Effectiveness of soil N availability indices in predicting site productivity in the oil sands region of Alberta

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Abstract

Background and Aims: quantitative relationships between soil N availability indices and tree growth are lacking in the oil sands region of Alberta and this can hinder the development of guidelines for the reclamation of the disturbed landscape after oil sands extraction. The aim of this paper was to establish quantitative relationships between soil N availability indices and tree growth in the oil sands region of Alberta.

Methods: *In situ* N mineralization rates, *in situ* N availability measured in the field using Plant Root Simulators (PRS^{TM} probes), laboratory aerobic and anaerobic soil N mineralization rates, and soil C/N and N content were determined for both the forest floor and the 0-20 cm mineral soil in eight jack pine (*Pinus banksiana* Lamb.) stands in the oil sands region in northern Alberta. Tree growth rates were determined based on changes in tree ring width in the last six years and as mean annual aboveground biomass increment.

Results: soil N availability indices across those forest stands varied and for each stand it was several times higher in the forest floor than in the mineral soil. The *in situ* and laboratory aerobic and anaerobic soil N mineralization rates, soil mineralized N, *in situ* N availability measured using PRS probes, soil C/N ratio and N content in both the forest floor and mineral soil, as well as stand age were linearly correlated with tree ring width of jack pine trees across the selected forest stands, consistent with patterns seen in other published studies and suggesting that N availability could be a limiting factor in the range of jack pine stands studied.

Conclusions: *In situ* and laboratory aerobic and anaerobic N mineralization rates and soil C/N ratio and N content can be used for predicting tree growth in jack pine forests in the oil sand region. Laboratory based measurements such as aerobic and anaerobic N mineralization rates and soil C/N ratio and N content would be preferable as they are more cost effective and equally effective for predicting jack pine growth.

Keywords: Aerobic and anaerobic incubation, Site productivity, Plant Root Simulator (PRS) probes, Soil N availability, Soil N mineralization, Tree ring width

Introduction

Nitrogen (N) is generally thought to be the most growth-limiting nutrient in forest ecosystems, particularly in boreal forests (Nordin et al. 2001; Gundersen et al. 2009). Net primary production is known to be broadly related to N availability in forests (Powers 1980; Reich et al. 1997). Linking soil N availability with tree growth is fundamental for understanding whether soil N availability can be used as an index to predict site productivity (Nordin et al. 2001; Yamashita et al. 2004; Gundersen et al. 2009). Some literature documented significant relationships between soil N availability and forest productivity (Pastor et al. 1984; Lennon et al. 1985; Nadelhoffer et al. 1985; Zak et al. 1989; Gower and Son 1992; Reich et al. 1997; Finzi and Canham 2000; Yamashita et al. 2004; Wilson et al. 2005), while others found no relationships (Gower et al. 1993; Grigal and Homann 1994; Joshi et al. 2003; White et al. 2004). The relationship between forest productivity and soil N availability maybe stand type specific and may be affected by the soil N availability index used, as well as whether N is limiting for the forests being evaluated. When N is a growth-limiting factor, forest productivity would be significantly related with soil N availability (Reich et al. 1997), otherwise other factors such as soil water availability maybe more limiting.

Northern Canada is home to a vast expanse of the boreal forest, which stretches across Canada and occupies 5.8 million square kilometres (Anielski and Wilson 2009). In northern Alberta, a vast area of the boreal forest contains mineable oil sands deposits. Part of the mineable area has been cleared for surface mining. The Government of Alberta's Environmental Protection and Enhancement Act requires that all land disturbed by industry activities must be reclaimed and returned to an equivalent or better land capability than pre-disturbance for appropriate end land use; those disturbed land will be largely reclaimed to re-establish self-sustaining forest ecosystems. Jack pine (*Pinus banksiana* Lamb.), a native species to the Canadian boreal region, is an early successional species occupying sandy and nutrient-poor sites. It is a target species in the reclamation practice and closure plans for the oil sands industry in northern Alberta.

To better establish jack pine stands on abandoned oil sands mining sites, we need to understand the relationship between pine tree growth and soil N availability. Although oil sands extraction in northern Alberta has been on-going for the last forty years, the majority of the disturbed sites are only now starting to be reclaimed. However, the relationship between soil N availability and jack pine growth is poorly understood and quantitative relationships between soil N available indices and forest growth are lacking in the oil sands region, particularly for reclaimed lands as few jack pine stands of any advanced growth stages are available. The regulatory needs and local reclamation practices require clearly defined relationships and boundary conditions to advance land reclamation. Soil N availability to tree growth relationships established on existing undisturbed sites maybe used as an analog for soil N availability and forest performance on reclaimed sites and to support policy development and local reclamation practices; such an approach is often used to understand potential productivity and assess reclamation success (Rowland et al. 2009; Lilles et al. 2010; Purdy et al. 2005).

