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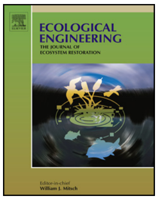

# Coarse woody debris extract decreases nitrogen availability in two reclaimed oil sands soils in Canada

Jin-Hyeob Kwak[a], Scott X. Chang[a,*], M. Anne Naeth[a], Wolfgang Schaaf[b]

[a] Department of Renewable Resources, 442 Earth Sciences Building, University of Alberta, Edmonton, AB, Canada T6G 2E3
[b] Soil Protection and Recultivation, Brandenburg University of Technology, Cottbus-Senftenberg, P. O. Box 101344, 03013 Cottbus, Germany

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## ABSTRACT

Forest floor mineral soil mix (FMM) and peat mineral soil mix (PMM) are common cover soils and sources of organic matter for reclamation of open-pit mining disturbed land in the Athabasca oil sands region. Coarse woody debris (CWD) can be an additional source of organic matter and can provide nutrient and habitat for plant growth. However, the effect of CWD on nitrogen (N) cycling in reclaimed oil sands soils has not been studied. A laboratory incubation experiment was conducted to assess chemical effects of a CWD extract on gross and net N transformation rates in FMM and PMM using the $^{15}$N pool dilution method. The CWD extract was used to simulate CWD leachates (with rainwater as a control) that are produced in the field. The effect of the simulated CWD leachate on the cover soils was studied in a 2 (FMM vs PMM) × 2 (CWD extract vs rainwater addition) factorial design. There was no difference in gross N mineralization rates between FMM and PMM, although net N mineralization rates were greater in FMM than in PMM ($p < 0.001$) due to greater $NH_4^+$ immobilization rates in PMM. Gross and net nitrification rates were greater in FMM than in PMM ($p < 0.001$). The ratio of gross nitrification to gross $NH_4^+$ immobilization rates (N/IA) was greater in FMM than in PMM ($p < 0.001$), as the greater $NH_4^+$ immobilization rates in PMM decreased gross nitrification rates by decreasing $NH_4^+$ availability. Addition of the CWD extract decreased gross ($p < 0.01$) and net ($p < 0.001$) N mineralization rates, increased ($p < 0.001$) $NH_4^+$ immobilization and decreased ($p < 0.001$) gross nitrification rates in both cover soils. The N/IA ratios were decreased by the CWD extract addition, indicating that heterotrophic $NH_4^+$ immobilization was superior to autotrophic nitrification due to the high C/N ratio of the CWD extract. We conclude that FMM will have greater N availability for oil sands reclamation than PMM. Leachates from CWD would decrease N availability by decreasing gross N mineralization and nitrification rates and by increasing N immobilization rates.

## 1. Introduction

Open-pit mining in the Athabasca oil sands region (AOSR) has disturbed 767 km$^2$ of boreal mixedwood forests by 2013 in Alberta, Canada and 4800 km$^2$ of land could be open-pit mined (Government of and Alberta, 2013). Such disturbed land must be returned to ecosystems with land capability equivalent to pre-disturbance levels (Province of and Alberta, 2014). Applying forest floor mineral soil mix (FMM) or peat mineral soil mix (PMM) as cover soils is the most common practice for land reclamation after oil sands mining (DePuit, 1984; Sydnor and Redente, 2002) and is beneficial for increasing organic matter (OM) content, improving soil fertility and water holding capacity (WHC) and providing a source of propagules and soil microorganisms (DePuit, 1984; Sydnor and Redente, 2002; Mackenzie and Naeth, 2010). The PMM has high OM content and WHC and is readily available in northern Alberta (Fung and Macyk, 2000). The FMM has a large propagule bank and applying it in land reclamation increases native plant abundance and diversity (Mackenzie and Naeth, 2010). The FMM is considered more readily decomposable than PMM because of its lower carbon to nitrogen (C/N) ratios (Mackenzie and Naeth, 2010), greater microbial biomass (McMillan et al., 2007; Brown, 2010; Hahn and Quideau, 2013) and greater enzyme activities (Brown, 2010; Jamro et al., 2014).

