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1. Context

Canada has joined over 120 countries in committing to net-zero emissions by 2050 (Government of Canada, 2022). Key emission reductions can be realized through the implementation of renewable energy sources in place of current fossil fuels—such as the utilization of forest biomass as a source of bioenergy as identified in the Pan-Canadian Framework on Clean Growth and Climate Change (ECCC, 2016). The promise of bioenergy as a potential way to reduce emissions must be quantified through model applications examining different forest biomass feedstocks and fossil fuel substitutions, and by simulating realistic scenarios which reflect local forest and industrial conditions against a fossil-fuel baseline scenario.

Misconceptions about the atmospheric carbon benefit associated with bioenergy are associated with the perceived immediate carbon neutrality of bioenergy. The assumption that carbon released during combustion is not a net additive to atmospheric GHG concentrations disregards the time required to reach pre-bioenergy forest carbon stocks (Ter-Mikaelian et al., 2014; Cowie et al., 2021). Instead, bioenergy feasibility should be determined according to the time to carbon sequestration parity and the substitution benefits of avoided fossil fuel burning. The time to carbon sequestration parity estimates the delay before atmospheric GHG benefits are achieved in bioenergy-use scenarios (Ter-Mikaelian et al., 2014; Laganière et al., 2017). Generally, biomass combustion causes an initial period of C-debt where there are net emissions to the atmosphere (Laganière et al., 2017). When the time to C-parity is reached, a period of C-benefit occurs in which forest biomass combustion results in net carbon sequestration from the atmosphere. Substitution benefits quantify the GHG emission reductions associated with using bioenergy in place of burning fossil fuels (Smyth et al., 2017). Combining these two metrics in order to quantify the magnitude and timing associated with achieving atmospheric GHG benefits from bioenergy relative to a baseline fossil scenario is essential to inform sound implementation strategies.

The choice of forest biomass feedstock and spatial scale of assessment are key considerations which affect the timing of atmospheric GHG benefits of bioenergy. Bioenergy operates under a range of potential feedstock choices such as harvest residues, salvage harvested trees or harvest of live trees, which affect the GHG balance. Harvest residues provide a valuable use for previously under-utilized biomass which would normally be left on site to decay or piled and burned depending on the locality (Ter-Mikaelian et al., 2014). Scale of assessment refers to the use of a landscape or stand-level assessment on the impact of bioenergy implementation. Where stand-level assessments give detailed assessments on local carbon dynamics, landscape-level assessments provide a representation of the forest carbon dynamics within a forested area (Cowie et al., 2021). Landscape-level assessments identify the impact forest management strategies have on the forested area's carbon stocks and fluxes and better support policy decisions at a national scale (Cowie et al., 2021).

Individual bioenergy models integrate these complexities differently and have different methodologies and inputs. Quantifying these differences and exploring how the methodologies differ will help inform future models to create a more robust perspective on the feasibility of bioenergy implementation in relation to Canada's emission goals.

The Generic Carbon Budget Model (GCBM) [and associated models within the mitigation framework] and the Bioenergy GHG model are two Canadian Forest Service (CFS) models that can estimate the emission reductions associated with the implementation of bioenergy, relative to a fossil fuel baseline, under a variety of local conditions. These approaches were created to assess different aspects of the bioenergy emission cycle, and thus answered different questions. The objective of the report is to identify the commonalities and differences in the methodology and results from the two respective emissions-based frameworks using common bioenergy implementation scenarios from three strategic regions across British Columbia.

The completion of this comparison will help quantify the differences in model estimates of emission reductions associated with bioenergy and highlight sources of variation across the models. This is in an aim to harbour closer collaboration to enhance model estimates and increase confidence in our conclusions in order to better implement the use of bioenergy more broadly.

2. Model Backgrounds

The two complementary model frameworks were both developed similar to a life-cycle approach (LCA) which assesses the GHG emissions associated with all phases of the analyzed scenario, from initial collection to eventual end-use, at a scale appropriate for the analysis (Ter-Mikaelian et al., 2014). The estimated GHG mitigation potential associated with the implementation of bioenergy is assessed relative to a pre-defined counterfactual scenario, where fossil fuel usage within a region continues into the future.

2.1. CBM mitigation potential framework

2.1.1.Introduction

The Carbon Budget Model (CBM) mitigation potential framework consists of three models which build on each other to estimate the GHG mitigation potential of the tested scenario. The framework consists of: the Generic Carbon Budget Model (GCBM), a harvested wood products (HWP) model to track harvested wood emissions from wood products and bioenergy and a Linear Programming (LP) model to quantify substitution benefits of avoided fossil fuel burning.

The GCBM is built upon the well-established CBM-CFS3, which is a core component of Canada's National Forest Carbon Monitoring Accounting Reporting System (NFCMARS) developed for a wide array of users and uses (Kurz et al., 2009). This empirical yield data driven model simulates forest carbon stock changes and transfers over time under multiple disturbance events and differing forest biomass management scenarios (Kurz et al., 2009). This is accomplished through the tracking of multiple living and dead carbon pools and carbon fluxes to and from the atmosphere. Input data is comprised of a variety of verifiable field measurements of forest-stand inventory, biomass yield tables, harvest rates and disturbance information. The GCBM is built on the open-source platform of the Full Lands Integration Tool (FLINT) developed and maintained by moja global (http://moja.global). The GCBM currently uses the same structure, equations, logic, and default assumptions of the CBM-CFS3 (Kurz et al., 2009), but in a spatially explicit modelling environment.

The integrated framework includes substitution benefits associated with the forest sector including the use of forest biomass and products in place of current emissions-intensive options (e.g., Smyth et al., 2020). One motivation of this comparative analysis on forest biomass was to assess how avoided GHG emissions could be maximized in regionally differentiated bioenergy scenarios. An integrated modelling environment connecting GCBM and a linear programming (LP) optimization estimated the substitution benefit of using bioenergy in place of current fossil fuels, in 46 Timber Supply Areas (TSA) in British Columbia. TSAs are spatial regions designated across BC which integrate local timber conditions and resource management practices for estimating allowable annual cuts (Government of British Columbia, 2023).

2.1.2. Methodology

The three models serve methodologically unique purposes and build upon each other to assess the GHG mitigation potential of bioenergy within a region, as summarized in Figure 1.

