The Potential of Transforming Forestry Biomass from Firebreaks in Yellowknife into Sustainable Value-added Products: Biopolymer, Syngas and Biochar

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Executive summary

Firebreaks are fuel management controls to slow down wildfires by removing biomass from hazardous areas (Zong et al., 2021). During the 2023 wildfire evacuation in Yellowknife, firebreaks were created along the highways, around the city and in certain high-risk areas (City of Yellowknife, 2023). Since the firebreaks were constructed urgently, limited consideration was given to sustainably handling the generated forestry biomass, resulting in biomass material being disposed of at the landfill as organic waste rather than repurposing as feedstocks - a common practice in biomass waste management. Although the current disposal method does not incur additional disposal costs for the City of Yellowknife, the additional organic forestry biomass from firebreaks indeed shortened the usable lifespan of the landfill and will likely increase greenhouse emissions over time as the forestry waste decomposes. Furthermore, the total firebreak areas, quality and the volume of forestry biomass generated were not quantified, which led to challenges in identifying appropriate waste management solutions.

Furthermore, the feedback of many local residents indicated concerns about the removal of vegetation (Blake, 2023) and raised questions about the long-term maintenance plans for the firebreak areas (Lamberink, 2023). Therefore, performing an environmental assessment, accurately estimating the existing and future firebreak areas, and quantifying the quality and potential volume is essential for determining the environmental impact as well as making informed decisions on disposal methods.

Performing an environmental assessment on the firebreak areas according to the Canadian Environmental Assessment Act 2012 (Impact Assessment Agency of Canada, 2023) and gathering disposed biomass information from the landfills can be the first step in reviewing and assessing the disposal method process. This preliminary assessment will estimate existing

and future firebreak areas and quantify the quality and volumes of biomass, which is essential for the City of Yellowknife to determine the best disposal solutions based on the characteristics of the biomass materials. This led to a full lifecycle analysis (LCA) to explore the feasibility of each potential disposal solution. As multiple key pieces of information are currently missing, this paper will provide an overview of two potential forestry biomass applications: (1) production of plant-based polymer for industrial application and (2) biorefinery for biochar and bioenergy production.

Introduction

In the Northwest Territories (NWT), over 4.1 million hectares of land were impacted by wildfire and nearly 70% of the population was evacuated in 2023 (Public Safety Canada, 2023). Climate change has altered the fire patterns in Canada, such as increasing frequency and intensity (de Groot et al., 2013). The costs associated with wildfire damages and management expenses are expected to rise (Butry et al., 2001). Historically, wildfires burned an average of 2.1 million hectares of Canadian forests annually (NRCan, 2024a). However, over 16.5 million hectares of Canadian forest were burned in 2023 (NRCan, 2024b). Wildfire fuel management strategies, such as using firebreaks to reduce fuel load, have become critical tools for preventing and mitigating fire risks (Tymstra et al., 2020). Firebreaks were created in and around the City of Yellowknife in 2023 as an emergency measure to slow down fire spread (City of Yellowknife, 2023). However, due to the emergency nature of the event, little to no consideration was given to managing the forestry biomass generated from the construction of firebreaks at the time.

Firebreaks mimic large-scale clearcut harvesting and removal of the upper layer of organic soil. Forests and soils play a critical role in carbon sequestration (Peng et al., 2008) and young harvested sites often have a lower carbon sequestration capacity (Rebane et al., 2020).

Previous research indicates that the disturbance of soil altered the methane (CH_4) flux cycle due to changes in microbial communities (Nazaries et al., 2013; Vantellingen and Thomas, 2021). From an ecological perspective, this artificial disturbance is distinctive from a natural disturbance from wildfire, where biomass and vegetation are burned and converted into pyogenic carbon as a carbon sink and remain on site (Ohlson et al., 2009). Natural charcoal residue often provides nutrients for the soil and promotes ecosystem functions (Hart and Luckai, 2013). However, when vegetation is removed from the fuel-managed sites and disposed of at landfills, not only does the potential carbon sink from the biomass become a carbon source, but the changes in soil properties will also likely have an impact on greenhouse gas fluxes, particularly in CH_4 emission which is a more impactful gas than carbon dioxide (CO_2) gas in the context of global warming (Mar et al., 2022). A more sustainable forestry biomass management solution for firebreaks that does not contribute to increased greenhouse gas emissions is urgently needed.

