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Refining Displaced Emissions from British Columbia's Heat and Electricity Production

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Contents

Figures

Tables

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Abstract

A previous national-level study examined the mitigation potential of bioenergy produced through the combustion of harvest residues. In the current study, we determine how the estimated displaced emissions in British Columbia could change from the use of bioenergy, compared to the previous analysis, by refining the spatial allocation of fuel mix and energy demand. The spatial refinement of fuels throughout the province resulted in a higher mitigation potential, which was related to the larger demand associated with industrial facilities in low population regions. The potential impacts of a high carbon tax on the mitigation potential of bioenergy were also estimated by using the predicted fuel mix and energy use from an additional future carbon tax model. When compared to the previous national-level study, this scenario resulted in a lower mitigation potential, which was related to the anticipated fuel mix switching to a lower emissions fuel mix. This analysis suggests that the use of harvest residues for bioenergy in British Columbia has the potential to help the forest sector mitigate climate change through reduced carbon emissions, especially when harvest residues are used to meet the energy demand of industrial facilities throughout the province.

1. Introduction

With ambitious goals for greenhouse gas (GHG) emissions reduction targets of 17% and 30% below 2005 levels by 2020 and 2030, respectively (Environment Canada 2014a; Government of Canada 2015), Canada is committed to identifying strategies that can be undertaken to help mitigate anthropogenic climate change. Forests within Canada can play a part in the mitigation of climate change through strategies involving forest management and society's use of wood products (Smyth et al. 2014). With an abundance of forested land and the ambitious goal of reducing GHG emissions 80% below 2007 levels by 2050 (Province of British Columbia 2007), British Columbia could increase mitigation and adaptation in the forest sector to diminish the negative effects of climate change (Lemprière et al. 2008).

Forestry projects aimed at reducing carbon dioxide emissions can include conservation, enhanced sequestration and storage, and substitution (Nabuurs et al. 2007). Through analyses examining the cumulative effects of carbon (C) pools in the forest ecosystem, wood use and harvested wood product storage, and substitution benefits from using wood in place of other products or energy sources, the mitigation potential of wood use strategies can be estimated through comparisons to a forward-looking baseline (Smyth et al. 2014). As a mitigation strategy, wood substitution examines the use of forest biomass to replace fossil fuels or fossil fuel products (Lasocki 2001; Gustavsson et al. 2006; Creutzig et al. 2015). This includes the use of harvested wood products that store C while limiting the consumption of emissions-intensive construction materials such as concrete or steel, or the use of forest biomass for production of energy while limiting the use of emissions-intensive fuels such as coal or fuel oil (Werner et al. 2010). The forest biomass used in the production of bioenergy can be sourced from a dedicated biomass supply or through the collection of harvest residues (Stennes et al. 2010). A national-level study by Smyth et al. (2017a) examined the mitigation potential of bioenergy, produced by the combustion of harvest residues, for Canada. Using a displacement factor approach (Schlamadinger and Marland 1996; Smyth et al. 2017b) to quantify the amount of emissions that are avoided when bioenergy is substituted for fossil fuels, Smyth et al. (2017a) used an optimization model to select the type, size, and number of bioenergy facilities that could be built to produce heat and/or electricity for 502 forest management units (FMU) across Canada. Their results show that in regions with high energy demand, sufficient available harvest residues, and high fossil fuel emissions intensities, the use of harvest residues for bioenergy reduced GHG emissions. However, in areas with large amounts of harvest residues but low energy demand, the displacement factors were low because excess residues were converted to electricity and were assumed to displace the relatively low-emissions electricity grid. Electricity grids outside of British Columbia were beyond the scope of this analysis, and were not included in calculations.

The magnitude of displaced emissions is linked to the displaced fuel source's emissions intensity (Cintas et al. 2015; Cleary and Caspersen 2015). Smyth et al. (2017a; hereafter referred to as the "original analysis") assumed that regional electricity and heat demands for each FMU were determined by the region's population and provincial average per-capita energy usage, with adjustments for remote community fuel mixes. This methodology makes the simplifying assumption that industrial energy use was directly proportional to the population; however, industrial fossil fuel facilities are not always located in populated regions and can be in remote areas where the resource is located (e.g., oil and gas, or mining). Furthermore, British Columbia has a large latitudinal range in temperature, which could cause an increase in per capita emissions in colder regions. If the spatial allocation of the fuel mix and energy demand throughout the province was refined, the original analysis could have overestimated or underestimated the mitigation potential in British Columbia.

