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Research paper

Estimating the spatial distribution and locating hotspots of forest biomass from harvest residues and fire-damaged stands in Canada's managed forests

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ABSTRACT

Strategies for increasing the mobilization of forest biomass supply chains for bioenergy production require continuous assessments of the spatial and temporal availability of biomass feedstock. Using remote sensing products at a 250-m pixel resolution, estimates of theoretical biomass availability from harvest residues and fire-killed trees were computed by combining Canada-wide maps of forest attributes (2001) and of yearly (2002–2011) fires and harvests. At the national scale, biomass availability was estimated at 47 ± 18 M ODT year^{-1} from fire-killed trees and at 14 ± 2 M ODT year^{-1} from harvest residues. Mean biomass densities in burned and harvested pixels were estimated at 34 ± 3.0 ODT ha^{-1} and at 24 ± 1.2 ODT ha^{-1}, respectively. Mean biomass densities also varied dramatically among ecozones, from 14 ODT ha^{-1} to 206 ODT ha^{-1} and from 6 ODT ha^{-1} to 63 ODT ha^{-1} for burned and harvested pixels, respectively. Spatial averaging with a 100-km radius window shows distinct hotspots of biomass availability across Canada. The largest hotspots from fire-killed trees reached 3.6 M ODT year^{-1} in the Boreal Shield and the Boreal Plains ecozones of northern Alberta and Saskatchewan, where fires are large and frequent. The largest hotspots from harvest residues reached 1.2 M ODT year^{-1} in the Montane Cordillera ecozone of British Columbia. The use of spatially explicit remote sensing products yields estimates of theoretical biomass availability that are methodologically consistent across Canada. Future development should include validations with on-the-ground forest inventories as well as the factoring in of environmental, technical and economic considerations to implement operational biomass supply chains.

1. Introduction

Woody biomass for energy production could play an important role in the emerging bioeconomy including the mitigation of greenhouse gas (GHG) emissions, energy security, jobs and revenue generation [1,2]. Current policy frameworks, notably for GHG emission mitigation entail functional international biomass markets to support the increasing demand for wood-based bioenergy [3]. For example, the exports of wood pellets to the European Union (EU) are expected to reach 15–30 Tg by 2020, with the United States and Canada as two of the biggest exporters [4]. To supply the international biomass trade and modern bioenergy systems, Canada's forest sector is interested in mobilizing its forest biomass supply chains, which requires a comprehensive assessment of biomass location, costs and logistics.

Although definitions vary in the literature, the Intergovernmental Panel on Climate Change defines forest biomass feedstock as surplus forest growth or roundwood within sustainable harvest limits (but that is not utilized for conventional wood products), residues from forest operations (e.g. tree tops and branches), and wood processing (e.g. sawdust, wood shavings and wood chips) [5]. In Canada, mill residues are almost fully utilized for in-house energy generation or are transformed into wood pellets [3,4]. Therefore, the further deployment of bioenergy pathways will rely on the

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mobilization of residues from forest harvesting operations [6–8], and surplus forest growth. A special case of the latter is standing dead trees resulting from natural disturbances such as fire, defoliating insects and disease [9–12]. Dead trees can contaminate supply chains of conventional wood product industries due to their degraded fibre, but keep cost-effective physical and chemical properties for processing into bioenergy streams [13]. For example, biomass sourced from areas affected by the mountain pine beetle (*Dendroctonus ponderosae*) outbreak in western Canada has been used to make pellets for the international market [14,15]. Recent studies have shown that both harvest residues and dead trees from natural disturbances represent a large potential across Canada that could ensure the growth of the bioenergy sector [8,16,17]. Not only are they abundant but they can be transformed into bioproducts (i.e. pellet) that can meet the 3% or less ash content required by the European standard EN 14961-2 for wood pellets [18]. Indeed, ash content for roundwood from fire-killed trees has been found to be lower than 1% (Barrette, unpublished results). The costs of harvest residues and salvage harvesting also compare favourably with those for other feedstock types, such as biomass from dedicated short-rotation plantations [19].

Although feedstocks from disturbances are deemed to be abundant across Canada's managed forests, large uncertainties exist around estimates of their availability. Despite the need for national reporting to the biomass market, empirical and consistent assessment of the quantity, location and stability over time of woody biomass sourced from natural disturbances has yet to be achieved at the national level. Ralevic et al. [20] provides national biomass estimates however the sources, methods and assumptions are not methodologically and spatially-explicit consistent across Canada. Pan-Canadian estimates given by Dymond et al. [16] are based on simulations with the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3) and provide harvesting residue and dead wood annual production at the ecozone level from 2005 to 2020. The modelling is based on stand theoretical growth curves, but methodologies for defining them vary between provinces. In addition, the high uncertainties associated with biomass availability from natural disturbances [8] represent a challenge given that events like wildfires in the boreal forest are often controlled by climate drivers and are stochastic in nature [21,22]. Woody biomass is generally scattered at low densities over large areas and the logistics of collection and transportation from forest sites to processing facilities underpin the profitability of the supply chain [23–25]. Yet, the development of operational woody biomass supply chains, the heart of strategic industrial investment decisions, requires consistent forest biomass feedstock inventory and projections.

The goal of this study was to improve the national forest biomass feedstock inventory to support the development of Canada's woody biomass sector for energy production using a spatially-explicit and consistent approach across Canada. The approach developed in this study capitalizes on two recent Canadian-wide remote sensing products at 250 m pixel (6.25 ha) resolution. The first dataset is an inventory of forest attributes such as composition and biomass [26] and the second one is a 10-year assessment of areas disturbed by fire and harvesting [27]. By combining these two products, the study aims to map and quantify the national woody biomass potentially available from the salvage logging of fire-damaged stands and the harvest residues from clearcut areas. As a proof of concept, we have chosen to test our methodology on fires and clearcuts and have excluded all other forest disturbance types, including insect outbreaks and partial harvests. Fires and clearcuts are easily detectable at 250 m resolution on a yearly basis while mortality due to other disturbances such as insect outbreaks or wind storms are not yet available at this resolution at the national level. The amounts of biomass considered in the current assessment refer to the maximum theoretical biomass potential as fixed by biological and climatic parameters [28]. This theoretical biomass potential is related to the forestry activities and fire impacted areas captured in remote sensing products, as well as to stand characteristics. The use of the term "biomass" in the text below refers strictly to either harvest residues or fire-salvaged residues. The specific objectives of this study are: 1) to determine the amount of biomass made available annually over a 10-year period from fire and harvest at the disturbed site (in mass per hectare of disturbed area) and at the regional scale; 2) to quantify the spatial and temporal variability of these feedstocks; 3) to compare our biomass estimates with the published figures of Dymond et al. [16] who used a totally independent approach based on theoretical growth curves and harvest forecasts for Canadian managed forests.

