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Coarse woody debris effects on greenhouse gas emission rates depend on cover soil type in oil sands reclamation

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ABSTRACT

Peat mineral soil mix (PMM) and forest floor mineral soil mix (FMM) are cover soils commonly used for land reclamation, while coarse woody debris (CWD) can be added to create structural diversity and provide an additional source of organic matter. However, the effect of cover soil type and CWD on emission rates of greenhouse gases, such as carbon dioxide (CO_2) methane (CH_4) and nitrous oxide (N_2O) in reclaimed oil sands soils has not been studied. Soil respiration, CH_4 uptake and N_2O emission rates were studied in a factorial experiment consisting of 2 cover soils (FMM vs PMM) × 2 sampling distances from the CWD (near vs away from CWD). Greenhouse gas emission rates were measured in July, August, and September 2012 and 2013 using static chambers. Soil respiration rates were greater in FMM than in PMM regardless of the distance from CWD at each sampling time ($p < 0.05$). Rates ranged from 461 to 1148 and 293 to 677 mg CO_2 m^{-2} h^{-1} for FMM and PMM, respectively, in 2012, and from 355 to 1318 and 235 to 700 mg CO_2 m^{-2} h^{-1}, respectively, in 2013. The CWD increased soil respiration by 22–33% in FMM but not in PMM. Soil respiration rates were positively related to microbial biomass carbon ($p = 0.004$) and nitrogen ($p < 0.001$). Soil respiration rates decreased from July to September in 2012 and 2013, and were positively related to soil temperature ($p < 0.01$) but not with soil water content measured at 5 cm depth. Methane uptake rates were greater in FMM (0.026–0.037) than in PMM (0.015–0.028 mg CH_4 m^{-2} h^{-1}). The CWD increased CH_4 uptake rates only in July and August 2012 in FMM, and were negatively related to soil water content ($p < 0.001$) but not to soil temperature. Nitrous oxide emission rates (0.001–0.016 mg N_2O m^{-2} h^{-1}) were not affected by either cover soil type or CWD. Global warming potential of CO_2, CH_4 and N_2O effluxes was greater in FMM than in PMM and near CWD than away from CWD, especially in FMM. Our study demonstrates that applying CWD for oil sands reclamation increases organic matter decomposition (increased CO_2 evolution), driven by the effect on microbial populations. Results from this study provide support to findings in earlier studies that CWD application benefits vegetation establishment through enhancing soil processes in reclaimed oil sands lands.

1. Introduction

The Athabasca oil sands region (AOSR) in northern Alberta, Canada has the largest single bitumen deposit in the world (Alberta Government, 2014). Surface mining is one of the common practices for oil sands extraction and has disturbed 767 km^2 of boreal forest until 2013 (Alberta Government, 2014), thereby reducing the potential for atmospheric carbon dioxide (CO_2) sequestration and methane (CH_4) uptake. Total greenhouse gas emissions due to oil sands activities, such as mining, transportation, extraction and upgrading, were 55 Mt in 2011 and account for 23 and 8% of total greenhouse gas emissions in Alberta and Canada, respectively (Alberta Government, 2014). Land disturbed by oil sands operations is regulated to be returned to equivalent land capability of pre-disturbance levels (Province of Alberta, 2014).

Land reclamation can increase atmospheric CO_2 sequestration by supporting plant growth but can simultaneously promote CO_2 emission from cover soils by enhancing microbial decomposition of soil organic matter (Welham et al., 2012). Soil respiration rates are influenced by several factors, such as soil temperature and water content (Davidson et al., 1998; Davidson and Janssens, 2006; Lee et al., 2006; Raich and Schlesinger, 1992), vegetation and substrate quality (Raich and Tufekcioglu, 2000; Wang et al., 2003), net ecosystem productivity (Raich and Potter, 1995; Raich and Tufekcioglu, 2000), microbial population size and activities

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(Jenkinson et al., 1976; Rice et al., 1996; Shen et al., 1997), and land use and disturbance regimes (Rustad et al., 2000).

Methane has 25 times greater global warming potential than CO_2 over a time scale of 100 years (IPCC, 2007) and is considered the second most common greenhouse gas after CO_2 emitted from soils (IPCC, 2007). Forest soils are the most active CH_4 sinks in upland soils due to the higher methanotrophic activity relative to other ecosystems, such as grass land or cultivated land (Mer and Roger, 2001). Therefore, returning disturbed land to upland boreal forest has high potential for oxidizing atmospheric CH_4 and mitigating global warming. Methane oxidation in upland soils is less intensively studied than CH_4 emission in wetlands, and soil water content, gas diffusivity, and nitrogen fertilization are main determinants for CH_4 oxidation and uptake rates in soils (Steudler et al., 1989; Mer and Roger, 2001; Smith et al., 2000).

Nitrous oxide (N_2O) is an important greenhouse gas emitted from soils, with 298 times greater global warming potential than CO_2 over a 100-year span (IPCC, 2007). Nitrification and denitrification are the main microbial processes that produce N_2O in soils, and therefore, ammonium (NH_4^+) and nitrate (NO_3^-) concentrations are two of the most important determinants of N_2O emission (Keller et al., 1983; Smith et al., 2003). Soil water content and temperature are also important determinants of N_2O emission as they regulate microbial processes and are positively related to N_2O emission (Keller et al., 1983; Smith et al., 2003).