In this research, the objective was to investigate the relationship between soil N availability indices and tree growth in natural jack pine stands in the boreal oil sands region. We hypothesized that N availability indices could effectively predict the productivity of forest stands. This research would help to identify suitable soil N availability indicators that can be used to predict tree growth in the oil sands region. Currently different research groups and industrial operators quantify N availabilities using different methods and that makes comparisons between projects difficult and some of the N availability indices used may not be related to forest productivity.

Materials and methods

Study area and research plots

This study was conducted near Fort McMurray (56°39' N, 111° 13'W) in northern Alberta, in the Boreal forest region. The study area is characterized by a continental boreal climate where winters are typically long and cold and summers are short and cool. Mean daily temperatures range from -18.8 °C in January to 16.8 °C in July (based on Canadian climate normals or averages between 1971 and 2000; Environment Canada 2002). Mean annual precipitation is 455 mm, which falls predominantly as rain (342 mm) during the summer season. The main tree species include jack pine, white spruce (*Picea glauca* (Moench) Voss), black spruce (*Picea mariana* (Mill.) BSP), trembling aspen (*Populus tremuloide*s Michx.), balsam poplar (*Populus balsamifera* L.), and white birch (*Betula papyrifera* Marsh.) (Fung and Macyk 2000). The majority of soils have developed on glacial and glacial-fluvial deposits. Gray Luvisols (based on the Canadian system of soil classification, same below) are generally associated with till and lacustrine deposits, while Dystric Brunisols with coarse parent materials such as glaciofluvial outwash and eolian sands (Turchenek and Lindsay 1982). In this area, jack pine usually grows on broad outwash plains with a uniformly sandy texture. It is a relatively fast growing, small to medium sized tree, normally 10 to 15 m tall and 10 to 20 cm in diameter on good sites.

In May and June of 2008, we selected eight mid-rotation to near mature jack pine stands ranging from 43 to 78 years old for this study. These eight stands were located on similar positions of outwash plains and the soils were developed from glacial and glacial-fluvial deposits (Turchenek and Lindsay 1982). The eight stands were selected among the stands established for long-term monitoring by the Cumulative Environmental Management Association (CEMA) that cover a broad range of jack pine stands in the area affected by current and projected oil sands mining activities in northeast Alberta. Soil bulk density and soil texture were rather uniform among the eight stands, with a sandy soil texture (Table 1). Therefore, soils were consistently dry with no obvious difference in soil moisture content as was determined in this study (Table 1), suggesting that soil water holding capacity was not a factor causing differences in stand development. In each stand, a 20 × 20 m plot at least 50 m away from the edge of the forest was established for soil sampling and tree measurement. The details of the plots are given in Table 1.

The first step was to examine the N availability in the forest floor and 0-20 cm mineral soil. Several soil N availability indicators, including *in situ* net N mineralization rates, potential N supply rates measured in the field using Plant Root Simulators (PRS™ probes), laboratory aerobic and anaerobic N mineralization rates, and inorganic N contents in both the forest floor and 0-20 cm surface mineral soil were determined to estimate soil N availability. The second step was to explore the relationship between tree growth rates (tree ring width and mean annual aboveground biomass increment) and soil N availability indices. This approach was used to investigate if any of the N availability indices can be used to predict forest growth and productivity.

Determination of net N mineralization in the forest floor and surface mineral soil

Nitrogen mineralization rates in the forest floor and 0-20 cm mineral soil were measured four times from July 2008 to October 2009 using the *in situ* incubation method (Raison et al. 1987). Incubations were conducted from July to September 2008, October 2008 to May 2009, June to July 2009, and August to October 2009. Over winter rates here and for other parameters described below were measured in order to obtain annual N mineralization rates even though the over winter rates were expected to be low.

At the commencement of each incubation period, soil cores were taken with PVC tubes (10 cm in diameter and 30 cm long) from four randomly chosen locations in each plot. The bottom of the PVC tubes was sharpened to assist the insertion and to minimize soil compaction. One set of tubes (four tubes each plot, the initial sample) was removed, manually divided into the forest floor and 0-20 cm surface mineral soil layers, and then stored in a cooler and shipped to the laboratory for determination of soil ammonium (NH^{+}_{4}-N) and nitrate (NO^{-}_{3}-N) concentrations. Before performing chemical analysis, the soil samples from the four tubes within each plot were combined to form a composite sample for each depth or sample type (forest floor vs. mineral soil samples). The other four PVC tubes were inserted into the soil and left in place (the incubated sample). The top of the tube was covered to prevent rain water from getting into the tube and leaching away N during the field incubation. At the end of each incubation period, the incubated samples were removed, composited and analyzed for mineral N concentrations (as described below) in the same way as the initial samples.

