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Exponential fertilization promotes seedling growth by increasing nitrogen retranslocation in trembling aspen planted for oil sands reclamation

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ABSTRACT

Vegetation reestablishment in land reclamation is often challenged by high mortality and slow growth of planted species because of low nutrient availability and severe understory competition. We tested the effectiveness of exponential fertilization in nursery trembling aspen (*Populus tremuloides* Michx.) seedling production for improving revegetation success on reconstructed soils in the Oil Sands in a two-year field experiment using a 2 (exponentially vs conventionally fertilized seedlings) × 2 (weed intact vs weed removed) factorial design. The experiment was conducted on two different cover soil types: peat mineral soil mix (PMM) and LFH mineral soil mix (LFH). Nitrogen (N) retranslocation in outplanted seedlings was traced using ^{15}N labeling. Exponential fertilization and weed removal increased height and root collar diameter growth but did not affect seedling survival over two growing seasons. Exponential fertilization increased new stem and leaf biomass and N content but decreased the percent allocation of biomass to roots. On average, 80% (on the PMM site) and 73% (on the LFH site) of total N demand of new tissues was met by internal N retranslocation. Exponential fertilization increased N retranslocation by 34% ($P < 0.01$) and 25% ($P = 0.02$) on the PMM and LFH sites, respectively. Weed competition reduced N retranslocation by 37% ($P < 0.01$) and N uptake by seedlings from the soil by 61% ($P = 0.01$) on the LFH site. We conclude that greater accumulation of nutrient reserves and greater N retranslocation helped to increase the growth of exponentially fertilized aspen seedlings that were outplanted for oil sands reclamation. Exponential fertilization of aspen seedlings for oil sands reclamation should be operationally tested for improving land reclamation in the Oil Sands.

1. Introduction

Oil sands extraction by open-pit mining in northern Alberta has disturbed a large area of the boreal region (about 813 km^2 as of December, 2013; Government of Alberta, 2014), and reclamation of these disturbed lands to an equivalent capability similar to that which existed pre-disturbance has been a priority for the industry and the provincial government. During open pit mining all vegetation, surface soil, overburden (nutrient poor layers of rock and soil below the surface soil) and oil sands are removed, leaving large pits (several kilometers wide and up to 100 m deep) or the unwanted mine dump where overburden from the mine is placed. A soil is reconstructed during reclamation of these pits and overburden storage areas after mineral extraction is complete using tailings sand (a by-product of bitumen extraction) or overburden substrates. Reclamation cover soils are then placed on these substrates to complete soil reconstruction depending on the substrate type and landform. Experience with revegetation in such reconstructed soils in reclamation of upland sites is increasing (Macdonald et al., 2015). However, success of revegetation in a reclaimed area largely depends on the establishment of understory vegetation and planted tree seedlings (Kimaro and Salifu, 2011) as most of the disturbed area was originally boreal forest. Reclamation success is often affected by unsuitable growth conditions, such as nitrogen (N) deficiency and soil salinity with electrical conductivity greater than 4 ds m^{-1} (Duan et al., 2015), pH (Jamro et al., 2014; Zhang et al., 2013), and soil compaction (Jamro et al., 2015) that is associated with reconstructed soils in oil sands reclamation. Although the use of peat mineral soil mix (PMM) or LFH (organic horizons that sit on the surface of a forest soil) mineral soil mix (LFH) as capping materials placed over tailings sand or overburden substrates has been a common practice for improving soil quality

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(Kwak et al., 2015; MacKenzie and Naeth, 2007; Rowland et al., 2009), early establishment of planted seedlings can still be problematic (Duan et al., 2015; Landhaeusser et al., 2012). In addition to the specific physical/chemical site conditions described above, cover crops that are sometimes established on these reclaimed soils to control soil erosion and may increase the competition with planted seedlings for resources such as light, water, and nutrients (Franklin et al., 2012). Field fertilization could alleviate nutrient deficiencies (Duan et al., 2015; Rowland et al., 2009), but may also encourage the growth of the understory vegetation, which subsequently intensifies competition for nutrients and other resources (Chang et al., 1996).