2. Materials and methods

2.1. Study area

The geographical scope of the study area varies according to specific objectives based on a combination of jurisdictional and ecological boundaries in Canada (Fig. 1a). For the first two objectives, the study area (ca. 4×10^6 km^2) encompasses the managed forests of the 11 forested ecozones across the ten provinces using the national ecological framework for Canada [24], the Yukon and the Northwest Territories (Fig. 1b). For the third objective, we used the same limits as those used by Dymond et al. [16]. More precisely, the study area is limited by Canadian managed forests south of 60 °N, and encompasses 12 ecozones distributed across the ten Canadian provinces (Fig. 1b). The Prairies and Mixedwood Plains ecozones were not considered because they encompass mostly agricultural lands. Most results below are reported by spatial units defined by the intersection of provincial and ecozone boundaries.

2.2. Estimation of biomass

Estimates of the theoretical biomass availability from harvest residues and fire-damaged stands were computed by overlapping spatial datasets of forest attributes [26] and forest disturbances [27] both at a 250-m MODIS grid resolution and covering the Canadian forest landbase (Fig. 1a). The first dataset provides spatially explicit quantities of aboveground biomass in forest stands, measured in mean pixel-level oven-dry metric tonnes per hectare (ODT ha^{-1}), and sorted by species and by tree compartment (branches, stems, bark and foliage) for the year 2001. The mapping approach used the k nearest neighbours (kNN) method with 26 geospatial data layers including MODIS spectral imagery, climatic and topographic variables to produce maps of 127 forest attributes at a 250 × 250 m resolution. The stand-level attributes include land cover, structure, and tree species relative abundance. The second dataset uses regression and decision-tree models with MODIS imagery to detect pixels affected by harvesting (clearcuts only) and wildfires every year from 2001 to 2011, and also gives the fraction of the pixels affected by these disturbances. The robustness of both remote sensing products have been demonstrated and used in recent studies [8,29,30]. For the first dataset, the accuracy of biomass estimates using an independent validation dataset was on average about 70% [26] and for the second dataset, the accuracy of detection of burnt and harvested was 82 and 80%, respectively [27].

By overlaying the 2001 maps of forest properties and the maps of harvest and fire for years 2002–2011, we were able to calculate for each pixel the annual amount of biomass generated by wildfire or by clearcut, by species and tree compartment and to attribute a specific year to each event. More specifically, the availability of

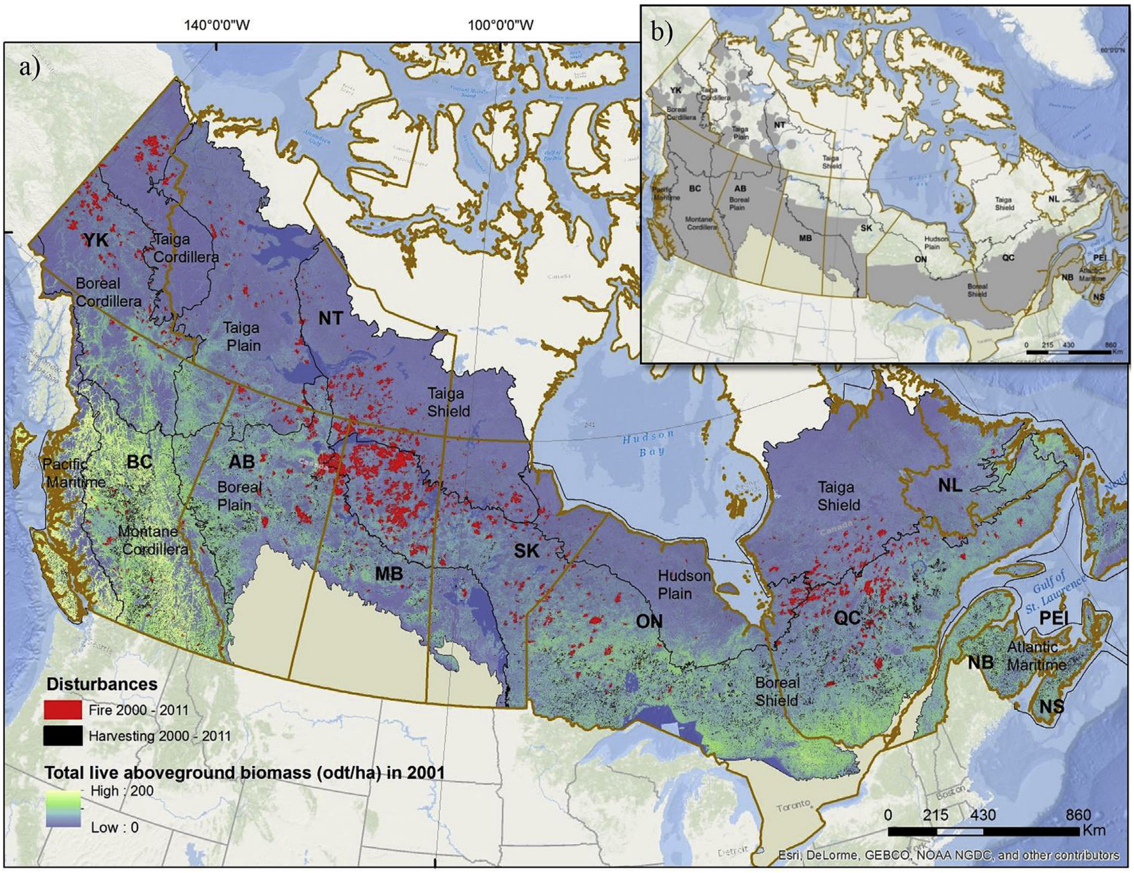

Fig. 1. a) Limits of the ecozones (in black) and provinces* (in brown) and the dataset used to estimate the biomass available. The disturbance mapping between 2001 and 2011 comes from Ref. [27] and the total live aboveground biomass comes from Ref. [26]. 1b) The extent of the study area in grey is used for the first and second objectives of the study. The same study area minus the area above 60 °N (which means that Yukon and Northwest Territories are excluded) is used to compare our estimates with [16]. (*AB: Alberta; BC: British Columbia, MB Manitoba, NB: New Brunswick; NL: Newfoundland and Labrador; NS: Nova Scotia; NT: Northwest Territories; ON: Ontario; PE: Prince Edward Island; QC: Quebec; SK: Saskatchewan; YT: Yukon*). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

