Estimating Mill Residue Surplus in Canada: A Spatial Forest Fiber Cascade Modeling Approach

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Abstract

The potential development of a Canadian forest-based bioeconomy requires an assessment of both fiber availability and associated marginal supply costs. To a large extent, the bioeconomy is expected to rely on wood fiber made available through primary products, sawnwood, and pulp production processing streams. Therefore, it is important to understand the regional wood fiber flows and mill residue availability through various processing streams. In this study, we developed a spatially explicit Forest Fiber Cascade Model (FCM) to estimate regional fiber flows and availability of untapped residue surplus. The FCM was calibrated to 2013 production levels, and we evaluated the wood fiber cascade through existing forest industry in Canada. The results show that, under current conditions, there is limited availability of surplus mill residues in Canada, especially in the Eastern provinces. It is therefore critical to consider the impacts on regional fiber flows and feedstock availability to the secondary industries when designing feedstock supply strategies and policies for the emerging forest-based industries.

Canada has access to abundant biomass resources, especially woody biomass from forests. Regional forest sector bioeconomy development in Canada could produce energy, fuel, and chemical products; this development has been the subject of many recent policy initiatives in Canada (Benoit 2008, Cantelon and Rustad 2011, Alberta Innovates Bio Solutions 2013). An active bioeconomy in Canada could reduce dependence on hydrocarbons, revitalize the forest sector that faces downturn in traditional markets such as pulp and paper, mitigate greenhouse gas emissions, and possibly mitigate adverse ecological phenomena such as pest outbreaks and wildfires (if it leads to resource extraction and forest health restoration in the affected areas). Long-term viability of the bio-based establishments will require a sustainable and efficient fiber supply (Chapotin and Wolt 2007, Jenkins 2008, Tyndall et al. 2011, Axelsson et al. 2012).

To support development of sustainable regional forest-based bioeconomies, supply strategies that incorporate multiple feedstocks are required (Kumar et al. 2003, Séguin 2011). Ideally, these strategies will include biomass procurement from a combination of primary (harvested wood from forests), secondary (harvesting and processing residues), and tertiary (disturbance deadwood and waste) sources (Röser et al. 2008). Until regional biomass supply chains are well established, however, the emerging bioeconomy is most likely to rely on the wood fiber made available through secondary streams, i.e., harvest residues left at logging sites and processing residues from solid wood or pulp and paper products (Mabee et al. 2006, Dymond and Kamp 2014). In British Columbia, it is estimated that about one-third of harvested wood ends up in a residual form, some of which is currently used for bioenergy production (Dymond and Kamp 2014).

The amount of timber and biomass harvested by the traditional forest industry depends on markets and is regulated by government, which sets caps on harvest levels. In the past decade, downturns in Canada's traditional forest products markets, combined with supply shocks such as the

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Mountain Pine Beetle (MPB) outbreak in British Columbia and Alberta, have resulted in a general decline of mill activity levels, up to closures, and hence directly decreasing the amount of wood fiber that might support the emerging industries in the bioeconomy (Wood and Layzell 2003). Figure 1 shows how Canada's roundwood production has fluctuated since 1990, with a constant downturn of pulpwood and a sharp decline of log supply since 2005.

To date, most published studies on wood biomass availability are either historical reviews or theoretical biomass stock estimates made at very large spatial scales (Wood and Layzell 2003, Hedegaard et al. 2008, IEA Bioenergy 2008, Mabee et al. 2011, Paré et al. 2011, Surisetty et al. 2012, Bradley et al. 2013). These studies usually report on ''biomass potential'' and do not provide details on accessibility, concessions, type, quality, cost, geospatial aspects, or temporal aspects of the available biomass that are vital information for developing practical biomass supply strategies. Data and information on the amount, types, and geographical location of produced or unexploited wood residue at the secondary wood processing mills is either scarce or not available (Perlack et al. 2005).

A number of studies have tried to quantify available processing residues from Canadian forest products industry at a more refined spatial scale. In 2004, the Forest Products Association of Canada (FPAC 2005) carried out a survey of mill residue production, consumption, and surplus in various provinces and provincial subregions. The surveyed sawmills in this study covered 96 and 71 percent of total lumber production capacity in western and eastern provinces of Canada, respectively. Although the FPAC study did not provide data describing historical variability of residue generation rates at specific processing mills, it demonstrates how accounting for factors such as regional residue demand, interprovincial and international exports, mill activity level, recovery factors, internal use, and residue type would yield very different estimates of actual residue availability for exploitation in the emerging bioenergy sector. In 2007, Agriculture and Agri-Food Canada developed a Biomass Inventory Mapping and Analysis Tool (BIMAT), which provides a geographic information systems–based tool linked to a comprehensive biomass inventory database describing national biomass supplies. The BIMAT database includes tools to estimate theoretical availability of softwood or hardwood residue production at wood processing facilities, based on information such as mill capacity and historic wood consumption, harvest volumes, forest product type, and wood fiber recovery of active Canadian mills between the years 2004 and 2006 (Agriculture and Agri-Food Canada 2007). Finally, Krigstin et al. (2012) developed a geo-referenced data set of available volumes of different residue types (e.g., saw dust, shavings, chips, and hog fuel) across Eastern Canada based on a wood recovery model to estimate mill residue production from specific mill types.

In addition to biomass availability and historic production levels, opportunity cost and hauling distances are recognized as critical factors in feasibility assessment of biomass supply (FPAC 2005, Perlack et al. 2005, Mabee et al. 2011). The establishment of new bio-based industries is likely to change regional fiber allocation and may create competition for fiber access between established and emerging feedstock demanders (Stennes et al. 2010).

An important consideration in fiber allocation is the interdependence between users of primary wood and users of secondary residues within the forest sector. Traditionally, wood fiber from forests has been harvested and processed by primary forest industries mainly to make structural wood products such as lumber, plywood, and oriented strandboard (OSB), or pulp and paper products (Dymond and Kamp 2014). Residue streams generated from these harvesting and manufacturing processes, in turn, have been increasingly used as feedstock sources by traditional secondary industries such as medium-density fiberboard (MDF) and particleboard manufacturers, as well as new entrants such as wood pellet and bioenergy producers (Dobie 1981, Food and

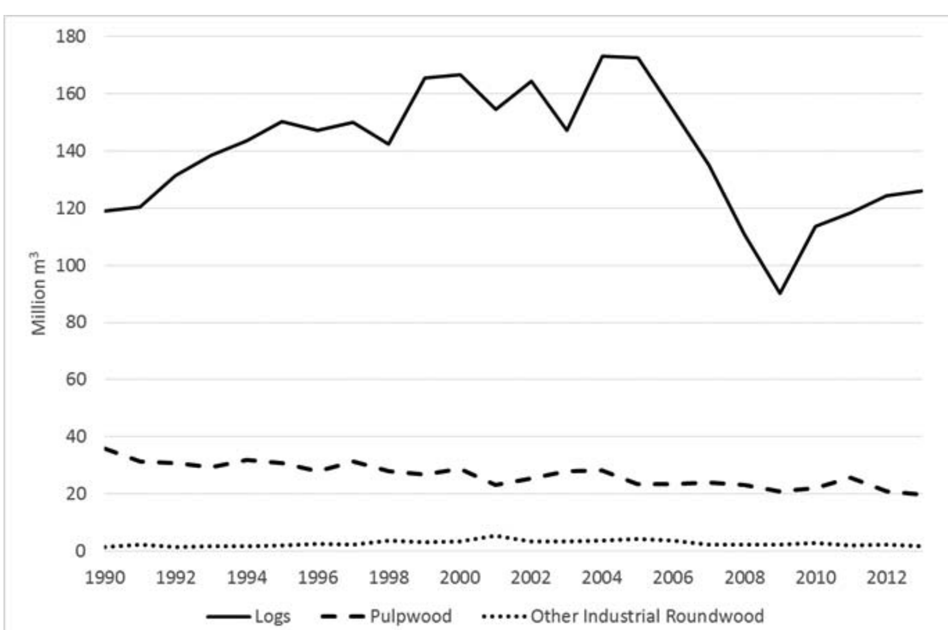


Figure 1.—Total roundwood production in Canada from 1990 to 2013.

