Yukon Biomass Energy Life Cycle Assessment

Project Report (Final Version)

March 17, 2022

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EXECUTIVE SUMMARY

INTRODUCTION AND CONTEXT

Yukon Government (2020)'s *"Our Clean Future: A Yukon strategy for climate change, energy and a green economy"* strategic planning document committed to a goal of reducing greenhouse gas (GHG) emissions 30% from 2010 levels by 2030; this target was recently expanded to a 45% reduction as per the Minister of Environment mandate letter. One strategy that is expected to contribute to the Yukon's GHG reduction target is the increased use of biomass energy to displace fossil fuel-based heating. According to the *Yukon Biomass Energy Strategy* (2016), biomass sources currently represent about 18% of the Yukon's heating energy needs, with about 75% of heating energy supplied by fossil fuel (heating oil, propane) or electricity. This indicates that while there is an existing level of awareness in the Yukon of biomass as a legitimate and viable energy source, there is a significant opportunity for increased capacity to replace fossil fuels for heating. Currently biomass energy is used in a range of applications from small-scale residential consumption of cordwood to industrial-scale consumption of pellet fuel.

When considering the adoption of increased use of locally-sourced wood-based biomass energy in the Yukon it is important to quantify the associated life cycle GHG emissions. This includes the use of fossil fuels in harvesting, transporting, and treating wood biomass prior to use, as well as the emissions from land use change and changes to carbon stocks associated with the harvesting activity. This project has combined the complementary approaches of life cycle assessment (LCA) and forest carbon stock modeling to determine the carbon intensity of various locally-sourced bioenergy pathways for heating in commercial and residential applications, and to compare these to reference pathways (existing sources of heating energy in the Yukon) from fossil fuels and imported wood pellets.

LIFE CYCLE ASSESSMENT AND FOREST CARBON MODELING

This LCA follows the ISO 14040/44 standards, including being consistent with boundaries, dealing with coproducts, applying conservative approaches to data use, and sensitivity analysis on methods and data. According to the ISO 14040/44 standards, if there are comparative assertions to be made to the public about the carbon intensity of the bioenergy fuels relative to the current fuels, an independent critical review of the LCA study (including methodological approach, assumptions, data used, and results) should be undertaken. However, if the results are to be used within the Yukon Government, or to be published without making any claims of superiority of one fuel over another, a critical review is not necessary.

The use of forest carbon modeling approaches provided the ability to quantify the impacts of increased usage of forest biomass on the near-term (20-year) and long-term (100-year) carbon budget of Yukon's land-use based GHG emissions, known as LULUCF (land use, land use change, forestry). The forest carbon model used in this project is the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3). The CBM-CFS3 model results provided the biogenic GHG emissions used in the LCA for both the bioenergy and reference pathways. These biogenic emissions represent the net carbon budget, including carbon released from the soil or in the feedstocks, through decay, or recaptured over time through regrowth. For the bioenergy pathways, the biogenic GHG emissions represent the net carbon contained in the feedstocks and soils that are released and recaptured when biomass is harvested for energy. For the reference pathways the biogenic GHG emissions represent the carbon budget if the same amount of biomass was not removed for bioenergy.

RESULTS

The results of the LCA and forest carbon modeling performed in this study indicate that several viable pathways exist for the Yukon Government to consider in the establishment of a strategy that increases reliance on bioenergy sources. The table on the following page provides a summary of the modeled percentage change in global warming potential over a 20-year timeframe of several bioenergy pathways compared to the existing sources of heating energy used in the Yukon (reference pathways). The table indicates the following:

74(1)(a)

If the biomass feedstocks with the lowest carbon intensity can be combusted in technologies of the highest efficiency and energy content (90% and 18 MJ/kg), annual GHG reductions would be 23,999 tonnes CO_2e, assuming they replace 50% of current reference pathway heating fuels.

Additional scenarios and sensitivity analyses were performed in this study that indicate the following:

- Viability of bioenergy pathways is impacted by the combustion efficiency of the methods used for heating and the energy content of the biomass fuel source
- The timeframe of the analysis is a significant factor for consideration in the increased utilization of bioenergy, as the use of fire-kill and beetle-kill exhibit significant reductions in carbon intensity when the forest modeling results are averaged over a 100-year time period

74(1)(a)

Modeled percentage change of carbon intensity of several bioenergy pathways compared to reference pathways for a 20-year global warming potential timeframe. Green cells represent recommended bioenergy pathways, red cells are not recommended bioenergy pathways, and orange cells represent potential bioenergy pathways for consideration.

		REFERENCE PATHWAYS		
		Imported Wood Pellets (avg. of AB and BC pellets)	Diesel / Heating Oil	Propane
BIOENERGY PATHWAYS	Incidental Biomass – average of all sources (wood chips @75% combustion efficiency)	74(1)(a)		
	Incidental Biomass – fire protection initiatives (wood chips @75% combustion efficiency)			
	Fire-Kill (cordwood @75% combustion efficiency)			
	Beetle-Kill (cordwood @75% combustion efficiency)			
	Live standing trees			

OTHER CONSIDERATIONS

74(1)(a)

1.BACKGROUND & CONTEXT

1.1 ENERGY SUPPLY AND DEMAND IN THE YUKON

Yukoners' current demand for energy is 7.9 PJ/year, based on a 2017 assessment (Government of Canada, 2021 *in* Stantec, 2021). Thermal energy (for heating) accounts for 21% of total energy consumption in the Yukon (YG, 2020 *in* Stantec, 2021).

Woody biomass currently supplies 18% of the thermal energy demand in the Yukon (YG, 2016). Cordwood fulfills 13,000 tonnes / year (almost 90%) of woody biomass consumption for energy with the remainder being split between woodchips and wood pellets (Stantec, 2021). Fossil fuels and electricity supply the remainder of the thermal energy demand.

Previous studies have demonstrated that locally-sourced woody biomass could supply a much larger share of the Territory's thermal energy demand and perhaps part of the non-heating electricity demand (YG, 2021). A range of locally-sourced woody biomass sources are available in the Yukon, including incidental biomass (e.g. from land clearing from aggregate extraction, mining projects, agricultural land establishment, other land development, FireSmart activities), residues from forest industry processing, standing dead trees from forest fire and spruce bark beetle infestations, and live standing trees. An estimate of the supply of locally-sourced biomass is presented in Table 1, listed according to the carbon intensity (defined in Section 2.4) of the biomass source as a bioenergy feedstock.

1.2 FOREST MANAGEMENT IN THE YUKON

Yukon forests play an important role in the social, spiritual, and economic well-being of Yukoners (Preto, 2011). They provide many ecosystem services, including fish and wildlife habitat, cultural and historical resources, outdoor recreation opportunities, natural beauty, as well as timber, fuelwood, and other forest products. Yukon has 28 million ha of forest land (YG, 2021), with the most productive forests situated in the southeast corner of the Territory, with productivity gradually decreasing moving west and north of this region (YG, 2016).

Management of forest as a source of biomass poses particular challenges in terms of sustainability. The Yukon's *Forest Resources Act* aims in safeguarding sustainable management of Yukon's forests and prescribes the co-development of Annual Allowable Cuts (AACs) for every region of the Territory as determined in Forest Management Plans. AACs are determined for standing merchantable trees (> 16 cm diameter at breast height [DBH]) in consideration of the evidential forest capacity, as well as economic, environmental and social factors. They are calculated irrespective of end-usage, amalgamating both timber (sawlogs) and fuelwood (energy biomass) harvest. AACs are re-assessed every 5-20 years. Where forest stands are significantly affected by insect infestations, volumes can be added to the AAC to encourage sanitation cuts and salvage of merchantable trees; this addition is non-replaceable and generally will not last for more than 20 years. Wherever an AAC has not yet been developed, harvest levels are capped by an Annual Limit (AL). The latter are purposefully more conservative than an AAC would be.

Table 1: Supply of dry biomass and carbon intensity of locally-available biomass sources in Yukon.

	Biomass Source	Available dry biomass (t / year)	Geographic Area	Comments and Source
LOWER	**OTHER INCIDENTAL BIOMASS SOURCES**			
	Aggregate development	17,255	Within 150 km of Haines Junction or Watson Lake	Tetra Tech, 2017.
	Agriculture land clearing	1,425	Within 150 km of Haines Junction or Watson Lake	Tetra Tech, 2017.
	Land development	1,297	Within 150 km of Haines Junction or Watson Lake	Tetra Tech, 2017.
	Mining development	763	Within 150 km of Haines Junction or Watson Lake	Tetra Tech, 2017.
	TOTAL OTHER INCIDENTAL	**20,740 tonnes / year**		
	INCIDENTAL BIOMASS FROM FIRESMART INITIATIVES (not including landscape-level projects)			
CARBON INTENSITY	FireSmart residues	1,030	All Yukon Territory	Tetra Tech, 2017
	FORESTRY INDUSTRY RESIDUE BIOMASS			
	Forestry industry residues	1,196	Within 150 km of Haines Junction or Watson Lake	Tetra Tech, 2017.
	STANDING DEAD BIOMASS			
	Fire-kill	2,579,133	All Yukon Territory	Includes all forest fire area in YT. Would be reduced significantly if limited to accessible areas (within proximity to road network) Stantec, 2021
	Beetle-kill	64,994	Forest Health Zones 1 & 2	Stantec, 2021
	TOTAL STANDING DEAD	**2,644,127 tonnes / year**		
	LIVE STANDING BIOMASS			
HIGHER	Live standing trees	146,245	Annual allowable cut for all Yukon Territory	Stantec, 2021
	TOTAL (all sources)	**2,813,338 tonnes / year**		

Currently, the vast majority of harvest of standing merchantable trees (fire-kill, beetle-kill or live-standing trees) is performed in first-generational blocks. Therefore, access to the resource involves the construction of forest roads that extend from the public roads system or existing forest roads. This also involves the clearing of landings[1]. Forest roads and landings are thus built as needed when new blocks open. Only active blocks are maintained, for instance plowing of roads and landings during the winter.

1.3 FOREST ECOLOGY IN THE YUKON

Spruce bark beetle *(Dendroctonus rufipennis)* is a natural and endemic disturbance agent of boreal North American spruce (Picea spp.) forests. Moreover, climate change will likely increase the frequency and intensity of infestations (Williamson et al., 2009). Infestations can contribute to a potential fire hazard for communities, increase the risk of catastrophic loss of property, affect visual landscapes, impact ecosystems, and reduce the value of the forest for timber, fuelwood and other usage (Preto, 2011). Sanitation logging can be recommended to control an infestation or when attempting to stop an outbreak in its early stages.

In the boreal forest, wildfire is part of the natural succession cycle. Climate change will likely increase the frequency and intensity of forest fires (Williamson et al., 2009). In a wildfire the combustion rarely consumes more than 10-15% of the biomass (Preto, 2011), leaving the rest as salvageable wood. In an attempt to control the fire hazard, forest fuel reduction initiatives (e.g. FireSmart, landscape-level forest clearing) can be deployed to protect infrastructures such as roads, buildings and towns. Such initiatives are based on the probability of a wildfire occurring and its potential consequences. The extent of the forest fire reduction initiatives takes into account social acceptability and tolerance to risk. For instance, the defensible space around Fairbanks Alaska covers 1,200 hectares.

[1] A landing is an open area where trees are brought for processing and stacking before they are loaded onto a truck. It also typically is where machinery is stored. Landings are typically spaced such as to keep distance from the felling site short (e.g. 100 metres).

2. GOAL & SCOPE

2.1 GOAL

The goal of this LCA study is to determine the life cycle carbon intensity of various locally-sourced wood-based biomass pathways for heating in commercial and residential applications, and to compare these to the current situation where fossil fuels are a main source of heating energy, with a other sources being imported biomass pellets, cordwood, and electricity. The carbon intensity is defined in section 2.4.

The results of this LCA study should not be used to make comparative assertions to be disclosed to the public about the performance of the carbon intensity of the bioenergy fuels relative to the current fuels. If the Government of Yukon wishes to make such public assertions (I.e. claims of environmental superiority of bioenergy), a critical review of the LCA study (including methodological approach, assumptions, data used, and results) should be undertaken.

This study follows the ISO 14040/44 (Canadian Standards Association, 2006) LCA standards. The LCA principles for a rigorous study are followed, particularly:

- **conservativeness** in applying data, meaning that the data chosen for analyzing the product system (i.e. biomass for heating) should not oversell the benefits; this is also consistent with internationally-recognized carbon accounting protocols (WBCSD, n.d.)
- **transparency**, meaning that all data, assumptions, methods are clearly and transparently documented.

This study is an attributional LCA, meaning that the analysis is conducted only on the direct boundaries of each product system, and does not consider how the introduction of the product system into the market will affect other systems, which would require conducting what is known as consequential LCA. The consequential modelling approach links activities outside of a product system that are expected to shift due to a change in a demand for a unit of the product. Consequential LCA requires advanced economic modeling, and results in more uncertainty around the carbon intensity, so it is out of scope for this project. In Carbon Accounting, how a product affects GHG emissions indirectly is known as 'leakage'. Although this study does not quantify leakage, it provides a qualitative assessment of potential sources of leakage in shifting towards a biomass-based heating strategy.

2.2 SYSTEM BOUNDARIES

In LCA, a product system is made up of various activities or stages. The system boundary denotes which aspects of the overall product system will be included in the study and should be justified based on the goal of the study. In this study, the boundaries for the LCA are 'cradle-to-grave', because the fuels are used to produce heat, which is then dissipated, and has no further use. The activities include biomass extraction (cradle), including carbon change dynamics associated with removal of biomass as appropriate, biomass processing (e.g. chipping wood, pelletization), biomass conversion (from solid to liquid fuels for example), and combustion of the fuels (Figure 1). It also includes transportation across all the life cycle stages. For each activity, the boundaries are 'cradle-to-gate', in that materials (e.g. chemicals) and energy (e.g. diesel, electricity) inputs into each activity include the impacts of upstream production of those inputs. The capital equipment and infrastructure associated with all activities will also be included as they are part of the database being used. However, research and development activities, indirect activities associated with fuel production, such as marketing, accounting, and commuting, are excluded.

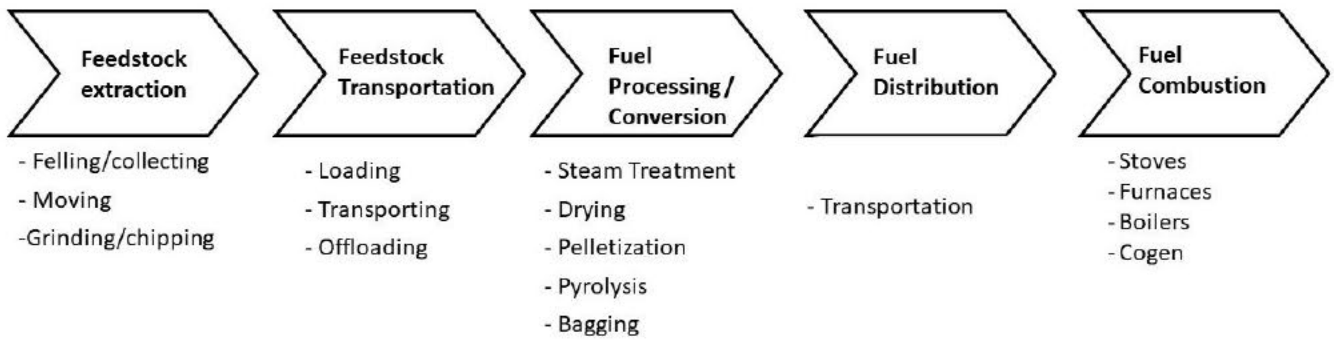


Figure 1. Stages in biomass fuel production, distribution, and combustion.

As previously mentioned, indirect impacts, such as indirect land use change, will not be considered in the boundaries, as this is an attributional LCA. For example, although forest fuel reduction initiatives (e.g. FireSmart) are known to have a potential impact on carbon emissions and climate change through reduction of risk of forest fires, these are happening independent of salvage of the incidentally-produced biomass, therefore this impact is not accounted for in this LCA. Note that direct land use changes (e.g. harvesting of forest areas) are included in the boundary of the LCA.

The geographical boundary for this study is the Yukon Territory for the foreground processes (i.e. those activities that are under the control of the decision-maker who commissions the LCA study). For background processes, (i.e. activities over which the decision-maker has no influence or indirect influence, such as packaging, raw materials such as crude oil) the geographical boundary depends on where materials and energy are sourced.

The temporal boundary for the LCA is 10 years, which represents the time period for which this LCA data and its findings are applicable. The temporal boundary has been defined with a shorter time frame for multiple reasons:

- Several of the biomass fuel pathways (e.g. beetle-kill stands, fire-kill stands) have a limited timeframe whereby the available biomass is deemed usable as a biomass energy input.
- Forest carbon dynamics are affected by climate change, and therefore need to be updated regularly to ensure representativeness.
- Rapid technology development in conversion and utilization of biomass fuels that could affect efficiency of technologies.

2.3 PRODUCT SYSTEM DESCRIPTION FOR HEATING PATHWAYS

The following sections provide detailed cradle-to-grave descriptions of the bioenergy and reference pathways to be modeled for this LCA, with consideration of the specific circumstances of the Yukon.

2.3.1 Bioenergy Pathways

The bioenergy pathways are those that could be implemented as a strategy to increase Yukon's locally-sourced biomass energy portfolio. Table 2 presents each stage of the bioenergy pathways, starting with the sources where feedstocks are extracted through to combustion technologies. In the Yukon, locally-based biomass can be extracted from a variety of sources, including sustainably harvested standing merchantable trees and collection of residues, incidental and recycled biomass. Extraction includes the harvest / collection stages through to processing, including transport.

Additional detail on potential local sources of biomass from within the Yukon are presented in Appendix A.

Table 2: Stages of the bioenergy pathways for this LCA study.

Biomass extraction	Biomass processing	Biomass conversion	Biomass combustion
• Collection of biomass residues: - Generated by harvest - Generated by processing • Collection of incidental biomass • Generated by forest fuel reduction initiatives (FireSmart or landscape-level projects) or land clearing • Generated by development and maintenance of infrastructure • Collection of recyclable biomass (waste wood) • Harvest of merchantable standing trees - Fire-kill - Beetle-kill - Live-standing trees	• Cordwood production (incl. bucking, splitting, drying) • Chipping (incl. drying) • Pelletizing (incl. drying)	• Pyrolysis	• Wood Stoves • Pellet stoves • Outdoor wood furnaces • Biomass Heating Plants • Boilers • Furnaces • Cogeneration Plants

2.3.2 Reference Pathways

Reference pathways define the 'business as usual' scenarios that are currently in place in the Yukon, against which the bioenergy pathways (locally-sourced biomass) have been compared. Feedstocks for these reference pathways include imported fossil fuels, imported biomass energy sources, and some locally-sourced biomass energy (Table 3). The reference pathways have been modelled using typical sources, technology, and handling for Yukon conditions. It is assumed fuels are transported by barge or road to Yukon, with distances depending on the source of fuels (Burrows, 2021, see also Table 7, Section 3.2.2.1).

Table 3: Stages of the reference pathways defined in this life cycle assessment.

Feedstock type		Feedstock source	Origin and Transportation	Transport Mode	Combustion Technology
Imported fossil fuels	• Diesel • Heating Oil	Alaska crude	Anchorage AK to Whitehorse (1133 km)	Truck	Furnace
	• Diesel • Heating Oil	Mixed source crude	Seattle to Skagway AK (1630 km barge) Skagway, AK to Whitehorse (176 km)	Barge Truck	Furnace
	Propane	Natural gas (methane, ethane)	Vancouver, BC to Whitehorse (2400 km)	Truck	Propane Furnace
Imported pellets (2,000-3,000 tonnes / year)		Biomass residues: by-product of processing (sawmills) Fire-killed trees	LaCrête (AB) to Whitehorse (1900 km) Chetwynd (BC) to Whitehorse (1465 km)	Truck Tractor trailer (super B)	Modern pellet boiler systems Modern pellet stoves
Locally-sourced biomass	Cordwood (13,000 tonnes / year)	Primary (57% of the total): beetle-killed trees	Haines Junction area to Whitehorse (154 km)	Truck	Modern cordwood boiler systems Wood stoves / boilers (more or less modern) Outdoor wood furnace
		Secondary: fire-killed trees	Throughout the Yukon, e.g. Fox Lake burn to Whitehorse	Truck	
		Other: harvesting of live-standing trees, collection of incidental biomass	Variety of sources	Truck	

Feedstock type		Feedstock source	Origin and Transportation	Transport Mode	Combustion Technology
		from forest fuel reduction initiatives (e.g. FireSmart)			
	Wood chips (1,600 tonnes / year)	Beetle-killed trees Fire-killed trees Biomass residues (by-product of sawmill processing)	Haines Junction area to Whitehorse (600 tonnes / year) Dawson City, inter-region (600 tonnes / year) Teslin, inter-region (400 tonnes / year)	Truck	Modern woodchip boiler systems

2.4 FUNCTIONAL UNIT

To compare different fuels for heating using a life cycle approach, a common unit for comparison (the functional unit) is required. The function of the bioenergy systems is to provide heat for commercial and residential applications. Therefore, the life cycle impacts for each bioenergy pathway are reported based on a functional unit of **1 MJ of lower heating value (LHV)[2] energy delivered**.

The **carbon intensity** of each pathway is defined in kg CO_2e per 1 MJ of LHV energy, where CO_2e is the unit of Global Warming Potential (GWP). This allows comparison of GWP reductions based on different bioenergy pathways as well as relative to the current energy use for heating in the residential and commercial sectors. The carbon intensity is also used to scale up emission reductions based on a shift from current energy use (fossil fuels, imported pellets) to Yukon-sourced woody biomass energy use.

2.5 CO-PRODUCT TREATMENT

When an economic activity, process or product system produces more than one useful product (is multi-functional), it presents a problem as to how should the impacts be divided, or allocated, between the two products.

According to ISO 14044 (ISO, 2006), wherever possible, allocation should be avoided by:

[2] LHV is a measure of available thermal energy produced by a combustion of fuel which considers energy losses, such as the energy used to vaporize water in the fuel/feedstock.

- Dividing the activity or process into two or more sub-processes and measuring material and energy input and output (emissions, waste) data related to these sub-processes. This is often not possible or practical.
- Using the system expansion approach, which requires expanding the product system boundaries to include additional functions provided by the co-products and using 'substitution' to determine which product in the economy is displaced by the co-product. If LCA results are available for this product then the impact of the substituted product is subtracted from the product system being modeled. This is a consequential LCA approach, as economic modeling is required to understand whether substitution results in changes in production output of the substituted product, and therefore reduces impacts of that production.

If allocation cannot be avoided, then inputs, outputs, and impacts should be divided based on their underlying physical relationships (e.g. mass, energy, volume). This approach has been used to allocate the impacts of co-products of forestry, for example. The exception is for electricity from cogeneration, where we consider that this would displace Yukon electricity, and use an approach of making the two systems equivalent in their functions.

In biological and energy systems, the standard approach to allocation is to divide the impacts based on energy characteristics (Pelletier et al., 2015), such as the energy content. This approach was used in this study and has also been used in other biofuel models, such as GREET (Argonne National Laboratory, 2021) and GHGenius ((S&T) Squared Consultants, 2021), and for low carbon fuel standards being used in California and Canada (CARB, n.d.; ECCC, 2017).

2.6 DATA QUALITY REQUIREMENTS

ISO 14044 (ISO, 2006) requires a description of the "characteristics of data that relate to their ability to satisfy stated requirements" of the goal. The required data quality to provide high quality and robust carbon intensity values for each pathway is provided in Table 4.

Table 4: Data quality requirements and indicators for meeting the goal of this LCA study.

Data Quality Category	Requirement	Data Quality Indicator
Temporal	Data within 10 years of study	Data is from 2011 to 2021
Geographical	Data matches local production/ use	Data comes from the Yukon territory for biomass and from location of production for reference fuels
Technological	Average and most common production processes or technologies	All processes used in study are representative of most common practices

2.7 LIFE CYCLE IMPACT ASSESSMENT METHOD

Life cycle impact assessment methods are used to convert life cycle inventory indicator data (material and energy use, emissions to air, water, soil, and waste) into environmental impacts and resource use through characterization factors. The software used to model the carbon intensity is openLCA, which includes a suite of impact assessment methodologies.

Since the goal of this study is to determine the carbon intensity of heating fuel pathways, both biomass and fossil based, the impact assessment method is based on the global warming potential (GWP) approach. The methodology to be used is Intergovernmental Panel on Climate Change (IPCC) GWP100, based on the IPCC's Fifth Assessment Report (AR5) (IPCC, 2014). However, time horizon choice can strongly affect the characterization factors used for gases other than CO_2, which has a GWP of 1 under any time horizon used. The GWP100 represents the global warming potential of emissions for a 100-year time horizon. Although there are GWPs with other time frames, the 100-year time horizon is the most-widely used approach in bioenergy studies and allows comparison of the carbon intensity with various jurisdictions and studies. Table 5 provides a summary of the GWP for the main GHGs.

Table 5: Factors for GWP according to the IPCC AR5 GWP100 (IPCC, 2014))

Greenhouse gas	GWP Factors (kg CO2e/kg greenhouse gas)
Carbon dioxide	**1**
Methane	**28**
Nitrous oxide	**265**

2.8 GENERAL ASSUMPTIONS AND LIMITATIONS

Forest and woody biomass use is already part of the heating mix in the Yukon Territory (Stantec, 2021). As such, existing combustion technologies may be older and less efficient than newer technologies. To maintain a conservative approach, this study assumes an average efficiency for these technologies, as well as for the reference fuel technologies. This will affect the amount of biomass or fuel required to generate 1 MJ of heat, and in turn affect the carbon intensity of the reference and biomass systems. However, we assume that any replacements or new installations may have increased efficiencies and have conducted a sensitivity analysis to determine the impact of this assumption on the potential GHG reductions associated with biomass energy.

Additionally, some technologies are not currently in use, but have been evaluated in this study as scenarios, specifically cogeneration and pyrolysis. This study uses data from literature sources and expert opinion and assumptions to make the technologies as representative as possible for Yukon applications. However, these scenarios need further research to determine whether the assumptions used are representative for the Yukon.

In terms of limitations, this study only applies to forest biomass used for residential and commercial heating for the Yukon Territory. The carbon intensity values are specific to heat produced in Yukon Territory, with Yukon-sourced biomass and electricity, based on the specific reference and bioenergy pathways described. The results do not apply to any changes or variations from these pathways, which would need additional modeling. A sensitivity analysis and data quality assessment was conducted, and the results have been interpreted with respect to whether the data quality affected the robustness of the carbon intensity values.

The purpose of applying the LCA methodology is to provide insights into environmental considerations across various impact categories (from environmental impacts to resource use) and how impacts may shift from one impact to another, one life cycle stage to another, or from one region to another. However, this study only quantifies the carbon intensity based on the goal and purpose of the study. To ensure that carbon reductions do not come at a trade-off with other environmental impacts (e.g. biodiversity loss, air quality), further analysis of other environmental considerations should be performed.

3. LIFE CYCLE INVENTORY

3.1 DATA COLLECTION APPROACH

The data collection for the life cycle inventory (LCI) of foreground processes utilized a stratified approach as follows:

1) Yukon-specific data for foreground processes. This includes data on the biomass amounts, types, characteristics, locations, technologies, electricity, energy, water, etc. These data were collected from government reports, official Canadian statistics, and through expert consultation.

2) Journal articles and reports on Canadian-specific activities, processes or technologies. This includes pelletization, pyrolysis and combustion technologies.

3) Volumes of available biomass carbon from the various bioenergy feedstock pathways (e.g. fire-kill, beetle-kill, live-standing wood, etc.) were estimated using the CBM-CFS3 forest carbon model using Yukon-specific vegetation inventory data as model inputs (more detail about the CBM-CFS3 model is provided in Section 3.2.3 of this report).

4) Modified ecoinvent processes. The ecoinvent database is a collection of thousands of material and energy processes which provide the life cycle inventory of material and energy inputs and outputs used in processing various products. These processes are modeled based on cradle-to-gate (e.g. crude extraction including all materials, emissions, etc.), gate-to-gate (manufacturing or processing energy for different materials such as metal working, or gate-to-grave processes (e.g. waste treatment). These processes are often either regional or global market averages (I.e. representing global averages of production and associated transportation). Processes can be modified to use Canadian or Yukon-specific data, such as the fuel mix used to generate electricity.

