Spatial and temporal variability in economic availability of residue biomass from timber harvest in west-central Alberta, Canada (1990–2015)

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There is increasing interest in the use of forestry residues for biofuels, yet little is known about the temporal and spatial variability regarding the economic availability of these residues in Canada. We use historical forest harvest data from Alberta, Canada to develop a description of the spatial and temporal distributions of the availability of forest harvest residues for the period 1990—2015. Using a GIS coverage of the road network in Alberta, we developed estimates of round-trip haul costs from each harvest location to each of three potential bioenergy plant locations. This information was used to create supply curves (or cost-availability curves) for each of the three potential locations and each of the 26 years. This information provides insights into the variability in delivered costs of forest residue for bioenergy use spatially and over time. These descriptions of variability are historical but could inform future investments in the bioenergy sector.

We focus on the area surrounding the towns of Hinton, Edson, and Whitecourt in west-central Alberta. These three potential bioenergy plant locations were chosen as they host several forest products companies and are located near forest areas with substantial harvesting activity. For each location, we conduct sensitivity analysis on three alternative bioenergy plant capacities as measured by residue feedstock requirements: 200 Gg/a, 400 Gg/a, and 800 Gg/a. For the 200 Gg/a capacity the three locations are almost indistinguishable in terms of average delivered residue cost (~ 87 $·Mg-1). At 400 Gg/a, Edson is the low-cost location (98.6 $·Mg-1). At 800 Gg/a, Whitecourt is clearly the low-cost location (122 $·Mg-1), however, it is important to note that the average cost of supplying an 800 Gg/a plant is over 40% greater than supplying a 200 Gg/a plant.

forest residues , road network , supply curve, biofuel, bioenergy facility siting, feedstock supply, economic accessibility.

# Introduction

Liquid biofuels (*e.g.,* ethanol and biodiesel) have been produced in commercial quantities from food crops since the 1980s. In some jurisdictions, policies to promote the use of these first-generation biofuels are being phased out due concerns that they compete with food production, and that their production may lead to land use change [1].

Second generation biofuels rely on processes that convert lignocellulosic materials (such as corn stover and wood) to liquid biofuels. An advantage of this process is that the feedstock can be residue created as byproducts of food or forest products production, which would otherwise be considered waste. Second generation biofuel production is still largely in a pilot or demonstration phase. For example, the Silva Green Fuel renewable crude oil plant in Tofte, Norway was expected to begin operations in 2021 [2]. As of the date of writing (2022-07-14), the plant is not yet operational.

Technologies to pelletize wood are more established than technologies to produce liquid fuels from wood. It was projected that Canada would produce 3.8 million Mg of wood pellets in 2021, of which 87% will be exported, largely to the United Kingdom, Japan, and Europe [3]. Wood pellets are replacing coal as the primary energy source in electricity generating plants, particularly in Europe [4].

Most of the wood pellet production in Canada comes from mill residues. There is interest in expanding the source of residues from mills to the forest by collecting residues from cutblocks after stemwood harvest; a practice well-established in Europe. Forest residues generated as by-products of conventional forest harvesting operations include tree tops, branches and non-merchantable logs. These residues are typically left behind in slash piles, which are burned during winter to mitigate against the risk of wildfires. Canada has a forestry sector that produces approximately 20 million oven-dry metric tons of forest residues annually [5]. For the remainder of this paper we will express biomass using SI units, and all quantities of biomass will be expressed on an oven-dry basis: 1 oven-dry metric ton is equivalent to 1 Mg.

A number of studies have shown that collection and transportation costs may be the biggest impediment to widespread use of forest harvest residues in bioenergy systems [8]. Availability of forest residues for a bioenergy plant largely depends on commercial harvesting operations and the production of traditional forest products. Fluctuations in the volume of stemwood harvested for forest products has a direct impact on residues available for biofuels. Major factors, such as the 2008 housing crisis and the ongoing softwood lumber dispute with the United States have resulted in sawmill closures and reductions in forest harvesting activities in Canada [9] [10]. This relationship between volatile harvest volumes and subsequent residue variability is explored in detail by Niquidet and Friesen [11], who model forest residue supply in Alberta as a function of lumber prices. Given that biomass feedstock accounts for 40 to 60% of a bioenergy plant’s total costs ([12] [13] cited in [14]), a number of studies have shown that collection and transportation costs may be the biggest impediment to widespread use of forest residues in bioenergy systems. Since a forest-residue based bioenergy plant is dependent on stemwood harvesting for feedstock, any variability in harvesting directly influences the volume of residues that would be available. Therefore, consideration of long-term variability associated with feedstocks in different potential locations affect the site location decision for a bioenergy plant.

