Forest Ecology and Management 430 (2018) 33–42

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Dynamics of detrital carbon pools following harvesting of a humid eastern Canadian balsam fir boreal forest

Fanny Senez-Gagnon[a], Evelyne Thiffault[b,*], David Paré[c], Alexis Achim[b], Yves Bergeron[a,d]

[a] Centre for Forest Research, Université du Québec à Montréal, P.O. Box 8888, Centre-ville stn, Montreal, QC H3C 3P8, Canada
[b] Renewable Materials Research Centre, Université Laval, 2425 rue de la Terrasse, Gene-H.-Kruger Building, Quebec City, QC G1V 0A6, Canada
[c] Natural Resources Canada, Canadian Forest Service, Laurentian Forestry Centre, 1055 du P.E.P.S., P.O. Box 10380, Sainte-Foy Stn, Quebec City, QC, Canada
[d] NSERC-UQAT-UQAM Industrial Chair in Sustainable Forest Management, Forest Research Institute, Université du Québec en Abitibi-Témiscamingue, 445 de l'Université blvd, Rouyn-Noranda, QC J9X 5E4, Canada

ARTICLE INFO

Keywords:
Carbon pools
Time since harvest
Chronosequence
Carbon transfer
Dead wood
Buried wood
Forest soil

ABSTRACT

Forest management strongly influences the carbon (C) budget of boreal forests and their potential to mitigating greenhouse gas emissions. A better quantification of the net changes of carbon pools with time since harvesting is necessary to guide the development of climate-friendly forest management practices. The objective of this study was to assess the evolution of forest C pools, with a special focus on detrital biomass, in an 80-year post-harvesting chronosequence consisting of 36 very homogenous stem-only harvested plots from a humid boreal balsam fir forest of eastern Canada. Dead wood C stocks comprised of snags, stumps, downed woody debris and buried wood averaged 37 Mg C ha^{-1} and evolved according to an upward-facing «boomerang» shape pattern throughout the chronosequence (rapid decrease in the first years followed by a constant increase until the end of the time horizon). In contrast, soil C stocks (FH and mineral) averaged 156 Mg C ha^{-1} and remain constant through time. Stand C sequestration increased rapidly in the early stages up to age 50 when it reached about 250 Mg C ha^{-1}, and then continued to accumulate at a slower rate. The temporal trends observed in C pools suggest that C originating from aboveground dead wood (snags, stumps, downed woody debris) is either leaving the system (respired or leached) or transferred into buried wood, and does not appear to influence the C stocks of the fine fraction of the organic and mineral soil horizons. However, the ultimate fate of dead wood C is still poorly understood and further research is needed in this field. We recommend fixing the length of harvest rotation at a minimum of 50 years for this ecosystem to allow the build-up of its dead wood capital, and to promote dead wood retention on site. We also recommend including buried wood in carbon inventories as this pool represents an important share of the detrital C stock in these humid boreal forests.

1. Introduction

Forests and the products they generate have a strong potential to mitigate climate change (Pan et al., 2011). Forests store great amounts of carbon (C) and provide renewable sources of wood products and energy that are considered as ecological alternatives to more carbon-intensive materials (Nabuurs et al., 2007). As a result, several initiatives are taken by both scientists and practitioners to implement climate-friendly forest management and wood production practices (Schulze et al., 2000; Millar et al., 2007; Malmsheimer et al., 2011).

