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January 30, 2023

Rec'd LCO
January 30, 2023

Hon. Kelly Regan, MLA
Chair of the Standing Committee on Public Accounts
C/O Legislative Committees Office
1700 Granville Street, One Government Place 2nd Floor
Halifax, Nova Scotia B3J 1X5

Dear Kelly Regan:

Re: NRR Public Accounts Appearance on January 13, 2023 re: Accountability Report and the Management of Crown Lands

In response to the letter dated January 16, 2023, from Kim Langille with the Legislative Committees Office, please find below the information requested during Deputy Minister Karen Gatien's Public Accounts appearance on January 13, 2023.

1. Is the department planning on releasing any kind of a step-by-step, year-by-year analysis of how we're going to meet the 2030 goal? Will the government release a year-to-year plan that explains on the path to 80 per cent renewable energy and the phaseout of coal - what proportion of energy will come from what source each year?

   Electricity planning is a dynamic exercise that requires ongoing market and technology assessment, as well as consideration of available funding and financing tools, such as the Canada Infrastructure Bank or the upcoming federal tax credits, to determine what is the next most cost-effective step to achieving our provincial goals.

   Over the next years, the success of the Green Choice Program and the Community Solar program will determine the remaining renewable energy requirement that will need to be added to the system to meet our 2030 goal. In addition, the ongoing assessment of the cost effectiveness of the options to retire coal, which includes the Atlantic Loop, will be better understood. The results are dependent on federal supports for the various options, as well as federal regulations.

2. In 2019, Nova Scotia Power failed to meet its legislated targets, and therefore the company was levied a financial penalty of around $165 million. Were there terms to the agreement, and if there were terms to the agreement of the forgiveness of that penalty, what were those terms? Is there a way to ensure that when Nova Scotia Power doesn't meet targets or performance standards that there is a real consequence?

   There was no penalty levied in 2019 for a failure to meet a target. NSP is anticipated to have missed its GHG targets during the cap-and-trade compliance period. NSP has estimated it would have had to purchase ~$165M in GHG credits through the auction or

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reserve. ECC has stated that they will produce a regulatory change that will have the effect of reducing NSP's compliance obligations under cap-and-trade, resulting in NSP not needing to purchase $165M worth of GHG credits. That regulatory mechanism is under development.

Regarding NSP and performance standards overall: NSP performance standards were introduced at the UARB in 2017. At that time, the standards were limited to day-to-day customer service; storm response; and reliability of service. In Spring 2022, Government introduced changes to the Public Utilities Act that would enable Governor-In-Council to create regulations pertaining to 20 performance standards that consider the utility's performance across a broader range of issues, including rural/urban outage response and industrial reliability. The full list can be found at section 52 (A) of the Public Utilities Act: Public Utilities Act (nslegislature.ca). To date, two regulations have been created under Section 52 (A), regarding outages and reliability, and power quality. The regulations can be found at: Nova Scotia Power Incorporated Performance Standards Regulations - Public Utilities Act (Nova Scotia)

3. What percentage of that program (heat pump program) is being funded by the federal government and what percentage is by the provincial government?

The province is investing $140 million, which will leverage $215M in Federal funding from 3 separate funding streams administered by ECCC and NRCan. In percentage terms, it rounds out to 39% provincial and 61% federal.

4. Does the department have plans to bring forward a lifecycle analysis about biomass-generated electricity?

There are no plans by NRR (or ECC), currently, to bring forward a lifecycle analysis of biomass generated for electricity; however, James Steenberg, a Senior Research and Planning Forester with NRR has co-authored a peer-reviewed article with researchers at Dalhousie and the Canadian Forest Service, that looks at the GHG dynamics of combined heat and power from forest biomass in the province. I have included the article for your information.

If you require any further information, please do not hesitate to contact my office.

Yours truly,

Karen M. Gatien

Karen M. Gatien
Deputy Minister

Attachment (steenberg_et_al_2023)

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Research Article

Forest Management

Life-Cycle Greenhouse Gas Emissions from Forest Bioenergy Production at Combined Heat and Power Projects in Nova Scotia, Canada

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Abstract

Forest bioenergy production can represent a renewable energy supply while benefiting the forest sector. However, greenhouse gas (GHG) reductions are often not immediate. The point of carbon parity where bioenergy starts delivering GHG benefits may be years to decades in the future. This study examined the life-cycle emissions associated with bioenergy production at combined heat-and-power (CHP) projects in Nova Scotia, Canada. We examined the effects and sensitivities of different feedstock mixes of chips from harvested roundwood and mill residues, the implementation of intensive and extensive silviculture strategies, and different market/supply-chain assumptions around additionality and product substitution. We found contrasting GHG outcomes for bioenergy, depending largely on additionality assumptions and biomass type. When primary biomass (roundwood) was used as the feedstock type, carbon parity was achieved within four to nine years when pulp and paper products were substituted, whereas carbon parity was achieved in 86–100 years or longer when biomass harvests were additional. Net GHG benefits were achieved in 10 years with the use of secondary biomass (mill residues) as the bioenergy feedstock, although they were delayed when at lower energy conversion efficiencies. Adoption of more intensive silvicultural practices (plantations) reduced the time to carbon parity because of increased yields, although uncertainties in long-term soil carbon storage exist.

Study Implications: Our analysis shows that the use of forest biomass in local CHP facilities can deliver GHG benefits in the short term but there is substantial variability. Carbon parity times were the longest with the use of additional primary biomass feedstocks (i.e., roundwood) but were substantially reduced when biomass harvests substituted harvests for pulp and paper products and when secondary biomass (i.e., mill residues) was used. This study highlights the nuance of different forest management dimensions (e.g., silviculture) while also presenting novel findings on the importance of assumptions around biomass harvesting being additional to current practices or a substitution for declines in traditional forest products.

Keywords: forestry, biomass, bioenergy, carbon, carbon parity

International agreements like the United Nations Framework Convention on Climate Change, the Kyoto Protocol, and the Paris Agreement reflect the global effort to reduce greenhouse gas (GHG) emissions to mitigate climate change. The Pan-Canadian Framework on Clean Growth and Climate Change represents Canada's recent move towards a low-carbon economy (Government of Canada 2016). One of the primary approaches used by countries to reduce emissions shifting their energy sectors towards a greater mix of renewable energy sources, such as solar, wind, and hydroelectricity (Edenofer et al. 2011; IPCC 2014). Bioenergy from forest biomass represents an option for energy production that is included in the category of renewables among international and national guidelines and reporting standards (Edenofer et al. 2011; IPCC 2014).

Government agencies responsible for emissions reporting, including Environment and Climate Change Canada and the United States Environmental Protection Agency, dictate how biogenic carbon emissions from bioenergy production are accounted for in reporting. The CO_2 emissions resulting from the combustion of biomass (i.e., biogenic carbon emissions) are excluded from energy sector GHG emissions in GHG inventories. Biogenic carbon emissions and removals associated with forests, including biomass combustion, are currently accounted for in the Agriculture, Forestry, and Other Land Use sector (also called land use, land-use change, and forestry or just the land sector). However, often these biogenic carbon emissions from the land sector are not accounted for at the scale of individual projects or studies that are focused on bioenergy production alone (Beagel and Belmont 2019;

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McKechnie et al. 2016; Morrison and Golden 2017; Nova Scotia Environment 2020). This can lead to considerable underestimates in GHG emissions associated with bioenergy production (Sterman et al. 2018).

Researchers have recently highlighted this issue and argued that more representative modeling approaches that account for both the energy and land sectors are needed to account for changes in forest carbon balance associated with biomass energy activities (Johnson 2009; Smyth et al. 2017; Ter-Mikaelian et al. 2015). In fact, the actual point at which forest bioenergy may yield net reductions in GHG emissions relative to fossil fuels may be immediate in some cases, take years or decades in others, or may not be achieved at all (Liu et al. 2018). The point in time when net GHG balance is achieved is called carbon parity (Laganière et al. 2017; Mitchell et al. 2012; Ter-Mikaelian et al. 2015). Carbon parity can be defined as "… the time needed for the newly established bioenergy system to reach the cumulative carbon emissions of a fossil fuel, counterfactual system" (Laganière et al. 2017, 385). Before this point, it is possible for GHG emissions from bioenergy to be higher than those from fossil-based energy production. After this point, it is possible to achieve net emissions reductions and contribute to climate change mitigation.