A second potential source of uncertainty investigated in this study was the projection of fossil fuel emissions associated with future electricity production. British Columbia's carbon tax on fossil fuel emissions is currently set at a level of \$30/t$C0_2$e (Province of British Columbia 2008) with potential incremental increases in the future. Such a tax could also economically stimulate the use of biofuels and increase the demand for renewable energy (Timilsina et al. 2011; Allan et al. 2014), or decrease the amount of C intensive fuels that are available for displacement. Therefore, the overall impact of the tax could increase or decrease the mitigation potential. English et al. (2017) estimated the effects of different C taxes on the electricity fuel mix within the provinces of Alberta and British Columbia, and developed future scenarios for electricity production.

In the current work, the first objective was to refine the spatial allocation of fossil fuels using community-level fuel usage data (British Columbia Ministry of Environment 2014) and large industrial emitter location information (Environment Canada 2015). Based on the refined allocation, the mitigation potential was estimated for each FMU. The second objective of this study was to use the alternate future electricity scenarios for low and high C tax levels and estimate the impact on the mitigation potential. We tested the following three hypotheses related to the refinement of displaced emissions for British Columbia.

1. Refinement of the spatial allocation of the energy demand will increase the mitigation potential of using harvest residues for bioenergy because industrial energy demand will increase in FMUs with low populations but high bioenergy capacity (i.e., increased refinement will result in greater regional opportunities for displacement of fossil fuels).
2. The implementation of a high C tax in British Columbia will decrease the mitigation potential of using harvest residues for bioenergy because displaced fuels will have lower emissions intensities (i.e., future baselines with higher C taxes will have already reduced some fossil emissions through incentivized fuel switching, reducing the amount of mitigation opportunities available).
3. Of the two tested scenarios, the effect on mitigation potential of changing the future fuel mix through an increased C tax will be greater than the effect of refining the spatial allocation of the fuel mix and energy demand.

2. Methods

The original analysis determined the benefits of using harvest residues for bioenergy across Canada using a systems approach with multiple components, including forest ecosystem C dynamics, local bioenergy combustion, substitution benefits in the energy sector, and harvested wood products tracking. For the current analysis, our study area only considers British Columbia, where additional information regarding fuel consumption has recently become available.

The original analysis compared the C emissions of fossil fuel sources to the emissions from bioenergy for nine different bioenergy facilities, where fossil fuels were ranked for substitution according to emissions intensities. A detailed description of the methods used to create the original analysis, along with the optimization and displacement factor equations, is described by Smyth et al. (2017b) but is briefly outlined here. A linear programming (LP) model was developed in Microsoft Excel that maximized the total avoided emissions for each FMU by determining the optimal combination of regional bioenergy facilities for stationary heat and power generation based on the available captured residues and fossil fuel demand. This model was transferred to R (R Development Core Team 2015) for ease of use and quicker computation. The outputs of the model included the displaced fuel mix, configuration of bioenergy facilities (size, type, and number), avoided emissions, and displacement factors. We assumed that FMU population, remote community population, and captured harvest residues were the same as in the original analysis.

2.1 Refined Spatial Allocation of Fuel Mix

The total annual energy demand for both heat and electricity and the total amount of fuels available were both kept the same as those in the original analysis; however, the spatial allocation of fuels throughout British Columbia was refined using the reported energy consumption by fuel type at the community level and locations of industrial emitters. The Community Energy and Emissions Inventory Report data set describes energy consumption and GHG emissions from communities; including transportation, buildings, and solid waste (British Columbia Ministry of Environment 2014). The Greenhouse Gas Emissions Reporting Program industrial facilities data set describes GHG emissions from industrial facilities that emit at least 50 ktCO_2e per year (Environment Canada 2014b). The British Columbia Greenhouse Gas Inventory was not used for this analysis, owing to some gaps in geographical information that was necessary for the linear programming model. Although transportation and solid waste emissions are available in the data sets used, we did not include these in this study as we only considered stationary combustion for heat and electricity production. A spatial join was performed using ArcGIS 10.3.1[1] to estimate the energy consumption in each FMU for commercial, small–medium industrial, large industrial, and residential sectors.