biomass from either fire-killed trees or harvest residues for a given pixel was estimated as:

$$Biom_{res} = Pixel_{fc} \times Pixel_{res} \times Pixel_{a} \quad (1)$$

where $Biom_{res}$ is biomass density in either fire-killed trees or harvest residues (ODT ha^{-1}), $Pixel_{fc}$ is pixel fractional change (fraction), $Pixel_{res}$ is the amount of residues (ODT ha^{-1}), where the hectares are those of the full pixel area, and $Pixel_{a}$ is pixel area (ha). Biomass density is therefore an estimate of the amount of biomass residues available per hectare of a disturbed pixel. This analysis was carried out using the Geospatial Data Abstraction Library (GDAL). The resulting matrix was then used to estimate the theoretical biomass availability from fire and harvest independently and both combined between the years 2002 and 2011.

Similarly to Dymond et al. [16], biomass from fire-damaged stands was computed as the sum of branches and stems, whereas harvesting biomass residues were computed as the sum of branches and foliage for the three objectives. We assumed that the other compartments were either harvested for sawlog production (stems and bark in clearcut areas), or were too severely damaged by fire (branches and bark on burned areas). Our estimates therefore represent an upper limit of biomass availability since no constraints were applied on the amount estimated except for the third objective (see below). While Dymond et al. [16], used a modelling approach combined with expert knowledge to project the annual area infested by insects and the resulting biomass available, it was not possible to retrieve similar information using remote sensing products at 250 m resolution and at the national scale. Therefore, the biomass sourced from trees killed by insects was not estimated in this study.

To compare the distributions of biomass availability across ecozones, we used the non-parametric kernel density estimation method [31] to smooth out the biomass histograms representing the 95th percentile of the distribution of biomass from either fire-killed trees or harvest residues. The kernel density diagram uses a nonparametric density estimation method to average and smooth out the histogram. This was accomplished using a weight function (i.e., kernel) that ensures the enclosed area of the curve equals 1. This analysis was done using the plot density functions within the SM package in R [32].

2.3. Mapping biomass availability

Canada-wide maps of regional biomass availability were generated for biomass sourced from fire-killed trees, harvest residues, and from both sources combined. Yearly biomass estimates at the pixel level were first expressed as means within grid cells of 10 km × 10 km. The results were further averaged using a moving window within a 100-km radius. The 100-km radius is a first-order estimate of the cost-effective harvest-to-mill transport distance for biomass in Canada [8,17]. This moving average was calculated using the Focal statistics tools in ArcGIS 10.2 (Esri). The resulting maps give a spatially-explicit display of the annual average of biomass residues available between 2002 and 2011 in M ODT year^{-1} within a 100-km radius from any disturbed pixel. We used the term "hotspot" thereafter to refer to cells or groups of cells with the highest biomass density within this radius.

2.4. Comparison with Dymond et al. (2010)

Dymond et al. [16] reduced their gross biomass estimates by 50% to take into account potential technical, financial and environmental recovery constraints. We applied a similar factor for this comparison. In addition, only estimates from the forest area covered by Dymond et al. [16] in their study (see Fig. 1b) were used. Note that the reference period is between 2002 and 2011 for our study and between 2005 and 2020 for Dymond et al. [16].

3. Results

3.1. Availability of biomass by ecozone and by feedstock

At the national scale, fire and harvest residues generate a potential of 47 ± 18 M ODT year^{-1} and 14 ± 2 M ODT year^{-1} of biomass, respectively (Fig. 2a). Average pixel-level biomass density from fire and harvest are 34 ± 3 ODT ha^{-1} and 24 ± 1 ODT ha^{-1}, respectively (Fig. 2b), with the standard deviation expressing inter-annual variability. Biomass available from fires shows greater annual variability relative to biomass from harvest residues, which are more stable from one year to the next. Biomass from harvest residues decreases from 18 M to 9 M ODT year^{-1} between 2004 and 2009 and increases slightly until the end of our time series in 2011.

Across Canada, the density of biomass decreases from west to east and from north to south (Fig. 3; more data are available in the Appendices). The Pacific Maritime, Montane Cordillera, Boreal Cordillera and Boreal Plains ecozones in British Columbia show some of the largest value of biomass densities from both fire (respectively 206, 109, 82 and 72 ODT ha^{-1}) and harvest (respectively 63, 38, 18 and 28 ODT ha^{-1}), while the Montane Cordillera ecozone in Alberta has the third largest biomass density from fire residues at 92 ODT ha^{-1}. Conversely, Atlantic Maritime in Quebec and Prince Edward Island show no biomass availability from fire during the period under analysis, while biomass from harvest residues is estimated at 20 ODT ha^{-1} on average. Taiga Plains and Pacific Maritime in Yukon, which cover a small area in northwestern Canada, were not disturbed by either fire or harvest during the period considered. The Atlantic Maritime ecozone in Nova Scotia and the Boreal Shield ecozone in Newfoundland show between 22 ODT ha^{-1} and 25 ODT ha^{-1} of biomass from harvest