The GCBM and CBM-CFS3 summarize carbon dynamics across 21 carbon pools for forest landscapes, with 10 being live biomass pools (including merchantable stemwood, foliage, coarse roots, fine roots and non-merchantable products such as branches) and 11 being dead organic matter (DOM) pools (including snag branches and stems and above and within the mineral soil DOM) with each pool varying in its respective decay rates (Kurz et al., 2009). For each harvest event, transferred carbon was described through a disturbance matrix which quantifies carbon fluxes between pools, the forest sector and to the atmosphere (Kurz et al., 2009). Harvest residue collection was defined through a disturbance matrix to use a portion of the 'other' pool (branches, small trees, tops and stumps), a portion of the unused merchantable-sized trees, and a portion of standing dead trees (snags) [Smyth et al., 2020].

The LP model determined the regionally avoided emissions and uses as input data the extracted harvest residues, regional energy demand, and existing fuel sources and their emissions intensities for heat and electricity production (Smyth et al., 2017). The model included a selection of nine candidate bioenergy facilities which are selected to maximize the avoided fossil fuel emissions for each region. These facilities are generalized descriptors based on facility data described in the literature (Smyth et al., 2017). Regional facility selection was constrained by the available biomass and local heat demand, with any excess biomass used to generate electricity (Smyth et al., 2020). Under these requirements, the optimization model determined the type (heat, power, combined heat and power [CHP]), size (small, medium, large) and number of bioenergy facilities needed within each TSA to achieve the maximum avoided fossil fuel emissions.

These selected optimized facilities provided the input data for the tested TSA scenarios, whose emission outputs are compared between the models.

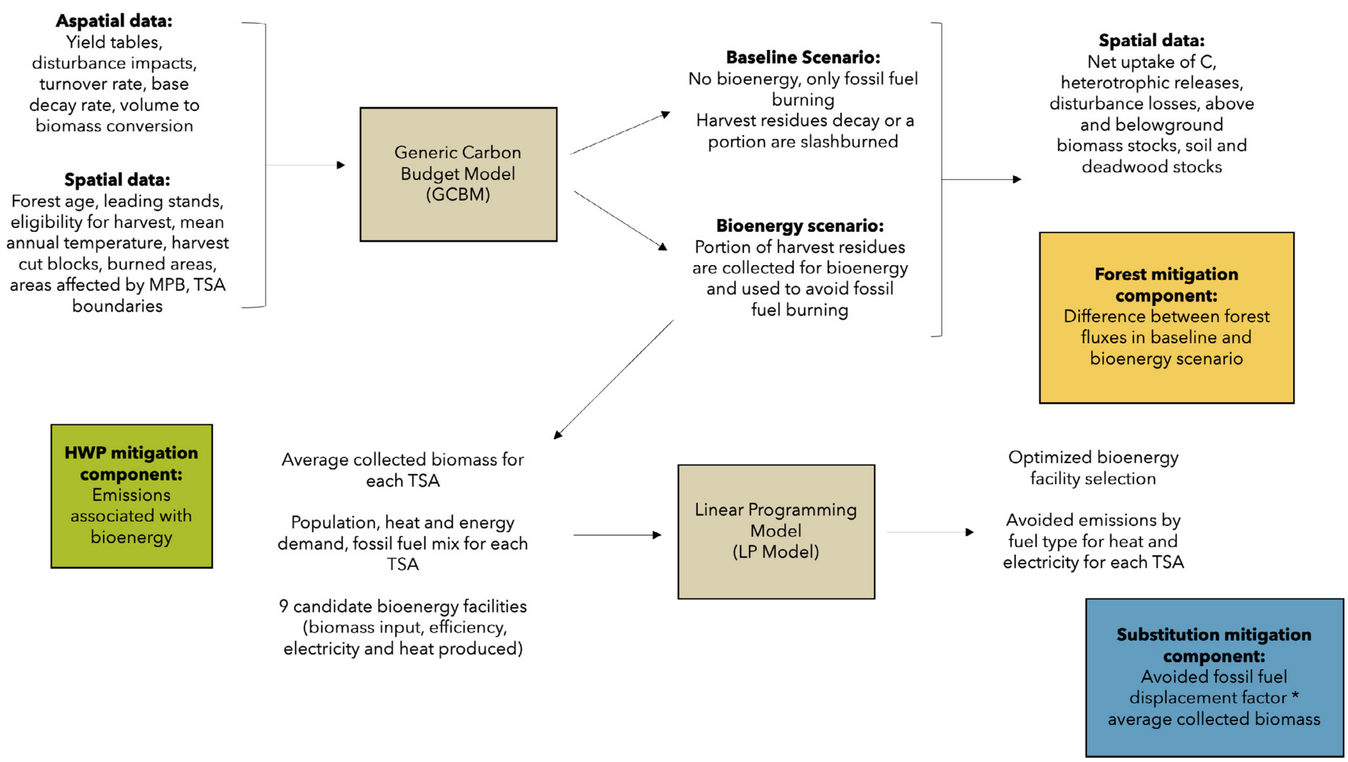

Figure 1: Conceptual framework of the CBM mitigation potential framework

Table 1: Descriptions of the nine bioenergy facilities

Facility Type	Facility description	Biomass demand (kodt/yr)	Electrical conversion rate (MWh/odt)	Thermal conversion rate (GJ/odt)
Heat	0.4 MWth boiler for district heating	0.782	-	75
	2.3 MWth boiler for district heating	3.97	-	85
	6.62 MWth process heat via syngas	11.58	-	84
Power	0.2 MWe gas turbine	1.60	1.02	-
	5 MWe steam cycle	34.97	1.17	-
	10 MWe steam cycle	63.86	1.28	-
CHP	0.2 Mwe, 0.98 MWth Organic Rankine Cycle	2.09	0.78	70
	1.8 MWe and 4.5 MWth steam turbine	10.58	1.39	54
	8 MWe CHP steam turbine	46.87	1.39	29

2.2. Bioenergy GHG Model

2.2.3.Introduction

The Bioenergy GHG Model is a computing tool developed to evaluate the timing and uncertainty of GHG emission reductions associated with the use of bioenergy in place of current fossil fuel sources (Laganière et al., 2017). The model allows for deployment of individualized bioenergy scenarios which have unique modelling variables related to the forest carbon dynamics, supply chain and deployment of both the future bioenergy scenario and the current fossil fuel scenarios. The goal of this model is to provide a common accounting system of GHG mitigation potentials associated with different bioenergy scenarios in order to provide more universal guidance on what feedstock sources, replaced fossil fuels and localities may provide the best pathways for bioenergy-related GHG mitigation in the future, while highlighting the uncertainty associated with the emissions estimates through the inclusion of an uncertainty period (Laganière et al., 2017).