Maximising the potential for climate change mitigation by the forest sector relies in good part on an understanding of the forest C cycle. However, many aspects of this cycle remain poorly understood, especially the decay dynamics of downed woody debris (DWD, i.e. laying dead wood) and C transfers to the soil or the atmosphere (Magnússon et al., 2016). Global vegetation (e.g. LPJ (Sitch et al., 2003), LM3V (Shevliakova et al., 2009)) or C dynamics models (e.g. Yasso (Rantakari et al., 2012), CBM-CFS3 (Kurz et al., 2009)) generally assume that a substantial portion of dead wood (i.e. snags, stumps, downed logs, large branches and dead roots) C is transferred to the soil organic matter reservoir (Cornwell et al., 2009). However, according to two syntheses (Nave et al., 2010; Thiffault et al., 2011a), the on-site retention of debris in the form of harvest residues (consisting of tree tops and branches) do not generally lead to significantly higher C content in the fine fraction of soil. Hence, it remains unclear to which extent dead wood contributes to soil stable organic matter formation and long-term soil C storage.

Since DWD constitute a large C pool (Laiho and Prescott, 2004;

* Corresponding author.
E-mail address: evelyne.thiffault@sbf.ulaval.ca (E. Thiffault).

https://doi.org/10.1016/j.foreco.2018.07.044
Received 25 April 2018; Received in revised form 23 July 2018; Accepted 25 July 2018

Russell et al., 2015), contribute to maintain soil fertility (Brais et al., 2006; Zhou et al., 2007; Angers et al., 2012) enhance ecosystem biodiversity (Harmon et al., 1986; Lassauce et al., 2011), may become more abundant (Cornwell et al., 2009; Hu et al., 2017) and have their decomposition rates affected by a changing climate (Olajuyigbe et al., 2012; Pietsch et al., 2014), characterizing their C dynamics is of crucial importance to provide adequate management guidance.

Worldwide, boreal forests (1135 Mha) are estimated to contain 32% of the total forest C stocks (Pan et al., 2011). They represent a net sink of 0.5 ± 0.1 petagrams (Pg) of C year^{-1}, which compensates for about one half of the annual anthropogenic C emissions (Pan et al., 2011). Based on the categories of the International Panel on Climate Change (IPCC), forest C pools consist of aboveground biomass (i.e. all living biomass above the soil), belowground biomass (i.e. live roots), litter (i.e. non-living biomass that is not in the dead wood pool), dead wood (above- and below-ground) and soil organic matter (Penman et al., 2003). Over two decades (1990–2008), Canadian boreal forests (270 Mha) have represented a net C sink of 11 teragrams (Tg) of C year^{-1}, but there is uncertainty about the perennity of this sink due to rising temperatures and accelerated frequency of natural disturbances.

The wood decay process is a major source of C emissions in biomes with great amounts of DWD (Wu et al., 2010), which is the case in boreal ecosystems, where DWD can account for between 10% (Stinson et al., 2011) to as much as 54% (Laiho and Prescott, 2004) of the total biomass at the forest stand level. The abundance of DWD is strongly influenced by stand age and generally follows a U-shaped pattern after disturbance, which is first explained by the degradation of the trees killed by the disturbance, followed by the gradual "recruitment"of dead trees as the new stand ages (Hély et al., 2000; Harmon et al., 2011; Russell et al., 2015).

Decomposition rates are highly variable, and in moist and cold stands presenting a thick moss layer, buried wood can be abundant and remain intact for decades or even centuries (Jacobs et al., 2015; Moroni et al., 2015). Post-decay C pathways are difficult to quantify and include one or more of the following: mineralization and emission of C towards the atmosphere, dissolution and leaching in the water system, incorporation in live organisms or stabilization in soil organic matter (Cornwell et al., 2009). The fate of C from the DWD will determine the amount of C that will ultimately be transferred to the soil. The lignin-rich carbon inherited from DWD could potentially be inferred by the concentration of lignin in FH horizons, with the presence of decomposing wood and the specific microclimate conditions in the forest floor promoting the accumulation/preservation of lignin or lignin-like compounds (Strukelj et al., 2013).