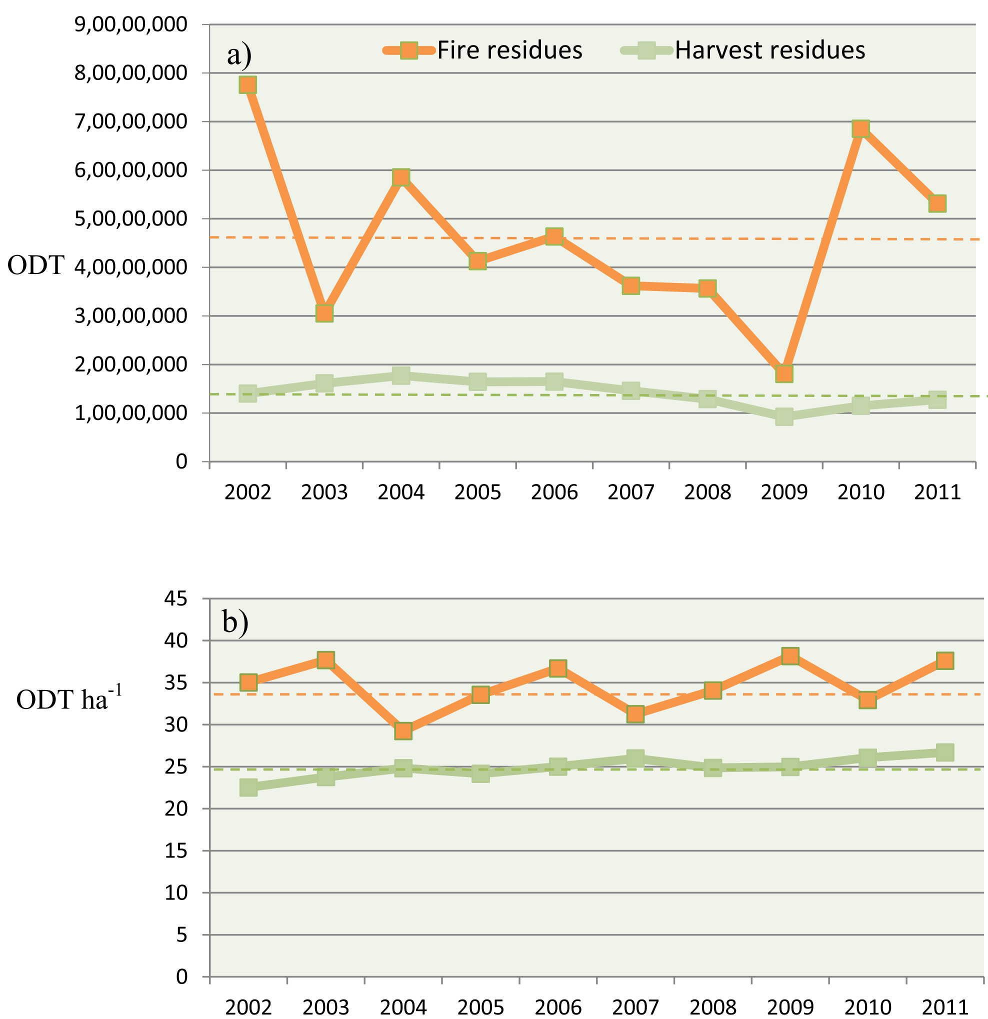

Fig. 2. a) Annual biomass available (ODT year^{-1}) produced by fire and harvest residues across the managed forest of Canada. b) Annual density of biomass available (ODT ha^{-1} year^{-1}) disturbed by fire and harvest residues across the managed forest of Canada. For each curve, the dotted line shows the annual mean over the 10- year period (more data are available in the Appendices).