The basis of this model has been adapted and improved upon through the development of the Bioenergy GHG R-package available from CRAN (Roussel et al., 2019). This package allows for greater flexibility and more nuance in scenario development by the user, permitting the modelling of more robust and realistic scenarios to assess the carbon-mitigation potential across a region.

This extension allows for users to fully customize the underlying carbon processes which contribute to a scenario, including the modification of efficiency factors, flexible calculation of C uptake characteristics in stands and the ability to combine multiple fossil fuels replaced and energy use at the same time.

2.2.4. Methodology

The Bioenergy GHG Model calculates the GHG mitigation potential of a bioenergy scenario, relative to a counterfactual scenario, through the use of a general equation applicable to all scenarios. The GHG mitigation potential is calculated as follows:

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

Equation 1: GHG mitigation potential equation from the Bioenergy GHG Model

where ΔGHG_t is the cumulative difference in CO_{2eq} emissions between the bioenergy and fossil fuel scenarios at time t (kg CO_2/GJ). $GHG_{t\,BIO}$ and $GHG_{t\,FOSSIL}$ are the cumulative emissions associated with the collection, processing, transport, and combustion of the respective bioenergy or fossil fuel source over the time-step (Laganière et al., 2017). $FC_{t\,BIO}$ and $FC_{t\,FOSSIL}$ are the forest carbon status of the bioenergy and fossil fuel scenarios at time t. Harvest residues are defined by the model as all woody debris generated in harvest operations, including branches, tree tops and bark. The decomposition rate of harvest residues is governed by a choice from one of the nine DOM pools modelled as in CBM-CFS3 (Roussel et al., 2019). CE_{BIO} and CE_{FOSSIL} are the energy conversion efficiencies of both respective scenarios. When ΔGHG_t is zero, C parity has been reached and GHG mitigation benefits begin to occur.

ΔGHG_t is calculated through the use of a hierarchy of building blocks which are built upon each other to produce the separate bioenergy and fossil fuel scenarios, whose respective GHG emissions are compared. The hierarchy, as described in Figure 2, is as follows: Process / Scenario / Delta / System.

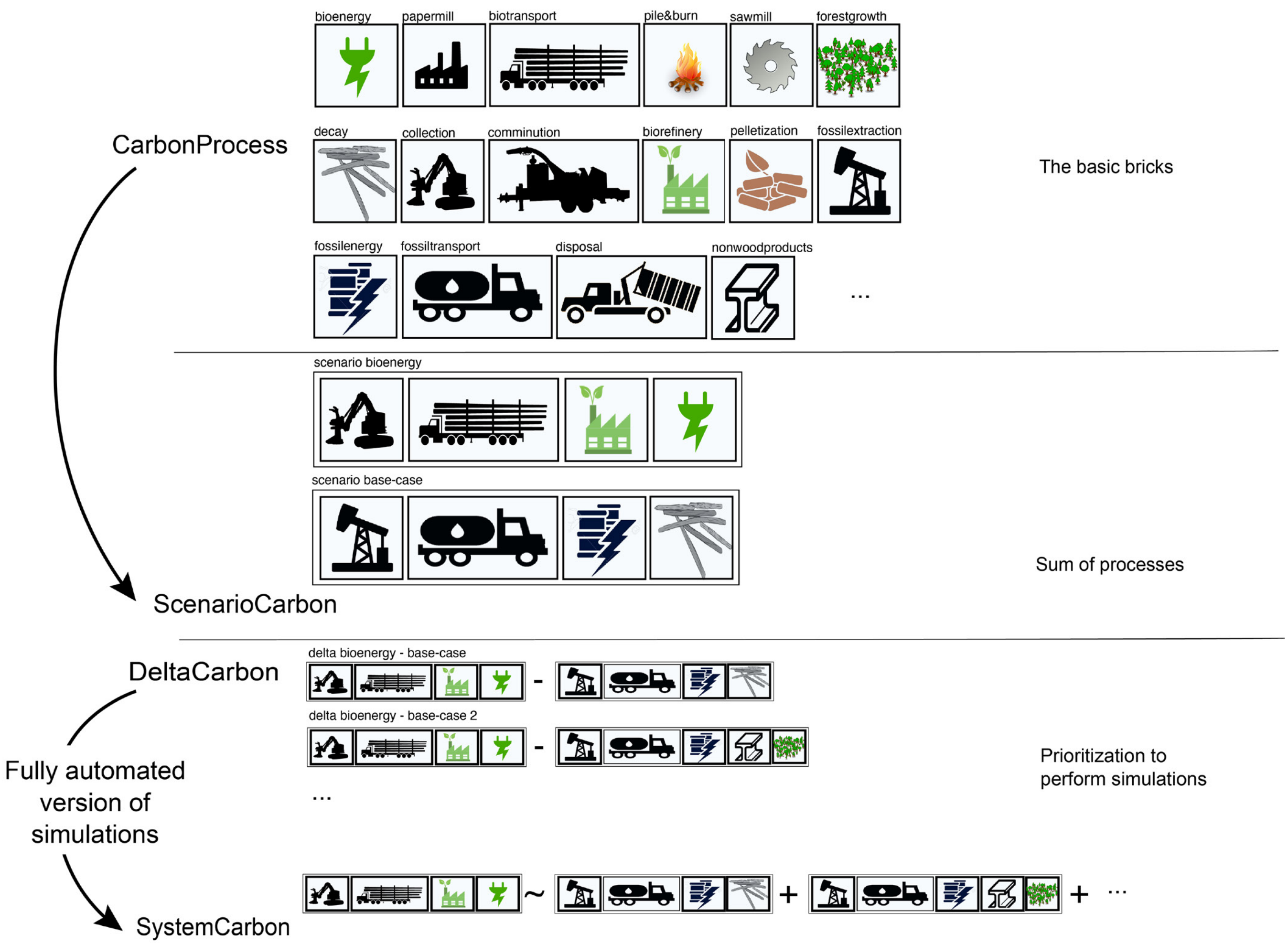

Figure 2: Conceptual framework of the Bioenergy GHG model

A Process is the basic building block to the model which quantifies the GHG emissions of a biological or industrial processes as a function of time (Roussel et al., 2019). Processes are open-ended by definition with separate processes being quantified and applied differently depending on the user's application. A collection of processes that simulates a given theoretical reality refers to a Scenario. Under the scope of this report, the quantified Processes for each given case study will combine to create the two distinct bioenergy and counterfactual fossil fuel scenarios. Delta refers to the difference in GHG emissions between the defined bioenergy and fossil fuel scenarios as described in equation 1. A System quantifies the C-parity time and the uncertainty inherent within the model runs through the combining of multiple Delta objects; allowing different simulations to be run under the same test scenario.