An alternative approach to improving revegetation success in heavily disturbed and competitive sites involves the use of quality seedling stocks (Landhaeusser et al., 2012). The nutrient loading technique based on exponential fertilization (Timmer and Aidelbaum, 1996) is designed to increase the nutrient reserve in seedling stocks by inducing luxury nutrient consumption in nursery seedling production (Malik and Timmer, 1998); this is one of the techniques that can be employed to produce quality seedling stocks. Nutrient-loaded seedlings have access to a larger nutrient reserve and can promote early seedling establishment in the field, resulting in superior survival, growth, and competitiveness over conventionally produced seedlings (Timmer and Aidelbaum, 1996; Timmer and Munson, 1991). Exponential nutrient fertilization has been successfully used to improve early establishment of seedlings of coniferous species such as black spruce (*Picea mariana* [Mill.] BSP) (Imo and Timmer, 2001; Malik and Timmer, 1996; Salifu and Timmer, 2003b), China-fir (*Cunninghamia lanceolata* [Lamb.] Hook.) (Xu and Timmer, 1999), and Lutz spruce (*Picea* × *lutzii* Little) (Jonsdottir et al., 2013). Outplanting experience with nutrient loaded deciduous species is limited (Birge et al., 2006), and non-existent with trembling aspen (*Populus tremuloides* Michx.), which is a widely distributed species across boreal North America, and is commonly used for land reclamation and commercial forestry (Pinno et al., 2012). Moreover, successful application of nutrient loading in aspen seedlings has not been tested in oil sands reclamation. However, nursery or greenhouse pot studies have been conducted on aspen (Hu, 2012; Hu et al., 2015; Schott et al., 2013). In the early stage after outplanting, seedlings can meet part of the sink demand for N that is required for new growth by retranslocating nutrients from old tissues; this has been demonstrated especially with evergreen species (Nambiar and Fife, 1991; Salifu and Timmer, 2003a). Quantification of N retranslocation from old to new tissues, which is referred to as N derived from plants (NDFP), versus N derived (or taken up) from the soil (NDFS) in newly transplanted seedlings are very important (Choi et al., 2005) for understanding which N pool is critical for promoting seedling growth (Salifu et al., 2009a). In this study, we determined the amount of N that was retranslocated to meet the sink demand in aspen seedlings after transplantation by using the ^{15}N tracing technique, which can more precisely discriminate the various N sources (such as NDFP) in the soil-plant system (Barraclough, 1995; Nommik, 1990; Proe and Millard, 1994). Although several studies have quantified NDFP, which accounts for 40–100% of annual N demand in newly transplanted conifer seedlings (Millard, 1996; Nambiar and Fife, 1991; Salifu and Timmer, 2003a), the relative contributions made by NDFP and NDFS to new tissue growth in nutrient-loaded hardwood seedlings are poorly understood (Salifu et al., 2009a).

To demonstrate the potential use of nutrient-loaded seedlings of aspen for improving revegetation success in heavily disturbed sites, we studied the growth of aspen and N retranslocation within its tissues on newly reclaimed sites with both PMM and LFH as cover soils. The field experiment was conducted in the Oil Sands region of northern Alberta. The objectives of this study were to examine the growth performance and to determine N retranslocation response of exponentially and conventionally fertilized seedlings in competition with understory vegetation on reconstructed soils. In this study we tested the following hypotheses: (i) exponentially fertilized aspen seedlings would have better growth than conventionally fertilized ones after transplantation due to the greater N storage in the exponentially fertilized seedlings, (ii) there would be a greater contribution of NDFP to new tissue growth in the exponentially than in the conventionally fertilized seedlings because of the greater nutrient reserve in the former, and (iii) the effect of understory vegetation competition for nutrients would be lower with the exponentially fertilized than with the conventionally fertilized seedlings again due to greater nutrient retranslocation to new growth in the nutrient-loaded seedlings as weed competition will not directly affect nutrient retranslocation. We focused on N in this study because N is usually the growth limiting nutrient in reclaimed soils in the Oil Sands (Duan et al., 2015; Rowland et al., 2009). Its internal cycling is similar to other mobile macronutrients (Nambiar and Fife, 1991). Thus, an improved understanding on the N nutrition has implications for the management of other mobile macronutrients.

2. Materials and methods

2.1. Seedling nursery production and fertilization regimes

Containerized stocks of conventionally (C) and exponentially fertilized (E) trembling aspen seedlings were produced in 2013 at the Smoky Lake Forest Nursery (Smoky Lake, AB, Canada). In the conventional fertilization regime, a seasonal total of 120 mg N per seedling was applied for twelve weeks at a constant rate delivered weekly; this rate was based on the rate being used in the Smoky Lake Nursery that had been found to be the optimum application rate. In the exponential fertilization regime, 240 mg N per seedling (the optimum exponential fertilization rate identified in the nursery part of the study (Hu, 2012)) was delivered on a schedule based on the modified exponential model (Birge et al., 2006; Imo and Timmer, 1992). Details of the nursery culture of seedlings can be found in Hu (2012) and Hu et al. (2015). To determine NDFP and NDFS in seedlings after transplantation, labeled urea (60 atom%) was applied in solution to the seedlings in week eight during nursery seedling production. After twelve weeks of nursery culture, the seedlings were tested for hardiness, harvested, and kept in a cold storage (at −2 °C) until they could be taken to the field for transplanting.

Before transplanting, the nutritional status, size, and biomass of seedlings were determined to assess whether exponentially fertilized seedlings were successfully loaded or not with the required nutrients. To do that, three seedling samples of each of exponential and conventional fertilization from each of five storage boxes representing different replications used in nursery production were collected from cold storage just before transplantation. Individual seedlings were assessed for component biomass and nutrient concentrations. Nutrient concentrations in the seedlings were analyzed following the procedure described below. Exponentially fertilized seedlings were confirmed to have a size and component biomass similar to that of conventionally produced seedlings but different N status prior to transplanting (Table 1).

2.2. Study site

The study was conducted at a reclamation site (56°58′N and 111°19′W) near Fort McMurray, in northern Alberta. The area was characterized by long cold winters and short warm summers, with mean annual temperature of 1 °C and precipitation of 418.6 mm (316.3 mm as rain and 102.3 mm as snow) between