Following removal of roots and stones, each composited sample was homogenized by hand and then passed through a 6 mm sieve. A subsample of about 20 g (fresh weight) was extracted in 100 mL of 2 mol L^{-1} KCl for 1 hr and filtered through a Whatman 42 filter paper. The NH^{+}_{4}-N and NO^{-}_{3}-N concentrations in the extracts were analyzed using alkaline phenol and cadmium reduction techniques, respectively, on a flow-injection autoanalyser (Skalar Analytical B.V., Breda, the Netherlands). Another sub-sample (20 g, fresh weight) was used to determine soil moisture content after drying in an oven at 105 °C for 24 hrs. The inorganic N concentrations and other analyses reported below were expressed on an oven-dry weight basis.

Net N mineralization rates for the different incubation periods were obtained by subtracting the NH^{+}_{4} and NO^{-}_{3} concentration of the initial sample from that of the incubated sample divided by the incubation time (Raison et al. 1987). Net nitrification rates were obtained by subtracting the NO^{-}_{3} concentration in the initial sample from that of the incubated sample divided by the incubation time. Thereafter, portions of the remaining soil samples were air-dried for 30 days, and passed through a 0.5 mm sieve. The samples were then analyzed for total C and N concentrations using a Carlo Erba NA1500 elemental analyzer (CE Instruments, Italy).

Determination of aerobic and anaerobic N mineralization

The forest floor and mineral soil samples used in the laboratory aerobic and anaerobic incubations were collected in July 2009. When those samples were retrieved and shipped to the laboratory, a portion of those samples were immediately air-dried. For aerobic incubation, about 10 g air-dried sample was mixed with 30 g of washed 60-mesh quartz sand. The mixture was distributed evenly over the bottom of a 250 mL bottle containing 6 mL of distilled water to moisten the mixture. The bottles were tapped gently to level the surface of the mixture. Each bottle was fitted with a rubber stopper having a central hole sealed tightly with a septum. The bottles were placed in an incubator at 30 °C. After 14 days, 100 mL of 2 mol L^{-1} KCl was added to each bottle and the bottles were fitted with rubber stoppers and shaken for 1 hr in a shaker, and the content in the bottle was filtered through a Whatman 42 filter paper, and then NH^{+}_{4}-N and NO^{-}_{3}-N concentrations in the extract were analyzed with a Skalar flow-injection auto-analyser as described above.

Anaerobic incubation involved the incubation of a sample under waterlogged conditions in a 16 × 150 mm test tube with as little head space as possible in the test tube. Twelve millilitres of distilled water was placed in the test tube, and then 5 g of oven-dried equivalent forest floor or mineral soil sample was added to the tube. The test tubes were stoppered and placed in an incubator at 40 °C. After 7 days of incubation, the tubes were removed from the incubator and shaken briefly to mix the content. The soil-water mixture in each tube was quantitatively transferred to a 150 mL plastic bottle. Then 15 mL of 4 mol L^{-1} KCl was added to the bottle (so that the final KCl concentration in the extraction was 2 mol L^{-1}) and shaking for 1 hr, the extractant was then filtered through a Whatman 42 filter paper, and NH^{+}_{4}-N and NO^{-}_{3}-N concentrations were analyzed with a Skalar flow-injection auto-analyser as described above.

The NH^{+}_{4}-N and NO^{-}_{3}-N concentrations in the initial samples for both aerobic and anaerobic experiments were determined in the same way. The difference in NH^{+}_{4}-N and NO^{-}_{3}-N concentrations between the initial and incubated soils was used to calculate aerobic and anaerobic N mineralization rates. The anaerobic N mineralization method measures the potentially available N in a soil sample, which therefore differs from the mineral N measurement, which is based on what is directly extractable by a 2 mol L^{-1} KCl extractant. The mineral N concentration in a soil is known to be variable in a growing season but the anaerobic N mineralization measurement overcomes some of that deficiency.