3. Case study regions

In order to make results from the two models comparable, model assumptions and inputs were made as similar as possible. Through strategic case-study selection (Figure 3), the scenarios being examined by the models can provide realistic implementation analysis on the feasibility of bioenergy within regions in addition to the model comparison analysis.

Model scenarios were based on British Columbian TSAs because BC has publicly available spatially explicit forest inventory (BC Ministry of Forests, Lands, Natural Resource Operations and Rural Development [BC FLNRORD] through the 2015 Vegetation Resource Inventory [VRI]) and regional energy use data and has recent modelling results available for comparison (Smyth et al., 2020). Restricting the analysis to these TSAs reduced model uncertainty by considering the local forest conditions and energy demand to better understand the potential bioenergy implementation. The diversity of conditions across BC allowed for strategic selection of model scenarios to test the impacts a variety of assumptions on bioenergy-related emission reductions.

The Community Energy and Emissions Inventory, which provides direct fuel emissions from residential, commercial, and small or medium industrial users across BC, was used to estimate local energy demand (BC MOECCS 2015, 2016). Industrial community fuel types were assigned based on the local ratios of methane to nitrous oxide emissions (Smyth et al., 2020). One third of energy usage was assumed to be used for electricity and two thirds for heat. The geo-referenced community energy usage was overlaid with TSA boundaries to determine the TSA-specific energy demand. Choice of forest biomass feedstock for bioenergy production was limited to the use of harvest residues.

Model scenarios were run under 50-year time-steps—a timescale appropriate for realizing long-term atmospheric benefits relevant to Canada's emission goals. The time to carbon sequestration parity was indicated for each scenario.

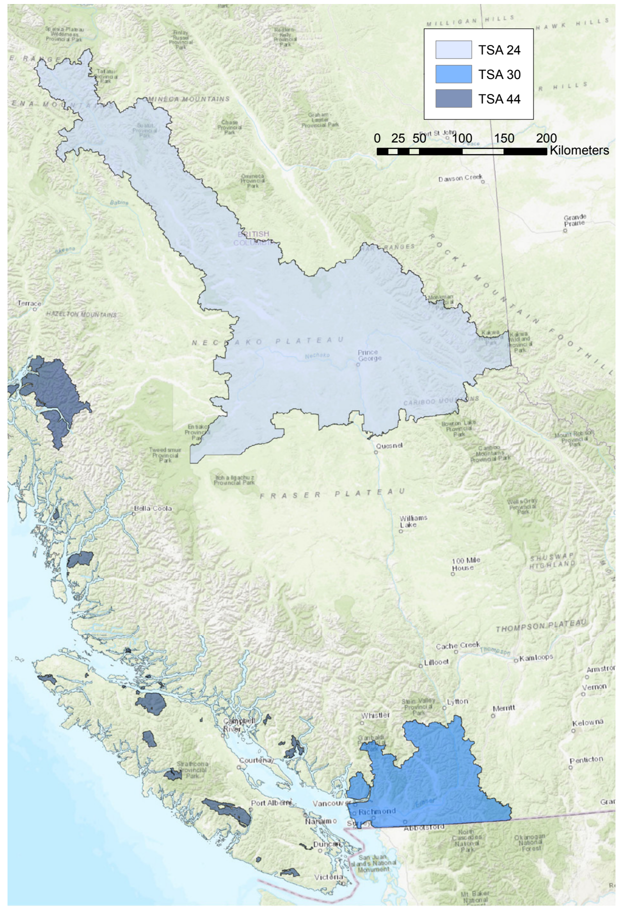

Figure 3: Three chosen TSA case study regions

3.1. TSA 24 – Prince George

TSA 24 is located in the northern interior of BC, encompassing the city of Prince George, spanning a total of 7,966 kha (Figure 4). TSA 24 was forecasted to produce the large amount of 654.4 kodt of biomass locally and has an average demand for its electricity (1.50 TWh) and heat (2.99 TWh) needs given its moderate population of 103,000.

The optimized facility configuration for TSA 24, as determined by the LP model, selected 60 medium-sized combined heat and power (CHP) facilities and 5 medium-sized heat facilities. The production of bioheat in this region avoided heat generated from low emissions electricity and burning natural gas and fuel oil; the production of bioelectricity avoided low-emissions hydro-electricity. Through the use of these facilities, Prince George TSA would meet most of its heat demand and almost 60% of its electricity demand. Without using harvest residues for the production of bioenergy, they would be piled and burned on site to abate the risk of wildfire, or left to decay.

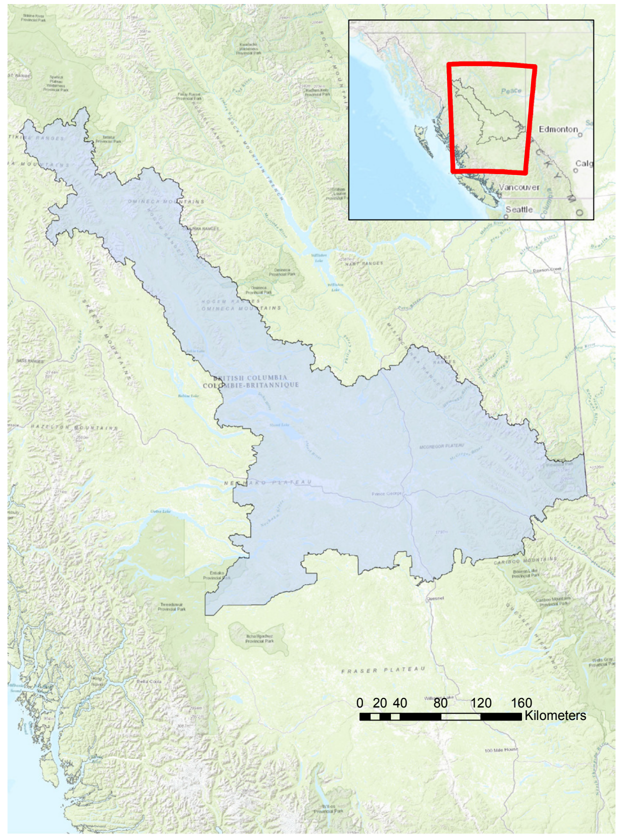

Figure 4: TSA 24 - Prince George

3.2. TSA 30 – Fraser

TSA 30 is located along BC's southern coastline and border, encompassing the Lower Mainland, spanning a total of 1,540 kha (Figure 5). Fraser TSA has a very large population of over 2.6 million people and produces a moderate, 102 kodt of biomass locally. Given its large population, Fraser TSA has a large demand for both electricity (38 TWh) and heat (76 TWh).