Forestry biomass

Forestry biomass is a renewable bioenergy feedstock that can potentially reduce dependency on fossil fuels (Chum and Overend, 2001). However, the production costs of bioenergy from forestry biomass are high, especially when the moisture content is high and requires extra energy for drying (Wang et al., 2020). In the NWT, previous feasibility assessments by multiple consultant firms had focused on the LCA of liquid biofuel production, especially biodiesel, generally concluded that it is not economically feasible due to high production costs, limited feedstock availability and concerns over cold flow operability (Emery et al., 2021; Navius Research Inc., 2023; Robinson, 2016). However, as technology advanced, winterization methods to improve the freezing point of biodiesel are widely available, such as fuel blending and using cold flow improver additives (Hazrat et al., 2020; Sia et al., 2020). Furthermore, previous studies have not considered carbon offset in their assessment and generally lack of comprehensive investigations on other potential biofuels and bioproducts, such as syngas and biochar.

Various federal government policies, such as the Canadian Net-Zero Emissions Accountability Act and the 2030 Emission Reduction Plan, aim to reduce carbon emissions (ENR, 2024a). The 2024 federal benchmark for carbon pollution pricing is set at $80 per tonne of carbon dioxide equivalent (tCO_2e) and is expected to increase to $170 per tCO_2e by 2030 (ECCC, 2021). Efforts are being made across Canada to transition from fossil fuels to renewable energy; for example, the Forest Biomass Program (Natural Resources and Forestry [NRF], 2024) and the construction of a forestry biomass-based renewable natural gas facility in Ontario (NRF, 2022). Other carbon reduction projects included the biochar production plant in Québec, the CARBONITY project aims to decarbonize by converting forestry waste into biochar (NRCan, 2023a). Saskatchewan invested in a biorefinery facility for biochar, wood vinegar and biofuel production from low-grade and forestry-based residuals and promoted local employment opportunities (NRCan, 2023b). The NWT is committed to reducing carbon emissions (Energy Division Infrastructure, 2023) and has investigated options for bioenergy (Navius Research Inc., 2023). The City of Yellowknife is a transportation hub for the NWT, there is potential for future studies to explore biomass-based decarbonized technology, such as biochar and syngas production, at a smaller scale that is suitable for the municipality.

Firebreaks

Forests play a critical role in the carbon cycle. Bradshaw and Warkentin (2015) estimated that roughly 184.2 total carbon (Pg) is stored in the Canadian boreal forest, where 15% is stored in vegetation, 32% and 53% are in soil and peatland, respectively. Forests influence the carbon cycle through carbon uptake and storage. Vegetation removes CO_2 from the atmosphere through photosynthesis (Peng et al., 2008) and their roots are a key source of soil organic matter (Peng et al., 2008). Carbon is stored in the forest soil and peatland as soil organic matter (Lehmann and Kleber, 2015). Therefore, when vegetation, especially roots, is removed from the soil, it impacts carbon allocation and soil respiration, such as increased CO_2 released from soil (Peng et al., 2008). During the construction of firebreaks in the City of Yellowknife, vegetations were harvested, but it is unclear if the below-ground biomass was also removed. Uprooting had a more profound impact on the carbon potential than harvesting the timber only. Nonetheless, the disruption of soil alters the microbial communities and impacts the soil carbon sequestration potential (Post and Kwon, 2000) and greenhouse gas fluxes (Mar et al., 2022). More information on firebreak construction methods, harvested vegetation and the post-harvest status of firebreak sites is needed to provide a more detailed environmental assessment and carbon reporting.