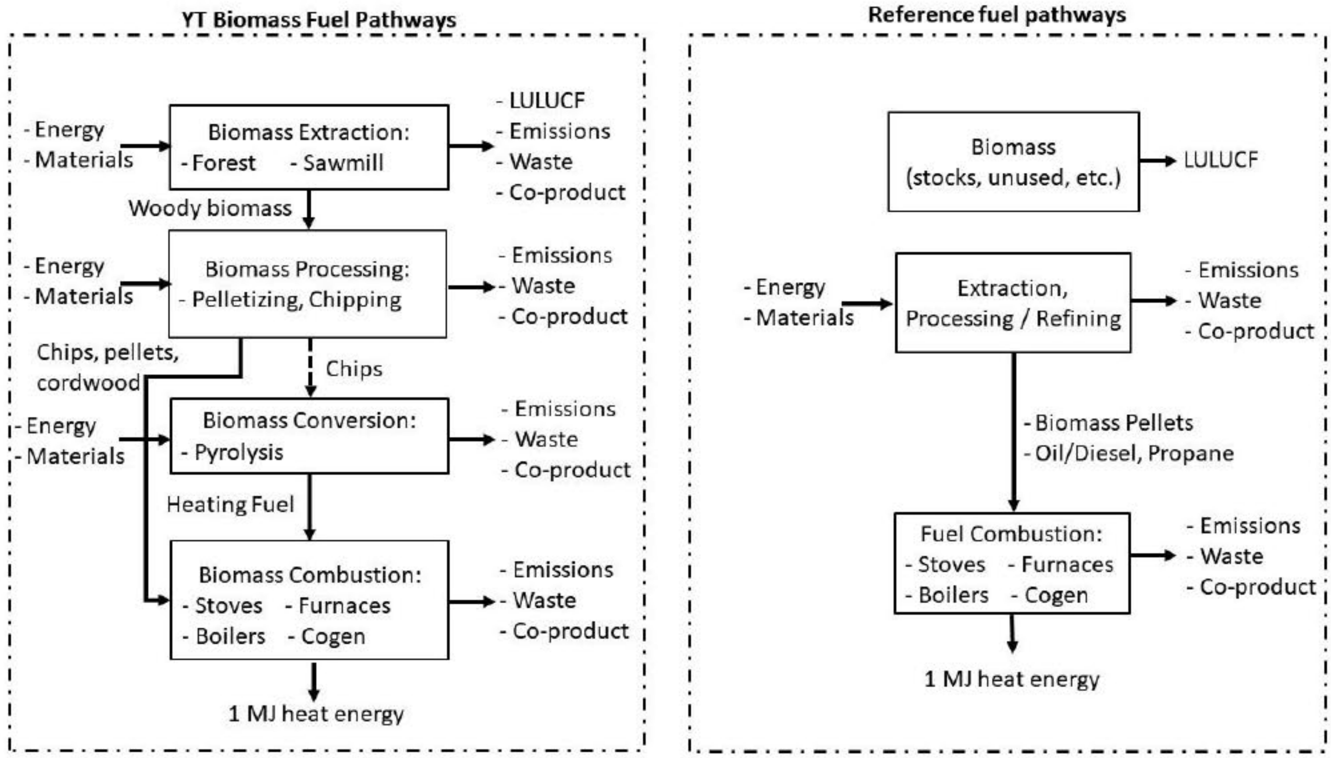
Thus, the LCI is comprised of Canadian- and Yukon-specific data, data from other representative regions that has been modified to include Canadian energy and emissions or data that is adequately representative without revision.

The data quality for foreground processes decreases from level 1) to 4); however, as mentioned in the limitations, this has been addressed using a sensitivity analysis and a qualitative data quality assessment (Weidema & Wesnæs, 1996) presented in Section 4.2.

Data in the ecoinvent database has been used for background processes. For example, the processing and transport of crude oil from Alberta can be used to 'build' a diesel process that reflects Canadian conditions.

3.2 LIFE CYCLE INVENTORY

For each bioenergy and reference pathway, a flow diagram was developed that describes all the material and energy inputs and outputs, including co-products and waste. A generalized flow diagram is presented in



2.

Figure 2. Generalized life cycle flow diagram for Yukon bioenergy pathways and for the reference fuel pathways, indicating inputs and outputs from extraction, processing/conversion, and combustion of heating fuels. The 'LULUCF' output in the bioenergy pathways indicates net effects of harvesting biomass feedstock on forest carbon balance. In the reference fuel pathways, the LULUCF represents the forest carbon dynamics had the biomass not been removed for bioenergy. (See Section 3.2.1, 3.2.2, and 3.2.3 for further details).

A data collection sheet was developed for each pathway to transparently document raw data used, constants and parameters (e.g. energy content of biomass, combustion efficiencies), assumptions, calculations, and data sources. These data are presented in the following sections as they pertain to different pathways.

Models were built in the openLCA software based on the flow diagrams and the data from the spreadsheets. Some of the variables were parameterized within the software to facilitate sensitivity analysis on uncertain data (e.g. efficiencies, moisture contents, etc.).

3.2.1 Bioenergy (Biomass) Pathways

The bioenergy pathways represent the use of locally sourced biomass feedstock in the Yukon as a potential future heat source. The biomass is assumed to be sourced from live-standing trees, beetle-killed and fire-killed trees, residues from sawmill processing and harvest activities, as well as incidental biomass from various land clearing activities. After harvesting, the biomass feedstocks are processed into cordwood, chips, and pellets, before combustion in a variety of technologies at different scales, ranging from wood stoves and furnaces to boilers and cogeneration plants. Additional detail on potential local sources of biomass from within the Yukon are presented in Appendix A.

3.2.1.1 Biomass Extraction

The extraction stage of biomass feedstock includes felling, delimbing, cutting, hauling, and transportation activities, as relevant for each feedstock, and described in detail in the following sections. It also includes the forest carbon changes due to biomass removal, decay, and regrowth, as relevant for each type of feedstock. The approach to the forest carbon dynamics modeling is presented in section 3.2.3, and is reported in the results as LULUCF (biogenic), as this represents both emissions related to changes in forest carbon dynamics related to the extraction of biomass and those resulting from the combustion of the biomass itself.

3.2.1.1.1 Merchantable standing trees

In the Yukon, the technologies used for harvesting and processing are similar for dead standing trees (beetle-killed, fire-killed) and live trees. However, the harvesting of merchantable standing trees takes place on three scales (larger scale, mid-scale, and smaller scale), with each requiring different machinery, as outlined in Table 6.

Table 6: Harvesting steps of merchantable standing trees by scale, technology, and fuel type used.

Activity	Scale	Machinery	Fuel
Tree-felling	Larger	Feller-buncher	Diesel
	Mid- to smaller-scale	Two-stroke chainsaw	Gasoline
On-site delimbing (into roundwood)	Larger	Feller-buncher	Diesel
	Mid- to smaller-scale	Two-stroke chainsaw	Gasoline
Roundwood Cutting to Log Length (4 to 8’)	Larger	Feller-buncher	Diesel
	Mid- to smaller-scale	Two-stroke chainsaw	Gasoline
Log Hauling (from felling site to landing)	Larger	Grapple/Line skidder or Forwarder	Diesel
	Mid-scale	Small line skidder	Diesel

Activity	Scale	Machinery	Fuel
	Smaller-scale	Winch, ATV, snowmobile, or by hand	Gasoline
Transportation of roundwood (from landing to yards)	Larger	Large capacity log truck	Diesel
	Mid- to smaller-scale	Smaller truck with trailer	Diesel

Fire-kill and beetle-kill trees are usually sufficiently dry (assumed to be 25% moisture content) that no additional drying is needed for traditional use, such as firewood. However, live standing trees typically have about 45% moisture content on a wet basis and requires passive air drying before post-processing (e.g., cutting and splitting into firewood, chipping) before use for energy.

As no information were available on energy use in forestry harvesting for the Yukon, we modified an existing ecoinvent 3.7.1 forest harvesting process, based on average data from Northern Quebec boreal forestry. We assumed that the energy use, tree species and stand density, and harvesting technologies are the same as in the Yukon. The Quebec data was based on black spruce being 80% of the harvest, with reported 406 kg/m^3 biomass density for oven dry biomass. Although some of the activities included for Quebec may not apply to the Yukon (e.g. scarification, forest camp establishment), there was no way to remove them because they were aggregated based on energy used for machinery. The total energy use from this process, due to all forestry activities was 238 MJ/m^3 of harvested roundwood, at a landing or roadside. This number is higher than that for Western Canada forestry (Athena Sustainable Materials Institute, 2018a, 2018b) but is likely most representative as it is based on boreal forest and is also conservative (higher estimate) for LCA purposes.

Since the ecoinvent 3.7.1 forestry life cycle inventory for Quebec is based on volume of roundwood harvested (residues are not collected and are left on the forest floor), we allocated the life cycle inventory in the ecoinvent 3.7.1 forestry process between roundwood and residues. For large-scale harvesting of residue in the Yukon, it is assumed that collectible biomass residue is 5% of the total harvestable biomass, based on discussion with the Yukon Government. Therefore, the life cycle inventory was allocated as 95% to roundwood harvesting and 5% for collectible residue harvesting (Table 7).

After allocation and conversion to output per kg using the oven dry density, the CBM-CFS model results for carbon dynamics associated with each type of standing tree was added to this process as an emission.

Table 7: Roundwood harvesting, summary of assumptions and values used in LCA modeling

Parameter/Assumption	Value	Unit	Comment
Black Spruce	80	%	Proportion of stand
Wood density	406	Kg m^{-3}	Average used in modified Quebec process
Energy use, live-standing trees	238	MJ m^{-3}	Diesel and propane
Roundwood-to-residue (collectible) proportion	95:5	%	Information from Yukon Government
Energy use, fire-kill, beetle-kill trees	80	%	Relative to live-standing tree harvest

3.2.1.1.2 Biomass Residues

The biomass residue feedstock comprises two categories: 1) residues generated from harvesting; and 2) biomass from processing operations, such as sawmills.

1) Harvesting residues: The residues generated by harvest activities occurs either where trees are felled, or at landing. Since the ecoinvent 3.7.1 forestry process for Quebec is only for roundwood harvested, and residues are not collected, we allocated the life cycle inventory in the ecoinvent 3.7.1 forestry process between roundwood and residues using a mass allocation of all inputs into harvesting of 95% towards roundwood harvesting and 5% for collectible residues.

2) Processing activities, such as sawlog and firewood processing in the Yukon also generate a mix of biomass residues, such as sawdust and wood chips that can be collected and used (such as for pellet or woodchip production). This pathway has not yet been modeled for the Yukon, as this sort of waste is mostly created by sawmills that are not operated at scale currently performed in the Yukon. For cordwood production it is estimated that 1% of the processed wood is residues.

A report on harvesting of biomass in Yukon (Tetra Tech, 2017b) makes assumptions based on expert opinion on uses of biomass (including residues) from various incidental scenarios, compared to merchantable biomass harvest (Table 8). The assumption of residue amounts has been changed from 15% in the Tetra Tech report to 5% in this study, based on information obtained through discussions with Yukon Government during preparation of the methodology report because only a fraction of the residues is deemed collectible. Further, it is assumed that fire-kill and beetle-kill tree harvesting generates negligible amounts of residues (e.g., needles, leaves, small stems, etc.) because larger slash would have burned or been rendered as non-collectible due to death of trees.

Generally, for the incidental harvest scenarios in Table 8, the same assumptions are used as for merchantable timber harvest, in that live trees are cut down. It is assumed that in the baseline 95% of the biomass harvested is merchantable and becomes usable feedstock, while 5% is collectible biomass residue that would be burned on site or left to decompose. It is further assumed that only the residues would be collected for bioenergy.

Table 8: Summary of roundwood and residue harvesting assumptions for incidental biomass scenarios (excluding fire protection initiatives) based on Tetra Tech (2017b), and discussion with Yukon Government.

Harvest scenario	Reference System	Bioenergy System
Gravel extraction, land clearing	The roundwood may be used for lumber or burned on-site and the residues are burned on-site	The stand is used for lumber, and the residues are used for bioenergy
Mining, land clearing	The roundwood may be used for lumber or burned on-site and the residues are burned on-site	The stand is used for lumber, and the residues are used for bioenergy
Agriculture	30% of biomass is used on-site (e.g. fencing, firewood) and the remainder is burned or decayed	30% of biomass is used on site (e.g. fencing, firewood) and the remainder is used for bioenergy

3.2.1.1.3 Incidental Biomass and Wood Waste

The incidental biomass category comprises three main categories: 1) forest fuel reduction initiatives (FireSmart and landscape-level projects); 2) other land conversion and land clearing activities, and 3) recyclable wood waste biomass (e.g. construction waste, pallets, Christmas trees).

Forest fuel reduction initiatives generate both merchantable wood and biomass residue feedstocks. According to TetraTech (2017b) biomass from FireSmart initiatives is left on-site for residents to salvage or burned on-site. Although published data on existing or planned landscape-level forest fire protection projects is not available, it is assumed that the volume of available biomass from these projects will be significantly higher than the smaller-scale FireSmart projects. The harvesting activities and energy use of this biomass for bioenergy was assumed to be the same as for merchantable standing trees as in Section 3.2.1.1.1. The modeling of LULUCF associated with leaving the FireSmart biomass compared to harvesting it is described in Section 3.2.3.

Other land conversion and land clearing includes complete biomass removal for the following activities:

- land clearing for agriculture
- land clearing for residential development
- infrastructure related developments such as transportation rights of way
- development of aggregate extraction and mining

It should be noted that current methods for land clearing make utilization of agricultural land-clearing biomass difficult due to contamination of the harvested biomass with rocks and soil. This has not been considered in the modeling (i.e. either cleaning the biomass or using alternative ways of harvesting or collecting it).

In modeling both the incidental biomass from land clearing activities and waste wood disposal, a two-fold approach described in Table 9 included modeling the current reference scenarios. For the reference system, it is assumed that incidental biomass is burned onsite with air curtain burners. For waste wood, it is assumed that the waste wood is collected by a larger truck with up to 16-ton capacity (e.g., garbage trucks) and transported an average of 50 km to the waste collection stations and incinerated in air curtain burners without energy capture. Emission factors for air curtain burners are from a study by the Forestry Service of US Department of Agriculture (USDA, Forest Service, 2005). Additionally for this modeling, the boundaries include fossil fuel so that both the reference and bioenergy system have the same function. Therefore, 1 MJ worth of fossil fuel (propane) is included in the reference system. The LULUCF emissions for the reference and bioenergy systems were assumed to be the same, and were not modeled, as it was out of scope and the emissions would have canceled out when taking the difference between the bioenergy and reference systems.

For the bioenergy pathway using waste wood, combustion for heat energy capture is assumed, as with the reference system it is assumed that the recyclable waste wood, consisting of packing pallets, untreated construction and demolition waste, Christmas trees, and cardboard, is collected by larger trucks with up to 16-ton capacity (e.g., garbage trucks) and transported on average 50 km to a facility where the waste wood is chipped using larger type chipper with capacity of 50-ton hr^{-1}, as described in Section 3.2.1.2.2. Subsequently the chips are distributed to consumer by a smaller size dump truck (up to 7.5-ton capacity) and transported 50 km, where the waste wood chips are incinerated in boilers with 75% efficiency. Emission factors for burning of waste wood chips are assumed to be as listed in Canada's NIR (UNFCCC, 2021b).

In the analysis of the waste wood system, the GHG emissions for current waste practice (air curtain burner) plus emissions for avoided fossil fuel use (propane) is compared to the emission from waste wood utilization, using the same amount of wood waste for both systems needed for 1 MJ energy output.

Table 9. Summary of inputs for LCA modeling of incidental biomass and waste wood for current practices (the reference system=REF), and bioenergy system with heat energy capture (BIO).

System	Parameter/assumption	Value	Unit	Comment
REF/BIO	Waste wood collection	50	km	Larger truck, ≤ 16-ton
BIO	Chipping of wood, diesel fuel	0.09524	Kg MJ^{-1}	50-ton hr^{-1} capacity chipper
REF/BIO	Combustion efficiency	75	%	Furnaces, boilers
BIO	Chip distribution distance	50	km	Smaller truck, large pickup
REF/BIO	Energy density, wood	14.0	MJ kg^{-1}	NRCAN (2008)
REF/BIO	CO_2 emissions	1.809 (REF) / 1.539 (BIO)	kg kg^{-1}	Sources: (USDA, Forest Service, 2005) / (UNFCCC, 2021b)
	CH_4 emissions	0.00063 (REF) / 0.00412 (BIO)		
	N_2O emissions	* / 0.000059 (BIO)		

*No value; not measured or nondetectable

3.2.1.2 *Biomass Processing*

3.2.1.2.1 Cordwood

Feedstock from merchantable standing trees is assumed to be transported 150 km from landing to a large scale processing yard, using a logging truck (Tetra Tech, 2017b). Cordwood processing can be accomplished by splitting merchantable trees after bucking (16"-32") the felled and delimbed trees and cutting to log lengths of (4'-8'), previously harvested using smaller to larger scale methods. The splitting is done using large or small splitting machines. These machines are either diesel or gasoline powered and are usually located at the processing yard.

Cordwood production from feedstock other than merchantable wood takes place at harvesting site, at either medium, smaller, or personal use scale, again using similar splitting machines as in yards.

Specifications and assumptions used in modeling of large scale cordwood production are presented in Table 10. This information was used to create a process for splitting wood.

After splitting the cordwood is distributed to consumers by trucks of various sizes; larger scale operations may use diesel powered truck with trailer, hauling 2-3 tons (3-5 cords) per load, while mid and smaller scale operators often use truck with or without trailer carrying 1-ton (1-2 cord) per load, with diesel or gasoline fuel use depend on distance to consumer. For the modeling of large-scale cordwood production, a 50 km distance by a small truck or a large pickup vehicle was used, both using diesel as fuel.

Table 10: Summary of cordwood production assumptions and parameters used in LCA modeling

Parameter / assumption	Value	Unit	Comment
Roundwood transportation	150	km	Forest to yard
Splitter capacity	5	cords hr^{-1}	Cord King (Tetra Tech, 2017b)
Fuel use	1.75	gal hr^{-1}	From Cord King manufacturer
Wood density, fire-kill, beetle-kill	474	kg m^{-3}	See report (Tetra Tech, 2017b)
Wood moisture content, fire-kill, beetle-kill	25	%	Assumption, best MC for efficient burning (NRCAN, 2008)
Cord volume, solid wood	2.52	m^3	(NRCAN, 2008)
Cordwood distribution	50	km	Small diesel dump truck, large pickup

3.2.1.2.2 Woodchips

Woodchips can be processed from a variety of feedstocks; however, feasibility is often dependent on transportation distances from feedstock source to market, and location of chipping (Table 11). Sources of feedstock are assumed to be the same as for cordwood, however woodchip generation at the yard is assumed to be economically limited by distance of less than 250 km from harvesting location to consumer market. Typical moisture content of woodchips is 20-30%, with 25% assumed in this study. Chipping at yard using merchantable wood is done by an electrical- or diesel-powered stationary chipper following debarking and air drying. Onsite chipping is done in the field, at roadside or landing, by a larger, diesel-powered mobile chipper.

For large scale woodchip production, the chipper used is assumed to be a mobile Bandit model 3680 drum grinder[3] with 50 tonne / hr capacity, or similar (p. 18-19 Tetra Tech, 2017b). Because the technical data (e.g., fuel use and engine power) for the Bandit matched an existing ecoinvent 3.7.1 process for wood chipping, it was modified so the source of diesel and electricity were from the Yukon. Wood chipping was assumed to be accomplished by the same equipment both at the yard and forest location.

Transportation distances depend on location of chipping. If roundwood is to be processed, it is more efficient to use a log truck to transport wood from forest to yard, an assumed distance of 150 km, and the processed chips transported by a light dump truck over 50 km average distance to consumers. However, if chips are to be produced from biomass residues, the chipper would be transported on average 150 km to forest location, while the generated chips would be transported back to yard by a large dump truck, 150 km, and distributed from there to consumers, an average 50 km distance.

Table 11: Summary of woodchip pathway modeling parameters and assumptions

Parameter/ assumption	Value	Unit	Comment
Moisture content	25	%	Assumed
Chipper capacity	50	tons hr^{-1}	(Tetra Tech, 2017b)
Chipper fuel use	58.6	kg hr^{-1}	From ecoinvent 3.7.1 process
Roundwood transportation	150	Km	Forest to yard, log truck
Woodchip delivery	50	Km	Yard to consumer, light dump truck

3.2.1.2.3 Wood Pellets

Wood pellets can be produced from any of the biomass feedstocks. However, feasibility of feedstock use is hampered by distances from source to market, approximately 250 km from Dawson City, Teslin, Whitehorse, or Watson Lake.

The pelletizing processing steps are all electrically powered consisting of a hammer mill for size reduction, followed by sawdust compressor that forms the pellets, which are subsequently fed into a cooler, and the complete pellets are then loaded into bags or silos ready for distribution to consumers. For energy use the numbers provided in Section 3.2.2.1.3 represent Canadian production, although drying of pellets may be a defining factor for overall

3 http://www.banditchippers.com/bandit_equipment/product_line/product/88

energy use. Drying energy can be supplied by fossil fuels, wood waste or electricity. Typical pellet moisture content is ≤10%, therefore drying energy use will depend on pellet feedstock properties.

The process used to model imported pellets from BC and AB was modified to represent Yukon-produced pellets at a large scale, assuming chipped fire-kill roundwood as feedstock. The feedstock and chipping process is described in Appendix A. The same energy use was assumed for pellet production for both BC./AB and Yukon (Table 12).

Table 12: Summary of Yukon pellet pathway modeling parameters and assumptions, per kg produced pellets

Parameter/ assumption	Value	Unit	Comment
Fire-kill feedstock transportation	150	km	From forest landing to yard
Chipper capacity and fuel use			Assuming same as Section on woodchips
Pelletization			At yard/same location as feedstock chipping, same process as for imported pellets, modified for Yukon use
Energy use	0.096	kWh	Electricity from Yukon grid
Heat energy	0.11	MJ	For drying
Distribution	50	km	To consumer by truck; loose pellets

3.2.1.3 Biomass Conversion- Pyrolysis

No pyrolysis plant is currently operating in the Yukon and the long feedstock supply distances may be limiting to the feasibility of this processing option. However there exist mobile pyrolysis units that may be introduced to the Yukon, limiting the need for transportation of feedstock.

The pyrolysis process can generate various outputs depending on process design; syngas is common, but synthetic diesel fuel is also possible along with several other liquid and gaseous fuels. Fast pyrolysis can process various feedstocks of different sizes. The material is air dried using electrical blower before feeding into a reactor for pyrolyzing, followed by a cyclone, filter, and condenser steps to separate and condense or capture the fuels generated.

3.2.1.4 Biomass Combustion

Combustion of biomass fuels is currently done on various scales, using different technologies based on fuel type and form. Efficiency of the technologies used varies greatly with age and design. For this first version of Yukon heating energy pathways, the assumed energy and moisture content is as in Table 13.

Table 13: Assumed energy content and moisture content for Yukon bioenergy heating fuel pathways (Source: NRCAN 2008).

Fuel	Energy content (MJ kg^{-1})	Moisture Content (%)
Cordwood	14	25
Wood chips	14	25
Pellets	19	5 (≤10)

The amount of biomass required to produce 1 MJ of energy was calculated as follows:

$Mass_{BIO}$= Ho/ (Eff*EC)

Where $Mass_{BIO}$ is the mass of biomass feedstock required, Ho is the heat generated (1 MJ), Eff is the efficiency of the technology, EC is the energy content (lower heating value in MJ/kg).

Current estimates for combustion efficiency of technologies for use in the Yukon were applied, as well as test results from the Burnwise EPA program that uses a standardized methodology for certified wood burning room and central heaters in North America (US EPA, 2021). This program is the only science-based efficiency rating available for biomass burning technologies, and was used along with information on common practices in the Yukon (e.g. Stantec Consulting Limited, 2021). A summary of sources, efficiency ranges and parameters used in LCA modeling are listed in Table 14.

Table 14: Technology and efficiency used for combustion of bioenergy fuels in LCA study

Technology	Fuel used	Efficiency (%)			Comment
		Used in model	Low	High	
Wood Stoves – w. convection	Cordwood	35	30	40	Based on Stantec lifecycle report (Stantec Consulting Limited, 2021), and EPA Wood Stove Database (US EPA, 2021)
Wood Stoves – w. Secondary combustion	Cordwood	75	70	80	
Furnaces	Chips, pellets	75	70	80	
Pellet stoves – room	Pellets	73	58	87	
Pellet furnaces	Pellets	77	58	90	

CO_2 emission factors applied to modeled Yukon feedstocks are based on modeling outcomes from CBM-CFS3 forest model. N_2O and CH_4 emission factors were obtained from the Canadian National Inventory Report (Table 15).

Table 15: Emission factors applied to Yukon bioenergy pathways.

Fuel	CO_2	CH_4	N_2O	Unit	Source
Wood Fuel / Wood Waste – industrial combustion	1715	0.1	0.07	g/kg^{-1}	Canada National Inventory Report (UNFCC, 2021b) *Table A6.6–1: Emission Factors for Biomass*
Conventional Stoves	1539	12.9	0.12	g/kg^{-1}	
Conventional Fireplaces and Inserts	1539	12.9	0.12	g/kg^{-1}	
Stoves/Fireplaces with Advanced Technology or Catalytic Control	1539	5.9	0.12	g/kg^{-1}	
Pellet Stove	1652	4.12	0.059	g/kg^{-1}	
Other Wood-Burning Equipment	1539	4.12	0.059	g/kg^{-1}	

3.2.1.4.1 Cordwood

Cordwood is currently the most common biomass fuel in the Yukon, its use being up to 90% of biomass heating fuels used. The type and efficiency of the combustion technologies used vary from less than 10% for fireplaces, to about 80% for modern woodstoves and furnaces. In this study cordwood from large scale production operations was modeled for a range of scenarios, including low efficiency combustion in open fireplaces with 10% efficiency (Stantec Consulting Limited, 2021) and a wood stove with secondary combustion and assumed 75% efficiency (US EPA, 2021).

3.2.1.4.2 Woodchips

Currently in Yukon, woodchips are mostly used by large scale government buildings and operations using modern design boilers (Stantec Consulting Limited, 2021). The combustion efficiency modeled in this project was assumed to be 75%, which would apply to a residential boiler, or a larger boiler system for municipal or government buildings such as schools, offices or recreation centres.

3.2.1.4.3 Wood Pellets

Technically wood pellets can be used at a range of scales (residential to industrial), using a variety of technologies (i.e. stoves, boilers, and cogeneration plants), with a range of efficiencies (70-85%). Advantages of pellets compared to cordwood and chips is that manufacturing standards promote uniform quality, including moisture content, resulting in lower particulate emissions during combustion. Current use of pellets in the Yukon is all based on imports, however as the infrastructure and market for utilizing pellet exists in the Yukon, domestic production is possible.

During this first assessment of combustion in smaller pellet room heating stoves a 75% efficiency was used, as average efficiency difference for pellet stoves and furnaces is small.

3.2.1.5 Scenarios

3.2.1.5.1 Combined heat and power / Co-generation

Combined heat and power (CHP), also known as cogeneration (cogen), is a mean to achieve dual output from heating fuel use with higher overall thermal efficiency than producing heat and electricity separately, on a scale from residential to industrial.

In modeling cogen for Yukon conditions, the feedstock was assumed to be fire-kill roundwood, using harvesting process described in Section 3.2.1.1.1. It is assumed that harvested roundwood is transported 150 km on a log truck to a processing yard, where it is chipped using assumptions from large-scale chipping process in Section 3.2.1.2.2. Subsequently, the chips are fed to a cogen plant burner with 85% energy efficiency located at the same place as the processing yard (Table 16). The relative output from the system was assumed to be 83% heat and 17% electricity, based on values from an existing ecoinvent 3.7.1 process for an Organic Rankine Cycle system. This ratio was used to allocate the results of the LCA model between heat and electricity in the impact analysis.

Table 16. Cogen LCA modeling main parameters and assumptions.