The large emitter data does not describe the fuel mix, and only reports the carbon dioxide emissions. To estimate the amount of energy produced from those emissions values, we assumed a natural gas and electricity fuel mix based on the reported industrial facility information in the Community Energy and Emissions Inventory data set; that is, 47.95% electricity and 52.05% for heat, as natural gas. In this way, total energy for both electricity and heat could be calculated as

$$\text{Total Energy} = \frac{Ind}{0.4795eei + 0.5025hei} ,$$

where the Total Energy is in MWh; *Ind* is the industrial emissions in ktCO_2e; *eei* is the electricity emissions intensity (variable by spatial unit); and *hei* is the heat emissions intensity (natural gas; 255 kg CO_2e MWh^{-1}). Two industrial facilities from the Greenhouse Gas Emissions Reporting Program data set did not contain a natural gas pipeline, and therefore it was assumed that these facilities were using coal.

For the Community Energy and Emissions Inventory data sets, propane was listed but was not included in the fuel mix of the original analysis; we, therefore, included propane with fuel oil because they have similar emissions intensities (Smyth et al. 2017a). The electricity fuel mix was not specified in this data set, and was assumed to be the same as in the original analysis. The electricity consumption entries were split into electricity and electricity for heat, with the assumption that two-thirds of the province's electricity was consumed for heat, which was an assumption carried over from the original analysis.

2.2 Projected Electricity Mix Based on Carbon Tax Levels

English et al. (2017) provided projections of the British Columbia electricity demand by fuel type that would materialize through a hypothetical high C tax and the current C tax. For the current C tax scenario, the existing C tax level of $30/t was assumed to remain constant to 2060. The high C tax scenario was assumed to start at the currently implemented C tax level of $30/t and gradually increase to $100/t in 2060. Specific fuel intensities were lower than the original analysis for coal and natural gas (Table 1) because technological advancements are expected to lead to higher efficiencies for generators using these fuels. The percentage of each fuel in the electricity fuel mix was determined by taking the average energy demand for each fuel category over the 50-year period.

The heat fuel mix was not estimated by English et al. (2017); therefore, it was assumed the same as that in the original analysis. The current British Columbia carbon tax could drive some transition to lower-intensity heating fuels, so this assumption could contribute to an overestimate of avoided emissions. The total electricity demand value was changed to match the value reported by English et al. (2017) (i.e., to maintain assumptions made in the original carbon tax model regarding the influence of a C tax on energy demand), and was distributed across the FMUs in the

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[1] Esri. 2015. Esri ArcGIS 10.3.1. Redlands, CA.

Table 1. Fuel emissions intensities for electricity generation from the original analysis and Lyseng et al. (2016). Only fossil fuels were estimated for substitution, and other energy sources (e.g., hydro, existing biomass, wind, solar, nuclear, geothermal) were not considered.

Fuel Type	Emissions intensities (kg CO_2e/MWh)[a]	Fuel Type[b]	Emissions intensities (kg $C0_2e$/MWh)[c]
Coal	1000	Coal with carbon capture and storage	109
Fuel oil and propane	800		800
Diesel	800		800
Natural gas	450	Combined cycle gas turbine, and combined cycle gas turbine–carbon capture and storage	187

[a] From Smyth et al. (2017a).
[b] From Lyseng et al. (2016).
[c] From English et al. (2017).

same proportions used in the original analysis. The electricity demand comprised 33% of the total energy demand in British Columbia in the original analysis and 22% in the high C tax scenario. Although this assumption may affect the results of the analysis, it was considered important to use the value of electricity demand used in the C tax model to maintain the validity of the model's results.