Forestry biomass potential usage and required processing methods largely depend on its quality and volume, this information is critical in terms of setting up a scenario analysis and ultimately leads to the LCA of the target solution. The LCA should include the carbon balance of the forest ecosystem in the calculation. Although the construction of firebreaks in the NWT is necessary from the fuel management perspective to mitigate fire risk, it is likely to have a negative environmental impact in terms of carbon sequestration capacity if no remediation in the affected area. When more information is available, an open-source model such as the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3) can be used to calculate the carbon stock and monitor changes (Kull et al., 2011). It is important to note that the environmental impact assessment should assess the forest ecosystem rather than the soil and vegetation individually, as the carbon cycle is dynamic. Understanding the soil carbon dynamics is important to predict and manage the firebreak sites in terms of carbon budgeting.

Vegetations

The City of Yellowknife is within the taiga shield ecozone (Environment and Climate Change [ECC], 2022). Only 4% of the forest area is considered productive for timber production, the dominant species include trembling aspen (*Populus tremuloides* Michx.), white birch (*Betula papyrifera* Marshall), Alaska birch (*Betula neoalaskana* Sarg.), balsam poplar (*Populus balsamifera* Lyall.), white and black spruce (*Picea glauca* (Moench) Voss; *Picea mariana* Kuntze), Jack pine (*Pinus banksiana* Lamb.) and tamarack (*Larix laricina* (Du Roi) K. Koch) (Bohning et al., 1997). Since the locations of firebreaks are not timber plantations and the age class of the vegetation is unclear, this paper will use the assumption that biomass harvested is low quality and ungraded conifer that is unsuitable for lumber or solid wood products and can only be used as wood chips or low-valued fibre for paper and pulp industry.

Scenario 1: Business as usual – dispose of biomass in landfill

Under the current practice, the biomass is transported and disposed of at the landfill, and there is no revegetation plan in the firebreak area. From the operation perspective, there are no immediate additional financial costs for this approach, however, the extra biomass reduced the lifespan of the landfill facility. From the environmental perspective, this approach altered the carbon allocation (Peng et al., 2008), reduced the carbon sequestration capacity of the area and changed soil carbon cycling in the ecosystem (Shao et al., 2023). To quantify the impact, the carbon budget model CBM-CFS3 can be used, but limitations in the model should be aware, such as bias in estimating certain types of biomasses, e.g. snags and coarse woody debris (Heffner et al., 2021). As there is no revegetation plan, the recovery of the site through natural seed sources will likely be slow. Soils without vegetation covers are more prone to wind and water erosion, and changes in vegetation modify the hydrology cycle in the watershed (Wei et al., 2022), as well as the CH_4 flux and increase greenhouse gas emissions (Nazaries et al., 2013). One of the critical issues with this solution is the underutilization of biomass. Even if the feedstock is low-valued fibre, there are demands in the paper and pulp industry and other industrial uses.

Scenario 2: Industrial application - biomass-derived cellulose and lignin-based materials

The main components of forestry biomass and residue are cellulose and lignin (Okolie et al., 2021). Biomass can be derived into polymer composites, and cellulose-based materials are biodegradable (Faruk and Sain, 2015). This sustainable material is commonly used in the engineering industry for various applications (Aziz et al., 2022). In the food industry, cellulose nanofibrils are added to ice cream to prolong the dripping time (Velásquez-Cock et al., 2019). Cellulose is used as an active packaging material for cheese for longer shelf life (Al-Moghazy et al., 2020). As composites are a lightweight material, the automotive industry, e.g. Ford Motor, is replacing traditional materials with reinforced wood fibre composites to reduce carbon emissions (Akhshik et al., 2019). For the construction industry, cellulose-based fillers (e.g. lignin-containing nanocellulose fibrils) are replacing the traditional toxic insulation fillers that contain isocyanate (Bello and Yan, 2024). Government policies are promoting renewable energy and moving away from fossil fuels; the need to develop batteries with more storage capacity increases. An overwhelming amount of research is exploring cellulose-based conductive polymer batteries (Du et al., 2024; Wang et al., 2024; Xia et al., 2024). Bioplastic is more sustainable than petroleum-based plastic. More importantly, most of these industrial products are commonly derived from low-cost and low-value fibre that are residues and waste wood pulps from forestry operations and paper productions.