Past studies regarding bioenergy plant locations have improved our understanding of feedstock availability and constraints. One key consideration that has largely been absent from the literature is feedstock supply variability over time. Commercial stemwood harvests vary year-to-year, largely based on market conditions for forest products. Since a forest-residue based bioenergy plant is dependent on stemwood harvesting for feedstock, any variability in harvesting directly influences the volume of residues that would be available. Therefore, considering the variability associated with feedstocks in different locations could be important in choosing the best location for a bioenergy plant.

Understanding the Variability of feedstock supplies is important for making a number of different economic decisions. One such decision is choosing the location of a biorefinery (source). Studies have also considered variable feedstock supplies when investigating whether and when to expand the production of bioenergy from burning residues [15] [16] [17]. Other studies have explored the context of variable supplies when making decisions about capital investments in forest residue-based biorefineries [18] [19] [20]. Variable feedstock supplies are also shown to affect capital investment decisions related to investing in a residue preprocessing facility [19], types of storage infrastructure for bioenergy plant feedstocks [20], as well as whether to invest in biofuels versus bioenergy, and when to invest in processing facilities [18].

Our study contributes to the literature by considering variability in forest residue feedstock supplies for the purpose of selecting the best location for a bioenergy plant from three potential locations. More specifically, we use precise information on the location and year of historical timber harvests in Alberta, Canada to quantify the spatial and temporal variability of timber harvest and corresponding variability of forest residue availability. We estimate transportation costs (based on cycle times for road networks in Alberta) between bioenergy plant sites and areas of timber harvested during our study period. The spatial and temporal variability of forest residues results in variability in the transport cycle time from the residue collection areas to the bioenergy plant, which in turn leads to variability in delivered residue cost. From this information we develop historical cost curves for collecting and delivering forest residues to each of the three potential bioenergy plant locations for each of the 26 years in our study period (1990–2015). We conduct sensitivity analysis on 3 different bioenergy plant capacities, as defined by annual forest residue feedstock requirements: 200 Gg/a (e.g. for a small wood pellet mill, 400 Gg/ (e.g. for a large pellet mill or a small biorefinery), and 800 Gg/a (e.g. for a large biorefinery).

The methods used for this study are similar to that used by FPInnovations for their biomass availability estimates for timber supply areas in British Columbia (e.g. [21]. Like us, FPInnovations develops supply curves, or cost-availability curves, based on a road network and historical harvests. However, their approach to modeling temporal variability is limited to comparing the averages of two 5-year periods. As well, they limit their analyses to the boundaries of timber supply areas. The only boundary that limits our analysis is the provincial border.

Our analysis also shares similarities with work published by Yemshanov *et al.* [22]. They develop supply curves at national and regional levels based on a national forest inventory and the location of cogeneration facilities associated with forest products manufacturing facilities. However, their analysis is based on reported annual volumes of processed wood at each manufacturing plant in a single year (2010), and the corresponding residue delivery cost. Instead, we consider the spatial location of all the harvest sites over a 26-year period (1990-2015) and calculate the delivery cost for each harvest site in the year it was harvested.

In the next section we describe our study area and data sources. We then describe how we aggregate and analyze the data. We present our results in the form of marginal delivered biomass cost for each of the 26 years in the study period, and for each of the three alternative plant locations. We conclude with a discussion of financial considerations regarding forest residues as a biofuel feedstock, with relevance to forest companies, policy makers, and bioenergy investors.

# Study area and data

## Study area

We use the province of Alberta in western Canada as our study area, which occupies 661 848 km2 (Fig. 1). The southeastern part of the province is largely privately owned agricultural land, and the northern and western parts are largely publicly owned forested land. There is, however, a substantial area of privately owned agricultural land in the Peace River region of northwestern Alberta. There are also large areas in National Parks along the Rocky Mountains and in the far north of the province. The provincial government identifies the area of mostly publicly owned forested land (excluding the National Parks) as the Green Area, and the area of mostly privately owned agricultural land as the White Area (Fig. 1). About 90% of the harvested timber volume in Alberta comes from the Green Area.

