		–		–
3: Low Demand	Low Demand	Current Harvest	7%	−1%	−42%	112%	5%	18%	7%	40,612	−51,174

and size/density class combination in the ForGATE tool. The Maine Forest Service Silvicultural Activities reports provide the most comprehensive assessment of actual harvest activities conducted each year within the region. We designated a baseline allocation of silvicultural regimes for the study area based on most recent data available for Maine [20] and assumed that the statewide nature of the data, and broad classes of silvicultural activities could be applied to managed forest area elsewhere in the region (Table 1). The 'New Harvests' and 'Low Demand' scenarios were designed to achieve a change in harvest volume (harvest residues and pulpwood) relative to the "current harvest level" that would be required to supply a pellet mill with 45,359 bone-dry (at 0% moisture content) MT; equaling 50,000 bone-dry short tons) per year. Harvest allocations were made in a manual iterative process until the desired harvest volume output change was achieved. The harvest acreage allocation to different silvicultural regimes ultimately used in the analyses generates the annual wood product volume variation as intended (Table 2). The differences in hardwood and softwood sawlogs and pulpwood harvest were used to evaluate changes in forest live and dead carbon pools and relevant wood "in use" pools as the trees were either left to grow or harvested.

2.2. Life cycle assessment (LCA) tool

2.2.1. ForGATE - A Forest Sector Greenhouse Gas Assessment Tool for Maine

We conducted the LCA in the ForGATE model, which is a publicly available tool that calculates GHG balances associated with the harvest, processing, and use of wood products including bioenergy applications (15) and all relevant biogenic and fossil-fuel related carbon emissions associated with changes to the landscape carbon pools and fossil fuel emissions occurring throughout the entire forest products chain (harvest and in-forest processing, transport to and from a mill, processing at a mill). Aiming at a trade-off between user friendliness and the greater complexity of representing ecological and management dynamics of forest carbon (21), ForGATE provides predefined forest management options, inventory, and growth and yield data on the forest sector side. The user can define allocation of acreage by silvicultural management regime, GHG emissions from wood products processing, assumptions for wood products in-use and post-use, GHG emissions from electricity production and consumption, and wood product substitution. While built for Maine's forest conditions using FIA data as a starting point, ForGATE can be applied across the Northern Forest because its forest sector data is relevant regionally; the foundation of growth and yield projections come from the Northeast Variant of the Forest Vegetation Simulator.

2.2.2. Pellet module

We added a module to the ForGATE tool to track changes in GHG emissions when producing and consuming pellets sourced from a defined forest landscape (see Supporting Information SI2). The module allows the user to identify economic scenarios, predefined state-specific grid electricity data (updated to 2015 data), feedstock mix, transport distances of biomass to and pellets from the plant (assuming empty returns as default), energy source for plant processing heat, alternative heating technologies and associated annual fuel utilization efficiencies. We derived default pellet processing GHG emissions from Hansson et al. [21]. For sawmill residue dust currently not directed to pellets, we assumed complete decomposition in less than one year (e.g., use for animal bedding, landscaping, etc.). For sawmill residues not used for pellets, we assumed decomposition rates of less than one year. For harvest residues, we applied northeastern US specific annual coarse woody debris decomposition rates of 5.3% and 6.9% for residues [22].

The fossil-fuel heating alternatives analyzed included home heating oil, propane, natural gas, and air-source (electric) heat pumps with a global warming indicator (GWI) of 357, 290, 267, and 61 g CO_2 equivalent (CO_2e)/kWh, respectively. The GWIs for home heating oil, propane, and natural gas were derived from Hennigar et al. [9] and an annual fuel utilization efficiency of 90% (80% for pellets) which includes cradle to gate primary and upstream emissions. The air-source heat pump GWI was based on the GHG emissions of Maine's 2015 grid electricity mix [23] and a performance coefficient of three [24].

2.3. Pellet plants

We surveyed the ten known existing wood pellet plants in Northern Forest states of Maine, New Hampshire, Vermont, and New York in January 2015 to understand operational scale, feedstock inputs, and energy use of wood pellet production in the region (see Supporting Information SI3). Contacts at all existing pellet facilities were emailed a link to an online survey followed up by a phone call. Nine of the 10 facilities responded to the 16-question survey (three from New York, three from Maine, one from New Hampshire, and two from Vermont). Survey questions addressed feedstock consumption and composition, information about forester involvement and third-party certification, transport distance (to and from mill), delivery mechanism, production capacity, electricity source, and process heat energy source. Responses were tabulated and summarized at both a facility level and for the sector as a whole. Results are reported here anonymously and in aggregate to protect proprietary information. Results were used to develop ForGATE scenario inputs.

