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Gross nitrogen transformation rates differ in reconstructed oil-sand soils from natural boreal-forest soils as revealed using a ^{15}N tracing method

Jacynthe Masse [a,*], Cindy E. Prescott [a], Christoph Müller [b], Susan J. Grayston [a]

[a] Department of Forest and Conservation Sciences, Faculty of Forestry, University of British Columbia, 2424 Main Mall, Vancouver, BC V6T 1Z4, Canada
[b] Department of Applied Microbiology, University of Giessen, Heinrich-Buff-Ring 26-32, 35392, Giessen, Germany

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ABSTRACT

The Athabasca Oil Sands deposit is one of the largest single oil deposits in the world. Following surface mining, companies are required to restore soil-like profiles that can support the previous land capabilities. Re-establishment of nutrient cycles in reconstructed soils is one of the most critical factors in ensuring long-term sustainability of these reconstructed boreal landscapes. We compared soils from nine reconstructed oil-sand sites with those from three natural boreal-forest sites of similar age since wildfire disturbance. We (1) measured soil total N, NH_4^+, and NO_3^- content; (2) quantified gross N transformation rates in reconstructed and natural soils using a ^{15}N tracing method; (3) compared gross rates of N transformations in reconstructed soils under different vegetation types to compared N-cycling processes in these soils. The ^{15}N tracing approach highlighted key distinctions in N-cycling processes in reconstructed and natural soils. In reconstructed soils, NH_4^+ was mainly cycled through the recalcitrant organic-N pool, whereas in natural soils, NH_4^+ was produced from the recalcitrant organic-N pool but predominantly consumed in the labile organic-N pool. The mineralization of NH_4^+ from the labile organic-N pool was also higher in natural soils compared to reconstructed soils, suggesting greater prominence of microbial N-cycling activity in the natural soils compared to the reconstructed soils. Gross nitrification rates were similar in natural and reconstructed soils, but net nitrification rates were higher and apparently of heterotrophic origin in reconstructed soils. The higher net nitrification rates in reconstructed soils indicate a surplus of N relative to microbial requirements in reconstructed soils. N-transformation rates were similar in reconstructed soils under the three types of vegetation.

1. Introduction

The Athabasca Oil Sands deposit, located in the boreal forests of northern Alberta, is part of the largest single oil deposit in the world, with proven reserves of 166 billion barrels of bitumen, and covering 142,200 km^2 (Government of Alberta, 2016). Most (80%) of the bituminous sands can be extracted using in situ recovery methods, but 20% of the resource is shallow and can be recovered through open-pit mining (Government of Alberta, 2012). To date, about 895 km^2 of land has been disturbed by oil-sand mining activity (Government of Alberta, 2016). According to the Conservation and Reclamation Regulation of Alberta, following surface mining companies are required to restore soils that can achieve equivalent land capability which is described as “the ability of the land to support various land uses after conservation and reclamation [that] is similar to the ability that existed prior to activity being conducted on the land, but that the individual land uses will not necessarily be identical” (Government of Alberta, 1993; Powter et al., 2012). After soil reconstruction, the area is revegetated. When reclamation in the area began in the 1980s, revegetation predominantly focused on erosion control, and used both native and introduced grasses and shrubs. However, more recent revegetation practices use native tree species (conifers, i.e., jack pine, white and black spruce; deciduous, i.e., aspen) and understory shrubs (e.g., blueberry and willow) to re-establish a boreal-forest plant community. Differences in soil organic matter composition, soil available N, and microbial communities between reconstructed oil-sand soils and natural boreal-forest soils of northern Alberta have been previously identified (Dimitriu et al., 2010; Hahn and Quideau, 2013; Hemsley, 2012; Turcotte et al., 2009). As such, it is unlikely that these reconstructed forest soils will exactly mirror pre-existing boreal-forest soils (Chazdon, 2008; Hobbs et al., 2006). Thus, novel soil ecosystems will most probably rise from the reconstruction efforts. Aiming at re-establishing soil functions, and chiefly nutrient cycling, rather than simply trying to replicate structural qualities of previous soil ecosystem is key to ensure the long-term sustainability of reclaimed boreal forest landscapes (Quideau et al., 2013).