Agriculture Organization of the United Nations [FAO] 1990). There have been modeling efforts in Canada in the past to predict wood residue allocation and use. In Quebec, Gautier et al. (2000) developed a linear programming model to investigate the behavior of the wood chips market in response to exogenous factors such as timber supplies, production capacities, technology (product recovery), commodity prices, and production and transportation costs. This model examined the flows of wood chips between independent sawmills and pulp and paper plants, as well as integrated mills in order to assess the impact of market price on commodity flow. In western Canada, Stennes et al. (2010) and Niquidet and Friesen (2014) each studied the potential change in wood fiber allocation and trade within and between provincial subregions in British Columbia and Alberta in response to forest sector bioenergy development. In these models production capacities, log harvests, transportation costs, and fiber use were estimated at a subregion level. In general, researchers have concluded that in order to arrive at more accurate and realistic estimates of wood fiber availability for emerging products, such as biofuels, improved models for tracking fiber use in various sectors are required (Dymond and Kamp 2014).

Residual fiber allocations in Canada follow a variety of market forms. Fiber supply may be secured for operational life of the plant in case of integrated mills or may be based on short-term contracts. The price of residue may also be set based on end product prices (e.g., chips pricing based on Northern Bleached softwood kraft pulp) or on supply and demand signals in an auction-based or spot market. The buyer will typically incur the transportation cost in addition to the residue price (BC Hydro 2013, Canfor Corporation 2013).

The primary objectives of this study were to quantify the forest fiber cascade among Canada's primary and secondary forest products sectors and spatially estimate mill residue surplus from the forest products sector. Since the Forest Products Association of Canada study in 2004 (FPAC 2005), which estimated that about 2.7 million bone dry tonnes (Mbdt) of surplus mill residue was available in Canada on a yearly basis, there has not been an updated estimate of unutilized mill residue in Canada. This study will also shed light on the assumption that there is a very limited amount of untapped mill residue left in certain regions in Canada to support development of the bioeconomy in Canada.

Materials and Methods

Model overview

Rapid development of the bioenergy sector and downturn of the traditional forest sector in Canada have changed the flow of wood fiber from the forests to the forest sector as well as wood residue streams since 2004 when a national scale survey of forest sector processing capacity and wood residue availability at the processing mills was carried out by FPAC (2005). On the other hand, continuous development of the forest-based bioeconomy in Canada will influence the regional distribution of wood fiber. In order to accomplish the study objectives, we developed a spatially explicit Forest Fiber Cascade Model (FCM) to simulate the flow of roundwood from forests to the primary and secondary forest products sectors and to show the distribution of mill residues from the primary mills to the secondary industry. The FCM allows us to track on a spatial basis the cascade of wood fiber in different regions across Canada. The model also allows analyses of wood fiber supply and demand balance on a regional basis and interregional flow of wood fiber with a high degree of resolution regarding wood fiber type and its source and destination. In addition, the model could be used as a scenario analysis tool to evaluate the impact of increase or decrease of wood fiber supply or demand owing to change in capacity of processing mills.

The FCM uses estimates of processed log volumes and costs at each primary (log-receiving) facility provided by the Canadian Forest Service–Forest Bioeconomic Model (CFS-FBM; Yemshanov et al. 2007). CFS-FBM was originally developed to assess bioeconomic implications of sequestration of carbon in forest stands using the basic concepts of biomass partitioning. However, since its creation, CFS-FBM has been further developed and used as a simple, but spatially explicit harvest and allocation model for various categories of forest biomass. In other words, CFS-FBM is used in the FCM to spatially allocate biomass and logs from forest over time to various demand points (primary mills). The secondary facilities, demanding residue from primary facilities, will then compete in a simulated auction-based residue market to meet their respective demands based on their feedstock purchase power, determined by their operating margins and haul costs. To better reflect the feedstock requirement or efficiency of various processes using various feedstock types, three categories of wood residue are considered in the FCM: (1) wood chips, (2) whitewood residue (sawdust and shavings), and (3) hog fuel (i.e., bark-contained or coarse wood refuse suitable mostly for bioenergy production).

Each forest products mill is modeled as an agent within the Agent-Based Resource Optimization Modelling Arena (AROMA) modeling platform. AROMA is a proprietary spatial multiagent modeling platform developed based on Jaamsim simulation engine (King and Harrison 2013). For each facility, the techno-economic factors of processing such as conversion rates, costs, input feedstock types, and output materials are defined. Furthermore, the geographic locations of the mills were used in connection to Canada's transportation network database (Natural Resources Canada 2008; Statistics Canada 2015) in order for the model to estimate the least cost fiber transportation costs through the optimized routes, considering multiple modes of transportation and/or intermodal transportation, between suppliers and buyers.

The residue allocation from residue suppliers to demanders is facilitated through an auction-based market simulation module. The main components of a multiagent auction-based model are buyers' bidding strategy and an auction mechanism to allocate items to successful bidders (Cramton et al. 2006). Multiagent systems have been used widely to simulate behavior of competitive markets such as electricity or financial markets (Collins et al. 1997, Lux and Marchesi 1999, Praça et al. 2003, Conzelmann et al. 2005).

In our model, at each bidding round, suppliers would provide trade volumes for each residue type to the market module. We assume that the buyers follow a truth-revealing bidding strategy to place bids for the demanded residue types, i.e., residue demanders would bid at their willingness-to-pay for the feedstock price, the cost at which the average revenue from selling end products equals their average production costs (consisting of feedstock, feedstock transportation, operation, and equity costs). Truth-revealing bidding strategies have proved to be optimal bidding strategies in certain auction mechanisms, such as a multi-item Vickrey-Clarke-Groves (VCG) auction (Makowski and Ostroy 1987). In the VCG mechanism, bidders submit sealed bids for multiple items without knowing the bids of others, and the items are allocated such that the sum of utilities of all participants in the market is maximized. Owing to important features such as no demand distributional assumptions, efficient choices, and existence of a truth-revealing dominant bidding strategy, the VCG mechanism has been widely studied and used in game-theoretic and computer models (Cramton et al. 2006). However, the VCG mechanism has not found much real world application because of several practical issues such as potential existence of multiple weak equilibria, potential revenue deficiency, and nondeterministic polynomial time (NP) completeness of determining winning bids (Rothkopf 2007). For the purpose of this model, we used a simplified VCG approach, where the market module determines allocation to successful bidders based on a maximum bid allocation strategy, using a heuristic algorithm that chooses the subset of highest bids until either supply runs out or there is no more demand. Figure 2 schematically shows the agents' participation and information flow in the simulated auction-based market.