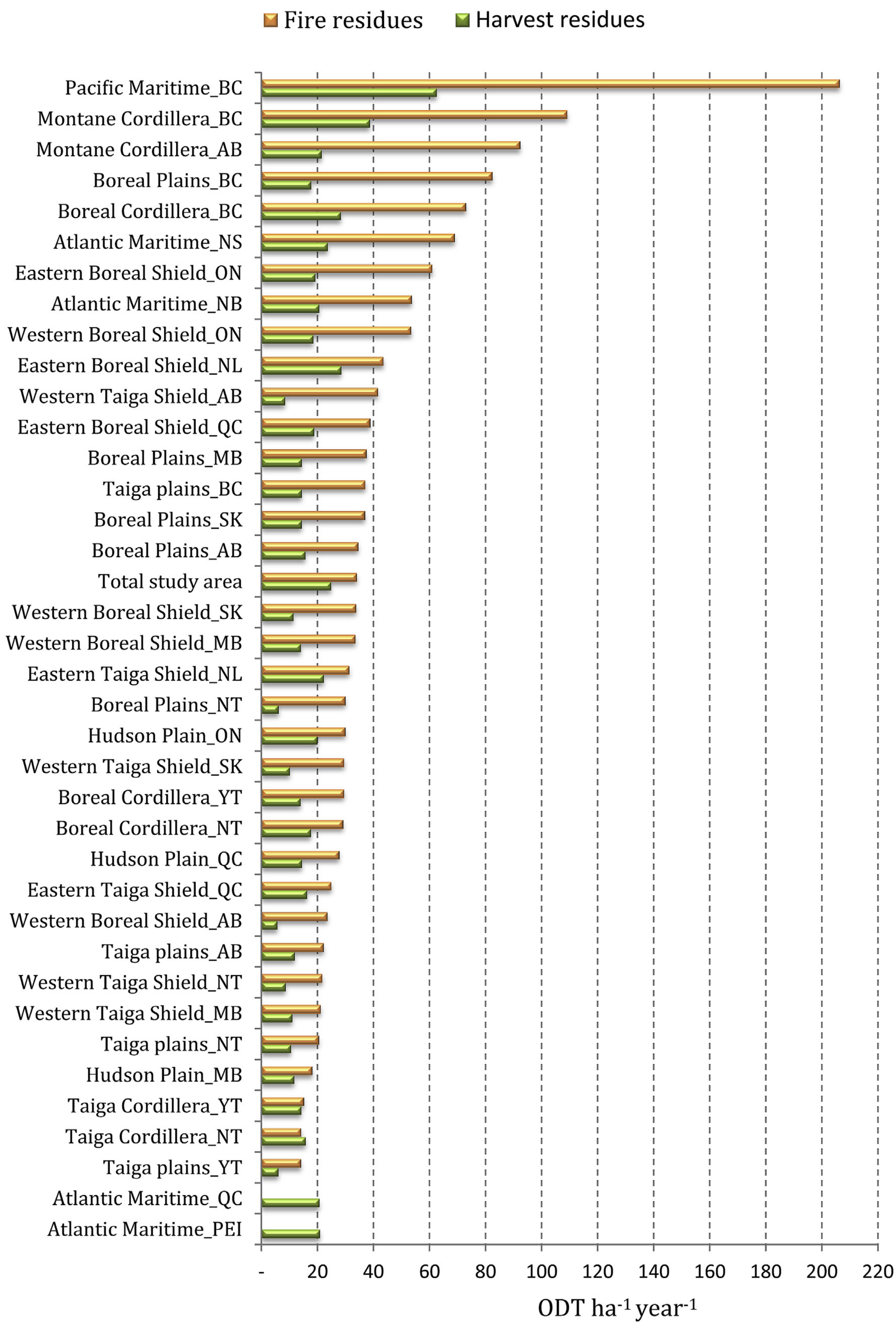

Fig. 3. Mean biomass density (ODT ha^{-1} year^{-1}) produced by fire and harvest residues among the ecozones between 2002 and 2011 (more detailed data are available in the Appendices).

residues.

The availability of harvest residues follows a normal distribution in most ecozones, while that from fire-damaged stands follows a much flatter platykurtic (wide base) distribution (Fig. 4). This reflects the selectivity of harvest activities for mature stands in contrast to the more random nature of fire across forests of all ages. In ecozones that have very low fire activity, such as the Atlantic Maritime and Pacific Maritime ecozones, the higher biomass density from fires reflects the higher prevalence of mature stands within these landscapes.

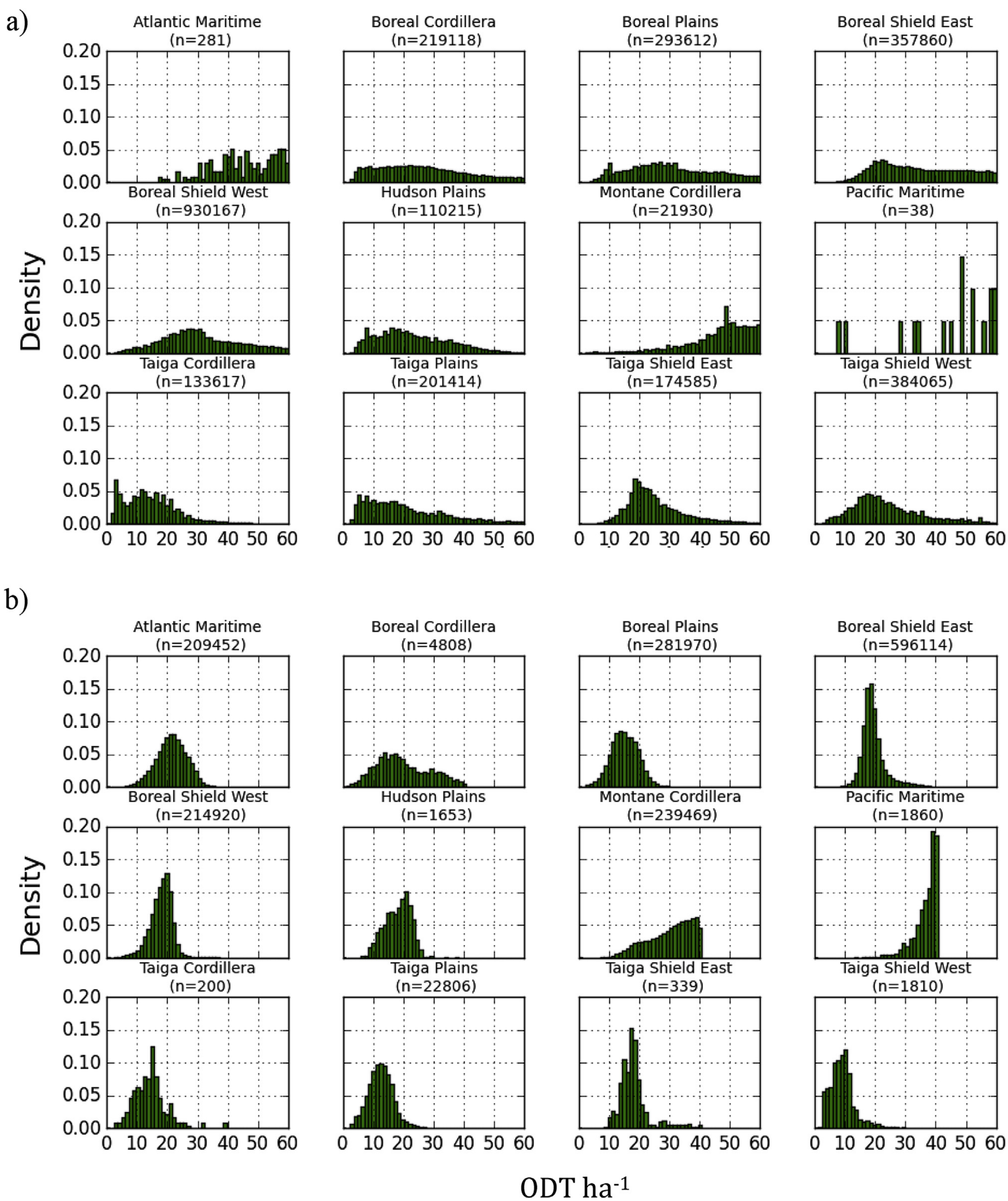

Fig. 4. Biomass distribution (ODT ha^{-1}) by ecozones between 2002 and 2011 (n equal the 95th percentile of the total number of pixels disturbed). a) from the fire residues and b) from the harvest residues.

3.2. Biomass hotspots

Spatial averaging within the 100-km radius window shows distinct hotspots of biomass availability for fire and harvest residues (Fig. 5). The Boreal Shield ecozone in Saskatchewan and Alberta shows the highest density of biomass from fire, i.e. up to 3.6 M ODT year^{-1} within a 100-km radius (Fig. 5a). Medium-sized hotspots of biomass from fire are located in central Quebec and in western Ontario with about 0.8 M ODT year^{-1} and 1.9 M ODT year^{-1} of available biomass, respectively. Smaller hotspots are found in British Columbia and Yukon, with biomass availability from fire ranging from 0.50 to 1 M ODT year^{-1}.

