NRC Research Press

ARTICLE

Forecasting the spatial distribution of logging residues across the Canadian managed forest

Julie Barrette, David Paré, Francis Manka, Luc Guindon, Pierre Bernier, and Brian Titus

Abstract: There is a growing interest in using logging residues as feedstock in the bioeconomy. Quantifying the amount of this resource over large areas has been difficult due to the lack of availability of and consistency in forest inventory data across jurisdictions and the lack of a clear definition of what constitutes logging residues. The goal of this study was to develop an approach to spatially estimate the amounts of logging residues that would potentially be available in the near future for public lands across the Canadian managed forest using remote sensing maps and to compare these estimates with field assessments. Remote sensing estimates of branch and foliage biomass, although only a fraction of total postharvest residual biomass, were generally comparable with estimates from field assessments of recoverable residues after harvesting at the forest management unit (FMU) scale or at the 100 km² scale. However, they tended to not capture the strong variability between sites and to underestimate observed field values in regions that have very high biomass density. On average, the national logging residue density is estimated to be 26 ± 16 oven-dry tonnes (ODT)·ha⁻¹, and annual national availability is estimated to be 21 M ODT·year⁻¹. Maps produced are available at doi:10.23687/dd94871a-9a20-47f5-825b-768518140f35 and doi:10.23687/5072c495-240c-42a3-ad55-c942ab37c32a.

Key words: logging residues, remote sensing, inventory, bioenergy, field assessment.

Résumé : L'utilisation des résidus de coupe comme matière première dans le secteur de la bioéconomie suscite de plus en plus d'intérêt. Il est difficile d'évaluer la quantité de cette ressource sur de vastes superficies à cause du manque de disponibilité et de consistance de données d'inventaire forestier à travers différentes juridictions et de l'absence d'une définition claire de ce qui constitue des résidus de coupe. Cette étude visait à développer une approche pour estimer spatialement la quantité de résidus de coupe potentiellement disponibles dans un proche avenir dans la forêt aménagée du Canada sur terres publiques à l'aide de la cartographie par télédétection et de comparer ces estimations à des évaluations réalisées sur le terrain. Les estimations de la biomasse des branches et du feuillage obtenues par télédétection, bien qu'elles ne représentent qu' une fraction de la biomasse résiduelle après coupe, étaient généralement comparables aux évaluations des résidus de coupe récupérables après coupe réalisées sur le terrain. Les estimations fondées sur la télédétection étaient en moyenne comparables aux valeurs obtenues sur le terrain à l'échelle de l'unité d'aménagement forestier ou à l'échelle de 100 km². Par contre elles avaient tendance à ne pas détecter la forte variabilité entre les sites et à sous-estimer les valeurs observées sur le terrain dans les régions où la densité de la biomasse est très élevée. En moyenne, la densité des résidus de coupe à l'échelle nationale est estimée à 26 ± 16 tonnes anhydres (t.a.)·ha⁻¹ et la disponibilité nationale annuelle à 21 M t.a.·an⁻¹. Les cartes qui ont été produites sont disponibles sur doi:10.23687/dd94871a-9a20-47f5-825b-768518140f35 et doi:10.23687/5072c495-240c-42a3-ad55-c942ab37c32a. [Traduit par la Rédaction]

Mots-clés : résidus de coupe, télédétection, inventaire, bioénergie, évaluation sur le terrain.

Introduction

Secondary forest residues (i.e., processing or mill residues such as sawdust, shavings, and wood chips) are currently almost fully utilized in Canada (Natural Resources Canada 2006; Bradley 2008; Industrial Forestry Services 2015). Further deployment of bioenergy and other bioproducts must therefore rely on the use of logging residues or other feedstocks such as salvage wood, unmerchantable live stems (Dymond et al. 2010), and urban wood waste (e.g., Ralevic et al. 2008; Gronowska et al. 2009). Forest logging residues are still a largely untapped resource (e.g., Paré et al. 2011) with short-term greenhouse gas (GHG) mitigation benefits when used wisely (Haberl et al. 2012; Lamers et al. 2014; Laganière et al. 2017). For example, GHG benefits to the atmosphere begin sooner when logging residues replace coal than when they replace natural gas (Laganière et al. 2017). GHG benefits will vary depending on the fossil fuel and the fossil fuel system to be replaced (Lamers and Junginger 2013; Laganière et al. 2017; Smyth et al. 2017). Forest logging residues are a large and relatively accessible biomass resource with a reasonably stable rate of production and are therefore a feedstock of interest for the nascent Canadian bioproducts sector. Logging residues can be converted into electrical and heat energy, transport fuel, renewable natural gas (Canadian Gas Association 2014), and chemicals (Demirbaş 2001; McKendry 2002; Mabee and

Received 5 March 2018. Accepted 5 September 2018.

J. Barrette, D. Paré,* F. Manka, L. Guindon, and P. Bernier. Natural Resources Canada, Canadian Forest Service, 1055 du P.E.P.S, P.O. Box 10380, Stn. Sainte-Foy, Québec, QC G1V 4C7, Canada.
B. Titus. Natural Resources Canada, Pacific Forestry Centre, 506 Burnside Road West, Victoria, BC V8Z 1M5, Canada.
Corresponding author: David Paré (email: david.pare@canada.ca).

*David Paré currently serves as an Associate Editor; peer review and editorial decisions regarding this manuscript were handled by Timothy Fahey and Peter Newton.

Saddler 2010; Hsu 2012) and can thus be used as feedstock for a range of applications that can both contribute to global climate change mitigation efforts (Chum et al. 2011) and support the Canadian forest sector's competiveness.

Definitions of logging residues vary, but they are essentially composed of all tree-based biomass that remains on-site after harvesting operations are completed. They generally include the tops and branches of harvested trees remaining on-site in cutblocks, especially when trees are delimbed "at the stump", and roadside residues when aboveground portions of merchantable trees are moved to roadside for delimbing and slashing. Not all residues are suitable as feedstock for specific products; for example, logging residues used for bioenergy production must meet different quality standards (e.g., species, amount of rot, amount of bark, water content, ash content, etc.) and must be technically and economically recoverable and recovery must comply with relevant environmental regulations and guidelines to ensure the sustainability of ecosystem processes and the maintenance of biodiversity.

Logging residues are a by-product of forest harvesting and, therefore, their future availability can only be estimated using information on the predicted location and extent of future forest harvesting activities. This spatial information is available in local forest management plans, but aggregation of maps of both past and future harvest plans over large areas is virtually impossible because these plans vary regionally in the methodologies used to develop them, in their temporal coverage, and in their availability to analysts. Spatial estimates of logging residue availability in Canada have nevertheless been made using different inventory methods, including (*i*) using harvesting plans to estimate logging residue production based on allometric tree biomass equations (e.g., Wood and Layzell 2003), (*ii*) using point-source mill survey data to back-calculate roundwood consumption and then spatially estimate the resultant logging residue production with allometric equations for tree components (e.g., Sidders et al. 2008; Parzei et al. 2014), and (*iii*) using dynamic forest carbon models from which tree components that become logging residues (tops, branches, foliage) can be predicted within large spatial units of forests (e.g., Dymond et al. 2010; Smyth et al. 2014) similar in size to some forest management units (FMU).

However, remote sensing maps of past forest harvesting disturbances across large areas (Guindon et al. 2014, 2017, 2018) can also be combined with remotely sensed wall-to-wall information on forest composition, biomass, and volume (Beaudoin et al. 2014, 2018) to estimate past logging residue amounts and distribution (e.g., Mansuy et al. 2017). These remote sensing products make it possible to predict where future forest harvesting could occur based on the extent of past harvesting and natural disturbances plus current stand conditions. Increasing interest in the application of forest data from large areas along with the decreasing availability of financial resources for collecting field data combine to make the use of remote sensing technologies for forest inventory processes increasingly attractive (White et al. 2016).

Predicting the future availability of logging residues is important for estimating the size of the potential contribution that this feedstock could make to the nascent Canadian bioeconomy and the resultant climate change mitigation potential. Thus, the overall goal of this study was to forecast the location and amount of logging residues that would be available annually over the next ≈20 years across the Canadian managed forest, which is a time span that covers the amortization period of most forest-sector capital investments and the 2030 target date by which Canada must meet its Paris Accord commitments. We define logging residues as all branches and foliage not hauled to mills for use in manufacturing standard forest products. Results must be used with caution because additional ecological, technological, and economic factors were not considered and yet should be accounted for when considering the potential for bioenergy (Chum et al. 2011) or other bioproducts. For example, applying a 50% logging residue retention factor for ecological reasons in large-scale biomass inventories has been recommended (Titus et al. 2009), which coincides with average techno-economic amounts left operationally at a site level (Thiffault et al. 2015).

Specific study objectives were to (*i*) develop and validate a methodology based on remote sensing for producing estimates of total future potential logging residues availability, (*ii*) evaluate the effects of the spatial scale to which the results are aggregated on the resulting estimates and their uncertainties, and (*iii*) compare these estimates with field assessments of logging residues left on-site. To meet our objectives, we developed a methodology for combining estimates of past logging rates within FMUs with information on stand attributes (both of which can be extracted from new Canada-wide remote sensing products) to generate standardized Canada-wide 20-year forecasts of potential logging residue availability. This forecasting tool can be used to improve forest management strategies and wood utilization efficiency, inform strategies on how to site new bioproduct industries, and inform policies related to the bioeconomy and climate change mitigation.