A number of recent scientific publications (Laganière et al. 2017; Liu et al. 2017; McKechnie et al. 2011; Mitchell et al. 2012; Ter-Mikaelian et al. 2015; Wolf et al. 2016), including the IPCC's Fifth Assessment Report (IPCC 2014), indicate that when life-cycle emissions are considered, forest bioenergy systems can be either a source or a sink of atmospheric CO_2, depending on many factors. These factors include the type of biomass used (e.g., mill residues versus harvested trees), conversion efficiencies, upstream emissions associated with the supply chain (e.g., transportation), and the type of fossil fuel that the bioenergy is displacing (e.g., coal versus natural gas) (Buchholz et al. 2016). The extensive nature of forest management, complexities of forestry supply chains, and the influence of forest ecosystem type and forest management regimes make conducting assessments and comparisons difficult. Finally, the results of life-cycle GHG emission assessments of wood biomass energy can vary, depending on the assumptions and methodological choices made by practitioners when accounting for these various elements (Cintas et al. 2016; Cowie et al. 2021). Consequently, there is a high degree of uncertainty and variability around determining the carbon implications of forest bioenergy production.

The purpose of this study was to quantify the life-cycle emissions associated with bioenergy production from woody biomass feedstocks at combined heat and power (CHP) systems in northeastern mixedwood (i.e., mixed softwood and hardwood species) forest regions. The analysis focused on quantifying the cumulative life-cycle GHG emissions over a 100-year study period and estimating the length of time required for the bioenergy system to achieve carbon parity. In particular, we examined the effects and sensitivities of different biomass feedstocks and forest management assumptions, including (1) different feedstock mixes of wood chips from harvested roundwood (also referred as primary biomass) and mill residues (also referred as secondary biomass), (2) the implementation of intensive and extensive silviculture strategies, and (3) different market and supply chain assumptions, including bioenergy as entirely additional (i.e., no harvest in absence of bioenergy demand) or as a substitution for other forest products that have declining demand, such as pulp and paper products.

Methods

Study Area

This analysis is focused on all forest bioenergy CHP projects in Nova Scotia, Canada, as of 2017 (figure 1), when the most recent and complete data were publicly available at the time of analysis. Nova Scotia is a province on the Atlantic coast of Canada that is situated within the Acadian Forest Region, which is a transitional zone between boreal, conifer-dominated forests to the north and temperate, nonconifer-dominated forests to the south. The province has a total land area of 5.5 million ha and a forested area of 4.2 million ha, with an annual harvest of approximately 3.3 million m^3 in 2017 (Nova Scotia Department of Natural Resources 2018). There were five CHP bioenergy projects in Nova Scotia in 2017. The Port Hawkesbury Biomass Plant is a 60 MW CHP plant owned by the province's energy utility and located adjacent to a pulp mill and is capable of meeting approximately 4% of the province's electricity demand (in 2017). Brooklyn Power is a 30 MW CHP plant owned by the energy utility's parent company, located at the former site of a pulp mill that closed in 2012. Northern Pulp is the other pulp mill in the province, which is owned and operated by the mill and not the energy utility, and it has a 25 MW CHP capacity. Hefler Forest Products is a softwood sawmill that was funded under the province's community feed-in tariff program in 2015, with 3.1 MW CHP capacity. Taylor Lumber is another softwood sawmill, with 1.15 MW CHP capacity. Nova Scotia's bioenergy capacity is highly integrated with the province's forest sector and its supply chains.

Data describing the primary biomass feedstocks used for bioenergy production in 2017 were derived from the Nova Scotia Registry of Buyers of Primary Forest Products annual report (Nova Scotia Department of Natural Resources 2018). A total of 74,710 t (all biomass reported as green metric tonnes unless otherwise stated) of primary biomass were reported as used for energy purposes. This category does not include firewood or fuelwood, the latter of which is defined as wood to be used for nonresidential heating or heating product production (e.g., pellets). The amount of secondary products (e.g., mill residues) used for energy generation is not tracked or reported and must be estimated. In this study, primary biomass refers to harvested roundwood and secondary biomass refers to mill residues. Current practice in the province does not include the use of harvest residues for bioenergy production.

The Statistics Canada Report on Energy Supply and Demand in Canada (Statistics Canada 2019) reports 1,287,000 GJ of electricity generation from biomass in 2017 in Nova Scotia (2.5% of total electricity generation). Conversion efficiencies are not reported, so values from the literature must be used, including 26% efficiency for electricity generation from biomass and 76% efficiency for CHP from biomass ((S&T) Squared Consultants Inc. 2015; Laganière et al. 2017; Wolf et al. 2016). It is known that older facilities (e.g., Port Hawkesbury Biomass Plant) have conversion efficiencies for CHP as low as 30% to 40% (The Shaw Resource Group Inc. 2010), whereas newer CHP facilities may have higher efficiencies than the above average from the literature. Consequently, we conducted a sensitivity analysis on conversion efficiency rates.

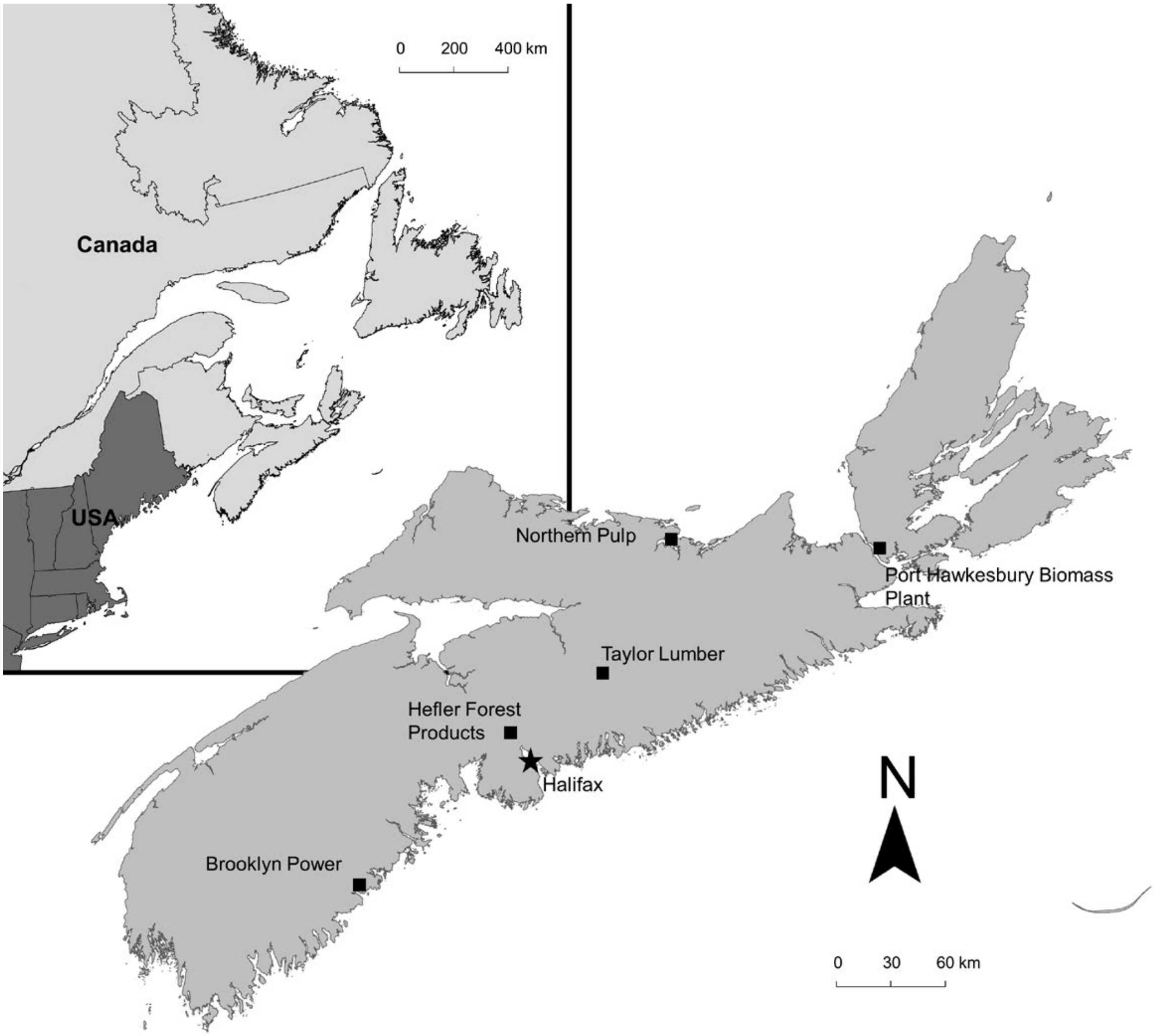

Figure 1 Location of the five forest bioenergy projects active in 2017 that were included in the study, along with the provincial capital of Halifax in Nova Scotia, Canada.