The main hotspot of biomass from harvest residues is located in the Montane Cordillera ecozone following a north-south gradient in British Columbia where the average biomass availability ranges from 0.6 M ODT year^{-1} to 1.2 M ODT year^{-1} within a 100-km radius (Fig. 5b). A smaller hotspot of biomass is located in the western-most part of the Pacific Maritime ecozone, where the biomass availability from harvest residues ranges from 0.3 M ODT year^{-1} to 0.8 M ODT year^{-1}. Even smaller hotspots of biomass are spread across Ontario, Quebec, New Brunswick and Nova Scotia, with biomass availability from harvest residues ranging from 0.15 to 0.46 M ODT year^{-1}. The northern regions show very low amounts of biomass from harvest residues (less than 0.02 M ODT year^{-1}). When both sources of biomass are combined, four hotspots of biomass are clearly identifiable: one in central British Columbia, one in northern Alberta and Saskatchewan, one in western Ontario and one in central Quebec. Across these four hotspots, the average biomass available from both harvest and fire ranges from 0.8 M ODT year^{-1} to 3.6 M ODT year^{-1} (Fig. 5c).

3.3. Comparison with Dymond et al. (2010)

Across the Canadian managed forest, south of 60 °N, and after a 50% adjustment of our figures, based on the current analysis, the density of biomass available after harvest is estimated to be 1.2 kg year^{-1} per square meter of harvested area between 2001 and 2011 (Table 1). This figure is about 38% lower than the one predicted by Ref. [16] who predicted 2.0 kg m^{-2} year^{-1}. The differences in estimates between the two studies are variable across the ecozones, but our estimates are always lower. The most similar estimates appear in the Boreal Shield East ecozone, where biomass residue availability estimated by Ref. [16] is on average 21% larger than our own estimates. In contrast, the most dissimilar estimates occur in the Boreal Plains, Taiga Plains and Boreal Cordillera ecozones (in British Columbia and Ontario) where biomass estimated by Ref. [16] are between 61% and 86% larger than ours. Considering the availability of biomass following fire, we estimate the density of biomass across Canada to be 2.4 kg m-^{2} year^{-1} (Table 1), which is approximately 31% lower than the value of 3.5 kg m^{-2} year^{-1} estimated by Ref. [16]. Estimates from Dymond et al. (2010) are most often higher than ours except in the Pacific Maritime ecozone in British Columbia (−4%), in the Boreal Shield East in Ontario (−39%), Boreal Shield West in Manitoba (−25%) and in Saskatchewan (−13%).

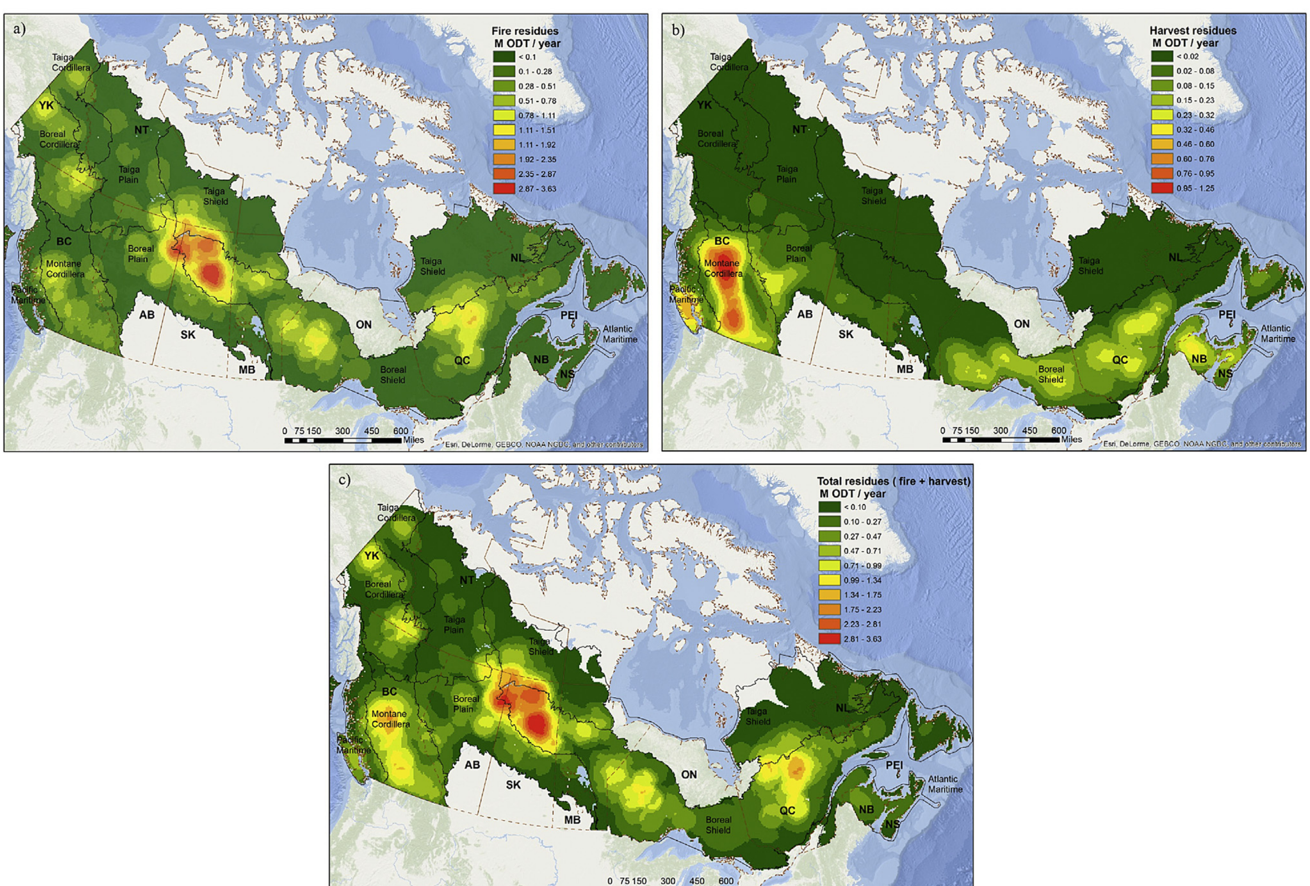

Fig. 5. Biomass available (M ODT year^{-1}) within a 100 km-radius circle from any disturbed pixels between 2002 and 2011 from a) fire residues b) harvest residues and c) fire and harvest residues combined (Maps are also available in .kmz format in the appendix section).