2.3 Mitigation Potential

Cumulative displaced emissions, from 2016 to 2050, were estimated from refined spatial allocation of the energy demand, and projected electricity fuels for high and current C tax scenarios. Updated avoided emissions estimates were then used to re-estimate the cumulative mitigation potential, using the sector emissions from the original analysis. Cumulative mitigation estimates were also estimated for all British Columbia, and for those FMUs with positive mitigation potential.

3. Results

Our analysis results include the amount and type of fuel displaced from the spatially refined and C tax scenarios, and a comparison of the mitigation potentials and facilities selected in these scenarios. First, we present the results for the refined spatial allocation of the fuel mix, followed by the results of the projected electricity mix based on C tax levels and the resulting mitigation potentials from each scenario.

3.1 Refined Spatial Allocation of Fuel Mix

The total amount of electricity displaced by bioenergy was higher when the demand was spatially refined, as compared to the original analysis (Table 2). The type of fuel that had the most energy displaced in both the original analysis and in the spatially refined analysis was natural gas. A large amount of electricity was exported to the grid in the original analysis, whereas this value was slightly lower in the spatially refined scenario (Figure 1). When comparing the two scenarios, the original analysis displaced about two-thirds the amount of natural gas that the spatially refined scenario displaced. This demonstrates the increase in locally displaced fossil fuel energy attributed to the spatial refinement of the fuel mix and energy demand, which provided more displacement opportunities within the FMUs.

Table 2 provides data for the total amount of heat displaced in the original analysis and the spatially refined analysis. The fuel types with the most heat displaced in the original analysis were natural gas, coal and petcoke, and fuel oil (Figure 2). The fuel type with the most TWh displaced in the spatially refined analysis was fuel oil, closely followed by natural gas. When comparing the two scenarios, the original analysis showed displacement of a similar amount of natural gas, although the spatially refined scenario showed more fuel oil displaced.

Table 2. The amount of annual electricity displaced, electricity exported, heat displaced, avoided emissions, and FMU average displacement factor for each scenario analysis.

Scenario	Electricity displaced (TWh)	Electricity exported to grid (TWh)	Heat displaced (TWh)	Avoided emissions ($MtCO_2e$)	Average displacement factor
Original	3.13	4.33	15.83	6.96	0.48
Spatially Refined	4.57	3.66	14.92	7.23	0.44
High Carbon Tax	0.16	5.46	17.7	5.27	0.34
Current Carbon Tax	0.21	5.41	17.7	5.29	0.34

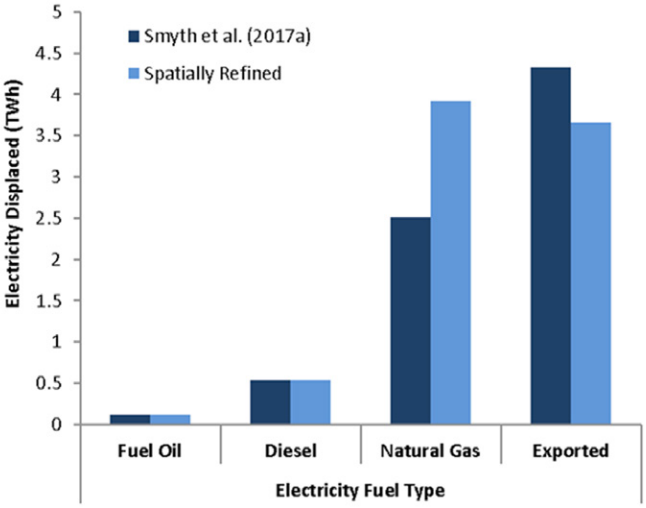

Figure 1. Cumulative electricity displaced by 2050 by fuel type for both the original analysis and the spatially refined analysis. Electricity exported from the FMU displaces an average grid electricity fuel mix.