2.4. Economic scenario and forest sector assumptions

Pellet mill inputs for the ForGATE scenarios used insight from the survey data to frame the input parameters and assumptions. Based on the survey results, pellet mills in the region fall into three categories of feedstock inputs: 1) 100% pulpwood and small

diameter trees; 2) 100% sawmill residue; and 3) some combination of pulpwood/small diameter trees and sawmill residue. While individual facilities vary in terms of feedstock inputs, 55.7% of total feedstock consumption by the nine facilities came from forest harvesting operations, 43.8% from sawmill residues (primary and secondary), and 0.5% from other sources such as municipal waste and landscaping/yard trimming. Of the feedstock from forestry operations, only 2% of the volume came from tops and limbs (i.e., "harvest residues"), the remainder was classified as pulpwood (76%) or small diameter trees (22%). All nine facilities across the Northern Forest consumed a combined 497,500 MT of wood in 2014, which is 79% of the stated total capacity of the nine facilities. Hardwood feedstock represented 65.9% of the total green weight of inputs, the remainder was softwood feedstock. Mean production per facility for 2014 was 57,152 MT and ranged from 10,886 MT to 105,233 MT. For the analyses below, we assumed a single 45,359 MT/year) of output pellet facility was added to the landscape, which is slightly lower than the average production based on the survey results but within the typical range for the region. Most facilities use wood for process heat (one uses natural gas and another uses a mix of electricity, home heating oil, and wood). All facilities use electricity from the grid.

A dynamic forest sector market context made it necessary to evaluate different baseline and alternative pellet production market scenarios. We identified three primary economic scenarios on which to base our analyses (Fig. 1):

Scenario 1 'New Harvests': All harvested low-grade material such as pulpwood has a market at current harvest levels. The baseline forest sector does not include a pellet plant. If pellets are to be produced, an increase of harvested wood in addition to current levels is required to supply pellet production for the alternative future.

Scenario 2 'Market Shift': Pulpwood consumption in the region is reduced below recent levels, which creates a surplus of low-grade material. Recent (2008–2015) harvest levels of low-grade material such as pulpwood are maintained and used to make pellets instead of pulp, paper, or fiberboard. This trend is currently observed in Maine [20]. The annual harvest volume does not change between the baseline forest sector and the alternative future pellet forest sector.

Scenario 3 'Low Demand': Pulpwood consumption in the region drops; consequently, harvest levels are reduced below current levels to create a counterfactual baseline with low demand relative to recent history. The alternative future is the addition of a new pellet facility that generates enough demand to return harvest activity to recent levels.

In the case of Scenario 2 'Market Shift' where pellets are made instead of pulp and paper or fiberboard building material (e.g., oriented strand board), the baseline forest sector GHG emissions include the tracking of wood disposition fate throughout the 50-year study period. However, GHG emissions from the lumber, paper, and other wood product manufacturing are not assumed to be avoided because global production is increasing or at least stable [25,26]. By conducting the LCA in this manner, we seek to address the impact of leakage GHG emissions from our analysis boundary. All economic scenarios were forecast using a 50-year time horizon to evaluate long-term trends, though forest growth and yield projections do not include climate change factors and natural disturbances.

The GHG impact of wood product substitution, i.e. the use of wood products instead of fossil-fuel intensive products such as steel or concrete, was evaluated using a mean value of 2.1 MT carbon substituted per MT carbon stored in lumber used [27].