Parameter/assumption	Value	Unit	Comment
Roundwood transport	150	km	Forest to yard using log truck
Chipping of roundwood	0.084	kg MJ^{-1}	Using existing process, Section 3.2.1.2.2
Cogen overall efficiency	85	%	ecoinvent 3.7.1 process information
Heat energy output	83	%	Relative to total energy output
Electricity energy output	17	%	Relative to total energy output

3.2.1.5.2 Pyrolysis

The LCA model for pyrolysis (Table 17) was based on original published research by Ayer and Dias (2018), describing mobile fast pyrolysis plant used in Quebec utilizing forest harvest residue. This plant consists of a wood chipper, a feedstock dryer, and a fast pyrolysis unit. The chipper used is assumed to be the same as for other chipping in this study; a 50-ton per hour mobile chipper. The drier from the Ayer and Dias (2018) study is started by propane gas (4 kg hr^{-1}) but otherwise runs on already dried woodchips. Drier capacity is 4,206 kg hr^{-1} of chips (45% MC) input and 2,313 kg hr^{-1} (2% MC) output, of which 152 kg hr^{-1} are used to power the drier fluidized bed heating source. Additional 125 kg hr^{-1} of the drier yield is used to power the pyrolysis unit, providing 2,037 kg hr^{-1} as feedstock for the pyrolysis process (2,313-152-125 = 2,037). Additional power for the pyrolysis stage is provided by electricity, 101 kW hr^{-1}, assumed to come from grid. This fast pyrolysis unit generates as outputs; 1,352 kg hr^{-1} of bio-oil (17.7 MJ kg^{-1}); 416 kg hr^{-1} of biochar (25.6 MJ kg^{-1}); and 313 kg hr^{-1} of syngas (12.7 MJ kg^{-1}). The percent ratio of those 3 products by energy content was 65% bio-oil, 20% biochar, and 15% syngas. The syngas is used internally in the drying process, while the bio-oil is considered to be main product and functional unit, replacing energy from fossil fuels (heating oil) for heating. The biochar is considered a co-product and can be used as energy rich fuel or applied to soil as a powerful soil amendment, providing increased fertility and carbon capture potential of soils, both of which are limiting in Yukon ecosystems.

As bio-oil can be burned in modern oil furnaces it is assumed there that the combustion process is the same for light heating oil and diesel, with 86% efficiency, although a more likely use for bio-oil is in a blend with other heating oils and/or in larger heating systems for commercial or institutional buildings. It is also possible that bio-oil may need refinement to be used in a Yukon climate (Butcher et al., 2016) that necessitates use of light fuel oil for heating over heavier, less processed grades. Bio-oil from pyrolysis is still a novel heating fuel and the full effect of its use are being evaluated, nonetheless it seems to compare well to use of biomass fuels for heating (e.g., Sippula et al., 2019).

Table 17. Summary of values used for LCA modeling of pyrolysis used for YT biomass utilization, based on Ayer and Dias (2018). Values are per kg dried chips for drying and kg biooil functional unit for the drying stage.

Stage	Parameter/assumption	Value	Unit	Comment
Chipping	Wood chips	1.85	kg	Chip mass needed for 1 kg biooil
Drying	Propane, fuel	0.00201	kg kg^{-1}	Dryer start-up, twice weekly
Pyrolysis	Chips, fuel	0.0096	kg	Chips at 2% MC from drier output
	Electricity, power	0.075	kWh	Low voltage, from YT grid
	Biooil, output	1	kg	Functional unit (17.7 MJ kg^{-1})
	Biochar, output	0.308	kg	Coproduct (25.6 MJ kg^{-1})
Combustion	Efficiency	86	%	Oil furnace; domestic or industrial use

3.2.2 Reference Pathways

The reference fuels for this LCA study are heating oil and propane, as well as imported wood pellets. Information on these reference fuels is provided in the following sub-sections, including sources of the fuel (Table 18), transportation distances (Table 19), and combustion stage assumptions (Table 20).

In addition to considering the life cycle carbon intensity of the fossil fuels, the reference pathway includes the net GHG emissions related to the forest carbon dynamics associated with leaving the forest biomass intact instead of removing it for bioenergy. The net GHG emissions were modeled separately for each biomass type and resulted in different numbers for LULUCF. The modeling method is described in section 3.2.3.

Table 18: Origin of crude oil used in Yukon heating fuels.

Refined fuel source	Origin of crude oil	Mix (%)	Yukon heating fuel supply (%)
Washington state	Alaska	29.6	25% of Yukon heating fuel (Burrows, 2021)
	North Dakota	25.9	
	Canadian Oil Sands	16.6	
	Other	8.6	
Alaska	Alaska	100	75 % of Yukon heating fuel (Burrows, 2021)

3.2.2.1 Reference Fuel Types

3.2.2.1.1 Heating oil

The heating fossil fuels were modeled based on the origin of crude oil, where 75% of Yukon heating fuel imports are from Alaska and 25% are from Seattle WA (Burrows, 2021). Washington does not produce any crude within state, the origin of crude oil mix supplying Washington refineries in 2019 is as shown in Table 18 (Washington Research Council, 2021). Alaskan heating fuels come from crude that is 100% domestically produced and refined (Alaska Business Magazine, 2018), and it is assumed that these refineries supply the heating oil imported to Yukon. In Alaska, two oil refineries that are in the vicinity of Anchorage produce about 75% of Alaska's oil (Alaska Business Magazine, 2018). It is assumed that fuel produced in Alaska is trucked from a supplier in Anchorage AK to Whitehorse YT (1,133 km). Imported heating fuels from Washington State are assumed to be transported on barges from Seattle WA to Skagway AK (1,630 km), and from there, transported by truck to Whitehorse (176 km). Additional distances for heating oil from Whitehorse depend on location of heating fuel consumers in Yukon, but is assumed to be on average 50 km. A summary of all distances used for modeling reference fuels is found in Table 19.

The cradle-to-gate processes for crude oil from these origins were available in ecoinvent 3.7.1, including their transportation to refineries. We modified existing processes for refining crude to heating oil by changing the source of crude oil and electricity based on the origin of the fuel.

Table 19: Transportation and distribution of imported heating fuels in the Yukon

Fuel	From	To	Distance (km)	Mode
Heating fuel (Washington origin)	Seattle, WA	Skagway, AK	1630	Barge
	Skagway, AK	Whitehorse, YT	176	Truck
Heating fuel (Alaska Origin)	Anchorage, AK	Whitehorse, YT	1133	Truck
Propane	Tilbury, BC	Whitehorse, YT	2500	Truck
Pellets	Chetwynd, BC La Crête, AB	Whitehorse, YT	1458 1856	Super B, approx. 40 tons per load
All	Whitehorse, YT (storage)	Consumers in Yukon	50	Small truck

3.2.2.1.2 Propane

The propane comes from natural gas imported to the Yukon from British Columbia from both conventional wells and fractionation fields. The propane is stored at a small-scale facility at Tilbury near Vancouver. Natural gas has the same geological profile[4] in both BC and AB, is extracted and processed similarly, and in Canada's National Inventory Report, both NG sources have the same emission factor (UNFCCC, 2021b). Therefore, we used an existing propane

4 https://www.capp.ca/natural-gas/what-is-natural-gas/

process from the ecoinvent 3.7.1 database, based on traditional well extraction, and modified it using regional inputs where applicable. It is assumed that the liquefied propane is transported by road to Whitehorse, 2,500 km from Tilbury. It is further assumed that the propane is distributed from Whitehorse to local consumers in the Yukon via light tanker trucks using an average distance of 50 km.

3.2.2.1.3 Imported Pellets

It is assumed that imported pellets originate in British Columbia or Alberta and are transported from Chetwynd BC and La Crête, AB[5]. The pellet feedstock is assumed to be waste from sawmill activities, which is transported 30 km by a large truck to a pellet facility. The pellets are transported to a storage facility in Whitehorse, YT (1,458 km from Chetwynd and 1,856 km from La Crête), and from there they are distributed to consumers by a smaller transport truck (average 50 km distance).

To model imported pellets from BC and AB, a modified ecoinvent 3.7.1 process describing production of pellets meeting German DIN-plus certified quality standards was used. This process describes pelletization of sawmill waste consisting of shavings, sawdust, and woodchips using 0.096 kWh of electricity and 0.11 MJ of heat energy from pellets, to produce 1 kg of pellets.

3.2.2.2 Reference fuel combustion

Currently, fossil fuels provide about 75% of Yukon thermal energy demand, with propane meeting about 15% and heating oil about 60% of thermal energy needs. Each type of fuel requires a specialized furnace, assumed to be a mix of older and newer technologies, with a range of efficiencies. All technologies used can be applied in various settings and scales of users.

Combustion of pellets is by pellet stoves or pellet boilers with 73% and 77% average efficiency, respectively. An average efficiency of 75% was used for both types of technologies (Table 20).

Table 20: Technology and combustion efficiency assumptions used for heat from reference fuels

Technology	Fuel used	Efficiency (%)			Source/Comment
		Used in model	Low	High	
Furnaces	Propane, natural gas	95	91	99	Average of all Energy Star rated propane furnaces (n = 3952) (EPA, 2021)
Furnaces	Heating oil	86	85	97	Average of all Energy Star rated oil furnaces (n = 304) (US EPA, 2021)
Pellet stoves/boilers	Pellets	75	73	77	(Stantec Consulting Limited, 2021; US EPA, 2021)

5 https://www.canadianbiomassmagazine.ca/canadian-biomass-pellet-mill-map/

For estimates of emissions from fossil fuel combustion, Canadian values from the National Inventory Report (UNFCCC, 2021b) were applied (Table 21).

Table 21: Emission factors used for fossil fuels and imported pellets in LCA model

Fuel	CO_2	CH_4	N_2O	Unit	Source (Canada NIR)
Propane	1515	0.027	0.108	$g\ L^{-1}$	Table A6.1–4: Emission Factors for Natural Gas Liquids
Light Fuel Oil*- Residential	2753	0.026	0.006	$g\ L^{-1}$	Table A6.1–5: Emission Factors for Refined Petroleum Products
Pellet Stove	1652	4.12	0.059	g/kg-1	Table A6.6–1: Emission Factors for Biomass
Other Wood-Burning Equipment	1539	4.12	0.059	g/kg-1	

*Also used for diesel

3.2.3 Forest Carbon Modeling

Forest carbon modeling determines the effect of removal of biomass from multiple bioenergy fuel pathways on the short-term and long-term carbon balance of the Yukon forest. The use of forest carbon modeling approaches provides the ability to quantify the impacts of increased usage of forest biomass on the near-term and long-term carbon budget of Yukon's LULUCF emissions sector. Additional background information on forest carbon accounting and modeling is available in Appendix B.

3.2.3.1 Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3)

CBM-CFS3 (Kurz et al., 2009) is a stand- and landscape-level modelling framework developed by the Canadian Forest Service (Natural Resources Canada) to simulate the annual dynamics of all forest carbon stocks required under the UNFCCC (Figure 3). It is compliant with the carbon estimation methods outlined in the guidelines of the IPCC. CBM-CFS3 has emerged as one of the leading products for modeling forest carbon fluxes and has been applied for national and sub-national assessments of forest carbon dynamics around the world. CBM-CFS3 uses similar information as is required for forest management planning, including forest inventory, tree species, growth and yield curves, natural and human-induced disturbance information, forest harvest schedule and land-use change.

There are three critical datasets upon which the CBM-CFS3 modelling framework relies:

- forest inventory data to describe current conditions of the modeled land base
- site, planning, and other spatial data used to stratify the land base
- growth and yield data (i.e., strata-level merchantable volume [m^3/ha]) to describe how the forest changes over the course of a simulation

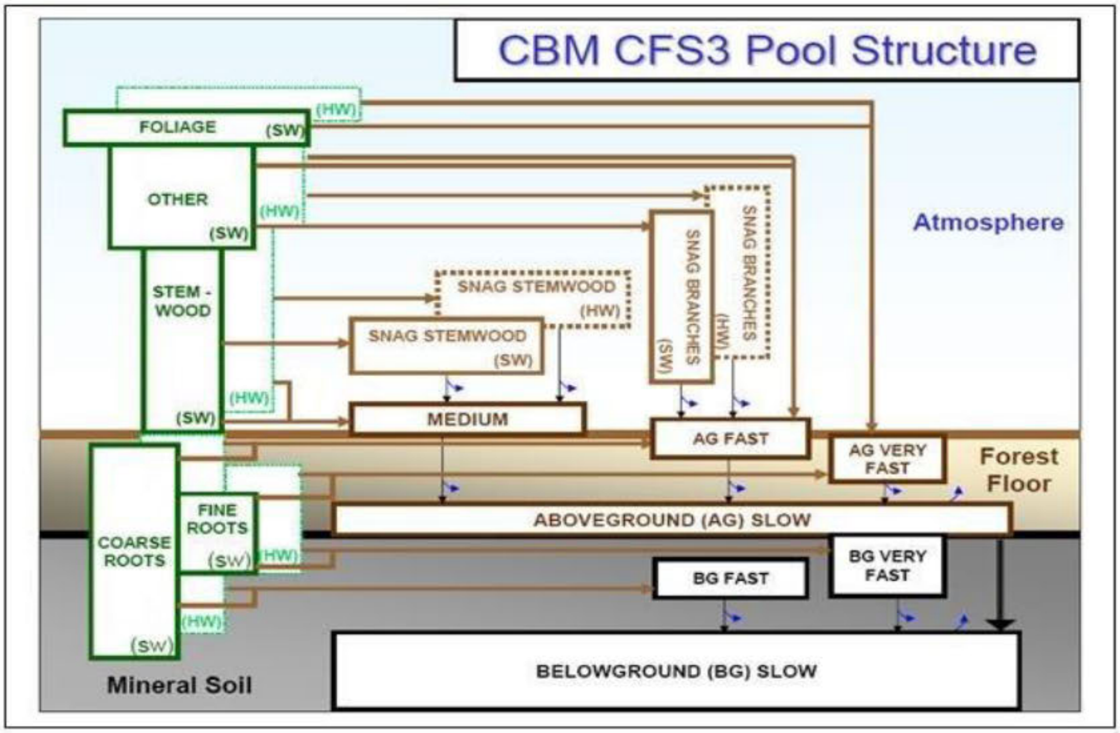


Figure 3: Carbon pools modeled in CBM-CFS3 for both softwood (SW) and hardwood (HW) forests. Green pools represent living biomass; brown pools represent non-living biomass; black pools represent soil (Image courtesy of Canadian Forest Service).

The data sources for the required CBM-CFS3 data inputs for this project are presented in Table 22. The CFS does model forest carbon for the LULUCF sector within Canada's National Inventory Report. However, their land base would most likely not align with the land base in this report (e.g., salvage harvests outside of the working forest land base). Moreover, the modelling in this study required the development of new carbon yield curves tailored specifically to this study and biomass harvesting of different feedstocks at different levels and only examines emissions from certain harvested wood products (i.e., biomass and not solid wood products).

The vegetation inventory data was derived primarily from air photos from 2012 and 2007, though the photo year for the inventory does date back to 1986 for some areas. In the initial data processing, stands were grown forward to 2021 from their photo year in order to have more currency. However, this is a source of uncertainty in the data and that uncertainty increases as photo year becomes older.

Table 22: Input data requirements for the CBM-CFS3 model with data sources for this project.

Data Input Category	Description of Data Required	Data Source
Forest Inventory Data (Forest Land Base)	Stand-level information on the following variables: - Area, Age, Species, Volume, Last disturbance type	2017 Yukon Vegetation Inventory 1:5000 Map Series (Haines Junction, Teslin, Whitehorse forest management areas) Yukon Vegetation Inventory 1:40,000 (Dawson City forest management area)
Disturbances	Type of disturbance (e.g. fire, insect) Area of disturbance	
Land-Use Change Events	Area changed from forest to non-forest (e.g. to mining, aggregate, or other development)	
Harvest Events (past events)	Area of disturbance	
Harvest Events (future events)	Rules for harvest eligibility	Defined in the modeling scenarios (see Section 3.2.3.3 of this report)
Growth and Yield Curves	Merchantable volume by age class (species-specific)	Calculated from the following datasets: 1. G.M. Bonnor and P. Boudewyn. 1990. *Taper-Volume equations for major tree species of the Yukon Territory.* Canadian Forest Service report BC-X-323. 2. Forsite Consultants, 2018. *Dawson Forest Planning Area Timber Supply Analysis.* 3. BC Ministry of Forests (2007). *Variable Density Yield Projection (VDYP 7).*

3.2.3.2 Development of Yukon-Specific Growth and Yield Tables

The development of new strata-level growth and yield tables was a considerable component of the forest modeling initiative. For the Dawson plan area where a recent timber supply analysis (Forsite Consultants, 2018) was conducted, growth and yield tables were constructed from a vegetation inventory file with stand-level merchantable volume (m^3/ha) included in the attribute data. For the Haines Junction, Teslin, and Whitehorse plan areas, growth and yield tables were generated using the Variable Density Yield Projection (VDYP 7) Model, which was developed by the British Columbia Ministry of Forests, Lands, Natural Resource Operations and Rural Development (MFLNRORD) for natural/unmanaged stands (Ministry of Forests, 2007). Yields were generated for each leading species group (Table 23) and site class combination at five-year periods. From the VDYP 7 model output, stand diameter at breast height

(DBH), average height (m), and frequency (stems/ha) were used in combination with taper-volume equations for the Yukon Territory (Bonnor & Boudewyn, 1990) to generate the merchantable volume (m^3/ha) tables.

The volume tables for the Haines Junction, Teslin, and Whitehorse plan areas were adjusted further according to the *Yield Assumptions for Southeast Yukon* document provided by the Yukon Government. These assumptions included a localization factor (i.e. reduction factor for the yield curves) of 89% for all volume records for the Teslin and Whitehorse plan areas and 68% for the Haines Junction plan area. Lastly, the yields were adjusted further according to the Yukon Forest Management Branch procedures to account for age-related yield declines, with decline-initiation ages of 80 years, 120 years, and 220 years, decline-end ages of 150 years, 200 years, and 350 years, and decline-end volumes of 35 m^3/ha, 35 m^3/ha, 50 m^3/ha for deciduous-leading, pine-leading, and spruce-leading yields, respectively. To obtain these volumes, linear interpolation between the decline-initiation and decline-end ages was used. Figure 4 shows an example of the yield generation and adjustment process for spruce-leading strata on good site classes in the Whitehorse plan area. The *Yield Assumptions for Southeast Yukon* were also used to define the merchantability criteria for harvest operations in subsequent modelling.

Table 23: Leading species groups used in land base stratification (as defined in Yukon vegetation inventory datasets and Dawson Forest Resources Management Plan Timber Supply Analysis).

Leading Species Group	Description
Spruce	Spruce leading stands where spruce exceeds 80% based on crown closure
Pine	Lodgepole pine leading stands where the pine component exceeds 80%
Deciduous	Aspen, balsam poplar and white birch leading stands where these exceed 80%
Spruce / Pine	Spruce leading stands where the secondary species is lodgepole pine
Spruce / Deciduous	Spruce leading stands where the secondary species is aspen, balsam poplar or birch
Pine / Spruce	Lodgepole pine leading stands where the secondary species is white spruce or black spruce or fir
Pine / Deciduous	Lodgepole pine leading stands where the secondary species is aspen or balsam poplar or white birch
Deciduous / Spruce	Aspen, balsam poplar or birch leading stands where the secondary species is spruce or fir
Deciduous / Pine	Aspen, balsam poplar or birch leading stands where the secondary species is lodgepole pine
Fir	Fir stands where the fir exceeds 80%
Fir Mix	Fir where secondary species is > 30%
Other	Any species or species group not described in the other categories

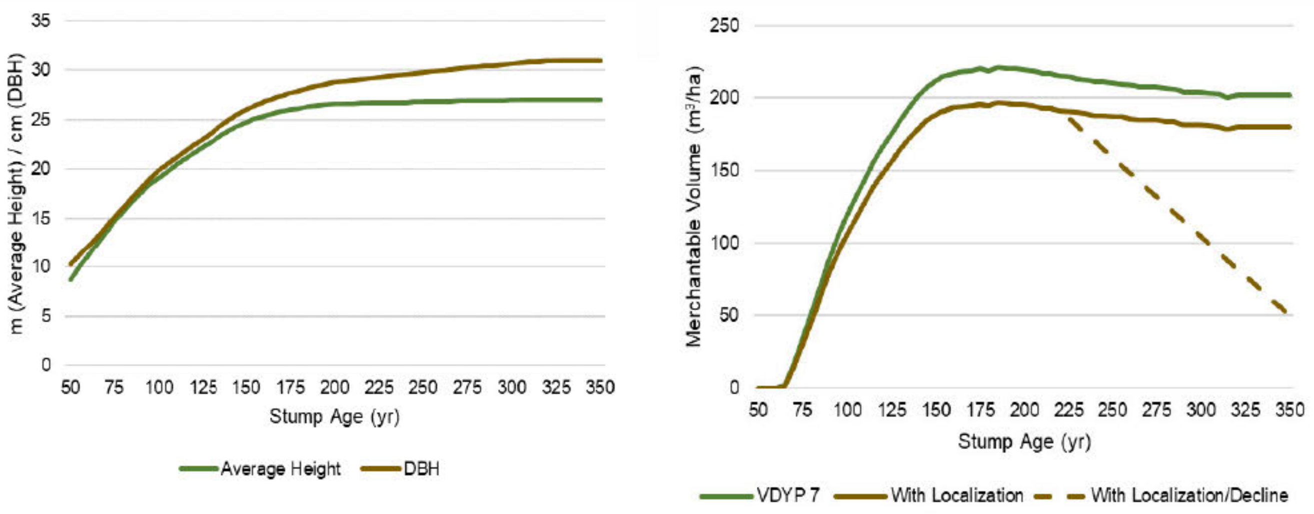


Figure 4: Growth and yield modeling results for spruce-leading strata on good site classes in the Whitehorse plan area, including VDYP 7 model output and Yukon-specific localization and decline adjustments.

3.2.3.3 CBM-CFS3 Modeling Scenarios for YT Biomass Energy LCA

Multiple forest carbon modeling scenarios were used to assess the impact of a biomass energy industry on the near-term and long-term carbon budget of Yukon's LULUCF emissions sector. A 100-year simulation was conducted for each feedstock type where forest modelling with CBM-CFS3 occurred (i.e., not land-clearing for both a bioenergy and reference pathway).

The following assumptions were applied in the modeling analysis to reduce the complexity of the modeling exercise and to reduce the number of dynamic impact variables:

- Predicted climate change impacts on forest fire frequency/severity and insect outbreaks were not considered – areas impacted by fire and insect were applied as per historic averages
- Energy demand for heating in the Yukon will remain constant and will not fluctuate due to population changes, building efficiency upgrades, or a warming climate
- Where biomass residue feedstocks are modelled with CBM-CFS3 (i.e., harvest of standing trees and collection of incidental biomass from fire protection initiatives), the amount of residual material generated will occur at the same annual rate as the 2012 – 2018 time period
- Incidental biomass feedstocks involving land-use change (i.e., land-clearing for development) are not modelled using CBM-CFS3 and captured fully in the LCA alone

Table 24 summarizes the key assumptions for forest carbon modelling with CBM-CFS3 for those biomass feedstocks in the LCI associated with a forest land base for both bioenergy and reference pathways. In addition to the assumptions outlined in Table 22, the following restrictions were applied to the modeling:

- Salvage harvests after wildfire or spruce beetle outbreaks are permittable in the modeling in the entire study area in strata where these disturbances will occur, though beetle salvage was set to only occur in the Haines Junction plan area
- Forest harvesting in the model was scheduled randomly once merchantability and/or natural disturbance criteria were achieved, accounting for leading species, management status, site class, and plan area.
- Biomass from forest fuel reduction initiatives was permittable in the entire study area in spruce-leading strata
- Loss of forest carbon to the atmosphere due to wildfire follows the assumptions of CBM-CFS3 which are specific to each living and dead carbon pool in the model and equate to approximately 10-15%, depending on the stratum. These emissions from combustion during the actual wildfire are not included in the modelling and not allocated to the salvaged feedstocks.

Table 24: Forest carbon dynamics and associated modeling assumptions for the different modeled pathways.

Bioenergy pathway	Reference pathway
Merchantable standing trees (primary fibre) → Live-standing trees → From mature or senescent forest and from actively growing forest	
- Occurrence in working land base only in all four plan areas following Yukon-specific merchantability and harvesting criteria - Spruce strata are the predominant harvest and the only harvested deciduous strata are in the Dawson plan area where white birch is abundant - Harvesting of merchantable roundwood only - Partial/multi-age harvest systems with 20% retention - Natural regeneration	- Forest continues to grow and/or decline - Natural disturbance and stand senescence are included in growth and yield assumptions
Merchantable standing trees (primary fibre) → Dead-standing trees → Fire-kill	
- Occurrence in all four plan areas in all strata excluding deciduous-leading strata - 100% mortality in salvaged areas with biomass loss due to combustion following CBM-CFS3 assumptions (~12% loss) - Clear-cut/single-age harvest systems - Harvesting of merchantable roundwood only - Natural regeneration - Combustion emissions from wildfire are not included	- Occurrence in all four plan areas in all strata excluding deciduous-leading strata - 100% mortality in salvaged areas with biomass loss due to combustion following CBM-CFS3 assumptions (~12% loss) - Decomposition of fire-killed trees in forest - Natural regeneration delay of 12 years - Combustion emissions from wildfire are not included

<table>
<tr><th>Bioenergy pathway</th><th>Reference pathway</th></tr>
<tr><td colspan="2">Merchantable standing trees (primary fibre) → Dead-standing trees → Beetle-kill</td></tr>
<tr><td>- Occurrence in the Haines Junction plan area in spruce strata only
- 59% mortality due to spruce beetle
- Removal of beetle-killed trees only, leaving a mature surviving cohort (41% of biomass) and a new regeneration cohort
- Harvesting of merchantable roundwood only</td><td>- Occurrence in the Haines Junction plan area in spruce strata only
- 59% mortality due to spruce beetle
- Decomposition of beetle-killed trees in forest, leaving a mature overstory cohort (41% of biomass) and a new regeneration cohort with a 50-year delay (tentative)</td></tr>
<tr><td colspan="2">Biomass Residues (secondary fibre) → Generated by harvest activities → At landing</td></tr>
<tr><td>- Occurrence in working land base only in all four plan areas following Yukon-specific merchantability and harvesting criteria
- The only harvested deciduous strata are in the Dawson plan area where white birch is abundant/harvested
- Harvest activities remove only merchantable stemwood
- Collection of residue material (i.e., other wood + bark, as defined by CBM-CFS3) generated by existing harvest activities
- Partial/multi-age harvest systems with 20% retention</td><td>- Occurrence in working landbase only in all four plan areas following Yukon-specific merchantability and harvesting criteria
- The only harvested deciduous strata are in the Dawson plan area where white birch is abundant/harvested
- Harvest activities remove only merchantable stemwood and leave residue material on site
- Partial/multi-age harvest systems with 20% retention
- Decomposition in forest (82% of remaining)
- Combustion without energy capture (18% of remaining)</td></tr>
<tr><td colspan="2">Incidental forest products (secondary fibre) → Generated by forest fuel reduction initiatives (liability biomass) → Merchantable-size wood biomass</td></tr>
<tr><td>- Occurrence in all four plan areas in spruce-leading strata only
- Thinning with 65% retention
- Harvesting of merchantable roundwood only
- Continued growth of retention cohort and natural regeneration of new cohort</td><td>- Occurrence in all four plan areas in spruce-leading strata only
- Thinning with 65% retention
- Continued growth of retention cohort and natural regeneration of new cohort
- Decomposition of harvested trees in forest (50% of remaining)
- Combustion of harvested trees without energy capture (50% of remaining)</td></tr>
</table>

3.2.3.4 Spatial Extent of CBM-CFS3 Modeling

The spatial extent of the Yukon vegetation inventory input datasets and the associated forest land base used in the forest carbon modeling is presented in Figure 5 and described in Table 25. The modeled land base included the Dawson, Champagne and Aishihik Traditional Territory (Haines Junction), Teslin Tlingit Traditional Territory (Teslin), and Whitehorse and Southern Lakes (Whitehorse) Forest Management Plan Areas only. Within the Plan areas, Landscape Management Units describe the working forest land base and restricted land base, with the former delineating where harvests of live, merchantable trees are permittable in the modeling, as well as the collection of harvest residues.

Table 25: Suitability criteria used to define potential harvest areas in the modeling analysis.

Suitability Criteria	Description of Suitability Criteria
FOREST LOCATION	Forest must be within one of the four existing or planned forest management plans in the Yukon.
MANAGEMENT STATUS	Only 'working' status will be selected.
SITE CLASS* **The site class criteria will only be applied to refine candidate areas for greenwood harvesting; it is assumed that areas of standing dead or residue will not be impacted by site class considerations*	Only forested areas with a 'good' or 'medium' site class will be selected in the Yukon Vegetation Inventory product.