If the City of Yellowknife is willing to collaborate with the plant-based bioplastic industries, it could consider donating the materials for conversion or a pilot project with local bioplastic companies. A California-based company, Origin Materials (NASDAQ: ORGN), recently opened a bioplastic plant in Sarnia, Ontario, specializing in biomass conversion. There are many possibilities and economical solutions to convert the feedstocks generated from the firebreaks to bioproducts. Existing Canadian bioproduct companies include Bosk Bioproduct in Quebec and TerraVerdae in Alberta. This scenario requires further collaboration and liaison with local bioproduct and paper and pulp companies on the logistics of biomass collection. However, one of the critical challenges of this solution is the requirement for feedstocks in terms of volume and standardized quality. Most bioplastic companies directly or indirectly source their feedstocks from farmers, plantations, and waste management companies so that they can control the quality of feedstocks. Therefore, a preliminary assessment of harvested biomass and discussions with the industry to understand their needs would be a good starting point. Future firebreak construction and maintenance plans should incorporate the industry feedstock harvesting requirements. For biomass already harvested during the 2023 firebreak construction, it will likely be necessary to organize and sort the materials to meet the conversion standards. Converting forestry biomass to engineered products provides a more sustainable solution compared to low-value-added product alternatives such as woodchips and wood pellets, which directly release CH_4 and CO_2 as they decompose and are burnt as fuels. If the biomass meets the industry requirements, the City and the partnering companies can then work on the transportation arrangement. The viability of this solution highly depends on the quality and quantity of the biomass.

Scenario 3: Carbon-neutral opportunities – biorefinery for biochar and syngas

Canada is committed to the net-zero emissions goal by 2050 as outlined in the Canadian Net-Zero Emissions Accountability Act. Canada focuses on five key CO_2 removal strategies: direct air CO_2 capture and storage, bioenergy with carbon capture and storage, biochar and nature-based solutions (ENR, 2024b). Among them, biochar is the most feasible and promising solution, and provinces initiated multiple biochar projects. Three companies (SUEZ, Airex Energy, Groupe Rémabec) are building the largest biochar plant in North America to convert forestry residues into biochar (NRCan, 2023a). BC Biocarbon and Dunkley Lumber Ltd. invested in a biorefinery to transform residues from forestry operations into biochar, syngas, bio-oil, and wood vinegar (NRCan, 2023b).

Biochar is a high-carbon content engineered product made from pyrolyzed organic biomass under limited to no oxygen conditions (Lehmann & Joseph, 2015). It is a waste management solution as the feedstock materials are mostly agricultural wastes and forestry residues, such as coconut coir, corn and wheat straw, manure/biosolids, sawdust, tree needles and bark etc. (Ippolito et al., 2020; Qambrani et al., 2017). It is considered a carbon sequestration technology because plants remove CO_2 from the atmosphere through photosynthesis and store the carbon in their biomass; when the biomass is converted into biochar, the carbon is sequestered stably in biochar, especially when it is applied to soil (Lehmann et al., 2021; Trelouw et al., 2021). The chemical and physical properties of biochar can be customized for specific applications by feedstock selection, altering pyrolysis methods, heating temperature, residue time and post-processing method (Ippolito et al., 2020). Biochar is a versatile material traditionally used for soil amendment (Lehmann and Joseph, 2015) but has also been used for industrial catalysts (Lee et al., 2017; Zhao et al., 2023), renewable energy production (Bhatia et al., 2021), construction materials (Zhang et al., 2022), and in various ecological restoration contexts, such as water treatment (Qambrani et al., 2017), mining site restoration (Rodriguez-Franco & Page-Dumroese, 2021; Williams and Thomas, 2023), road salt (Tang et al., 2023; Thomas et al., 2013) and arsenic remediation (Kumar et al., 2024).