3. Results

3.1. Climate impacts by economic scenario and feedstock choice

Net GHG emissions were mostly influenced by economic scenario and feedstock source when comparing wood pellet heating scenarios that displace a home heating oil baseline (Table 2). Considering the uncertainty associated with forward modeling of ecosystems paired with economic scenarios (see 4.2), results in Table 2 need to be interpreted cautiously and on a high level. We

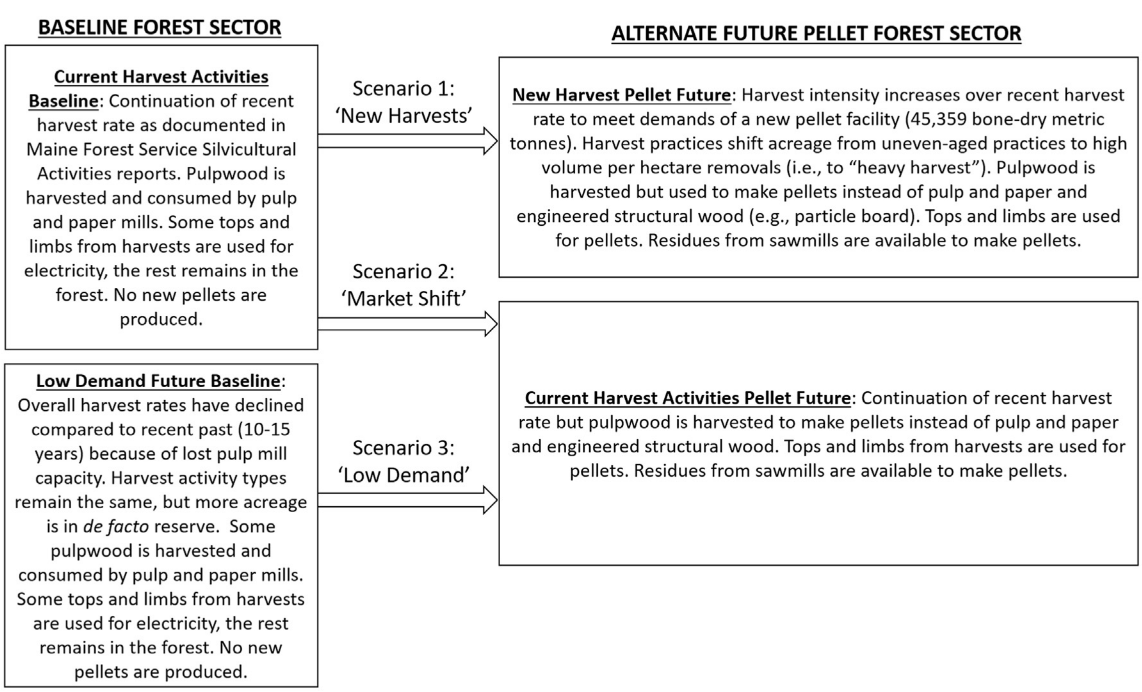

Fig. 1. Forest sector market comparison pathways.

categorized the results as: 1) Climate Negative; 2) Climate Neutral; or 3) Climate Beneficial. Climate Negative indicates that the alternate pellet future generally results in >5% GHG emissions greater than the baseline forest sector. Climate Neutral alternative pellet future results were within + or − 5% of the baseline forest sector emissions. A Climate Beneficial alternate pellet future emissions result was >5% below the baseline forest sector emissions.

3.1.1. *Climate Negative*

When additional material needed to be harvested to meet the demands of a new pellet facility (Scenario 1 "New Harvests"), the alternate future pellet forest sector emissions for the wood supply area was always greater than 5% more than the baseline forest sector emissions. This held true even as sawmill residues were mixed in with the pulpwood quality material up 70%. For the 'Market Shift' scenario (Scenario 2), when 100% pulpwood was used as the feedstock, GHG emissions were 5% greater than the baseline forest sector for the entire study period.

3.1.2. *Climate Neutral*

In the 'Market Shift' scenario (Scenario 2), when 50–75% of the feedstock came from sawmill residue (and 25–50% from pulpwood), the alternate future pellet sector GHG emissions were generally in the Climate Neutral category ranging from +1% to −3% difference from the baseline forest sector emissions. Also in this category was the 'Low Demand' scenario (Scenario 3, 100% pulpwood feedstock).

3.1.3. *Climate beneficial*

Using 100% sawmill residues always resulted in distinct climate benefits under all market scenarios. The use of harvest residues also provided clear climate benefits over the entire study period. Using pulpwood for pellets due to a market shift away from pulp, paper, or fiberboard (Scenario 2, 'Market Shift') was beneficial only when 25% or less of the feedstock came from that source.

3.1.4. *Variability*

With the exception of harvest residues that showed considerably increased climate benefits with increased timescale, climate benefits were less affected by the timescale analyzed. Pellet net GHG emissions measured in MT CO_2e/MT pellets produced was more sensitive to a change in timescale than total net GHG emissions change across the wood supply area.