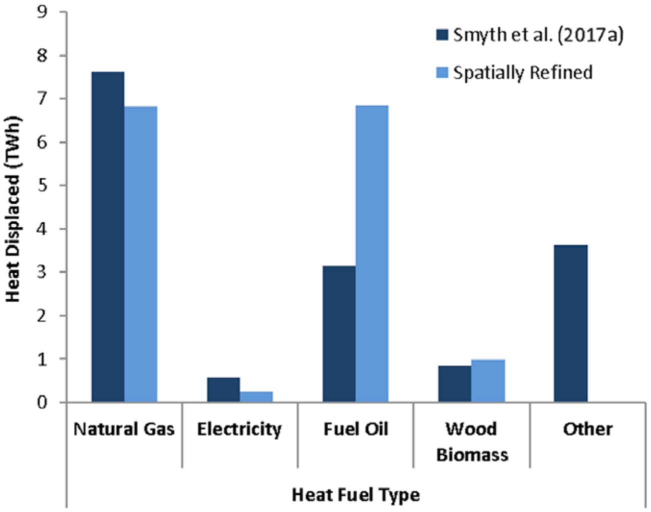

Figure 2. Cumulative heat displaced by 2050 by fuel type for both the original analysis and the spatially refined analysis. "Other" includes coal and petcoke.

Table 2 also provides results for the total amount of avoided emissions and average displacement factors for both the original analysis and the spatially refined analysis. After spatial refinement, the FMU with the largest increase in avoided emissions was the Merritt Timber Supply Area (no. 18), with an increase in avoided emissions of 0.33 $MtCO_2e$ (Figure 3). The Williams Lake Timber Supply Area (no. 29) showed the largest decrease in avoided emissions (0.18 $MtCO_2e$). This FMU had an overall decrease in demand related to the spatial refinement, along with a very small number of industrial facilities, which led to less energy demand, as well as displacement of fewer high-intensity emissions fuels. Seventeen FMUs had an increase in potential avoided emissions, whereas 57 FMUs had a decrease in potential avoided emissions.

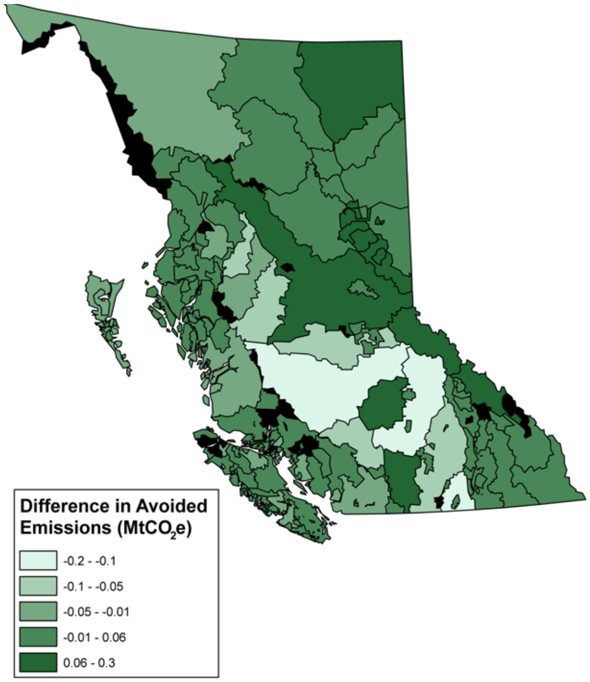

Figure 3. The difference in avoided emissions, in $MtCO_2e$, between the spatial refinement analysis and the original Smyth et al. (2017a) analysis. Regions in black were not included in the mitigation estimates.

3.2 Projected Electricity Mix Based on Carbon Tax Levels

Regional electricity demand is lower in the high C tax scenario owing to fuel switching, which has been assumed to already occur, and lower fossil fuel emissions intensities, which contribute to fewer local opportunities of fossil fuel displacement. Because of these energy assumptions, harvest residues are more likely to be converted to electricity and exported outside the FMU via the electricity grid. Compared to the original analysis, the amount of natural gas displaced was much lower and the amount of electricity exported was higher (Figure 4). Table 2 describes the total amount of electricity displaced in the high and current C tax analyses. In both scenarios, none of the available fuel types were frequently displaced, and the amount of electricity exported was very high. In comparing the two scenarios with the original analysis, the scenarios had an average 93% decrease in displaced natural gas and an average 26% increase in electricity exported from the FMU.