Table 1
Mean density of biomass (oven-dry kg m^{-2}) produced by fire and harvest residues across the managed forest of Canada forest south of 60° N. Our values are netted down by 50% in compliance with Dymond et al. [16]. The biomass is estimated between 2005 and 2020 for Dymond et al. [16] and between 2002 and 2011 for this study.

Provinces and ecozones		Harvest			Fire		
		Dymond et al. [16]	This study	Differences (%)	Dymond et al. [16]	This study	Differences (%)
NL	Boreal Shield East	1.8	1.4	21	2.7	2.0	22
NS	Atlantic Maritime	1.9	1.2	37	3.6	3.4	5
PEI	Atlantic Maritime	2.2	1.0	52	na	0.0	na
NB	Atlantic Maritime	1.3	1.0	20	2.8	2.6	4
QC	Atlantic Maritime	1.4	1.0	26	3.1	0.0	100
QC	Boreal Shield East	1.1	0.9	14	3.4	2.2	33
ON	Boreal Shield West	1.3	0.9	29	2.6	3.6	−39
	Boreal Shield East	1.2	1.0	20	3.6	3.0	14
MB	Boreal Shield West	1.2	0.7	41	1.6	2.0	−25
	Boreal Plains	1.6	0.7	55	2.1	1.8	10
SK	Boreal Shield West	1.0	0.7	33	2.0	2.2	−13
	Boreal Plains	1.8	0.7	60	2.6	1.9	25
	Taiga Plains	2.8	0.6	79	4.5	1.2	72
AB	Taiga Shield West	na	0.4	na	2.3	2.0	10
	Boreal Shield West	na	0.3	na	3.4	1.1	65
	Boreal Plains	2.7	0.8	71	4.9	1.6	65
	Montane Cordillera	2.6	1.1	58	5.0	4.7	5
BC	Taiga Plains	5.3	0.7	86	7.6	1.8	75
	Boreal Plains	3.5	0.9	74	6.1	4.1	32
	Boreal Cordillera	3.6	1.4	61	5.1	3.7	27
	Pacific Maritime	6.7	3.1	53	9.6	10.0	−4
	Montane Cordillera	3.1	1.9	37	6.0	5.6	6
Study area total from Ref. [16]		**2.0**	**1.2**	**38**	**3.5**	**2.4**	**31**

na: not applicable.

4. Discussion

4.1. National estimates and spatial variations

The use of national-level remote sensing products make it possible to quantify and locate consistently across Canada the amount of biomass made available in burned forest stands and in clearcut harvest areas at historical fire and harvest regimes. At the national level, our results confirm that salvage logging from fire-killed stands can potentially yield more biomass than the retrieval of harvest residues from clearcuts only across Canada [8,16]. Our results also show that the density of biomass (ODT ha^{-1}) available for salvage logging from fire-killed stands is on average higher but much more variable both in time and in space than for harvest residues (Figs. 2b and 4). The large variability in space translates into potentially low economic viability of biomass recovery for a large proportion of fire-killed stands in comparison to feedstocks from harvest. On the other hand, the large inter-annual variability in burned areas is not such a constraint since wood affected by fire maintains its fiber quality for bioenergy use for many years, at least 8 years in the boreal forest of eastern Canada [13]. However, the increased falling of dead trees and the presence of regeneration with time since disturbance enhances the logistical challenge of salvaging wood from older fires [13].

Hotspots showing the highest biomass density from fire-killed stands within our 10-year window of analysis (2001–2011) are located in the northern part of the managed forest, where roads are sparse and industrial infrastructure modest, whereas the reverse is true for harvest residues that, by definition, are accessible by roads that link them to an industrial network. Lack of direct access to deep-water ports needed to reach international markets also reduces the economic attractiveness of feedstock procurement from hotspots of fire-generated biomass [4]. Nevertheless, the use of this remote feedstock could be attractive to the more nimble or specialized users who are prepared to deal with such shortcomings. For example, small-scale decentralized energy production systems based on biomass sourced from wildfire-affected areas may represent an interesting alternative to fossil fuels for remote communities, with the potential to support local development and employment, a factor that could mitigate the cost of feedstock procurement [33,34].

Over large regions, our estimates of biomass from fire-killed trees were more similar to those of Dymond et al. [16] than our estimates of harvest residues which were lower by about 38% in our study (Table 1). Several factors can explain this difference. First, the detection of harvested areas by remote sensing is applied to clearcut harvested areas [27] only, and therefore does not account for the thinning and partial forest harvesting areas that were included in Dymond et al.'s estimates. More importantly, however, in their study Dymond and colleagues projected increased harvest rates over time and failed to anticipate the massive 2005–2009 contraction in the US housing market and the ensuing drop in forest harvest rates across Canada. Using the yearly harvest areas, the remote sensing approach used in our study was able to accurately detect the decline between 2005 and 2009 as recorded in the National Forestry Database [35] (Fig. 6b). Harvest residues are a secondary product of forest harvesting operations and as such are tributary to this primary activity. Fluctuations in the solid wood products market are difficult to predict but significantly impact the stability of this biomass supply. Mitigation of this uncertainty must therefore be managed proactively through actions related to the improvement of residue mobilization at the regional level or the development of alternative feedstock sources that can be drawn upon as needed.

