Spatial and temporal variability in forest harvesting in west-central Alberta, Canada,between 1990 and 2015: an analysis of forest residue costs for bioenergy use

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This is the abstract.

It consists of two paragraphs.

# Introduction

Humans have been using biofuels since learning to control fire a million or so years ago. In developed economies, early biofuels were largely displaced by coal during the industrial revolution, and by petroleum starting in the mid-nineteenth century. In recent times, biofuels are once again becoming an important source of energy because of their potential to reduce greenhouse gas emissions. In the European Union, the United Kingdom, and Japan, many heat and power plants have been converted to use wood pellets instead of coal and natural gas.

Liquid biofuels (*e.g.,* ethanol and biodiesel) have been produced in commercial quantities from food crops starting in the 1980s. These are called first generation biofuels. In some jurisdictions policies to promote first generation biofuels are being phased out because of concerns that they compete with food, and that their production may lead to land use change (Campbell et al 2016).

Second generation biofuels rely on processes that convert lignocellulosic materials (such a corn stover and wood) to liquid biofuels. An advantage of this process is that the feedstock can be waste residue left over from food or forest products production. Second generation biofuel production is still largely in a pilot or demonstration phase. An interesting example using forest residues is the Silva Green Fuel renewable crude oil plant in Tofte, Norway which was expected to begin operations in 2021 [1].

Technologies to pelletize wood are more established than technologies to create 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 [2]. Most of the wood pellet production in Canada comes from forest product mill residues, such as sawdust and bark. There is interest, however, in expanding the biomass source to the forest by collecting the residues left within harvested areas: a practice that is rare in Canada, but reasonably well-established in Europe.

Forest residues are generated as by-products of conventional forest harvesting operations and include the treetops, 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 Mg[[1]](#footnote-2) of forest residues annually [4]. Despite this huge potential supply of feedstock, there are key questions about the financial viability of investments into production facilities that would convert forest harvesting wastes into biofuels. How much volume is spread over what areas? Which areas are best for locating a potential bioenergy plant when considering collection and transport costs? Would feedstock volumes be available on a year-to-year basis? In this paper we attempt to answer these questions.

There are several studies regarding plant location decisions for forest residue-based bioenergy facilities, as reviewed by Johnson *et al*. [19]. Although these studies have improved our understanding of feedstock availability, they tend to use limited datasets and often focus on average levels of biomass availability. A key area that has largely been omitted in the bioenergy plant location literature is consideration of feedstock supply variability over longer periods of time. Instead of just focusing on average residue levels, a bioenergy investor is likely to be concerned about the financial impact of years when residue availability is low, which is the focus of our study.

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 between Canada and the United States have resulted in sawmill closures and reductions in forest harvesting activities in western 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 {from (Caputo et al., 2005; Leistritz et al., 2007) which are cited in [12]}, 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 [8]. 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 long-term variability associated with feedstocks in different potential locations could be important in choosing the optimal site for locating a bioenergy plant.

Although few studies consider long-term forest residue variability for the purposes of optimizing the location of a potential bioenergy plant, there are studies that consider variability for other purposes. Some studies have considered variable feedstock supplies when investigating whether and when to expand the production of bioenergy from burning residues [13] [14] [15]. Other studies have explored the context of variable supplies when making decisions about capital investments in forest residue-based biorefineries [16], [17] [18]. Variable feedstock supplies are also shown to affect capital investment decisions related to investing in a residue preprocessing facility (Chen and Fay 2011) [17], types of storage infrastructure for bioenergy plant feedstocks [18], as well as whether to invest in biofuels versus bioenergy, and when to invest in processing facilities [16].

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 out of three potential locations. More specifically, we use precise information on the location and year of historicaltimber harvest in the western Canadian province of Alberta to quantify the spatial and temporal variability of timber harvest and relate that information to spatial and temporal variability of forest residue availability. We develop transportation cost estimates to the timber harvest areas based on cycle time estimates developed from the road network in the province. 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 leads to variability in delivered residue cost. From this information we develop historical cost curves [22] for collecting and delivering forest residues to each of the three potential bioenergy plant locations for each of 26 years in our study period (1990–2015). In addition to considering locations for the potential bioenergy plants, we considered 3 different plant capacities defined by annual forest residue feedstock requirements: 200 Gg/a corresponding to a small wood pellet mill, 400 Gg/a corresponding to a large pellet mill or a small biorefinery, and 800 Gg/a corresponding to 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 (see Ref. [21] for an example). Like us, FPInnovations develops supply curves (cost-availability curves) based on a road network and historical harvests. However, their take on temporal variability is limited to comparing two 5-year periods. As well, they limit their analyses to the boundaries of timber supply areas. We do not limit ourselves with arbitrary boundaries.