Peat mineral soil mix (PMM) and forest floor mineral soil mix (FMM) are cover soils commonly used over substrates such as geological overburden or tailings sand to provide organic matter, improve soil fertility and water holding capacity, and provide a source of plant propagules and soil microorganisms for land reclamation in the AOSR (DePuit, 1984; Mackenzie and Naeth, 2010; Sydnor and Redente, 2002). Cover soils such as FMM and PMM used for land reclamation have different physical, chemical, and biological properties (Jamro et al., 2014; Mackenzie and Naeth, 2010; McMillan et al., 2007) mainly because organic matter in the PMM salvaged from wetlands is less decomposed than the FMM salvaged from upland forests. The FMM therefore contains more decomposable material because of its lower carbon to nitrogen (C:N) ratio (Mackenzie and Naeth, 2010), and it has higher nitrogen (N) availability and microbial and enzyme activities relative to PMM (Brown and Naeth, 2014; Dimitriu et al., 2010; Jamro et al., 2014; McMillian et al., 2007). The FMM also contained more native plant propagules (Mackenzie and Naeth, 2010) and vegetation cover was typically greater in FMM than in PMM (Brown and Naeth, 2014; Mackenzie and Naeth, 2010).

In the AOSR, coarse woody debris (CWD), which includes dead trees, downed boles, large branches, and dead coarse roots (Harmon et al., 1986; Stevens, 1997), has been applied to the soil surface as a novel land reclamation method to help increase the success of vegetation establishment in early ecosystem development (Brown and Naeth, 2014; Forsch, 2014). Application of CWD increases soil organic matter content, creates microsites which increase germination and emergence of plant propagules, regulates soil temperature and water content, increases microbial and enzyme activities, and controls soil erosion (Brown and Naeth, 2014; Gonzalez-Polo et al., 2013; Harmon et al., 1986; Stevens, 1997). Large amounts of CWD are produced during clear-cutting of forest stands prior to open-pit mining. Application of CWD for land reclamation is a relatively new practice and its effect on greenhouse gas emission rates has not been studied.

The purpose of this study was to determine the effects of CWD on soil respiration rates and CH_4 uptake in reclaimed oil sands soils with FMM and PMM as cover soils. We hypothesized that (1) soil respiration rates in FMM would be greater than those in PMM regardless of CWD application due to greater microbial and enzyme activities and vegetation cover in FMM, (2) application of CWD would increase soil respiration rates in cover soils due to enhanced microbial activity resulting from increased soil water content and narrow soil temperature range, and the effects of CWD on soil respiration rates would be greater in FMM than in PMM as FMM is drier than PMM and changes in soil water content and microbial activity will be greater in FMM, (3) CH_4 uptake rates would be greater in FMM and without CWD due to drier conditions and (4) N_2O emission rates would be greater in PMM and with CWD due to higher soil water contents. To test these hypotheses, field experiments in the AOSR were conducted 5 and 6 years after land reclamation, which was completed after oil sands mining activities.

2. Materials and methods

2.1. Study site

The research site is located on an oil sands company lease (56° 58′N, 111° 22′W), about 24 km north of Fort McMurray, Alberta, Canada. The site is located in the mixedwood boreal forest which consists of upland forest, wetlands, and rolling plains which were cleared in 1999 for open-pit oil sands mining. The site was thereafter used for a saline-sodic overburden waste dump until 2004. In the area of oil sands mining, upland forest is dominated by Gray Luvisolic soil with some Dystric and Eutric Brunisols and the wetland is composed predominantly of Mesisols based on the Canadian system of soil classification (Soil Classification Working Group, 1998). A detailed description of the research site and experimental plots is provided in Brown (2010) and Brown and Naeth (2014).

Average annual temperature from 1981 to 2010 was 1.0 °C and average annual precipitation was 418.6 mm, with 316.3 mm as rain and 133.8 cm as snow (Environment Canada, 2014). The mean average temperature and total precipitation between July and September (sampling period) were 15.9 and 16.0 °C for 2012 and 2013, respectively, and 244.8 and 120.0 mm for 2012 and 2013, respectively (Environment Canada, 2014).

2.2. Experimental design and plot establishment

This experiment was conducted with a 2 (FMM vs PMM) × 2 (near vs away from CWD) factorial design with 6 replications. The study plots were established between November 2007 and February 2008 and were 10 × 30 m in size. Six plots were covered with FMM and six plots with PMM. The FMM was salvaged from a mesic aspen-white spruce mixed forest to a depth of 20 cm and applied at a 20 cm thickness, over 30 cm of B and C horizon mixed subsoil and 100 cm of overburden. The PMM, approximately 60% peat and 40% underlying mineral soil, was salvaged from a wetland on the open-pit mining site before mining and applied at a 30 cm thickness over 100 cm of clean overburden material (Brown and Naeth, 2014). Trembling aspen (*Populus tremuloides*) CWD with a minimum of 10 cm diameter was salvaged and applied on each plot in February 2008. The CWD was placed to provide maximum contact with the soil surface. The CWD pieces did not overlap or contact each other and covered approximately 10–20% of each plot. A mixed fertilizer ($N:P_2O_5:K_2O$) was applied as per standard reclamation practice at a rate of 300 kg ha^{-1} (23.5:25.0:8.0) in June 2008 and at 250 kg ha^{-1} (31.5:16.0:5.0) in August 2009 (Brown and Naeth, 2014).

Within each plot, four 1 × 1 m subplots were established for gas and soil sampling, two within 5 cm from the CWD and the other two more than 1 m away from the CWD. Near and away from CWD subplots represent areas that have been affected by CWD or not, respectively. Plots were covered by native forbs, grasses, shrubs, and mosses (Brown and Naeth, 2014). Overall vegetation and