4.2. Limitations and future developments

While this study focuses only on biomass sourced from harvest residues and fire-damaged stands, our estimates of biomass availability will need to be complemented by other sources of feedstock available in Canada such as plant residues, stand thinning, and by others natural disturbances such as insects and wind, in order to portray the full picture of biomass potential at the national level. Methodological improvements can also be made with respect to

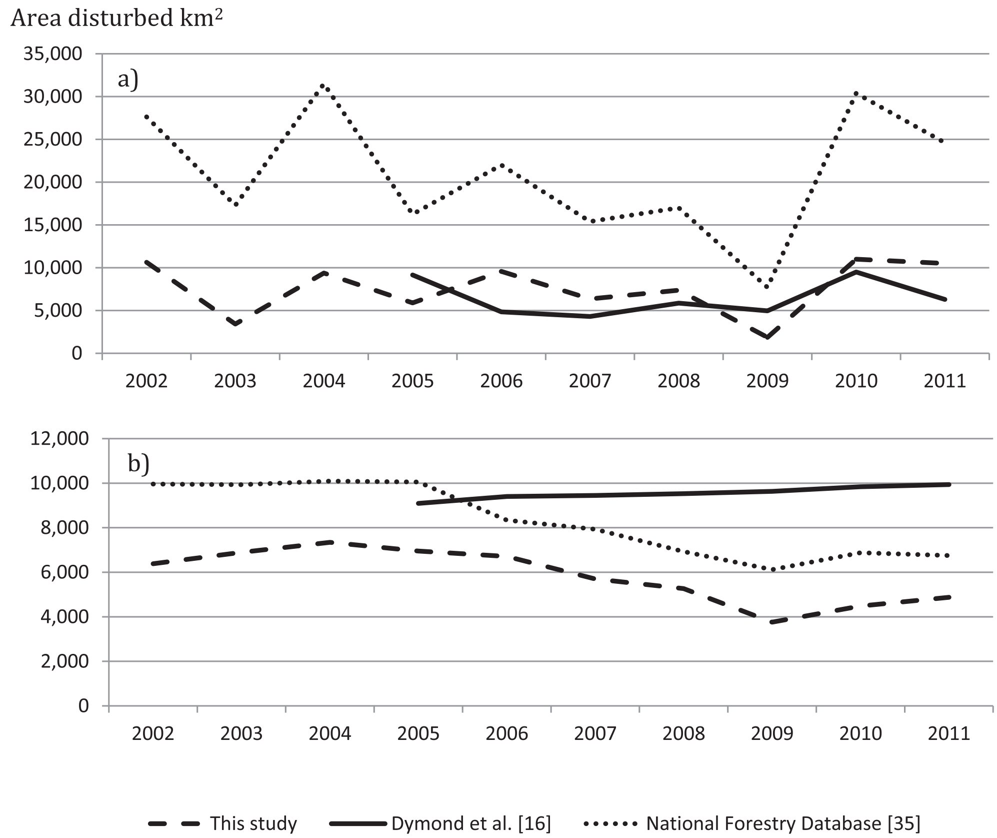

Fig. 6. Comparison in area disturbed from this study and different sources between 2002 and 2011. a) burned area and b) harvested area. Sources are from Dymond et al. [16] and the National forestry database [35]. Canada's National Forest Inventory is an ongoing forest measurement program. Repeated measurements are taken at a network of sampling points across Canada to provide consistent information on the extent, composition and characteristics of Canada's forests and how they are changing over time [35].

harvest residues through empirical studies to better capture the greater biomass of undesirable material left on sites. Similarly, economics of biomass recovery of fire-killed stands is a significant concern because of limited road access, but also because fires affect stands of all biomass density classes.

In addition, the operational amount of available biomass is likely to be lower than these estimates when considering environmental and technical constraints [36]. Average biomass recovery rate (expressed as the proportion of residues operationally recovered from a given cutblock from the original total amount of residues) in Canada is estimated at 52%, with a rate varying between 4% and 89% depending on local factors [37]. By comparison, Nordic countries generally have a higher recovery rate (72%) due to better practices, technology and policy support for forest bioenergy [37]. Understanding how local conditions and technical constraints limit and affect recovery rates in Canada could serve the double purpose of supporting the enhancement of recovery rates and increasing confidence in our biomass estimates.

Uncertainties remain in terms of location and prediction of the quantities of potentially available biomass feedstock. In particular, uncertainties in the two core datasets used in our study [26,27] are carried over to our calculations. For example, the estimates of harvested and burned areas across Canada from Guindon et al. [27] are respectively 30% and 26% lower than the values reported in the National Forestry Database [36] (Fig. 6), in large part due to the difficulty in detecting small or partial harvests or burns at a 250 m pixel resolution. However, even if our biomass estimates are somehow conservative, they are consistent with the observed annual variability of the disturbed areas from the National Forestry Database (Fig. 6) suggesting that the method used in this study represents a solid base for future developments of remote sensing products for biomass mobilization.

Continuous improvements in the remote sensing tools used for forest change detection and reporting of natural and anthropogenic disturbances [38] should result in more accurate estimates of biomass availability across Canada. National products at a 30 m resolution with Landsat images (compared with the 250 m one from MODIS) could detect partial harvesting and thinning at the national scale. Similarly, the difficult task of detecting insect-caused tree mortality should be easier to tackle using 30 m products, thereby possibly enabling the estimates of biomass available from insect outbreaks. This is an important current issue, as can be attested by the importance of the unfolding outbreak of spruce budworm (*Choristoneura fumiferana*) in eastern Canada.

5. Conclusion

The range of our biomass estimates made available in burned forest stands and in clearcut harvest areas appears conservative relative to other national studies [16,17] but are consistent with the observed annual variability of the disturbed areas at the national level. While climate change is predicted to increase the occurrence and the extent of natural disturbances in the boreal forest [39,40], forest management strategies are needed to adapt and mitigate their impacts [41,42]. Adapting forest product value chains to capitalize on forest feedstock from disturbed stands is an integral part of a larger framework of forest management adaptation to climate change [3,43]. Large variations in ecological and operational conditions exist across Canada's forests. Within this variability, any new biomass supply chains must be regionally relevant, sustainable and compliant with international certification frameworks [44]. The merging of all such considerations for supply chain development requires ever-improving methods for assessing the quantity, quality and location of biomass on the landscape. Continual and multidisciplinary assessments of the biomass flow are also required to support economic feedback between biomass mobilization practices and other forest services [45].

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.biombioe.2016.12.014.

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