Material and methods

Study area

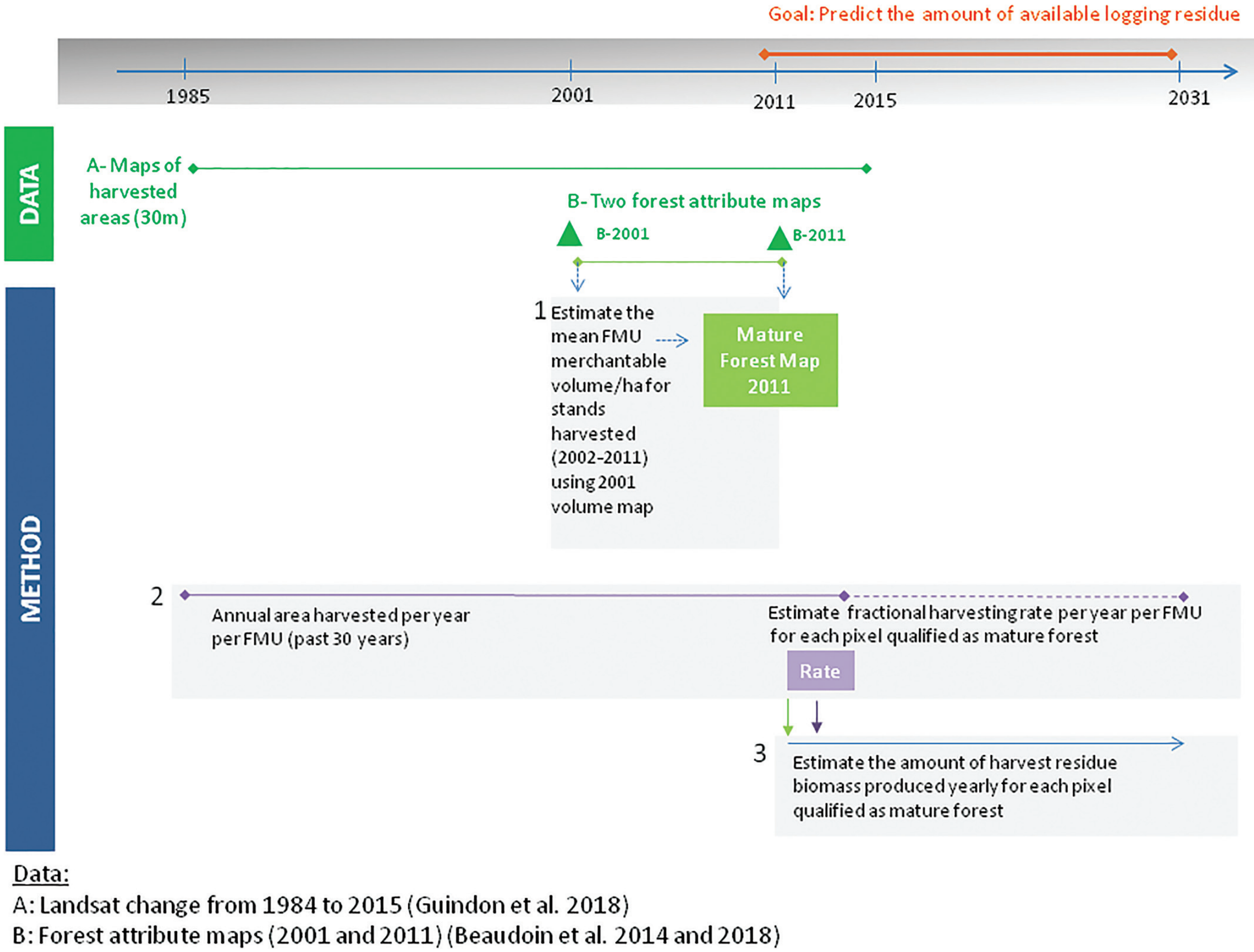
Our study covered nine of Canada's 10 provinces; we excluded Prince Edward Island and the three territories because of the lack of or the relatively small size of their managed forest; we also excluded all parks and conservation and protected areas. Forests are managed within defined areas on the landbase that are typically (but not always) called forest management units (FMUs), and we use this term in a generic sense to refer to all management units within all provinces. FMU boundaries were obtained from each province (for further details, see Supplementary Table S1[1]), except for Nova Scotia where districts were used because they are similar size to FMUs in neighbouring provinces (mean forest area of FMUs is about 570 000 ha). Estimates of logging residue availability were compiled both within 100 km^2 (10 km × 10 km) grid cells (as used by Sidders et al. 2008) and within individual FMUs.

Generating biomass estimates

Forecasts of the mass per unit area and spatial distribution of logging residues across the Canadian managed forest were based on three remote sensing products (Fig. 1): (A) a set of harvest maps (1985–2015) at 30 m Landsat pixel resolution (Guindon et al. 2017, 2018), and B-2001 and B-2011, two sets of maps of forest attributes (2001 and 2011) at 250 m MODIS pixel resolution (Beaudoin et al. 2014, 2018). Annual harvest maps (referred as CanLaD products) provided spatial delineation of clearcuts with the year of first detection, based on a decision-tree algorithm and reference harvest block information, validated using the provincial inventories. Forest attribute maps provided two other critical pieces of information for our study for 2001 and 2011: estimates of merchantable volume and aboveground biomass by species and by four tree compartments (branches, stems, bark, and foliage). As described in Beaudoin et al. (2014, 2018), maps were created using the *k*-nearest-neighbors (*k*NN) approach and information from Canada's National Forest Inventory (NFI) as a reference data source in which both merchantable volume and the biomass of each of the four compartments are expressed as totals per pixel (250 m × 250 m). We used the within-pixel proportion of forest to re-express these values per hectare of forest area.

[1]Supplementary material is available with the article through the journal Web site at http://nrcresearchpress.com/doi/suppl/10.1139/cjfr-2018-0080.

Fig. 1. Steps used to forecast the spatial distribution of logging residues (branches and foliage) for the managed forest of Canada using remote sensing. Step 1: creation of a map of "mature forests" available for harvesting as of 2011, defined as all areas containing a merchantable volume per hectare of a value greater than 80% of that of the average merchantable volume of stands harvested in that FMU during the past 10 years. Step 2: determination of an annual area-based harvesting rate by FMU. Step 3: determination of the amount of logging residues that would be available in the future (beyond 2011). [Colour version available online.]

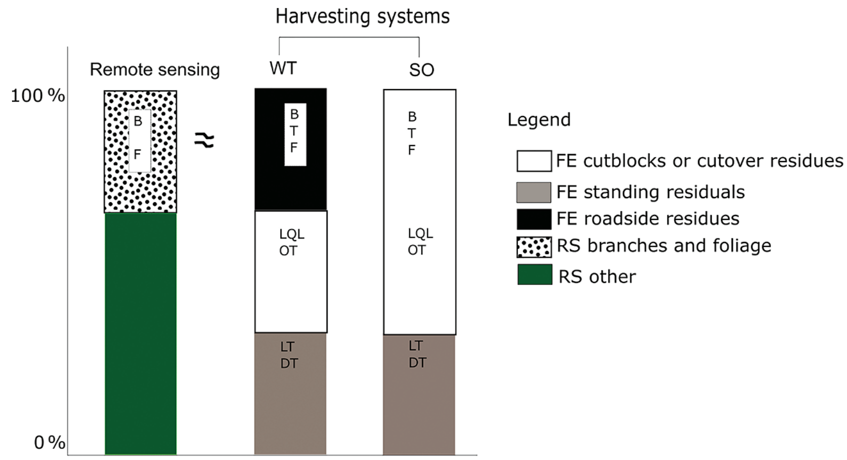


Procedurally, there were three different steps in which all calculations were done for each FMU (Fig. 1) by (1) creating a map of forest available for harvesting (named "mature forest") as of 2011, (2) estimating the annual area harvested by FMU based on the last three decades of harvesting (1985–2015), and (3) estimating logging residues (using the biomass of branch and foliage as a proxy) that would be available in the future (beyond 2011: ≈2012–2031) based on estimates from the first two steps.

In step 1, we identified all pixels in which forests could be classified as harvestable in 2011. For each FMU, we estimated the mean merchantable volume per hectare of all harvested pixels. To do this, we intersected a map showing all of the clearcuts that occurred between 2002 and 2011 (gives location) with the 2001 map of forest attributes (gives merchantable volume per hectare). Aggregation of the two products was done using simple areal averaging and the centroid of each Landsat 30 m resolution pixel. We then assumed that pixels classified as "mature forest" or forest available for harvesting during the next 20 years would have a merchantable volume per hectare that exceeds a value of 80% of the mean 2001 merchantable volume of the pixels that had been harvested (2002–2011) within specific FMUs. With this information, we produced a mature forest map (available at doi:10.23687/dd94871a-9a20-47f5-825b-768518140f35).

In step 2, we first calculated the area harvested per year per FMU for a 30-year period (1985–2015) using Guindon et al. (2018). We then assumed that the area harvested per year per FMU would remain constant over the 20 years beyond 2011 because forests are typically managed for a constant wood flow at the FMU level by taking into consideration both forest productivity and harvesting constraints. We also expressed annual harvesting rate (as a percentage of total forest area per FMU) as an overall indicator of forest productivity. Finally, we attributed the total area to be harvested annually per FMU to all pixels containing mature forest. In effect, a fractional harvesting rate per year per FMU was estimated for each mature forest pixel so that the total area harvested per year per FMU remains constant and equal to that of the past 30 years. This procedure spreads the area to be harvested over all mature forest pixels in all years. In reality, harvest would be more concentrated geographically, but because we do not have the information on the location of future harvest, we simply use the assumption that harvest will be conducted in mature forests proportionally to their abundance.