[ Figure 1 about here ]

Our focus for this study is the areas surrounding the towns of Hinton, Edson, and Whitecourt in west-central Alberta. We used the Weyerhaeuser Company Limited oriented strand board plant in Edson, the Millar Western Forest Products Ltd. pulp mill in Whitecourt, and the West Fraser pulp mill in Hinton as the three locations that we consider for a potential forest residue-based bioenergy plant.

These 3 potential bioenergy plant locations were chosen as they host forest products companies and are located near forest areas with substantial harvesting activity. We assume that a potential forest residue-based bioenergy plant would be located near an existing forest products mill, as timber harvesting is occurring to supply those mills, and the requisite forest road network would already be developed. Locating a forest residue processing plant near a forest products mill could also allow for convenient access to mill residues.

## Data

Several publicly available datasets were used to create the township-level (typically 9.778 km by 9.716 km, or 9 500 ha) summary data used in our analysis (townships provide the basis for legal land descriptions in Alberta). Most of the data are freely available on the World Wide Web. All national level data were clipped to the Alberta provincial boundary for further analysis.

The datasets are introduced here. Their uses will be discussed in detail later.

### Altalis

Altalis manages much of the spatial data created by or for the Government of Alberta. We use several coverages from their base features database product [23]: boundaries for the province, the Green and White Areas, forest management units (FMUs), forest management agreement areas (FMAAs), and Alberta Township Survey System.

### Alberta Geospatial Services

Alberta Geospatial Services is operated by the Alberta Ministry of Environment and Parks [24]. We obtained road access coverages from this database.

### National Forest Information System

The National Forest Information System (NFIS) provides spatial data layers representing forest properties at a 250 m (6.25 ha) resolution for all of Canada [25]. We used the merchantable volume, stand age, and species composition attributes from these data layers.

Another product of NFIS is a set of spatial datasets derived from satellite data [26]. The dataset used for this study shows the location of timber harvest for each of the years 1985-2015. The dataset is described by Hermosilla *et al.* [27]. It consists of a raster for Canada at 30 m (0.09 ha) resolution indicating the year of harvest for each cell.

The NFIS also provides a web-based individual tree biomass calculator [28], which we used to calculate stem wood, stem bark, branch, and foliage biomass for a tree based on province, ecozone, species, diameter at breast height (DBH) and height.

### Natural Resources Canada

Ref. [29] describes the tree taper models developed for Canada. We use these taper models to estimate merchantable stemwood volumes and the amount of forest residues (branches and tops) available from harvested areas in each of the townships in each year.

### National Forestry Database

The National Forestry Database (NFD) [30] provided the timber harvest volumes and total harvest areas from Alberta for the years 1990-2015. We used this information to adjust the spatial NFIS volumes mentioned above to better reflect the actual aggregated harvest volumes observed in Alberta.

### Forest management plans

The Alberta government requires Forest Management Agreement (FMA) holders to develop a forest management plan for each FMA. The forest management plans were used to obtain information on utilization standards and average piece size of harvested trees for the FMA [24].

### Agriculture and Agri-Food Canada

The boundaries of Canada’s terrestrial ecozones can be found on Agriculture and Agri-Food Canada’s website [31]. Ecozone is an input into the NFIS individual tree biomass calculator [28], described in section 2.2.3.

# Data aggregation and modeling

We quantify the spatial and temporal variability of the costs associated with collecting and transporting the forest residues left following stemwood harvest. The variability of costs is largely related to variability in the transport distance from the residue collection areas to the bioenergy plant.

Running our simulations required us to aggregate township-level summaries of data for use by the model. Much of this data processing involved the manipulation of spatial data, which was done using the QGIS geographic information system (GIS) software [32] and add-ons. Data summaries and statistical analysis were done using R [33] with RStudio [34] and the tidyverse [34] collection of R packages.