The general aim of this study was to study the dynamics of the main carbon pools, and especially those of detrital biomass and soil, along a post-harvest forest rotation occurring in a humid eastern Canadian balsam fir boreal forest. Using a chronosequence approach, we pursued the following two specific objectives: (1) to assess temporal changes in the size of all forest carbon pools as defined by the IPCC (Penman et al., 2003) following stem-only clearcut harvesting, and (2) to analyse the interactions between downed woody debris and other carbon pools to determine whether a pulse of debris will later lead to any observable increases in soil organic matter pools. We hypothesized that (1) dead wood is more abundant at the beginning and the end of the rotation, (2) the temporal pattern of the soil (FH and mineral horizons) C pool does not relate to the patterns of dead wood presence and abundance; however, the temporal pattern of the buried wood C pool follows that of dead wood and (3) the composition of the organic matter in the FH horizons does not show any chemical enrichment from decay of debris, that is, its lignin concentration will not vary significantly through time or in accordance with the dead wood accumulation curve.

2. Material and methods

2.1. Study site

The Forêt Montmorency (47°19′19.6″N 71°08′49.6″W), the research forest of Laval University (Quebec, Canada), covers 412 km^2 in the southeastern portion of the Canadian boreal forest. It is located within the balsam fir - white birch bioclimatic domain and is characterized by a cold and moist climate. Mean annual temperature and precipitation are 0.5° and 1583 mm (964 mm in rain and 620 mm in snow) (Environment and Climate Change Canada, 2017). The natural disturbances shaping this forest landscape are recurrent spruce budworm outbreaks (with intervals of 30–40 years) and windthrows, the significant pluviometry limiting wildfires. The main soil type is ferro-humic podzol, with relatively frequent seepage. Historically, the Forêt Montmorency was covered by a fine heterogeneous mosaic of mostly mature and irregular stands of balsam fir companioned by white birch, white spruce and, less commonly, black spruce and trembling aspen. Although partial cuts are gaining importance in the Forêt Montmorency's management strategy, the main harvest type is clearcut harvesting with protection of advance regeneration and soils.

2.2. Experiment design

Data were collected from a chronosequence of forest stands of various ages located within Forêt Montmorency, all originating from clearcut, stem-only harvesting (i.e. tree tops and branches were left on site). The chronosequence consisted of 36 plots ranging from 1 to 80 years after harvest. They showed nearly identical ecological and geomorphological properties (parent material, soil granulometry, slope, aspect, altitude and drainage) based on mapping info and site evaluation (see Appendix A for ecological and geomorphological information). All plots were classified as belonging to the same ecological type according to Quebec classification (MS22: Balsam fir-white birch stand on shallow to deep deposits, with medium drainage and medium soil texture) (Ministère des Ressources naturelles de la Faune et des Parcs, 2004), and had site index ranging from 13.5 to 15 m at age 50.

2.3. Data collection

The protocol for data collection was inspired by the guidelines for ground plots of Canada's National Forest Inventory (NFI) (National Forest Inventory, 2008) and by the protocol of Thiffault et al. (2011b). Each plot of the chronosequence was circular in shape with a 20-m radius (area of 1250 m^2). At the center of the main plot, two smaller circular inventory plots of a 11.28-m (400 m^2) and 3.99-m radius (50 m^2) were installed to measure large vegetation and snags, and small vegetation and stumps, respectively. In addition, two 20 m-long perpendicular transects intersected at the center of the main plot were established for woody debris inventory. Soil was sampled in 6 stations positioned within the boundary of the main plot.

2.3.1. Downed woody debris

On the two perpendicular 20-m long transects, every piece of laying dead wood of more than 1 cm in diameter crossing the transect (i.e. laying on the ground or suspended above it) was counted and its decay class was categorised (from Class 1: Intact and hard, to Class 5: Totally decomposed and soft; National Forest Inventory (2008)). The diameter of each woody debris was measured using a calliper held perpendicular to the debris at the point where it intersected the transect. DWD were divided in two size categories: 1.1–3 cm and > 3 cm in diameter, which correspond, respectively, to small and coarse DWD. Debris ≤ 1 cm or