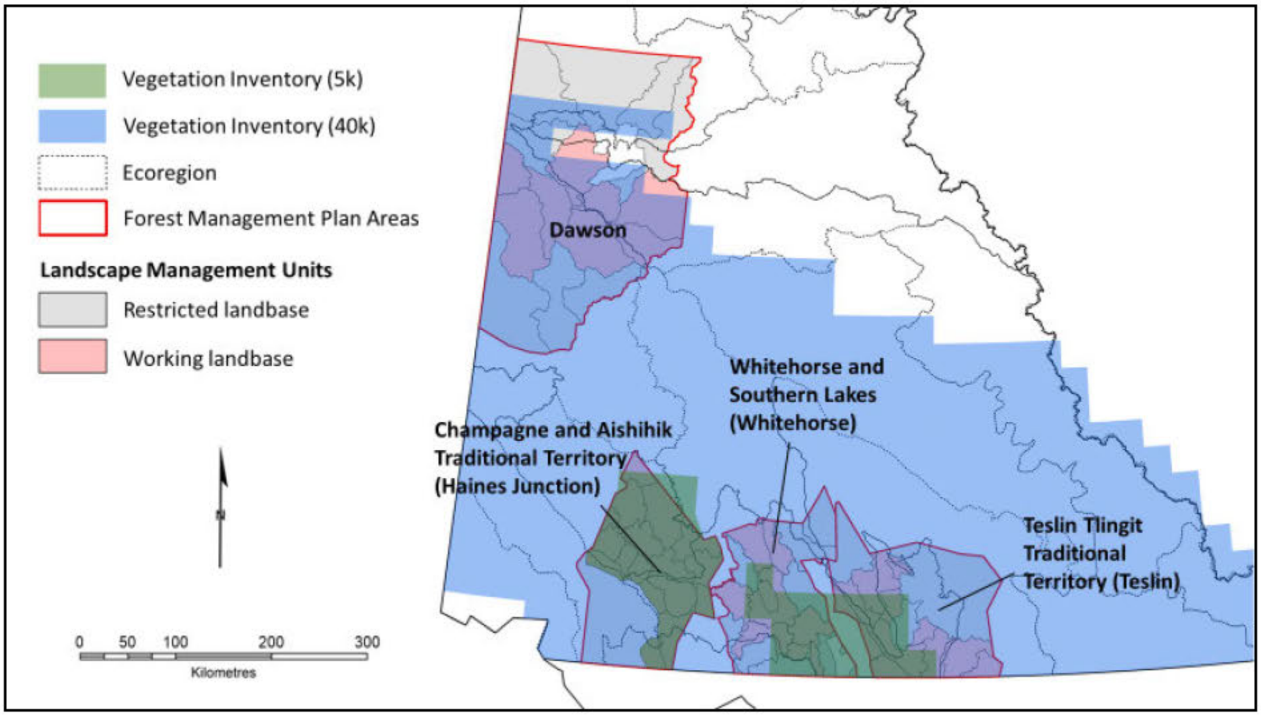


Figure 5: Study area and associated forest land base used for forest carbon modeling with CBM-CFS3.

4. LIFE CYCLE IMPACT ASSESSMENT

4.1 LIFE CYCLE IMPACT ASSESSMENT RESULTS

The results are presented as a summary of the net carbon intensity for all pathways, followed by a detailed analysis of each bioenergy pathway in comparison to the reference fuel pathways. The results are presented for:

- Live-standing (LS) trees (from both roundwood and residues harvested from the forest)
- Fire-kill (FK) and Beetle-kill (BK) trees (roundwood only)
- Incidental biomass from residues of forest fire protection initiatives, e.g. FireSmart (FS)
- Incidental biomass (IB) from sources other than fire protection activities (i.e. from land clearing activities) and waste wood (WW) biomass (e.g. wood pallets, construction waste)

These feedstocks can be used as cordwood (CW), wood chips (WC), or pellets (PELL) in various combustion technologies with different efficiencies. Given the similarities in processing and treatment of incidental biomass from land clearing (with the exception of fire protection initiatives) and waste wood biomass the two types of feedstock have been consolidated within the LCA modeling analysis (IB/WW).

The biogenic emissions from forest carbon modeling were averaged over a 20-year time frame, to see whether the pathways were climate-neutral over this period, which is a crucial time to be reducing emissions to the atmosphere in order to meet greenhouse gas reduction targets. Since the Yukon Government wants to reduce carbon emissions by 30% by the year 2030, it is important to consider what happens in that timeframe. A sensitivity analysis in Section 4.2.1 shows preliminary results of how the biogenic emissions change on a 100-year time frame. The reference pathways represent the carbon intensity per functional unit (kg CO_2e/MJ of heat generated) plus the emissions/removals related to the biomass that would have occurred in the absence of additional use of biomass for energy.

4.1.1 Summary Results: Net Carbon Intensity of all Bioenergy and Reference Pathways

The net carbon intensity for each pathway is shown in Table 26. **The incidental biomass (IB)/waste wood (WW) bioenergy pathway (WC IB/WW 75) has lower emissions than all reference systems, because it is being compared with waste wood being incinerated without energy capture in the reference systems**. The bioenergy pathways from fire-killed trees at 75% efficiency (CW FK 75, WC FK 75, PEL FK 75) and incidental biomass from forest fire protection residues (WC LS-FS 75) have lower net emissions than imported wood pellets.

The higher average furnace efficiency for fossil fuels, and the energy density of the fossil fuels, which is 2 to 3 times higher than biomass, also play a role in the lower carbon intensity for the fossil fuels, because less feedstock (fuel) is required to deliver 1 MJ of energy.

Ultimately the emissions in the bioenergy pathways that include standing trees (fire-kill, beetle-kill, live trees) are highly impacted by the biogenic LULUCF emissions associated with the carbon contained in the biomass feedstocks and changes to forest carbon pool dynamics (Figure 6b).

Detailed results for each bioenergy pathway are further explained and discussed in the following sections.

With regards to the results of the forest carbon modelling using CBM-CFS3, it is important to differentiate between two distinct streams of biogenic carbon emissions and removals (Figure 6). The first stream of biogenic carbon emissions and removals is from biomass combustion. The carbon that is emitted directly from the combustion of the harvested biomass feedstocks for thermal energy generation is a fixed value (i.e., approximately 1.8 kg CO_2 per kg of dry biomass feedstock) and usually comprises the large majority of biogenic emissions (Figure 6a). In the reference pathways, these biogenic carbon emissions are zero and replaced by combustion emissions from fossil fuels for thermal energy generation.

The second stream of biogenic carbon emissions and removals is the carbon that is stored on the forest land base in living biomass and dead organic matter. This stream of biogenic carbon is variable over time and its dynamics are highly dependent on feedstock types. For all feedstocks except new harvests of living merchantable trees, the land base alone is a net sink of atmospheric carbon (Figure 6b), especially when the fate of a portion of the feedstock in the reference pathway is combustion without energy capture (i.e., slash burning).

The entire land sector (i.e., forest land base and harvested biomass) will only achieve the point of carbon parity where net carbon benefits start to accrue (Ter-Mikaelian et al., 2015) when emissions/removals from forest regrowth and/or decomposition have caught up to emissions compared to the reference pathway. While the net carbon benefits of converting fossil fuel heating to biomass can be large, this parity can occur within years, decades, or even over a century, depending on factors like feedstock type, climatic conditions, forest productivity and management approaches, energy efficiency, and the types of fossil fuels being replaced. In project-level GHG accounting and sometimes in the literature, the approach has been to exclude the emissions from biogenic carbon from accounting. However, increasingly life cycle assessments are including biogenic carbon accounting of both the forest land base and harvested feedstocks.

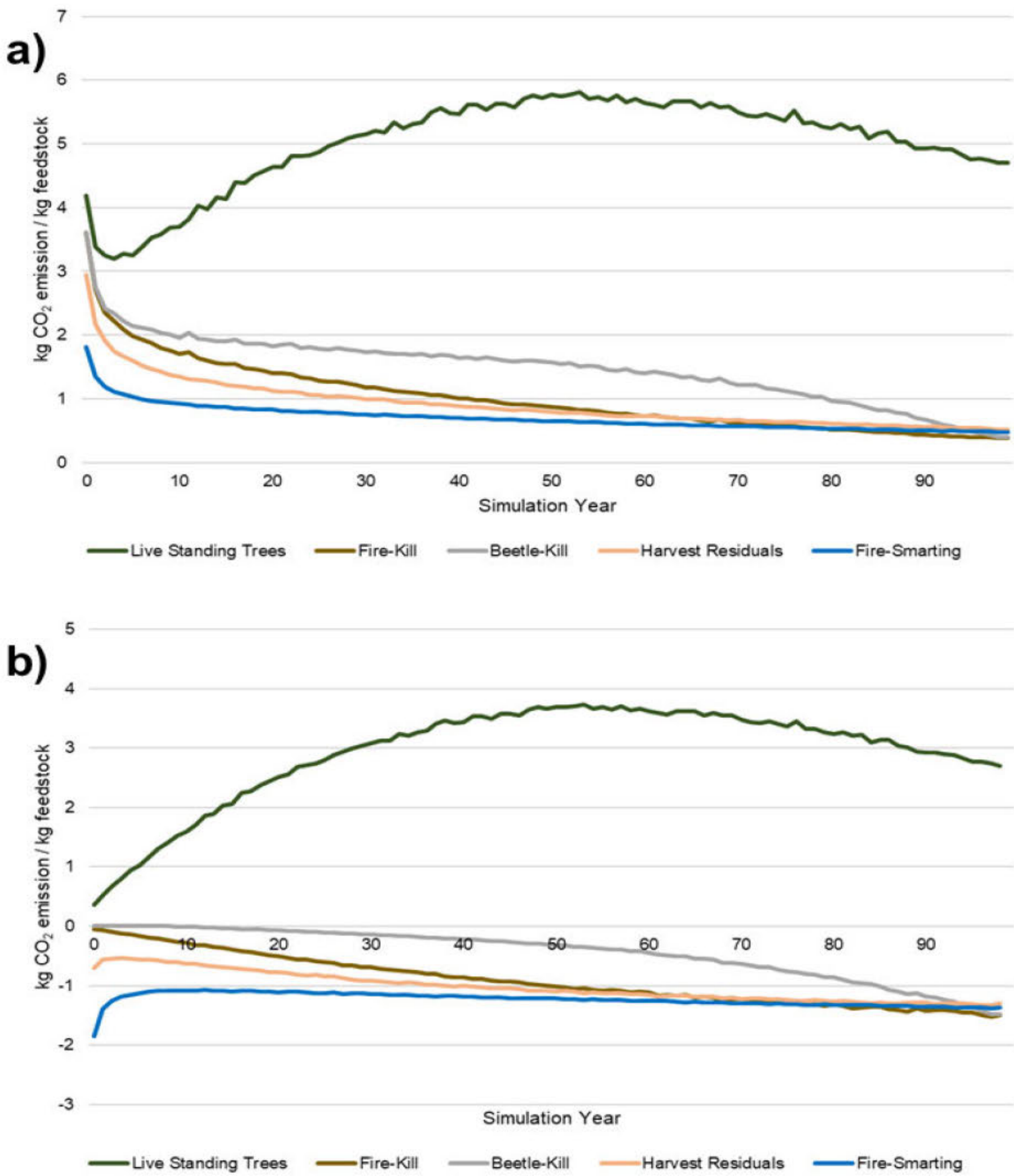


Figure 6: Average net emissions of CO_2 per kg of biomass feedstocks for the different bioenergy feedstocks that a) include emissions from combustion of the biomass feedstock and b) do not include combustion emissions (i.e., carbon stored in the forest only). Note the difference in scale of net emissions of CO_2 per kg of biomass feedstocks between the two graphs.

Table 26: Net carbon intensity from bioenergy pathways, relative to the reference system in kg CO_2e/MJ of heat generated. CW = cordwood, RW = roundwood, WC = wood chips, PELL = pellets, LS = live-standing, FK = fire-kill, BK = beetle-kill, IB/WW = incidental biomass and waste wood. The numbers indicate the burn efficiency of the combustion technology used and the GWP timeframe in years. For example, '75-20' indicates 75% burn efficiency with a 20-year GWP timeframe.

Bioenergy Pathway	Bioenergy	Reference System				
		Propane	BC Pellets	AB Pellets	Heating Oil	Diesel
	Net carbon intensity (20-year biogenic C time frame) in kg CO2e MJ^{-1}					
WC IB/WW 75-20	**0.164**	**0.238**	**0.328**	**0.336**	**0.259**	**0.261**
Change in carbon intensity of bioenergy relative to reference system (NO CBM RESULTS)		**-0.074**	**-0.164**	**-0.173**	**-0.095**	**-0.097**
% difference relative to reference system		**-31%**	**-50%**	**-51%**	**-37%**	**-37%**
WC LS-FS 75-20	**0.326**	**0.296**	**0.386**	**0.394**	**0.316**	**0.319**
Change in carbon intensity of bioenergy relative to reference system		0.030	**-0.059**	**-0.068**	0.010	0.008
% difference relative to reference system		10%	**-15%**	**-17%**	3%	2%
WC LS-R 75-20	**0.392**	**0.339**	**0.429**	**0.437**	**0.360**	**0.362**
Change in carbon intensity of bioenergy relative to reference system		0.053	**-0.036**	**-0.045**	0.033	0.031
% difference relative to reference system		16%	**-8%**	**-10%**	9%	8%
PELL FK 75-20	**0.207**	**0.159**	**0.248**	**0.257**	**0.179**	**0.181**
Change in carbon intensity of bioenergy relative to reference system		0.048	**-0.041**	**-0.050**	0.028	0.026
% difference relative to reference system		31%	**-17%**	**-19%**	16%	14%
CW FK 75-20	**0.278**	**0.193**	**0.283**	**0.291**	**0.213**	**0.216**
Change in carbon intensity of bioenergy relative to reference system		0.085	***-0.005***	***-0.013***	0.065	0.062
% difference relative to reference system		44%	***-2%***	***-5%***	30%	29%
CW FK 35-20	**0.596**	**0.341**	**0.431**	**0.440**	**0.362**	**0.364**
Change in carbon intensity of bioenergy relative to reference system		0.254	0.165	0.156	0.234	0.232
% difference relative to reference system		75%	38%	36%	65%	64%
WC FK 75-20	**0.278**	**0.193**	**0.283**	**0.291**	**0.213**	**0.216**
Change in carbon intensity of bioenergy relative to reference system		0.085	***-0.004***	***-0.013***	0.065	0.063
% difference relative to reference system		44%	***-1%***	***-4%***	31%	29%
CW BK 75-20	**0.354**	**0.238**	**0.328**	**0.337**	**0.259**	**0.261**
Change in carbon intensity of bioenergy relative to reference system		0.115	0.026	0.017	0.095	0.093
% difference relative to reference system		48%	8%	5%	37%	36%
CW BK 35-20	**0.596**	**0.439**	**0.528**	**0.537**	**0.459**	**0.461**
Change in carbon intensity of bioenergy relative to reference system		0.157	0.068	0.059	0.137	0.135

Bioenergy Pathway	Bioenergy	Reference System				
		Propane	BC Pellets	AB Pellets	Heating Oil	Diesel
	Net carbon intensity (20-year biogenic C time frame) in kg CO2e MJ-1					
% difference relative to reference system		36%	13%	11%	30%	29%
WC BK 75-20	**0.354**	**0.238**	**0.328**	**0.337**	**0.259**	**0.261**
Change in carbon intensity of bioenergy relative to reference system		0.116	0.026	0.018	0.095	0.093
% difference relative to reference system		49%	8%	5%	37%	36%
CW LS 75-20	**0.397**	**0.035**	**0.125**	**0.133**	**0.056**	**0.058**
Change in carbon intensity of bioenergy relative to reference system		0.362	0.272	0.263	0.341	0.339
% difference relative to reference system		1025%	218%	197%	614%	585%
CW LS 35-20	**0.850**	**0.0034**	**0.0047**	**0.0096**	**0.0119**	**0.0142**
Change in carbon intensity of bioenergy relative to reference system		0.847	0.846	0.841	0.838	0.836
% difference relative to reference system		24615%	18030%	8748%	7076%	5905%
WC LS 75-20	**0.397**	**0.035**	**0.125**	**0.133**	**0.056**	**0.058**
Change in carbon intensity of bioenergy relative to reference system		0.362	0.272	0.264	0.342	0.339
% difference relative to reference system		1026%	218%	198%	614%	586%

4.1.2 Incidental Biomass from Fire Protection, Other Incidental Biomass and Wood Waste

Incidental biomass from forest fire protection initiative has lower net carbon intensity than imported wood pellets (Table 27). Propane has a higher energy content and higher average combustion efficiency which are reasons that it consistently shows the lowest carbon intensity.

Using incidental biomass (other than fire protection residues) and wood waste for bioenergy results in the lowest carbon intensity relative to the reference pathways (Table 28). In this case, the feedstock collection in both the bioenergy and reference pathways would result in the same changes in forest carbon dynamics, and therefore would cancel each other out. However, the biogenic carbon stored in the biomass was included at combustion. Because the technologies for bioenergy capture and incineration of incidental/wood waste biomass are different, this results in different biogenic emissions. Additionally, to maintain equivalent boundaries and function of the bioenergy system, an equivalent amount of fossil fuels (1 MJ) that could potentially be displaced by bioenergy is included.

Table 27: Carbon intensity (kg CO_2e/ MJ) for pathways using wood chips from incidental fire protection residues combusted in a Furnace, with 75% efficiency. The biogenic emissions are based on a 20-year average. In the reference system, the biogenic emissions are associated with combustion of incidental fire protection residues without energy capture and assuming 50% of the residues remain on site (to decay slowly), while in the bioenergy pathway, it is assumed that 100% of the residues are combusted.

Life Cycle Stage/Source	Bioenergy	Reference System -20 year biogenic				
	WC LS-FS 75-20	Propane	BC Pellets	AB Pellets	Heating Oil	Diesel
Feedstock Harvest/Extraction[1]	0.0073	0.0075	0.0047	0.0096	0.0119	0.0142
Processing	0.0005					
Transportation	0.0068		0.0110	0.0145		
Combustion[2]	0.0030	0.0556	0.1371	0.1371	0.0716	0.0716
Biogenic (LULUCF)[3]	***0.3088***	***0.2328***	***0.2328***	***0.2328***	***0.2328***	***0.2328***
Net GHG emissions	**0.3264**	**0.2960**	**0.3856**	**0.3941**	**0.3163**	**0.3186**

[1] For bioenergy pathways, this refers to the emissions associated with energy to fell and collect biomass. For fossil fuel reference pathways, the numbers represent cradle-to-transportation gate emissions, while for BC pellets, it represents cradle-to-processing gate emissions.

[2]The 'Combustion' stage includes the emissions of combustion related to nitrous oxide only, plus life cycle emissions associated with electricity used in furnaces, and some emissions from infrastructure associated with the combustion technology.

[3] Biogenic emissions represent the net emissions from all forest carbon pools, including the feedstock, soil, decomposition, etc. as described in Section 3.2.3. In the Reference system, the biogenic emissions represent what would have occurred if the SAME amount of biomass used for bioenergy was not removed.

Table 27: Carbon intensity (kg CO2e/ MJ) for pathways using wood chips from incidental biomass/ wood waste combusted in a Furnace, with 75% efficiency. The biogenic emissions are due to the carbon stored in the wood waste and does not include LULUCF. In the reference system, the biogenic emissions are associated with combustion of wood waste without energy capture, while in the bioenergy pathway, the wood waste energy is captured. No LULUCF carbon included, only carbon in wood.

Life Cycle Stage/Source	Bioenergy	Reference System				
	WC IB/WW 75	Propane	BC Pellets	AB Pellets	Heating Oil	Diesel
Feedstock Harvest/Extraction	n/a	0.0075	0.0047	0.0096	0.0119	0.0142
Processing	0.0005					
Transportation	0.0037		0.0110	0.0145		
Combustion		0.0556	0.1371	0.1371	0.0716	0.0716
Biogenic (from carbon in biomass)- combustion	0.160	0.1741	0.1741	0.1741	0.1741	0.1741
Transport associated with reference biomass burning	N/A	0.0011	0.0011	0.0011	0.0011	0.0011
Net Carbon intensity	**0.1638**	**0.2383**	**0.3279**	**0.3364**	**0.2586**	**0.2609**

4.1.3 Fire-kill and Beetle-kill Bioenergy Pathways

In all the fire-kill and beetle-kill bioenergy pathways the net carbon intensity is higher than the reference system except for pellets from Yukon, which has a lower net carbon intensity than imported pellets in the reference pathways (Tables 29 to 35) on a 20-year time frame. The biogenic emissions contribute to over 90% of the emissions in the bioenergy pathways. In this case, over the 20-year time period, the regeneration of the forest is slow relative to the instantaneous combustion of the forest biomass in the bioenergy pathway. Additionally, in the beetle-kill scenario there is a lag in regeneration, making the biogenic emissions higher for this pathway.

Table 29: Carbon intensity (kg CO_2e/ MJ) for pathways using cordwood from fire-kill biomass used in wood stoves with secondary combustion and 75% efficiency. The biogenic emissions are based on a 20-year average.

Life Cycle Stage/Source	Bioenergy	Reference system -20 year biogenic				
	CW FK 75-20	Propane	BC Pellets	AB Pellets	Heating Oil	Diesel
Feedstock Harvest/Extraction	0.0067	0.0075	0.0047	0.0096	0.0119	0.0142
Processing	0.0001					
Transportation	0.0059		0.0110	0.0145		
Combustion	0.0030	0.0556	0.1371	0.1371	0.0716	0.0716
Biogenic (LULUCF)	***0.2623***	***0.1299***	***0.1299***	***0.1299***	***0.1299***	***0.1299***
Net Carbon intensity	**0.2780**	**0.1930**	**0.2826**	**0.2912**	**0.2133**	**0.2156**

Table 30: Carbon intensity (kg CO_2e/ MJ) for pathways using cordwood from fire-kill biomass used in wood stoves with secondary combustion and 35% efficiency. The biogenic emissions are based on a 20-year average.

Life Cycle Stage/Source	Bioenergy	Reference system -20 year biogenic				
	CW FK 35-20	Propane	BC Pellets	AB Pellets	Heating Oil	Diesel
Feedstock Harvest/Extraction	0.0144	0.0075	0.0047	0.0096	0.0119	0.0142
Processing	0.0001					
Transportation	0.0127		0.0110	0.0145		
Combustion	0.0065	0.0556	0.1371	0.1371	0.0716	0.0716
Biogenic (LULUCF)	***0.5621***	***0.2783***	***0.2783***	***0.2783***	***0.2783***	***0.2783***
Net Carbon intensity	**0.5958**	**0.3414**	**0.4311**	**0.4396**	**0.3618**	**0.3641**

Table 31: Carbon intensity (kg CO_2e/ MJ) for pathways using cordwood from beetle-kill biomass used in wood stoves with secondary combustion and 75% efficiency. The biogenic emissions are based on a 20-year average.

Life Cycle Stage/Source	Bioenergy	Reference system -20 year biogenic				
	CW BK 75-20	Propane	BC Pellets	AB Pellets	Heating Oil	Diesel
Feedstock Harvest/Extraction	0.0067	0.0075	0.0047	0.0096	0.0119	0.0142
Processing	0.0001					
Transportation	0.0059		0.0110	0.0145		
Combustion	0.0030	0.0556	0.1371	0.1371	0.0716	0.0716
Biogenic (LULUCF)	***0.3380***	***0.1753***	***0.1753***	***0.1753***	***0.1753***	***0.1753***
Net Carbon intensity	**0.3537**	**0.2384**	**0.3280**	**0.3365**	**0.2587**	**0.2610**

Table 32: Carbon intensity (kg CO_2e/ MJ) for pathways using cordwood from beetle-kill biomass used in wood stoves with secondary combustion and 35% efficiency. The biogenic emissions are based on a 20-year average.

Life Cycle Stage/Source	Bioenergy	Reference system -20 year biogenic				
	CW BK 35-20	Propane	BC Pellets	AB Pellets	Heating Oil	Diesel
Feedstock Harvest/Extraction	0.0144	0.0075	0.0047	0.0096	0.0119	0.0142
Processing	0.0001					
Transportation	0.0127		0.0110	0.0145		
Combustion	0.0065	0.0556	0.1371	0.1371	0.0716	0.0716
Biogenic (LULUCF)	***0.5621***	***0.3755***	***0.3755***	***0.3755***	***0.3755***	***0.3755***
Net Carbon intensity	**0.5958**	**0.4387**	**0.5283**	**0.5368**	**0.4590**	**0.4613**

Table 33: Carbon intensity (kg CO_2e/ MJ) for pathways using wood chips from fire-kill biomass used in furnaces with secondary combustion and 75% efficiency. The biogenic emissions are based on a 20-year average.

Life Cycle Stage/Source	Bioenergy	Reference system -20 year biogenic				
	WC FK 75-20	Propane	BC Pellets	AB Pellets	Heating Oil	Diesel
Feedstock Harvest/Extraction	0.0067	0.0075	0.0047	0.0096	0.0119	0.0142
Processing	0.0005					
Transportation	0.0059		0.0110	0.0145		
Combustion	0.0030	0.0556	0.1371	0.1371	0.0716	0.0716
Biogenic (LULUCF)	***0.2623***	***0.1299***	***0.1299***	***0.1299***	***0.1299***	***0.1299***
Net Carbon intensity	**0.2784**	**0.1930**	**0.2826**	**0.2912**	**0.2133**	**0.2156**

Table 34: Carbon intensity (kg CO_2e/ MJ) for pathways using wood chips from beetle-kill biomass used in furnaces with 75% efficiency. The biogenic emissions are based on a 20-year average.

Life Cycle Stage/Source	Bioenergy	Reference system -20 year biogenic				
	WC BK 75-20	Propane	BC Pellets	AB Pellets	Heating Oil	Diesel
Feedstock Harvest/Extraction	0.0067	0.0075	0.0047	0.0096	0.0119	0.0142
Processing	0.0005					
Transportation	0.0059		0.0110	0.0145		
Combustion	0.0030	0.0556	0.1371	0.1371	0.0716	0.0716
Biogenic (LULUCF)	***0.3380***	***0.1753***	***0.1753***	***0.1753***	***0.1753***	***0.1753***
Net Carbon intensity	**0.3541**	**0.2384**	**0.3280**	**0.3365**	**0.2587**	**0.2610**

Table 35: Carbon intensity (kg CO_2e/ MJ) for pathways using pellets from fire-kill biomass used in pellet stove/furnace with 75% efficiency. The biogenic emissions are based on a 20-year average.

Life Cycle Stage/Source	Bioenergy	Reference system -20 year biogenic				
	PELL FK 75-20	Propane	BC Pellets	AB Pellets	Heating Oil	Diesel
Feedstock Harvest/Extraction	0.0050	0.0075	0.0047	0.0096	0.0119	0.0142
Processing	0.0031					
Transportation	0.0037		0.0110	0.0145		
Combustion	0.0022	0.0556	0.1371	0.1371	0.0716	0.0716
Biogenic (LULUCF)	***0.1933***	***0.0957***	***0.0957***	***0.0957***	***0.0957***	***0.0957***
Net Carbon intensity	**0.2073**	**0.1588**	**0.2485**	**0.2570**	**0.1792**	**0.1814**

4.1.4 Live-standing Trees-Roundwood and Forest Residue Pathways

With the exception of wood chips from live-standing residues compared to imported wood pellets, all bioenergy pathways have higher net carbon intensity than the reference pathways (Tables 36 - 38) on a 20-year time frame for forest carbon. This is primarily due to the biogenic (LULUCF) emissions, which contribute over 90% to the overall carbon intensity of the bioenergy pathways (the exception is residue bioenergy pathways for which biogenic emissions contribute ~80% of the carbon intensity). The biogenic emissions represent eight carbon pools, including the carbon in the feedstock itself, as well as the pools associated with forest regeneration, soil carbon, decomposition, etc. as described in Section 3.2.3. We assumed that all the carbon in the feedstock undergoes complete combustion and did not include this biogenic carbon in the 'Combustion' life cycle stage.

Table 36: Carbon intensity (kg CO_2e/ MJ) for pathways using cordwood from live-standing trees, used in wood stoves with secondary combustion with 75% efficiency. The biogenic emissions are based on a 20-year average.

Life Cycle Stage/Source	Bioenergy	Reference system -20 year biogenic				
	CW LS 75-20	Propane	BC Pellets	AB Pellets	Heating Oil	Diesel
Feedstock Harvest/Extraction	0.0073	0.0075	0.0047	0.0096	0.0119	0.0142
Processing	0.0001					
Transportation	0.0068		0.0110	0.0145		
Combustion	0.0030	0.0556	0.1371	0.1371	0.0716	0.0716
Biogenic (LULUCF)	***0.3796***	***-0.0279***	***-0.0279***	***-0.0279***	***-0.0279***	***-0.0279***
Net Carbon intensity	**0.3968**	**0.0353**	**0.1249**	**0.1334**	**0.0556**	**0.0579**

Table 37: Carbon intensity (kg CO_2e/ MJ) for pathways using cordwood from live-standing trees, used in fireplaces with 35% efficiency. The biogenic emissions are based on a 20-year average.