Fig. 2. Type of logging residues produced by stem-only (SO) and whole-tree (WT) harvesting systems and estimated using remote sensing (RS). B, branches; T, tree tops; F, foliage; LQL, low-quality logs; OT, overturned or snapped trees; LT, standing live trees; DT, standing dead trees; FE, information from field experiments or field surveys. [Colour version available online.]



In the third and final step, we calculated the amount of biomass that would be available each year over the next 20 years using branch plus foliage biomass as a proxy for logging residue biomass. This was first calculated at the pixel level (250 m × 250 m) using Beaudoin et al. (2018), which gives the branch plus foliage biomass in 2011 multiplied by the fractional harvesting rate per pixel and per FMU calculated in step 2. This generated a map forecasting available harvest residues, which is available at doi: 10.23687/5072c495-240c-42a3-ad55-c942ab37c32a.

The results from each pixel were then summed both at the FMU level and at the 10 km × 10 km grid cell level. This scale has been found to be practical for estimating biomass for bioenergy applications as in the Biomass Inventory and Mapping Assessment Tool (Sidders et al. 2008).

Validation of remote sensing estimates

Our remote sensing estimates of logging residue availability (oven-dry tonnes (ODT)·ha^{-1}) could not be evaluated using data from independent sources because branches and foliage were not reported separately from other types of logging residues. However, our estimates of both merchantable volume and area harvested can be compared with those reported annually by provinces (National Forestry Database, http://nfdp.ccfm.org/en/data/harvest.php, accessed 30 October 2018). For this, we compared the total harvested area provided by CanLaD with the sum of annual areas harvested reported by each province for 2002 to 2011 (National Forestry Database). Moreover, we compared remotely sensed estimates of harvested wood volumes (intersection of the CanLaD harvest map and the *k*NN volume map of 2011) with the annual harvested volumes reported by each province for the same 10-year period (sum of softwoods and hardwoods; National Forestry Database). The purpose of presenting the relationships between the National Forestry Database's figures and the approach developed was to illustrate that these two independent approaches provide biomass estimates that are in general agreement. The CanLaD product used within this study had already been reported to have a detection level of harvested areas of 91.1% using a polygon validation dataset (Guindon et al. 2018) and had been compared with the State of Canada's Forest report (Natural Resources Canada 2017) at the national level (Guindon et al. 2018).

Comparison with field assessments of logging residues

Our remote sensing estimates of logging residues per unit area (ODT·ha^{-1}) were also compared with georeferenced field assessments of logging residue biomass (which can include roadside and cutblocks residues and standing residuals) averaged at the provincial level in Quebec, Ontario, and British Columbia, where about 70% of Canada's timber harvesting takes place (Supplementary Fig. S1[1]). The comparison was done to validate the assumption that the branch plus foliage biomass from Beaudoin et al. (2014, 2018) could be used as a proxy for total logging residues.

In those provinces, the two most common harvesting systems are whole-tree (WT) harvesting (i.e., processed at roadside or full-tree harvesting systems) and stem-only (SO) harvesting (i.e., processed at stump or cut-to-length harvesting systems). Whole-tree harvesting systems are widely used in softwood and mixed forest types, and trees are cut and hauled to the roadside where they are then delimbed (processed). This produces two types of residues: most is piled at the roadside, although a smaller amount may break off during extraction and is hence scattered across the cutblock. Roadside residues are mostly composed of tree tops, branches, and foliage, while cutblock residues can include low-quality logs left from bucking operations and overturned or snapped trees (Fig. 2). Standing residual trees can also be left in cutblocks and consist of unmerchantable live and dead trees that cannot be used by the sawmill industry because of their small size or poor quality. In stem-only harvesting systems, trees are delimbed, topped, and bucked at the stump, and only resulting logs are forwarded to the roadside. There are no roadside residues, and cutblock residues mostly include tree tops, branches, foliage, low-quality logs, and overturned or snapped trees.

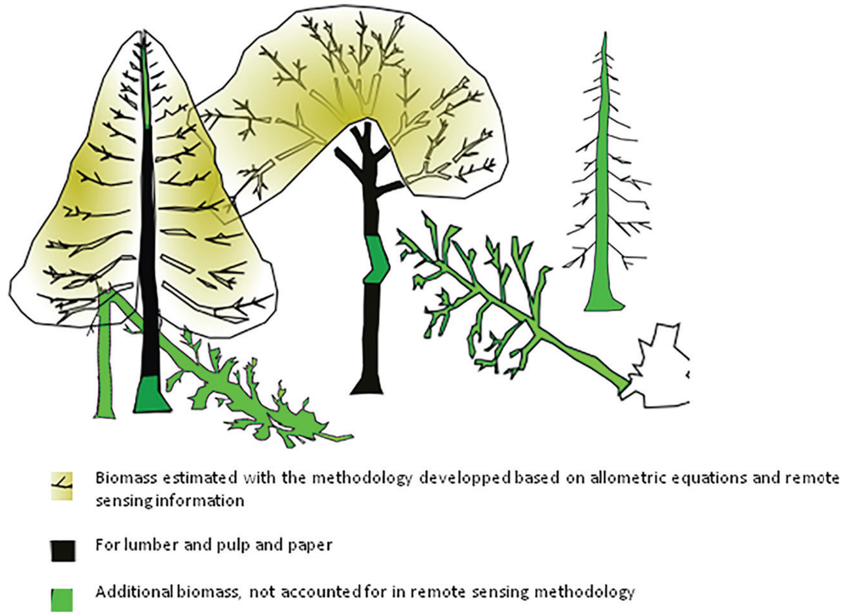
Where possible, estimates of logging residues obtained from field assessment included cutblock residues, roadside residues, and standing residuals. Further details describing field assessment data and the methods used in this study to estimate logging residue biomass per unit area (ODT·ha^{-1}) in Quebec, Ontario, and British Columbia are provided in Supplementary Table S2[1].

Our methodology only predicted branch and foliage biomass, and these components are illustrated as a subset of all potential logging residue biomass components in Fig. 3.

Aggregation of remotely sensed logging residues

Data on logging residues are usually reported as spatially aggregated estimates, but the aggregation of data from one scale to another may affect the results and their associated uncertainties (Quattrochi and Goodchild 1997). We therefore analyzed the effect of reporting scale for remotely sensed logging residues by comparing data for both the 100 km^2 grid cells and the FMUs with values from the field, expressed as the sum of all logging residues (which can include roadside and cutblock residues, as well as standing residuals) reported in Quebec, Ontario, and British

Fig. 3. Different components that make up logging residues on a forest site. Live trees adapted from Lambert et al. (2005); dead trees adapted from Hunter (1990); broken trees adapted from https://www.coloradofirecamp.com/s-212-chainsaws/glossary_T-Z.htm; overturned trees adapted from http://thealmonddoctor.com/2014/12/15/recent-storms-tree-loss/. [Colour version available online.]



Columbia. Variability within and between each dataset was calculated and displayed using descriptive statistics (i.e., boxplots). Moreover, we tested the relationships between the remote sensing logging residue estimates aggregated at both scales with values from field experiments using the lm function in R (R Core Team 2015).

Our estimates of residues (branches plus foliage) were also expressed as a proportion of total live aboveground biomass (sum of stemwood, stem bark, and branch and foliage biomasses) because this is a useful metric through which one can relate the biomass of residues to the biomass of stemwood. Results are again presented by province.

Results

Development and validation of a methodology based on remote sensing products for producing estimates of total future potential logging residue availability

Comparisons between both our remote sensing estimates of merchantable volume and harvested areas with those reported by the National Forestry Database by province are presented as Supplementary Fig. S1[1] and Supplementary Table S3[1], with strong relationships (R^2 = 0.94) for both comparisons.

The creation of the maps of mature forest stands (step 1) revealed that the area of mature forest expressed as a proportion of total forested area within individual FMUs varied from less than 20% to over 80% across the country (Fig. 4*a*). In general, the greatest proportions of mature forests were found in FMUs in the southernmost forest regions, perhaps because of the reduced proportions of unproductive land and a lower wildfire frequency (Gauthier et al. 2015) and the use of partial harvesting, which is frequently used in, for example, southwestern Quebec (area in red in Fig. 4*a*). Across the country, more than 50% of FMUs contained 40% or more of mature forests, and about one-third of FMUs contained more than 60% of mature forests.

FMUs with the greatest mean merchantable volume per hectare were found in British Columbia, where values were more than twice those found in other provinces (Fig. 4*b*). Apart from British Columbia, the mean merchantable volume of mature forest in FMUs ranged between 86 and 151 $m^3 \cdot ha^{-1}$ (Fig. 4*b*). Merchantable volume was comprised nearly exclusively of softwoods in British Columbia and in Newfoundland and Labrador (Fig. 4*c*). Merchantable volumes of hardwoods were greater in FMUs in southern forest areas, except for Alberta and Saskatchewan, where hardwoods extend to the northern extremities of the managed forest. Merchantable volumes of mixed composition were most common in FMUs in Quebec and Ontario (Fig. 4*c*).

Determination of annual area-based harvesting rate by FMU based on the last three decades of harvesting (1985–2015) (step 2) showed that the mean area harvested annually ranged from <0.16% to 1.6% of total forest area within FMUs (Fig. 5*a*) but was <0.3% to 4.5% of mature forest area (Fig. 5*b*). In both cases, the greatest areas of annual harvesting were found in FMUs in central British Columbia, Ontario, Quebec, New Brunswick, and Nova Scotia, where it was over 0.9% of total forest area and over 2.3% of mature forest area. Areas with the least proportion of annual harvesting were found in northern Manitoba, Saskatchewan, and Labrador (from <0.16% to <0.3%) where tree growth rates are typically low.