In situ N availability measured using PRS probes

We used the Plant Root Simulator (PRS™, Western Ag Innovations Inc., Saskatoon, SK, Canada) probes to measure potential soil N supply rates (PRS-N). The PRS probe consists of an ion exchange membrane encapsulated in a plastic casing. The membrane is chemically pre-treated so that it exhibits surface characteristics and nutrient sorption phenomena that resemble a plant root surface. When buried in the soil, the PRS probe can assess nutrient supply rates by continuously adsorbing charged ionic species over the burial period (PRS Probe Operations Manual 2009). We used two types of PRS probes: anion and cation exchange probes. The anion exchange PRS probe simultaneously adsorbs all anion nutrients, such as nitrate and sulfate. Cation exchange PRS probes simultaneously adsorb cation nutrients such as ammonium and calcium.

In this study, the PRS probes were installed three times from July 2008 to October 2009, i.e., July to September of 2008, October 2008 to May 2009, and June to October 2009. At the start of each incubation period, the PRS probes were inserted in pairs (one anion and one cation) at four locations within each plot for each of the forest floor and 0-20 cm mineral soils outside of PVC tubes. At the end of the incubation, the PRS probes were retrieved and new PRS probes were installed. In each time, all collected PRS probes were washed as clean as possible using deionized water, then kept cool and sent to Western Ag Innovations Inc. in Saskatoon for analysis. The data for each stand was based on the composite sample of four anion or cation probes.

Determination of tree ring width and mean annual biomass increment

We used tree increment cores to determine the diameter growth of trees in the last 6 years as an index of recent tree growth rate. Sample collection from living trees was conducted using a 5 mm diameter increment corer. At the end of the growing season (i.e., at the end of October) in 2009, we selected five trees, which differed in breast height diameter (DBH) to represent the range of the tree growth in each plot, for collecting tree cores. For each tree, one core was taken at breast height. These cores were air-dried, mounted, and sanded prior to having their last 6 years of ring widths measured on a tree-ring measuring system (Velmex Stage Inc., USA). Ring widths were measured to the nearest 0.01 mm.

We determined the height and DBH of all the live trees in each plot in 2009. Biomass estimates of separate tree components (wood, bark, branch and leaf) were calculated based on the tree height and DBH using published species-specific allometric equations in Ung et al. (2008). Then the annual aboveground biomass increment at the stand level was calculated based on the sum of biomass of all tree components of all trees per hectare to indicate site productivity.

Statistical analyses

Correlation and regression analyses were conducted to determine relationships between soil N availability indices and both tree ring width and site productivity. The data analysis included two steps. The first step was to find the pattern of variation of soil N availabilities and tree ring growth among plots. The second step was to analyze the relationship among soil N availability indices, tree growth indices, other soil N status measures and stand age, using Pearson correlation and linear regression methods. When a significant relationship (Pearson correlation) between soil N indices and each of tree ring width and forest productivity indices occurs repeatedly in a number of years, we conducted regression analysis to test whether the N availability index used could effectively predict the productivity index. Throughout this paper, statistical significance was set at α=0.05.

Results

In situ N mineralization rate, inorganic N concentration and PRS-N

Across all stands, the *in situ* N mineralization rates in the forest floor were almost ten times higher than that in the mineral soil (Table 2), were markedly different among the stands, and had a pronounced seasonal pattern: the rates were the highest in mid summer (June to July), intermediate in the fall (August to October), and the lowest in spring and winter (November 08 to May 09).

Similar to the *in situ* N mineralization rates, inorganic N concentrations were much higher in the forest floor than in the surface mineral soil (Table 2). Across the stands, the anaerobic N mineralization rates were higher than the aerobic rates, and both were several times greater in the forest floor than in the surface mineral soil (Table 2).

We calculated the amount of N mineralized per unit area per year (using the 5 cm forest floor, the 0-20 cm surface mineral soil, bulk densities and mineralization rates) to estimate the mineralized and nitrified N. Annual N mineralization rates on an area basis varied substantially among stands in both the forest floor and the surface mineral soil. In the forest floor, it was highest in S3, lowest in S2, S4 and S5 and intermediate in S1, S6, S7 and S8. In contrast, in the surface mineral soil, it was highest in S1, S7 and S8 and lowest in S2, S3 and S6 (Table 3). The annual nitrified N in the forest floor ranged from

0.03 to 0.64 kg ha^{-1} yr^{-1} among the 8 stands (Table 3). However, in the surface mineral soil, due to the very low nitrification rate (nitrate and nitrite were not detected in most samples), the nitrified N was nearly zero across all the stands (Table 3).

The N availability measured by PRS probes was higher in the forest floor than in the mineral soil for stands with relatively low N availability, but not very different between the soil layers in the stands with high N availability (Table 4).