In order to optimize avoided emissions, the LP model selected 3 large- and 17 medium-sized bioheat facilities. The production of bioheat would avoid the burning of fuel oil locally. The heat produced by these facilities would meet a small percentage of the high demand. When the harvest biomass is not collected for bioenergy uses, it is left on site to decay.

Figure 5: TSA 30 - Fraser

3.3. TSA 44 – Pacific

TSA 44 is located throughout Vancouver Island and along BC's southern coastline spanning a total of 663 kha (Figure 6). TSA 44 encompasses very remote localities with the low population of 68 and is a moderate to low producer of biomass with 74 kodt produced locally. Given Pacific TSA's remoteness, it has a very low electricity (984 MWh) and heat (1,970 MWh) demand.

The LP model selected for 1 large and 6 small bioelectricity facilities within the region to maximize avoided emissions. These facilities would produce electricity that exceeds local demand leading to electricity exports. The bioelectricity facilities would avoid a low-emissions hydro-electricity grid currently in use. Harvest residues would be left to decay on site if not used for bioenergy purposes.

Figure 6: TSA 44 - Pacific

4. Results comparison of model estimates

The emission variables being compared between the two models for each TSA are as follows: the emissions associated with the burning of biomass for bioenergy, the emissions associated with the fate of harvest residues if not used for bioenergy production (slash-pile burning and/or decay), and the emissions associated with the avoided fossil fuel burning. These variables were chosen as both the models define these variables similarly and pull from similar data sources and carbon pools. Additionally, these variables represent prominent emission sources within the bioenergy system and are therefore important to compare.

In order to make the emissions variables comparable between models, both models were established to have similar parameters so effective comparisons could be done. Efficiencies used within the Bioenergy GHG model associated with the combustion of biomass and fossil fuels along with efficiencies corresponding to the decay of harvest residues were taken from the CBM framework. When efficiencies couldn't be found in the CBM framework, the Bioenergy GHG model used available data from the literature. In the alternative fate of harvest residues, the CBM framework assumes that some portion will always be piled and burned regardless of the region, which was implemented within the Bioenergy GHG model for TSA 30 and 44. The Bioenergy GHG model is only flexible on the proportional representation of the alternative harvest residue fate; it is not flexible on the temporal scale which is reflected in the CBM framework. Lastly, the CBM framework's emission outputs, in $MgCO_2$, were updated to $MgCO_2$ per GJ of energy produced within the TSA, to be consistent with Bioenergy GHG model outputs. The majority of the changes made to coordinate model parameters were done on the Bioenergy GHG model due to its flexible computing nature where processes can be changed and updated easily by the user.

4.1. Total emissions

Total emissions associated with the bioenergy scenario (biomass combustion) and baseline scenario (harvest residue fate and fossil fuel use) were compared through the calculation of the difference between the two scenarios as bioenergy minus base emissions. The total net cumulative emissions estimate the time to C-parity within the TSAs. Net negative emissions indicate a C-benefit associated with bioenergy implementation in the TSA, whereas net positive emissions indicate a C-debt.

Results of our comparison analysis shows that the differences in the models total cumulative emissions at 2070 are consistently small across all TSAs, with the CBM framework estimating 31% (1.67 $MgCO_2$/GJ) more negative emissions than the Bioenergy GHG model (-3.49 $MgCO_2$/GJ vs. -1.82 $MgCO_2$/GJ) in TSA 24, 13% (1.18 $MgCO_2$/GJ) less negative emissions than the Bioenergy GHG model (-3.66 $MgCO_2$/GJ vs. -4.84 $MgCO_2$/GJ) in TSA 30 and 9% (1.16 $MgCO_2$/GJ) less positive emissions than the Bioenergy GHG model (5.58 $MgCO_2$/GJ vs. 6.74 $MgCO_2$/GJ) in TSA 44 (Figure 7). Both models show either immediate C-benefits, in the case of TSA 24 and 30, or never reach C-parity time, in the case of TSA 44. The CBM framework estimation of TSA 44's emissions has annual fluctuations with larger emissions during 2045–2055 when higher residues amounts were collected reflecting a change in harvest scheduling.

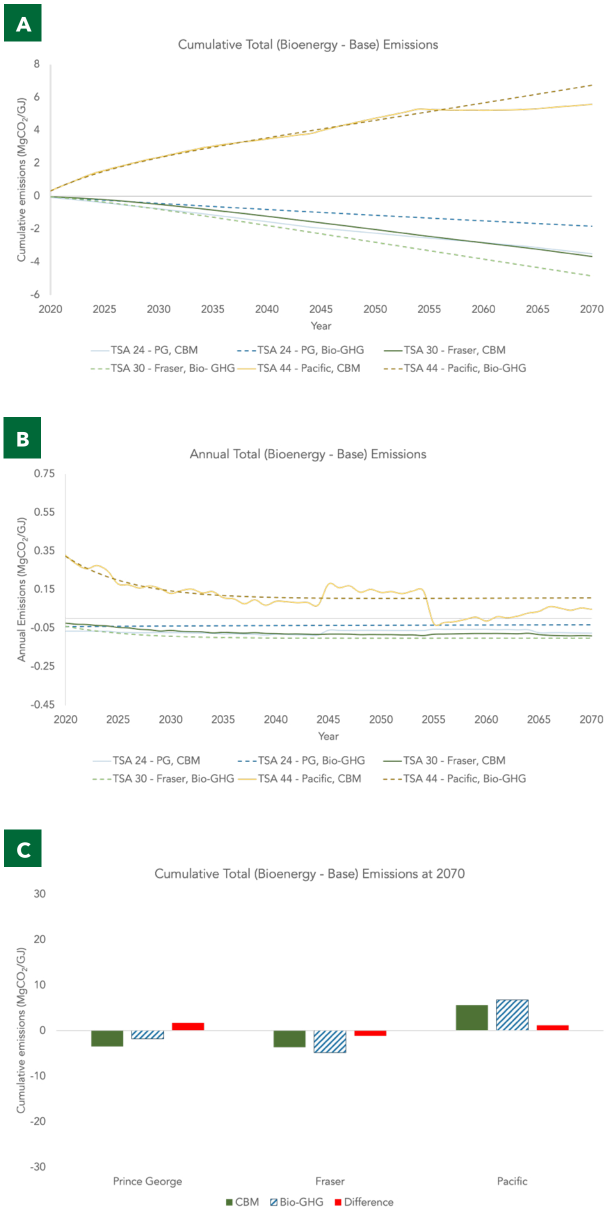

Figure 7: Timeseries of the (A) cumulative and (B) annual total emissions associated with the TSA as calculated by bioenergy emissions minus baseline emissions. (C) Cumulative emissions at 2070. Difference is calculated as Bioenergy GHG model minus CBM framework. Negative emissions indicate a C-benefit associated with bioenergy in the TSA; positive emissions indicate a C-debt associated with bioenergy in the TSA.