Nitrogen (N) is an essential nutrient for plant growth and metabolic activities, being a key element in amino acids, enzymes, proteins, and nucleic acids (Binkley and Fisher, 2013; Lupi et al., 2013). In forest ecosystems, N availability influences photosynthetic rates, tree growth,

* Corresponding author.
E-mail address: jacynthe.masse@alumni.ubc.ca (J. Masse).

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root size, root structure, and root distribution. In soil, N is present in many forms and transformations of N from one form to another are mediated by soil microorganisms (Robertson and Groffman, 2007). Inorganic forms of N – ammonium (NH_4^+) and nitrate (NO_3^-) – rarely comprise >1% of the total N pool and were previously assumed to be the only plant-available forms of N. However, it is now recognized that plants can take up simple organic-N compounds, such as amino acids and peptides (Näsholm et al., 2009; Paungfoo-Lonhienne et al., 2010; Inselsbacher and Näsholm, 2012).

Canadian boreal forest ecosystems are generally N-poor environments, and N availability is the primary limitation to plant productivity (Vitousek and Howarth, 1990; Matson et al., 2002). In Alberta, gross rates of ammonification (mineralization of NH_4^+) in mature upland forest soils ranged from 3.75 to 164 mg NH_4^- kg soil^{-1} day^{-1} and gross rates of NH_4^+ immobilization were similar, resulting in low net ammonification rates (Carmosini et al., 2002; Cheng et al., 2013). Gross rates of ammonification and NH_4^+ immobilization were lower (14 to 19 mg NH_4 kg soil^{-1} day^{-1}) in boreal forest soils in Ontario, but net ammonification was still close to zero (Westbrook and Devito, 2004). Gross rates of nitrification in the Canadian boreal forest are highly variable, but generally close to 0 mg NO_3^- kg soil^{-1} day^{-1} (Carmosini et al., 2002; Cheng et al., 2013; Westbrook and Devito, 2004). Stark and Hart (1997) measured high gross nitrification rates (25 mg N m^{-2} day^{-1} in a ponderosa pine site in New Mexico during summer to >300 mg N m^{-2} day^{-1} in a Douglas-fir site during spring) in eleven undisturbed forest ecosystems of New Mexico and Oregon. However, gross rates of NO_3^- consumption were similar to gross nitrification rates, resulting in nil net nitrification. Through their effects on litter chemistry, tree species can also influence N-transformation rates in boreal forest soils. Studies comparing N-cycling in boreal forest soils under deciduous stands (composed mainly of trembling aspen (*Populus tremuloides*), balsam poplar (*Populus baslamifera*), and paper birch (*Betula papyrifera*)) and coniferous stands (composed mainly of black spruce (*Picea mariana*), white spruce (*Picea glauca*), white cedar (*Thuja occidentalis*), and jack pine (*P. banksiana*)) found higher pH, higher base-cation contents, and lower C:N ratio in forest floors of deciduous stands compared to forest floors of coniferous stands (Jerabkova et al., 2006; Paré and Bergeron, 1996; Ste-Marie and Paré, 1999). Higher N availability, NH_4^+ pools, net rates of mineralization and nitrification, and nitrate accumulation were also measured in forest floors under deciduous stands compared to coniferous stands. The higher N content of deciduous litter positively affects net N mineralization rates, while the high C:N ratio and the low pH typical of coniferous litter seem to reduce net mineralization and nitrification rates (Jerabkova et al., 2006; Paré and Bergeron, 1996; Ste-Marie and Paré, 1999).

Wildfire is the primary natural disturbance in the boreal forest and both nitrogen mineralization and nitrification rates increase following fire (Ball et al., 2010; Binkley and Fisher, 2013; Raison et al., 2009; Yeager et al., 2005). Depending on the intensity of the fire, these effects may vanish after few seasons (Raison et al., 2009; Binkley and Fisher, 2013) but can last >14 years (Ball et al., 2010). Historically low, through-fall N deposition in the boreal forest of the AOSR is elevated and decreases to background levels with distance to from mine sites (Fenn et al., 2015; Proemse et al., 2013). Ammonium deposition, measured in the close vicinity of the mining sites (<3 km), varied between of 14.7 and 19.6 kg NH_4^+ ha^{-1} year^{-1}, whereas nitrate depositions were lower, ranging between 2.1 and 6.7 kg NO_3^- ha^{-1} year^{-1} (Fenn et al., 2015; Hemsley, 2012). These depositions were reduced to 0.81 kg NH_4^+ ha^{-1} year^{-1} and 0.27 kg NO_3^- ha^{-1} year^{-1} 120 km away from the mining sites (Fenn et al., 2015).