We develop a model based on the assumption that forest residue extractors follow an optimization procedure where they take the cheapest (closest) residue first, and stop when they have enough to satisfy the annual biomass requirements for each of the three scales of bioenergy plants: 200 Gg/a, 400 Gg/a, and 800 Gg/a. Township level residue yield (Mg·ha-1), cycle times (h), and harvest areas (ha) are the three essential summary parameters used by the model.

## Data aggregation

### Cycle time estimates

The provincial road network was divided into four classes: primary highways, other paved roads, two-lane gravel roads, and one-lane gravel or dirt roads. Loaded and unloaded travel speeds were assumed for each road class, according to Table 1. These travel speeds are based on those assumed by FPInnovations for the Dawson Creek Timber Supply Area in the neighbouring province of British Columbia [21].

The correct way of calculating an average of rates is to use the harmonic mean. For each segment in the road network, the harmonic mean of loaded and unloaded speeds was calculated using Eq. 1.

Where is the loaded speed and is the unloaded speed. Use of harmonic mean allows us to calculate the correct cycle time: the time required to travel from the mill to the collection site at the cutblock, and back to the mill. This provides the basis for our estimates of haul cost.

Figure 2 illustrates the road network in Alberta and estimates of cycle time based on the average of loaded and unloaded speeds from Table 1. The road network in the White Area of the province is dense and largely arranged as a grid defined by the Alberta Township Survey System. Most of the roads in the White Area are public. The road network in the Green Area is less dense and many of the roads are built and maintained by resource industries (*e.g.,* forestry, petroleum, and natural gas). The pattern of the road network is not as regular as in the White Area.

[ Figure 2 about here ]

One-way haul times based on the harmonic mean travel speed were generated using the QGIS Network Analysis Toolbox 3 plug-in (QNEAT3) [35], specifically its “iso-area as interpolation (from point)” algorithm. In our case, we used the algorithm to determine the minimum one-way travel time (using the harmonic mean of loaded and unloaded speeds) along the road network from each of our centers to each cell of a provincial level raster at a 200 m resolution. Off-road travel was assumed to be at 5 km/h . The Dijkstra algorithm [36] is the basis for travel time minimization in QNEAT3. Cycle time is double the one-way haul time with an extra hour added for loading and unloading.

QGIS zonal statistics were used to calculate the median cycle time to each township, from each of the three potential bioenergy plants. The cycle time in Figure 2 was limited to 14 hours because, in Alberta, drivers of commercial vehicles are not permitted to drive more than 13 hours in a 24-hour period and can spend no more than 14 hours on-duty, including loading and unloading times.

### Biomass collection and transportation costs

All costs and prices used in this study are in Canadian dollars ($). At the time of analysis (2021-11-05), the exchange rate between Canadian and US dollars (USD) was 0.8031 USD/$.

We assume that the biomass available for collection at a cutblock includes the tops, branches, and foliage left at a roadside landing after processing by a stroke delimber. The delimber is assumed to cut the top of the tree at the diameter specified in the utilization standard specific to the harvest area. Following Ref. [37], the cost of collecting residues left behind by a roadside stroke delimber, which includes pre-piling, chipping, road maintenance, supervision, and loading (but does not consider transport) is 41.60 $·Mg-1.

We assume that the residue will be transported from the forest using a live floor chip van with 100 m3 capacity. The USDA Forest Service’s Forest Residue Transportation Costing Model [38] assumes a default solid volume factor of 0.3 for biomass: a 100 m3 capacity trailer could hold the equivalent of 30 m3 of solid biomass. This equates to 11.40 Mg of biomass using the specific gravity of lodgepole pine wood and bark on a green volume basis (0.38) (Ref. [39]). Timber Tracks produces a publication describing forestry equipment hourly rates [40]. The rate reported for a tandem tractor with a tandem trailer was 157.31 $/h. We assume that the tractor-trailer combination used to haul biomass would cost this amount. Using these numbers, the cost of transporting residual biomass was set to 13.80 $·Mg-1/h.

### Aggregation of harvested area

The areas harvested by township in 2009 according to Refs. [26] [27] are shown in relationship to the three potential bioenergy plant locations and the Green Area in Figure 1. Similar aggregated data were created for each of the years 1990–2015. These data were created by using QGIS zonal statistics to sum the area harvested in each township in each year based on the 30 m resolution harvest data [26]. For each township, and each of the years between 1990 and 2015, we store the area harvested (ha) for use in our analysis. We can see from this map that much of the timber harvest in 2009 took place near our potential bioenergy plant locations.