4.2. Biomass Combustion

The two models are in broad consensus about the emissions associated with the combustion of biomass where the Bioenergy GHG model had 23% (3.33 $MgCO_2$/GJ) more cumulative emissions at 2070 than the CBM framework in TSA 24 (8.11 $MgCO_2$/GJ vs. 5.35 $MgCO_2$/GJ), 12% more (1.59 $MgCO_2$/GJ) in TSA 30 (7.12 $MgCO_2$/GJ vs. 5.53 $MgCO_2$/GJ) and 11% more (5.38 $MgCO_2$/GJ) in TSA 44 (26.29 MgCO2/GJ vs. 20.91 $MgCO_2$/GJ) (Figure 8). The Bioenergy GHG model includes the emissions associated with collection, transportation, transformation and decay from the processing of biomass, which is not possible to include in the CBM framework. These processes account for up to 6% of the Bioenergy GHG emissions model's estimates of biomass combustion and when excluded, the Bioenergy GHG model's cumulative emissions estimates decreased by 1% relative to the CBM framework's estimates (22%, 11% and 10% respectively for each TSA).

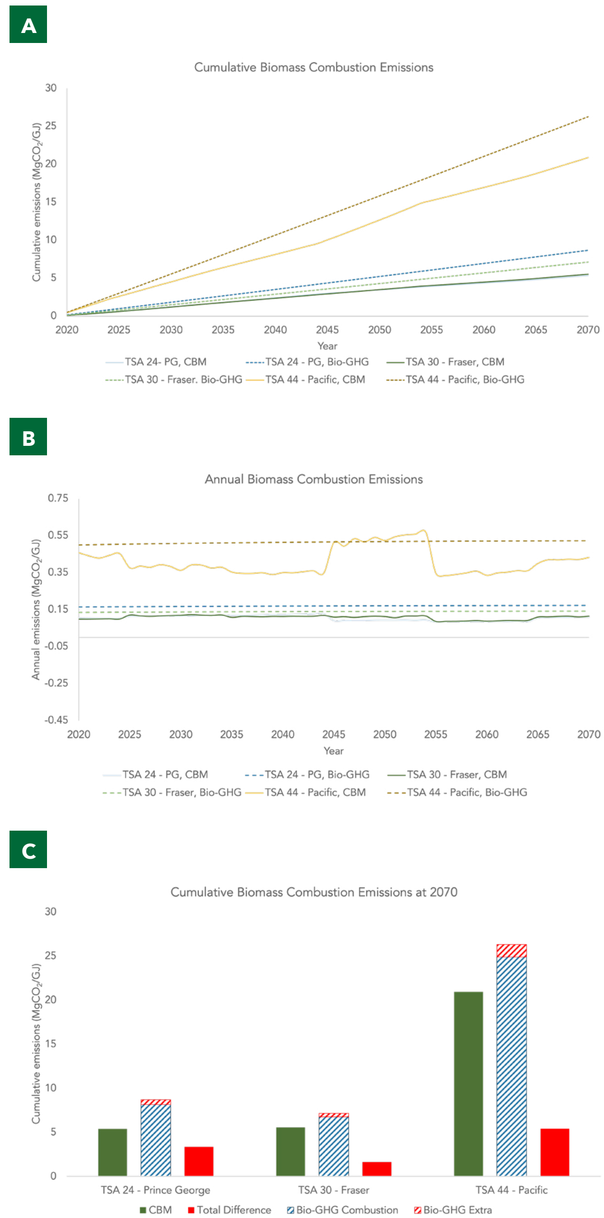

Figure 8: Timeseries of (A) cumulative and (B) annual emissions associated with the combustion of biomass in the bioenergy scenario. (C) Cumulative emissions at 2070. Difference is calculated as CBM framework minus Bioenergy GHG model. Bio-GHG Extra includes emissions associated with collection, transportation, transformation and decay from the processing of biomass.

4.3. Alternative fate of harvest residues

Results of the comparative analysis show that differences in the harvest residue decay and pile and burn emissions between the models are consistently small across all TSAs. Cumulative emissions at 2070 are 8% (-0.98 $MgCO_2/GJ$) larger in the Bioenergy GHG model than in the CBM framework for TSA 24 (-6.60 $MgCO_2/GJ$ vs. -5.62 $MgCO_2/GJ$), 15% larger (-1.52 $MgCO_2/GJ$) in TSA 30 (-5.56 $MgCO_2/GJ$ vs. -4.04 $MgCO_2/GJ$), and 12% larger (-4.21 $MgCO_2/GJ$) in TSA 44 (19.28 $MgCO_2/GJ$ vs. -15.07 $MgCO_2/GJ$) (Figure 9)