To estimate total primary and secondary biomass consumption and energy production values for 2017 and thus the total amount of carbon emissions and removals, we assumed an energy content for wood and wood waste at 50% moisture content of 9.6 GJ/t (Nova Scotia Environment 2020). This energy content value, the total reported amount of primary biomass consumed, the reported electricity generation from biomass, and the conversion efficiencies from the literature were used to derive the estimated values for secondary biomass and total energy production (Table 1). The final estimated ratios of primary and secondary biomass are 14.4% and 85.6%, respectively. Again, due to uncertainties in these estimations, we also conducted a sensitivity analysis to determine the influence of this ratio of primary to secondary biomass fuel on study results.

Life-Cycle Bioenergy Emissions

This study and its analysis were designed based on the study by Laganière et al. (2017) and the corresponding Natural Resources Canada (NRCan) Bioenergy GHG Calculator online tool (Natural Resources Canada 2015) and subsequent applied versions of this methodology in specific contexts (Buss et al. 2022). The Laganière et al. (2017) and Buss et al. (2022) accounting formulae were used, with additional values taken from the literature when not included in the original study or when needed to reflect local conditions in Nova Scotia. The Laganière et al. (2017) study was based on the entire boreal and temperate managed forest area of Canada. Under generic and theoretical scenarios of biomass utilization, it quantified the time required to reach carbon parity for bioenergy systems using harvest residue, salvaged tree, and green tree feedstocks that replace coal, oil, and natural gas feedstocks in both electricity and heating systems. Buss et al. (2022) updated the Laganière et al. (2017) equation so that both the bioenergy carbon and fossil carbon are standardized by total biomass to be directly comparable. In this study, we report the total amount of cumulative emissions of CO_2eq (i.e., the amount of all GHGs expressed as units of CO_2 according to their global warming potential) under different scenarios for CHP

Table 1. Reported and estimated energy production and biomass consumption for CHP bioenergy facilities in Nova Scotia in 2017 (Nova Scotia Department of Natural Resources 2018; Statistics Canada 2019).

Variable	Value
CHP generating capacity	119.25 MW
Conversion efficiency for electricity	26%
Conversion efficiency for CHP	76%
Total fuel energy	4,950,000 GJ
Net electricity production	1,287,000 GJ
Net thermal energy production	2,475,000 GJ
Total net energy production	3,762,000 GJ
Total biomass fuel	515,625 t
	464,401 t CO_2eq
Primary forest biomass	74,170 t
	67,520 t CO_2eq
Secondary forest biomass	441,455 t
	396,881 t CO_2eq

bioenergy facilities and the forested land base required for feedstock supply in Nova Scotia in 2017. For our modeling exercise, the 2017 biomass harvest and annual operating levels were fixed during our simulation period, although in reality, these parameters will vary by unknown amounts. A 100-year simulation length was selected both because it is the time horizon used for strategic forest planning in Nova Scotia and to capture a range of potential carbon parity times.

The life-cycle GHG emissions from forest bioenergy account for the avoided emissions from the displacement of fossil fuels (e.g., coal-based electricity in Nova Scotia) for bioenergies (figure 2). As such, the emissions from fossil fuels that would have been used in energy production are subtracted from the bioenergy emissions, and the carbon stored in forests that are not harvested for biomass or in other forest product types when using fossil fuels are accounted for and modeled. In one suite of scenarios, we assumed that bioenergy harvesting was additional to current rates of harvesting, with these forests remaining unharvested when using fossil fuels and not being affected by natural disturbance (Table 2). In a second suite of scenarios, we assumed that bioenergy was not additional, and biomass harvests replaced declining harvests of other forest products (e.g., lumber, pulp, and paper). The emissions from fossil fuels and associated forest carbon and product carbon dynamics together in any one scenario represent the business-as-usual (BAU) pathway. Every scenario contains both a bioenergy (i.e., biomass) pathway and BAU (i.e., fossil fuel) pathway. No other emissions from product substitutions were modeled because lumber consumption remains constant in all scenarios, and the replacement of pulp and paper products with biomass is the result of declining demand for pulp and paper, so no substitution emissions exist. The treatment of secondary biomass feedstock (e.g., mill residues) in the BAU pathway is different from primary biomass feedstock and is discussed in detail in the Upstream Emissions section.

Three sources of GHG emissions and removals are quantified and modeled over 100-year simulations (figure 2), following the approach of Laganière et al. (2017), NRCan (2015), and Buss et al. (2022). These include (1) direct emissions from stationary combustion of either forest biomass or fossil fuels; (2) upstream emissions associated with the supply chain for either forest biomass or fossil fuels, including collection, production, and transportation; and (3) emissions and/or removals of carbon associated with forest carbon pools, including living forest biomass, dead organic matter, and harvested wood products. The cumulative GHG emissions from forest bioenergy production were calculated as

$$\Delta GHG_t = \frac{GHG_{t\ BIO} + FC_{t\ BIO}}{CE_{BIO}} - \left(\frac{GHG_{t\ FOSSIL}}{CE_{FOSSIL}} + \frac{FC_{t\ FOSSIL}}{CE_{BIO}} \right)$$

where ΔGHG_t is the total life-cycle emissions from forest bioenergy at time t, $GHG_{t\ BIO}$ is the emissions from bioenergy production only (direct and upstream), $GHG_{t\ FOSSIL}$ is emissions from fossil fuel energy production (direct and upstream), $FC_{t\ BIO}$ and $FC_{t\ FOSSIL}$ are the forest carbon emissions/removals for the bioenergy only and coal pathways, respectively, and CE_{BIO} and CE_{FOSSIL} are the conversion efficiencies for bioenergy and fossil fuel, respectively (Buss et al. 2022).

The analysis included combinations of three biomass type scenarios, six forest management scenarios, and two scenarios on the assumption of additionality of forest bioenergy (Table 2). The combination of these three scenario categories yield a total of 15 experimental scenarios (Table 3), although these are grouped in the reporting of results for the sake of parsimony. Note that there is no single BAU scenario; rather, each of the 15 modeled scenarios has both a bioenergy pathway and BAU pathway and the scenario itself represents the difference between them. The biomass type scenarios included a 100% primary biomass fuel source, 100% secondary biomass fuel source, and 14.4% to 85.6% primary to secondary biomass ratio to reflect current conditions (i.e., 2017). When primary biomass was used in two of the three aforementioned fuel type scenarios, the forest management scenarios included a simple scenario with 60-year rotations in natural stands with clear-cut harvests, an intensive scenario where stands harvested for biomass are then converted to softwood plantations on 30-year rotations, and an extensive scenario where stands harvested for biomass are regenerated as natural stands with uneven-aged management with 20% removal in 20-year entry intervals. Again, when primary biomass is used in the two of three fuel type scenarios, the two assumption scenarios included an additional scenario where all biomass harvests are additional within forests that would remain unharvested in BAU conditions and a substitution scenario where all biomass harvests are not additional but a substitution for traditional harvested wood products (see the Forest Modelling section for more information on carbon modeling of harvested wood products).