Based on the two first steps, the map of estimates of logging residues (branches and foliage) that would be available in the future (beyond 2011) was created (step 3). The biomass available yearly from logging residues in 100 km^2 grid cells varied from 0.001 to more than 10 000 ODT across the managed forest (Fig. 6). The greatest values were found in both the coastal and interior regions of British Columbia, with large portions of these regions falling in the range of 2826 to 10 927 $ODT \cdot year^{-1} \cdot 100\ km^{-2}$. The yearly amount of available logging residues was quite similar in Ontario, Quebec, and Nova Scotia, generally ranging from 724 to 2826 $ODT \cdot year^{-1}$ in 100 km^2 grid cells (Fig. 6). The lowest range (0.001 to 37 $ODT \cdot year^{-1}$ in 100 km^2 grid cells) was mostly found in Saskatchewan, Manitoba, and Labrador (Fig. 6). Overall, the annual national amount of available logging residues was estimated at 21 M $ODT \cdot year^{-1}$.

Average logging residue biomass per unit area estimated across the Canadian managed forest using the remote sensing method (using data aggregated at the 100 km^2 grid cell level) was 26 ± 16 $ODT \cdot ha^{-1}$, and varied from 15 to 29 $ODT \cdot ha^{-1}$ except in British Columbia, where values were about twice that of the national

Fig. 4. Maps of mature forest stands (for definitions, see Material and methods) across the managed forest of Canada: (*a*) proportion of mature forest to forested area; (*b*) mean merchantable volume of mature forest per hectare ($m^3 \cdot ha^{-1}$); and (*c*) percentage of softwood in the mature forest.

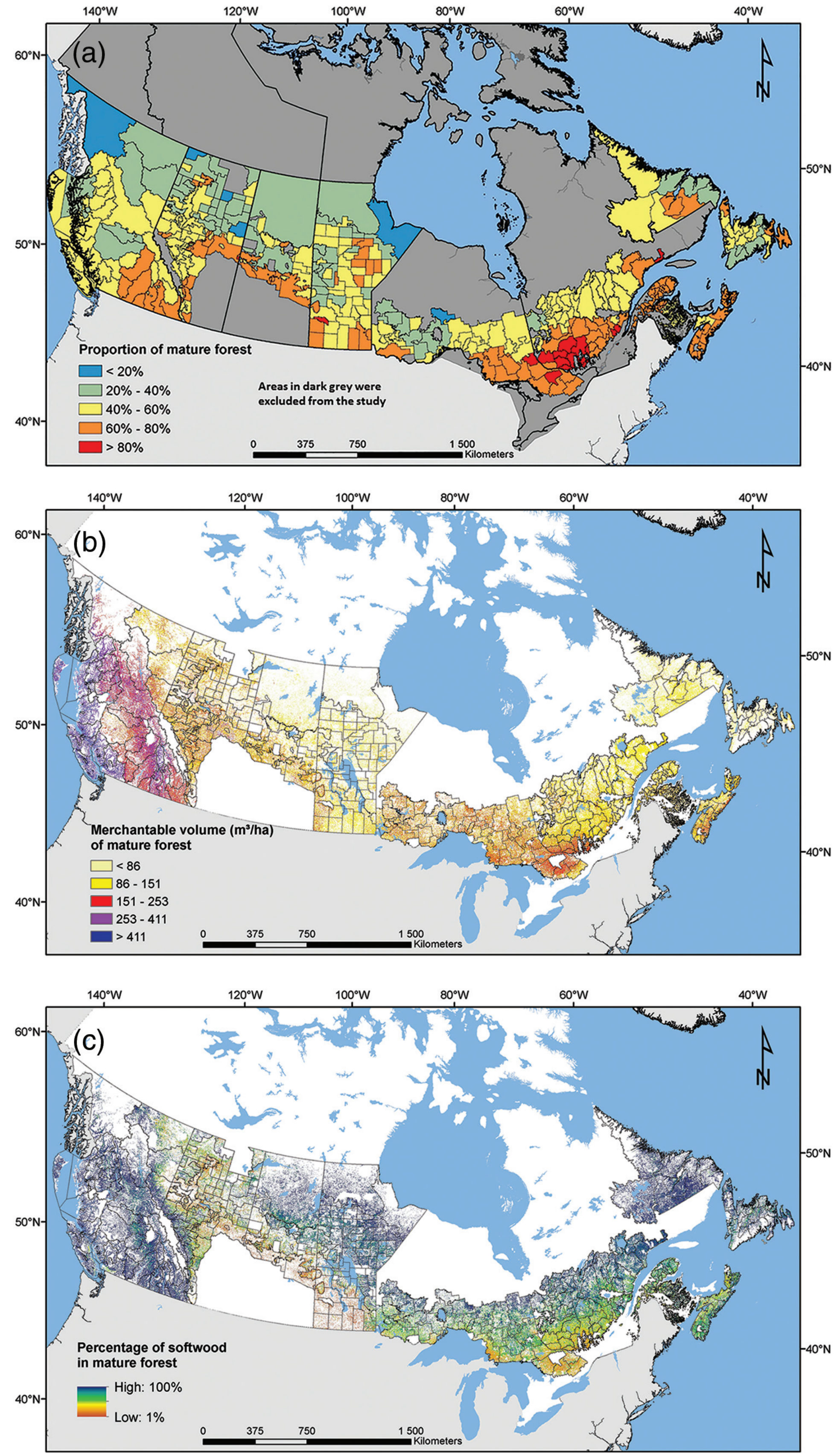
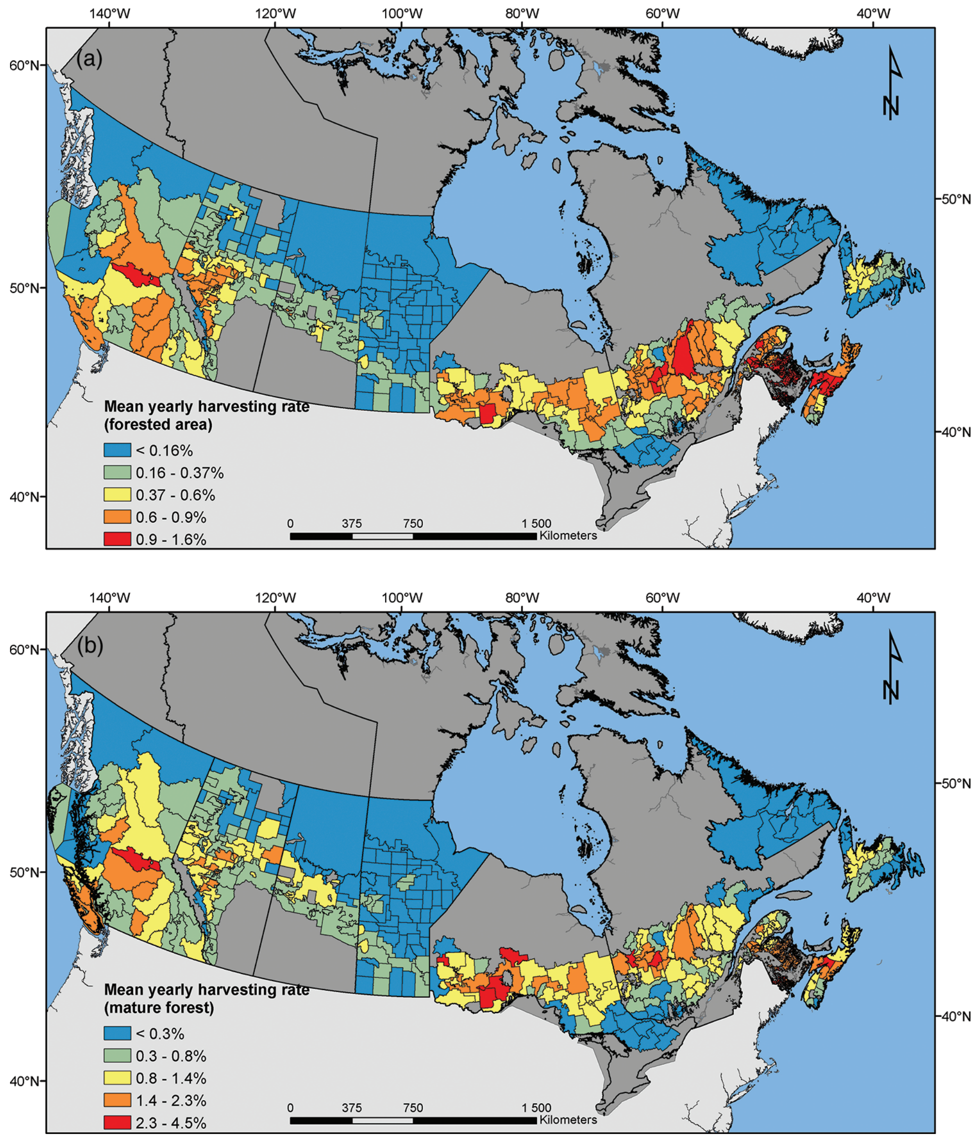


Fig. 5. Maps of the mean harvesting rate (per year) across the forest management units (FMUs) of Canada on (*a*) a forested area basis and (*b*) a mature forest area basis.



estimate (Fig. 7*a*). Across the provinces, standard deviations were generally proportional to the mean (Fig. 7*a*).

The proportion of logging residues to total live aboveground biomass before harvesting obtained using remote sensing varied from 15% to 31% across the provinces, with a national average of 21% (Fig. 7*b*). Values were greater in Newfoundland and Labrador, probably because of the small size of trees (i.e., stemwood biomass). Stemwood biomass made up about 69% of total live aboveground biomass, while stem bark biomass made up approximately 10% (Fig. 7*b*). These proportions are in the same range as those from allometric equations developed for Canadian tree species (e.g., Ung et al. 2008).