Annual tree ring width and aboveground biomass increment

The mean annual tree ring width over the last 6 years was the greatest in S3 and the lowest in S2 (Table 5). Among the 6 years studied, tree ring width was the lowest in 2009 and the greatest in both 2004 and 2005 for all stands. Annual biomass increment among the eight stands ranged from 0.63 Mg ha^{-1} yr^{-1} in S5 to 2.39 Mg ha^{-1} yr^{-1} in S7 (Table 5).

Relationships between tree growth and soil N availability indices

There were significant positive correlations between tree ring width and *in situ* forest floor N mineralization rates (Table 6). The *in situ* forest floor N mineralization rates in summer 2008 were correlated with each of tree ring width in 2008, 2007, 2006, 2005 and 2004, and the annual average tree ring width. The *in situ* forest floor N mineralization rates in summer 2009 were also correlated with tree ring width (Table 6). Moreover, the annual *in situ* forest floor N mineralization rate was significantly correlated with each year's tree ring width and the annual average tree ring width (Table 6).

Even though relationships between tree ring width and N mineralization rates in years different from that the tree ring was formed may seem ecologically meaningless, but when strong relationships were found between tree ring width and N mineralization rates of so many different periods, this is a strong indication that the relationship was widespread. Regression analysis indicated that mean annual tree ring width increased significantly with the increase of forest floor *in situ* N mineralization rates (Fig. 1).

Similar to the *in situ* N mineralization rates, aerobic and anaerobic N mineralization rates of forest floor samples incubated in the laboratory were also significantly correlated with tree ring width (Table 7). The relationship between each of aerobic and anaerobic N mineralization rates and the tree ring width in each of 2008, 2007, 2006, 2005, 2004 and the average width were significant. Regression analysis also showed a strong relationship between mean annual tree ring width and annual biomass increment and each of aerobic N mineralization and anaerobic N mineralization rates (Fig. 2).

Most N availability indices in the mineral soil were also correlated with tree ring width. The *in situ* soil N mineralization rates in the summer and the autumn correlated significantly with tree ring width in each of 2009 (*in situ* soil N mineralization rates in July-Sep. 08: $R=0.74$, $P<0.05$; Aug. 09-Oct. 09: $R=0.74$, $P<0.05$) and 2007 (*in situ* soil N mineralization rates in July-Sep. 08: $R=0.74$, $P<0.05$; Aug. 09-Oct. 09: $R=0.\ 74$, $P<0.05$) (data not shown). Tree ring width was significantly correlated with PRS-N in the surface mineral soil (Table 7, Fig. 3).

We found a significant relationship between annual biomass increment and PRS-N in the forest floor layer between July and September 2008 (Fig. 4a). The PRS-N in mineral soil layer in the winter incubation (i.e., October 08 to May 09) was significantly correlated with average annual tree ring width and annual biomass increment (Table 7,

Fig. 4b), and with each of tree ring width in 2007, 2005 and 2004 (Table 7). In the summer incubation, the PRS-N was also correlated with each of annual average, and 2008, 2005 and 2004 tree ring width (Table 7).

Relationships among stand age, tree growth, soil N availability indices and other soil N status

In addition to soil N availability indices, other soil N status in the forest floor and mineral soil were also correlated with tree ring width. As shown in Table 7, the C/N ratio of mineral soil was positively related with tree ring width in each of 2008, 2007, 2005, 2004 and the mean over six years, but not in the forest floor. Total N in the forest floor was negatively correlated with 2006 and mean tree ring width, but that in the mineral soil was positively correlated with tree ring width in 2008, 2005 and 2004. Annual mineralized N in the forest floor was positively correlated with tree ring growth in most cases, whereas in the mineral soil there was no significant correlation. The annual nitrified N was positively correlated with the 2009 tree ring width (Table 7).

Stand age was significantly correlated with tree growth parameters, soil N availability indices and other soil N status data (Table 8). There was significant negative relationship between stand age and each of tree ring width and annual biomass increment, and between stand age and each of *in situ* and laboratory incubated N mineralization rates in the forest floor and PRS-N in the mineral soil, as well as the C/N ratio in the mineral soil; however, stand age was positively correlated with total N in the forest floor. Most soil N availability indices were negatively correlated with C/N ratio and total N in the forest floor, but positively correlated with C/N ratio and total N in the mineral soil. In contrast, there were significant positive relationships between mineralized N and most N availability indices in the forest floor. Soil available N indices did not significantly correlate with each of the mineralized N in the mineral soil and the nitrified N in the forest floor.