### Conversion of harvested area to harvest volume and available biomass

Detailed procedures were undertaken to reflect the variability in utilization standards between the FMUs, determination of characteristics for the average broadleaf and the average needleleaf tree in each township, and the spatial and temporal distribution of stemwood harvests. The description of these procedures are in the Appendix.

## Aggregation of summary data files

The information was collated into a data set which had a record for each combination of township, plant location, year, and capacity. The fields in the data set were township, plant location, year, and capacity, cycle time, harvest area, and residue yield. This summary data set is the input to the model.

## Modeling

We assume that residue extraction is opportunistic in response to harvesting; residue collection occurs in the same year as timber harvest. The forest manager’s decision to harvest stemwood is made independently of the value of the forest residue, and our cost estimates do not include a payment to the forest manager for the residue. This assumption is appropriate, given that biomass extractors would be providing a service to the forest managers, who currently have to incur the costs of piling and burning the residues because they are not extracted.

Every township is associated with a cycle time required to transport forest residue from the township to each of the three potential bioenergy plant locations, for each of the 26 years in the study period. For each plant location and year, the model examines all the townships in the province that have a positive residual volume and begins the creation of cumulative residual biomass curves starting with the lowest cycle time first. These lists of cycle time and cumulative biomass provide the data for the marginal cycle time curves, which can then be converted to marginal cost curves using the hourly rate and payload for forest residue transport trucks.

The model uses an algorithm whereby the lowest cost residue for a location is extracted first. The model is summarized using pseudocode in Figure 3.

[ Figure 3 about here ]

# Results

## Distributional results

Our results assume that only one of the three potential bioenergy plants would be built. If more than one plant was to be built, the residue collection areas would overlap, thereby reducing the available residue for the both plants. Figures 4 and 5 display marginal cycle time (h) and marginal costs ($·Mg-1) for each of the 26 years in the study period, and for the 3 potential plant locations. Curves for 1990, 2009, and 2005 are highlighted represented the years of minimum, median, and maximum provincial harvest volume in the period. The inter-year variation in marginal costs increases as the cumulative amount of residue collected increases. We can also see that the relative position of the years in terms of cost varies between the plant locations: *e.g.,* the year 2005 was the year of highest provincial harvest, but from a residue availability standpoint was not as good for Hinton as it was for Edson and Whitecourt.

[ Figure 4 about here ]

[ Figure 5 about here ]

Figure 6 presents another view of the interannual variation in the distribution of costs between the plant locations and assumed capacity: the boxplots display the quartiles, and the minimum and maximum costs required to supply a bioenergy plant of a given capacity at each of the locations in each of the years. Here again, we can see the variability increasing as plant capacity increases.

[ Figure 6 about here ]

Figure 7 shows the average cost ($·Mg-1) for each potential location, plant capacity, and year. Overall, the average costs in Edson and Whitecourt are quite similar. Hinton is usually more expensive across years and capacities. The differences become clearer at a capacity of 800 Gg/a, for which Whitecourt is the lowest cost location for most years.

[ Figure 7 about here ]

Table 2 presents summary statistics over the 26 years for the locations and capacities. Average costs and the interannual variability of costs increase with increasing capacity. The variation in costs for Hinton is greater than for Whitecourt and Edson, particularly for the 800 Gg/a capacity.

[ Table 2 about here ]

Figure 8 shows the areas that would have been needed to supply a bioenergy plant of varying capacities in Whitecourt in the year of median harvest (2009) in relation to the proportional township area harvested. Note that there is some residue being collected from the White Area, but most is being collected from the Green Area.

[ Figure 8 about here ]

Figure 9 compares the supply areas for 2005, 2009, and 1990 (high, medium, and low harvest years, respectively) for Whitecourt. The area required to supply the bioenergy plant increases greatly in low timber harvest years, particularly for the 800 Gg/a capacity. Similar maps have been produced for the other locations and all 26 years and are available at the University of Alberta’s Education and Research Archive (ERA). **Put in a dummy URL for now.** Notice that the supply areas are largely within the Green Area. The contours indicate the cycle time associated with each of the capacities. In order to provide another way of visualizing interannual variation, we have created animations of these contour maps that show changes across all 26 years in the study period for the 3 locations (available at ERA).