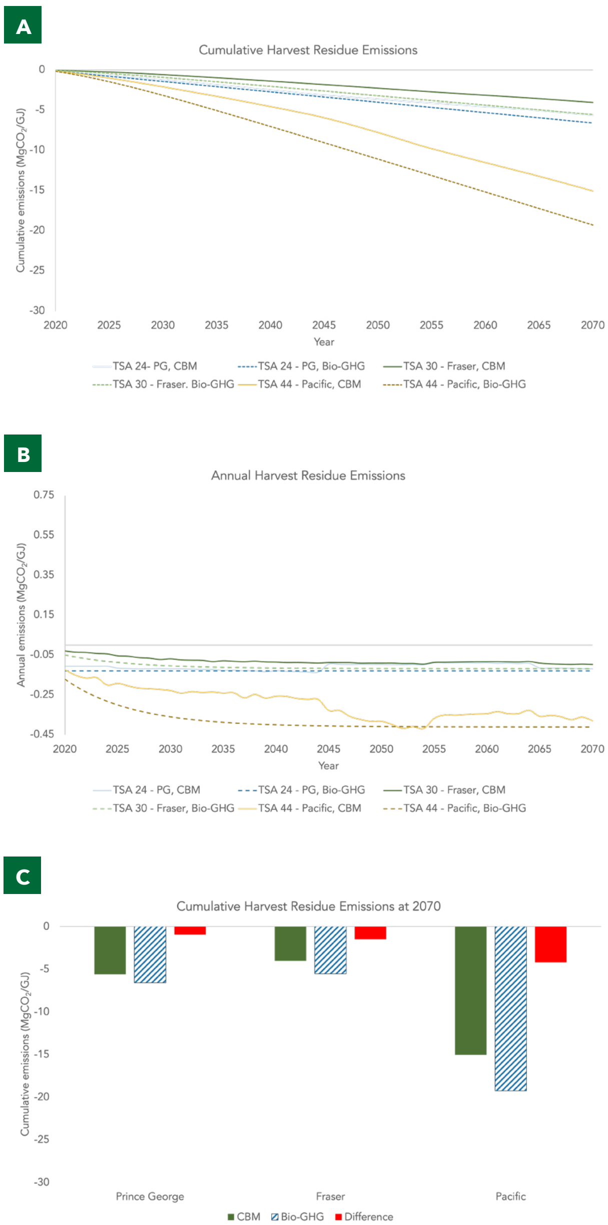

Figure 9: Timeseries of (A) cumulative and (B) annual emissions associated with the decay and slash burning of harvest residues in the baseline scenario. (C) Cumulative emissions at 2070. Difference is calculated as CBM framework minus Bioenergy GHG model.

4.4. Fossil Fuel Combustion

The comparative analysis of fossil fuel emissions shows that the difference in model estimates is consistently small and the smallest across the three compared emissions variables. The Bioenergy GHG model accounts for 9% (-0.67 $MgCO_2/GJ$) more cumulative emissions at 2070 than the CBM framework in TSA 24 (-3.89 $MgCO_2/GJ$ vs. -3.22 $MgCO_2/GJ$), 10% more (-1.25 $MgCO_2/GJ$) in TSA 30 (-6.39 $MgCO_2/GJ$ vs. -5.14 $MgCO_2/GJ$) and 0.4% more (0.002 $MgCO_2/GJ$) in TSA 44 (-0.26 $MgCO_2/GJ$ vs. -0.26 $MgCO_2/GJ$) (Figure 10).

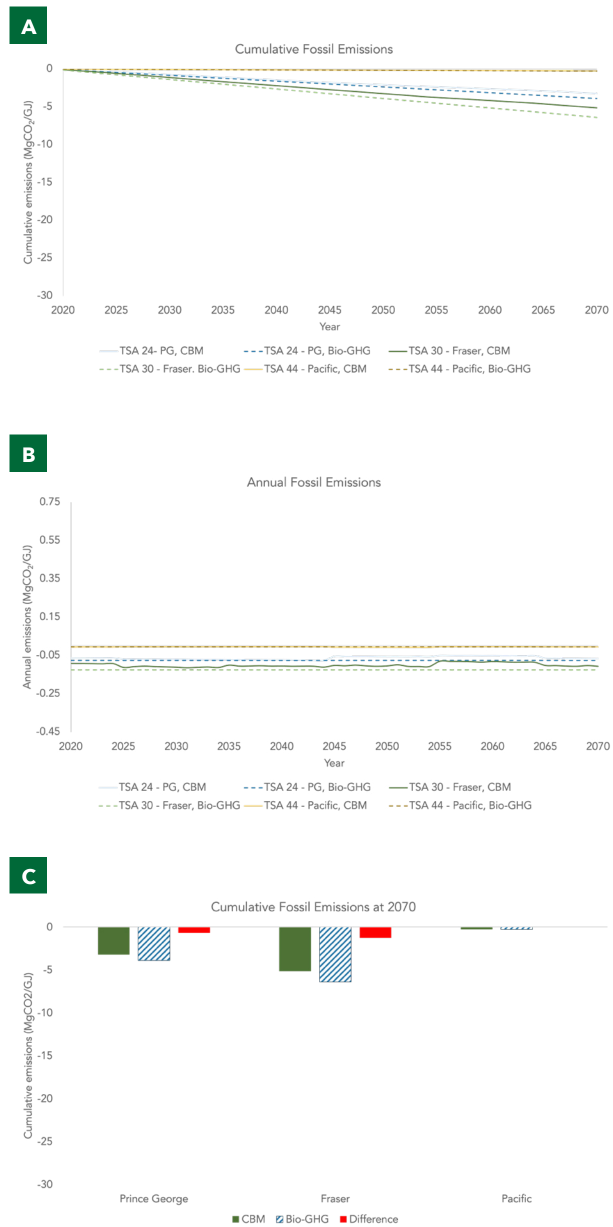

Figure 10: Timeseries of (A) cumulative and (B) annual emissions associated with the continued use of fossil fuels in the baseline scenario. (C) Cumulative emissions at 2070. Difference is calculated as CBM framework minus Bioenergy GHG model.

5. Discussion

The comparisons show that the models are regularly in consensus about the estimated emissions for all variables and TSAs, and differences are consistently small.

5.1. Total emissions

The consistent time to C-parity and small magnitude of difference in total emissions between the models illustrates the agreement associated with their respective methods. Calculation of total emissions has the potential to compound the differences associated with the individual variables to cause large differences in both the time to C-parity and magnitude of emissions, which was not reflected through the comparisons.

The fluctuation between yearly periods of C-benefit and C-debt seen in the CBM framework annual estimates in TSA 44 highlights the differences in how the two models estimate emissions over time. The CBM framework projects yearly changes in biomass type and harvest quantity through time as the forest carbon status changes following harvesting and natural disturbances.

This leads to fluctuations in yearly changes in the quantity of emissions. The Bioenergy GHG model assumes constant yearly emissions from the beginning of the timestep, not accounting for potential annual changes in available biomass quantity and type.

5.2. Biomass Combustion

The Bioenergy GHG model consistently estimates larger emissions associated with biomass combustion relative to the CBM framework. A source for this difference could be due to how the two models define the emission variable. The Bioenergy GHG model includes emissions associated with the collection, transportation, grinding and dry matter loss of biomass whereas the CBM framework does not include them, thus contributing to the observed lower emission values. The CBM framework considers those emissions to be negligible in relation to the significantly larger emissions associated with biomass combustion.