Coarse woody debris (CWD), which is dead woody material, including standing dead trees, downed boles, large branches and dead coarse roots (Harmon et al., 1986), plays an important role in forest ecosystems by providing habitat for planted tree seedlings, microorganisms and small animals, reducing soil erosion and nutrient leaching and increasing nutrient and OM content (Harmon et al., 1986; Stevens, 1997). As CWD has important ecological values,

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* Corresponding author.

*E-mail addresses:* jinhyeob@ualberta.ca (J.-H. Kwak), scott.chang@ualberta.ca (S.X. Chang).

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applying it for land reclamation after oil sands mining can help rebuild disturbed ecosystems. However, applying CWD in reclamation of disturbed oil sands land is a relatively new practice with few data on its benefit. The application of CWD for reclamation can reduce soil erosion (Whisenant, 2005) and increase vegetation cover and woody plant density in oil sands mining reclamation by increasing microsites (Brown and Naeth, 2014). No study has been conducted on effects of CWD on soil properties in reclaimed oil sands soils and most studies have been conducted in natural forests with CWD produced by natural disturbances. Nutrient cycling and enzyme activities under CWD were tested in forests in North America (Spears et al., 2003; Laiho and Prescott, 2004; Hafner and Groffman, 2005), Australia (Lindsay and Cunningham, 2011; Goldin and Hutchinson, 2013) and Argentina (Gonzalez-Polo et al., 2013) but all these studies were in natural ecosystems.

Available nitrogen (N) in soils is the most likely limiting factor for tree growth in the boreal forest ecosystem and N turnover rate is closely related to plant growth and forest productivity (Gundersen et al., 2009; Yan et al., 2012; Duan et al., 2015). Coarse woody debris will affect N cycling mainly in two ways: (1) it will change the physical environment, such as soil temperature and water content, resulting in changes in microbial and enzyme activities and N cycling and (2) CWD leachate will change soil chemical properties such as C/N ratio, dissolved organ C (DOC) and N (DON) concentrations; such changes will affect microbial processes and N cycling. Due to these different pathways, effects of CWD on N transformation rates or availability can be quite variable. For example, total N and nitrate ($NO_3^-$) concentrations increased under CWD in woodlands in Australia by greater mineralization associated with increased moisture availability under CWD (Lindsay and Cunningham, 2011; Goldin and Hutchinson, 2013). However, CWD application decreased N concentrations in forests in North America (Busse, 1994; Hafner and Groffman, 2005), N mineralization and nitrification rates in a mixed forest in New York State (Hafner and Groffman, 2005) and gross N mineralization rates in an old-growth mixed coniferous forest in Oregon, USA (Spears et al., 2003) mainly due to increased CWD leachate with a high C/N ratio and intercept of litterfall by CWD.

Measuring gross N transformation rates using the $^{15}N$ isotopic pool dilution method can provide more detailed information on N cycling processes (Hart et al., 1994; Murphy et al., 2003; Booth et al., 2005). However, most studies measured net N transformation rates, which may underestimate gross N transformation rates and confound several simultaneous processes (Davidson et al., 1991; Murphy et al., 2003). The $^{15}N$ isotopic pool dilution method permits independent estimation of each N transformation process including microbial assimilation of ammonium ($NH_4^+$) or $NO_3^-$ (Davidson et al., 1991, 1992; Stark and Hart, 1997). Furthermore, a laboratory incubation experiment allows us to test only the effect of the CWD extract without confounding effects of changing soil temperature and water content in the field. Our study focused on direct effects of CWD leachate on gross N transformation rates in reclaimed soils and will help to interpret N cycling under CWD in the field.

A laboratory incubation experiment using $^{15}N$ isotopic dilution was conducted to evaluate the effect of CWD leachate on gross and net N transformation rates in reclaimed oil sands soils such as FMM and PMM types of cover soils and to determine whether using CWD for land reclamation is beneficial for improving N availability. This study was specifically designed to improve our understanding of the effects of CWD leachate chemistry on soil processes. We hypothesized that (1) gross N mineralization and nitrification rates in FMM would be greater than that in PMM due to its higher microbial and enzyme activities and lower C/N ratio in FMM and (2) the CWD extract addition will increase N immobilization rates due to its high C/N ratio and would decrease nitrification rates and net N mineralization rates.

