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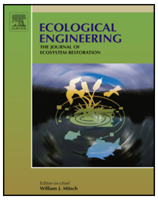

Limiting factors for lodgepole pine (*Pinus contorta*) and white spruce (*Picea glauca*) growth differ in some reconstructed sites in the Athabasca oil sands region

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ABSTRACT

Peat-mineral soil mix (PMM) over tailings sand (TS) or overburden (OB) is a commonly used prescription for oil sands reclamation. The TS and OB (the substrates) often have unfavorable conditions such as high salinity, soil compaction, low nutrient availability in OB, and low nutrient and water availabilities in TS, which may limit tree growth. The objective of this study was to identify limiting factors for growth of lodgepole pine (*Pinus contorta*) on PMM over TS and white spruce (*Picea glauca*) on PMM over OB in the Athabasca oil sands region, Alberta, Canada. In the pine sites, mean annual growth of height (HG), diameter at breast height (DBHG) and aboveground biomass (ABG) were significantly correlated with volumetric water content (VWC) in PMM and foliar $\delta^{13}C$ in current-year needles. Sites with high productivities had the lowest foliar $\delta^{13}C$ relative to sites with low and medium productivities. The VWC and dissolved organic carbon (DOC) together explained 80% of the variation in both the current annual increment of height (HI) ($p = 0.007$) and aboveground biomass (ABI) ($p = 0.008$). In the spruce sites, foliar potassium (K) and foliar and soil nitrogen (N) concentrations were positively correlated with HG, DBHG and ABG, consistent with patterns in K and inorganic N (the sum of NH_4^+-N and NO_3^--N) concentrations in PMM in those sites. Soil electrical conductivity (EC) and bulk density (Db) were greater in low than in medium and high productivity sites. The Db and inorganic N concentration together explained 67% of the variation in HI ($p = 0.037$), while Db and EC together explained 79% of the variation in ABI ($p = 0.009$). In conclusion, lodgepole pine trees planted on PMM over TS sites were limited by low water availability, while low soil N availability and high salinity limited the growth of white spruce trees planted on PMM over OB sites. Reclamation practices need to address water and nutrient limitations to ensure the success of reclaiming disturbed areas in the oil sands region.

1. Introduction

Oil sand deposits in northern Alberta, Canada, contain about 168 billion barrels of bitumen, making it the third largest crude oil reserve in the world (Alberta Energy, 2014). The Athabasca oil sands region (AOSR) is the largest oil sands deposit in the province, in which crude oil can be extracted by open-pit mining (Fung and Macyk, 2000). Large scale open-pit mining in Alberta has disturbed approximately 767 km^2 of land, which represents 0.2% of Alberta's boreal forest (Government of Alberta, 2014a). The legislation requires that the disturbed land should be returned to equivalent capability similar to that existed pre-disturbance (Government of Alberta, 2014b). The success of reclamation to upland forest after open-pit mining in the AOSR largely depends on the construction of landform and the placement of reconstructed soils. Reclaimed soils are reconstructed using peat-mineral soil mix (PMM) or LFH-mineral soil mix as capping soils above substrates such as overburden (OB) or tailings sand (TS) that are byproducts of the surface mining and oil sands extraction processes (Rowland et al., 2009; Naeth et al., 2013). However, reconstructed soils may lack growth conditions required for sustainable development of the reestablished vegetation.

Reconstruction of multi-layered soils can markedly change soil water availability for plant growth (Li et al., 2014). For example, the interface between the reclamation capping soil and the substrate restricts water movement between layers because of the low capillary action of TS or low permeability of OB that can be highly-

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compacted (Naeth et al., 2011; Jung et al., 2014). The dynamics of soil water content can greatly change during the growing season, making periodic soil water content measurement restricted for assessing soil water availability. However, foliar ^{13}C (carbon) isotope abundance (δ^{13}C) has been shown to be a good indicator of long-term soil water availability, as foliar δ^{13}C integrates soil water availability over time and is closely related to plant water use efficiency (Sun et al., 1996). The closure of stomata under water limitation increases the fixation of $^{13}CO_2$ and reduces the discrimination against ^{13}C during photosynthesis, resulting in less negative δ^{13}C in plant tissues (Choi et al., 2005; Matsushima and Chang, 2007). The same tree species under different moisture regimes may have different δ^{13}C patterns (Sun et al., 1996 Zhang et al., 1997). We therefore employed the ^{13}C technique to study if water stress was limiting tree growth in the reconstructed landscape.