Finally, we included three modified management scenarios to further investigate the uncertainties around forest management and forest biomass supply chains. When primary biomass is used as a fuel and forest biomass harvests are not additional, we included a scenario where biomass is a substitution of only pulp products under the assumption of declining demand for pulp products and/or pulp mill closures. We also included a second scenario where harvest residues are used in addition to roundwood harvests for bioenergy production for reference purposes (recall that harvest residues are not used for biomass in Nova Scotia). Regarding the intensive management scenario, it is unlikely that these silvicultural treatments would be implemented on 100% of the harvested land base, and where they are implemented, it is unlikely that planation growth rates would reach their

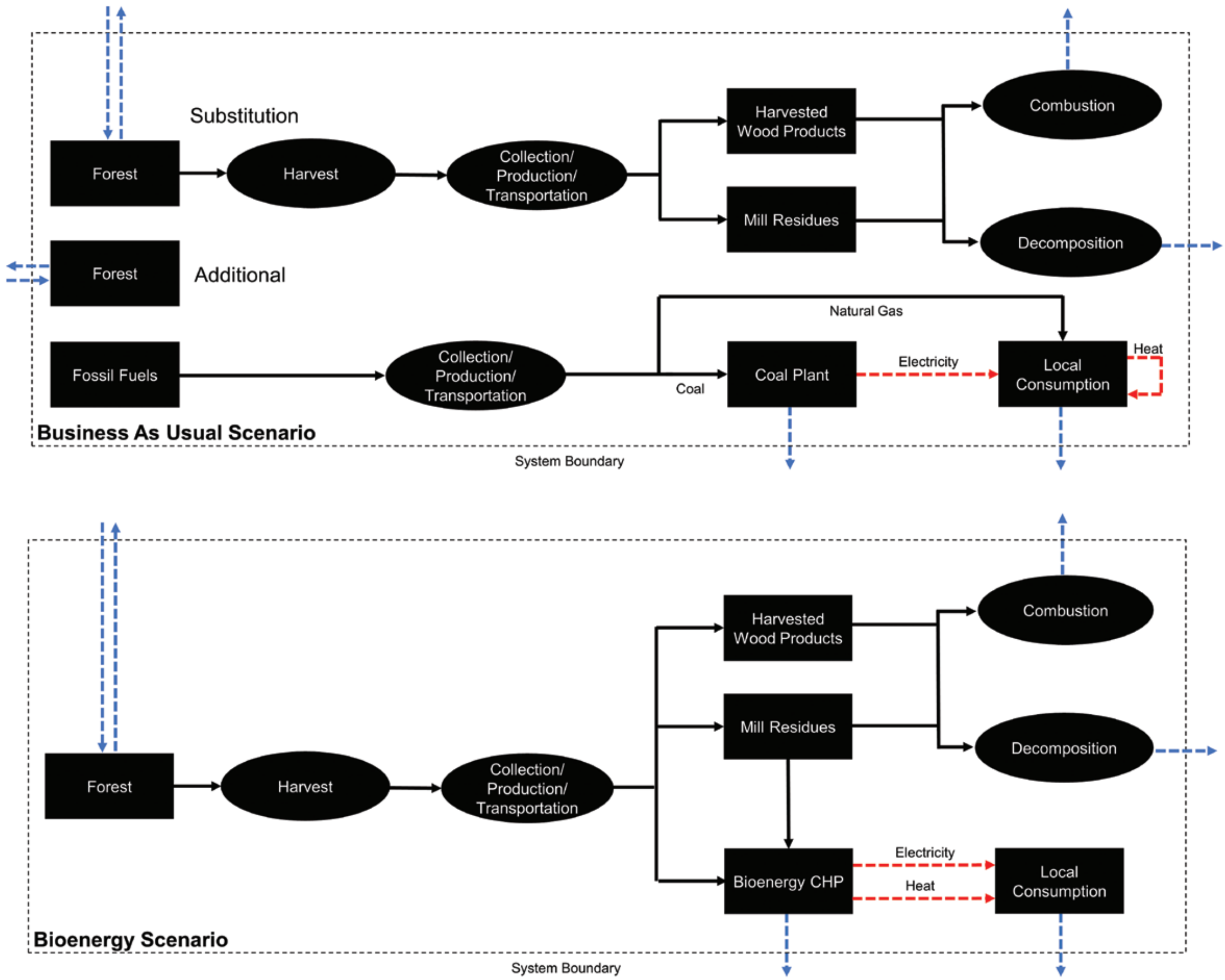

Figure 2 Process flow diagram showing the bioenergy scenarios and business as usual (BAU) energy scenario. Solid arrows indicate supply chain flows and dashed arrows indicate energy flows (captioned) or exchanges with the atmosphere.

full potential. Past surveys (Nicholson 2007; Nova Scotia Department of Natural Resources 1988, 2004) indicate that although plantation growth rates generally outperform natural stands, the full potential has historically been limited operationally by inconsistent establishment and competition control programs. However, the intensive management yields used in this study were derived from observed plantation trial data in the province and treatments were simulated as 100% implementation and success to better reflect the full potential of a successful plantation management regime and its associated carbon dynamics.

Direct Combustion Emissions

Direct emissions are those associated with the stationary combustion of a fuel source to produce energy. Different fuel sources will have different emission rates depending on the energy content and emissions factors of the fuel. These figures can also vary depending on the source of information. The IPCC's Emissions Factor Database reports energy contents of wood and waste as 10.9 GJ/t for green wood, 15.5 GJ/t for air-dried (humid zone), and 20.0 GJ/t for oven-dried (IPCC 2018a). Nova Scotia Environment's (NSE) standards for quantification, reporting, and verification of greenhouse gas emissions (Nova Scotia Environment 2020) reports 19.2 GJ/t for oven-dried wood and wood waste (0% moisture content; higher heating value) and 9.6 GJ/t for wood and wood waste at 50% moisture content. The NSE guidelines report an energy content for bituminous coal of 26.33 GJ/t. The amount of heat energy actually available for energy production with both fuels would be slightly lower than these values due to the latent heat of vaporization of moisture in the fuels.

Emissions factors are the amount of GHGs emitted per unit of total energy combusted (e.g., gigajoules). The IPCC's 2006 Guidelines for National Greenhouse Gas Inventories give an emissions factor of 94.6 kg/GJ for bituminous coal, 56.1 kg/GJ for natural gas, and 112.0 kg/GJ for biomass (solid wood and wood waste). The NSE standards give biomass emissions factors of 95.72 kg/GJ of CO_2eq for solid wood and wood waste, 85.88 kg/GJ of CO_2eq for coal, and 52.26 kg/GJ of CO_2eq for natural gas, with global warming potentials of 25 and 298 for CH_4 and N_2O, respectively (Nova Scotia Environment 2020). Table 4 shows complete details. This analysis used the standards published by NSE for Nova Scotia emissions reporting, which are lower than the IPCC standards that are based on global averages. The NSE standards are based on several sources, including the IPCC standards, other Canadian provinces (e.g., Ontario and British Columbia), and

Table 2. Final modeling scenarios can include a fuel, management, and/or assumption component, yielding 16 final scenarios.

Scenario Name	Description
Fuel (F)	
1. Primary biomass	Fuel source is 100% primary biomass from harvested trees
2. Secondary biomass	Fuel source is 100% secondary biomass from mill residues
3. Current conditions	Fuel source is 14.4% primary biomass and 85.6% secondary biomass
Management[a] (M)	
1. Simple	Natural stands under even-aged management in 60-year rotations with clear-cutting and harvest residues left on site
A. $Pulpwood_2$	Simple scenario with the additional assumption of pulp-sector decline and substitution with bioenergy
B. $Residues_2$	Simple scenario with the additional assumption that both roundwood and harvest residues are utilized for bio-energy
2. Intensive	Bioenergy harvesting occurs at the scenario start and forests are then converted to softwood plantations in 30-year rotations
3. Extensive	Bioenergy harvesting occurs at the scenario start and forests regrow as natural stands under uneven-aged selection management with 20% removal in 20-year intervals beginning at year 60
Assumption[a] (A)	
1. Additional	Bioenergy harvesting is additional, forests remain unharvested in the BAU scenario
2. Substitution	Bioenergy harvesting is not additional and replaces traditional harvested wood products

[a]Management and assumption scenarios apply only to the primary biomass in the primary biomass and current conditions fuel scenarios, and not the secondary fuel scenario.

Table 3. All 15 modeling scenarios included in the analysis.

