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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