It should be noted that for the purpose of this study, an auction-based allocation scheme and the truth-revealing strategy in determining buyers' bidding strategy, are used to arrive at a proxy of fiber allocation based on relative operational and spatial competitiveness of various facilities. No effort was made to determine a globally optimal allocation of wood residue feedstock among competing industries or to arrive at the most effective short- or long-term contractual agreements between various mill residue suppliers and buyers.

There are various sources of uncertainty that may cause deviation of results from reality in studies such as this one. Some of the main sources of discrepancy with reality are owing to fiber supply, fiber allocation logic, and associated assumptions. Fiber allocation may be based on an optimization formulation to minimize allocation costs, to minimize network production costs, or to maximize network profit, or may be based on an auction-based market (such as this study), or based on any other form of heuristic. Other sources of discrepancy include inherent uncertainty in data sets used, such as internal biomass use estimation, actual production, recovery rates, or varying production factors owing to feedstock characteristics or at mills' discretion.

Our model at this stage is meant to provide a spatial approximation of regional fiber balance and flow among primary and secondary forest products sectors. In the future, we intend to improve upon these sources of uncertainty in the model and data sets by adding, e.g., data and logic to reflect international residue exports, or strategic decision-making layers in the model for optimally directing fiber among integrated mills.

Data

Mills data set.—A database of all major wood processing and biomass-based bioenergy facilities in Canada was developed to estimate wood fiber input and demand as well as product and residue output at each specific facility. As shown in Figure 3, the primary forest products facilities (which directly use harvested wood) included in the database consist of sawmills, plywood mills, pulp and paper mills, and OSB mills. The pulp and paper sector represents 23 different categories of pulp and paper products, including multiple categories of pulp (refiner, groundwood, soda, sulfite, and kraft), newsprint, and 17 grades of specialty paper products. The secondary forest products mills (which use residues from primary facilities) produce outputs including OSB, pulp and paper, particleboard, and MDF. It should be noted that OSB and pulp and paper may be categorized as a primary or a secondary mill depending on whether or not they receive roundwood as feedstock. The bioenergy sector included in the model consists of pellet mills and independent biomass-based electricity generation facilities that sell electricity to provincial grids.

For each major primary and secondary mill as well as forest-based bioenergy facilities in Canada, several parameters were considered, including tree species mix (output of CFS timber supply model), processing mill production capacity, mill location, and wood and energy processing technology information, such as conversion rates and costs

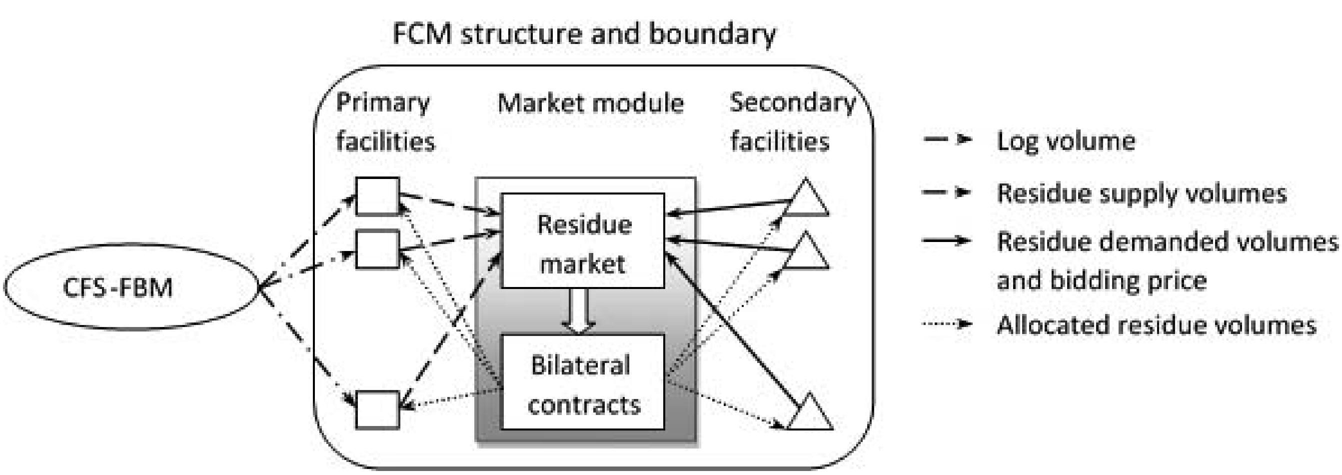


Figure 2.—Agents' representation and information flow in the Forest Fiber Cascade Model (FCM). CFS-FBM = Canadian Forest Service–Forest Bioeconomic Model.

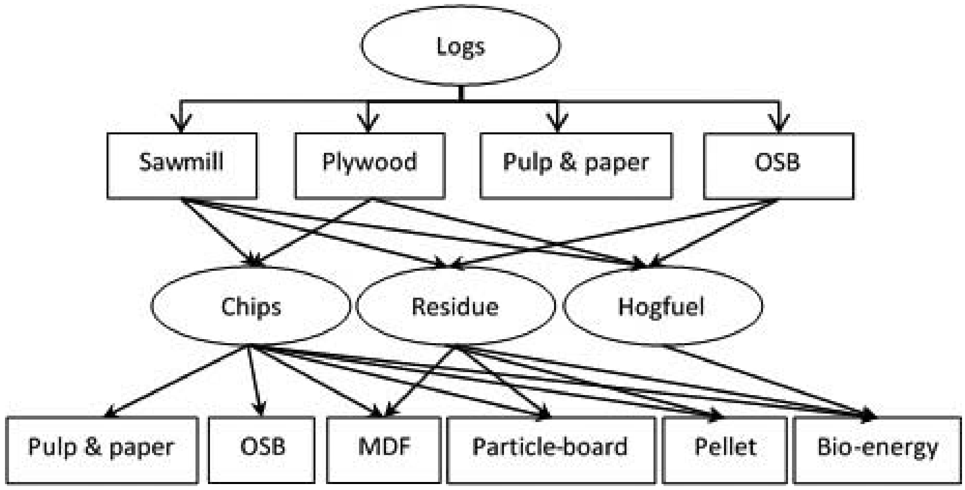


Figure 3.—Included wood processing facilities and forest fiber types in the model. OSB = oriented strandboard; MDF = medium-density fiberboard.

for each feedstock type. We also ensured the operational status of the wood products mills is considered based on the most recent information available through databases such as Spelter et al. (2009), Anonymous (2012), BC Hydro (2015), Hydro Quebec (2015), *Logging & Sawmilling Journal* (2015), or facilities' Web sites; this was particularly important given the rate of change in the industry over the past few years with shutdowns in the sawmilling and pulp and paper sectors as well as a rapid expansion of the bioenergy sectors (Krigstin et al. 2012). The bioenergy facilities data set consists of all the independent or integrated power or combined heat and power (CHP) plants listed in such purchase agreement programs across the country or already existing ones providing electricity to the grid in addition to internal or process energy production (Hydro Quebec 2011, BC Hydro 2015, Ontario Power Authority 2015).

The conversion coefficients and costs were assigned to processing lines at each facility to reflect mass balance between feedstock infeed and output products and by-products. It should be noted that the accuracy of conversion and processing information and data used for various industries depends on the type of data sources used. For instance, processing conversion rates and costs as well as feedstock types and output products were set at processing line level for each pulp and paper mill, resulting in 23 different pulp and paper processing pathway configurations (Fisher International 2015); however, average rates per feedstock type or species (hardwood vs. softwood) were used for solid wood products and bioenergy (FAO 1990, Meil et al. 2009). Table 1 shows the average conversion rates of major processes within each forest products industry.

