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Responses of lodgepole pine (*Pinus contorta*) and white spruce (*Picea glauca*) to fertilization in some reconstructed boreal forest soils in the oil sands region

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ABSTRACT

Low nitrogen (N) availability may affect lodgepole pine (*Pinus contorta*, Pl) and white spruce (*Picea glauca*, Sw) growth in some reconstructed boreal forest soils in the Athabasca oil sands region in Alberta, Canada. The objective of this study was to investigate the effect of fertilization (N alone or complete fertilizer) on foliar nutrient concentrations in and growth of Pl (planted in soils with tailings sand as a substrate) and Sw (planted in soils with overburden material as a substrate) in a single-tree fertilization study. Two growing seasons after fertilization, both N alone and complete fertilizer treatments increased the height, diameter at breast height and aboveground biomass growth of Sw ($p = 0.005$, 0.009 and 0.015, respectively). In contrast, fertilization did not affect Pl growth. Foliar N concentration and content in current-year needles of Sw were higher following fertilization than in the control treatment in 2012 ($p < 0.001$ for both), but not in 2013. Foliar $\delta^{15}N$ in current-year and 1-year-old needles was greater in the fertilization than in the control treatment for Sw ($p < 0.001$ for both), in association with the increase of $\delta^{15}N$ in soil NO_3^--N. No fertilization effect on foliar micronutrients (Fe, Mn, Cu, Zn, B and Mo) or soil NH_4^+-N, NO_3^--N or dissolved organic N was found in either Pl or Sw sites. We conclude that N was a limiting factor for tree growth in Sw but not in Pl sites and that N fertilization may be used to improve Sw growth in some reclaimed sites with overburden as a substrate in the oil sands region.

1. Introduction

Reconstructed soils placed for reclamation following surface mining in the oil sands region may exhibit unfavorable properties such as increased soil pH (Howat, 2000), salinity (Barbour et al., 2007), soil compaction, residual bitumen, and low availability of nutrients, nitrogen (N) in particular (Fung and Macyk, 2000), some of those are inherent properties of boreal forest soils. Those factors can negatively affect the early growth of trees planted during the land reclamation process. Understanding what factor or factors affect the reestablishment of plant communities and designing strategies to deal with factors limiting plant growth will help to ensure the success of reclamation to upland forests in the oil sands region (Macdonald et al., 2012).

Among those potential limiting factors, N availability may be the most limiting one for tree growth. Although organic amendments, including peat-mineral soil mix (PMM) or forest floor-mineral soil mix (FMM), are incorporated into the reconstructed capping layer above overburden (OB) or tailings sand (TS) (by-products of oil sands mining) substrates to improve nutrient availability, the slow decomposition rate of organic matter due to small microbial population sizes and reduced microbial activities in reclaimed soils (McMillan et al., 2007; Hemstock et al., 2010) may restrain the supply of N to plants. To overcome low N availability, planted seedlings are usually fertilized in the initial 5 years after planting (Fung and Macyk, 2000). As the planted stands develop, the demand for nutrients may increase; therefore, the need for fertilization in older stands should be assessed.

Fertilization is an important management practice to supply nutrients for plants and enhance tree growth and stand productivity (Yang, 1985a, 1985b, 1998), but effects of fertilization on tree growth vary and depend on nutrient demands of different tree species, nutrient reserves in soils, fertilizer types and fertilizer application rates and methods (Thomas and Mead, 1992a; Preston and Mead, 1994; Munson et al., 1995; Kishchuk et al., 2002; Khasa et al., 2005; Santiago et al., 2012; Sloan and Jacobs, 2013). Therefore, the effect of fertilization on tree growth may be

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positive, negative, or non-significant (Sutton, 1992; Yang, 1998; Kishchuk et al., 2002; Bennett et al., 2003; Brockley, 2007). Sutton (1992) reported that N fertilization at 56, 112, or 168 kg N ha^{-1} did not increase white spruce (*Picea glauca*, Sw) growth in slow-growing boreal plantations. Nitrogen fertilization at the rate of 360 kg N ha^{-1} significantly increased tree height, diameter at breast height (DBH, 1.3 m above the ground) and total volume by 19, 34 and 28%, respectively, compared to the no fertilization treatment in lodgepole pine (*Pinus contorta*, Pl) stands (Yang, 1998). However, N fertilizer applications at 540 kg N ha^{-1} resulted in a decrease of height growth in a 40-year-old stand (Yang, 1998). Improved growth in response to fertilization may be attributed to increased growth of shoot length, leaf area index (Albaugh et al., 2004; Amponsah et al., 2005), photosynthesis rate (Chandler and Dale, 1995; Murthy et al., 1996), and shifts in carbon (C) allocation between roots and shoots (Haynes and Gower, 1995).