Table 2 provides data for the total amount of heat displaced in the original analysis and the two C tax scenarios. In the original analysis, natural gas had the most energy displaced; the next highest was coal and petcoke, with about half the amount of displaced energy (Figure 5). In the C tax scenarios, natural gas was the type of fuel with the most energy displaced. When comparing the two scenarios, the original analysis and the C tax scenarios displaced similar heat fuel types, with the C tax scenarios displacing slightly more of each fuel type. This was expected because the electricity energy fuels had much lower emissions intensities in the C tax scenarios.

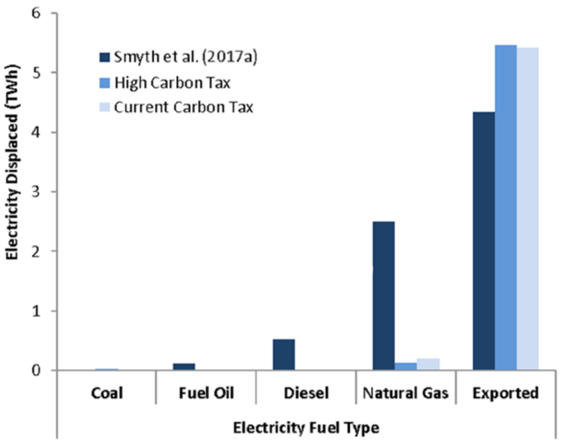

Figure 4. Total electricity displaced by fuel type for the original analysis, the high C tax analysis, and the current C tax analysis.

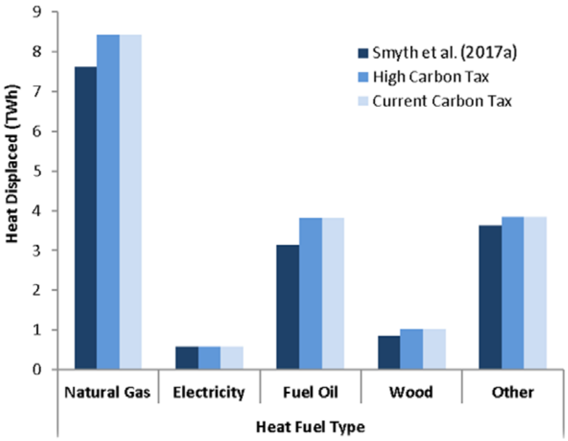

Figure 5. Total heat displaced by fuel type for the original analysis, the high carbon tax analysis, and the current carbon tax analysis.

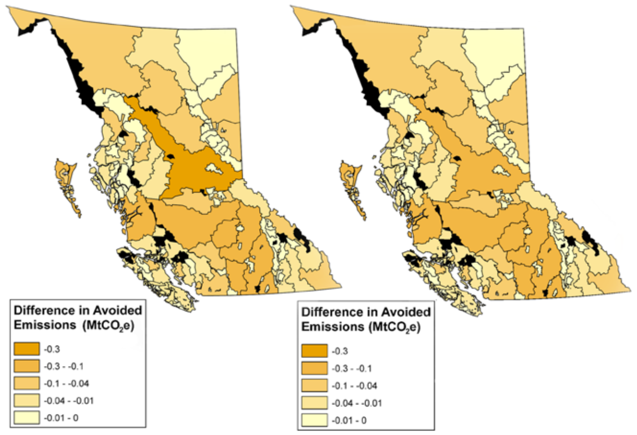

Figure 6. The difference in avoided emissions, in $MtCO_2e$, between the high (left) and current (right) C tax scenarios and the original Smyth et al. (2017a) analysis.

The total amount of avoided emissions and average displacement factors were lower in the high and current C tax scenarios than in the original analysis (Table 2). In the carbon tax scenarios, none of British Columbia's FMUs had an increase in avoided emissions, compared to the original analysis (Figure 6).

The Prince George Timber Supply Area (no. 24) had the largest decrease in avoided emissions related to the change in electricity fuel mix and lower fossil fuel emissions intensities; avoided emissions decreased by 186 and 181 $ktCO_2e$ in the high and current C tax scenarios, respectively. In both scenarios, 74 FMUs had a decrease in potential avoided emissions.