Also, the secondary sectors demanding residue from the primary mills have different requirements with respect to the feedstock. For instance, pulp and paper mills would mostly accept certain species of wood chips for pulp production or sawdust for sawdust pulp production because of specific requirements of the pulping process in terms of feedstock type and particle length and thickness (Gustafson et al. 1983). Flexibility in feedstock options has been considered in developing processing pathways logic at the individual mill level to capture specific processing requirements and flexibility with regard to feedstock choices. To this aim, alternative feedstock and corresponding conversion rates and costs have been set for processing lines that have the technical possibility of using a different type of feedstock. For instance, three different feedstock possibilities, i.e., wood chips, whitewood residues, or hog fuel, are defined for bioenergy processing lines. The respective conversion efficiency and generation costs are set for each feedstock type. As a result, bioenergy facilities will be able to participate in all three residue type markets and, depending on availability and costs of feedstock, satisfy their demands from the least cost options. This allows flexibility for residue demanders to satisfy their feedstock need from multiple residue markets depending on their relative competitiveness in those markets. The processing logic at residue producers, i.e., primary mills, is currently set at a constant production and residue conversion rate. Variation in the conversion rates of producers would reflect differences in species (hardwood vs. softwood) mix, as can be seen in Table 1.

Forest fiber availability and flow.—As can be seen in Figure 2, the CFS-FBM (Yemshanov et al. 2005, 2007, 2009) model provides estimated volumes of softwood and hardwood timber to each of the primary (log-receiving) facilities in the FCM from forests during the planning period. The CFS-FBM uses per-hectare growth and yield information along with a series of biophysical, carbon budget, and economic indicators, such as timber revenues net of any harvesting costs, on a raster-based setting to simulate harvest flows from grids with positive calculated net present values to the assigned log-receiving facilities. The simulation of forest harvest in CFS-FBM is carried out on a national scale and annual basis. The CFS-FBM outputs are translated into percent supply or shortage of timber from the timber requirement to match production levels of the primary facilities in that period (2013 base year).

Transportation.—Forest-based feedstocks in the form of logs, chips, sawdust and shavings, or slabs and hog fuel are usually transported by a multimodal transportation system involving road, rail, and/or water-based transportation (Epstein et al. 2007). Feedstock transportation cost is one

Table 1.—Average conversion rates of major processes within the forest products industries.[a]

	Infeed (%)[b]	Conversion rate (%)[c]				
		Product	Chips	Residue[d]	Hog fuel	Internal use/waste[e]
Sawmill	100 (softwood log)	43 (lumber)	35	13	2	7
	100 (hardwood log)	51 (lumber)	33	12	1	3
Plywood	100 (log)	49.9	19.4		10.2	20.5
OSB	100 (log)	79.3		2.9		17.8
	100 (chips)	93				7
Pulp and paper	100 (chips)	44 (kraft pulp)				
	100 (residue)	46 (kraft pulp)				
	100 (chips)	47 (sulfite pulp)				
	100 (chips)	71 (soda pulp)				
	100 (chips)	85 (TMP)				
	49 (kraft pulp)	123 (specialty paper)				
	95 (TMP)	99 (newsprint)				
	100 (TMP)	111 (specialty paper)				
	60 (soda pulp)	156 (specialty paper)				
	57 (sulfite pulp)	156 (specialty paper)				
Particleboard	100 (residue)	87.4				12.6
MDF	100 (residue)	86				14
Wood pellet	100 (residue)	82.5				17.5
	100 (chips)	82.5				17.5
Bioenergy (electricity)[f]	100 (chips)	1.546 MWh/t[g]				
	100 (residue)	1.410 MWh/t[h]				
	100 (hog fuel)	0.972 MWh/t[i]				

[a] After van den Broek et al. (1996), Meil et al. (2009), Evans et al. (2010), Zhang et al. (2010), and Fisher International (2015). OSB = oriented strandboard; TMP = thermos-mechanical pulp; MDF = medium-density fiberboard.
[b] Average percentage of infeed contribution as the main feedstock to the process. Does not include chemicals such as resins, clay, coating, etc. For pulp to paper feedstock, a blend of pulp feedstock such as recycled pulp or other grades of pulp would be used in addition to the pulp category cited.
[c] Conversion rate (except for bioenergy) is calculated as finished mass-unit of outfeed per mass-unit of main feedstock cited as infeed; hence, blended feedstock and chemicals used in the process cause the ratio for paper products to be greater than 100 percent.
[d] Whitewood residue (sawdust and/or shavings).
[e] Internal use and/or waste streams represent any output from the process that is waste or used internally as feedstock for, e.g., energy production purposes and is not available for trade. Pulp and paper waste or internal use of byproducts is not included due to complexity of interpretation of individual processes.
[f] Average power generation efficiency is at 35 percent.
[g] Green tonnes at 20 percent moisture content.
[h] Green tonnes at 30 percent moisture content.
[i] Green tonnes at 50 percent moisture content.

of the major cost components of forest-based products and may contribute as much as 50 percent of total feedstock costs (Gunnarsson et al. 2004, Frisk et al. 2010, Bradley et al. 2013, Mobini et al. 2013).

Transportation costs of biomass feedstock between supply and demand points are usually estimated roughly with a randomized distance using tortuosity factors (Sokhansanj et al. 2006), at an average regional aggregate level (Stennes et al. 2010, Niquidet and Friesen 2014) or by using Euclidean distance (Yemshanov et al. 2014). Often the transportation mode is not defined, and we think this introduces unknown variability in the estimated transportation costs in the model owing to disconnect with the actual transportation infrastructure in place in certain regions. For instance, tortuosity of roads might be higher in rough terrain, or access to rail services might be restricted or nonexistent in more remote regions. Because the Canadian forest products industry has traditionally been developed in remote communities and often faces challenges to access adequate transportation, we took a different approach.

In order to arrive at more accurate estimates of transportation costs, all facilities have been connected to Canada's transportation network database including rail, road, and barging routes (Government of Canada 2015a, 2015b). The multimodal transportation possibilities have been also considered by including reloading operations across Canada. This allows the model to optimize for the least cost transportation options for transporting various feedstock types for each mill. Such least cost supply routes may include single mode transportation (e.g., truck or train only) or multimodal transportation passing through reloading operations.

Results and Discussion

The model was run and calibrated to 2013 regional production levels (Natural Resources Canada 2014) and used to examine how Canadian forest fiber spatially cascades through primary facilities and the secondary forest products sector, to draw conclusions regarding forest fiber supply and demand balance in various regions, and to estimate mill residue surplus in Canada. Although the model reports fiber flow, feedstock intake, and product outputs on a mill by mill basis, the results were aggregated to summarize flows at a regional or national level. Some data, such as wood species for roundwood and residue streams, have been aggregated into hardwood versus softwood. For pulp and paper mills, 23 grades of pulp and specialty products were kept discrete.

Figure 4 shows for 2013 the Canadian industry cascade of forest fiber to and among primary and secondary forest products sectors. As shown in this figure, values for solid wood and pulp and paper products have been converted to mass-based units (tonnes), and the scale of the arrows in the Sankey diagram are proportional based on these measures, with the exception of bioenergy production, which is reported in terajoules (TJ). Bioenergy production represents the total biomass-based electricity generated by independent or integrated power or CHP plants. The actual purchase agreement price paid to these producers depends on a number of factors, such as capacity and region, and is not disclosed for individual producers.