Discussion

The effectiveness of soil N availability indices in predicting site productivity

Soil N availability represents the rate at which N is converted from unavailable to available forms as the majority of the soil N is present in the organic form and determines the extent to which plant production is constrained by a limited supply of available N in the soil (Binkley and Hart 1989). However, it remains a challenge to select a suitable indicator of soil N availability for predicting forest productivity (Joshi et al. 2003). No method provides a clear, accurate assessment of the N availability in a soil, or of the degree to which the soil N availability limits tree growth (Binkley and Hart 1989; Finzi and Canham 2000; Wilson et al. 2005). Therefore, understanding relationships between soil N availability and tree growth has been constrained by the lack of a suitable N availability index or indices that can explain tree growth performance very well, due to seasonal and interannual variability of N availability and the long-term nature of tree growth (Fisher and Binkley 2000).

Numerous methods, including biological and chemical methods, have been proposed for providing a relative index of soil N availability in forest ecosystems (Binkley and Hart 1989). In this study, N mineralization rates in the forest floor including field *in situ* incubation and aerobic and anaerobic incubations under controlled laboratory conditions, and PRS-N in the soil were tested as N availability indicators to link with tree growth. Notably, the above measures were all correlated with tree ring width, thus we conclude that they are suitable indices of potential site productivity. This is consistent with reports for other forests (Powers 1980; Nadelhoffer et al. 1985; Vitousek and Howarth 1991; Reich et al. 1997; Finzi and Canham 2000; Wilson et al. 2005; Gundersen et al. 2009) and supports the hypothesis. We further conclude that soil aerobic and anaerobic N mineralization rates, and the field *in situ* soil N mineralization rate can be used as surrogates for predicting tree growth performance for jack pine forests in the oil sands region.

This study also found that soil C/N ratio, total N content, mineralized N in the forest floor, and nitrified N in the mineral soil, as well as stand age could also be used to predict site productivity (Tables 7 and 8). Among these indices, stand age can predict each of tree growth, soil N availability and soil N contents. Soil N content can predict soil N mineralization rate and productivity. Soil N content is a relatively simple predictor of stand productivity than mineralization rates.

Selection of the most suitable soil N availability index will involve a compromise among reliability, cost, time, and the sensitivity of the test. The best indicator should have the best correlation with long-term tree growth trends and is also the easiest to measure. Since *in situ* incubations are time-consuming and costly, it is reasonable to deduce that the aerobic and anaerobic laboratory incubation approaches and direct measurement of soil total N are the most suitable methods to determine soil N availability in the studied jack pine ecosystem.

Interactions between soil N status and site productivity in jack pine forests

Significant linear relationships between soil N availability indices and tree growth suggest that N availability had a strong influence on the growth and productivity of jack pine forests. It is very well established that soil N mineralization rate has a positive linear relationship with forest productivity in ecosystems with limited N availability (Vitousek and Howarth 1991; Reich et al. 1997). Powers (1980) and Nadelhoffer et al. (1985) also found linear relationships between site productivity and N availability. The linear relationship between forest productivity and N availability is likely a fundamental feature of jack pine forests in the boreal region, as those forests often occur on sandy soils that are low in nutrient availability. The linear relationship we observed between tree ring width or annual biomass increment and soil N availability indicates that low soil N availability likely constrains the growth rate of jack pine trees, and in turn low site productivity might also limit the mineralization of soil N. Although jack pine is associated with ectomycorrhizal fungi, which have repeatedly been shown to access organic N (McAfee and Fortin 1989; Suzanne 1995; Gagné et al. 2006), we consider that the function of ectomycorrhizal fungi was to amplify the availability of N. If the site is N limited, ectomycorrhizal fungi might not change the fundamental relationship between N availability indices and forest productivity in this system. Therefore it is likely that changes in soil N availability patterns affect the rate at which tree biomass accumulates.

It is well known that forest productivity and N mineralization rates are closely linked; therefore, in the studied jack pine stands, if N availability drives productivity, the productivity in turn supports N availability. In these forests, soil N availability is directly dependent on productivity: it is the litterfall and fine root turnover that is the source of the carbon and nitrogen used by the microbes.

One of the very interesting relationships in this study is that stand age was negatively correlated with both tree growth measurements and N mineralization. The stand age – productivity relation is negative – as stands age, their growth rate declines and the biomass increment decreases. Young, aggrading stands tend to have a positive relationship, but the stands studied in this paper were closed-canopy stands. The negative relationships between stand age and N mineralization might be due mainly to the age-related canopy coverage that directly affects soil N processes. In young stands, the relatively large forest gap allows more light to reach the forest floor and increases soil temperature, causing increased soil microbial activity and N mineralization. Conversely, more mature forests with closed canopy have decreased light availability, and thus reducing soil temperature and N mineralization (Yan et al. 2009).