One consideration absent from our modeling is the cost of moving equipment such as the grinder and loader. Considering these costs, it is unlikely that small, dispersed harvested areas would be accessed. But such areas at our study sites are sufficiently small that we ignore them. [ Figure 9 about here ]

Whitecourt is the lowest cost location for most years at all capacities. There is a noticeable spike in costs 1999, which may be related to salvage harvest following the 1998 Virginia Hills wildfire [41]. Note that this spike also affects Hinton and Edson at 800 Gg/a capacity, because they reach into the Whitecourt area at that capacity level. The average cost of delivered forest residues are lower for the lower capacity plants, as they do not need to collect residues from as far to meet their biomass input requirements. In other words, the average cycle time is lower for the lower capacity bioenergy plants, which results in a lower average delivered residue cost.

Overall, the results show that there is a high level of interannual variability in the costs of retrieving a fixed amount of biomass from timber harvesting residues. The variability is related to the area and location of harvest, which varies from year-to-year, and directly impacts transportation costs.

# Conclusions

Our model demonstrates the importance of spatial and temporal variation in the availability of forest residue for bioenergy production. We conducted this study to answer three questions critical to bioenergy investors and policy makers.

**Which areas are best for locating a potential bioenergy plant when considering residue collection and transport costs?** We focus on the area surrounding the towns of Hinton, Edson, and Whitecourt in west-central Alberta. These three potential bioenergy plant locations were chosen as they host several forest products companies and are located near forest areas with substantial harvesting activity. For each location, we conduct sensitivity analysis on three alternative bioenergy plant capacities as measured by residue feedstock requirements: 200 Gg/a, 400 Gg/a, and 800 Gg/a. For the 200 Gg/a capacity the three locations are almost indistinguishable in terms of average delivered residue cost (~ 87 $·Mg-1). At 400 Gg/a, Edson is the low-cost location (98.6 $·Mg-1). At 800 Gg/a, Whitecourt is clearly the low-cost location (122 $·Mg-1), however, it is important to note that the average cost of supplying an 800 Gg/a plant is over 40% greater than supplying a 200 Gg/a plant.

**How much residue volume is available over what area?** The residue supply areas for the Whitecourt location shown in Figure 9 suggest that if a 400 or 800 Gg/a bioenergy plant was to be constructed, there would only be enough available residue to construct one plant in our study area. Whereas if a 200 Gg/a plant was deemed more viable, our findings suggest that perhaps two plants could be constructed in the study area – one in Whitecourt and one in Hinton. This makes for an interesting investment choice, since a single 800 Gg/a bioenergy plant would likely face an average delivered residue cost that is over 40% higher than the cost for the 200 Gg/a plants. Recall from above that 200 Gg/a is the appropriate scale for a pellet plant and 800 Gg/a is more representative of a biorefinery. Given that dried and compacted pellets are cheaper to transport than moist and bulky residues, it could be more viable to first transport residues to pellet plants, and then transport the pellets (perhaps via rail) from multiple pellet plants to a biorefinery. The optimal result of this analysis will depend on the cost of pellet production relative to the cost savings (transportation and production) to the biorefinery from using pellets instead of residues.

**Would residue volumes be consistently available on a year-to-year basis?** Given that a forest residue-based bioenergy plant is dependent on forest harvesting, transportation cost increases in years when harvesting levels are low or harvest areas are further from the bioenergy plant. Our results showed considerable variability in both marginal and average residue extraction costs from year-to-year for the 400 and 800 Gg/a capacities, suggesting that residue cost variability is an important source of risk for medium and large bioenergy plants. Our finding that the cost variability is lower for the 200 Gg/a might once again suggest that a 200 Gg/a is a more appropriate scale for a forest residue-based bioenergy plant in Alberta.