It should be noted that the model does not show the progress of harvest residues from forests into the bioenergy sector. In certain regions across Canada, and especially in British Columbia, the collection and transport of logging residue for bioenergy production is considered a viable future option. It is estimated that 8.8 Mbdt of harvest residues is produced annually in Canada, mainly in British Columbia and Quebec (Bradley et al. 2013).

The underlying assumption in this study is that mill residue is a more readily available option to be used as feedstock either for secondary products or bioenergy production if accessible within economic transportation distances. This assumption is consistent with other studies that have shown that mill residue surplus in British Columbia will be a preferred option in order to meet further biomass demand due to expansion of bioenergy production compared with logging residue, which in turn only enters the optimal bioenergy feedstock supply portfolio in a very limited capacity (<5% in central and northern regions; Stennes et al. 2010).

As indicated, the largest roundwood receiving sectors include lumber, pulp and paper, OSB, and plywood. The amount of hog fuel used internally for energy production purposes within the primary and secondary forest products sectors is discounted from the total residue output from the processing lines. The pulp and paper sector processed 15.8 million tonnes (Mt) of wood chips supplied by residue streams from the lumber and plywood sectors (including processing residues such as refused lumber or slabs) in addition to the roundwood directly from forests.

The Canadian bioenergy sectors (bioelectricity and wood pellet facilities) used about 8,554,218 tonnes (wet basis) of whitewood residue and hog fuel in 2013. This excludes the hog fuel and whitewood residue used internally at the wood products mills to provide processing energy. The results of the modeling exercise indicate that about 322,000 bdt of white wood for pellet production and 978,000 bdt of hog fuel for bioenergy production is required, in addition to mill residue to balance feedstock fiber demand with production output in the bioenergy sector in Canada in 2013. The additional sources of fiber may include logging residue, roundwood, or carried over inventories from a previous year. This indicates that in certain regions in Canada, demand for feedstock by the bioenergy sector has surpassed the processing residue available through primary mills. In general, sectors with lower production margins, such as bioenergy, would be at a disadvantage to compete in the residue market in regions with supply shortage. For instance, the bioenergy sector is generally not as compet-

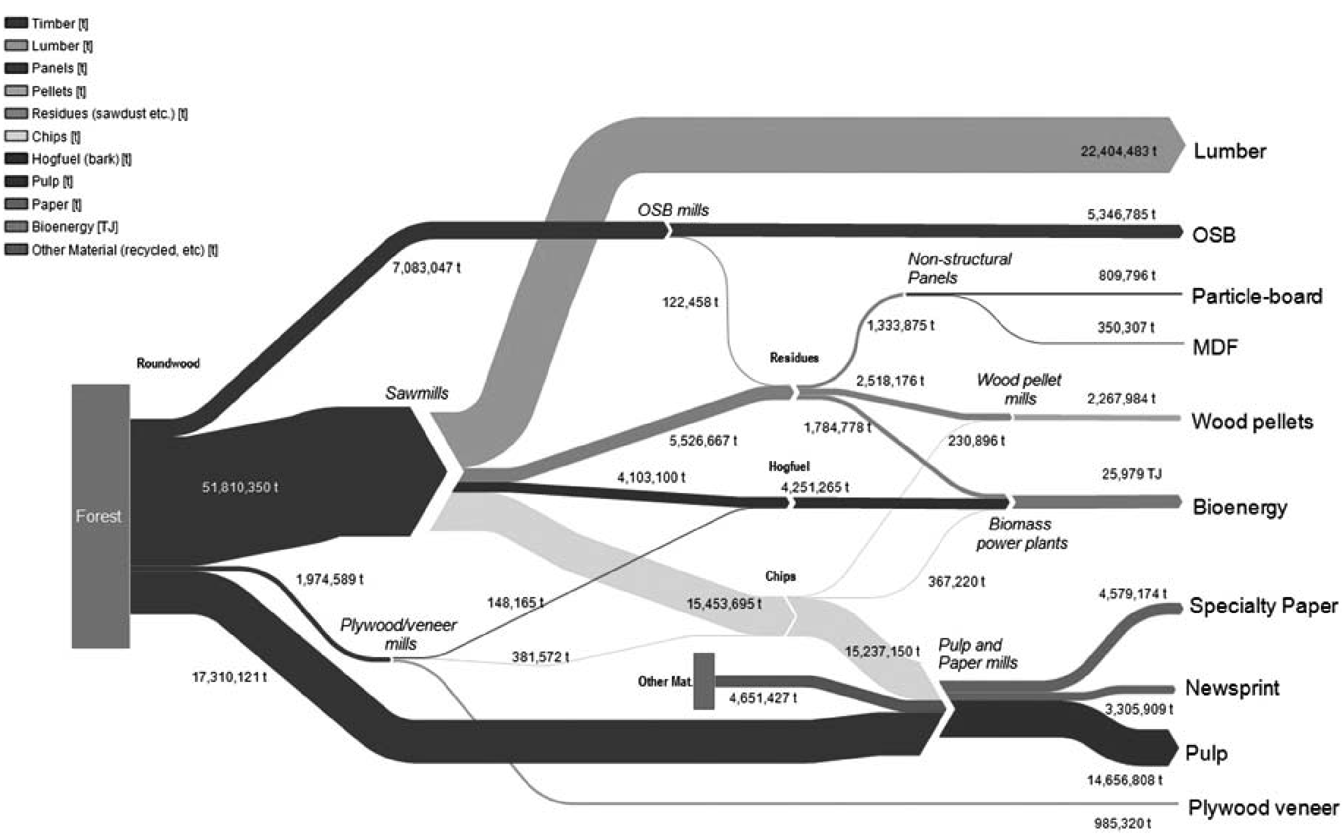


Figure 4.—Forest fiber cascade to and among primary and secondary forest products sectors in Canada in 2013. OSB = oriented strandboard; MDF = medium-density fiberboard.

itive as the pulp and paper sector in absorbing wood chips. In regions where bioenergy feedstock demand surpasses hog fuel and whitewood residue supply, however, close proximity to solid wood products mills and availability of wood chips surplus may allow the bioenergy sector to enter the wood chip market. Currently, we estimate that only 3 percent of the residual wood chips from solid wood sectors (including chips surplus) is directed toward bioenergy (wood pellets and biomass-based power) production.

Figure 5 shows the total roundwood intake versus total feedstock requirement by the secondary industries in Canada's economic regions based on the 2013 production levels. The detailed information about definition of regions and results per region is shown in Table 2.

As can be seen in Figure 5, the largest fraction of primary wood processing capacity in Canada is concentrated in British Columbia and Quebec, with about 40 and 25 percent of total processed roundwood share, respectively. The difference between total roundwood intake by the forest industry (black outer circle) and feedstock requirement by the secondary industries (gray inner circle) represents the amount of fiber used for lumber and plywood products production and mill residue surplus.

The total feedstock requirement to support the secondary forest products sector (including pulp and paper, OSB, particleboard, MDF, wood pellets, and biomass-based power) production in Canada was equivalent to 60 percent of the total processed roundwood on a mass basis in 2013. This suggests that about 40 percent of the total processed roundwood from the forests ends up in solid wood products of lumber and plywood veneer. Furthermore, as can also be seen in Table 2, especially in certain regions of the Eastern provinces, there is very little difference between feedstock demand from the secondary sector and the intake of roundwood by the region's forest sector. In regions such as West Coast, Northern Peninsula, and Labrador in Newfoundland (Code 18), North Shore and Cape Breton in Nova Scotia (Code 21), Northwest of Ontario (Code 24), and Saguenay and Lac Saint Jean in Quebec (Code 31), the feedstock demand by the secondary sector even surpasses the region's roundwood intake. Because fiber flow is modeled at the individual mill level, roundwood or residue flow may occur between regions. The map would therefore not suggest that all roundwood or residue would be supplied from within the region. However, the imbalance or limited difference between roundwood intake by primary mills and feedstock demand by secondary mills in regions implies scarcity of surplus residue from the primary industry to further develop the secondary sector in these regions. As a result, new developments in the secondary sector should consider supply of fiber from primary sources (forests).

