Spatial and temporal variability in forest harvesting in west-central Alberta between 1990 and 2015: a GIS 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, in particular, 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 is expected to begin operations in 2021 [1].

Technologies to pelletize wood are more established than technologies to create liquid fuels from wood. Indeed, it is projected that Canada will 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].[[1]](#footnote-1) For the remainder of 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 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 Mg of forest residues annually [4]. Yet 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, such as: How much volume is spread over what areas? Which areas are best for locating a potential biorefinery when considering collection and transport costs? And would feedstock volumes be available on a year to year basis? In this paper we attempt to answer these questions.

There have been a number of studies conducted regarding plant location decisions for forest residue-based bioenergy facilities, as are 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 are considerations of feedstock supply variability over longer periods of time. Indeed, instead of focusing on average residue levels, a bioenergy investor is more likely to be more concerned about the economic 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].~~

As mentioned above, 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 information on the location and year of timber 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 residues. We develop transportation cost estimates to the timber harvest areas based on cycle time estimates developed from the road network in the province. Indeed, the spatial and temporal variability of forest residues results in variability in the transport distance from the residue collection areas to the biofuel 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 estimations 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 examining 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, because their analysis is based on timber inventory data, the timber harvest locations are approximated across the national working forest based on the reported annual volumes of processed wood at each manufacturing facility in a single year (2010). Given that our analysis is based on the location and year of timber harvest, we do not approximate harvest sites (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 those 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 the Green 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.

~~The forest management areas which supply most of the timber to mills near our three locations are West Fraser Mills Ltd. (Hinton), West Fraser Mills Ltd. (Edson), Weyerhaeuser Company Limited (Pembina Timberlands), Millar Western, Blue Ridge Lumber Inc., and ANC Timber Ltd.~~

We used the Weyerhaeuser 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 a number of publicly available datasets to create the township-level (9.778 km by 9.716 km, 9 500 ha) summary data used in our analysis. Most of the data are freely available on the internet. 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).

~~The ATS boundaries are particularly important to this study as all the data used for this study are aggregated or disaggregated to the township level. ATS provides the basis for legal land descriptions in Alberta. The typical township is roughly square (9.778 km by 9.716 km, 9 500 ha) and is indexed by township (1–126), range (1–30), and meridian (4–6). The townships immediately east of Alberta’s western boundary, and immediately east of the 5~~~~th~~ ~~and 6~~~~th~~ ~~meridians (corresponding to 114°W and 118°W longitude, respectively) are partial townships and therefore deviate from the roughly square shape. ATS is described in detail by the Alberta Land Surveyor’s Association [30]. There are 7 237 townships in Alberta, allowing for spatial resolution appropriate for regional or provincial level analyses.~~

### Alberta Geospatial Services

Alberta Geospatial Services is operated by the Alberta Ministry of Environment and Parks [31]. We obtained road access coverages from there. A road access coverage is also available from Altalis but it does not have as detailed information on road class.

### National Forest Information System (NFIS)

The NFIS provides a set of spatial data layers representing forest properties at a 250 m by 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 by 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] contains 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

As mentioned above, 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 collectors follow a greedy optimization – *ie.,* they have no input in where forest harvesting takes place, so 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.

For each combination of potential bioenergy plant location and year, all the townships in Alberta were sorted by ascending cycle time, which equates to a marginally increasing transport cost. The model works through this list, accumulating harvest residue recovered from the harvest area associated for the township and year, and provided a file showing cycle time, total cost, and cumulative residue recovered. Once this file was created, the GIS was used to generate the results.

Our model is specified as follows:

*Cxit* = harvested area \* residue density \* (cycle time \* transportation cost) + collection cost (blah blah blah… this is really rough… there’s lots going on below, and I think it might be useful to structure the rest of the methods based on the variables in this equation, where everything below feeds into this main equation (as per Shooshtarian 2018 B&B paper) or as we discussed in the meeting it might be best to use a flow chart (as per Yemshanov 2014 B&B), or as Marty suggested, it might be best to include both

Where:

*Cxit* is the cost of collecting and delivering residue from township x to location I during year t;

As mentioned above, our model assumes that residue collection is opportunistic. In other words, forest managers decide when and where to harvest, and residue collection occurs sometime 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 collectors actually provide a service to the forest managers, who would have to incur the costs of piling and burning the resides 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.

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) ~created by Raffler~ [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 centres to each cell of a provincial level raster at a 200 m by 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 that 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 (2021-11-30 22:44:07 GMT), the exchange rate between Canadian (CAD) and US dollars (USD) was 0.7830 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 US 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 by 30 m resolution harvest data [33].