Another interesting result is the contrasting relationships between each of soil C/N ratio and soil total N and soil N mineralization that were negative in the forest floor but positive in the mineral soil. Given that the litterfall composition is likely similar between stands (they were all jack pine dominated), the starting point is the same. Faster mineralization means faster reduction in the remaining C and N in the forest floor. This does tend to assume the input rates were more or less the same (due to the fact that they were all canopy closed). Therefore, forest floor N and C/N ratio tend to have a negative relationship with N mineralization. In contrast, as the organic N content in the mineral soil was very low and the C/N ratio was quite low, between 10 and 15, decomposition was closely coupled to supply, so the C/N ratio and total N content in the mineral soil tend to be positively correlated with N mineralization. Furthermore, the relationship between tree ring width and PRS-N was positive in the mineral soil, but not statistically significant in the forest floor (data not shown), suggesting that the type of soil material used for reclamation of disturbed soils will influence the establishment and growth of jack pine trees. We suggest that future restoration efforts should place more emphasis on N availability in the mineral soil, rather than only addressing the quality and quantity of organic matter in the forest floor.

At a specific site, soil N status (*e.g.*, N stocks and N fluxes) depend on many factors such as site productivity and water availability. We tried to develop relationships between jack pine growth and soil moisture content, because soils in jack pine stands were coarse textured and thus had low water holding capacity (in addition to low nutrient availabilities). However, we found that soil moisture status among the stands were rather uniform (Table 1), and there was no significant relationship between tree growth and soil moisture content. Therefore, the data suggest that water availability was not a factor that would differentiate tree growth among the studied stands.

In summary, significant relationships between soil N availability indices and forest growth parameters were established for jack pine stands in the oil sands region in northern Alberta. The *in situ* and laboratory aerobic and anaerobic soil N mineralization rates, mineralized N and PRS-N, as well as soil C/N and total N content in both the forest floor and mineral soil were linearly related with tree ring width of jack pine trees. We conclude that *in situ* and laboratory aerobic and anaerobic N mineralization rates and soil C/N ratio and N can be used as effective surrogates for predicting site productivity in jack pine forests in the oil sands region. This work was conducted in undisturbed ecosystems in the oil sands region; the relationships described here would need to be tested in the reclaimed landscape when suitable reclaimed stands become available, as the amount of organic matter and decomposing microbes in undisturbed ecosystems are probably higher than that in recently reforested areas after oil sands mining, which may result in changes in the methods suitable for indicating N availability.

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References

Anielski M, Wilson S (2009) Counting Canada's natural capital: Assessing the real value of Canada's boreal ecosystems. Canadian Boreal Initiative, The Pembina Institute

Binkley D, Hart LSC (1989) The component of nitrogen availability assessment in forest soil. Adv Soil Sci 19: 57–l12

Environment Canada (2002) Canadian climate normals or averages, 1971-2000, for Fort McMurray, AB. http://climate.Weatheroffice.ec.gc.ca. Accessed 3 August 2010

Finzi AC, Canham CD (2000) Sapling growth in response to light and nitrogen availability in a southern New England forest. For Ecol Manage 131: 153–165

Fisher RF, Binkley D (2000) Ecology and management of forest soils, 3rd edn. John Wiley & Sons, Inc. New York

Fung MYP, Macyk TM (2000) Reclamation of oil sands mining areas. In: Barmhisel RI et al. (ed) Reclamation of drastically disturbed lands. American Society of Agronomy monographs, 2nd edn. 41, pp 755–744

Gagné A, Jany JL, Bousquet J, Khasa DP (2006) Ectomycorrhizal fungal communities of nursery-inoculated seedlings outplanted on clear-cut sites in northern Alberta. Can J For Res 36: 1684–1694

Gower ST, Son Y (1992) Differences in soil and leaf litterfall nitrogen dynamics for five forest plantations. Soil Sci Soc Am J 56: 1959–1966

Gower ST, Reich PB, Son Y (1993) Canopy dynamics and aboveground production of five tree species with different leaf longevities. Tree Physiol 12: 327–345

Grigal DF, Homann P (1994) Nitrogen mineralization, groundwater dynamics, and forest growth on a Minn esota outwash landscape. Biogeochemistry 27: 171–185