The choice of the residential heating alternative had an impact when determining climate benefits of using pellets. The overall climate impact presented in the above ranking (Table 3) did not change when pellets were compared to propane heating systems instead of home heating oil. Compared to natural gas, however, the Climate Beneficial and Climate Negative scenarios and feedstock combinations became less pronounced in their climate impact across the wood supply area. Comparing pellets to an air-source heat pump option created Climate Neutral results for all economic scenario and feedstock combinations except for net GHG emission increases when using pulpwood under Scenario 1 'New Harvests' in which case results for heat pumps are Climate Negative as well.

Including wood product substitution muted overall negative or positive climate effects across scenarios and feedstock choices. The ranking of feedstock and scenario combinations in terms of climate benefits remained unchanged.

We observed a negligible impact of the electricity grid mix (used at pellet facilities) and the associated GWIs across all scenarios. For instance, in the case of Scenario 2: 'Market Shift', an 80% lower GWI for grid electricity in Vermont [23] compared to Maine decreased

Table 3
GHG emissions by economic scenario and timescale when displacing home heating oil with regionally sourced wood pellets in the Northern Forest. Net GHG emissions (MT CO_2e/y) are across the wood supply area and inclusive of upstream and downstream forest sector emissions. Green and red shading indicate positive and negative climate benefits, respectively. Plant size was scaled for 45,359 MT of annual pellet production and partly limited by scenario-specific wood supply area forest growth limits.

	Feedstock				Pellet Net GHG emissions									
	0%	Source		100%	MT CO_2e/Y			% Change			MT CO_2e/MT Pellets			Results Category
Scenario Title	Pulpwood		Sawmill Residues		10 y	20 y	50 y	10 y	20 y	50 y	10 y	20 y	50 y	
1 'New harvests'	■	□	□	□	27,240	29,886	31,474	3%	4%	4%	0.6	0.7	0.7	Climate Neutral
1 'New harvests'	■	■	□	□	57,361	59,030	60,032	7%	8%	8%	1.3	1.4	1.4	Climate Negative
1 'New harvests'	■	■	■	□	87,553	88,245	88,660	11%	11%	12%	2.1	2.1	2.1	Climate Negative
1 'New harvests'	■	■	■	■	117,813	117,527	117,356	15%	15%	15%	2.8	2.8	2.8	Climate Negative
2 'Market shift'	Harvest Residues				20,665	2,231	-21,292	2%	0%	-3%	0.5	0.0	-0.5	Climate Neutral
2 'Market shift'	□	□	□	□	-85,185	-85,185	-85,185	-11%	-11%	-11%	-1.9	-1.9	-1.9	Climate Beneficial
2 'Market shift'	■	□	□	□	-53,411	-54,452	-55,077	-7%	-7%	-7%	-1.2	-1.2	-1.2	Climate Beneficial
2 'Market shift'	■	■	□	□	-21,558	-23,640	-24,889	-3%	-3%	-3%	-0.5	-0.5	-0.5	Climate Neutral
2 'Market shift'	■	■	■	□	10,376	7,253	5,379	1%	1%	1%	0.2	0.2	0.1	Climate Neutral
2 'Market shift'	■	■	■	■	42,388	38,224	35,725	5%	5%	5%	0.9	0.8	0.8	Climate Negative
3 'Low demand'	■	□	□	□	-76,441	-73,437	-71,635	-10%	-9%	-9%	-1.7	-1.6	-1.6	Climate Beneficial
3 'Low demand'	■	■	□	□	-44,604	-42,641	-41,463	-6%	-5%	-5%	-1.0	-0.9	-0.9	Climate Beneficial
3 'Low demand'	■	■	■	□	-12,674	-11,752	-11,199	-2%	-2%	-1%	-0.3	-0.3	-0.2	Climate Neutral
3 'Low demand'	■	■	■	■	19,343	19,224	19,153	2%	2%	3%	0.4	0.4	0.4	Climate Neutral

net GHG emissions for pellet production by only 17% over a 50-year timeframe with negligible net GHG emissions change at the wood supply area scale.