Nutrient availability, especially nitrogen (N) availability, can be another major factor that can restrict the reestablishment of plant communities. For example, planted trees growing on reconstructed mine sites were limited by low N availability in the substrates (Farnden et al., 2013). Mining and related activities may lead to severe loss of soil organic C and N because of the loss of topsoil and mechanical mixing of the A with B and C horizon soils (Ussiri and Lal, 2005; Shrestha and Lal, 2011). Although capping soils such as PMM and LFH-mineral soil mix have high organic N concentrations, the slow-release of organic N due to small microbial population sizes and reduced microbial activities may affect N availability (McMillan et al., 2007; Hemstock et al., 2010) and limit plant growth in the boreal forest region (Reeder and Sabey, 1987; Farnden et al., 2013). Low plant available N often limits the reestablishment and maintenance of vegetation on disturbed lands (Reeder and Sabey, 1987). Farnden et al. (2013) reported a positive relationship between tree height and soil organic matter content in a 21-year old jack pine stand in a reclaimed oil sands area, and they attributed the relationship to the contribution of organic matter to increased soil N availability. Although emissions of nitrogen oxides resulting from oil sands development in the last 40 years increased in the area surrounding oil sands mining, it was estimated that total N deposition into the ecosystems only ranged from 2.45 to 3.80 kg N ha^{-1} yr^{-1} in the AOSR (Laxton et al., 2010), which was lower than those in other parts of Canada and the United States (Watmough et al., 2005; Pardo et al., 2006), and many parts of Europe (Dise and Wright, 1995). In addition, N concentration and net N mineralization rates in soils were not affected by increased N emission (Laxton et al., 2010). Therefore, N deposition may not offer substantial relief for the demand for nutrients by the reestablished vegetation in oil sands reclamation.

Reconstructed soils in the AOSR are often affected by high salinity as well (Fung and Macyk, 2000). The salts, mainly composed of sodium, sulfate and chloride ions, normally migrate from the underlying processed TS or marine shale OB (Barbour et al., 2007). An upward movement of salts from the OB into the cover soil could raise the electrical conductivity (EC) level up to 6.0 dS m^{-1} in the lower part of the cover soil (Kessler et al., 2010). Boreal tree species have considerable variability in salt tolerance between and within species (Allen et al., 1994; Khasa et al., 2002). High salinity can affect water availability and nutrient uptake, and thus may have detrimental effects on plant survival and growth and site productivity (McFee et al., 1981; Allen et al., 1994; Andrews et al., 1998; Rodrigue and Burger, 2004).

Reconstructed soils often possess other properties such as increased soil pH (Howat, 2000), heavy soil compaction, and high concentrations of residual bitumen (Fung and Macyk, 2000); those properties also can negatively affect the growth of trees. Poor tree growth can be identified by foliar discoloration, stunted growth, or other symptoms. The objective of this study was to identify the limiting factors for growth of two tree species planted for oil sands reclamation, lodgepole pine (*Pinus contorta*, Pl) planted in PMM over TS and white spruce (*Picea glauca*, Sw) planted in PMM over OB on reconstructed sites in the AOSR, Alberta. We hypothesized that the growth of Pl would be likely limited by water availability due to the coarse-textured TS substrate, while nutrient availability and salinity would be major limiting factors for the growth of Sw because of the saline OB substrate with low nutrient availability.

2. Materials and methods

2.1. Site description

The study area, located within the Suncor Energy Inc. Lease 86/17 (56°59′N and 111°32′W), is 22 km north of Fort McMurray in northeastern Alberta, Canada. The site is characterized by a continental boreal climate with short and cool summers and long and cold winters. The mean annual temperature is 0.7 °C, with mean daily temperatures ranging from −18.8 °C in January to 16.8 °C in July; the mean annual precipitation is 455.7 mm, with an average of 342.2 mm as rainfall during the growing season (Environment Canada, 2013). In the study area, 12 sites were set up in June 2011 (six Pl sites, site no. 1–6; six Sw sites, site no. 10–15) and 6 sites were set up in April 2012 (three Pl sites, site no. 7–9; three Sw sites, site no. 16–18), for a total of 18 sites, with 9 Pl sites on PMM over TS and 9 Sw sites on PMM over OB (Fig. 1). On each site, a 10 × 10 m plot was set up. The thickness of PMM and tree age varied from site to site (Table 1). The 9 sites for each tree species

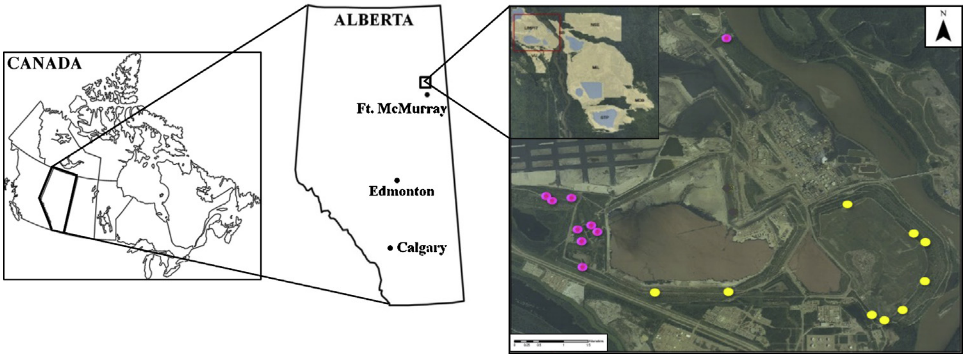

Fig. 1. Distribution of the studied lodgepole pine (*Pinus contorta*, Pl) and white spruce (*Picea glauca*, Sw) sites in Suncor Energy Inc. Lease 86/17 in the Athabasca oil sands region, Alberta, Canada. The yellow dots indicate Pl sites, and the purple dots indicate Sw sites. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)