Biochar was traditionally produced from pyrolysis (thermal degradation of biomass), but modern methods such as gasification (thermochemical conversion of biomass for syngas and hydrogen) and torrefaction are also used (Gabhane et al., 2020). For gasification, the primary goal is to produce bioenergy, with biochar as a solid residue (Caballero et al., 2022). In addition to forestry biomass, municipal solid waste is commonly used as feedstocks (Sajid et al., 2022). The scale and technology of biochar production vary largely from small farm scale using “Kon Tiki” kilns (Cornelissen et al., 2016) to an industrial scale with a continuous multi-function loop system to produce biofuel, syngas, biochar and other products (Khodaei et al., 2021). The scale of operation can be custom to the volume and type of biomass.

In Yellowknife, although the primary focus is on reducing the amount of firebreak biomass sent to the landfill, given the high upfront costs of setting up a syngas and biochar facility, a preliminary study to assess potential municipal feedstocks, such as municipal organic wastes, urban yard wastes, Christmas trees, compost and sewage sludge, is needed to determine the production scale and technique that is suitable for the municipality.

Multiple opportunities arise for biochar application in Yellowknife. The biggest challenge of renewable energy sources is their reliability, such as wind and solar, which are random and generated discontinuously (Panwar et al., 2011). Bioenergy, such as syngas produced from municipal wastes and forestry biomass, is a relatively more reliable energy source and carbon-negative (Caballero et al., 2022). The feasibility will likely depend on the biomass availability. The University of British Columbia is partnering with Nexterra System on a gasification project, and BC Biocarbon is one of the long-term collaborators with the University of Toronto on biochar and bioenergy refinery research. For the City of Yellowknife, exploring partnership opportunities with established biochar companies such as BC Biocarbon could be a first step.

Another potential application of biochar is soil remediation. Arsenic contamination from the decommissioning of the Giant Mine has been a long-standing problem in Yellowknife. Despite the ongoing remediation effort, such as freezing the arsenic trioxide, an economical and permanent solution is still needed (GNWT/CIRNAC, 2024). Renewing concerns on the changes in vegetation after the wildfire and the arsenic contamination in soil and water in the area. The proximity of an open mine tailings disposal site near residential areas is particularly concerning as gold mine tailings generally have high heavy mental content (Pelletier et al., 2020), low aggregation and fine texture of the tailing made it highly susceptible to wind and water erosion (Fashola et al., 2016) which potentially posed health risks to the nearby communities in Yellowknife (Chan et al., 2020). Currently, there are limited feasible carbon-negative solutions for arsenic remediation. A recent study investigated using biochar from a biorefinery facility to restore decommissioned gold mine sites in northern Ontario and found positive vegetation respond (Williams and Thomas, 2023). There is a potential for Yellowknife to develop a bioenergy facility for biofuel and biochar. A comprehensive LCA would be a good place to start.

Conclusions and recommendations

The current practice of disposing of valuable biomass in landfills poses multiple economic and environmental concerns, such as shortening the lifespan of the landfill facility and increasing greenhouse gas emissions. This paper suggests two potential solutions to upcycle and repurpose the biomass. The first solution involves collaborating with bioplastic companies and universities to redirect forestry biomass from firebreaks as low-cost feedstocks for biopolymer production.

This approach may incur upfront costs, such as biomass sorting and assessment. The City can work with the partnering companies on biomass transportation if the feedstocks are suitable. However, the viability of this solution highly depends on the quality of feedstocks.

The second solution is to convert the biomass into syngas and have biochar as solid residue where the city will have a reliable energy source from municipal solid wastes and forestry biomass, where the biochar from the refinery can be used for soil amendment. However, this option will likely incur costs in developing a facility. It is important to note that the usage of the facility is not exclusive to the forestry waste from the firebreaks; it serves as a long-term organic waste management solution for the City of Yellowknife. A comprehensive lifecycle analysis of biochar and syngas production is recommended to fully evaluate the costs and benefits.

In conclusion, the City of Yellowknife must assess the quality and quantity of biomass harvested from the firebreak to determine the feasibility of the bioproduct option. An assessment of the amount of municipal organic waste is necessary to explore the bioenergy and biochar option. With these assessments, the City can make an informed decision on the most suitable solution.

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