Our conclusions are based on an analysis of historical harvest levels, which might not be indicative of the future. However, we feel confident that our findings will be relevant into the future largely because public forest in Alberta is managed according to the sustained yield paradigm, which involves the determination of allowable annual cuts over a 200-year planning period. For evidence of this stability, Figure 11 shows that harvest volume rises until the year 1995, which coincides with the last of the major forest product mills in Alberta being constructed in the early-1990s, and after this date harvest levels flatten out and become fairly stable. Transportation costs can also be expected to be stable in the future because long-term forest management plans in Alberta require a balanced log haul distance. In other words, the Alberta government would not approve a plan whereby forestry firms concentrate harvest operations where haul distances are expected to significantly increase in the future. Hence, it is reasonable to assume that in the future, both average annual harvest levels and average annual transport distances – and thereby average annual forest residue costs – will be close to the historical values from our analysis.

Although we are confident that our conclusions will hold in the future over the long-term, it is nonetheless possible that over the long operating life of a forest residue-based bioenergy plant, there could be significant events that could impact residue availability over the short-term – *e.g.*, bad weather which prevents forest harvest and/or residue extraction, temporary mill shutdowns, and forest fires. This possibility makes it important for a forest residue-based bioenergy plant to have a comprehensive feedstock risk management program. If the bioenergy conversion technology allows it, this risk management program could consider creating a portfolio of different sources of feedstock. Such a portfolio approach might consider locating the bioenergy plant where it could also access other types of feedstock – such as agricultural residues and/or purpose-grown feedstocks – during periods when availability of forest residues is low. This approach is sometimes called “derisking” in the feedstock supply literature, whereby a supply of “buffer” feedstock is contracted to keep the bioenergy plant running during years when normal residue supplies are low [42]. Ref. [43] discusses the amount and variability of production of agricultural residue in Alberta; and Ref. [44] discusses the financial viability of establishing fast-growing hybrid poplar plantations in Alberta for use as a purpose-grown bioenergy feedstock.

When considering portfolios of different bioenergy feedstocks, an important factor will be the average delivered cost for each feedstock. Our estimates for average delivered forest residue costs range from approximately 87 $·Mg-1 for the 200 Gg/a capacity to approximately 122 $·Mg-1 for the 800 Gg/a capacity. Previous studies have estimated the cost of agricultural residue (straw) to fall within this range, with a plant gate cost in Alberta of 95.33 $·Mg-1 for a plant capacity of 150 Gg/a [45]. Given how close the cost of agricultural residues is to the cost of forest residues, these two feedstocks could be a good fit for a potential feedstock portfolio, assuming the bioenergy plant could use both types of feedstock. However, a previous study estimated that purpose-grown hybrid poplar in Alberta has a much higher delivered cost of 202 $·Mg-1 (125 $·Mg-1 to grow the trees, plus 77 $·Mg-1 to harvest, grind, and transport the trees to the bioenergy plant) [44], suggesting that hybrid poplar would have a more limited role (if used at all) within a feedstock portfolio. In the future we hope to build upon this research by optimizing the allocation of different feedstocks within a bioenergy feedstock portfolio.

Although forest residues are utilized for bioenergy in other parts of the world, they are still largely considered a waste product in Canada. Given that feedstock costs are critical to the economic viability of any bioenergy project, in order for forest residues to be extracted in Canada we will likely need to see improvements in bioenergy production technology and/or increases in future biofuel prices. Governments can play a role in improving bioenergy production technology through investment research and development, and can impact future biofuel prices through public policy.

On the Canadian public policy front, governments have set renewable fuel mandates and subsidize production of bioethanol and biodiesel, thereby impacting future biofuel prices [1]. The continuation of such subsidies will likely be an important factor for the emergence of a second-generation or advanced biofuel sector in Canada. Another factor that could provide important incentives for advanced biofuels is the Government of Canada’s Clean Fuel Standard, which is proposed to come into force in 2022, and which will require transportation fuel suppliers to lower the carbon intensity of their fuels [46]. Although these policies are focused more on liquid biofuels, there are also new policies which could promote burning pellets. The Government of Canada recently implemented carbon pricing regulations [47] which could provide incentives to use forest residue pellets in heat and power plants instead of coal and natural gas. In this case, since the pellets would likely generate lower greenhouse gas emissions than the fossil fuels they displace, the heat and power produced would thereby incur lower carbon taxes, thus improving the financial returns to using pellets.

# Data availability

The data compiled to the township level are currently available on github(<https://github.com/gwa-uab/histressup/tree/main/data>). Before publication it will be placed on ERA with a DOI.

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