Life Cycle Stage/Source	Bioenergy	Reference system -20 year biogenic				
	CW LS 35-20	Propane	BC Pellets	AB Pellets	Heating Oil	Diesel
Feedstock Harvest/Extraction	0.0157	0.0075	0.0047	0.0096	0.0119	0.0142
Processing	0.0001					
Transportation	0.0146		0.0110	0.0145		
Combustion	0.0065	0.0556	0.1371	0.1371	0.0716	0.0716
Biogenic (LULUCF)	***0.8134***	***-0.0597***	***-0.0597***	***-0.0597***	***-0.0597***	***-0.0597***
Net Carbon intensity	**0.8503**	**0.0034**	**0.0931**	**0.1016**	**0.0238**	**0.0261**

Table 38: Carbon intensity (kg CO_2e/ MJ) for pathways using wood chips from live-standing trees, used in wood stoves with secondary combustion with 75% efficiency. The biogenic emissions are based on a 20-year average.

Life Cycle Stage/Source	Bioenergy	Reference system -20 year biogenic				
	WC LS 75-20	Propane	BC Pellets	AB Pellets	Heating Oil	Diesel
Feedstock Harvest/Extraction	0.0073	0.0075	0.0047	0.0096	0.0119	0.0142
Processing	0.0005					
Transportation	0.0068		0.0110	0.0145		
Combustion	0.0030	0.0556	0.1371	0.1371	0.0716	0.0716
Biogenic (LULUCF)	***0.3796***	***-0.0279***	***-0.0279***	***-0.0279***	***-0.0279***	***-0.0279***
Net Carbon intensity	**0.3972**	**0.0353**	**0.1249**	**0.1334**	**0.0556**	**0.0579**

Biogenic emissions are high from live standing roundwood relative to the reference pathways because in the reference pathways the trees are left in the forest and the land base continues to accumulate carbon. The live-standing trees are subject to natural disturbance and stand senescence, which are included in the growth and yield assumptions in the forest carbon modeling. In contrast, in the case of wood chips from live-standing residues, the assumption is that in the reference pathways, 50% of the residue decomposes and 50% is burned without energy capture, while in the bioenergy scenario, all collectible residue is burned for energy.

Indirectly, the combustion efficiency also plays a major role in the carbon intensity, in that at lower efficiencies much more biomass feedstock is required to generate 1 MJ of heat. Since the feedstock is associated with specific biogenic emissions, these emissions will scale with the mass. For example, the biogenic emissions in the bioenergy pathway are 0.4053 kg CO_2e/MJ at 75% efficiency, while at 10% efficiency the biogenic emissions are 3.04 kg CO_2e/MJ.

All other life cycle stages contribute less than 10 to the carbon intensity of most bioenergy pathways. The emissions from cordwood and wood chips are similar because the feedstock is the same, but there is an additional step required to create woodchips from roundwood. However, these emissions are extremely small compared to the biogenic emissions.

4.1.5 Technology Scenarios

We explored both cogeneration and pyrolysis technologies to determine how they affect the net emissions of bioenergy pathways.

4.1.5.1 Cogeneration

Cogeneration of fire kill biomass results in lower bioenergy pathway emissions compared to all reference pathway with the exception of propane (Table 39). The net GHG emissions associated with producing heat are higher than those of propane and diesel. However, because electricity is also produced, there are overall benefits from the bioenergy pathway since the grid electricity in the Yukon has a higher carbon intensity than that produced from the bioenergy. In determining the final benefits of cogen systems it is also important to assess whether candidate cogen locations would be displacing Yukon grid electricity or non-grid generated electricity. The carbon intensity benefits of cogen systems could be further enhanced if they were to replace non-grid electricity that is generated from combustion of fossil fuels.

4.1.5.2 Pyrolysis

Using pyrolysis to convert solid biomass into bio-oil and biochar does not have as significant benefits as cogeneration of biomass. In the case of pyrolysis, the bioenergy pathway has lower emissions compared to the imported pellets in the reference pathway (Table 40). This is partly because there is some biomass that is needed to run the pyrolyzer, therefore more biomass is needed, which has implications for the LULUCF emissions. The biochar was assumed to be combusted in a furnace. Although there is some evidence that applying biochar to land can increase carbon sequestration, there are mixed findings in the literature due to soil and climatic conditions. Since there were no data available for carbon sequestration rates in cold climates similar to the Yukon, this analysis was not conducted.

Table 39: Carbon intensity associated with bioenergy generated in a cogen system. In this case there are two functions in the bioenergy system (the production of heat and electricity), therefore in the reference fuel system the boundary has been expanded to include an equivalent amount of electricity produced for the Yukon grid. The amount of electricity produced per 1 MJ of heat is .205 MJ.

Life Cycle Stage/Source	Bioenergy	Reference system -20 year biogenic				
	WC FK Cogen 85 - 20	**Propane**	**BC Pellets**	**AB Pellets**	**Heating Oil**	**Diesel**
Feedstock Harvest/Extraction	0.0059	0.0075	0.0047	0.0096	0.0119	0.0142
Processing	0.0004					
Transportation	0.0026		0.0110	0.0145		
Combustion	0.0013	0.0556	0.1371	0.1371	0.0716	0.0716
Biogenic (LULUCF)	***0.2315***	***0.1146***	***0.1146***	***0.1146***	***0.1146***	***0.1146***
Net Carbon intensity	**0.2417**	**0.1777**	**0.2674**	**0.2759**	**0.1980**	**0.2003**
Electricity coproduct	0.04949	0.0979	0.0979	0.0979	0.0979	0.0979
Total GHG w. coproduct	**0.2911**	**0.2756**	**0.3652**	**0.3737**	**0.2959**	**0.2982**
Bioenergy – Reference system		**0.0156**	**-0.0741**	**-0.0826**	**-0.0048**	**-0.0071**

Table 40: Carbon intensity associated with bioenergy produced through pyrolysis. In this case both bio-oil, the main product, and biochar, the coproduct, are produced in a pyrolyzer.

Life Cycle Stage/Source	Bioenergy	Reference system -20 year biogenic				
	PYR FK 86	**Propane**	**BC Pellets**	**AB Pellets**	**Heating Oil**	**Diesel**
Feedstock Harvest/Extraction	0.0066	0.0075	0.0047	0.0096	0.0119	0.0142
Processing	0.0005					
Transportation			0.0110	0.0145		
Combustion		0.0556	0.1371	0.1371	0.0716	0.0716
Biogenic (LULUCF)	***0.2564***	***0.1299***	***0.1299***	***0.1299***	***0.1299***	***0.1299***
Net Carbon intensity	**0.2635**	**0.1930**	**0.2826**	**0.2912**	**0.2133**	**0.2156**
Biochar co-product (combusted)	0.0782	0.0749	0.1097	0.1130	0.0828	0.0837
Total GHG w. coproduct	**0.3417**	**0.2679**	**0.3923**	**0.4042**	**0.2961**	**0.2993**
Bioenergy – Reference system		**0.0738**	**-0.0507**	**-0.0625**	**0.0455**	**0.0424**

4.2 LIFE CYCLE INTERPRETATION

According to the ISO standards, in the life cycle interpretation phase, assumptions and data are checked to determine their effect on final results. Additionally, scenario analysis is an optional step, where scenarios can be developed and analyzed based on the sensitivity analysis to determine if they can address impacts. All results are then interpreted based on the original goal and the data quality.

4.2.1 Sensitivity analysis

The sensitivity analysis was conducted on the parameters with the highest uncertainty that also contributed to the highest emissions in the life cycle. **In this case, the LULUCF emissions are driven by the amount of biomass needed to generate 1 MJ of heat. The amount of biomass needed depends on the energy content of the biomass, and the combustion technology efficiency.** Additionally, LULUCF emissions change with time due to the various carbon dynamics in the forest. Therefore the sensitivity analysis was conducted on these parameters.

The results for the bioenergy pathway were only compared to those of propane, imported BC pellets, and heating oil, because the BC pellets were similar to the Alberta pellets and the diesel results were similar to the heating oil results. All results are reported based on the difference in emissions between the bioenergy and reference pathways.

4.2.1.1 Effect of LULUCF averaging period- 20 vs. 100 year

The results of this sensitivity analysis (Figure 7), where the LULUCF emissions are averaged over a 100 year period, show that the results are very sensitive to this parameter, with the difference between bioenergy and reference pathways changing from being higher for bioenergy (positive values in figure), to being lower for bioenergy (negative values in figure), except for the situation of live-standing trees, and imported wood pellets across most cases. In the case of live-standing cordwood feedstocks, the net carbon intensity increases for both the bioenergy pathway and reference pathways when the timeframe increases to 100 years, as the carbon accumulation potential decreases with the maturing forest. For live-standing forest fire protection residue feedstock, only the residue is being removed and not the trees. In these cases the biogenic carbon losses decrease with time, resulting in lower net carbon intensity for bioenergy relative to reference pathways (with the exception of propane). The implications of these results are discussed further in Section 4.4.

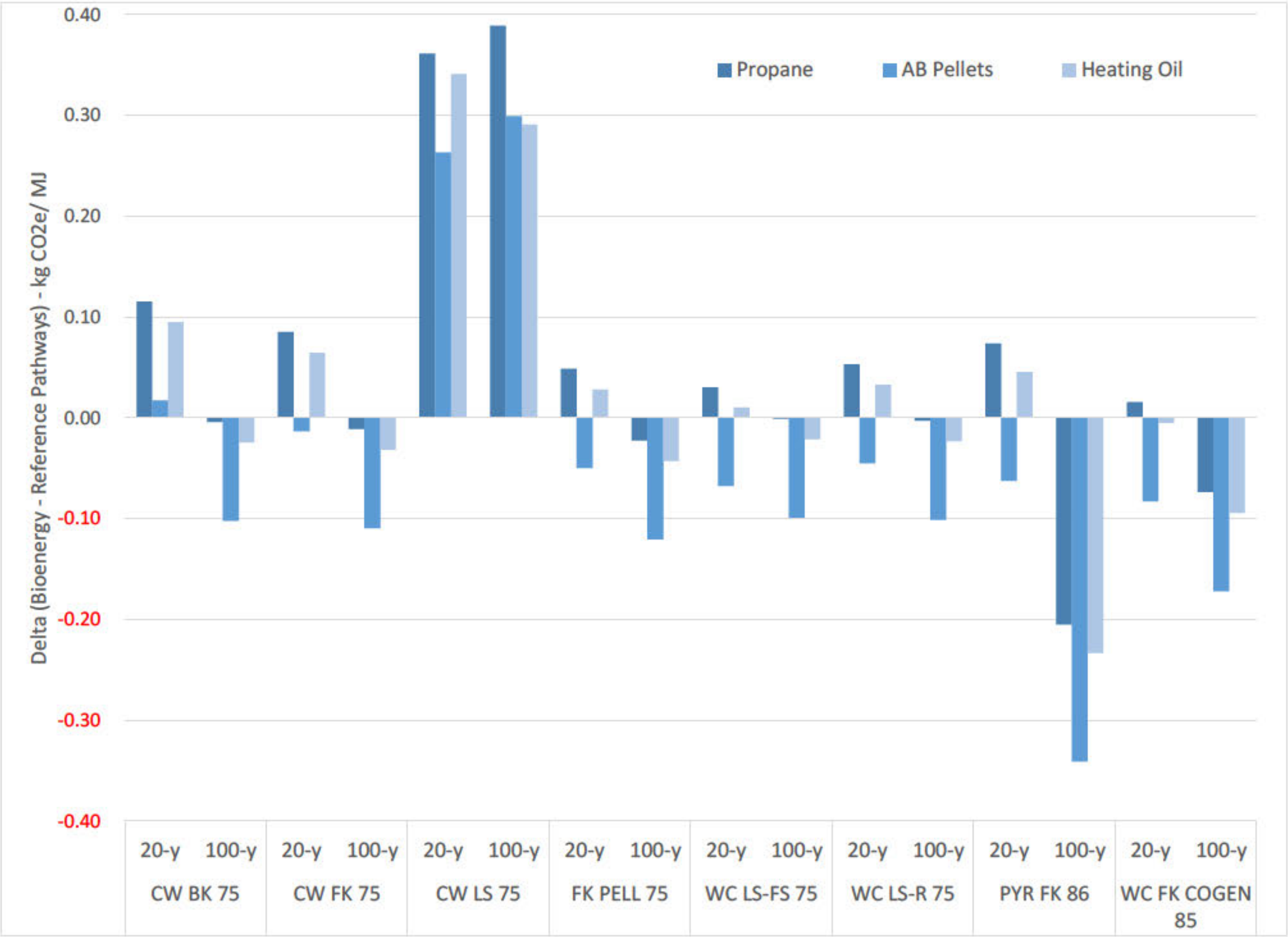


Figure 7: Effect of changing averaging period of LULUCF emissions on the carbon intensity difference between bioenergy and reference pathways. The base case is represented by the 20-year results.

4.2.1.2 Effect of LHV value

At higher LHV values, the difference between the bioenergy and reference pathways decreases, but does not change direction (Figure 8), except for CW BK 75 and WC FS LS 75 for the case of an LHV of 18 MJ. **This suggests that for the most part, the results are not sensitive to this value.**

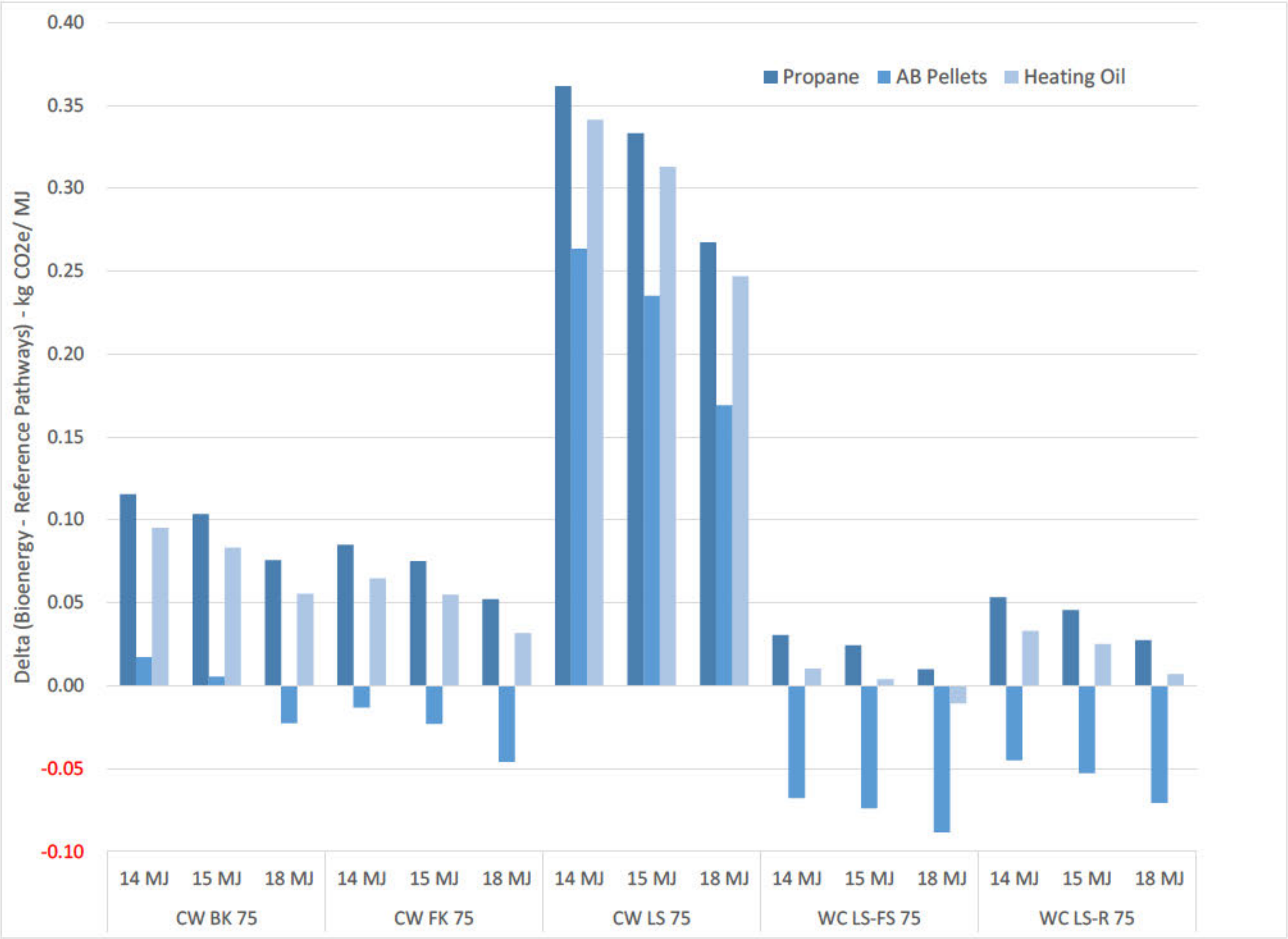


Figure 8: Sensitivity results showing the effect of LHV. The base case is represented by biomass energy content of 14 MJ/kg.

4.2.1.3 Effect of Combustion Efficiencies

The average combustion efficiencies for different technologies were used in the original results and ranged from 75 to 86%. The sensitivity analysis explored a value of 90% efficiency for all combustion technologies using biomass (Figure 9**). In all cases the difference between the bioenergy and reference pathways decreased but did not change direction meaning that the results are robust based on the efficiency used.**

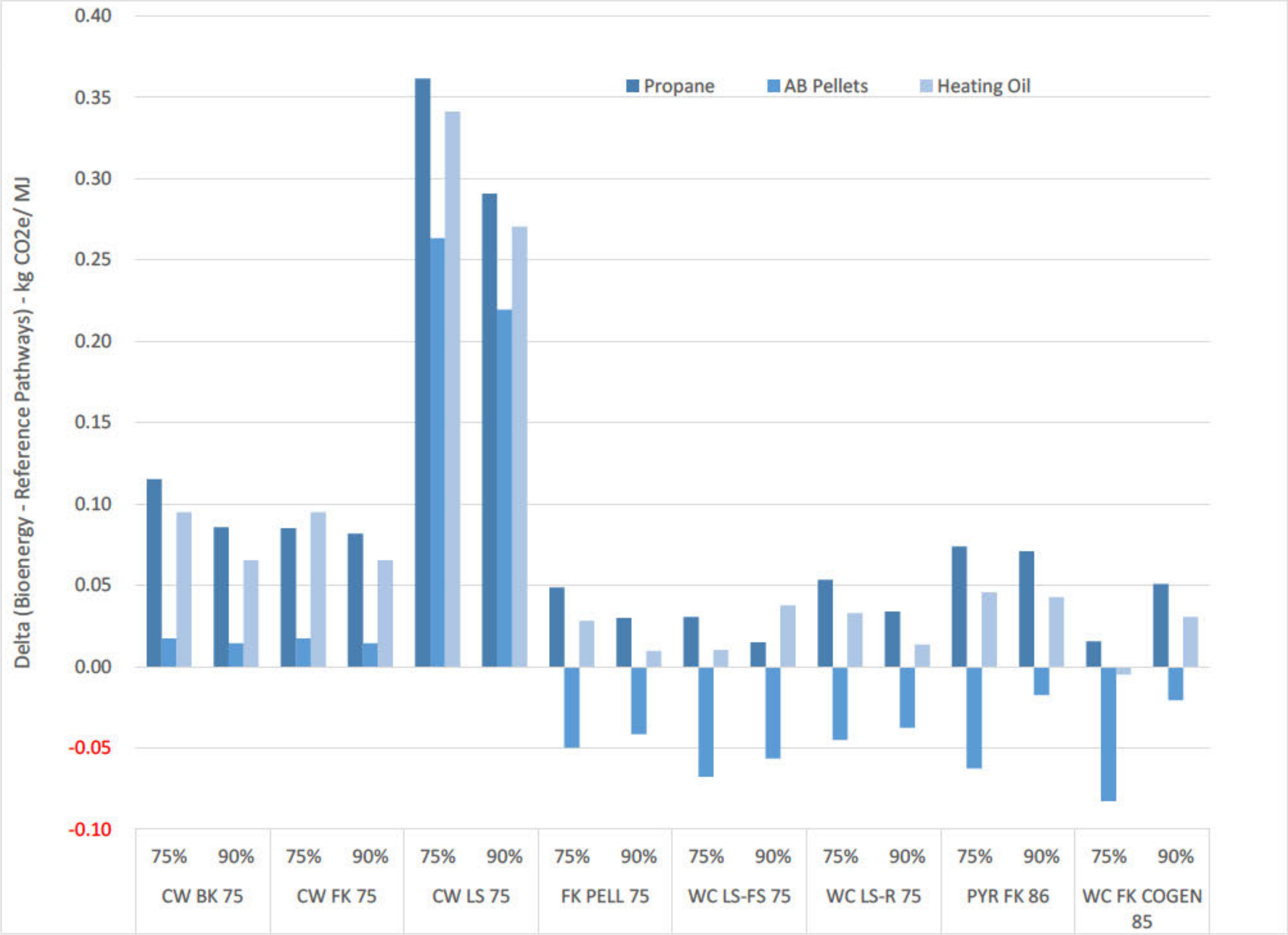


Figure 9: Sensitivity results showing the effect of combustion technology efficiency by the difference between bioenergy and reference carbon intensities. The base case is represented by 75% efficiency.

4.2.2 Best Case Scenario with Available Technologies

Given that the value of the LHV and combustion efficiency lowered the bioenergy pathway carbon intensities in the above analysis, we explored a scenario where both of these parameters were applied at the same time. Figure 10 shows that if the Yukon were to implement the best technologies and combust biomass that has an LHV of at least 18 MJ/kg, then all bioenergy pathways, except those using live-standing trees, would have better performance than imported wood pellets. It should be noted that the energy content of 18 MJ/kg is not specified as being LHV or HHV in the source using this number (Preto, 2011), so it is not clear whether this is achievable.

In all cases, waste wood has lower emissions, because it is assumed that it is combusted without energy capture in the reference case.

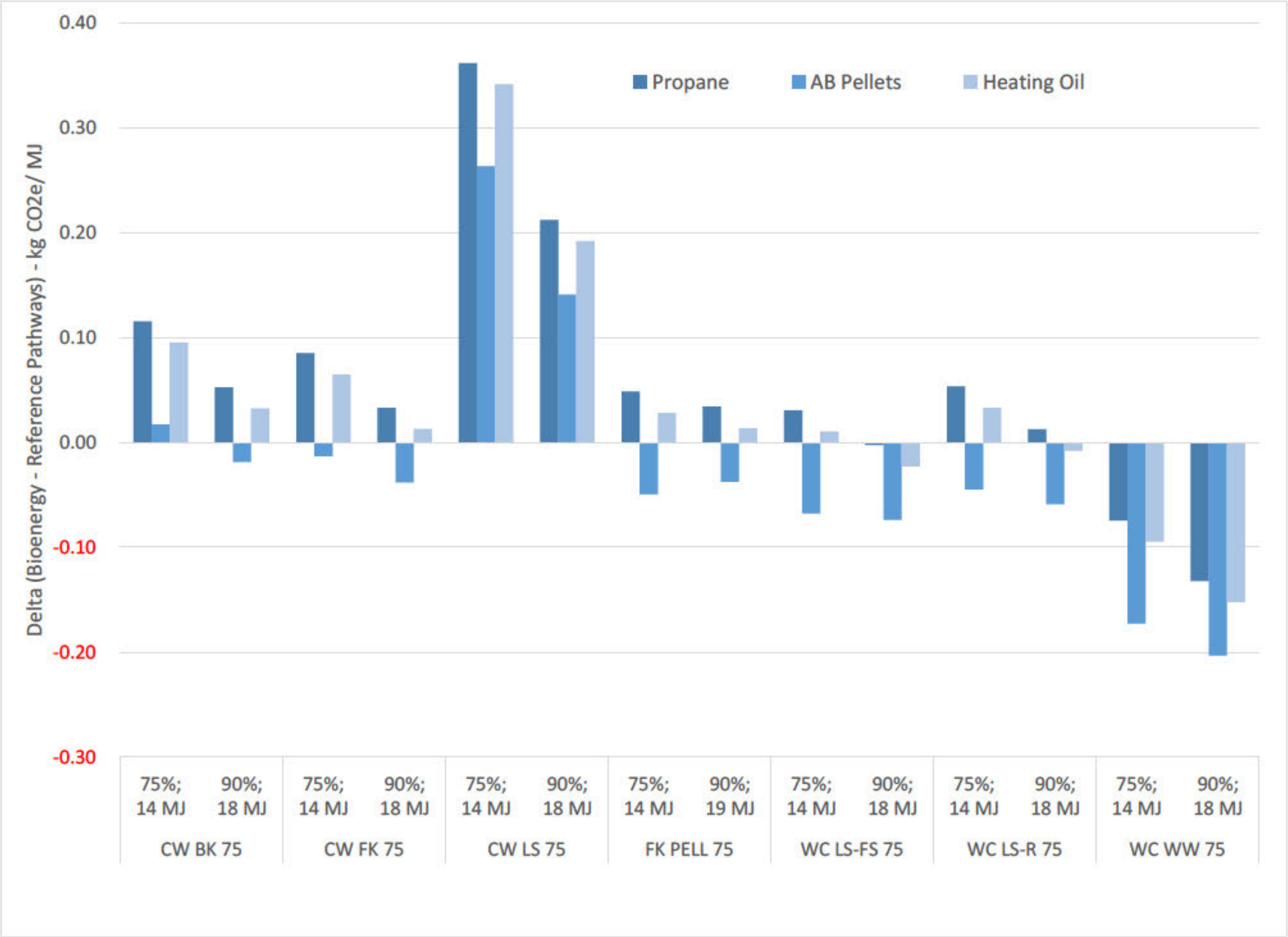


Figure 9: Scenario analysis assuming best available technology efficiency (90%) for biomass combustion and highest reported energy content values (18 MJ/kg). The base case is represented by 75% efficiency and biomass energy content of 14 MJ/kg. The y-axis shows the difference between the bioenergy pathways and the reference pathways of propane, AB pellets and heating oil. Positive values mean that bioenergy has higher emissions than reference pathways, while negative values mean that bioenergy pathways have lower emissions.

4.2.3 Data quality assessment and Consistency Checks

The data quality assessment involves considering the data quality requirements (Table 41) and comparing them to the actual data used. The data used for the bioenergy pathways are assigned values in the category of 3 to 5, which is average to poor data quality (Table 40). We have conducted sensitivity analysis to account for the data that has high uncertainty, except for the harvesting processes and the LULUCF modeling. No sensitivity analysis was conducted on the harvesting process because it contributes to less than 2% of the total carbon intensity, and according to the ISO LCA 14040/44 standards, it is only required to conduct sensitivity analysis on data that is uncertain AND has a high contribution to overall impacts. Sensitivity analyses were not conducted on the forest carbon modeling due to the challenges with determining the uncertainty in the CBM-CFS model.

Table 41: Data quality requirements and assessment. Ratings of data quality are based on pedigree matrix developed by (Weidema & Wesnæs, 1996)

Data Quality Category	Requirement	Data Quality Indicator	Data Quality Assessment
Temporal	Data within 10 years of study	Data is from 2011 to 2021	The data used for the CBM-CFS model are from sources from 1990, 2007, and 2018. this means that the data quality criteria is rated between 1 and 5 (1 is best, 5 is worst) because the data is between 3 and 30 years old.
Geographical	Data matches local production/ use	Data comes from the Yukon territory for biomass and from location of production for reference fuels	Data for forest harvesting came from Quebec boreal forest, predominantly black spruce, from boreal forest. The data quality is rated as 3: 'data from area with similar conditions'
Technological	Average and most common production processes or technologies	All processes used in study are representative of most common practices	Data for technological aspects (e.g. combustion technologies LHV) are based on North American or Canadian averages, respectively, so are rated 4 because they represent 'data on related processes or technology but same technology'.

Consistency check is the "process of verifying that the assumptions, methods and data are consistently applied throughout the study and are in accordance with the goal and scope definition performed before conclusions are reached" (ISO, 2006). Methods and data were consistently applied, such as energy allocation, and the accounting of biogenic emissions from either the LULUCF or the carbon in the biomass, for both bioenergy and reference pathways.