Nitrogen fertilization not only affects tree growth but also influences soil N dynamics. Long-term fertilization could affect the size of the microbial community that mediates ammonium oxidation, nitrate reduction and denitrification in soils, thus affecting N cycling (Hallin et al., 2009). Nemergut et al. (2008) reported that the activities of leucine amino peptidase and urease, two important enzymes directly involved in N transformations in soils, significantly decreased and increased, respectively, in response to N fertilization, and demonstrated that high levels of N fertilization could markedly change soil N availability and the chemical composition of soil organic matter pools. Such changes would be reflected in foliar chemistry, such as foliar nutrient concentrations and foliar ^{15}N isotope abundance. The ^{15}N natural isotope abundance ($\delta^{15}N$) of foliage integrates isotopic composition of external N and $^{15}N/^{14}N$ fractionation during N uptake, assimilation and retranslocation within plants (Högberg, 1997), and therefore can provide insights into effects of management practices such as forest floor removal, irrigation and fertilization, on plant and soil N dynamics (Choi et al., 2003, 2005a, 2005b). For example, application of compost (organic fertilizer) significantly increased $\delta^{15}N$ in plants and soil NO_3^--N as compared to inorganic fertilizer because the applied compost was ^{15}N-enriched (Choi et al., 2003).

Many studies have been conducted to test the effect of fertilization on seedling establishment and growth in oil sands reclamation (Khasa et al., 2005; Pinno et al., 2012; Sloan and Jacobs, 2013). However, no results have been reported on growth response of established trees to fertilization in reconstructed soils in the oil sands region. Fertilization effects in reclaimed sites may be different from those in natural forest sites because of dramatic disturbance and changes in soil physical, chemical, and biological properties during soil reconstruction.

A 2-year field study conducted on representative reclaimed sites in the Athabasca oil sands region (AOSR) has identified that N availability was limiting Sw growth on some reconstructed sites using PMM as a cover soil over OB substrate, while the growth of Pl on some sites reconstructed using PMM over TS substrate was mainly affected by water availability (Duan et al., 2015). The above results from a retrospective study should be experimentally tested to confirm what factors limit tree growth on the reclaimed sites. The objective of this study was to test the growth responses of Pl and Sw to fertilization in reconstructed boreal forest soils in the AOSR in Alberta, Canada. Testing tree species differences was not the objective of this study and both species belong to the family Pinaceae; they should have very similar properties in nutrient demand and utilization (Ballard and Carter, 1986; Lotan and Critchfield, 1990; Nienstaedt and Zasada, 1990). Therefore, the different responses to fertilization may reflect different prescriptions used in soil reconstruction. We hypothesized that (1) fertilization would increase nutrient uptake, improving tree growth, and (2) growth responses of Pl and Sw would differ mainly due to different substrates used in soil reconstruction.

2. Materials and methods

2.1. Site description

A detailed description of the study area can be found in Duan et al. (2015). Briefly, the research sites were located within reclaimed areas on an oil sands lease 22 km north of Fort McMurray in northeastern Alberta, Canada. The mean annual temperature from 1971 to 2000 was 0.7 °C, and the mean annual precipitation was 455.7 mm, with an average of 342.2 mm occurring as rainfall during the growing season (Environment Canada, 2013). The research sites ranged in age from 20 to 25 years, and were reclaimed by placing approximate 20 cm of PMM on underlying TS or OB substrates following oil sands mining. Lodgepole pine seedlings were planted on soils with TS as a substrate and Sw seedlings on soils with OB material as a substrate 2 years after soil reconstruction. Trees in the Pl and Sw sites in this study ranged from 18 to 23 years old. Understory plant communities on Pl sites were dominated by prickly rose (*Rosa acicularis*), raspberry (*Rubus idaeus*), sweet clover (*Melilotus* sp.), dandelion (*Taraxacum officinale*), and slender wheat grass (*Agropyron trachycaulum*), while willow (*Salix* sp.), green alder (*Alnus crispa*), sweet clover, dandelion, and bluejoint grass (*Calamagrostis canadensis*) were the dominant understory species on Sw sites.

2.2. Experimental design

The experiment used a randomized complete block design for each of the two studied species. Three Pl sites and three Sw sites with poor tree growth were selected (Table 1) and fifteen trees with similar height and DBH growth (based on observations and measurements of the trees) were randomly chosen in each site and tagged to receive the treatments. The selected trees were at least 10 meters apart to minimize interference between the treatments. Nitrogen (Nitrogen, 200 kg N ha^{-1}, applied as urea) or complete fertilizer (Complete, 15–30–15 ($N:P_2O_5:K_2O$) plus micronutrients, at a rate of 200 kg N, 20 kg P and 19 kg K per hectare, with urea used to provide the additional N) was applied to five randomly selected trees in each site in June 2012. No fertilizer was applied to the remaining five trees (Control). The fertilizers were broadcast applied over an area within a radius of two meters around the tree. The $\delta^{15}N$ of the N and complete fertilizers was $1.0 \pm 0.7‰$ ($n = 5$) and $1.5 \pm 0.9‰$ ($n = 5$), respectively. The three sites selected for this study within each species represented three replications.

2.3. Tree growth measurements

Tree growth was measured before the fertilizer application and two growing seasons after the fertilizer application. Tree height and DBH were measured using a height pole and a diameter tape, respectively. Aboveground biomass of trees was calculated with DBH and height-based allometric equations (Lambert et al., 2005; Ung et al., 2008). Annual increments of height, DBH and aboveground biomass were calculated based on the differences of height, DBH and aboveground biomass of trees between June 2012 and October 2013.

2.4. Soil and plant samplings

Soil samples in the capping layer were collected before fertilization in June 2012 from the top 20 cm using an auger in five randomly selected locations in each site (three sites per species) to obtain basic soil properties. Soil samples were collected again