Evaluation of the effects of the spatial scale to which the results are aggregated on the resulting estimates and their uncertainties

Logging residue values were more variable among 100 km^2 grid cells than among FMUs in Manitoba, Alberta, British Columbia, and Newfoundland and Labrador but showed similar variabilities between the two spatial scales in Quebec, Ontario, Nova Scotia, and New Brunswick (Fig. 8; Supplementary Table S4[1]). Values of logging residues estimated with remote sensing were always less variable than plot-level values from field assessments (Fig. 8; Supplementary Table S4[1]).

In general, predictions of logging residues from both remote sensing datasets (100 km^2, FMUs) tended to be symmetrical, with the median usually in the middle of the boxes in the boxplots (Fig. 8; Supplementary Table S4[1]); this contrasts with estimates from field assessments where medians were usually skewed to the left, indicating a high frequency of low amounts of logging residues even though some values were very high. With the exception of coastal British Columbia, estimates of logging residues obtained using remote sensing were generally within the range of variability of those from field assessments, as shown by the overlap of boxplots within the same province (Fig. 8*a*). In Ontario, the median of the field experiment (FE) boxplot was also slightly higher than the median of the remote sensing (RS) estimates (Fig. 8*b*). This may be because of the large proportion of jack pine in these trials, which is a tree species that produces a large volume of branches particularly at low stand densities. Further details on the relationships tested between the remote sensing estimates of logging residue estimates at both scales and values from field experiments are provided in the Supplementary material[1]. As for

Fig. 6. Map of the forecasted spatial distribution of future remote sensing logging residues available annually per grid cells of 10 km × 10 km across the managed forests of Canada.

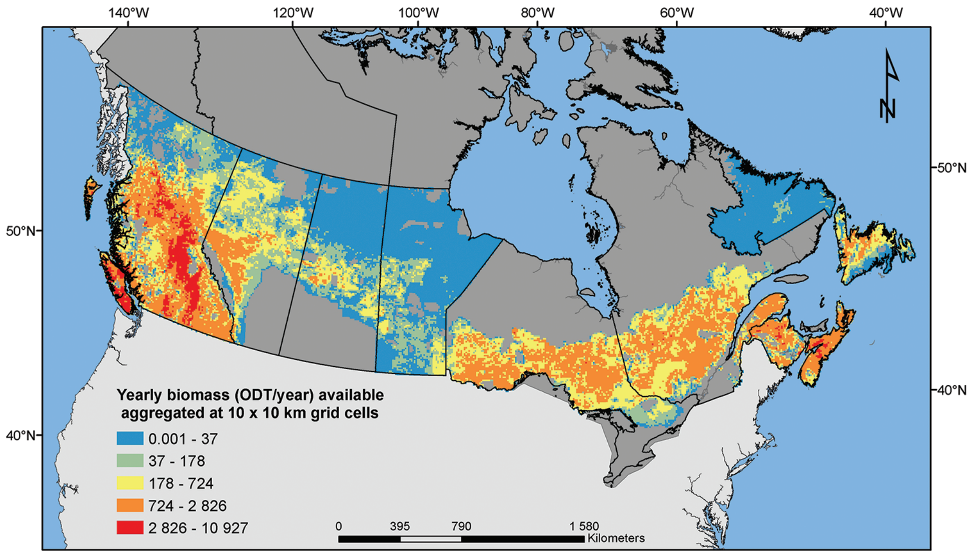
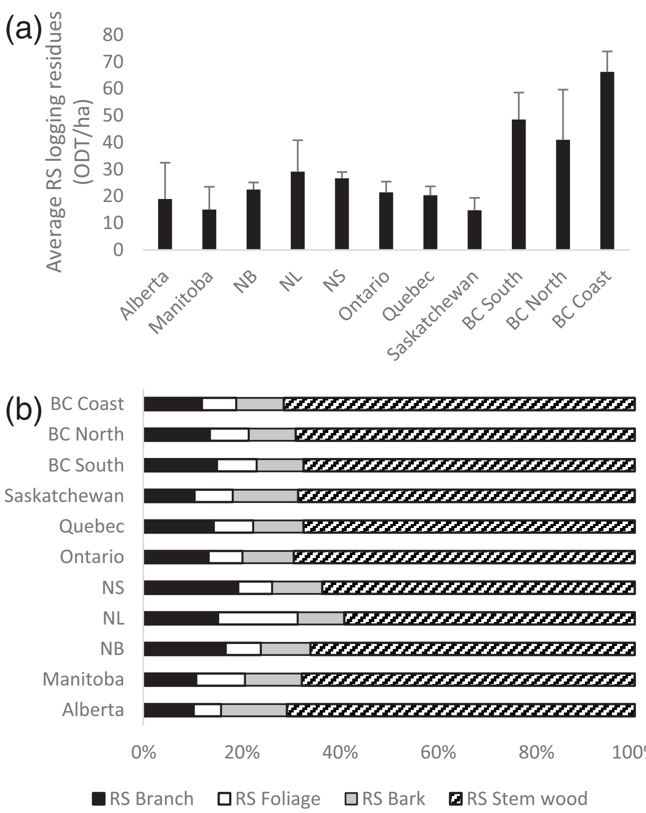


Fig. 7. (*a*) Average remote sensing (RS) logging residue availability (aggregated at grid cells of 10 km × 10 km) (oven-dry tonnes (ODT)·ha^{-1}) per province with their associated standard deviations. (*b*) Relative proportion (%) of the diverse RS biomass components to RS total live aboveground biomass per province. BC, British Columbia; NB, New Brunswick; NL, Newfoundland and Labrador; NS, Nova Scotia.



the boxplots, the relationships (Supplementary Figs. S2*a* and S2*b*[1]; Supplementary Table S5[1]) show that our estimates of RS logging residues (at the FMU or 10 km × 10 km scale) are generally unbiased (distribution on both sides of the 1:1 slope), except for values at the high end of the distribution, which are mostly found in coastal British Columbia.

Comparison of remote sensing estimates with field assessments by types of residues

At the provincial level, average remotely sensed logging residue estimates were comparable with roadside residue estimates from field assessments in Quebec and Ontario (Fig. 9), whereas logging residue estimates for British Columbia obtained using remote sensing were about 2× greater than roadside estimates for all regions studied (i.e., coast, north, and south; C. Friesen, personal communication). Across the three provinces, logging residue values obtained using remote sensing were generally less than total amounts of harvested residues from field assessments (i.e., sum of roadside piles, cutblock residues, and, when available, standing residuals), except for the southern region of British Columbia, where estimates were similar (Fig. 9). For this comparison, data from field experiments were first averaged by FMU and then by province. Only RS estimates aggregated at the FMU scale that matched the field experiment's FMUs were used.

Discussion

The approach developed in this study makes it possible to estimate the amount of logging residues that would be available for public lands across the Canadian managed forest in the near future at various spatial scales. Compared with some biomass assessment methods, this new approach does not require detailed, consistent, and updated inventory or survey information because it relies on the remotely sensed detection of harvesting history and estimates of forest attributes, which are easier to acquire and update. This new approach is different from existing ones (e.g., Sidders et al. 2008; Mansuy et al. 2017) in that the annual harvesting rate is applied to uncut mature forests and not to forests that had just been cut. Our model can be run over successive years to predict future logging residue availability, albeit constrained by the assumption of a constant harvesting rate and predictions of where future harvesting will take place. This advantage is particularly important at the local scales used in strategic analysis for investment planning. Calculations are made at a 250 m pixel resolution, but values reported at the 100 km^2 grid or FMU scale should be more robust, especially because of the assumption of a uniform harvesting rate across all pixels containing harvestable forests within FMUs.

As in other studies (e.g., Mansuy et al. 2017), we used the proxy of branch and foliage biomass to define our remotely sensed biomass of total logging residues. Estimates of branch and foliage

Fig. 8. Boxplots comparing remote sensing (RS) logging residues aggregated at grid cells of 10 km × 10 km and at the forest management unit (FMU) scale with logging residue estimates from field experiments (FE) for (*a*) regions of British Columbia and (*b*) the others provinces. Boundaries of the box indicate the 25th and 75th percentiles, the full line within the box marks the median, error bars indicate the 90th and 10th percentiles. RS 10*10, predictions of logging residues at 250 m pixel resolution aggregated into grid cells of 10 km ×10 km; RS FMU, predictions of logging residues at a 250 m pixel resolution aggregated into FMUs. The red open circles correspond to extreme values observed either in field experiments or in RS logging residues aggregated at grid cells of 10 km × 10 km and at the FMU scale. In British Columbia (BC), this includes cutblock residues and roadside residues from whole-tree (WT) harvesting system. In Ontario, it includes cutblock residues, roadside residues, and standing residuals (only from Cormier et al. (2012)) from whole-tree (WT) or stem-only (SO) harvesting systems. In Quebec, it includes cutblock residues and standing residual trees from the stem-only (SO) harvesting system and roadside residues (only from Cormier et al. (2012)). ODT, oven-dry tonnes; NL, Newfoundland and Labrador. For more details, see the Supplementary material.[1] [Colour version available online.]