Scenario	Biomass fuel	Management	Assumption
F1-M1-A1	Primary	Simple	Additional
F1-M2-A1	Primary	Intensive	Additional
F1-M3-A1	Primary	Extensive	Additional
F1-M1-A2	Primary	Simple	Substitution
F1-M1A-A2	Primary	Simple/pulpwood	Substitution
F1-M1B-A2	Primary	Simple/residues	Substitution
F1-M2-A2	Primary	Intensive	Substitution
F1-M3-A2	Primary	Extensive	Substitution
F2	Secondary	None	None
F3-M1-A1	Mix	Simple	Additional
F3-M2-A1	Mix	Intensive	Additional
F3-M3-A1	Mix	Extensive	Additional
F3-M1-A2	Mix	Simple	Substitution
F3-M2-A2	Mix	Intensive	Substitution
F3-M3-A2	Mix	Extensive	Substitution

the Canadian federal government's national standards and national inventory of GHGs.

This analysis assumed that in the absence of forest bioenergy, electricity needs would be met using coal-based electricity and thermal energy needs would be met using natural gas. The standard conversion efficiency in Eastern Canada for electricity from coal is 35% and for heat from natural gas is 85% ((S&T) Squared Consultants Inc. 2015; Laganière et al. 2017; Nova Scotia Environment 2020). As previously mentioned, conversion efficiencies of 26% for electricity (Laganière et al. 2017) and 76% for CHP (Wolf et al. 2016) from forest bioenergy were used. Efficiency can be increased either through improving the electrical efficiency or through improved utilization of thermal energy. The sensitivity analysis of efficiency rates assumes both improving electrical efficiency to a base rate of 26% and incrementally improving thermal efficiency through better utilization of the thermal energy in equal amounts

Upstream Emissions

Life-cycle emissions from forest bioenergy (Table 4) include the direct emissions from biomass combustion, upstream emissions from supply chain activities, and emissions/removals associated with forest carbon dynamics (described in the Forest Modelling section). It is important to include all of these sources emissions to obtain an accurate picture of the life-cycle carbon emissions from forest bioenergy. Accounting for upstream emissions (i.e., collection, production, transportation) adds an additional life-cycle emissions factor of 6.4 kg/GJ for coal and 9.0 kg/GJ for natural gas ((S&T) Squared Consultants Inc. 2015; Laganière et al. 2017), totaling 91.91 kg/GJ and 58.93 kg/GJ, respectively. Upstream emissions for primary biomass include 2.63 kg/GJ for harvest/collection, 0.76 kg/GJ for chipping, and 2.04 kg/GJ for transportation ((S&T) Squared Consultants Inc. 2015; Laganière et al. 2017; Lamers et al. 2014), totaling 5.66 kg/GJ. The 0.76 kg/GJ value is based on roadside chipping using diesel fuel (McKechnie et al. 2011), which may differ from emissions for chipping primary biomass at either mill sites or CHP sites. Upstream emissions for biomass do not include biomass storage. The silvicultural treatments in intensive management scenarios will correspond to increased upstream emissions. An additional emissions factor of 2.32 kg/GJ (Miner 2010) for herbicide application and fertilization was therefore used for these scenarios.

The 2.04 kg/GJ transportation emissions factor used a base rate of 0.1961 kg/t-km (i.e., kg of CO_2eq emitted to move 1 tonne of biomass for 1 km; (S&T) Squared Consultants Inc. 2015) and a mean transportation distance of 100 km. The 100-km limit is often used locally as it is considered the distance at which biomass products are economically viable

Table 4. Life-cycle emissions factors for coal and forest biomass.

Variable	Value	Source
Bituminous coal emissions factor (CO_2eq)	85.88 kg/GJ	2
Bituminous coal emissions factor (CH_4)	0.0008 kg/GJ	2
Bituminous coal emissions factor (N_2O)	0.0012 kg/GJ	2
Bituminous coal emissions factor (CO_2)	85.50 kg/GJ	2
Coal total upstream emissions[a]	6.40 kg/GJ	3
Coal conversion efficiency for electricity	35 %	3
Natural gas emissions factor (CO_2eq)	52.26 kg/GJ	2
Natural gas emissions factor (CH_4)	0.0128 kg/GJ	2
Natural gas emissions factor (N_2O)	0.0013 kg/GJ	2
Natural gas emissions factor (CO_2)	51.16 kg/GJ	2
Natural gas total upstream emissions[a]	9.00 kg/GJ	3
Natural gas conversion efficiency for heat	85.00%	3
Wood/wood waste emissions factor (CO_2eq)	95.72 kg/GJ	2
Wood/wood waste emissions factor (CH_4)	0.0302 kg/GJ	2
Wood/wood waste emissions factor (N_2O)	0.0042 kg/GJ	2
Wood/wood waste emissions factor (CO_2)	93.71 kg/GJ	2
Primary biomass collection	2.63 kg/GJ	4
Primary biomass chipping	0.76 kg/GJ	5
Primary biomass transportation	2.04 kg/GJ	3
Silvicultural application of herbicide and fertilizer	2.32 kg/GJ	6
Secondary biomass upstream emissions	0.92 kg/GJ	7
Biomass conversion efficiency for CHP	76 %	8

[a]Extraction, distribution, storage, production, transmission, land-use changes, and gas leaks and flares.
[b]Nova Scotia Environment 2020.
[c](S&T) Squared Consultants Inc. 2015.
[d]Laganière et al. 2017.
[e]Lamers et al. 2014.
[f]Miner 2010.
[g]Petersen Raymer 2006.
[h]Wolf et al. 2016.

based on market prices against trucking costs (Laganière et al. 2017; Serra et al. 2019). Given the 515,625 t of biomass and 4,950,000 GJ of total biomass fuel energy, this yields a transportation emissions factor of 2.04 kg/GJ. This emissions factor was used annually for the 100-year simulations, although in reality, wood supply points of origin would vary.

Current practice in Nova Scotia is that only stemwood is used for bioenergy, and residues are typically left on site to avoid potential soil degradation and nutrient depletion. The secondary biomass currently used at CHP facilities in Nova Scotia is mainly residues from pulp mills and sawmills. Accounting for emissions from residues is different than primary biomass because the residues are a co-product/waste from traditional forest products (e.g., sawnwood, pulp and paper). The key consideration in a bioenergy life-cycle emissions analysis is the alternate fate of the residues in the BAU scenario and absence of bioenergy production (Ter-Mikaelian et al. 2015). For harvest residues, the BAU scenario would be decomposition at the harvest site or slash burning, so the time required for carbon parity is dictated by the length of time the carbon is stored in the residues during decomposition or immediate, respectively. For mill residues, there are more potential BAU scenarios, such as combustion for energy generation, production of forest products, or decomposition. It is estimated that 70% of mill residues in Canada are currently used (Ter-Mikaelian et al. 2015). This analysis therefore assumed that 70% of mill residues had a fate of combustion with energy capture and 30% had a fate of decomposition in the BAU scenario. Actual utilization data for residues from local mills would be different from this simplified assumption but were not available, as mills are not required to report secondary fiber utilization to the Registry of Buyers. The carbon dynamics of secondary biomass were removed from the analysis where combustion occurs both in the BAU scenario and bioenergy scenario (i.e., 70%). The slower release of carbon from secondary biomass due to decomposition in the BAU scenario (30%) was calculated using the temperature-dependent decay function for fine and small woody debris from the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3; Kurz et al. 2009) with a mean annual temperature of 6°C (Environment and Climate Change Canada 2022). Methane emissions from biomass decomposition or forest products in landfills are not included in the analysis. Therefore, GHG emissions from the BAU scenarios may be slightly underestimated (Hennigar et al. 2008). However, these levels are both uncertain and variable and depend on the end-of-life fate of the product. Because higher levels of emissions in the BAU scenarios reduce net GHG emissions from bioenergy, we opted to exclude methane emissions under the principle of conservatism in life-cycle assessment (ISO 2006). Additional upstream emissions (i.e., harvesting, transport, and production) for mill residues of 0.92 kg CO_2eq/GJ are also included in the analysis (Kurz et al. 2009).

