Forest Ecology and Management 360 (2016) 181–194

Contents lists available at ScienceDirect

Forest Ecology and Management

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

Soil CO_2 efflux and net ecosystem exchange following biomass harvesting: Impacts of harvest intensity, residue retention and vegetation control

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ARTICLE INFO

Article history:
Received 4 August 2015
Received in revised form 13 October 2015
Accepted 19 October 2015

Keywords:
Bioenergy
Biomass harvesting
Soil respiration
Net ecosystem exchange
Forest management
Carbon

ABSTRACT

Biomass harvesting removes more woody material than would be taken with conventional forest harvesting. Harvesting residues, left on site are an important substrate for micro-organisms that maintain nutrient cycles essential for future forest productivity by mineralizing organic matter, and releasing carbon dioxide (CO_2) as a respiratory bi-product. We assessed the impact of biomass removal intensity (stem-only [SO], full-tree biomass [FT], full-tree biomass plus stumping [FT + S], full-tree biomass plus stumps and forest floor removed [FT + B]), and herbicide application on soil respiration and net ecosystem exchange of carbon (C) in a harvested 40-yr-old jack pine stand. Soil respiration (surface CO_2 efflux) normalized to 15 °C (R_{15}) was lower in biomass harvest treatments than in the uncut stand and a mature 80-yr-old fire-origin natural stand. Among harvest treatments, R_{15} was positively related to the amount of C retained, with the general pattern of FT + B < FT + S < FT ≈ SO. Differences in R_{15} among treatments were primarily related to residue and soil organic matter quantity and quality (i.e., presence of mineral soil and forest floor polysaccharide). Herbicide application further reduced R_{15} by diminishing root respiration, although herbicide treatments in the SO, FT and FT + S resulted in greater net CO_2 fluxes to the atmosphere in August because herbaceous photosynthesis was greatly reduced. We suggest that criteria for determining site-specific biomass retention should take into account the amount and type of residue required to maintain microbial soil respiration driving nutrient cycling.

1. Introduction

There is growing interest in the use of forest harvest residues and non-merchantable biomass (i.e., coarse and fine woody debris, non-target and undersized trees) for bioenergy production. Greater utilization of residues can partially replace the use of fossil fuels, reducing longer-term greenhouse gas emissions (i.e. carbon [C] offsets) and diversify a country's energy portfolio (Roach and Berch, 2014; Ter-Mikaelian et al., 2015). However, energy diversification and economic development should not compromise ecological sustainability (Lattimore et al., 2009).

Downed woody debris, including harvest residue, have important on-site roles in sustaining soil nutrient cycles (Nambiar, 1996; Powers et al., 2005; Wall, 2012). Biomass harvesting directly reduces the amount of labile residue, such as leaves, needles and fine woody debris (Ewel et al., 1987; Marshall, 2000; Wall, 2012), by removing smaller diameter trees than conventional harvesting for traditional wood products (i.e., saw logs and pulpwood). Residues provide a substrate for soil microbes that mineralize organic matter and release nutrients (e.g., nitrogen [N]) with carbon dioxide (CO_2) released as a respiratory by-product (Raich and Tufekcioglu, 2000). Harvesting and silvicultural prescriptions affect the near surface micro-climate (e.g., solar radiation, temperature, moisture and wind [Fleming et al., 1998; Proe et al., 2001]) and soil environment (e.g., compaction, profile turnover and mixing [McNabb et al., 2001; Marshall, 2000; Williamson and Neilsen, 2000]). If substrate or environmental conditions are limiting, decomposition slows and heterotrophic soil respiration declines, resulting in less mineralization of nutrients for plant uptake (Fox, 2000; Grigal, 2000; Marshall, 2000; Thiffault et al., 2011).

Harvesting intensity and reforestation practices affect net ecosystem exchange (NEE) of CO_2 with the atmosphere. NEE is a function of CO_2 released through soil respiration (Rs), which

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http://dx.doi.org/10.1016/j.foreco.2015.10.032
0378-1127/

includes both heterotrophic (from microbes) and autotrophic (from plants) respiration, minus CO_2 sequestered in regenerating vegetation. Factors affecting the re-establishment of ground vegetation and seedlings such as mineral soil exposure, changes to the soil environment (e.g., temperature, moisture) and application of herbicide (Roberts, 2007) also affect NEE following harvest.

Most studies evaluating the impacts of harvesting on soil respiration and NEE have not examined a broad gradient of biomass removal intensities and post-harvest reforestation practices (e.g., site preparation and herbicide application). Studies examining soil respiration following forest harvesting (typically conventional harvesting, occasionally whole-tree harvesting) have been few and have produced inconsistent findings (Peng et al., 2008). Studies report Rs in the first few years following clearcut harvesting in the boreal to increase (Gordon et al., 1987; Mallik and Hu, 1997), decrease (Striegl and Wickland, 1998; Pumpanen et al., 2004; Moroni et al., 2009) or have little change (Fleming et al., 2006). Clear patterns have been elusive due to the time between harvest and Rs measurements, variation in tree species, understory composition, stand age, site fertility, and amount of residues (Peng et al., 2008). However, harvesting generally results in sites being a net CO_2 source to the atmosphere after harvest (Liski et al., 1998; Pypker and Fredeen, 2002a; Zha et al., 2009) though some report a small sink (Pypker and Fredeen, 2002b).