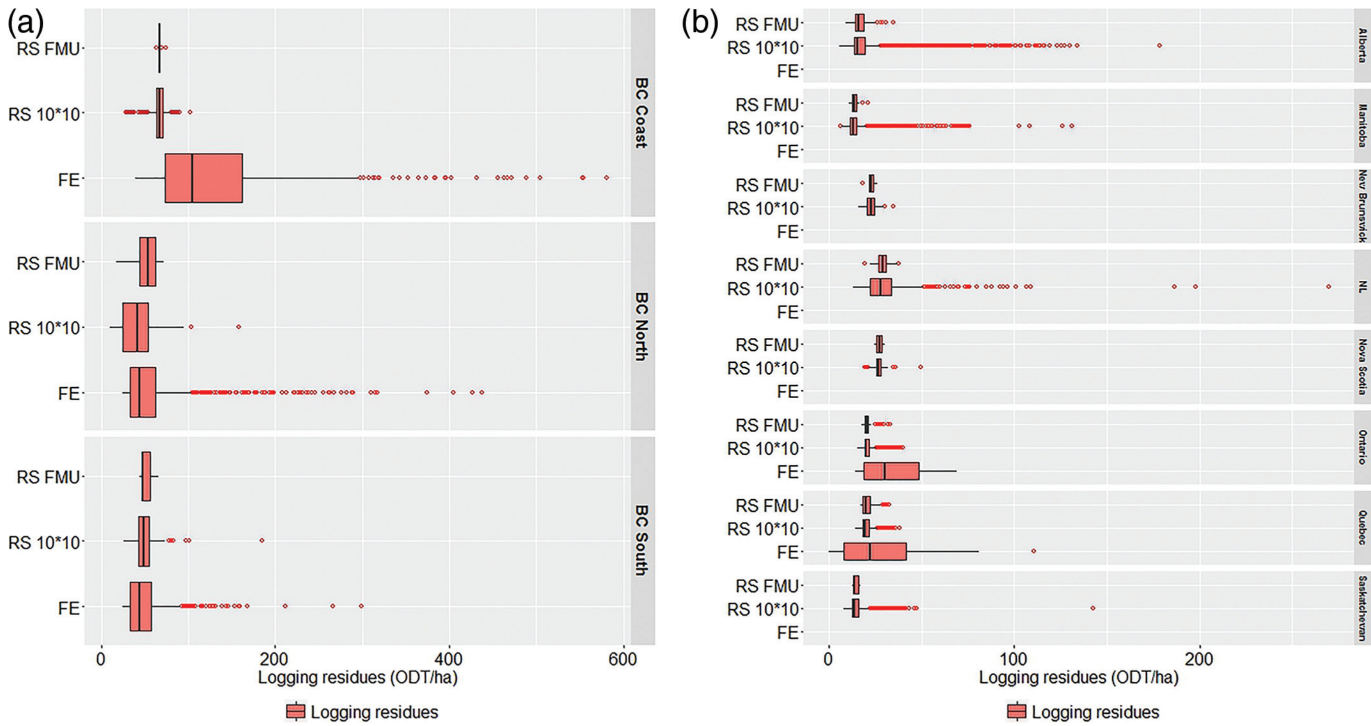
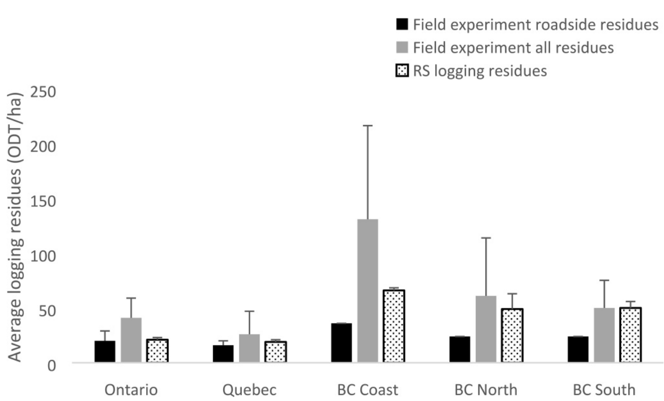


Fig. 9. Average field experiment roadside residues and all residues reported by diverse sources (see Supplementary material[1]) compared with average remote sensing (RS) logging residue (branch and foliage) estimates by province. Only RS estimates at the forest management unit (FMU) scale that matched the field experiment's FMUs were used for that comparison. Data from field experiments were averaged first by FMU (Ontario FMUs, $n = 10$; Quebec FMUs, $n = 9$; British Columbia (BC) Coast FMUs, $n = 9$; BC South FMUs, $n = 16$; BC North FMUs, $n = 15$) and then by province, while RS data aggregated at the FMU scale were averaged by province. The standard deviation associated to the mean refers to the variation between FMUs and is shown when known. ODT, oven-dry tonnes.



biomass are part of the total live aboveground biomass reported in forest attribute maps and can be extracted from remote sensing products such as Beaudoin et al. (2014, 2018). However, the use of a coarse spatial resolution at 250 m MODIS pixels may also imply a loss of accuracy, which may have affected our estimation of branch and foliage biomass (Lu 2006). According to Beaudoin et al. (2014), the precision of aboveground biomass estimates is supposed to be greater within the Boreal Shield ecozone (which lies within Quebec and Ontario) and lesser in the mountainous ecozones of western Canada and in areas with low biomass.

Comparison of stemwood biomass estimates (harvested merchantable volume) with independent sources such as government reports (National Forestry Database, http://nfdp.ccfm.org/en/data/harvest.php, accessed 30 October 2018) also suggests that the developed methodology slightly underestimates merchantable wood in most regions, but most importantly in British Columbia. This was expected as *k*NN tends to underestimate greater volumes (Beaudoin et al. 2018) and because the CanLaD product omits 9% of harvest, as well as generally missing partial cutting (Guindon et al. 2018). Overall, when harvested areas from the CanLaD product were combined with the volumes harvested from the MODIS product, our estimates of merchantable wood were about 30% lower than reported in the National Forestry Database.

Logging residues are a secondary product of forest harvesting operations and, consequently, depend on harvest rates, which are influenced by factors such as the demand for wood products, general economic conditions, forest stand productivity, and the goals set by provinces for the use of public forests (Masek et al.

2011). We integrate these factors by using historical harvesting rates within FMUs, but this assumes that future harvest rates will be the same as historical rates averaged over the past 30 years (1985–2015). Forests are typically managed to maintain a constant flow of fibre to mills, but unforeseen economic events or large natural disturbances can have a dramatic effect on fibre flow at the national, provincial, or FMU levels. For example, the annual area harvested in Canada was about 1 million hectares between 1985 to 2005, then declined to about 600 000 hectares in 2009 following reductions in house construction in the United States resulting from the 2007–2008 global financial crisis, and then slowly increased until the area harvested in 2015 was about 10% less than that in 2005 (Supplementary Fig. S2[1]; National Forestry Database, http://nfdp.ccfm.org/en/data/harvest.php, accessed 30 October 2018).

Natural disturbances can also affect the amount of forest available for harvesting and hence the amount of logging residues produced, sometimes leading to an increase in harvesting to salvage wood that would otherwise be lost and then to a decrease because of the resulting loss of mature forest. For example, the current mountain pine beetle (MPB) outbreak in British Columbia has led to an increase in allowable annual cut (AAC; $m^3{\cdot}year^{-1}$) to salvage dead trees and retain live trees for later harvesting in the three FMUs most affected (Lakes, Prince George, and Quesnel timber supply areas). This resulted in an 80% increase in harvesting compared with what it would have been if forests had been healthy (Snetsinger 2005). Similarly, increased future fire frequency as the climate changes is predicted to burn enough forest in the most vulnerable FMUs in Canada that an increased growth rate of at least 50% would be required to compensate for the loss in timber supply, although this level of increased productivity is unlikely to be achievable (Gauthier et al. 2015). Our estimates of future logging residue availability may thus be challenged by the increasing uncertainty regarding factors related to climate change (e.g., Evans et al. 2005), which affects fire frequency and the behaviour of both native and exotic diseases and insect pests. Consequently, the methodology that we developed does not replace the need for finer scale biomass availability assessments based on detailed forest management plans and a shorter time horizon.

The variability associated with estimates of logging residues obtained using remote sensing was less than for data originating from field assessments (Figs. 8 and 9). This is to be expected because remotely sensed estimates are produced by a model that averages reference data, but field assessments are greatly influenced by local circumstances such as prior natural disturbances and management activities (Briedis et al. 2011); for example, non-stand-replacing disturbances such as diseases or windthrow may create a high proportion of unmerchantable stems that cannot be used by the forest industry and will be left on-site and measured in field assessments but whose presence may not be captured in logging residue estimates from remote sensing.

Our remotely sensed logging residue estimates omit other residues such as tree tops, low-quality logs, and overturned or snapped trees that are left on-site, and our estimates of logging residue density (mass per unit area) from remote sensing were usually less than those from field measurements of total logging residues. It must be borne in mind when considering what amount of feedstock can actually be used in the bioeconomy that technical, ecological, and economic considerations reduce the amount of total biomass that can or should be extracted from a site (sensu Smeets and Faaij 2007). To date, there is no evidence of consistent negative impacts of logging residue removal on forest ecosystems in Canada (e.g., Thiffault et al. 2011; Lamers et al. 2013; Fleming et al. 2018). If the intensity of harvest removal increases due to developing bioenergy markets or improved extraction technologies, the assessment of the amount of residues that can be harvested to maintain environmental sustainability would need to be factored in. A broader discussion on the state of the knowledge of the ecological consequences of removing foliage and branch biomass can be found in Paré and Thiffault (2016). Technically, Thiffault et al. (2015) found that an average of 50% of total logging residues are usually left on-site because of operational difficulties in removing it all. Ecologically, based on a European Union wide spatial analysis of soil considerations and biodiversity (European Environment Agency 2006), Titus et al. (2009) proposed that 50% of total logging residues should be left on-site. Economically, Yemshanov et al. (2014) demonstrated the impact of biomass supply price on logging residue availability in a study that examined the impacts of different technical, ecological sustainablity, and economic considerations in Canada. We estimate the national potential availability of logging residues to be 21 M $ODT{\cdot}year^{-1}$, which is within the range of other recent estimates of 14 M $ODT{\cdot}year^{-1}$ (Mansuy et al. 2017; total potential availability), 20 M $ODT{\cdot}year^{-1}$ (Dymond et al. 2010; ecological availability), 17 to 23 M $ODT{\cdot}year^{-1}$ (Yemshanov et al. 2014; ecological to techo-ecological availability scenarios), and 31 M $ODT{\cdot}year^{-1}$ (Sidders et al. 2008; techo-ecological availability). Based on the above considerations (especially site-level operational (Thiffault et al. 2015) and large-scale ecological factors (Titus et al. 2009) that both suggest purposeful retention of 50% of logging residues in biomass inventories) and the fact that our remote sensing estimates of logging residues miss various logging residue components (Fig. 3), we consider our estimates of total branch plus foliage biomass to be a reasonable proxy for either ecologically or techno-ecologically extractable logging residues in Canada.