## Utilization standards

For administrative purposes, the Green Area is divided into Forest Management Units (FMUs). The province enters into long term agreements with forest products companies giving the companies the rights to timber harvest and the responsibility to manage the forest sustainably. These agreements are called Forest Management Agreements, and the areas under agreement are called Forest Management Agreement Areas (FMAAs). For the most part, the boundaries of the FMAAs are coincident with FMU boundaries, with the exception of the Alberta-Pacific FMAA in eastern Alberta which comprises 12 FMUs. Maps of the FMUs [26] and the FMAAs [27] can be found on the Government of Alberta website. The FMU and FMAA boundaries are used to assign utilization standards (discussed here) and average piece size (discussed in the next section).

Many forest products companies operate in Alberta, and the details of their agreements with the government with respect to forest management differ. Some companies have harvesting rights to just the needleleaf species, others have rights to just the broadleaf species, and some have rights to both needleleaf and broadleaf.

Utilization standards in Alberta are specified on the basis of stump height, minimum stump diameter (outside bark), and minimum log length to a specified top diameter (inside bark). Utilization standards vary by FMU. Stump heights used in Alberta are 15 and 30 cm; stump diameters are 13 or 15 cm; top diameters range between 7 and 12 cm; and minimum log lengths range between 2.44 and 4.88 m. These utilization standards are necessary to relate volumes calculated to the 13+/7 cm standard for the National Forest Inventory to the harvest volumes reported by the companies. Perhaps most importantly, the minimum top diameter will have an effect on the volume of residue left in the forest corresponding to the tops of trees.

Based on the FMU boundaries, we assign a needleleaf and broadleaf utilization standard to each township.

## Characteristics of the average tree

### Piece size

FMA holders are required by Alberta to project average piece size of harvested trees in the detailed forest management plans (DMFPs) for their FMAAs. We use these piece sizes projected for the first period of the DMFP. They range from 0.110 to 0.599 m3 per tree. We used the piece size reported for the first 5-year period of the 200-year planning horizon. For those areas where piece size was not reported we assumed an average piece size of 0.278 m3 for needleleaf trees and 0.264 m3 for broadleaf trees. These are the average of the values reported in the forest management plans. These values are based on the utilization standards used on the FMA. Based on the FMU boundaries we assign an average piece size for broadleaf and needleleaf trees to each township.

### Taper functions

Ref. [36] presents taper models and the associated coefficients for the tree species found in Canada. These taper models can be used to find the diameter at any point along the main bole of a tree given species and diameter at breast height (DBH). DBH is a commonly used tree measurement and is the diameter of the tree measured at 1.3 m above ground level, in most jurisdictions, including Alberta. It is straightforward to determine cross-sectional area of the tree at any height. Integrating this area function will yield volume between any two heights.

Ref. [36] describes a one-parameter model which is useful when both tree DBH and height measurements are available.

where is the diameter (cm) at height (m), and is the diameter at breast height (1.3 m above ground level), and is tree height (m).

For those cases where height measurements are unavailable, they present a 3-parameter model, where H is replaced with .

where is the diameter (cm) at height (m), and is the diameter at breast height (1.3 m above ground level)

Implicit in this equation is an equation for tree height

which we will use to create input for the biomass calculator

The radius of the tree (m) can be calculated from and using

where the constant 200 is used to convert a diameter (cm) to a radius (m).

The volume of the merchantable log between stump height and the height of the tree at the minimum top diameter () can then be calculated through integration.

Ref. [36] also presents a simple linear model relating outside bark to inside bark diameter. The taper function is for outside bark diameter, but piece sizes are reported as inside bark volume.

### DBH and height estimates

From information collected from forest management plans we have an estimate of average piece size calculated to a specified utilization standard for every combination of township and FMU, for both needleaf and broadleaf trees. We used a binary search procedure to find DBH and height of the “average” broadleaf and needleleaf tree in each township based on the FMU utilization standard. An average piece size to the 13+/7 utilization standard was also calculated by integrating the cross-sectional area function using the appropriate limits.

Most forest stands in Alberta are considered to be even-aged, as the majority originated following stand-replacing fire or clearcut harvest. It is common to describe stands using a distribution of diameters at breast height (DBH). The diameter distribution for an even-aged stand is usually approximately normal [50]. We use this to justify the use of the average tree.

Using these equations, we are able to calculate wood volumes and bark volumes between any two heights along the tree stem. We calculate the proportions of total tree and bark volumes in the top of the tree. We use this volume proportion later to calculate biomass of stemwood and bark in the top.

The merchantable volume for the average tree is calculated to both the 13+/7 cm utilization standard and the utilization standard specified for the FMU. The 13+/7 cm utilization standard is used to calculate the stand density (stems/ha) for both the needleleaf and the broadleaf species. The FMU utilization standard is use to calculate the volume adjustment factor.