This study examines the impacts of a range of biomass harvest intensities, including intensive bioenergy harvesting, of a 40-year-old second growth, irregularly spaced jack pine stand (*Pinus banksiana* Lamb.), in the boreal forest of northeastern Ontario. Jack pine woodlands are an important component of the boreal forest, covering over 2 million km^2 of predominantly well-drained uplands in northern North America (Law and Valade, 1994; Lowe et al., 1994). These deep, well-drained coarse-textured soils support productive forests but have limited water-holding capacity and nutrient reserves, which raises long-term sustainability concerns (Foster, 1996). These low quality mid-rotation stands are potential candidates for biomass harvest to allow for stand rehabilitation, yet there is little data on impacts on these sites and results from mature stands may not be applicable given the historical legacy of build-up of coarse woody debris and forest floor over time.

Rs and NEE are expected to change with increasing biomass removal due to changes in the quantity and quality of residues and in environmental conditions. The key question is how does intensification of biomass removal and regeneration practices affect the (1) magnitude, (2) source, and; (3) physical vs chemical controls on Rs and NEE. This information is essential to aid in determining the optimal level of biomass removal that still ensures sufficient decomposition of organic matter to mineralize nutrients that ensures future tree productivity while minimizing the site's C source to the atmosphere.

2. Material and methods

2.1. Study sites

The study was carried out at two boreal jack pine-dominated boreal sites near Chapleau, Ontario (Fig. 1). The first site (Island Lake N 47.7° W 83.6°) was a 40-year old second growth jack pine stand established following clearcut harvesting during the 1960s of a mature fire-origin stand. The site was mechanically site prepared with Young's teeth, hand seeded and subsequently fill planted. The second site currently supports an 84-year old fire origin jack pine stand (Nimitz N 47.6° W 83.3°).

Details related to the study sites are given in Kwiaton et al. (2014) and Fleming et al. (2014) and summarized briefly here. The height at age 50 (site index) is 19.3 m for the uncut control adjacent to the harvested area at Island Lake (UC) and 18.8 m for mature natural stand at Nimitz (MN). The soils are Dystric Brunisols (Soil Classification Working Group, 1998), formed over rapidly-drained, coarse textured, glacial–fluvial deposits. Surface organic horizons (forest floor) are classified as HumiFibrimors having an average depth of 10 cm – and support a continuous carpet of feathermoss and understory herbs and shrubs (Kwiaton et al., 2014).

For the Chapleau region the mean annual temperature (MAT) is 2.0 °C, with 1444 growing degree days (>5 °C) and 92 frost free days, typically from early June to early September. Daily maximum temperatures are highest in July and coldest in January. Mean annual precipitation is 827 mm (545 mm in rainfall, 282 cm in snowfall) with September being the wettest month and February being the driest (Environment Canada, 2014). During 2012 the months of May to October were warmer (by 1.3 °C) and slightly drier (by 17 mm) than the climate normal.

2.2. Island Lake biomass harvest experiment

At the Island Lake site a 50 ha area was set aside for harvesting (Fig. 1). Harvesting occurred during December 2010 and January 2011, with 70 × 70 m plot treatments laid out during July to September 2011. Plots were positioned at least 50 m from uncut forest to minimize forest edge effects, with individual plots separated by at least 20 m. There are five blocks (randomized complete block design) containing each of the four harvest treatments of stem-only harvest [SO], where only the bole of each tree was removed leaving stumps and upper branches on site after harvest; full tree biomass harvest [FT], where the entirety of each tree (including traditionally non-merchantable trees) upwards from the stump was removed; stumped [FT + S], where the full tree biomass harvest was followed by stump removal; bladed [FT + B], which consisted of a full-tree biomass harvest, stumping and removal of the forest floor by blading (Fig. 1). The applied treatments resulted in a broad gradient of removals, with the amount of C removed increasing with biomass removal intensity from SO (30.5 Mg ha^{-1}) to FT (54.6 Mg ha^{-1}) to FT + S (74.6 Mg ha^{-1}) and finally FT + B (108.5 Mg ha^{-1}) (Fig. 2; Kwiaton et al., 2014). Each of the harvested plots was subdivided into four 35 m by 35 m sub-plots, using a split plot design. Two sub-plots were sprayed with a glyphosate herbicide (Vision®, at 4 L of product ha^{-1}) to control vegetation, while the other two sub-plots had no vegetation control. Disc trenching within SO, FT, and FT + S created repetitive rows of flat areas, trenches and debris from trenches. At UC and MN there were 5 replicate 70 × 70 m plots within each site.

In May 2012, the buffer area was planted to jack pine, while sub-plots in each of the treatment plots were split between jack pine and black spruce (*Picea mariana* [Mill.] Britton), with each species planted in one herbicide-treated and one non-treated quadrant at approximately 1.8 by 2 m spacing. Seedlings were overwintered planting stock grown in jiffy pots with improved seed from Ontario seed zone 24.

2.3. Soil respiration and NEE sampling

Rs was measured monthly during the first growing season (May to October 2012) after harvest in 3 of the 5 treatment blocks, and at 3 of the 5 plots within UC and MN. In each plot, soil respiration was monitored in each of the 4 sub-plots, and for disc-trenched treatments, within the area of undisturbed forest floor between the trench and trench debris rows. All measurements were made between 1000 h and 1400 h using the static chamber method (Livingston and Hutchinson, 1995). This involved placing a portable acrylic flux chamber (49.5 × 49.5 × 40 cm = 90.2 L volume) over permanently installed square aluminum collars (0.21 m^2 measurement area; installed in fall 2011 to allow equilibration