Our analysis also shares similarities with work published by Yemshanov *et al.* [20]. 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 the reported annual volumes of processed wood at each manufacturing facility in a single year (2010), and the corresponding residue delivery cost). Instead, we consider the exact 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 then present our distributional 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

We describe here our study area, data sources, and methods.

## Study area

We use the province of Alberta in western Canada as our study area. It occupies 661 848 km2. Its southern boundary is 49°N latitude, northern boundary is 60°N latitude, eastern boundary is 110°W longitude, and its western boundary is defined by 120°W longitude and the Great Divide of the Rocky Mountains (Figure 1).

[ Figure 1 about here ]

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 Country of northwestern Alberta. There are also large areas in National Parks along the Rocky Mountains and in the far north of the province. The province calls the area of mostly publicly owned forested land (excluding the National Parks) the Green Area, and the area of mostly privately owned agricultural land the White Area. About 90% of the harvested timber volume in Alberta comes from the Green Area.

Our focus for this study is area surrounding the towns of Hinton, Edson, and Whitecourt in west-central Alberta. These locations were chosen as they host several 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 would also allow for convenient access to mill residues.

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 analyze for a potential forest residue-based bioenergy facility.

## Data

We used several publicly available datasets to create the township-level (typically 9.778 km by 9.716 km, or9 500 ha) summary data used in our analysis. 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 use 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 [29]: boundaries for the province, the Green and White Areas, forest management units (FMUs), forest management agreement areas (FMAAs), Alberta Township Survey System (townships provide the basis for legal land descriptions in Alberta).

### Alberta Geospatial Services

Alberta Geospatial Services is operated by the Alberta Ministry of Environment and Parks [31]. We obtained road access coverages from there. National Forest Information System (NFIS)

The NFIS provides a set of spatial data layers representing forest properties at a 250 m (6.25 ha) resolution for all of Canada [32]. 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 [33]. The dataset used for this study shows the location of timber harvest for each of the years 1985-2015. The dataset is described in detail in Ref. [34]. 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 [35], 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. [36] describes the tree taper models developed for Canada. We use these taper models to determine 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 [38] 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 FMA holders to develop a forest management plan for the FMAA. The forest management plans were used to obtain information on utilization standards and average piece size of harvested trees for the FMAA [39].

### Agriculture and Agri-Food Canada

The boundaries of Canada’s terrestrial ecozones can be found on Agriculture and Agri-Food Canada’s website [40]. Ecozone is an input into the NFIS individual tree biomass calculator [35], described above.

# Data aggregation and modeling

This paper quantifies 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 changes in the transport distance from the residue collection areas to the bioenergy plant.

Most of the effort expended on this study was spent in creating township-level summaries of data for use by the model. Much of this data processing was the manipulation of spatial data, which was done using the QGIS geographic information system (GIS) software [28] and add-ons. Data summaries and statistical analysis were done using R [41] with RStudio [42], and tidyverse [43].

We develop a model based on the assumption that forest residue harvesters follow a greedy optimization: they take the cheapest (closest) residue first, and stop when they have enough to satisfy the annual biomass requirements for the three scales of bioenergy plants: 200 Gg/a, 400 Gg/a, and 800 Gg/a.

[put data aggregation summary here]

Our model assumes that residue collection is opportunistic. In other words, forest managers decide when and where to harvest, and residue collection occurs afterwards, but within that same year of harvest. The forest manager’s decision to harvest stemwood is made independently of the biomass value of the forest residue, and no price is paid to the forest manager for the residue. This assumption is appropriate, given that biomass harvesters provide a service to the forest managers, who would have to incur the costs of piling and burning the residue if it was not collected.