Table 3 shows the estimated interprovincial flow of whitewood residue and hog fuel. The bilateral flow of residue between British Columbia and Alberta is very limited. This is mostly because of sufficient availability of regional residue, but it may also be influenced by the fact that the majority of large-scale secondary forest products mills in these provinces are located far enough from the provincial border that transportation cost is a limiting factor. In the east, the concentration of mills near provincial borders makes interprovincial flow of residue inevitable. For instance, 56 percent of the whitewood residue produced in Nova Scotia was used in New Brunswick to support panel production, and at the same time New Brunswick exported 17 percent of its hog fuel production to Nova Scotia for biomass-based power generation.

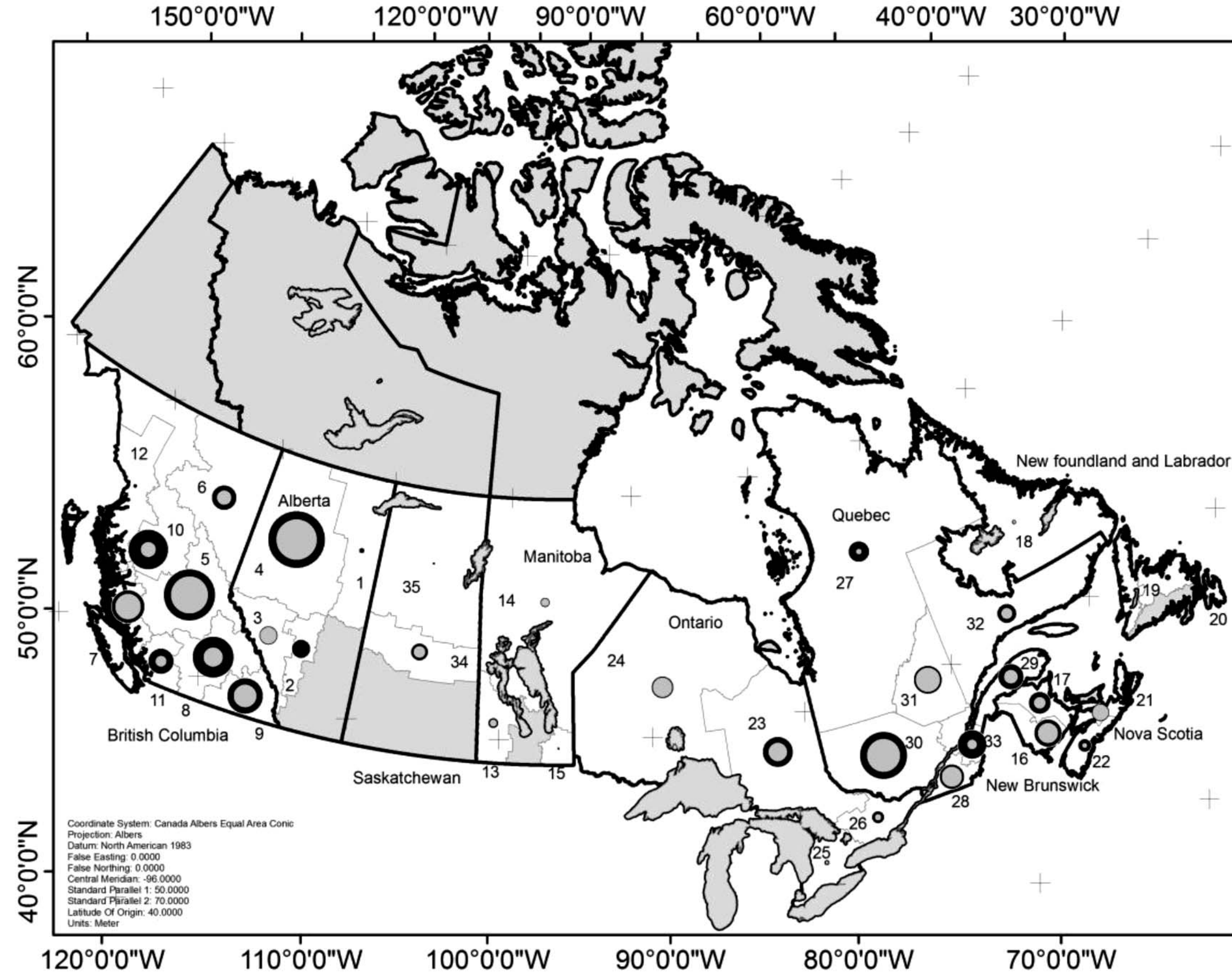
Figure 6 shows the estimated regional mill residue surplus in Canada's economic regions in 2013. The residue categories include (1) wood chips (from dimensional wood production process such as refused lumber and slabs), (2) whitewood residue (sawdust and shavings), and (3) hog fuel (i.e., bark-contained or coarse wood refuse suitable mostly for bioenergy production).

Table 4 shows the detailed estimated mill residue surplus by each region. The total whitewood residue and hog fuel produced at primary forest products mills in Canada, not including material and in excess of the amounts used for internal energy production purposes, was estimated at 14,793,771 bdt in 2013. The model suggests that 90.3 percent of this amount would have been required to support the regional secondary industry in Canada in that year, which means that only 9.7 percent of the total amounts of whitewood residue and hog fuel piles generated at the forest products mills, or 1,442,126 bdt, would be available in excess of the current secondary forest products demand to be used for export or further development of the value-added products and energy. In addition, the results of the model suggest that the mill-based hog fuel piles, once considered disposable waste and environmental management burden, may have already been fully committed in most regions in Canada and especially in British Columbia, to support biomass-based power and processing energy generation.

It should be noted that the wood chips reported in Figure 6 only include residual wood chips from solid wood products processing. Pulp log chips are only produced to supply pulp and paper or OSB demand and are therefore not anticipated to be available in surplus. Hence, attention should be paid when interpreting results of wood chip surplus from solid wood product mills in this study. Moreover, wood chips exported to international markets were beyond the scope of the study and are not included. By the same token, the decision-making process for pulp chip production and supply at integrated or nonintegrated facilities could not be modeled, meaning that any change to the production of chips could not be anticipated. Although wood fiber utilization and product recovery has improved significantly in the past decades (Cohen and Sinclair 1989, Rotherham and Burrows 2014), primary wood processing mills may in the future favor lower product recovery to produce more wood chips for the market (Gautier et al. 2000, Niquidet and Nelson 2010), depending on market conditions. Given these conditions, the wood chip residue surplus results presented here reflect the regional balance between the amount of roundwood processed by the primary and secondary sectors.

Results were validated using a survey of Canadian mill fiber surpluses (FPAC 2005) carried out in 2004. Owing to the structural transformation that Canada's forest sector has gone through during the past decade, general trends and findings of the two studies are discussed rather than used for numerical comparisons. To be consistent with the 2004 survey, the model results on two categories of mill residue, namely, whitewood residues (sawdust and shavings) and hog fuel, are considered in validation.