The aim of this study was to evaluate if the reconstructed soils of the AOSR are able to re-establish key soil functions, such as nutrient cycling. The specific approach taken was to assess whether soil N-transformation rates in oil-sand soils that were reconstructed 20–30 years previously are similar to those of natural boreal forest soils that were subject to wildfire disturbance at approximately the same time. In a previous study of N-cycling in reconstructed oil-sand soils, McMillan et al. (2007) detected no differences in gross ammonification rates between a 5-year-old reconstructed soil and a natural aspen-forest soil, despite the reconstructed soil having higher microbial biomass and higher N content. However, MacKenzie and Quideau (2012) found higher gross nitrogen mineralization rates in reclaimed material used for soil reconstruction than in boreal-forest soils, suggesting that the rates of both ammonification and nitrification are higher in reconstructed soils. In contrast to McMillan et al. (2007), we examined soils at least 20 years after reconstruction, at which point previous studies in the oils sands region (Rowland et al., 2009) and elsewhere (Frouz et al., 2001, 2008; Šourková et al., 2005) indicate that reconstructed soils have stabilized to some extent with respect to vegetation cover and composition, forest floor development, nutrient cycling processes, soil carbon, and soil faunal communities. We evaluated gross rates of N transformation, as this allowed us to separately examine microbial N production and consumption rates in order to better understand N-cycling processes in the reconstructed soils. We also assessed the influence of the vegetation treatments (conifers, deciduous trees, and grasses) used in reclamation on N-cycling rates.

2. Materials and methods

2.1. Study area

The study area was situated in the Athabasca Oil Sands Region (AOSR) in northern Alberta, Canada (56°39′N, 111°13′W, altitude: 369 m). Short warm summers and long cold winters characterize the climate. The mean annual temperature is 1 °C, ranging from −17.4 °C in January to 17.1 °C in July. Mean annual precipitation is 418.6 mm, of which 316.3 mm occurs as rainfall during the growing season (Environment Canada, 2015). Medium- to fine-textured Gray Luvisols (Haplocryalfs according to the U.S. soil taxonomy) and Dystric Brunisols (Dystrocryepts) underlie landscapes shaped by the impact of Pleistocene ice activity, deglaciation, and post-glacial modifications in upland areas. Organic soils (Cryaquepts) are found under wetland areas (Natural Regions Committee, 2006). This region falls within the central mixedwood region of the Canadian boreal forest. Dominant tree canopy species in upland landscapes are trembling aspen (*Populus temuloides* Michx), white spruce (*P. glauca* (Moench) Voss) and Jack pine (*P. banksiana* Lamb) (Natural Regions Committee, 2006). Fire is the major natural disturbance in these forests (Thomson, 1979).

Oil-sand mining activities involve the removal of surface soil materials followed by the removal of 40 m of overburden material (approximate regional average) to expose the oil-sand ore body. Salvaged soil materials are preferably used for reclamation of an area within the footprint of the mines that is ready for reclamation, or are stockpiled for later use. The overburden is used for berm, dyke wall, or road construction, or deposited in a dedicated disposal area to create large-scale overburden landform units. The oil-sand ore is transported to the extraction and upgrading facility. Oil-sand soil reconstruction involves a number of cover designs, depending on the landform substrate being reclaimed. There are two main cover designs: one that uses only cover soil and the other consisting of a combination of cover soil and subsoil. Cover-soil and subsoil materials are salvaged from surface soils within the mine-development footprint. Only sites at which cover soil had been placed on top of overburden material were used in this study. The cover-soil materials used consisted of surface peat mixed with mineral soils material having a loam or coarser texture and is hereafter referred to as "peat–mineral mix." In the studied soils, the depth of the peat–mineral mix ranged from 12 cm to >100 cm. Early revegetation objectives in the AOSR were to establish native or introduced grass and shrub species to control erosion; however, oil-sand operators are now required to use native trees and species with the intention of promoting the re-establishment of a boreal forest community. During the period when the sites used in this study were reclaimed (20–30 years ago),