3.3 Mitigation Potential

The cumulative mitigation potential of each scenario, from largest to smallest, was 124 $MtCO_2e$ in the spatially refined analysis, 111 $MtCO_2e$ in the original analysis, 76 $MtCO_2e$ in the current C tax analysis, and 75 $MtCO_2e$ in the high C tax analysis (Figure 7). In each scenario, only the contribution of FMUs with positive mitigation was included in the mitigation estimate. Of the 92 management units, 40 were positive for the original analysis, 36 for the spatially refined scenario, 26 for the current C tax scenario, and 26 for the high C tax scenario. Each scenario has a high percentage of overlap: 89% of the FMUs in the spatially refined scenario and 100% in both C tax scenarios were the same as in the original analysis.

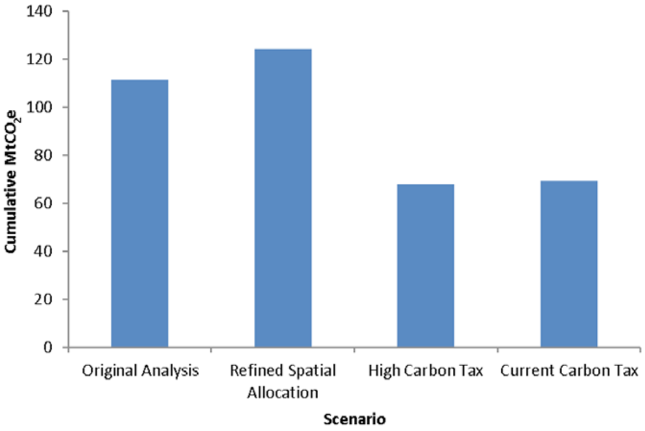

Figure 7. Cumulative mitigation potential (2017–2050) from the original analysis (Smyth et al. 2017a), the results from the spatial refinement of energy demand, and the results from the two C tax scenarios. Cumulative mitigation potential contains contributions from positive FMUs only.

Figure 8 shows the facilities selected by the LP model to maximize the avoided emissions for each scenario. In the original and spatially refined analyses, the type of facility chosen most often was combined heat and power (CHP). In both the high and current C tax analyses, a heat facility was selected more often.

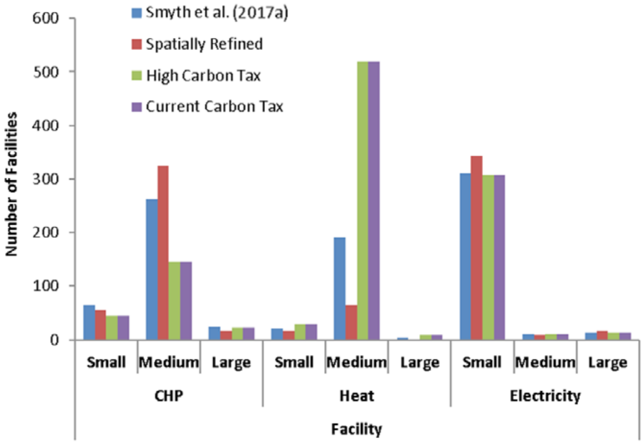

Figure 8. The number of facilities chosen by the LP model to maximize the avoided emissions for each scenario, including combined heat and power (CHP), heat, and electricity facilities, each with a small, medium, and large option.