Every township is associated with a cycle time required to transport forest residue from the township to each of the three potential 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 marginal cost curves using the hourly rate and payload for forest residue transport trucks. Although our model ignores the cost of moving equipment from one block to another, we believe it still provides useful information.

The model is summarized using pseudocode, below.

Text

Description automatically generated

Each parameter of the model is now discussed in turn.

## 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 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 very dense and largely arranged as a grid related to 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) [44], 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 [45] is the basis for travel time minimization. Cycle times were calculated by multiplying the one-way haul time by 2 and adding 1 hour 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 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 writing (2021-11-05), the exchange rate between Canadian (CAD) and US dollars (USD) was 0.8031 USD/CAD.

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 log off at the diameter specified in the utilization standard relevant to the harvest area. Following Ref. [46], 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 [47] assumes a default solid volume factor of 0.3 for biomass meaning that 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. [48]).

Timber Tracks produces a publication describing forestry equipment hourly rates [49]. 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 a similar amount.

Therefore, the cost of transporting residual biomass was set to 13.80 $·Mg-1·h-1.

## Harvested area

The areas harvested by township in 2009 according to Refs. [33] [34] 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. 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 a great deal of timber harvest took place near our potential plant locations in 2009.

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 [33].

## Utilization standards, average tree characteristics, and distribution of stemwood harvests

Much detailed work was done 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 the procedures used for this are in the Appendix.

## Residue yield by township

Township level residue yield (Mg ha-1), cycle times (h), and harvest areas (ha) are the three essential summary parameters that used by the greedy optimization model. Development of the residue yields required the most effort. Utilization standards, the residual biomass of the average needleleaf and broadleaf tree, and spatial variability in residue yields need to be accounted for. The procedures used are described in detail in the Appendix.

For each township, we calculate the number of stems by dividing the adjusted volume per hectare by the average piece size for both needleleaf and broadleaf trees. We assume that for the types of stands being harvested that the stem count per hectare for the 13/+7 utilization standard is close to the stem count based on the FMU utilization standard. We multiply the stem count by the average tree residual biomass. We assume an average recovery factor of 0.624 following what Peltola *et al.* [55] determined for Finland, recognizing that some of the residual biomass will be unrecoverable. Together this gives us an estimate of the average residue yield when a hectare of a stand in a particular township is harvested.

## Summary data files

The information collected above 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 of township, plant location, year, and capacity, cycle time, harvest area, and residue yield. This summary data set is the input to the greedy optimization model

# Results and discussion

## The volume adjustment factor

Figure 3 shows the actual harvest volume for Alberta between 1990 and 2015 using data from the national forestry database [38] compared to estimated harvest volumes calculated from harvest area and our calculated harvest volume per hectare. The largest discrepancy occurs in 1998 where the estimated volume is substantially larger than the actual volume. Note that in 1998, industrial salvage volumes of 369 791 m3 of softwood and 264 647 m3 are not included in the harvest levels shown in the graph.

[ Figure 3 about here ]

The estimated harvest volume was calculated using the harvest areas identified in the 30 m data, and the adjusted harvest volume per hectare determined for each township. We are satisfied that, at the provincial level, the adjustment factor produces estimates of harvest volume is similar to that recorded in the national forestry database and is appropriate for use for this study.

The adjustment factor was calculated by dividing the average harvest volume from the actual harvest volume by the from our estimated harvest volumes. The calculated value for the adjustment factor was 2.77. We multiplied the estimated harvest volumes for each township by the adjustment factor, to provide township-level harvest volumes that would be compatible with the province-level harvest volumes from the national forestry database.

The left panel of Figure 4 shows the spatial distribution of merchantable volume by township. The region surrounding the potential bioenergy plant locations contains high volume per hectare. The right panel shows the calculated merchantable volume per hectare for harvested area in each of the townships.

[ Figure 4 about here]

## 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 second plant. Figures 5 and 6 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 5 about here]

[ Figure 6 about here]

Figure 7 is another way of presenting the inter-annual variation in the distribution of costs between the plant locations and assumed capacity: the boxplots display the quartiles, and the minimum and maximum costs require 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 7 about here ]

Figure 8 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 8 about here ]

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

[ Table 2 about here ]

Figure 9 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 of it is being collected from the Green Area.