Gundersen P, Sevel L, Christiansen JR, Vesterdal L, Hansen K, Bastrup-Birk A (2009) Do indicators of nitrogen retention and leaching differ between coniferous and broadleaved forests in Denmark? For Ecol Manage 258: 1137–1146

Joshi AB, Vann DR, Johnson AH, Miller EK (2003) Nitrogen availability and forest productivity along a climosequence on Whiteface Mountain, New York. Can J For Res 33: 1880–1891

Lennon JM, Aber JD, Melillo JM (1985) Primary production and nitrogen allocation of field grown sugar maples in relation to nitrogen availability. Biogeochemistry 1: 135–154

Lilles EB, Purdy BG, Chang SX, Macdonald SE (2010) Soil and groundwater characteristics of saline sites supporting boreal mixedwood forests in northern Alberta. Can J Soil Sci 90: 1–14

McAfee BJ, Fortin JA (1989) Ectomycorrhizal colonization on black spruce and jack pine seedlings outplanted in reforestation sites. Plant Soil 116: 9–17

Nadelhoffer NJ, Aber JD, Melillo JM (1985) Fine roots, net primary production, and soil nitrogen availability: a new hypothesis. Ecology 66: 1377–1390

Nordin A, Högberg P, Näsholm T (2001) Soil nitrogen form and plant nitrogen uptake along a boreal forest productivity gradient. Oecologia 129: 125–132

NO_x-SO_2 Management Working Group (2004) A summary of work for the management of acid emissions in the oil sands: background information for the dynamic modeling of acid emissions. Workshop 2. Cumulative Environmental Management Association, Alberta

Pastor J, Aber JD, McClaugherty CA, Melillo JM (1984) Aboveground production and N and P cycling along a nitrogen mineralization gradient on Blackhawk Island, Wisconsin. Ecology 65: 256–268

Powers RF (1980) Mineralizable soil nitrogen as an index of nitrogen availability to forest trees. Soil Sci Soc Am J 44: 1314–1320

PRS™-Probe Operations Manual, 4th Printing, April (2009) Western Ag Innovations Inc. Saskatoon, Saskatchewan, Canada

Purdy BG, Macdonald SE, Lieffers VJ (2005) Naturally saline boreal communities as models for reclamation of saline oil sand tailings. Restor Ecol 13: 667–677

Raison RJ, Connell MJ, Khanna PK (1987) Methodology for studying fluxes of soil mineral-N in situ. Soil Biol Biochem 19: 521–530

Reich PB, Grigal DF, Aber JD, Gower ST (1997) Nitrogen mineralization and productivity in 50 hardwood and conifer stands on diverse soils. Ecology 78: 335–347

Rowland SM, Prescott CE, Grayston SJ, Quideau SA, Bradfield GE (2009) Recreating a functioning forest soil in reclaimed oil sands in northern Alberta: An approach for measuring success in ecological restoration. J Environ Qual 38: 1580–1590

Suzanne V (1995) Ectomycorrhizal fungal succession in jack pine stands following wildfire. New Phytol 129: 389–401

Turchenek LW, Lindsay JD (1982) Soils inventory of the Alberta oil sands environmental research program study area, Report 122. Alberta Research Council, Edmonton, AB Canada

Ung CH, Bernier P, Guo XJ (2008) Canadian national biomass equations: new parameter estimates that include British Columbia data. Can J For Res 38: 1123–1132

Vitousek PM, Howarth RW (1991) Nitrogen limitation on land and in the sea: How can it occur? Biogeochemistry 13: 87–115

Wilson SM, Pyatt DG, Ray D, Malcolm DC, Connolly T (2005) Indices of soil nitrogen availability for an ecological site classification of British forests. For Ecol Manage 220: 51–65

White LL, Zak DR, Barnes BV (2004) Biomass accumulation and soil nitrogen availability in an 87-year-old Populus grandidentata chronosequence. For Ecol Manage 191: 121–127

Yamashita T, Kasuya N, Nishimura S, Takeda H (2004) Comparison of two coniferous plantations in central Japan with respect to forest productivity, growth phenology and soil nitrogen dynamics. For Ecol Manage 200: 215–226

Yan ER, Wang XH, Guo M, Zhong Q, Zhou W, Li YF (2009) Temporal patterns of net soil N mineralization and nitrification through secondary succession in the subtropical forests of eastern China. Plant Soil 320: 181-194

Zak DR, Host GE, Pregitzer KS (1989) Regional variability in nitrogen mineralization, nitrification and overstory biomass in northern Lower Michigan. Can J For Res 19: 1521–1526