Transport distance for both raw material to the pellet plant and pellets to the end user as well as sourcing of process heat at the pellet plant was inconsequential in its impact on overall results for all scenarios. For instance, a ten-fold increase in both sourcing and delivery distance or a switch from natural-gas derived process heat to wood heat from wood-based mill residues changed the wood supply area net pellet emission profile by around one percent over a 50-year time frame.

For pellets made from harvest residues, results were highly dependent upon decomposition rate assumptions. However, since harvest residues constitute only two percent of pellet feedstock in the northeastern US (see section 2.4), decomposition rate assumptions for a baseline scenario have a limited impact.

3.2. GHG emissions by carbon pool

The significance of the carbon pools changes by the choice of the economic scenario. In economic scenarios that include a change in harvest regimes, forest carbon fluxes dominate net GHG emission results (Fig. 2 a,c). An unchanged harvest regime (Fig. 2 b) results in no difference in forest live and dead biomass storage. Avoided fossil-fuel GHG emissions from heat energy generation in conjunction with an increase in forests products in use generated net positive climate benefits over the baseline in this scenario. The temporal scale of analysis (10, 20 or 50 years) had a muted impact on results only in the scenario where harvest regimes did not change and results were driven by a change in forest products and respective product life cycles.

3.3. Results at the household level

While net GHG emission change at the wood supply area scale was generally muted (see Table 2), the change of net GHG emissions are more pronounced when looking at the household level (Fig. 3). Compared to the GHG emissions change at the wood supply area scale or net GHG emissions associated with a unit of pellets produced, using the household level metric of GHG emissions in g/kWh suggests the strongest differences in climate impacts of heating alternatives. For instance, Scenario 2, 'Market Shift' with a 50% sawmill residue, 50% pulpwood feedstock mix provides considerable climate benefits scaled to the household level compared to all heating alternatives except an air-source heat pump.

While net GHG emission change on a wood supply area scale was generally muted (e.g., <15% difference; see Table 2), the net GHG emissions margins between heating technology alternatives suggest more pronounced differences when using the household level metric of GHG emissions in g/kWh. For instance, the economic 'Market Shift' scenario (Scenario 2) with a 50% sawmill residue, 50% pulpwood feedstock mix provides considerable GHG emission benefits compared to other heating alternatives except an air-source heat pump (Fig. 3). Heat pumps in Maine that rely on grid electricity fare better against wood pellets because Maine's