Forest Modeling

Forest carbon dynamics were modeled using CBM-CFS3 (Kurz et al. 2009). There are two important milestones over the study period when modeling forest carbon in a bioenergy system (Mitchell et al. 2012; Ter-Mikaelian et al. 2015). The first is the length of time required for the regenerating stand harvested for biomass to recapture and store the same amount of carbon that was harvested, which is called carbon payback or debt repayment. The second is the length of time required for the carbon in the regenerating stand to reach the amount of carbon that has either (1) accumulated in the unharvested forest in the BAU scenario or (2) has accumulated in the harvested forest and in decomposing in forest products in the BAU scenario. This is the point of forest carbon parity, which is different from carbon parity in the entire bioenergy system that also accounts for emissions from bioenergy and coal energy production.

The CBM-CFS3 forest land base used for modeling was based on photo-interpreted forest inventory data for Nova Scotia and merchantable volume yield curves used by the provincial government for strategic modeling and wood supply analysis. Forest growth from this initial land base was simulated for 100 years in areas that are eligible for forest management (e.g., outside of protected areas). Stands were scheduled for harvest randomly once they met the eligibility criteria of 120 m^3/ha and harvests continued until the annual biomass supply required for CHP facilities was met (i.e., 74,170 t for current condition fuel scenarios and 515,625 t for primary biomass fuel scenarios).

Harvest volume was converted to biomass (green metric tonnes) using the province's biomass conversion factors for scaling (MacQuarrie and Hudson 2013). Because cumulative GHG emissions are analyzed, the harvest area and its subsequent regrowth was simulated for every year of the 100-year analysis. For example, if 1,000 ha was harvested in the first year of modeling to achieve the necessary harvest volume, the simulated land base would be 10,000 ha by year 10 and 100,000 ha by year 100. In the actual modeling, the annual harvest area varied slightly each year based on forest inventory conditions (i.e., volume) in stands scheduled for harvest, because this study employed harvest volume regulation in the modeling not harvest area. Harvest area also changes in scenarios where the amount of primary biomass harvested was altered, including the sensitivity analysis of fuel-type mix. All CBM-CFS3 forest carbon pools were modeled and reported (i.e., not just aboveground merchantable biomass).

For the substitution assumption scenarios (i.e., where biomass is not additional but replaces traditional forest products), we used product ratio data from the provincial Registry of Buyers of Primary Forest Products (Nova Scotia Department of Natural Resources 2018) and mill efficiency data from a recent life-cycle assessment of eastern Canadian softwood lumber (Athena Sustainable Materials Institute, 2018). In the simple management scenario with substitution, biomass replaces an equivalent harvest volume with 62.4% sawlog, 34.2% pulpwood, and 3.4% biomass for softwood and 7.1% sawlog, 73.7% pulpwood, and 19.2% biomass for hardwood (Nova Scotia Department of Natural Resources 2018). Of the total sawlog harvest, 37% is allocated to solid wood products, 38% is allocated to pulp and paper products (on top of the existing pulpwood harvest), and 25% is allocated to residues (Athena Sustainable Materials Institute 2018). For the solid wood products and pulp and paper products, decomposition was simulated in the BAU scenario using the IPCC (2006) standards with a 35-year half-life and two-year half-life, respectively.

Results

The experimental scenarios reporting life-cycle GHG emissions from bioenergy revealed substantive variability (Table 5). The secondary biomass fuel scenario achieved carbon parity in the tenth year of the simulation and accounted for the cumulative removal of 8 Mt (i.e., 10^6 metric tonnes) CO_2eq by year 100 when substituting for coal and natural gas (figure 3). A clear divergence in results could be seen in the primary biomass fuel scenarios across the additional and substitution assumption scenarios. All management scenarios achieved carbon parity in under 10 years when traditional forest products were substituted by biomass, whereas carbon parity times were substantially longer (e.g., over 100 years for the primary-simple-additional scenario) when biomass was additional (figure 3). The intensive management scenario with product substitution led to the greatest cumulative removal of CO_2eq of 62 Mt by year 100. Conversely, in the additional assumption scenarios, the simple management scenario showed cumulative CO_2eq emissions of 29 Mt by year 100 and, unlike the intensive and extensive management scenarios, did not achieve carbon parity by year 100. The current conditions (that is, mixed primary and secondary fuel sources) scenarios (figure 4) showed the same trends as the primary biomass fuel scenarios, with the difference that all scenarios achieved carbon parity within the 100-year simulation given the high percentage of secondary biomass.

The three modifications of the simple management scenario with primary biomass and an assumption of substitution showed some divergence from the simple management scenario (figure 5). Where biomass was a substitution exclusively for pulp and paper products and not the traditional mix of forest products, there was increase in the net removal of CO_2eq of an additional 3 Mt (i.e., 30 Mt by year 100).

Table 5. Years to achieve carbon parity and net cumulative emission/removals of atmospheric CO_2eq at year 50 and 100 for each scenario.

Scenario (fuel-management-assumption)[a]	Years to achieve carbon parity	Net cumulative CO_2eq emissions/ removals at year 50 (Mt)	Net cumulative CO_2eq emissions/ removals at year 100 (Mt)
Primary-simple-substitution	4	-13	-27
Primary-simple/pulpwood-substitution	4	-14	-30
Primary-simple/residues-substitution	7	-5	-12
Primary-intensive-substitution	8	-28	-62
Primary-extensive-substitution	9	-16	-61
Primary-simple-additional	>100	23	29
Primary-intensive-additional	86	8	-6
Primary-extensive-additional	95	21	-4
Secondary	10	-3	-8
Mix-simple-substitution	7	-5	-11
Mix-intensive-substitution	9	-7	-16
Mix-extensive-substitution	9	-5	-16
Mix-simple-additional	62	0	-3
Mix-intensive-additional	23	-2	-8
Mix-extensive-additional	52	0	-8

[a]Mix refers to the current conditions fuel scenario, where the fuel source is 14.4% primary biomass and 85.6% secondary biomass.

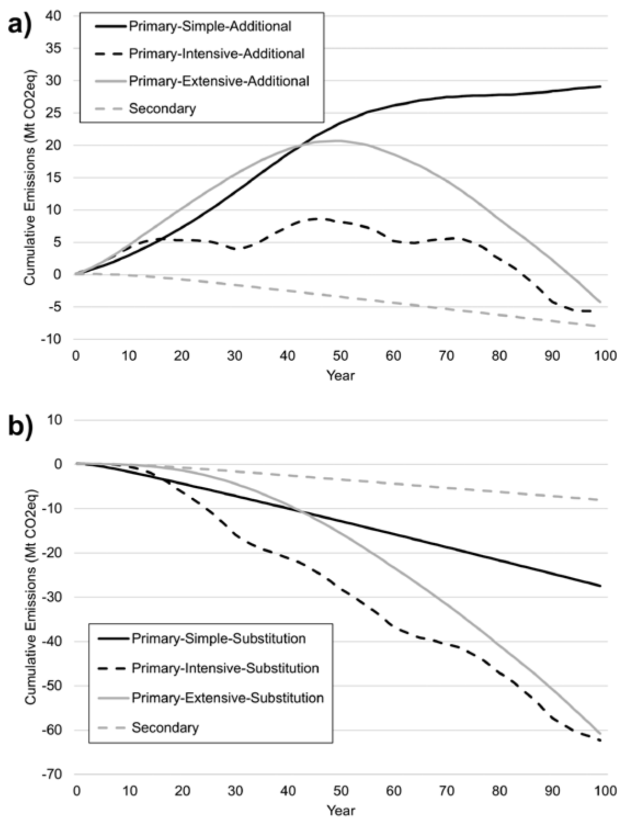

Figure 3 Cumulative GHG emissions for the primary biomass fuel scenarios for simple, intensive, and extensive management where bioenergy is (a) additional and (b) substitution. The secondary biomass scenario is included as reference.