In 2004, the FPAC (2005) reported that the total untapped mill residue surplus was 16 percent of the total production



Roundwood intake by secondary and primary industries
Scaled at 7.8 million tonnes (10% of Canada's roundwood production in 2013)

Residue demand by the secondary sector (pulp and paper, OSB, particle-board, MDF, Wood pellets, biomass-based power) - Scaled at 7.8 million tonnes

Regions without active forest product industry

*** Roundwood intake of the region and residue demand of the secondary sector in the region are closely matched and hence overlap**

Figure 5.—Total roundwood intake versus total feedstock requirement by the secondary panel, bioenergy, and pulp and paper industries in Canada's economic regions based on the 2013 production levels. OSB = oriented strandboard; MDF = medium-density fiberboard.

or 4.6 Mbdt across Canada. The difference between the studies could be largely explained by the decline in the sawmill sector, with total lumber production in 2013 at only 70 percent of the 2004 levels. In various regions across the country, and especially in British Columbia, the bioenergy sector has also expanded rapidly in the past decade; wood pellet production capacity has tripled in this period, and was at 3.5 Mt/yr in 2013 (Natural Resources Canada 2013).

As can be seen in Table 4, British Columbia had the highest share of mill residue surplus in 2013 at 43 percent, followed by Alberta at 20 percent and Quebec at 20 percent. An estimated 3.6 Mbdt of whitewood residue and hog fuel would be required to supply feedstock for the existing secondary production capacity in these provinces, including panels (about 82% of national capacity), pellets (32% of national capacity), and bioenergy (35% of national capacity). Surplus residues likely total about 1.18 Mbdt, suggesting significant, but still limited, room for expansion of secondary production. These findings may change at more local levels, however;

Table 2.—Definition of regions and total estimated roundwood intake by primary and secondary forest industries and total estimated residue demand by the secondary sector in 2013.

Code	Province	Economic regions	Roundwood intake (m^3)	Residue demand (m^3)
1	Alberta	Wood Buffalo, Cold Lake	115,399	—
2	Alberta	Edmonton, Red Deer, Calgary	1,177,862	—
3	Alberta	Banff, Jasper, Rocky Mountain House	980,084	1,319,435
4	Alberta	Athabasca, Grande Prairie, Peace River	10,966,118	7,425,188
5	British Columbia	Cariboo	8,752,843	6,435,018
6	British Columbia	Northeast	2,047,927	1,045,332
7	British Columbia	Vancouver Island and Coast	3,614,070	3,074,701
8	British Columbia	Thompson, Okanagan	5,751,098	1,753,933
9	British Columbia	Kootenay	4,263,069	2,402,553
10	British Columbia	Nechako	5,280,559	1,146,196
11	British Columbia	Lower Mainland, Southwest	2,201,892	641,503
12	British Columbia	North Coast	69,303	—
13	Manitoba	Southwest, Parklands	388,240	263,909
14	Manitoba	North	9,128	338,366
15	Manitoba	Southeast, Winnipeg	41,296	20,400
16	New Brunswick	Edmundston, Woodstock, Saint John, St. Stephen, Fredericton, Oromocto	2,541,857	1,965,157
17	New Brunswick	Moncton, Richibucto, Campbellton, Miramichi	1,699,923	742,170
18	Newfoundland and Labrador	West Coast, Northern Peninsula, Labrador	48,672	60,063
19	Newfoundland and Labrador	Notre Dame, Central Bonavista Bay	141,733	21,273
20	Newfoundland and Labrador	Avalon Peninsula	—	—
21	Nova Scotia	North Shore, Cape Breton	890,182	1,246,337
22	Nova Scotia	Southern, Annapolis Valley, Halifax	628,143	154,191
23	Ontario	Northeast	3,029,295	1,682,814
24	Ontario	Northwest	1,683,240	1,864,445
25	Ontario	London, Hamilton, Niagara Peninsula, Windsor, Sarnia, Toronto, Kitchener, Waterloo, Barrie, Stratford, Bruce Peninsula	110,249	61,452
26	Ontario	Muskoka, Kawarthas, Kingston, Pembroke, Ottawa	549,202	231,098
27	Quebec	Nord du Québec	1,505,509	192,898
28	Quebec	Montérégie, Centre du Québec, Estrie	2,030,345	1,985,417
29	Quebec	Bas Saint Laurent, Gaspésie, Îles de la Madeleine	2,186,175	933,149
30	Quebec	Mauricie, Laurentides, Outaouais, Abitibi, Témiscamingue, Lanaudière	7,571,936	5,145,246
31	Quebec	Saguenay, Lac Saint Jean	2,703,369	2,705,327
32	Quebec	Côte, Nord	1,297,296	647,336
33	Quebec	Chaudière, Appalaches	2,832,287	536,729
34	Saskatchewan	Prince Albert	1,038,513	726,160
35	Saskatchewan	Northern	31,295	—

the Coastal and Cariboo regions in British Columbia, which host about 65 percent of the pulp and paper production capacity in the province, show very limited or no wood chip surplus.

In the remaining provinces (Ontario, Quebec, New Brunswick, Nova Scotia, Newfoundland and Labrador, and Prince Edward Island), production capacity of the secondary industries more closely matches residue production of the same or nearby regions, leaving the estimated residue surplus at only 130,000 bdt. This is consistent with reports that show very little or no available mill residue surplus in various regions of Saskatchewan, Manitoba,

Table 3.—Interprovincial flow of whitewood residue and hog fuel in 2013.[a]

	To (%):								
From:	AB	BC	MB	NB	NL	NS	ON	QC	SK
Alberta	95	5	—	—	—	—	—	—	—
British Columbia	2	98	—	—	—	—	—	—	—
Manitoba	—	—	100	—	—	—	—	—	—
New Brunswick	—	—	—	67	—	17	—	16	—
Newfoundland and Labrador	—	—	—	—	100	—	—	—	—
Nova Scotia	—	—	—	56	—	44	—	—	—
Ontario	—	—	1	—	—	—	85	13	—
Quebec	—	—	—	1	—	—	—	99	—
Saskatchewan	—	—	—	—	—	—	—	—	100

[a] Percentage of total provincial production.