## 2. Materials and methods

### 2.1. Site description and soil sampling

The research site is located at an oil sands company lease located at 56° 58′ N, 111° 22′ W, about 24 km north of Fort McMurray, Alberta, Canada. Average annual temperature and precipitation from 1981 to 2010 were 1.0 °C and 418.6 mm, respectively (Environment and Canada, 2014). A total of 36 randomly located $10 \times 30\,m^2$ plots were established between November 2007 and February 2008. Half of the plots were covered with FMM and the other half with PMM. The FMM was salvaged from a mesic aspen-white spruce mixed forest and applied at a depth of 20 cm, over 30 cm of B and C horizon mixed subsoil. The PMM was applied at a depth of 30 cm over 100 cm clean overburden. A detailed description of the research site and experimental plots is provided in Brown (2010) and Brown and Naeth (2014).

Soil samples from 0 to 10 cm depth were collected from six FMM and six PMM plots with an auger in summer 2012. In the laboratory, soil samples were air dried and passed through a 2 mm sieve to remove plant roots and CWD, then combined to form a composite sample. Parts of samples were used for chemical analyses.

To simulate CWD leachate in the field, ground CWD was extracted with rainwater collected in the field. Aspen woody debris, of decay class 1 or 2 according to the classification system described in Master et al. (1988) and British Columbia Ministry of Environment and British Columbia Ministry of Forest (2010), was collected in a mixedwood forest near the study site and oven dried at 60 °C. Newly formed CWD was used for the experiment to simulate CWD initially applied for reclamation at the study site. Whole woody debris including bark, sapwood and heartwood was ground and passed through a 0.84 mm sieve. Rainwater was collected on site in summer 2012 using 1 L bottles and funnels with a screen (Jung et al., 2011) and then frozen until used for the experiment. Ground woody debris was extracted with the rainwater at a ratio of 1:10 (w:v) and shaken at 250 rpm on a mechanical shaker for 1 hr, then filtered through Whatman No. 42 filter papers.

### 2.2. Laboratory procedures

For the laboratory incubation experiment, 250 mL Nalgene HDPE bottles [2 (FMM vs PMM) × 2 (CWD extract vs rainwater) × 2 ($^{15}NH_4NO_3$ vs $NH_4{}^{15}NO_3$) × 3 replications × 5 samplings = 120 bottles] were prepared. A portion of an air dried soil (30 g, oven dry weight basis) was placed in a bottle and incubated for 7 days under 40% WHC. After 7 days, 2 mL $^{15}NH_4NO_3$ solution (10 atom.%) or $NH_4{}^{15}NO_3$ solution (10 atom.%) was added to the soil in each bottle, with an equivalent application rate of 20 mg N $kg^{-1}$ soil. Half of the $^{15}NH_4NO_3$ and $NH_4{}^{15}NO_3$ bottles received 2 mL of CWD extract and the other half received 2 mL of rainwater; the added CWD extract and rainwater are referred to as added solutions. Final water content was adjusted to 60% WHC with rainwater and the total weight was recorded on each bottle. Bottles were incubated at 25 °C for 4 days and sampled every day to determine N transformation rates in each day. For gross N transformation rate measurements, $(^{15}NH_4)_2SO_4$ and $K^{15}NO_3$ have been commonly used rather than $^{15}NH_4NO_3$ and $NH_4{}^{15}NO_3$ (Davidson et al., 1991; Hart et al., 1994). However, applying different forms of N can cause changes in the partitioning among N transformation processes (Mary et al., 1998; Murphy et al., 2003). Applying $^{15}NH_4NO_3$ and $NH_4{}^{15}NO_3$ enables all gross N fluxes to be consistently measured among all treatments thus permitting more robust comparisons between treatments (Murphy et al., 2003).

Bottles were covered with aluminum foil with tiny holes to allow aeration but to minimize water loss through evaporation. Rainwater was added every day to maintain water content and tiny