4. Discussion

The purpose of this analysis was to determine the substitution impacts in British Columbia from the use of harvest residues for local bioenergy production, through refining the spatial allocation of fuels and considering alternate projections of electricity fuel mixes. Because high energy industrial demand in low population regions was not considered in the original Smyth et al. (2017a) analysis, the first of several hypotheses tested was that the spatial refinement of the fuel mix within British Columbia would increase the mitigation potential of using harvest residues for bioenergy. Our analysis showed that the spatially refined scenario had a higher amount of avoided emissions than the original analysis, driven by higher avoided emissions in FMUs with low populations but higher industrial energy demand. For example, the Merritt Timber Supply Area (no. 18) had the largest increase in avoided emissions, experiencing an increase in both heat and electricity demand by approximately 600%. As a result, more combined heat and power facilities and heat facilities were selected in this region to accommodate this increase in demand; this contributed to the regional displacement factor increasing from 0.35 to 0.93. Fifty-eight percent of the region's energy demand was from industrial facilities. Another noticeable change was the increase in avoided emissions in the northeastern corner of British Columbia. The Fort Nelson Timber Supply Area (no. 8) experienced an increase of about 2500% in total energy demand and, similar to Merritt, more combined heat and power facilities and heat facilities were selected as a result. The displacement factor increased from 0.31 to 0.83, with 98% of the region's energy demand was determined to be from industrial facilities.

The presence of harvest residues in regions with high industrial energy demand could allow for the development of industrial symbiosis in the form of combined heat and power facilities. These facilities can offer a potential for communities to reduce greenhouse gas emissions, while simultaneously offering a profitable mode of electricity production (Danestig et al. 2007). Industrial symbiosis allows for the combination of two or more previously unrelated industries to create an advantageous relationship that utilizes resources (Lombardi et al. 2012); in British Columbia, the presence of unused harvest residues could allow for more efficient production of heat and electricity and concurrently offer a way to reduce carbon emissions (Martin and Eklund 2011). Although combined heat and power plants show promise in providing a renewable energy source to urban communities while reducing carbon emissions (Madlener and Vögtli 2008), the transportation costs involved in using harvest residues in the low population areas of British Columbia could prove expensive and potentially reduce the amount of emissions avoided. Further research with spatially explicit modeling of biomass location and transportation pathways in British Columbia could help answer this question.

Our second hypothesis tested whether the implementation of a high C tax in British Columbia would decrease the mitigation potential of using harvest residues for bioenergy because displaced fuels will have lower emissions intensities. Our analysis showed support for this hypothesis in that both the high and current C tax scenarios had a lower amount of avoided emissions than the original analysis. All FMUs experienced a decrease in avoided emissions related to the change in the electricity fuel mix and the introduction of high-efficiency combined cycle gas turbine units and carbon capture and sequestration for coal and natural gas, lowering the fuels' respective emissions intensities. Interestingly, English et al. (2017) determined that, after the implementation of a high C tax, the resulting electricity fuel mix in British Columbia in 2050 would be very similar to the electricity fuel mix if the C tax were to remain unchanged during that period. This caused the two scenarios to have such similar potential avoided emissions in this analysis (Figure 6). The avoided emissions in the C tax scenarios, while less than those in the original analysis, are still positive and show that bioenergy production using harvest residues may still be a viable choice in British Columbia, even after the implementation of a high C tax or the maintenance of the current C tax. Some studies suggest that introducing a C tax which offers subsidies for the construction of bioenergy facilities can be very successful in both maintaining bioenergy as a renewable energy source and reducing emissions (Wang et al. 2012; Song et al. 2015).

Our third hypothesis tested whether the uncertainty in the mitigation potential of using harvest residues for bioenergy would be greater because of the change in the potential future fuel mix, compared to refining the spatial allocation of fuels. Our results supported this hypothesis, showing that the high C tax scenario affected mitigation potential the most, when compared to the original analysis.

5. Conclusions

The spatial refinement of fuels throughout the province resulted in a higher mitigation potential, due to the higher demand associated with industrial facilities in low population regions. The implementation of a high C tax resulted in the most uncertainty in the mitigation potential, and had the lowest mitigation potential of all scenarios. For future energy production in British Columbia, it may be important to consider the development and implementation of new technologies to reduce the C emissions from fossil fuel use, as well as offer increased efficiency from the use of bioenergy. In communities with high heat and electricity demand, the development of combined heat and power facilities could create the most mitigation potential. Industrial symbiosis could allow regions with high industrial energy demand to take advantage of local harvest residues. The use of harvest residues for bioenergy in British Columbia has the potential to help the forest sector mitigate climate change through reduced carbon emissions, especially when harvest residues are used to meet the energy demand of industrial facilities throughout the province.

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