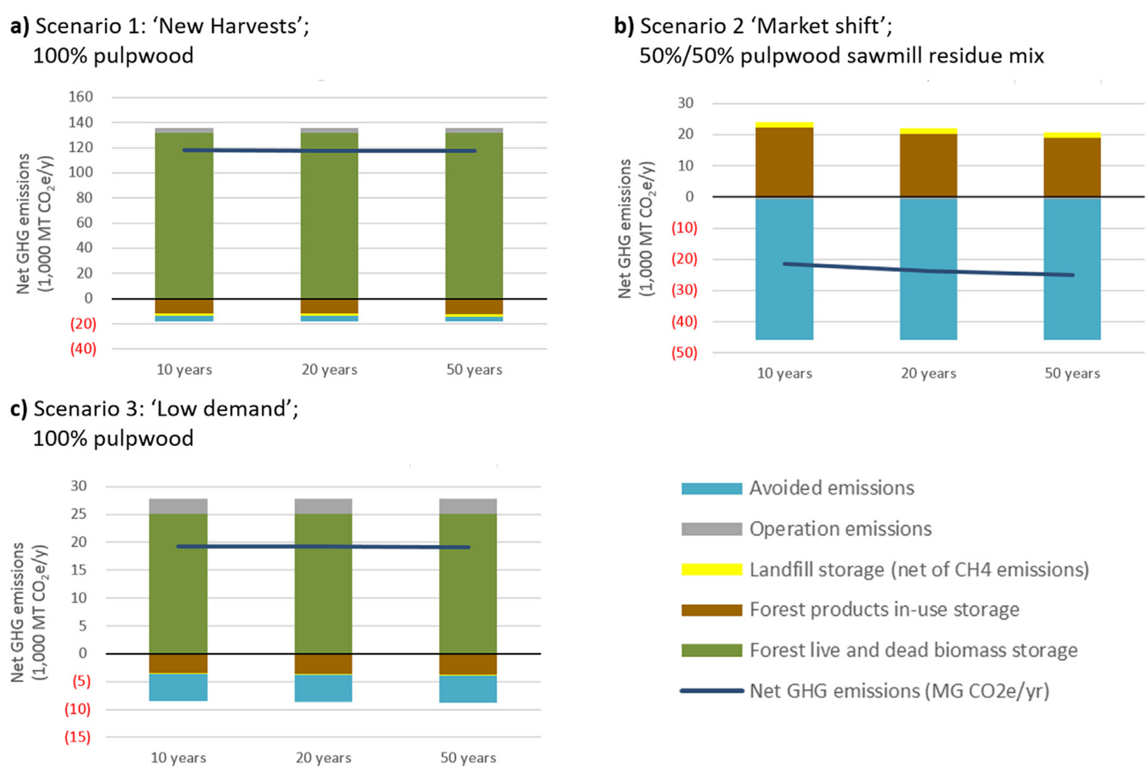

Fig. 2. Net GHG emissions across a representative wood supply area in the northeastern US by carbon accounting category and timescale with example feedstock mixes for each economic scenario. All scenarios assume that 50% of the feedstock is derived from sawmill residues while the remaining 50% are sourced from forest operations. Pellets from new harvests in addition to current harvest activities (Figure 2a) as well as pellets derived from harvests that would have not been executed due to the closing of pulp mills (Figure 2c) result in a net GHG increase mostly driven by net GHG emissions occurring in forest carbon pools (green). Pellets derived from harvests that would have occurred anyway to supply (now closed) pulp mills (Figure 2b) result in a net GHG decrease mostly driven by reduced avoided fossil fuel emissions from both pulp manufacturing and fossil-fuel based heat. See Fig. 1 for an explanation on the three forest sector market scenarios. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

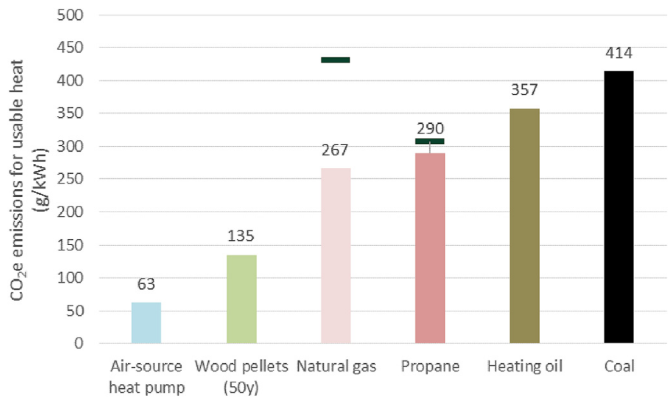

Fig. 3. Net GHG emissions for residential heat from heat of pellets vs. other heating alternatives in the Northern Forest for pellet Scenario 2 'Market Shift' and a feedstock mix of 50% sawmill residue, 50% pulpwood. While this metric suggests a strong impact of heating alternative, wood supply area analysis suggests only a muted impact of heating alternative on GHG emissions. Black bars for natural gas and propane present potential net GHG emissions for these fuels when including methane distribution losses of 2.4% natural gas [28] and 0.24% for propane.

electricity grid GHG profile is 40% below the US average. Heat pumps using the US average electricity grid mix would produce 164 g CO_2e/kwh emissions which is greater than our estimate of wood pellet emissions [23].

4. Discussion

4.1. Overall impact and GHG emissions metrics

Mixing pulpwood trees with sawmill residue to make wood pellets for residential heat produces climate benefits up to a certain point (around 75% pulpwood). This remains true particularly if harvest rates do not exceed current rates. Pellets made from sawmill residues alone show the strongest overall climate benefits in all scenarios as a residential heating source compared to other existing heating alternatives. We observed wide variability in feedstock inputs for existing pellet facilities in the northeastern US, which is important to note since we determined that market assumptions and biomass feedstock mix can create widely diverging GHG emission profiles for wood pellets.