Ensuring a sustainable bioeconomy in Canada depends on the prediction of a stable and secure supply of forest biomass as feedstock. Overall, we estimate a national average logging residue density of 26 ± 16 $ODT{\cdot}ha^{-1}$ (branch plus foliage) compared with other recent national estimates of 20 $ODT{\cdot}ha^{-1}$ (Dymond et al. 2010) and 24 $ODT{\cdot}ha^{-1}$ (Mansuy et al. 2017). Forecasting the spatial distribution of logging residues, especially if differentiated by species, plays a role in this and can help inform policy makers and stakeholders on the potential of these sources of biomass to support the development of the bioeconomy, including bioenergy. The present study focused only on logging residue potential estimated by coarse-scale remote sensing. In the future, a combination of multiscale remotely sensed data may allow for a greater inclusion of other types of biomass. More specifically, the integration of coarse, medium, and fine spatial resolutions could make it possible to quantify tree tops and submerchantable trees currently left on-site (either standing or broken and on the ground) and to quantify the potential from salvaged dead trees following stand-ending natural disturbances (Barrette et al. 2015, 2017; Mansuy et al. 2017). Other remote sensing technologies could help refine the assessment of logging residue availability; for example, several studies have used airborne LiDAR datasets to estimate forest attributes (Popescu et al. 2014; Boudreau et al. 2008; Zhao et al. 2009), but country-wide datasets and repeated measurements in time are only available regionally and generally are very limited in coverage. Regardless of model improvements, other future steps (adapted from Springer et al. 2017) could include (*i*) cross comparisons of objectives, methods, and results with other Canadian biomass inventories to understand discrepancies between them, (*ii*) sensitivity analyses of the effect of assumptions on results, and (*iii*) analyses for a wider variety of forest biomass feedstock types, including stock and flow estimates for technical, ecological, and economic availability of forest biomass.

Conclusion

This study forecasts the quantity and spatial distribution of logging residues for the Canadian managed forest using remote sensing products developed from MODIS and Landsat imagery. The methodology offers a potential alternative to field assessments, which are time-consuming and cannot provide spatial distribution of logging residues over large areas. According to our analysis, the average biomass per unit area of future logging residue availability at the national scale is 26 ± 16 ODT·ha−1, which is about 20% of the total live aboveground biomass of mature forests as estimated by remote sensing. Our predictions of logging residues were based on branch plus foliage biomass and are thus only a fraction of the total forest biomass that can potentially be available after harvesting; nevertheless, estimates provided by the approach developed can be used as a proxy for recoverable harvesting residues. Looking forward, the forest maps developed as part of this study (doi:10.23687/dd94871a-9a20-47f5-825b-768518140f35 and doi:10.23687/5072c495-240c-42a3-ad55-c942ab37c32a) may help support the development of new renewable energy projects or biochemical products and ensure sustainable forest management and value chain optimization across the full extent of Canada's forest.

Acknowledgements

This project was made possible through financial support from the Energy Innovation Program (EIP) of Natural Resources Canada and a postdoctoral scholarship to the first author from Fonds de recherche du Québec – Nature et Technologies. We are also grateful to Nancy Densmore of the Ministry of Forests, Lands and Natural Resource Operations of British Columbia, Denis Cormier, Charles Friesen, and Sylvain Volpé of FPInnovations, and Sébastien Dagnault of the Canadian Forest Service for access to their field experiment data on logging residues. We also thank those who provided us with FMU boundaries: Nicholas Walsworth for British Columbia, Scott Payne for Newfoundland and Labrador, and Nancy Podbielski for Saskatchewan. Our gratitude also goes to Alexis Achim (Université Laval) for his helpful comments on earlier drafts of the manuscript and to Isabelle Lamarre for copyediting the manuscript.

References

Barrette, J., Thiffault, E., Saint-Pierre, F., Wetzel, S., Duchesne, I., and Krigstin, S. 2015. Dynamics of dead tree degradation and shelf-life following natural disturbances: can salvaged trees from boreal forests "fuel" the forestry and bioenergy sectors? Forestry, **88**(3): 275–290. doi:10.1093/forestry/cpv007.

Barrette, J., Thiffault, E., Achim, A., Junginger, M., Pothier, D., and De Grandpré, L. 2017. A financial analysis of the potential of dead trees from the boreal forest of Eastern Canada to serve as feedstock for wood pellet export. Appl. Energy, **198**(Suppl. C): 410–425. doi:10.1016/j.apenergy.2017.03.013.

Beaudoin, A., Bernier, P.Y., Guindon, L., Villemaire, P., Guo, X.J., Stinson, G., Bergeron, T., Magnussen, S., and Hall, R.J. 2014. Mapping attributes of Canada's forests at moderate resolution through *k*NN and MODIS imagery. Can. J. For. Res. **44**(5): 521–532. doi:10.1139/cjfr-2013-0401.

Beaudoin, A., Bernier, P.Y., Villemaire, P., Guindon, L., and Guo, X.J. 2018. Tracking forest attributes across Canada between 2001 and 2011 using a *k* nearest neighbours mapping approach applied to MODIS imagery. Can. J. For. Res. **48**(1): 85–93. doi:10.1139/cjfr-2017-0184.

Boudreau, J., Nelson, R.F., Margolis, H.A., Beaudoin, A., Guindon, L., and Kimes, D.S. 2008. Regional aboveground forest biomass using airborne and spaceborne LiDAR in Québec. Remote Sens. Environ. **112**(10): 3876–3890. doi:10.1016/j.rse.2008.06.003.

Bradley, D. 2008. Canada report on bioenergy. Canadian Bioenergy Association, Ottawa, Ont.

Briedis, J.I., Wilson, J.S., Benjamin, J.G., and Wagner, R.G. 2011. Biomass retention following whole-tree, energy wood harvests in central Maine: adherence to five state guidelines. Biomass Bioenergy, **35**(8): 3552–3560. doi:10.1016/j.biombioe.2011.05.018.

Canadian Gas Association. 2014. Renewable natural gas technology roadmap for Canada. Canadian Gas Association, Ottawa, Ont.

Chum, H., Faaij, A., Moreira, J., Berndes, G., Dhamija, P., Dong, H., Gabrielle, B., Eng, A.G., Lucht, W., and Mapako, M. 2011. Renewable energy sources and climate change mitigation. Bioenergy IPCC Special Report. Cambridge University Press, Cambridge, U.K.

Cormier, D., Volpé, S., and Spencer, S. 2012. Wood flow assessments in Canadian biomass recovery operations. Biofor, Thunder Bay.

Demirbaş, A. 2001. Biomass resource facilities and biomass conversion processing for fuels and chemicals. Energy Convers. Manage. **42**(11): 1357–1378. doi:10.1016/S0196-8904(00)00137-0.

Dymond, C.C., Titus, B.D., Stinson, G., and Kurz, W.A. 2010. Future quantities and spatial distribution of harvesting residue and dead wood from natural disturbances in Canada. For. Ecol. Manage. **260**(2): 181–192. doi:10.1016/j.foreco.2010.04.015.

European Environment Agency. 2006. How much bioenergy can Europe produce without harming the environment? European Environment Agency, Copenhagen, Denmark, EEA Report No. 7.

Evans, H.J., Hopkin, A.A., and Scarr, T.A. 2005. Maladies et ravageurs forestiers d'importance en Ontario en 2005. Ressources naturelles Canada, Sault Ste. Marie, Ont.

Fleming, R.L., Leblanc, J.-D., Weldon, T., Hazlett, P.W., Mossa, D.S., Irwin, R., Primavera, M.J., and Wilson, S.A. 2018. Effect of vegetation control, harvest intensity, and soil disturbance on 20-year jack pine stand development. Can. J. For. Res. **48**(4): 371–387. doi:10.1139/cjfr-2017-0331.

Gauthier, S., Bernier, P.Y., Boulanger, Y., Guo, J., Guindon, L., Beaudoin, A., and Boucher, D. 2015. Vulnerability of timber supply to projected changes in fire regime in Canada's managed forests. Can. J. For. Res. **45**(11): 1439–1447. doi:10.1139/cjfr-2015-0079.

Gronowska, M., Joshi, S., and MacLean, H.L. 2009. A review of US and Canadian biomass supply studies. BioResources, **4**(1): 341–369.

Guindon, L., Bernier, P.Y., Beaudoin, A., Pouliot, D., Villemaire, P., Hall, R.J., Latifovic, R., and St-Amant, R. 2014. Annual mapping of large forest disturbances across Canada's forests using 250 m MODIS imagery from 2000 to 2011. Can. J. For. Res. **44**(12): 1545–1554. doi:10.1139/cjfr-2014-0229.