[ Figure 9 about here ]

Figure 10 compares the supply areas for 2005, 2009, and 1990 (high, medium, and low harvest years) 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). **cite** Notice that the supply areas include areas outside the Green Area with very little harvest. The contours indicate the cycle time associated with each of the capacities. Because of the cost of moving equipment such as the grinder and loader, it is unlikely that the small, dispersed harvested areas would be accessed, but the volumes are small enough that we ignore them. We have created animations of these contour maps for all 26 years in the study period for the 3 locations (available at ERA). These provide another way of visualizing the inter-annual variation.

[ Figure 10 about here ]

Whitecourt is 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 [56]. Note that this spike also affects Hinton and Edson at 800 Gg/a capacity, because they reach into the Whitecourt area.

The average cost of forest residue are lower for the lower capacity facilities, as they do not need to travel as far to meet their biomass input requirements.

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 spatial and temporal variation in the availability of timber harvest residue for bioenergy production. We did this using the location of timber harvest areas in the Canadian province of Alberta for the years 1990–2015. This is a historical study, but the information generated could be useful for investors exploring the potential of forest residues in Alberta for biomass energy production.

We examined three potential plant locations, and three alternative plant capacities as measured by biomass input requirements: 200 Gg/a, 400 Gg/a, and 800 Gg/a.

The results showed considerable variability in both marginal and average residue collection costs from year to year. The variability increases as input requirements increase.

The maps produced as output from this study demonstrate how the supply areas needed to meet the input requirements vary quite a bit from year to year. This would become especially interesting if multiple plants were established: they could be competing for biomass in some years, and not in others, depending on their locations.

For the 200 Gg/a capacity the three locations are almost indistinguishable in terms of mean 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). The average cost of supplying an 800 Gg/a plant is at least 40% greater than supplying a 200 Gg/a plant.

This makes for an interesting investment choice. If a large facility was built, would it make sense to haul comminuted biomass to the facility from far away? Perhaps it makes more sense to transport the comminuted biomass to smaller satellite pellet plants, and then transport the pellets to a larger plant (e.g., ethanol). Pellets are cheaper to transport than comminuted biomass, as they contain less moisture, and are denser. The answer to this question would depend on the costs associated with the satellite plants, and the relative transportation costs of comminuted biomass and pellets.

Residue cost variability is an important source of risk for a forest residue-based biomass processing facility. Being dependent upon stemwood harvests for the generation of residues can lead to cost variability over the long operating life of a biomass processing facility, making itimportant to have a comprehensive feedstock risk management program. If the conversion technology allows it, biorefineries could consider creating a portfolio of different sources of residues. Such a portfolio approach might consider locating the biorefinery where it could also access agricultural residues during periods when availability of forest residues is low. Ref. [57] discusses the amount and variability of production of agricultural residue in the province.

We plan to investigate feedstock portfolios in future research.

~~OTHER POTENTIALLY USEFUL TIDBITS.. I left these here as a reminder.~~

~~The need to go outside its normal delivery zone in bad years is similar to a scenario in the agriculture residue feedstock supply literature, called the the “derisked” scenario, whereby a buffer area outside the normal supply zone is contracted to provide residues during years when residue supply is low [23].~~

~~Modern biorefineries can expect to breakeven financially with delivered biomass costs of approximately $80 (US$60) Mg (Steeper 2021) [~~**~~Steeper2021?~~**~~] . Studies have shown that forest policy reforms could reduce delivered forest residue costs by incenting plantations of fast-growing tree species on lands close to pulpmill locations (Shooshtarian et al. 2021 [24], Anderson et al. 2012 [25]). Other important factors will be advances in biorefinery technology and increases in biofuel prices. In Canada, governments impact biofuel prices by setting renewable fuel mandates and paying subsidies for biofuel production (Campbell et al., 2016). The continuation of these mandates and subsidies will likely be an important factor for the emergence of a second-generation (“advanced”) biofuel sector. Also, the Government of Canada's Clean Fuel Standard, which is proposed to come into force in 2022 (Government of Canada, 2020), is expected to improve the economics of advanced biofuel production.~~

# 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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1. In this paper we express biomass using SI units, and all quantities of biomass will be expressed on an oven-dry basis such that 1 Mg is equivalent to 1 oven-dry metric ton. [↑](#footnote-ref-2)