The choice of the GHG emissions metric (% change in MT CO_2e/y for a wood supply area vs. MT CO_2e/MT pellets produced vs. CO_2e/kWh net usable heat) plays a crucial role when determining the efficacy of climate mitigation measures [29]. Both the magnitude and communicated certainty of results can differ by metric [30]. For instance, outcomes of Scenario 2 'Market Shift' with a 50% sawmill residue, 50% pulpwood feedstock suggest on a household level the opportunity to cut GHG emissions by over half when installing a wood pellet (135 g CO_2e/kWh for a 20y timescale) instead of a home heating oil (357 g CO_2e/kWh) fueled residential heating system (Fig. 3). At the same time, a pellet plant can assume net GHG emissions of −0.5 MT CO_2e for each MT of pellets produced (Table 2). The combined net GHG emission reductions across the wood supply area of 23,640 MTCO_2e/y equal the GHG emissions of over 5000 typical US passenger vehicles taken off the road when assuming GHG emissions of 4.7 MT CO_2e/y per vehicle [31]. Our model assumed that around 7300 households could be heated by pellets produced from a 45,530 MT/y pellet plant assuming a higher heating value of 15.6 Gigajoule per MT pellets at a moisture content of seven percent [32] and an average residential heating demand in the northeast of 21,634 kWh/y per household [33]. At the scale of the entire wood supply area (504,081 ha), our model suggests that the GHG reduction will be about three percent annually for the same scenario. The difference of impact based on scale and metric is analogous to the impact of driving an electric vs. a gasoline powered car: individual emissions can be reduced significantly, but a single electric car has a fractional impact on atmospheric GHG.

Altering ecological conditions had a diminutive effect on results. For instance, switching from a softwood to a hardwood dominated wood supply area changed net GHG emissions by around one percent (for hardwood wood supply area data see Supporting Information SI1).

The one-digit percentage range change in GHG emissions when switching from other home heating options to pellets is markedly muted, especially when considering the uncertainties associated with the climate-impact metric of choice [36], as well as the economic and ecological conditions (e.g. mineral soil carbon response to forest management; [34], large-scale disturbances such as insect calamities [35], modeling complex ecosystems under climate change). Consequently, we i) categorized the climate benefits of a heating fuel switch towards pellets under the a 'Market shift' scenario as Climate Neutral rather than Climate Beneficial and ii) focused on a short-term timescale of 20y. While the uncertainties derived from forward projections should not impede the use of models to explore the impact of policy decisions for planning purposes, the ultimate climate impact of mitigation efforts will eventually only be verifiable by continued monitoring of forest and wood products carbon stocks [37].

4.2. Choice of economic scenario

Considering the broad range of results presented in Table 2 by economic scenario, the question remains: which is the most realistic one? Any prediction on the future management of the US Northern Forest is fraught with uncertainty. Preceded by the decade-old decline of the sawmill industry [38], the current deterioration of the regional pulp, paper, and fiberboard industry [39] and highly volatile pellet markets [16] makes even short-term forecasts difficult. Forest operations economics relying on a multitude of sawlog, pulp, and biomass markets to generate profits and policy uncertainty create additional complexities for economic forecasts [40].

Scenario 1 'New Harvests' is unlikely considering the magnitude of the regional decline in the lumber processing and pulp, paper, and fiberboard sectors compared to the biomass demand of the nascent pellet sector. Moreover, recent research indicates current harvest levels in the northeastern US to be at its ecological capacity [41]. However, there could be specific contexts in the region where low-grade markets remain viable and markets for harvest outputs are saturated. In the example 80 km radii wood supply area, our model using the most aggressive (and therefore unlikely) switch in harvesting practices suggests a maximum of an additional 65,400 MT could be harvested. Even this comparatively small 11% increase in harvest levels across the wood supply area was only achievable by dramatic increases in harvest intensity (i.e., shifting to "heavy harvests") compared to current harvest regimes (Table 1).

We view the 'Market Shift' scenario (Scenario 2), which is based on actual harvesting and pellet manufacturing data from 2015, as the most likely near-term scenario, given its ability to stabilize the sawlog market by providing continuing markets for residues from sawmills and pulpwood. Additionally, harvest levels in Maine, for example, have remained relatively stable over the last 15 years in spite of changes in the marketplace [20]. This market interaction with local harvesting rates is likely buffered by a reduction in broader regional purchases of fiber at a greater haul distance from a

given mill. It remains to be seen how more recent mill closures play out in terms of a maintenance of harvest rates.