4.3 SCALING LIFE CYCLE EMISSIONS TO TOTAL ENERGY USE FOR YUKON

Life cycle emissions for the bioenergy pathways compared to reference pathways were scaled up based on the following assumptions:

- Bioenergy replaced propane, imported pellets, and heating oil use based on current use as shown in Table 42. The scaled distribution of the 1800 TJ total allocated to heating oil, propane, and imported pellet replacement are presented in Table 43.
- 50% of the 1800 TJ was replaced by locally-sourced bioenergy sources (900 TJ).

Two cases are considered:

1. Current technology: The biomass was combusted in average current combustion technologies (average efficiency =75% with biomass LHV=14 MJ/kg) and that lower efficiency furnaces (i.e. 35%) are a negligible share of the available furnaces for combustion biomass and are not considered.
2. Best available technology and energy content: The biomass was combusted with best available combustion technologies and high energy content (average efficiency =90% with biomass LHV=18 MJ/kg).

Only bioenergy pathways that showed reductions relative to at least one of the reference pathways were considered for the scaling up.

Table 42. Yukon heating energy use by fuel source.

Fuel	Amount	Energy (TJ)	Percentage	Comment
Electricity	49 GWh	176	7	Not scaled because it is based on electricity use (out of scope)
Heating oil	37,800 m³	1,436	60	Scaled proportionally
Propane	13,800 m³	350	15	Scaled proportionally
Cordwood	24,000 cords	409	17	Not scaled because Yukon cordwood was not modeled (out of scope)
Wood pellets (imported)	750 tonnes	14	1	Scaled proportionally
Total		**2,385**	**100**	

Sources: Yukon Government, 2016, Figure 1 p 11; Stantec Consulting Limited, 2020, Figure 2-1 p 5. NOTE: Both reports use the same data source, Energy Solutions Centre' with data from 2012.

Table 43. Proportional values of Yukon heating fuel used for scaling analysis.

Fuel	Amount	Energy (TJ)	Percentage
Heating oil	37,800 m³	1,436	79.8
Propane	13,800 m³	350	19.4
Wood pellets (imported)	750 tonnes	14	0.8
Total		**1800**	**100**

The amount of biomass available (dry tonnes / year at density of 374 kg/m³) was determined from Table 1. The density was adjusted to the density for biomass at 20% moisture content (448 kg/m³) to provide the mass available per year. The energy content and combustion efficiency for current and best technology were then applied to determine the amount of biomass needed to produce the energy required.

There were insufficient amounts of biomass from incidental biomass from other land clearing, incidental biomass from fire protection initiatives, and live standing tree harvest residuals to obtain 900 TJ, so the remainder of the biomass was from fire-kill stands. (Note, there is a surplus of fire-kill biomass required to meet 900 TJ, so we only used what was required to make up the difference).

The results for the current case and best available combustion technology/energy content case are presented in Tables 44 and 45, respectively.

Estimated GHG reductions on a life cycle basis for current case and best available combustion technology/energy content case are 3,923 and 23,999 tonnes CO_2e/year, respectively if scaled to meet 50% of Yukon heating demand. It should be noted that these are not entirely reductions within the Yukon, but rather reductions based on the life cycle of both the bioenergy and reference pathways.

Table 44: Results of scaling analysis of the current case

Bioenergy system	Share of fuel based on biomass availability based on current technology	Bioenergy	Propane	BC Pellet	AB Pellet	Heating Oil	Bioenergy	Propane	BC Pellet	AB Pellet	Heating Oil	Total reference emissions
	MJ	**Life cycle carbon intensity (kg CO2e/MJ)**					**Total emissions (Tonnes CO2e per year)**					
Incidental biomass and waste wood	261,440,455	0.164	0 238	0.328	0.336	0.259	42,834	12,112	333	342	53,934	66,722
Incidental biomass from fire protection, wood chips (WC LS-FS 75)	12,983,783	0.326	0 296	0.386	0.394	0.316	4,238	747	19	20	3,276	4,063
Residuals, wood chips (WC LS-R 75)	15,076,316	0.392	0.339	0.429	0.437	0.360	5,917	995	25	26	4,325	5,370
Fire-kill, pellets (PELL FK 75)	610,499,447	0.207	0.159	0.248	0.257	0.179	126,550	18,853	590	610	87,254	107,307
Total	900,000,000						179,539					183,462
Difference between Bioenergy and Reference Systems							**- 3,923**					

Table 45: Results of the scaling analysis of the best available combustion technology/energy content case.

Bioenergy system	Share of fuel based on biomass availability and best available technology	Bioenergy	Propane	BC Pellets	AB Pellets	Heating Oil	Bioenergy	Propane	BC Pellets	AB Pellets	Heating Oil	Total reference emissions
	MJ	Life cycle GWP (kg CO2e/MJ)					Total emissions (Tonnes CO2e per year)					
Incidental biomass and waste wood	403,365,273	0.106	0.238	0.302	0.310	0 259	42,834	13,452	370	380	59,901	74,103
Incidental biomass from fire protection, wood chips	20,032,123	0.212	0.214	0.278	0.285	0 234	4,238	834	22	22	3,745	4,623
Residuals, wood chips	23,260,601	0.254	0.242	0.306	0.313	0 262	5,917	1,095	28	28	4,870	6,021
Fire-kill, pellets	453,342,003	0.173	0.139	0.203	0.210	0.159	78,311	12,243	358	371	57,582	70,553
Total	900,000,000						131,300					155,299
Difference between Bioenergy and Reference Systems							**- 23,999**					

4.4 CONCLUSIONS, LIMITATIONS, AND RECOMMENDATIONS

The results from this study should not be applied to any conditions other than those described in section 3 for both the reference and bioenergy pathways. For example, it was assumed that for forest fire protection activities, 50% of the incidental biomass residues were left to decay in the forest in the reference pathway, while 100% was removed for bioenergy in the bioenergy pathway. Results would be different if 100% of the incidental biomass residues from fire protection initiatives are actually removed in the reference pathway.

Consideration of Carbon Neutrality

This LCA study followed the ISO LCA standards and IPCC GHG inventory practices by including all GHG emissions occurring across all life cycle stages from cradle-to-grave, including GHG emissions resulting from biomass removal, decay, forest regrowth, and soil carbon gains and losses at the forest as well as emissions from combustion of the biomass. In the long term (30 to 150 years) biomass from forest systems may be carbon neutral (i.e. all the carbon in the biomass is recaptured in regenerated biomass), but in the short term it is not necessarily climate neutral, as it adds to the stock of GHG emissions in the atmosphere. This study considered recent clarifications on accounting for GHG losses and gains due to forest carbon dynamics. The IPCC guidance on bioenergy states (Sec. 2, Q2-10):

> The overall IPCC approach to estimating and reporting bioenergy greenhouse gas emissions at the national level requires complete coverage of all IPCC sectors, including the Agriculture, Forestry and Other Land Use (AFOLU) and Energy sectors. All CO2 emissions and removals associated with biomass are reported in the AFOLU sector. Therefore, CO2 emissions from biomass combustion used for energy are only recorded as a memo item in the Energy sector; these emissions are not included in the Energy sector total to avoid double counting. The approach of not including these emissions in the Energy Sector total should not be interpreted as a conclusion about the sustainability, or carbon neutrality of bioenergy....
>
> ...Thus, the IPCC Guidelines do not automatically consider or assume biomass used for energy as "carbon neutral", even in cases where the biomass is thought to be produced sustainably.

Furthermore, a recent published paper (Cowie et al., 2021), which is an output of IEA Bioenergy Task 45 'Climate and Sustainability Effects of Bioenergy within the broader Bioeconomy', has a similar message. Specifically, when assessing the climate implications of policies that promote bioenergy, the paper concludes that:

- The assessment should be made at the landscape level, using a full life cycle approach that includes emissions occurring along the full supply chain as well as changes in land carbon stocks.
- Forest bioenergy cannot be assumed to be carbon neutral by default. The bioenergy system should be compared with reference scenarios (counterfactuals) that describe the most likely alternative land use(s) and energy sources that would be displaced by the bioenergy system, and the probable alternative fates for the biomass being utilized.

The next 10-20 years are crucial for reducing GHG emissions to limit global warming. Thus, the approach taken in this study was to include all supply chain emissions for both the bioenergy and reference scenarios, and to account for changes in land carbon stocks at the landscape level (i.e. biomass removal, growth, and regeneration) using the CBM-CFS3 model, based on the best available data.

Recommended Bioenergy Pathways for Yukon

74(1)(a)

If the biomass feedstocks with the lowest carbon intensity can be combusted in technologies of the highest efficiency and LHV (90% and 18 MJ/kg), annual GHG reductions would be 23,999 tonnes CO_2e, assuming they replace 50% of current reference pathway heating fuels.

74(1)(a)

Recommendations for Future Research

74(1)(a)

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APPENDIX A:
Additional Information on Bioenergy Fuel Pathways

BIOENERGY PATHWAYS

Biomass extraction

In the Yukon, locally-based biomass can be extracted from a variety of sources, including sustainably harvested standing merchantable trees and collection of residues, incidental and recycled biomass. Extraction includes the harvest / collection stages through to processing, including transport.

Harvest of merchantable standing trees

Merchantable standing trees are defined as those > 16 cm diameter at breast height (DBH). These exist throughout Yukon's 8.1 million ha of forest land that can support harvesting activities, and include fire-kills, beetle-kills, and live-standing trees. Accessibility is generally limited as per Forest Management Plans and AACs, with a notable exception for fire-kills which can be harvested anywhere. This type of biomass is preferably processed into cordwood, but it could eventually be processed into woodchips or pellets, or pyrolyzed.

Harvesting of merchantable standing trees is primarily performed by commercial operators. These can be generally classified in one of three scale-based categories (larger, mid-size, smaller), each with their own typical set of equipment and practices. It is important to note that these categories are general groupings and that some operators might fall outside of these or overlap more than one. Moreover, non-commercial operators also can harvest standing trees with a 'personal use license'; these non-commercial operators are unaccounted for in this study as they are unlikely to change significantly in the near future.

Larger Operations

Larger operations use conventional forestry equipment such as feller buncher, grapple and line skidder (possibly forwarder) that can bring full-length trees to a landing. De-limbing is performed mechanically on-site (where fallen) or at the landing. Full-length trees might be cut to log length (8') and are transported out of the woods using log trucks (both tandem and tri-drives) including self-loaders. Trailer configurations include tandem and triaxle pole trailers, 3 or 4 bundle b-trains and superbees, as well as a small number of hayrack trailers. Trees or logs can be distributed directly to users but are typically further processed at a processing yard situated closer to consumption centers, where they are bucked into bolts of fuelwood length (12"-24") and split. Fuelwood is subsequently distributed to users, typically by the cord (4'x4'x8'; 2.265m^3).

Mid-size Operations

Mid-sized operations hand-fell trees using a chainsaw and use small line skidders to haul full-length trees to a landing. Delimbing is hand-performed with a chainsaw on-site or at the landing. Trees are processed into logs or bolts at the landing. Fuelwood is hauled out of the woods with 1-5 tonne trucks and trailers, and sometimes brought to a processing yard where they are further processed (e.g. bucked into bolts and split), or distributed to users.

Smaller Operations

Smaller operations use hand-felling, and the trees are hauled to the landing using ATV skidding, winching, or by hand. Processing is also done at the landing using chainsaws, and hand bailing logs or bolts into a pick-up truck box or trailer that will deliver directly to the user.

Extraction of standing trees also sometimes involves land use changes and forestry practices such as the building and maintenance of roads to access the feedstock. Existing roads and landings may be considered 'paid for' by previous harvests and subsequent carbon sequestrations, but new ones need to be taken into account, as well as maintenance.

Fire-kill

Standing fire-killed trees currently exist throughout Yukon and can be harvested regardless of Forest Management Plans and AACs; there is no yearly restriction on the quantity that can be salvaged, merchantable or not. Burns exist and continue to be generated on a stochastic pattern throughout Yukon, with significant ones situated within a 250 km radius of Whitehorse at the moment. Some of it has already been removed or is no longer useful, and some of it currently is being used as part of reference pathways, but there is significant room for increase of usage.

Fire damaged dead trees do not remain standing indefinitely. The quality of a fire-killed stand generally increases for the first few years as a result of decreasing wood moisture content, after which it decreases as trees start decaying and falling to the ground (Figure A-1; Preto, 2011). Fallen trees generally are non-usable because decay is too advanced. The number of years fire-killed trees will remain usable as a biomass source for fuelwood depends on a variety of factors. For instance, firewood harvesting is still ongoing in areas such as the Fox Lake burn even though this area was burnt over 20 years ago. Removal of this biomass can accelerate regeneration and regrowth of the forest, with potential consequences on carbon intensity.

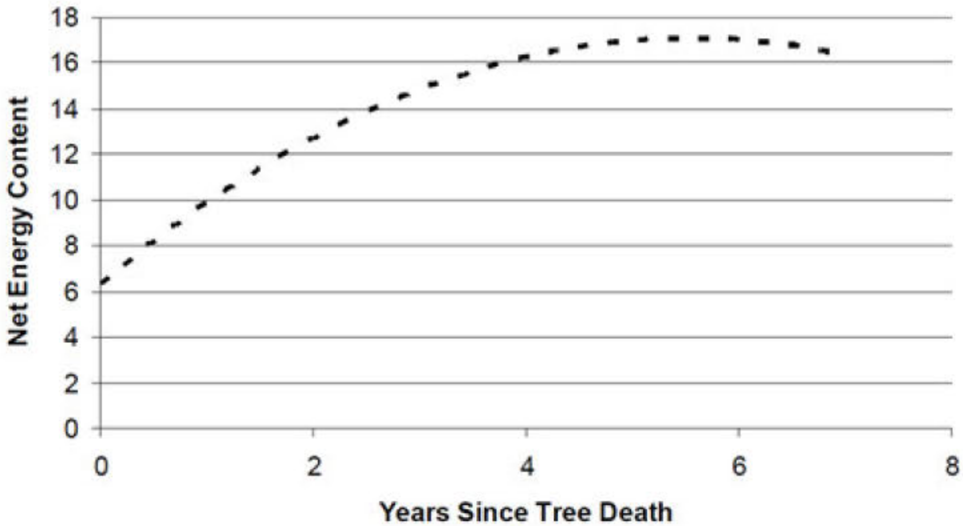


Figure A-1: Standing dead tree energy content (adapted from Preto, 2011).

Extraction of fire-killed trees is performed as described above for any standing trees (larger-smaller commercial operations). In burns where wood was generally mature at time of fire and depending on stand and age of the burn, typically all dead and merchantable trees can be removed in a clear-cut style. This typically has a smaller footprint than selective cutting and thus impacts the carbon intensity.

It is important to note that no curing/drying is generally required for fire-killed wood before usage.

Beetle-kill

Standing beetle-killed trees of merchantable size currently exist in Southwest Yukon (primarily in Haines Junction area) and can be harvested within the local Forest Management Plan. Some of it has already been removed or is no longer useful, and some of it currently is being used as part of reference pathways, but there is significant room for increase of usage.

Insect-damaged dead trees do not remain standing indefinitely. The quality of a beetle-killed stand generally increases for the first few years as a result of decreasing wood moisture content, after which it decreases as trees start decaying and falling to the ground (Figure A-1; Preto, 2011). Windthrows complicate harvesting and fallen trees generally are non-usable because decay is too advanced. The number of years beetle killed trees will remain usable as a biomass source for fuelwood depends on a variety of factors. For instance, firewood harvesting is still ongoing in the Haines Junction area some 30 years after the beginning of the beetle infestation. Removal of this biomass can accelerate regeneration and regrowth of the forest, with potential consequences on carbon intensity.

Extraction of beetle-killed trees is performed as described above for any standing trees (larger-smaller commercial operations). In stands where wood was generally mature at time of infestation and depending on stand and stage of the infestation, all dead and merchantable trees can be removed in a clear-cut style. This typically has a smaller footprint than selective cutting and thus impacts the carbon intensity.

It is important to note that no curing/drying is generally required for beetle-killed wood before usage.

Live-standing trees

Live-standing trees of merchantable size exist throughout Yukon's 8.1 million ha of forest land that can support harvesting activities, however access is strictly limited as per Forest Management Plans and AACs. Only those that are situated in regions for which forest plans have been approved are accessible, and quantities are limited. Considering the ample supply and relatively easier harvest of dead-standing trees (fire-kill and beetle-kill), harvest of live-standing trees is marginal in the Yukon.

The main target species for live-standing trees is spruce, with very minor harvesting of birch in Dawson City region, and some poplar. If not harvested, this biomass continuously grows, dies and decays and re-grows over cycles of approximately 300 years. Sustainable harvesting of this biomass can accelerate forest cycling with potential impact on the carbon intensity of the forest land cover.

Extraction of live-standing trees is performed as described above for any standing trees (larger-smaller commercial operations) —with a qualifier that green wood needs to be cured/dried for at least one year before usage. Most of the volume harvested currently is using selective harvest where there is a range of 40-60% basal area retention (this can increase harvest footprint versus clear cut with reserves).

In some cases, harvesting of live trees involves additional post-harvest sylviculture practices that may involve scarification and planting.

Non-merchantable standing trees

Any material that is ≤ 16 cm in diameter is considered 'non-merchantable'. Harvest of non-merchantable standing tree is generally prohibited or limited by restrictions in harvest prescription and level of harvest activity. Naturally, quantities generated would increase proportionally with the increase of harvest of merchantable standing trees.

In the case of dead-standing trees, this material is almost entirely left onsite to decay (90%). In the case of live-standing trees, this is split in half between being left onsite to decay and being left onsite to be part of the natural cycle (grow, age, wildfire or disease, die and decay). The rest is used for (unaccounted for) personal cordwood (10%).

Collection of biomass residues

Biomass residues are generated wherever merchantable standing trees are harvested or processed for fuelwood or for timber (sawlogs). Extraction and utilization of this biomass entirely falls outside the scope of AACs and Forest Management Plans, meaning **there is no restriction on the quantity that can be salvaged. Therefore, biomass residues have the** distinct advantage of not having upstream GHG emissions as it is considered a waste that results from activities for which GHG emissions are already accounted for.

Depending on accessibility, collection of this biomass would simply require picking it up and trucking it out. Depending on the size and quality, it could be processed into woodchips or pellets, or pyrolyzed.

Generated by harvest activities

Residual biomass generated by harvest activities includes limbs, tree tops, and off-cuts and is estimated to amount to 15% of the total biomass that was fallen in the first place (Tetra Tech, 2017). Approximately 10% of this biomass consists of needles, small branches, and deciduous trees therefore is not useful. Some of the material is disposed of using the lop and scatter method at place of felling and therefore is largely inaccessible. It can thus be estimated that 5% or the original volume could be salvageable from the landing/roadside. Considering that 13,000 tonnes / year cordwood currently is harvested, only 650 tonnes / year would be presently available as residual biomass generated by harvest activities. Naturally, this would increase proportionally with the increase of harvest of merchantable standing trees.

Most of what is generated at the place of felling is left onsite to decay (85%), releasing its entire carbon content over a period of approximately 10 – 25 years. Some of it is used for personal cordwood (15%). The material that is generated at the landing/roadside also typically is left to decay (70%), but some of it gets burnt, rapidly releasing its carbon content. Some of it also is used for personal cordwood (15%).

Generated by processing activities

Biomass residues are generated at sawlog processing facilities (sawmills) and fuelwood processing yards such as sawdust, bark trimmings, shavings, trim ends, scrap lumber, chipper fines, and hog fuel. The potential feedstock available from this reference pathway is unknown but is suspected to be generally insignificant (G. Dykshoorn, personal communications).

A majority of the residues that are generated at sawmills already are being used as part of the reference pathways as woodchips for energy (90%), while un-utilized material is typically stockpiled to be burned (5%) or left to decay

(5%). By contrast, very little residues generated at fuelwood processing yards is used as woodchips for energy (5%), while half of it is burned (50%), a significant proportion is stockpiled and left to decay (30%), and some of it is chipped and ultimately used as ingredient to compost (10%) or for trail maintenance (5%).

Collection of incidental biomass

Biomass that is generated in conjunction with activities other than the harvesting of merchantable standing trees is deemed incidental as it is generated regardless. These activities can generate large quantities of biomass and include what is generated by forest fuel reduction initiatives (liability biomass) and what is generated by conversion of land, and maintenance thereof, for instance land clearing for agriculture and residential subdivisions. Extraction and utilization of this biomass also entirely falls outside the scope of AACs and Forest Management Plans, meaning **there is no restriction on the quantity that can be salvaged. Therefore, incidental biomass also has the distinct advantage of not having u**pstream GHG emissions as it is considered a waste that results from activities for which GHG emissions are already accounted for. Depending on accessibility, collection of this biomass would simply require picking it up and trucking it out.

Generated by FireSmart forest fuel reduction initiatives

Forest fuel reduction initiatives are conducted to reduce wildfire hazard in and around populated areas of the Yukon and generate large quantities of incidental biomass. FireSmart initiatives are carried out within settlements and generally involve manual spacing/thinning of coniferous trees 3-4 meters apart, pruning limbs, and removing all spruce less than 4 meters tall. Landscape-level projects remove a much more significant proportion of the forest and are generally carried out on the outskirts of communities at higher risk.

Resulting roundwood > 12.5 cm in diameter is sometimes cut into 4-foot logs and made available for local residents to pick it up for personal usage (outside of reference pathways). Often these materials are not collected as greenwood is heavy and requires curing/drying. Most of the material is burned on site, as well as any remaining slash (smaller trees, limbs, branches, stumps, root balls). When air quality or fire hazard is an issue and there is a need to use or clean the space, the material sometimes gets chipped and left on site or carried to a waste facility.

This biomass typically is easily accessible as those activities are performed around populated areas. Depending on quality, this material could be processed into cordwood, chips or pellets, or pyrolyzed. For instance, the school in Tok Alaska is almost entirely heated with biomass sourced from FireSmart activities (Lowell et al., 2015).

Generated by conversion of land and maintenance thereof

"Landscape-level" forest fuel reduction initiatives (liability biomass)

Landscape-level projects remove a much higher proportion of the forest than FireSmart activities. They are generally carried out on the outskirts of communities at higher risk. Up to 100% of the stand volume is removed, with an objective to shift the forest from resinous (e.g. spruce, pine) to deciduous (e.g. poplar).

Quantities that are produced are unknown but are suspected to be significant. These are typically burned (30%) or left out to decay (30%), but some of it is salvaged as cordwood by smaller scale operators (20%) and for personal firewood (20%).

Generated by clearing of land for agricultural land or residential subdivisions

Clearing of land for conversion to agriculture and residential subdivisions is practiced throughout the Yukon and especially around densely populated areas.

Over and above biomass that is sometimes partly salvaged by local residents for personal usage (5%, outside of reference pathways), clearing of land generates large quantities of slash that gets pushed into slash piles. In agricultural fields, these can take up 20-30% of the cleared space and they are typically (85%) or left to decay (10%). In residential subdivisions, some of the biomass is similarly salvaged by local residents for personal usage (5%, outside of the reference pathways), but a majority is burned (60%) and when air quality or fire hazard is an issue and there is a need to use or clean the space, the material sometimes gets chipped and carried away to ultimately be used for trail maintenance (10%), as ingredient for compost (15%), or burned in an air curtain burner at a waste management facility (10%).

This biomass typically is easily accessible due to its proximity to land being developed. However, the material is of varying sizes (e.g. stumps, root balls, full length trees and debris) and its character also varies, with some pieces being green, others fully dry or coming from old growth, yet others in different states of decomposition or damp from rain or snow. Most importantly, this biomass is characterized by contamination from rocks and soil: only a fraction would likely be usable for cordwood, woodchips or pellets.

Generated by the development and maintenance of infrastructure

The development, improvement, expansion and maintenance of infrastructure results in the generation of large quantities of biomass throughout the Yukon. These include 1) roads, trails, powerlines and other rights of way, as well as 2) deposits for aggregates (sand, gravel, rocks), and 3) mining developments.

Some of this biomass is made available for salvaging for personal usage (5%, 10% and 15%, respectively), but this biomass typically gets burned (40%, 75% and 75%, respectively) or shredded/chipped and left on site to decay (5%, 15% and 10%, respectively).

Depending on distance from populated areas, this biomass could be considered accessible. For instance, road building activities are happening throughout the Territory that are in very remote areas. Depending on quality, this biomass could be salvaged for cordwood, woodchips or pellets, or pyrolyzed.

Collection of wood waste (recyclable biomass)

Waste management facilities exist throughout the Yukon that receive waste wood such as construction / demolition waste, used pallets and Christmas trees, as well as cardboard. Similar to residual and incidental biomass, extraction and utilization of recyclable biomass entirely falls outside the scope of AACs, and its salvage implies no upstream GHG emissions.

Management of recyclable wood typically involves stacking it and periodically burning it in an air-curtain burner (75%). Some of it already is salvaged for biomass energy (5%), for instance pallets at Raven Recycling which are grinded and used as feedstock in a Hargassner boiler (G. Dykshoorn, personal communications). Some of it also is chipped to be ultimately used for trail maintenance (10%) or as an ingredient to compost (10%). Cardboard typically gets shipped out of the Yukon for recycling (100%), with a resultant impact on carbon intensity.

This biomass is very easily accessible as the waste facilities are situated close to populated areas. Depending on quality, it could be salvaged for chips or pellets or it could easily be pyrolyzed. With little change in how the waste is handled, air-curtain burners could be utilized that can recover the heat and perhaps transform it into electricity and generate biochar as a marketable by-product. Also, conversion of cardboard to pellets is a technology that is showing potential as a viable biomass feedstock (Pruys, S., 2021).

Biomass Processing

In the Yukon, woody biomass can be converted to a variety of types of fuels, including cordwood, wood chips, and pellets.

Cordwood

Currently cordwood is primarily processed from merchantable standing trees, almost exclusively from fire-kill and beetle-kill trees and rarely from live-standing trees. These feedstocks can be harvested at smaller to larger scale. Additionally, land conversion and maintenance for agricultural land and residential subdivisions, as well as development and maintenance of infrastructure (e.g. roads, deposits, mining) can be large sources of cordwood.

Cordwood processing can be accomplished by splitting merchantable trees after bucking (12”-24”) the felled, delimbed and cut (4’-8’) trees, previously harvested using smaller to larger scale methods. The splitting is done using large or small, either diesel or gasoline powered, splitting machines, usually located at processing yard for larger and mid scale harvesting, while splitting for smaller scale harvesting operations more often occurs in the forest, at felling or landing sites using similar machinery. Cordwood production from feedstock other than merchantable wood takes place at harvesting site, at either medium, smaller, or personal use scale, again using similar splitting machines as in yards.

After splitting the cordwood is distributed to consumers by trucks of various sizes; larger scale operations may use diesel powered truck with trailer, hauling 2-3 tons (3-5 cords) per load, while mid and smaller scale operators often use truck with or without trailer carrying 1-ton (1-2 cord) per load, with diesel or gasoline fuel use depend on distance to consumer.

Wood chips

Woodchips can be processed from a variety of feedstocks; however, feasibility is often dependent on transportation distances from feedstock source to market, and location of chipping. Sources of feedstock are broadly same as for cordwood, however woodchip generation at yard is economically limited by distance of less than 250 km from harvesting location to consumer market. Typical moisture content of woodchips is 20-30%

Chipping at yard using merchantable wood is done by a stationary chipper, following debarking, both using electricity, and air drying of live-standing trees. Onsite chipping is done in the field, at roadside, or landing, by a larger, diesel-powered mobile chipper. While cordwood can be chipped directly at those locations, other biomass needs detangling in the forest with two-stroke gasoline mix powered chainsaw, is picked up by diesel powered skidsteer to be loaded onto diesel or gasoline powered truck with 1-ton (1-2 cord) capacity hauling biomass to landing, where chipping takes place.

Pelletization

Pelletization requires drying of the woody biomass. This can be quite energy intensive if the biomass has a high moisture content such as greenwood in climates that are not arid, which has an average moisture content of 45%. Conversely, beetle-killed or fire-killed biomass typically has a lower moisture content. Plants typically have to use electricity for drying and pelletizing the biomass, but it is unclear if this would be necessary in the Yukon. Pellets are typically 5% moisture content. The mass input of woody biomass to produce 1 oven dry tonne (ODT) output of pellets depends on the moisture content, which needs to be considered for each type of biomass being pelletized and considering the local climate. Yukon currently has no commercial-scale pelletization capacity. Experiments have been conducted by Bear Creek Logging in Haines Junction. The main constraint seems to be lack of supply certainty.

Fuel Conversion: Pyrolysis

Pyrolsysis is a thermochemical type of biomass conversion technology, which also includes gasification and torrefaction (Preto, 2011). It consists of "cooking" biomass at relatively high temperature in an oxygen-limited environment. Small scale, mobile pyrolysis units have been developed in Canada and remain a promising future option for forestry applications. In the Yukon context, Duteau (2019) established that pyrolysis could be a valuable option, especially for 'dirtier' incidental feedstocks such as slash generated by land clearing.