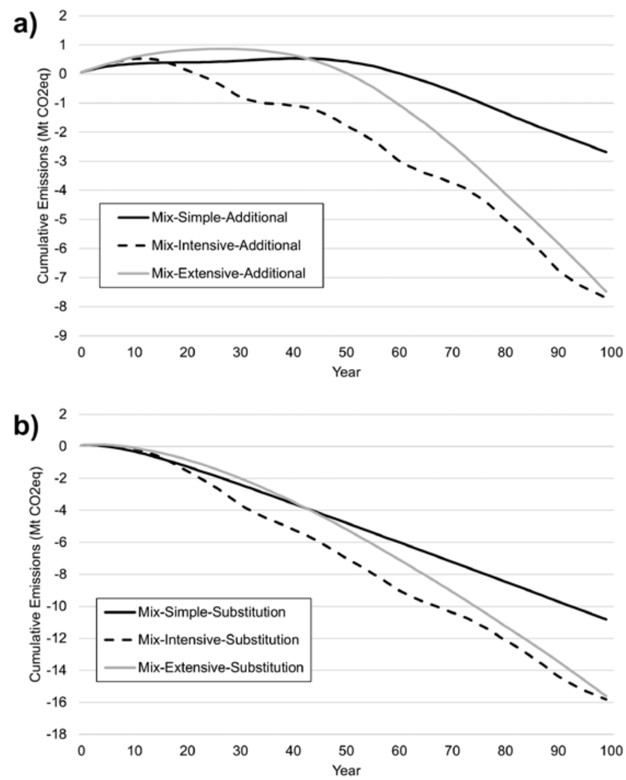

Figure 4 Cumulative GHG emissions for the current conditions (i.e., mix) biomass fuel scenarios for simple, intensive, and extensive management where bioenergy is (a) additional and (b) substitution. The secondary biomass scenario is included as reference.

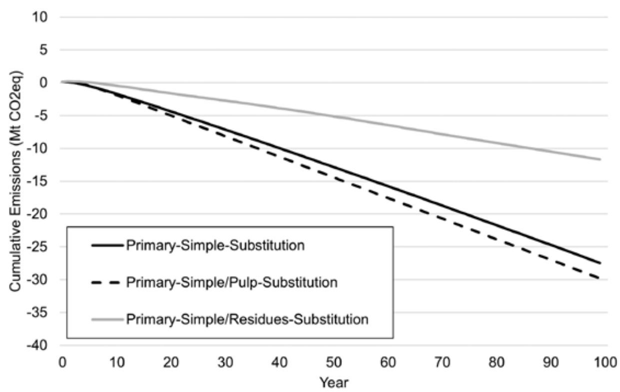

Figure 5 Cumulative GHG emissions for the primary biomass fuel scenarios with the two modifications of the simple management scenario.

Conversely, where biomass harvests used both harvested roundwood and harvest residues, there was a decrease in net removals of CO_2eq of 15 Mt (i.e., 12 Mt by year 100). Recall that there was no scenario where harvest residues only are used for bioenergy production. A large factor explaining these differences is the size of the land base included in the modeling. Using both merchantable roundwood and harvest residues leads to more biomass removal from a given harvest and therefore a smaller land base.

The sensitivity analysis of feedstock mixes between primary and secondary biomass revealed a high degree of sensitivity of life-cycle emissions over 100 years (figure 6). Carbon parity was achieved in less than 10 years for all feedstock mixes where biomass was a substitution for traditional forest products. However, with the assumption of additionality for biomass harvests and bioenergy systems, carbon parity was not achieved when percent of primary biomass was 25% or greater. The sensitivity analysis of conversion efficiency also revealed that the study results are quite sensitive to this parameter (figure 7). The sensitivity analysis for biomass-feedstock mix showed that bioenergy scenarios with the assumption of additionality could be a carbon sink or source depending on the percent of primary biomass. In contrast, all additional scenarios were a net source of CO_2eq, with lower efficiencies increasing the net emissions over the 100-year simulation. Where biomass was assumed to be a substitution for traditional forest products, the bioenergy scenarios all achieved carbon parity within the 100-year simulation, but lower efficiencies led to much longer parity times (e.g., 84 years for 40% efficiency) and much higher cumulative emissions during the middle of the simulation.

Discussion

This study revealed several potential outcomes for the life-cycle GHG emissions of bioenergy production at CHP facilities in Nova Scotia, depending largely on assumptions around additionality and feedstock fuel type. The consideration of whether a forest bioenergy system and associated biomass harvesting is additional to current harvest rates for

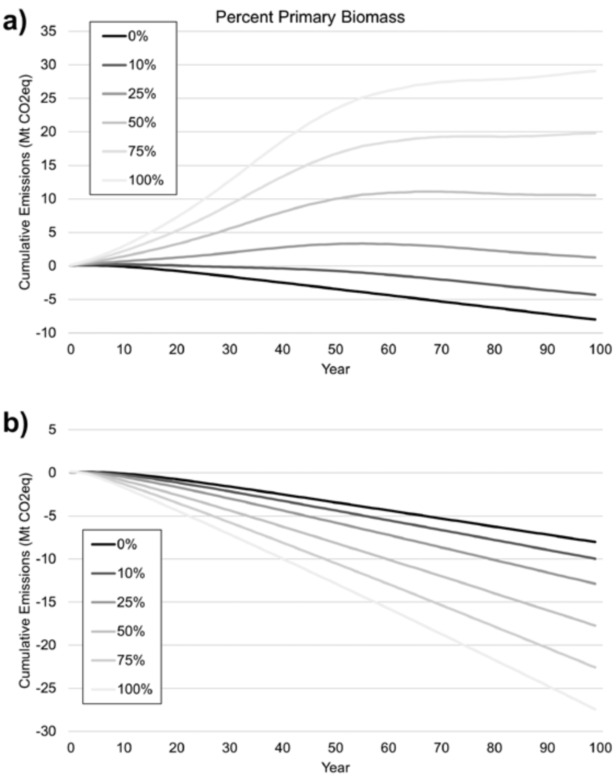

Figure 6 Sensitivity analysis of fuel-type mix showing life cycle GHG emissions at different percentages of secondary biomass for the assumption of (a) additionality and (b) substitution.

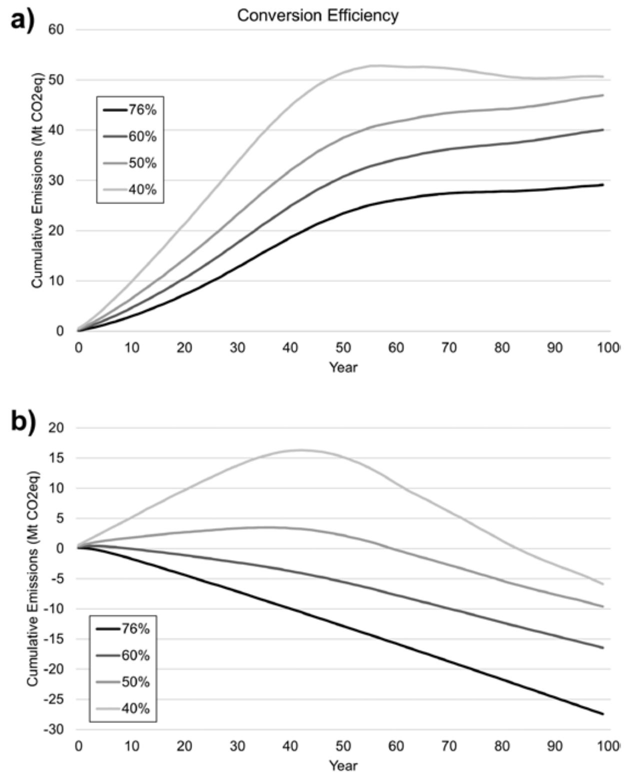

Figure 7 Sensitivity analysis of conversion efficiencies showing life cycle GHG emissions at different conversion efficiencies for the assumption of (a) additionality with primary biomass and (b) substitution with primary biomass.

traditional forest products like lumber and paper or replacing them is a critical consideration for assessing the long-term carbon impacts of forest bioenergy. In the two extreme scenarios of entirely additional or entirely substitution used in this analysis, we found that all primary biomass scenarios assuming additionality were net sources of emitting carbon to the atmosphere for close to or over, a century, whereas all primary biomass scenarios assuming substitution were net sinks within a decade. In real-world market conditions, it is likely that forest biomass supply chains are situated somewhere between these two extremes. From an accounting perspective, it is also challenging to determine whether biomass harvests are additional or not in the context of evolving forest product markets and demand.