Another source of variation between the models arrives from how the CBM framework accounts for differences in the amount of harvest residue collected yearly based on the scheduled harvest of stands available within the region which have a variety of stand ages, leading species and disturbance histories. These yearly biomass changes are not included within the Bioenergy GHG model which assumes the initial biomass conditions in 2020 continue throughout the time-step. This simplification by the Bioenergy GHG model in assuming that biomass harvest is stable could be a descriptor for the model's emissions being consistently larger than the CBM framework.

The emissions factor associated with the combustion of biomass is considered differently between the two models. The Bioenergy GHG model uses the default emission factor for wood biomass combustion from the Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories. The CBM framework assumes that carbon from harvest residues available for bioenergy is immediately oxidized to the atmosphere as CO2, and that no other gases were produced, nor ash. This singularity may also explain the observed difference in biomass combustion estimates between the models.

5.3. Harvest Residue Fate

The methodology of how the two models simulate decay differs, which could account for the observed larger Bioenergy GHG model's estimates. The CBM framework includes multiple decay rates that represent various types of DOM pools, as well as regionally specific slash-pile burning rates. This fine-tuning allows for very specific modelling of the decaying conditions of harvest residues when not used for bioenergy—which is not able to be replicated in the Bioenergy GHG model's current form. The Bioenergy GHG model uses an average decay rate for the entire simulation.

The modelled assessment of the way the harvest residues decay is consistent with the difference in complexity of the simulated decay pools. Drawing upon the previously used decay pools, the GCBM models decay where most of the emissions are released to the atmosphere, but a portion (~ 17%) is transferred to humified soil organic matter which decays very slowly. Given that the Bioenergy GHG model does not simulate this underlying carbon-soil structure, it assumes decay emissions are released to the atmosphere. This simplification of the decay processes could account for the higher estimates generated by the Bioenergy GHG model.

Through model standardization, both models assume that within the baseline scenario there is some slash-pile burning and decay of harvest residues with the respective amount differing based on regional practices—although the accounting of harvest residue fate in the bioenergy scenario differs between the two models. The GCBM assumes differing percentages of the DOM pools will burn according to a disturbance matrix for slash-pile burning.

5.4. Fossil Fuel

Fossil emissions between the two models consistently have the smallest differences between the estimated variables due to the use of the same fossil fuel emissions intensities.

5.5. Model Purposes

The small discrepancies in emissions estimates reflect the individual model's goals in accounting for bioenergy-related GHG emissions.

The GCBM is used in comparative analyses of climate change mitigation options, and models forest management as well as wood use scenarios, including bioenergy. The GCBM framework starts with understanding the forested ecosystem C balance, considers emissions from harvested wood products and bioenergy as well as substitution benefits, then operates to understand how the various forest management and wood use scenarios would change the net emissions over time. Given the fine-scale analysis of the forest carbon structure, the GCBM allows for specific fine-tuning of model parameters in order to reflect the regional conditions to better understand impacts of management on emission reductions.

The Bioenergy GHG model is exclusively developed for understanding and estimating bioenergy-related emission reduction potential. Model analysis begins at the project scale where emissions profiles are calculated with respect to what type of processes will be occurring within the region, as opposed to what type of biomass conditions are reflected regionally. The facility focus in the Bioenergy GHG model gives a broader view into emissions as a whole by simulating the larger processes in the bioenergy system without fine detail. This generalized view allows for full customization of the model's processes according to the objectives and the data available for the region—which was utilized to synchronize the two models before comparisons. The model qualifies this broad generalization of emissions through the calculation of an uncertainty period which provides context on best-case and worst-case emissions scenarios to be calculated for a bioenergy project or set of projects.

5.6. Policy Implications

Understanding how and when to utilize these models most appropriately is paramount to accurately assessing bioenergy-related emissions potential to make sound implementation strategies. The two compared models can be applied individually, or in conjunction with each other utilizing each according to their strengths. The project focus and flexibility of the Bioenergy GHG model allows it to be a good initial model to test the feasibility of implementing a bioenergy production facility within a region based on its regional conditions. The CBM framework's forest-status focus could simulate a selected few implementation scenarios estimated to have C-benefits by the Bioenergy GHG model, to better understand how the facilities will affect the greater forest ecosystem for the region. Moreover, forest dynamics' output data from GCBM can also be integrated into the Bioenergy GHG model to take advantage of more complex forest ecosystem processes as done in Steenberg et al. (2023).

The ability to communicate which model would work best to answer the questions asked by policy-makers is key to being able to assess the potential of bioenergy in contributing to reach Canada's 2050 emission goals.

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7. Appendix

A.1. Model Parameters

This appendix documents the emissions factors used within the Bioenergy GHG model, the percent allocation and efficiency values used within both the Bioenergy GHG model and CBM framework. These parameters are used to calculate the respective emissions associated with the three compared variables (biomass combustion, alternative fate of harvest residues, fossil fuel combustion).

Emissions factors (kgCO2/GJ)	TSA 24	TSA 30	TSA 44
Collection	0.86	0.86	0.86
Transformation	0.76	0.76	0.76
Transportation	0.012	0.012	0.012
Combustion	112.1	112.1	112.1
Natural gas	70.84	-	-
Fuel oil	100.28	100.28	-
Hydroelectricity	-	-	5.17

Allocation (%)	TSA 24	TSA 30	TSA 44
Bioheat	68	100	0
Bioelectricity	4	0	100
Natural gas	68	-	-
Fuel oil	4	100	-
Hydroelectricity	28	-	100
Decay	0	70	70
Pile and burn	100	30	30

Efficiency (%)	TSA 24	TSA 30	TSA 44
Bioheat	54	85	-
Bioelectricity	25	-	23
Fuel oil electricity	25	-	-
Default	-	85	23
Hydroelectricity	-	-	100

A.2. Bioenergy GHG Model Biomass Combustion Emissions

This appendix documents the Bioenergy GHG model's allocation of biomass combustion emissions between the pure combustion emissions and collection, transportation, transformation and dry matter loss (DML) emissions.

Bio-GHG Biomass Combustion ($MgCO_2/GJ$)	TSA 24	TSA 30	TSA 44
Total	8.67	7.12	26.29
Combustion	8.11	6.73	24.86
Percent of Total	93.54%	94.51%	94.55%
Collection, transportation, transformation, DML	0.56	0.39	1.43
Percent of Total	6.46%	5.49%	5.45%