Fast pyrolysis can be seen as way of densifying biomass to facilitate economical transportation of bioenergy. Fast pyrolysis produces 1) bio-oil (on the order of 65% by mass), 2) syngas (usually used to keep the pyrolyzer running), and 3) biochar. The bio-oil can be combusted in furnaces, boilers, and cogeneration plants. The biochar can also be combusted, but often it is applied to agricultural land as a soil amendment to sequester carbon and provide soil health benefits that improve productivity of crops. It could also perhaps be applied to forest land, which might provide benefits for regeneration.

Biomass Combustion

Several types of technology are used for the combustion of biomass for energy in the Yukon:

Cordwood: wood stoves, outdoor wood furnaces[6], cogeneration plants

Pellets and Wood Chips: biomass heating plants and boilers, cogeneration plants

Bio-oil from pyrolysis: oil furnaces, cogeneration plants

Currently neither pyrolysis nor cogeneration plants exist in the Yukon but have been included in this analysis as scenarios of potential future technologies. Combustion of biomass fuels is currently done on various scales, using different technologies based on fuel type and form. Efficiency of those technologies used varies greatly with technology age and design (Table A-1).

6 Outdoor wood furnaces are typically connected to heat demand via underground piping using glycol as energy carrier and can typically accommodate larger bolts (up to 4') and have longer down-time periods..

Table A-1: Details on the types of combustion technology used for different forms of biomass feedstock.

Biomass Type	Combustion Technology	Scale / type of user	Qualifier	Efficiency (%)
Cordwood	Fireplace	Residential	Older	≤ 10%
			Modern	
	closed, indoor woodstove/wood furnace		Older	30-40%
			Modern (forced-air, non-catalytic)	65-75%
			Modern (forced air, catalytic)	70-80%
	outdoor wood furnace		Modern	50-60%
		Commercial / Institutional / Industrial	Modern	50-60%
Wood chips	Boiler	Commercial / Institutional / Industrial	Older	
			Modern	
	Cogeneration plant		Modern	
Wood Pellets	Pellet stove	Residential	Older	
			Modern	80%
	Pellet boiler	Commercial / Institutional / Industrial	Older	70%
			Modern	>70%
	Cogeneration plant		Modern	
	Oil furnace	Residential	Modern	
	Oil boiler	Commercial / Institutional / Industrial	Modern	
	Oil cogeneration plant		Modern	

APPENDIX B:
Forest Carbon Accounting and Modeling

FOREST CARBON POOLS

Forest ecosystems store a significant amount of carbon in the living biomass of the vegetation (aboveground and belowground), debris (litter), and soil. The main pools of carbon in forest ecosystems and the primary carbon flux pathways are shown in Figure B-1.

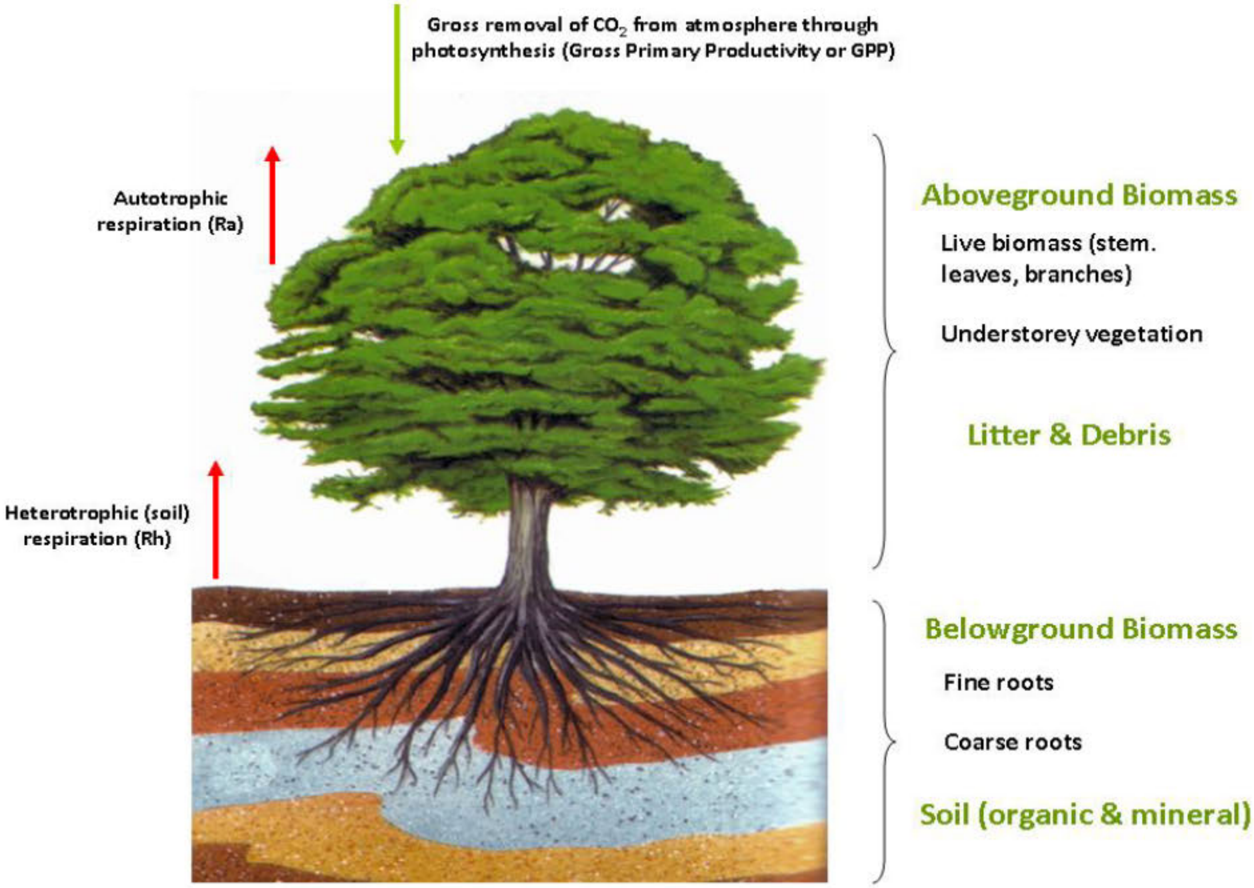
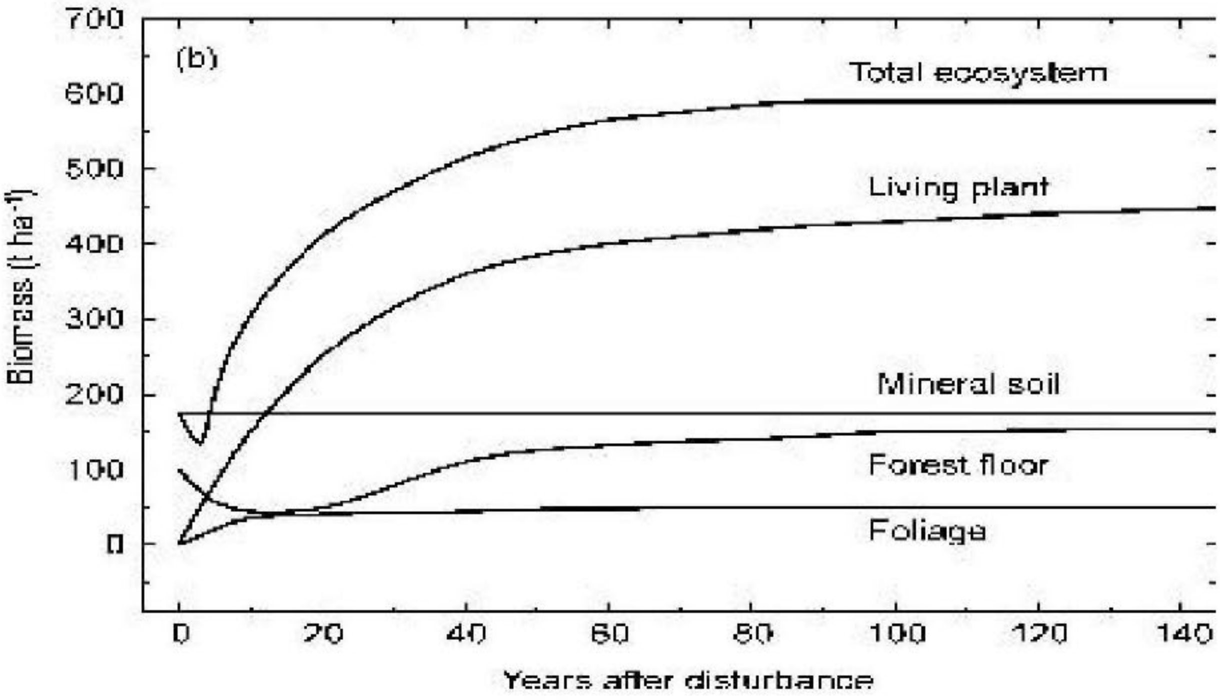


Figure B-1: Forest carbon cycle, with the main carbon pools labeled in green. Primary carbon pathways are indicated with arrows. Net carbon gains through photosynthesis are shown as a green arrow; net carbon losses from respiration are shown as red arrows

The overall amount and rate of accumulation of carbon in a forest ecosystem is driven by the processes of photosynthesis and respiration. Photosynthesis is the process within plants that converts atmospheric carbon dioxide into carbohydrate food compounds using energy from the sun. Respiration is essentially the opposite of photosynthesis, whereby the carbohydrate compounds are converted to energy, releasing carbon dioxide in the process.

One of the key factors influencing the rate of accumulation of carbon in a forest ecosystem is tree age (Figure B-2). Carbon accumulation increases rapidly in the first few decades after forest establishment and reaches a plateau at the intermediate life stage. A large amount of variability exists between different tree species in the rate of increase / decrease of carbon accumulation and the age at which the plateau is reached. The partitioning of carbon within forest components is also dependent on stand age (Figure B-2). Immediately following forest establishment, the soil and litter components contain the majority of the forest carbon. However, after the first few years the living vegetation has become the primary carbon sink. In mature forests the vegetation component contains over 50% of the total carbon (Colombo et al. 2005). Other key factors influencing carbon accumulation include climate and the frequency and severity of disturbance events.

Figure B-2: Allocation of carbon amongst major forest components over the lifetime of a typical tree. Graphic courtesy of Columbo et al. (2005).



FOREST CARBON ACCOUNTING

Existing Best Practices in Forest Carbon Accounting (National Level GHG Reporting)

Central to accurate LCA modelling of emissions from forest products, including biomass fuel pathways, is how to account for biogenic carbon emissions. Biogenic emissions arise from the natural carbon cycle (Figure B-3), as well as products from biomass sourced from the agriculture and forestry sectors (Figure B-4). This can include biological decomposition of forest, agricultural and municipal wastes, and combustion of biologically derived fuels. Carbon accounting for forests is challenging due to the complexity of the ecosystems and the long temporal cycles between harvest or decay and the regrowth of new biomass stands. It is essential that all spatially relevant biogenic carbon pools such as sinks (sequestration), reservoirs (e.g. stocks, harvested wood products), and sources (emissions) be included in estimates of carbon intensity of forest biomass pathways.

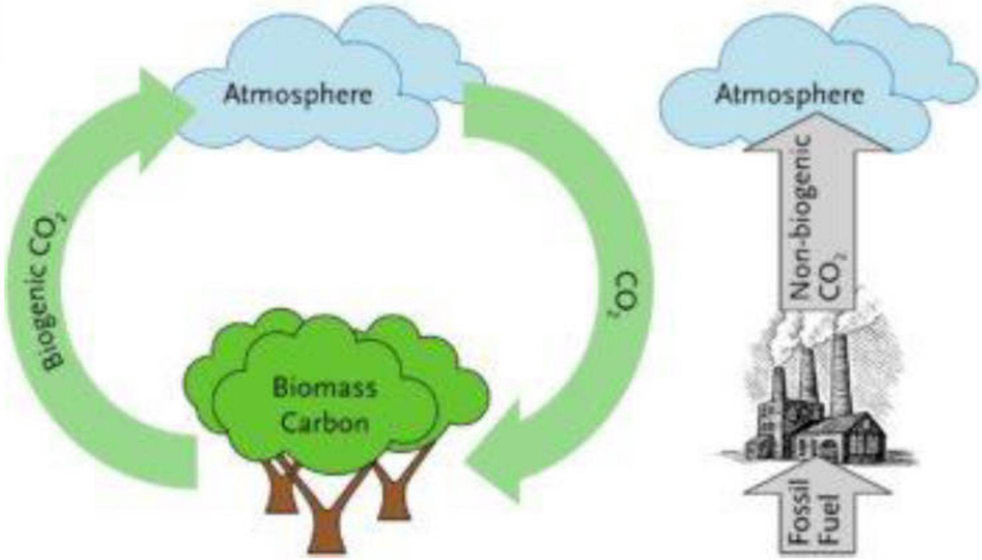


Figure B-3: Biogenic vs. fossil fuel non-biogenic CO_2 emissions (IEA Bioenergy, 2018).

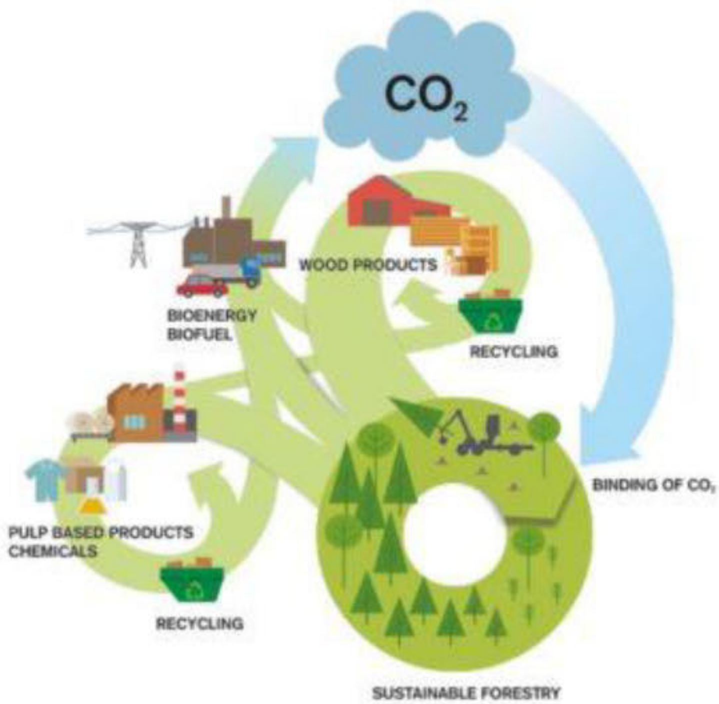


Figure B-4: Forest bioenergy supply chain and biogenic emissions cycle (IEA Bioenergy, 2018).

Arguably the most comprehensive and important GHG emission inventory and reporting protocol worldwide is the Intergovernmental Panel on Climate Change (IPCC) *Guidelines for National Greenhouse Gas Inventories*. The IPCC methodologies are used by countries around the world (including Canada) to monitor and report national-level commitments to United Nations Framework Convention on Climate Change (UNFCCC) accords on climate change. Canada's reporting is submitted annually as the National Inventory Report compiled by Environment and Climate Change Canada for all sectors of the economy and natural processes. Forest GHG inventories are compiled under the Land Use, Land Use Change, and Forestry (LULUCF) sector of the UNFCCC, which includes "anthropogenic GHG fluxes between the atmosphere and Canada's managed lands, including those associated with land-use change and emissions from Harvested Wood Products, which are closely linked to Forest Land" (UNFCCC, 2021a, 2021b).

As per the IPCC forest accounting methodology which has been adopted by Canada, all biomass that is harvested is primarily released to the atmosphere as biogenic CO_2, with lesser amounts of methane and nitrous oxide also being released (Figure B-5). This applies to small-volume instances of harvesting for residential firewood consumption as well as larger-volume instances of harvesting for commercial applications (e.g. bioenergy wood pellets, pulp and paper, lumber). The timing of the release of the stored biomass carbon to the atmosphere varies based on the use of the biomass. For example, biomass that is harvested for bioenergy feedstock has a carbon release timeframe that is often within a few years of the harvest time, while biomass harvested for building lumber can be stored for several decades before its eventual release to the atmosphere.

With regard to the quantification and reporting of GHG emissions from combustion of biomass energy sources, it is very important to note the differences in how carbon dioxide, methane, and nitrous oxide emissions are treated (Table B-1). As per the IPCC methodology, CO_2 emissions from biomass energy is reported at the point of harvesting within the 'LULUCF' reporting section. Note that the combustion of biomass energy sources is actually reported as zero CO_2 emissions in the 'Energy' reporting section of national GHG inventories. The assignment of zero CO_2 emissions for biomass energy combustion in the 'Energy' reporting section avoids double-counting of the emissions that are already accounted for at the point of harvest. In LCA studies of forestry biomass for energy, this has incorrectly been interpreted as not having to include LULUCF in the boundaries of the study, likely because the LCA practitioners see bioenergy as being in the bioenergy sector. However, in LCA, all sources should be included, but should only be counted once, either at the biomass harvesting stage, or at the combustion stage.

Table B-1: Treatment of GHG emissions arising from combustion of biomass energy.

	CO_2	CH_4	N_2O
Categorization	Biogenic	Non-biogenic	Non-biogenic
Quantification Point	Harvesting	Combustion	Combustion
IPCC/NIR Reporting Sector	LULUCF	Energy	Energy

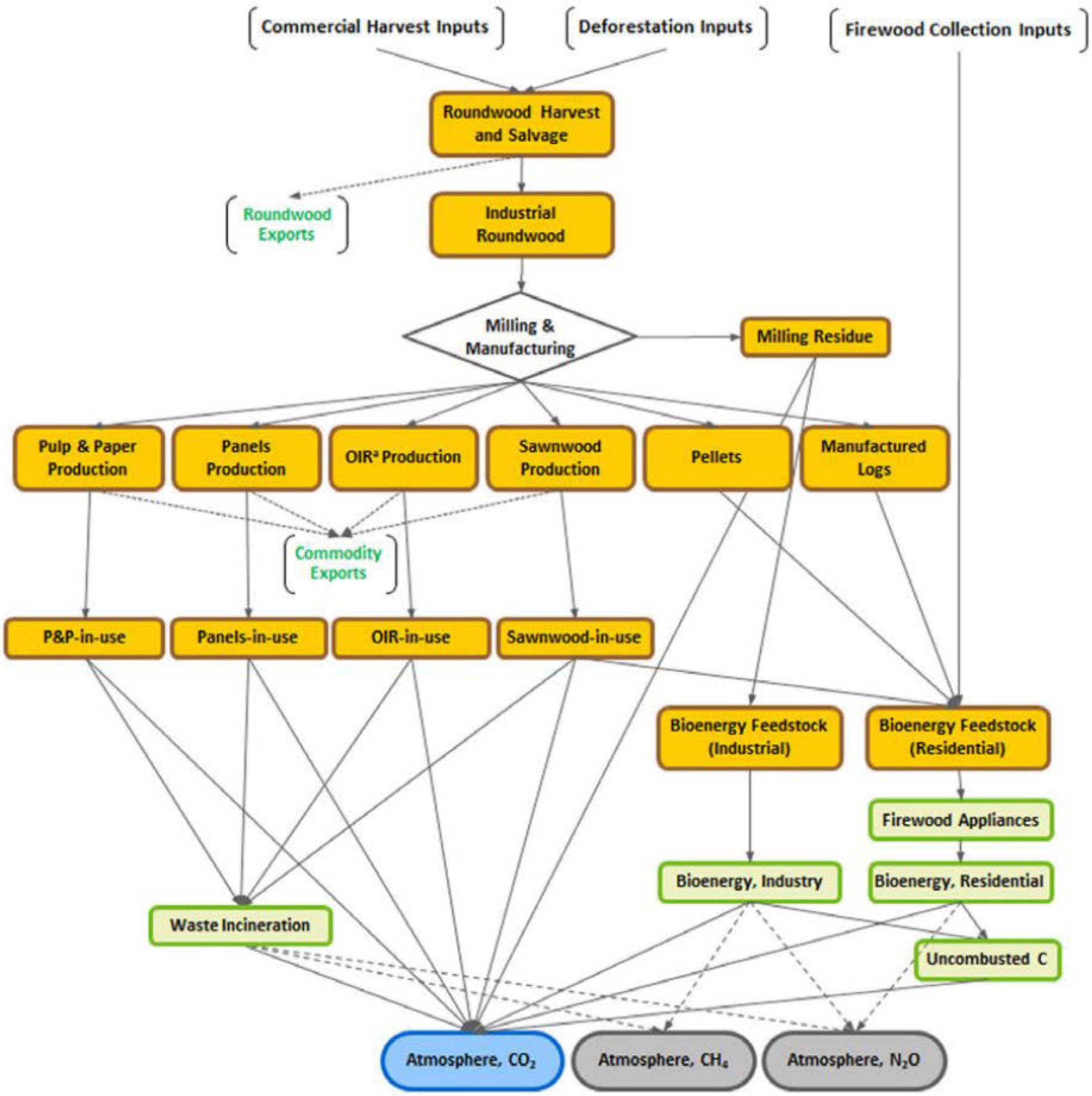


Figure B-5: Carbon flow in harvested wood products (UNFCCC, 2021b).

Canadian low carbon fuel standards use in regulating and reducing carbon intensity of heating fuels

To facilitate decarbonization of energy use, low carbon fuel standards (LCFS) have become a common jurisdictional tool that quantify carbon intensity (CI), of fuel pathways, and often impose limits and/or CI reduction requirements on fossil fuels. In conjunction with carbon offset creation and trading, LCFSs can facilitate investment and development in clean technology, and effectively lead to decrease in the important emission sectors, transportation, building heating and cooling, and industry.

The Canadian federal government has developed the Clean Fuel Standard (CFS) (ECCC, 2017) that will utilize the in-house developed Fuel Life Cycle Assessment Tool to calculate CI (as CO_2e/MJ energy) for liquid, gas, and solid fuels, produced or imported to Canada (ECCC, 2019). An average CI will be applied to both Canadian-made and imported liquid, natural gas-derived and solid (e.g., coal) fuels, with requirement for liquid fuels to reduce CI by approximately 11% by 2030, compared to 2016 values. The CI values will include all production, distribution and combustion process-related emissions, along with direct land change impacts. Biomass-derived fuels will not be assigned an average CI; however, biofuel suppliers have the opportunity to generate credits if their fuels have lower CI than a reference fossil fuel replaced by a biomass fuel type. Further, an end user of a fuel, as well as a fossil fuel supplier, will also be eligible to a credit by fuel switching from a fossil fuel to a lower CI biomass fuel. The credits will be marketable on a trading system platform between participants in the LCFS system.

Other LCFS in Canada include British Columbia's low carbon fuel standard (BC-LCFS) that predates and is designed similarly to the federal CFS, and applies to liquid and gaseous fuels (B.C. Ministry of Energy, n.d.). Calculation of CI under BC-LCFS is required to be done with the Canadian transport fuel model GHGenius, that has the same boundaries as the federal model ((S&T) Squared Consultants, 2021).

Alberta has its own LCFS, the Renewable Fuels Standard (RFS) that assigns reference CI to liquid fuel, has a renewable fuel volumetric mandate, and demands 25% lower CI for a renewable fuel compared to its reference fossil fuel pathway CI, to qualify as a fuel pathway. The Alberta RFS uses GHGenius as the official tool for estimation of biomass fuel CI, and publishes a lookup table for 'established pathways' as a reference (Alberta Government, 2021).

As the federal Clean Fuel Standard includes biomass fuel pathways and will report CI for both average and regional biomass pathways, the intensity, as well as methodology used for the standard, will become important reference points for jurisdictions within Canada. The additional features such as credit creation and carbon offset trading will further affect fuel production and use in Canada. As both Alberta and British Columbia supply heating fuels to Yukon, both fossil and biomass energy, the regulatory mechanisms and modeling methodology should be of interest to the Yukon government.

Evolving Science-Based Approaches to Forest Carbon Accounting

Although the IPCC methodology used for emission estimates and changes in terrestrial carbon stocks is widely recognized and internationally used, there remain issues with current use of forest biomass and associated biogenic emissions, identified by climate scientists, forest biologists and other related fields. Those concerns recently generated an open letter, from more than 500 prominent scientists and economists, to political leaders of the European Union, USA, Japan, and Korea (WWF, 2021). The letter warns against current plans to increase use of forest biomass fuel to battle climate change without increased efforts to ensure sustainable harvest practices, where biomass fuel production practices may cause up to 2-3 times more carbon emissions than fossil fuel use does.

Increasingly, the temporal issue of forest regrowth (known as the 'carbon debt') has become central due to the long interval between logging or harvesting of forest biomass and subsequent combustion of forest biomass fuels (source), and regrowth of the forest carbon stock with sequestration of atmospheric carbon (sink, reservoir). The time scale can be from a few years for fast growing coppice feedstock to decades or centuries for a forest stand. This issue is also related to human induced or anthropogenic land use change, which in turn affects net terrestrial carbon emissions, as land use changes due to forest harvest infrastructure, such as access roads and harvest landings, can have significant effects on forest carbon pools.

The assumption that biogenic carbon emissions are carbon neutral arises from the fact that the feedstocks come from terrestrial biomass that will regrow and re-sequester the carbon, presumably without net impacts on climate change, therefore having a global warning potential (GWP) of zero (Holtsmark, 2015). Further, the methodological choice to count biogenic CO_2 emissions under LULUCFC in the IPCC accounting scheme, and not as energy sector emissions has resulted in the frequent practice of not counting biogenic carbon emissions in life cycle studies, as it is assumed that this is double-counting. This practice in bioenergy LCA studies ignores the IPCC methodology for carbon accounting and both the immediate effect on forest carbon stocks from harvest, as well as the timescale between carbon emissions release from biomass fuel combustion to carbon sequestration in the forest biomass (the carbon debt).

It is important to point out the difference between carbon neutrality and climate neutrality. For instance, after 50 years of regrowth a harvested forest may have gained carbon neutrality by sequestering the same mass of carbon as initially harvested, while the effect of released carbon from harvested biomass, e.g. through combustion may still linger and climate neutrality is not yet accomplished. The effect on carbon balance in forestry depends largely on timeframe of harvest and regrowth where short rotation biomass can be considered close to climate neutral while a slow growth forest is not due to the climate impact from released CO_2 during regrowth (Baral, 2014). This issue is further complicated by the fact that the baseline for estimating carbon emissions is what would happen in the forest without harvest, the 'no use' case. This is conceptually demonstrated in Figure B-6, where the carbon removed at harvest is repaid relatively early ('C debt repayment') compared to the 'C offset parity point', when carbon that would have been sequestered in the absence of the initial harvest operation has been 'repaid'.

For these reasons, the assumption of treating biogenic carbon emissions as climate neutral is increasingly under scrutiny. The 'Biogenic GWP' method (GWP_{bio}) was developed by Cherubini et al. (2011) for use in LCA modeling studies of bioenergy, and takes into account the net potential warming impact of biogenic CO_2 at combustion relative to fossil CO_2 GWP of one. It has been estimated that biomass CO_2 from a system with 100-year rotation time has 43% of the GWP of fossil CO_2, hence having a GWP_{bio} of 0.43 (Baral, 2014). The GWP_{bio} thereby accounts for the temporal factor of biomass regrowth as well as atmospheric GHG decay (Holtsmark, 2015). If fossil fuel CO_2 emissions are assigned a GWP value of 1, as in the IPCC methodology, GWP_{bio} have been estimated at a range of 0.00-0.96, depending on modelling parameters (Cherubini et al., 2011; Guest et al., 2013; Holtsmark, 2015), instead of zero as is commonly done in estimations of GWP of biogenic CO_2. LCA modeling using GWP_{bio} indexes has shown increased GHG emissions from some biomass fuel pathways due to the biogenic emissions, with biomass pellets showing relatively good performance; however ethanol and bio power may show higher emissions than fossil source diesel (e.g. Liu et al., 2017). The modeling required to include LULUCF is often out of the scope and expertise of LCA practitioners, and therefore the GWP_{bio} approach is an approximation.

Based on ongoing developments in research and model development on biogenic emissions, it is likely that increased pressure will build in the near future to address forest management in a more holistic way, including state-of-the art carbon accounting methods, as well as other issues that affect forest ecosystem health and productivity. This, along with increased awareness evident in the open letter discussed earlier, will likely lead to policy changes that will affect forest management and fuels made from forest biomass.