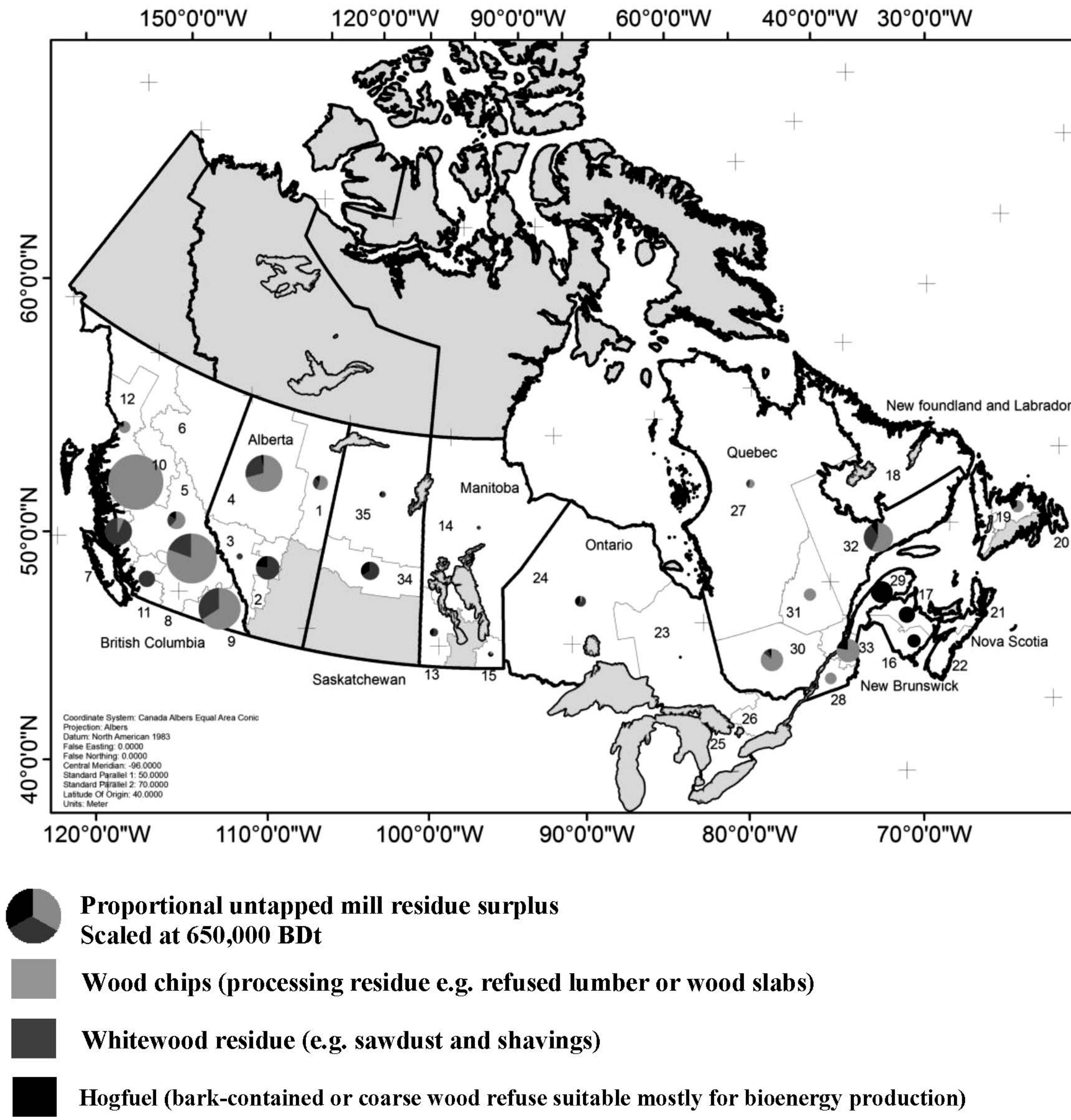


Figure 6.—Estimated regional mill residue surplus in Canada's economic regions in 2013.

Ontario, and the Maritimes (FPAC 2005). This suggests that further development of the biomass-based power generation in Eastern Canada regions without adequate mill residue surplus will either require supplying biomass from sources such as roundwood or logging residue from the forests, or competing in the regional residue markets.

It is interesting to note that the national share of the Eastern provinces (including Quebec) in terms of producing mill-based whitewood residue and hog fuel surplus is estimated to be 30 percent, up from previous estimates of 5 percent in 2004 (FPAC 2005). The proportional increase of Eastern provinces' mill residue surplus on a national scale may be explained by increased consumption of residue by the bioenergy sectors in British Columbia, which has reduced the size of the national surplus in absolute terms.

Conclusions

In this study, a spatially explicit FCM was developed in order to track flows of roundwood from forests to the primary and secondary forest products sectors and distribution of mill residues from the primary mills to the secondary industry. The utility of this model is in its ability to estimate regional fiber flows and availability of untapped residue surplus based on the activity levels of various primary and

Table 4.—Definition of regions and total estimated untapped mill residue surplus in 2013.

Code	Province	Economic regions	Whitewood residue (bdt)	Hog fuel (bdt)
1	Alberta	Wood Buffalo, Cold Lake	14,933	7,893
2	Alberta	Edmonton, Red Deer, Calgary	114,269	34,738
3	Alberta	Banff, Jasper, Rocky Mountain House	6,193	—
4	Alberta	Athabasca, Grande Prairie, Peace River	99,432	13,480
5	British Columbia	Cariboo	18,508	12,813
6	British Columbia	Northeast	—	—
7	British Columbia	Vancouver Island and Coast	190,676	2,502
8	British Columbia	Thompson, Okanagan	141,539	—
9	British Columbia	Kootenay	170,769	—
10	British Columbia	Nechako	—	—
11	British Columbia	Lower Mainland, Southwest	67,522	—
12	British Columbia	North Coast	3,232	6,237
13	Manitoba	Southwest, Parklands	7,208	5,738
14	Manitoba	North	1,181	778
15	Manitoba	Southeast, Winnipeg	—	3,521
16	New Brunswick	Edmundston, Woodstock, Saint John, St. Stephen, Fredericton, Oromocto	—	41,697
17	New Brunswick	Moncton, Richibucto, Campbellton, Miramichi	—	64,231
18	Newfoundland and Labrador	West Coast, Northern Peninsula, Labrador	—	—
19	Newfoundland and Labrador	Notre Dame, Central Bonavista Bay	—	12,099
20	Newfoundland and Labrador	Avalon Peninsula	—	—
21	Nova Scotia	North Shore, Cape Breton	—	—
22	Nova Scotia	Southern, Annapolis Valley, Halifax	—	—
23	Ontario	Northeast	—	641
24	Ontario	Northwest	14,130	10,996
25	Ontario	London, Hamilton, Niagara Peninsula, Windsor, Sarnia, Toronto, Kitchener, Waterloo, Barrie, Stratford, Bruce Peninsula	—	—
26	Ontario	Muskoka, Kawarthas, Kingston, Pembroke, Ottawa	—	—
27	Quebec	Nord du Québec	6,845	—
28	Quebec	Montérégie, Centre du Québec, Estrie	—	—
29	Quebec	Bas Saint Laurent, Gaspésie, Îles de la Madeleine	—	123,449
30	Quebec	Mauricie, Laurentides, Outaouais, Abitibi, Témiscamingue, Lanaudière	10,505	8,976
31	Quebec	Saguenay, Lac Saint Jean	—	—
32	Quebec	Côte, Nord	78,617	21,948
33	Quebec	Chaudière, Appalaches	—	32,304
34	Saskatchewan	Prince Albert	55,953	28,991
35	Saskatchewan	Northern	4,050	2,668

secondary forest products sectors. This model bridges the gap of currently available tools and models for regional mill residue inventory estimation in Canada by providing a means to reflect temporality of mill residue availability in various regions owing to changes in activity levels of various sectors or emergence of new forest-based bioproducts facilities.

The model was calibrated to 2013 production levels to evaluate wood fiber cascade through the existing forest industry in Canada in that year. The model estimates that the total surplus of whitewood residue and hog fuel produced at primary forest products mills in Canada was about 14.8 Mbdt in 2013; this biomass is what is available after internal energy production requirements are met. Of this biomass, however, only 1.4 Mbdt were untapped, the majority of which was found in British Columbia, Alberta, or Quebec; the rest was diverted to existing secondary producers, including bioenergy applications, which suggests that the ability to grow the Canadian bioeconomy on mill residue fiber is very limited.

The limited availability of untapped surplus mill residues highlights the importance of devising feedstock supply strategies and policies for the emerging forest-based industries such that the impacts on regional fiber flows and feedstock availability to the existing secondary industry are considered. Further expansion of Canada's bioeconomy will be largely dependent upon the ability of producers to access primary fiber from forests.

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