The results of the study also indicated that the life-cycle GHG emissions of wood biomass energy are strongly linked to the use of primary versus secondary biomass feedstocks. The use of predominantly secondary biomass from sawmills and pulp mills at CHP facilities in Nova Scotia resulted in net carbon benefits relative to fossil fuels in just 10 years, although benefits can be reduced or reversed when secondary biomass is mixed with primary biomass or used at lower conversion efficiencies. The analysis revealed a strong sensitivity of life-cycle emissions and carbon parity times to the ratio of secondary to primary biomass used for bioenergy production. These findings are consistent with the literature on the use of mill residues in bioenergy systems (see the review by Ter-Mikaelian et al. 2015).

From a policy perspective, the results of this study provide a number of insights for consideration. First, with regards to the considerable carbon implications of the substitution harvest scenarios compared to the additional harvest scenarios, it is more difficult for policy to influence the market forces driving declining demand for one forest product (e.g., pulp and paper) and increasing demand for another (e.g., biomass) than it would be to regulate biomass harvest practices and feedstocks. However, with regards to additionality, the explicit consideration of biomass in fiber allocation for tenure agreements could be one avenue to address potential carbon implications of bioenergy systems in a given jurisdiction. Second, there is potential value in developing guidelines, standards, and/or policies that favor the utilization of secondary biomass for bioenergy production as well as the need for better accounting systems for secondary biomass supply chains (e.g., mill residues). However, it is also important to highlight that the economic feasibility of a bioenergy production system favoring secondary biomass would depend on a reliable supply of sawmill or pulp mill residues in relatively close proximity to a biomass plant. Harvest residues are often highlighted in the literature as an ample source of secondary biomass with low life-cycle emissions (Camia et al. 2021; Smyth et al. 2014). However, there are scientific uncertainties around long-term adverse effects on soil carbon storage, soil fertility, and biodiversity attributable to the removal of harvest residues (Giuntoli et al. 2022; Repo et al. 2011; Thiffault et al. 2011).

This study reinforces the high degree of variability in the life-cycle GHG emissions associated with bioenergy systems as a source of renewable energy to mitigate climate change. Some of the factors behind this variability are more tangible and measurable than others. For instance, the effects of biomass-type mix on emissions and forest carbon dynamics can be quantified and modeled using established methods and sources of data (Kurz et al. 2009; Laganière et al. 2017). Rates of forest growth and the effects of silvicultural measures on growth rates can be derived from traditional forest inventories, long-term monitoring, and growth and yield models, which are standard tools in forest management. Moreover, product mixes from harvesting (e.g., sawlogs, pulpwood, biomass) are typically monitored in most jurisdictions. In addition to being more tangible and measurable, these factors also have the potential to be influenced by policy and management.

There are also less-tangible factors in modeling life-cycle GHG emissions from bioenergy that are based on broad assumptions about the forestry and energy sectors in Nova Scotia and abroad. The BAU scenario that defines the energy and forest management conditions that would be in place in the absence of bioenergy is where many of these assumptions materialize. For example, Laganière et al. (2017) and many similar life-cycle studies adopt the assumption that harvest rates for bioenergy are additional and that a given stand that is harvested for biomass would remain undisturbed in the BAU scenario. These studies and our findings indicate that the time to achieve carbon parity when biomass and bioenergy are additional can be decades to over a century. Conversely, if that stand would have traditionally been harvested for other forest products in the BAU scenario and is being substituted for biomass harvest and bioenergy production, then our findings show that the time to achieve carbon parity would be reduced. This is because the forest carbon in the BAU scenario is no longer stored in living forest biomass but is released to the atmosphere over several years or decades through forest product decomposition. Further complicating this latter issue are the implications of declining traditional forest products. If there is a genuine decline in product demand (e.g., some pulp and paper products) then bioenergy production has good potential for achieving net GHG emissions reductions. However, if the decline in harvesting of a product (e.g., lumber) is not driven by reduced demand and leads to imports from other jurisdictions or use of alternative materials (e.g., steel, concrete), it becomes more difficult to assess life-cycle GHG implications.

Natural disturbance is another source of uncertainty (MacLean et al 2022; Taylor et al. 2020). If a stand harvested for biomass was to be affected by natural disturbance during regrowth, then the time to achieve carbon parity would be lengthened. The inverse is true if natural disturbance affects stands continuing to grow in the additional BAU scenario. The type of fossil fuel energy being displaced and conversion efficiency were also shown to be important factors determining the life-cycle GHG emissions for wood bioenergy systems (Cowie et al. 2021). When primary biomass is substituting fossil fuels with higher conversion efficiencies, the time required to reach carbon parity is longer. Assumptions around the alternative fate of the secondary biomass are also influential. If, for example, carbon in the BAU scenario was to be stored for longer with a higher ratio of longer-lived solid wood products, there could be the potential for CHP bioenergy systems to become a net carbon emitting source.

It is also important to consider the conversion efficiencies of bioenergy systems. A recent meta-analysis found a mean conversion efficiency of approximately 76% for CHP bioenergy systems (Wolf et al., 2016). Although the efficiency of all CHP systems in Nova Scotia is not known, there is evidence that the largest facility, the 60 MW Port Hawkesbury Biomass Plant, likely has a much lower efficiency due in part to the age of the biomass boiler (The Shaw Resource Group Inc. 2010). Moreover, other factors can reduce bioenergy conversion efficiency, such as higher moisture content of the biomass fuel or the incineration of the secondary treatment sludge at pulp mills. Higher moisture content of the fuel or sludge reduces the efficiency of the biomass boiler due to the energy required to evaporate the water (Mahmood and Elliot 2006). Importantly, overall efficiency and, ultimately, the carbon footprint of a CHP bioenergy system are also dependent on the optimal use of thermal energy, such as for pulp mill process steam or district heating systems. If a CHP system has high conversion efficiency but the thermal energy is not used, then a displacement of fossil fuels used for thermal energy is not occurring. The findings of this analysis highlight the importance of maximizing conversion efficiencies and thermal energy utilization in bioenergy production systems.

Conclusions

This study investigated the life-cycle emissions from CHP facilities in Nova Scotia, Canada. It drew from the methodology of Laganière et al. (2017) and Buss et al. (2022) but is distinct in its integration of these life-cycle methods with CBM-CFS3 to assess coupled energy and forest management systems. It reinforces the bioenergy literature on the emissions profiles of secondary versus primary biomass feedstocks and makes further contributions to the literature around the effects of silviculture, market/supply chain assumptions, and nuances around additionality versus product substitution. In particular, the nuance of different forest management dimensions (e.g., silviculture, alternative products, forest inventory conditions) are often lacking in life cycle assessments of forest bioenergy production.

The results of this study should be interpreted in light of several limitations and sources of uncertainty. In addition to the uncertainty associated with key life-cycle assumptions that were discussed previously, there is some variability in life-cycle GHG emissions associated with mill residues reported in the literature. The upstream emissions factors for mill residues used in this analysis were the best match found in the literature and derived from a study of the harvest, production, and transport of bark for bioenergy production in large combustion facilities in Norway (Petersen Raymer 2006). The focus of this analysis was also limited to bioenergy production systems and their life-cycle GHG emissions. It did not consider other potential impacts on biodiversity, soils and forest productivity, or hydrology, nor did it consider bioenergy emissions for heating purposes only. There is also the previously mentioned limitation of fixing the bioenergy and fossil fuel use for a 100-year simulation. The reduction in coal use, for example, has been observed in Canada in recent years and Canada has committed to phase out coal by 2030 (Government of Canada 2016), which would mean that forest bioenergy would likely displace less emissions-intensive energy sources in the future. Conversely, bioenergy with carbon capture and storage is not currently widely deployed but may become more prominent with technological advancement and is featured in many global mitigation pathways (Fridahl and Lehtveer 2018; IPCC 2018b).

There are also benefits and possible opportunities associated with forest bioenergy that are not addressed in this study. In addition to the potential for being a source of renewable energy under certain conditions, forest biomass and bioenergy production can offer a new revenue stream for the forest sector or compensate for lost revenue from declining demand for some traditional products. Moreover, forest bioenergy creates a market for mill residues and lower-quality wood that is unsuitable for traditional forest products. Given existing bioenergy production in Canada and the potential for new development, it will be important to have a fulsome understanding of its potential opportunities and limitations for climate change mitigation.

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Conflict of Interest

None declared.

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