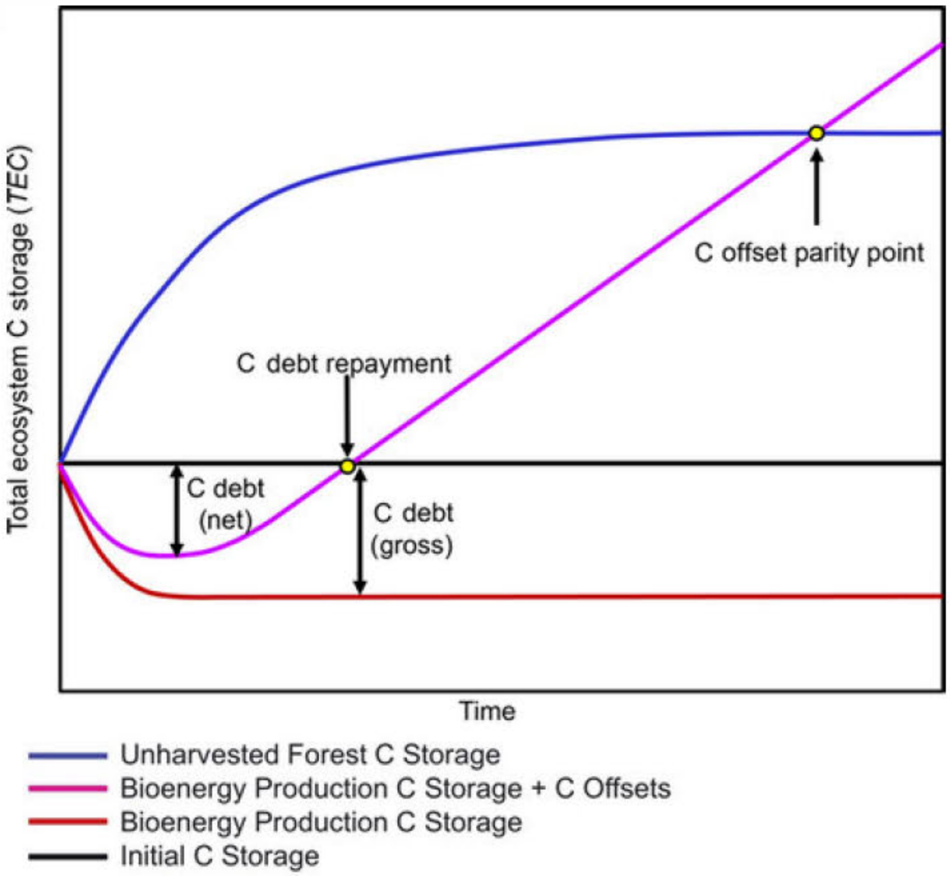


Figure B-6: Conceptual look at carbon debt vs. carbon sequestration of forest biomass (Mitchell et al., 2012)

Biomass Energy Carbon Accounting Protocols Relevant to Yukon

While it is recognized that the approaches for quantifying GHG emissions from biomass energy sources are evolving, it is also recognized that due to Canada's commitment to UNFCCC climate accords, and the role of the Government of Canada (e.g., ECCC) in regulating and monitoring emissions, the protocols used by the Canadian government to report emissions are used in this project. Specifically, the National Inventory Report used the IPCC methodology for GHG emission accounting, which includes emissions from the LULUCF, transportation, and energy sector, all of which come together in the life cycle of bioenergy. Additionally, of the biomass carbon energy accounting or reporting protocols reviewed for this analysis, the potential relevancy of each approach to the Yukon is described in Table B-2.

Table B-2 Carbon accounting and reporting protocols relevant to YT biomass LCA pathway development

Accounting protocol	Emission quantification role	Applicability to YT biomass LCA project
UNFCCC (IPCC)	Reporting framework for Canada's NIR (UNFCCC, 2021b)	Methodology used for emission estimates for Canadian forests largely based on IPCC methodology (IPCC, 2021)
ECCC	Manages Canadian emission estimates and regulatory management, including CFS and NIR	Provides details on NIR methodology, which for forests is a mix of IPCC 2006 methodology (IPCC, 2021), and Canadian (Tier 2-3) methodology
CFS	Canada's Clean Fuel Standard (CFS) will regulate and reduce carbon intensity (CI) of fuels used in Canada (ECCC, 2019)	Fuel Life Cycle Assessment Modelling Tool determines carbon intensity of fuels used in Canada (ECCC, 2017) CFS becomes a fossil and renewable fuel CI benchmark by 2022, with CI reduction requirements for fossil fuels. CFS will include a carbon credit market
BC LCFS	Regulation for CI of fuels produced and used in British Columbia (B.C. Ministry of Energy, n.d.) Uses GHGenius for CI estimates: 'is LCA compliant with ISO 14040/44' Covers liquid and gas fuel types, and electricity	Neighboring jurisdiction to YT, a fuel trading partner, BC produces heating fuels currently used in YT BC also offers Forest Carbon Emission Offsets for forestry management (Ministry of Forests, n.d.) Direct land use change included
AB RFS	Regulates CI of fuels (gasoline and diesel) supplied in Alberta Uses GHGenius (AB version) for CI	Neighboring jurisdiction to YT, a fuel trading partner, AB produces heating fuels currently used in YT
EU LULUCF	Proposed land use and forestry regulation for 2021-2030 (European Commission, 2016)	Europe is a major importer of biomass fuels from Canada, EU fuel emission policy will impact Canadian biofuels.
CARB	Regulatory tool and default methodology for California Government Includes LCFS standard	The Western Climate Initiative (WCI) (WCI, Inc., n.d.) is an umbrella organization for emission trading from California, Quebec, and Nova Scotia

CBM-CFS3 MODELING RESULTS

A description of the CBM-CFS3 model is provided in Section 3.2.3 of this report.

Modeling of Base Carbon Yields

Base carbon yields were generated using CBM-CFS3 for the feedstock type, pathway (i.e., bioenergy or reference), and stratum combinations requiring different disturbance/management assumptions in the LCI that have a forest land base in both bioenergy and reference pathways (i.e., not biomass from land-clearing activities). The living biomass carbon yields are shown in Figure B-7, the dead organic matter excluding soils yields are shown in Figure B-8, and the dead organic matter in soils yields are shown in Figure B-9.

The base carbon yields for stands that were harvested were constructed assuming 100% removal (i.e., clear-cut) with no recovery of harvest residues. The establishment of new cohorts and continued growth of existing cohorts at the time of harvest were then scaled based on the harvest retention level for a given feedstock. Partial harvests of living, merchantable trees (i.e., 20% retention), FireSmart initiatives (i.e., thinning with a 35% removal), or the collection of residues from harvest operations involved changes to the living biomass and dead organic matter pools. These procedures were done during the 100-yr biomass harvest scenarios for each feedstock with the aforementioned base carbon yields and did not involve the generation of separate base yields.

Importantly, these results do not account for the effects of climate change. These will likely include more frequent and severe wildfires and insect outbreaks, affecting direct emissions from forests but also feedstock supply from salvage harvests. Moreover, climate change may affect forest productivity and forest decomposition rates, with both increases in productivity and decomposition rates due to warming and decreases in productivity due to drought. Future research on forest-based bioenergy production should addresses these issues. In particular, the effect increased decomposition rates may reduce the overall emissions associated with biomass energy, particularly from salvaged and residue feedstocks.

4.4.1 Modeling of Bioenergy and Reference Pathways

Using CBM-CFS3, 100-yr simulations were conducted for each feedstock for the bioenergy and reference pathways. Figure B-10 shows the cumulative emissions and removals of CO_2 to/from the atmosphere from the entire modeled land base for merchantable standing trees. Figure B-11 shows the cumulative emissions and removals of CO_2 to/from the atmosphere from the entire modeled land base for scenarios using biomass residues generated from land clearing and FireSmart activities.

This analysis was focused on the primary defined objective of assessing the impact of a biomass energy industry on the near-term and long-term carbon budget of YT's LULUCF emissions sector. It examined the carbon footprint of each biomass feedstock at different harvest levels in the study area exclusively, not the available supply of biomass for energy production in the entire YT. Thus, the CO_2 emissions and removals for the increased levels of thermal energy demand in YT assume that each feedstock or mix of feedstocks is available. Importantly, while this analysis provides some preliminary estimates on the supply of different biomass feedstocks under the defined modelling, inventory, and growth and yield constraints, the available biomass harvest in YT under higher energy-demand scenarios should include more a more detailed timber/biomass supply analysis.

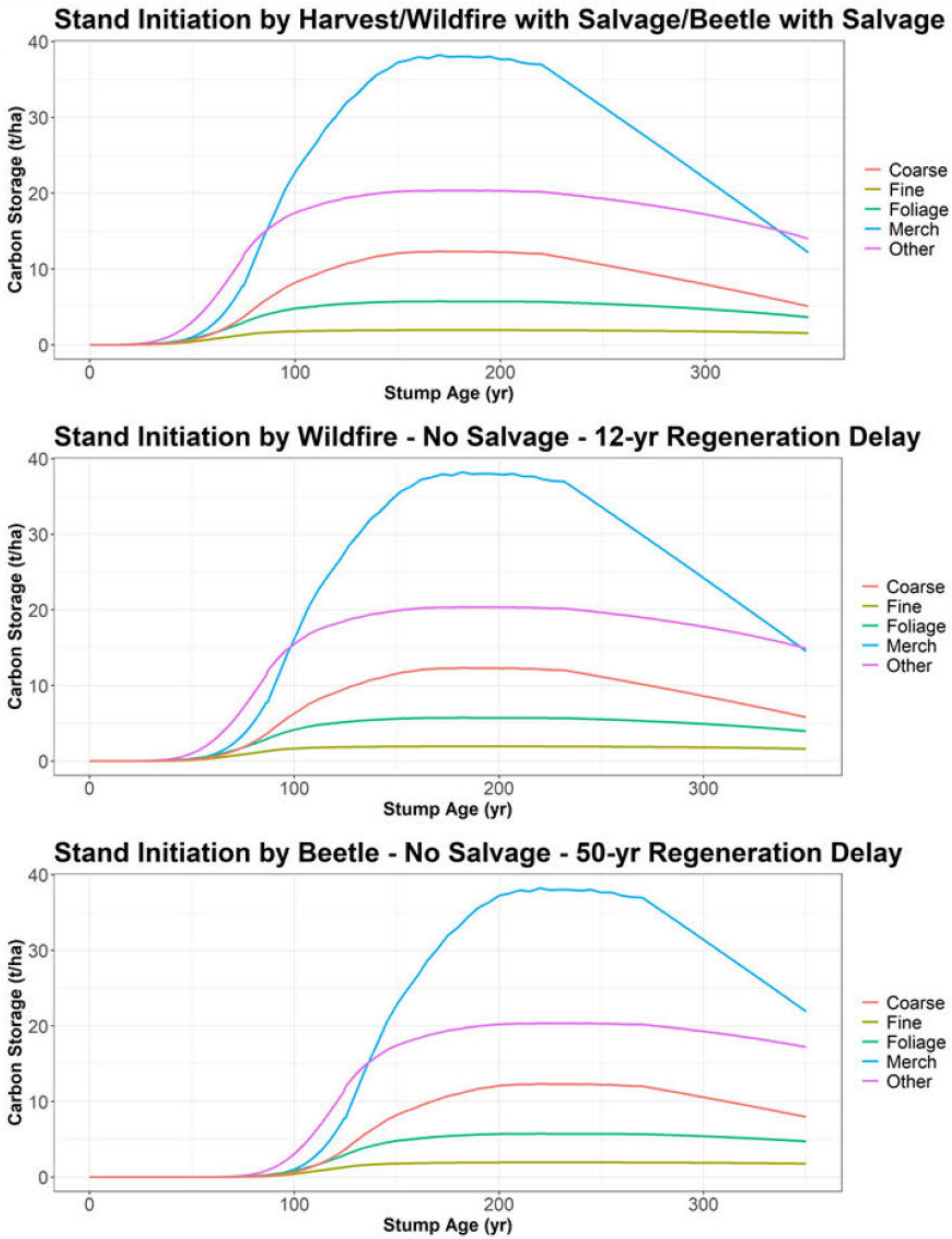


Figure B-7: Carbon storage in living forest biomass for different biomass feedstocks under different management / disturbance scenarios. Coarse roots (Coarse); Fine roots (Fine); Foliage (Foliage); Merchantable wood with bark (Merch); Non-merchantable wood with bark, including branches, tops, stumps, and small unmerchantable trees (Other).

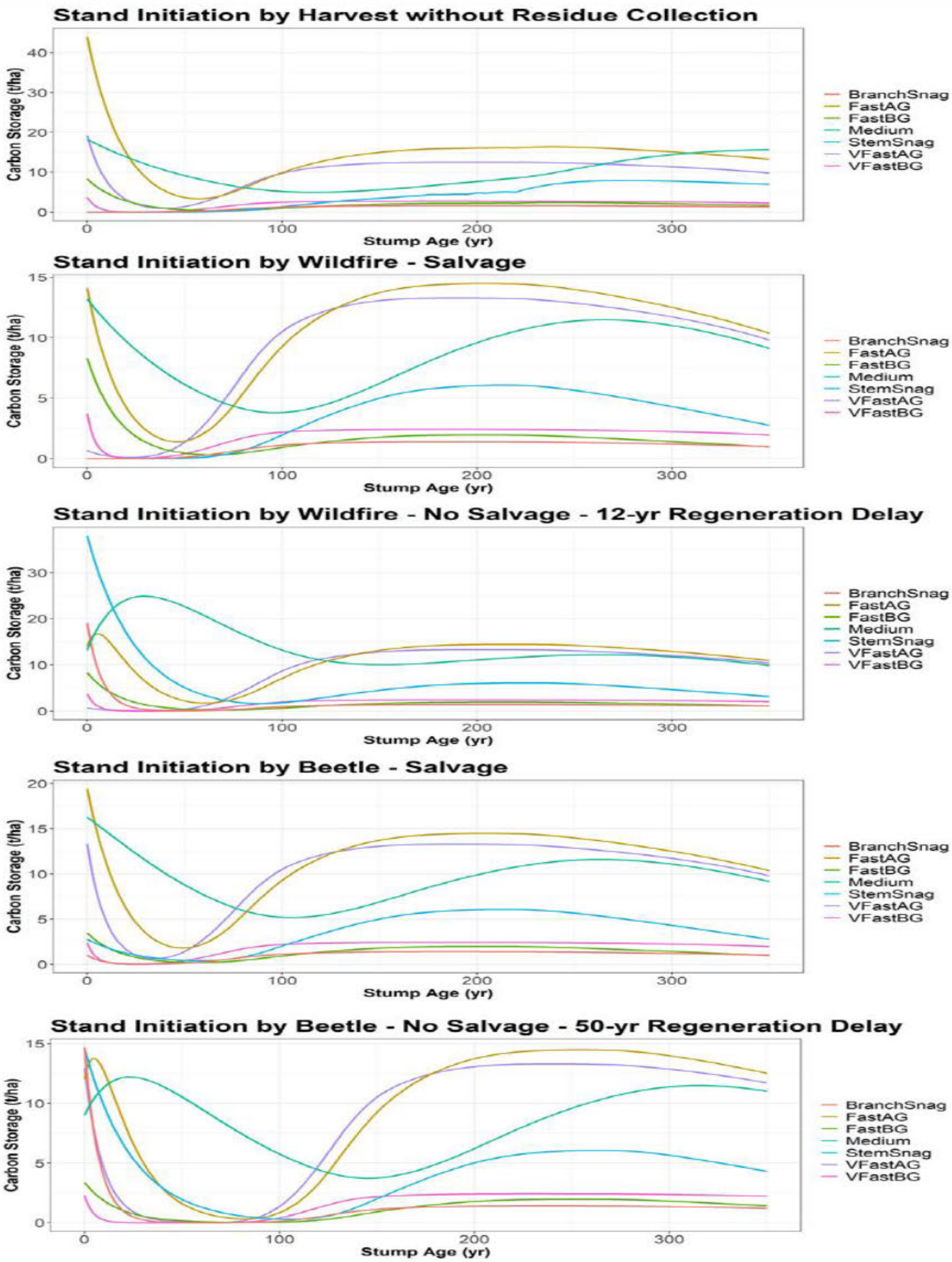


Figure B-8: Carbon storage in dead organic matter excluding soils for different biomass feedstocks under different management/disturbance scenarios. Standing dead tree branches (BranchSnag); Fine woody debris and dead coarse roots in the forest floor (FastAG); Dead coarse roots in the mineral soil (FastBG); Coarse woody debris (Medium); Standing dead tree stems (StemSnag); Litter and dead fine roots in forest floor (VFastAG); Dead fine roots in the mineral soil (VFastBG).

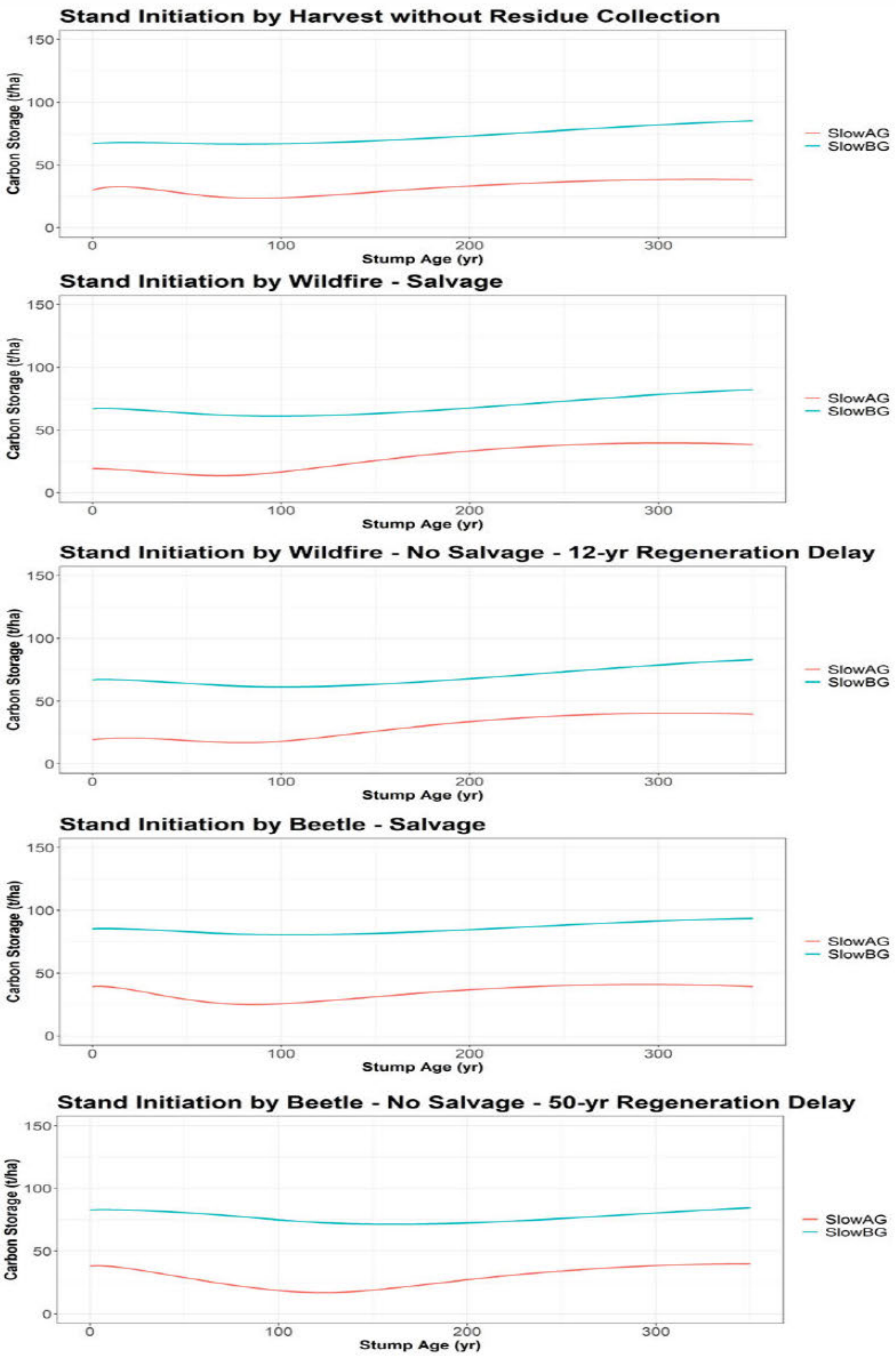


Figure B-9: Carbon storage in dead organic matter in soils for different biomass feedstocks under different management/disturbance scenarios. Forest floor/F, H, O soil horizons (SlowAG); Mineral soil (SlowBG).

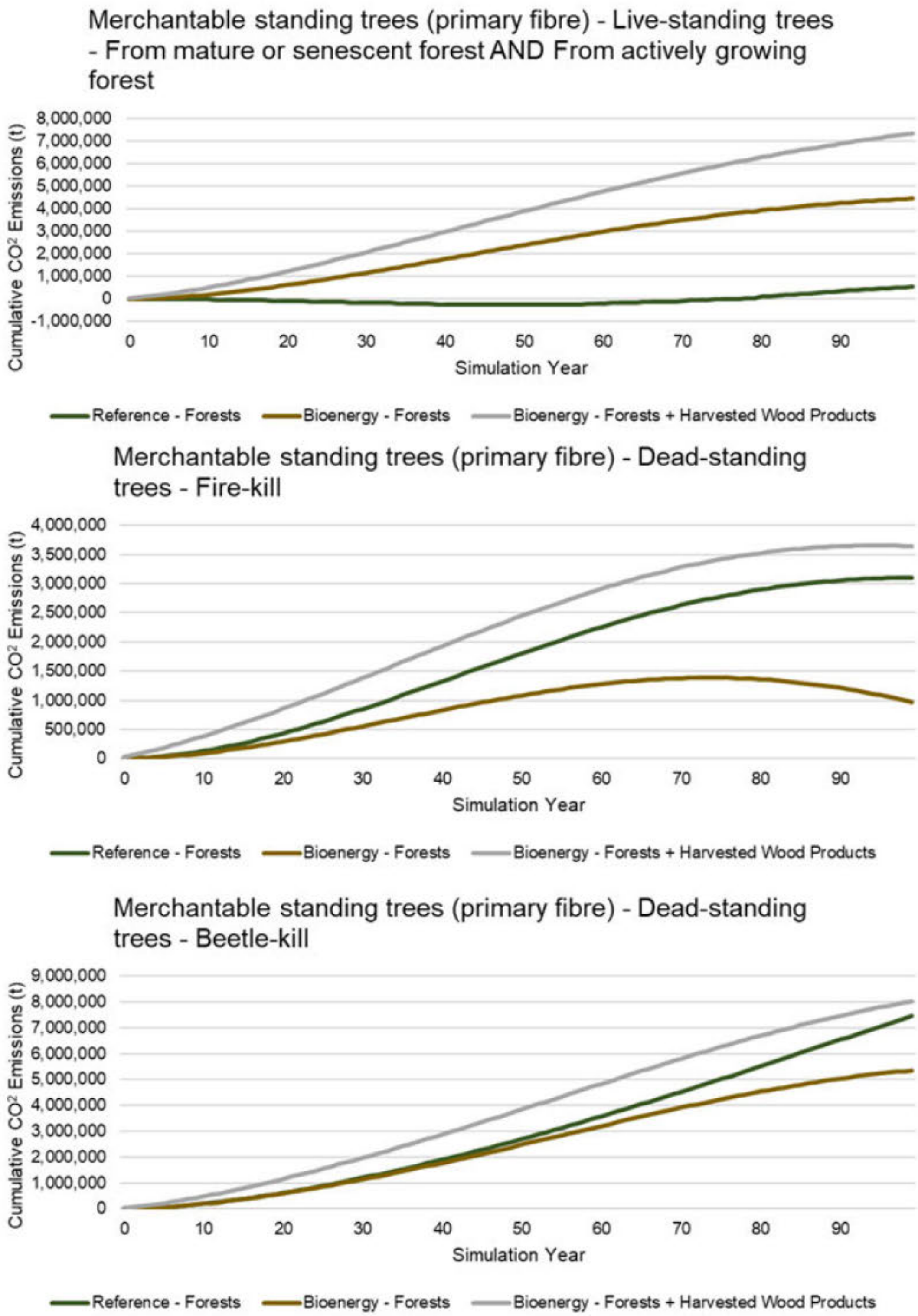


Figure B-10: Cumulative emissions of CO_2 from forests with and without harvested wood products (i.e., biomass) in the bioenergy and reference pathways for merchantable standing tree feedstocks including green wood (top panel), fire-kill standing trees (middle panel), and beetle-kill standing trees (bottom panel).

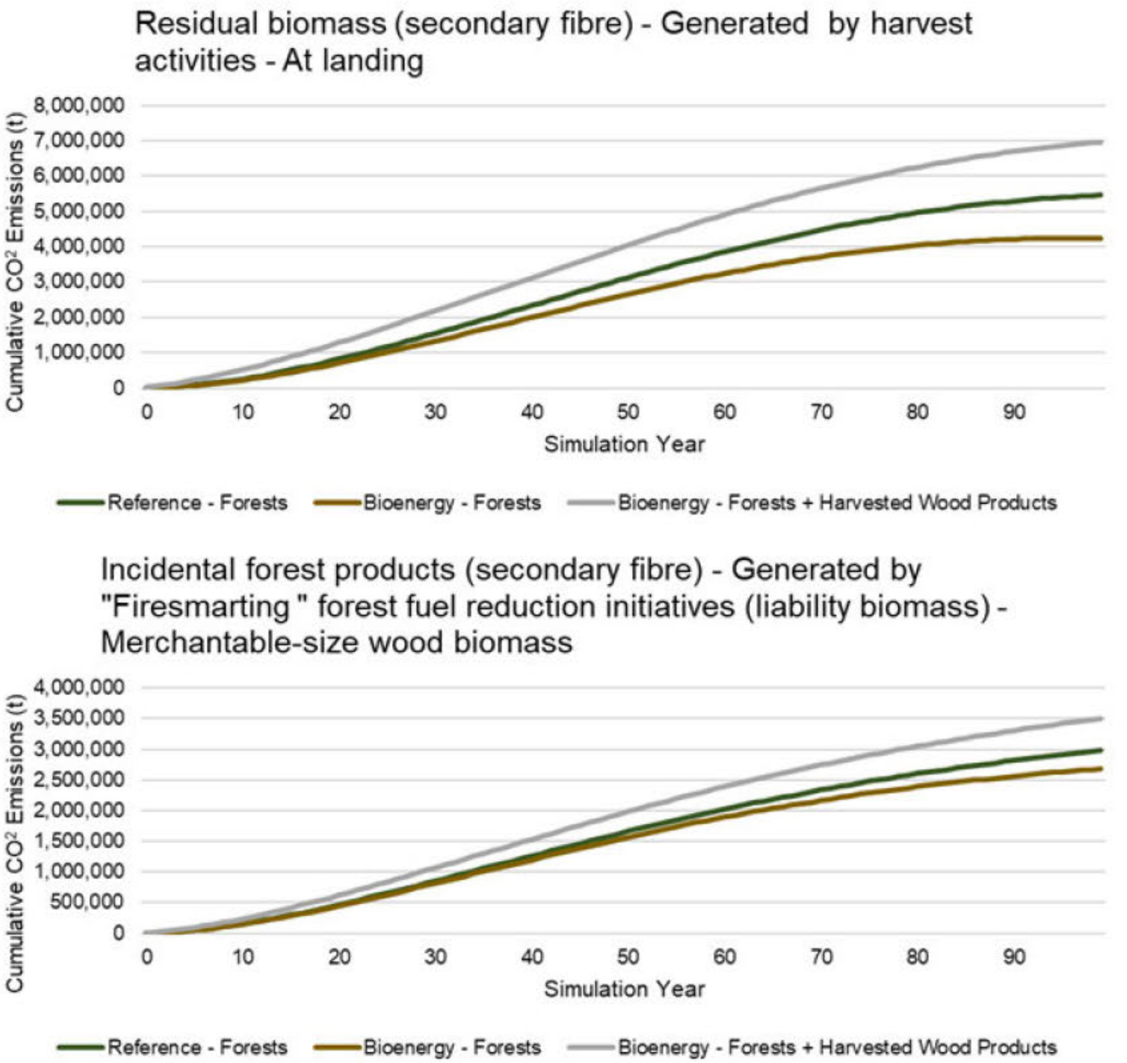


Figure B-11: Cumulative emissions of CO_2 from forests with and without harvested wood products (i.e., biomass) in the bioenergy and reference pathways for biomass residue feedstocks from land clearing activities (top panel) or fire-smarting activities (bottom panel).