### Individual tree residual biomass.

Canada’s National Forest Inventory website provides a useful individual tree biomass calculator [35]. It calculates the biomass of tree components (stem wood, stem bark, branches, foliage, and total) using province/territory, terrestrial ecozone, species, DBH, and tree height as input. It is possible to upload a file to the calculator so that the biomass of many trees can be calculated at once. The calculator is based on Ref. [51].

We created an input file for the NFIS biomass calculator that included all 125 unique combinations of species, ecozone, DBH, and height assigned to the townships in section @ref(dbhht). (**Create cross-references**).

We assume that the residual biomass comes from the stem wood and stem bark from the tops of the harvested trees, and the branches and foliage removed by the stroke delimber. The residual biomass from the tops is calculated using the total biomass of stem wood and stem bark adjusted by the volume proportions calculated as described above.

## Spatial variability in residual biomass production

There is considerable spatial variability in the amount of timber harvest residues available for biomass collection. The variability relates to the distribution of harvested species and age classes across the landscape, to the timber harvesting practices of different operators, and to other factors. We used the 250 m resolution raster maps of Canada’s forest attributes for 2011 from Natural Resources Canada [32] to retrieve information on species composition, age classes, and merchantable volume. The data were clipped to the Alberta boundary. Merchantable volumes for Alberta in this dataset were compiled to the 13+/7 cm utilization standard, meaning that stump height for each merchantable tree was assumed to be 30 cm, that stump diameter (outside bark) was at least 13 cm, and that the length of the log to a 7 cm inside bark diameter was at least 4.88 m. This is one of the utilization standards used in Alberta and was the one used for Alberta data in Canada’s National Forest Inventory (NFI henceforth) [52].

Forestry companies are selective in the stands they harvest. Some stands will be comprised of undesirable species. The most commercially important needleleaf species in Alberta are white spruce (*Picea glauca* (Moench) Voss), lodgepole pine (*Pinus contorta* var. *latifolia* Engelm.) and jack pine (*Pinus banksiana* Lamb.). Trembling aspen (*Populus tremuloides* Michx.) is the most commercially important broadleaf species. Some stands may have too little volume to be worth harvesting. Some stands may be too young. We selected cells that contained at least 50 m3·ha-1 of merchantable volume, as that corresponds with merchantability limits specified in Alberta [53]. We filtered out cells with more than 50% crown closure of larch (*Larix spp.* Mill.) and birch (*Betula spp.* L.) combined, as those genera are rarely harvested at a commercial scale in Alberta. We filtered out cells with stand age less than 80 years as it is unusual to harvest stands younger than that in Alberta. QGIS zonal statistics were used to average the merchantable volume per ha of the merchantable cells in each township.

Then for each township, we determined the most common needleleaf and broadleaf species, and calculated the average volume per hectare of needleleaf and broadleaf these harvestable stands.

These average volumes are still considerably less than the average volume per hectare harvested in Alberta, indicating that the forestry companies are even more selective about timber harvest than our simple filter rules suggest.

Based on data retrieved from the National Forestry Database, the average harvest volume in Alberta between 1990 and 2015 was 277.8 m3·ha-1 [54]. The average township volume after the filter was applied was 100.3 m3·ha-1. We used a harvest volume adjustment factor of 2.77 to make the volumes we calculated comparable to the average harvest volume (m3·ha-1) for Alberta.

## Residue yield by township

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 hectre 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.

# 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 by 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 similar to that recorded in the national forestry database, and is appropriate for use for this study.

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. Indeed, 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 year for the locations and capacities. It is clear that 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, median, 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 cut area would be accessed, but the volumes are small enough that we ignore them.

[ Figure 10 about here ]

Whitecourt is lowest cost location for most years at all capacities. There is a noticable 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.

As expected, residue costs are lower with lower capacities because they don’t have to transport resides from such far distances.

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 availablity 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 residue collection costs from year to year. The variability increases as input requirements increase.

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 a 800 Gg/a plant is at least 40% greater than supplying a 200 Gg/a plant.

**Comparison with ag residue? amount and variability? [57]**

Perhaps it makes sense to transport to smaller plants (e.g. pellets), and then aggregate at a larger plant (e.g. ethanol). Pellets are cheaper to transport than comminuted biomass.

Residue variability is an important source of risk for a forest residue-based biomass processing plant. Being dependent upon stemwood harvests for the generation of residues can lead to cost variability over the long operating life of a biomass processing plan, making it is important 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. 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 oven-dry metric ton is equivalent to 1 Mg. [↑](#footnote-ref-1)