Guindon, L., Villemaire, P., St-Amant, R., Bernier, P., Beaudoin, A., Caron, F., Bonucelli, M., and Dorion, H. 2017. Canada Landsat Disturbance (CanLaD): a Canada-wide Landsat-based 30-m resolution product of fire and harvest detection and attribution since 1984. doi:10.23687/add1346b-f632-4eb9-a83d-a662b38655ad.

Guindon, L., Bernier, P.Y., Gauthier, S., Stinson, G., Villemaire, P., and Beaudoin, A. 2018. Missing forest cover gains in boreal forests explained. Ecosphere, **9**(1): e02094. doi:10.1002/ecs2.2094.

Haberl, H., Sprinz, D., Bonazountas, M., Cocco, P., Desaubies, Y., Henze, M., Hertel, O., Johnson, R.K., Kastrup, U., Laconte, P., Lange, E., Novak, P., Paavola, J., Reenberg, A., van den Hove, S., Vermeire, T., Wadhams, P., and Searchinger, T. 2012. Correcting a fundamental error in greenhouse gas accounting related to bioenergy. Energy Policy, **45**: 18–23. doi:10.1016/j.enpol.2012.02.051. PMID:23576835.

Hsu, D.D. 2012. Life cycle assessment of gasoline and diesel produced via fast pyrolysis and hydroprocessing. Biomass Bioenergy, **45**: 41–47. doi:10.1016/j.biombioe.2012.05.019.

Hunter, M.L., Jr. 1990. Wildlife, forests, and forestry. Principles of managing forests for biological diversity. Prentice Hall, Upper Saddle River, N.J.

Industrial Forestry Services. 2015. Wood based biomass in British Columbia and its potential for new electricity generation. Industrial Forestry Services Ltd., Prince George, B.C.

Laganière, J., Paré, D., Thiffault, E., and Bernier, P.Y. 2017. Range and uncertainties in estimating delays in greenhouse gas mitigation potential of forest bioenergy sourced from Canadian forests. GCB Bioenergy, **9**(2): 358–369. doi:10.1111/gcbb.12327.

Lambert, M.-C., Ung, C.-H., and Raulier, F. 2005. Canadian national tree aboveground biomass equations. Can. J. For. Res. **35**(8): 1996–2018. doi:10.1139/x05-112.

Lamers, P., and Junginger, M. 2013. The "debt" is in the detail: a synthesis of recent temporal forest carbon analyses on woody biomass for energy. Biofuels, Bioprod. Biorefin. **7**(4): 373–385. doi:10.1002/bbb.1407.

Lamers, P., Thiffault, E., Paré, D., and Junginger, M. 2013. Feedstock specific environmental risk levels related to biomass extraction for energy from boreal and temperate forests. Biomass Bioenergy, **55**: 212–226. doi:10.1016/j.biombioe.2013.02.002.

Lamers, P., Junginger, M., Dymond, C.C., and Faaij, A. 2014. Damaged forests provide an opportunity to mitigate climate change. GCB Bioenergy, **6**(1): 44–60. doi:10.1111/gcbb.12055.

Lu, D. 2006. The potential and challenge of remote sensing-based biomass estimation. Int. J. Remote Sens. **27**(7): 1297–1328. doi:10.1080/01431160500486732.

Mabee, W.E., and Saddler, J.N. 2010. Bioethanol from lignocellulosics: status and perspectives in Canada. Bioresour. Technol. **101**(13): 4806–4813. doi:10.1016/j.biortech.2009.10.098. PMID:20006494.

Mansuy, N., Paré, D., Thiffault, E., Bernier, P.Y., Cyr, G., Manka, F., Lafleur, B., and Guindon, L. 2017. Estimating the spatial distribution and locating hotspots of forest biomass from harvest residues and fire-damaged stands in Canada's managed forests. Biomass Bioenergy, **97**: 90–99. doi:10.1016/j.biombioe.2016.12.014.

Masek, J.G., Cohen, W.B., Leckie, D., Wulder, M.A., Vargas, R., de Jong, B., Healey, S., Law, B., Birdsey, R., Houghton, R.A., Mildrexler, D., Goward, S., and Smith, W.B. 2011. Recent rates of forest harvest and conversion in North America. J. Geophys. Res.: Biogeosci. **116**(G4): G00K03. doi:10.1029/2010JG001471.

McKendry, P. 2002. Energy production from biomass (part 2): conversion technologies. Bioresour. Technol. **83**(1): 47–54. doi:10.1016/S0960-8524(01)00119-5. PMID:12058830.

Natural Resources Canada. 2006. Estimated production, consumption and surplus mill wood residues in Canada — 2004. Natural Resources Canada, Ottawa, Ont.

Natural Resources Canada. 2017. The State of Canada's Forests. Annual report 2017. Canadian Forest Service, Ottawa.

Paré, D., and Thiffault, E. 2016. Nutrient budgets in forests under increased biomass harvesting scenarios. Curr. For. Rep. **2**(1): 81–91. doi:10.1007/s40725-016-0030-3.

Paré, D., Bernier, P., Thiffault, E., and Titus, B.D. 2011. The potential of forest biomass as an energy supply for Canada. For. Chron. **87**(1): 71–76. doi:10.5558/tfc87071-1.

Parzei, S., Krigstin, S., Hayashi, K., and Wetzel, S. 2014. Forest harvest residues available in Eastern Canada — a critical review of estimations. For. Chron. **90**(6): 778–784. doi:10.5558/tfc2014-150.

Popescu, S.C., Wynne, R.H., and Nelson, R.F. 2014. Measuring individual tree crown diameter with lidar and assessing its influence on estimating forest volume and biomass. Can. J. Remote Sens. **29**(5): 564–577. doi:10.5589/m03-027.

Quattrochi, D.A., and Goodchild, M.F. 1997. Scale in remote sensing and GIS. CRC Press, Boca Raton, Fla.

R Core Team. 2015. R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.

Ralevic, P., Karau, J., Smith, C.T., and Richardson, J. 2008. Country Report Canada. International Energy Agency, Paris, IEA Bioenergy Task 31.

Sidders, D., Joss, B., and Keddy, T. 2008. Project TID8 25B: GIS-based inventory and analysis of forestry and agriculture biomass. Natural Resources Canada, Ottawa, Ont.

Smeets, E.M.W., and Faaij, A.P.C. 2007. Bioenergy potentials from forestry in 2050. Clim. Change, **81**(3–4): 353–390. doi:10.1007/s10584-006-9163-x.

Smyth, C.E., Stinson, G., Neilson, E., Lemprière, T.C., Hafer, M., Rampley, G.J., and Kurz, W.A. 2014. Quantifying the biophysical climate change mitigation potential of Canada's forest sector. Biogeosciences, **11**(13): 3515–3529. doi:10.5194/bg-11-3515-2014.

Smyth, C., Kurz, W.A., Rampley, G., Lemprière, T.C., and Schwab, O. 2017. Climate change mitigation potential of local use of harvest residues for bioenergy in Canada. GCB Bioenergy, **9**(4): 817–832. doi:10.1111/gcbb.12387.

Snetsinger, J. 2005. Guidance on landscape- and stand-level structural retention in large-scale mountain pine beetle salvage operations [online]. B.C. Forests, Lands, Natural Resource Operations and Rural Development. Victoria, B.C. Available from https://www.for.gov.bc.ca/hfd/library/documents/bib95960.pdf [accessed 22 February 2018].

Springer, N., Kaliyan, N., Bobick, B., and Hill, J. 2017. Seeing the forest for the trees: how much woody biomass can the Midwest United States sustainably produce? Biomass Bioenergy, **105**: 266–277. doi:10.1016/j.biombioe.2017.05.011.

Thiffault, E., Hannam, K.D., Paré, D., Titus, B.D., Hazlett, P.W., Maynard, D.G., and Brais, S. 2011. Effects of forest biomass harvesting on soil productivity in boreal and temperate forests — a review. Environ. Rev. **19**: 278–309. doi:10.1139/a11-009.

Thiffault, E., Béchard, A., Paré, D., and Allen, D. 2015. Recovery rate of harvest residues for bioenergy in boreal and temperate forests: a review. WIREs Energy Environ. **4**(5): 429–451. doi:10.1002/wene.157.

Titus, B.D., Maynard, D.G., Dymond, C.C., Stinson, G., and Kurz, W.A. 2009. Wood energy: protect local ecosystems. Science, **324**(5933): 1389–1390. doi:10.1126/science.324_1389c. PMID:19520938.

Ung, C.-H., Bernier, P., and Guo, X.-J. 2008. Canadian national biomass equations: new parameter estimates that include British Columbia data. Can. J. For. Res. **38**(5): 1123–1132. doi:10.1139/X07-224.

White, J.C., Coops, N.C., Wulder, M.A., Vastaranta, M., Hilker, T., and Tompalski, P. 2016. Remote sensing technologies for enhancing forest inventories: a review. Can. J. Remote Sens. **42**(5): 619–641. doi:10.1080/07038992.2016.1207484.

Wood, S.M., and Layzell, D.B. 2003. A Canadian biomass inventory: feedstocks for a bio-based economy. BIOCAP Canada Foundation, Kingston, Ont.

Yemshanov, D., McKenney, D.W., Fraleigh, S., McConkey, B., Huffman, T., and Smith, S. 2014. Cost estimates of post harvest forest biomass supply for Canada. Biomass Bioenergy, **69**: 80–94. doi:10.1016/j.biombioe.2014.07.002.

Zhao, K., Popescu, S., and Nelson, R. 2009. Lidar remote sensing of forest biomass: a scale-invariant estimation approach using airborne lasers. Remote Sens. Environ. **113**(1): 182–196. doi:10.1016/j.rse.2008.09.009.