Scenario 3 ‘Low Demand’ relied on similar drastic changes in silvicultural practices to produce a baseline that reduced harvest levels equivalent to the pellet plant capacity of 45,350 MT represented in the contrasting alternative pellet future. This was only achievable in our model by increasing clearcutting from 7% in the baseline to 46% of total harvested area in the alternative pellet future (Table 1). A rationale for this dynamic playing out in the real world would be that the forest sector response to constrained markets would require a shift to more intensive silvicultural regimes to reduce costs while accepting reduced forest productivity. Such a shift is plausible, though perhaps not socially acceptable in the region.

In terms of choosing an appropriate fuel alternative to bioenergy systems for GHG emission analysis, Macintosh et al. [42] stress the importance of choosing current and potentially renewable alternatives to bioenergy options rather than dated fossil-fuel based options. However, the high percentage of current installations of home heating oil, natural gas or propane-fueled heating technology in rural homes in the northeastern US [5] as well as the continued trend in installing fossil-fuel technologies [43] justifies this paper's comparison of pellets to GHG-emission intensive fossil-fuel options. At the same time, York [44] and Bird [45] point out that a non-fossil-fuel source usually replaces only a fraction of units of fossil-fuel sources, therefore considerably tempering perceived climate benefits. However, evaluating bioenergy substitution dynamics on the regional heating sector was beyond the scope of this analysis.

4.3. Leakage

Leakage, defined as activity shifting in the presence of a biomass project [46], has the potential to drive forest harvest outside the project area to continue meeting *a priori* economic demand for biomass (e.g., pulp). The uncertainties associated with economic causalities in a globalized economy provide considerable challenges for leakage analysis [47]. The pulp, paper, and fiberboard market is driven by global forces [25]. By excluding manufacturing-based GHG emission savings from closed pulp, paper, and fiberboard production (Scenario 2 ‘Market shift’) we provide conservative estimates of potential GHG emission savings, therefore partly addressing leakage concerns. Since this analysis focused on GHG emissions on a wood supply area scale only, a full leakage analysis was beyond the scope. However, a recent paper by Galik et al. [19] showed GHG emission leakage effects from changes at a national level could outweigh any benefits observed for a region when a switch from fossil energy to bioenergy was widespread and large scale.

4.4. Results in context of other literature

Results are consistent with insights gained in comparable ecoregions. For Massachusetts, Walker et al. [13] detected climate detrimental impacts when increasing harvests to satisfy bioenergy demands. Hennigar et al. [48] concluded for New Brunswick that using biomass for electricity resulted in comparable climate impacts as a ‘Low demand’ scenario.

Full accounting of fossil-fuel use along forest product life cycles, similar bioenergy pathways, and a consistent use of GHG impact metrics frequently make it difficult to compare results. For instance, Mika and Keeton [49] and Keith et al. [50] conclusion for Vermont and natural hardwood forests in Australia, respectively, that bioenergy scenarios resulted in increased net GHG emissions compared to the non-bioenergy harvests was based on models that did not account for fossil-fuel GHG emissions for processing forest products and focused on electricity generation instead of (residential) heat applications. At the same time, studies in comparable ecosystems in Europe have found considerable climate benefits when generating bioenergy from forest biomass instead of a ‘Low demand’ scenario [51,52]; potentially due to using other GHG impact metrics such as albedo effects. Besides affecting leakage as discussed above, economic assumptions such as anticipated market effects further can drive GHG impact results of bioenergy systems as shown by Wang et al. [53].

5. Conclusions

An industry-average feedstock mix consisting of equal parts of sawmill residues and pulpwood-quality wood appears to generate pellet heat in the northeastern US that is at least climate-neutral compared to fossil-fuel heating alternatives when harvest levels are not changed as a result of wood pellet demand and contribute to energy independence in rural areas. The recent loss of pulp and paper and biomass electric facilities creates a surplus of harvested low-grade wood that could be used to make regionally sourced pellets for heat, which is the basis for Scenario 2 ‘Market Shift’. In this current context, switching to pellet heat creates the highest net GHG emission savings or increases at the household level, while the benefit is still present but more muted across a pellet facility's wood supply area. If harvest levels increase due to pellet production, GHG emissions are greater than the baseline in all feedstock combinations that include wood coming directly from the forest. If baseline harvest levels drop (e.g., following the loss of low-grade markets), GHG emissions from new wood pellet heat would at least remain stable relative to fossil alternatives. Pellets from sawmill residues alone show the strongest overall GHG benefits in all scenarios as a heating source compared to other existing fossil heating alternatives.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.energy.2017.09.062.

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