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Nitrogen recovery in planted seedlings, competing vegetation, and soil in response to fertilization on a boreal mine reclamation site

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ABSTRACT

Field fertilization during reforestation often yields variable results, particularly on harsh restoration sites. An improved understanding of the recovery of applied nitrogen (N) under different fertilization practices should aid in developing more effective fertilizer prescriptions. We evaluated field establishment of white spruce (*Picea glauca* (Moench) Voss) and trembling aspen (*Populus tremuloides* Michx.) seedlings as well as N recovery within planted seedlings, soil, and competing vegetation on a mine reclamation site in the oil sands region of northern Alberta in response to immediately available fertilizer (IAF) and polymer-coated controlled-release fertilizer (CRF) applications. ^{15}N-enriched urea was applied as IAF and as a polymer-coated CRF (20 g N seedling^{-1} and 4 g N seedling^{-1}, respectively) to each species. Seedling survival, growth, and nutritional status, along with occurrence of competing vegetation and plant and soil ^{15}N recovery were quantified after the first field season. Seedlings receiving CRF exhibited increased diameter and organ dry mass relative to the IAF and control treatments. Both IAF and CRF promoted comparable increases in seedling N status, and fertilizer type did not influence within-seedling ^{15}N allocation. Neither IAF nor CRF affected vegetation cover or dry mass. Recovery of fertilizer-derived ^{15}N was low, with much of the recovered ^{15}N remaining in soils and only small amounts observed in seedlings and competing vegetation for both fertilizer treatments. Findings indicate that directed root zone application of CRF promotes first-year seedling growth and nutritional responses similar to or better than those induced by broadcast IAF applications, but at substantially lower N application rates. Our results suggest that a shift from broadcast IAF to targeted soil applications of CRF may produce similar or improved early seedling growth and nutrient uptake on reclamation sites, while greatly reducing overall quantities of N applied during the regeneration phase, much of which appears to be lost from the site of application regardless of fertilizer type.

1. Introduction

Surface mining of oil sands deposits has disturbed over 715 km^2 of boreal forest in northeastern Alberta (The Oil Sands Developers Group, 2009; Alberta Government, 2014). After mining takes place, reclamation of the affected area is required, with the goal of achieving a level of ecological capability equivalent to that which existed prior to disturbance (Alberta Environment, 2006). Thus, reclaimed areas in the oil sands region are required to have species characteristic of native plant communities (Alberta Environment, 2009), but extensive reclamation efforts are required to return these lands to productive forest lands that meet needs for ecosystem services (Ciccarese et al., 2012; Oliet and Jacobs, 2012; Jacobs et al., 2015).

Soils in NE Alberta's reclamation areas are often reconstructed using a mixture of peat and mineral soil materials that were salvaged prior to mining (Sorenson et al., 2011; MacDonald et al., 2015). These new soils may have low fertility as well as substantial physical and chemical differences compared with natural soils, such as high soil pH, increased salinity, and compaction in the overburden (Farnden et al., 2013; Lilles et al., 2012; Sorenson et al., 2011). These areas are then planted with species such as trembling aspen (*Populus tremuloides* Michx.), jack pine (*Pinus banksiana* Lamb.), and white spruce (*Picea glauca* (Moench) Voss), which are components of local native plant communities and representative of the pre-mining species composition (Fung and Macyk, 2000; Johnson et al., 1995), as well as relatively fast growing and drought tolerant (Lieffers et al., 2001). These species have also shown tolerance to salinity and other limitations that may

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characterize soils on reclaimed mine sites (Lieffers et al., 2001; Lilles et al., 2012). Seedlings of these species often exhibit transplant stress, however, and grow slowly for several years after outplanting (Martens et al., 2007; van den Driessche et al., 2003).

While site limiting factors vary across regions, attempts to improve regeneration success on mine reclamation sites have included herbicide use to control competing vegetation and field fertilization (Andersen et al., 1989; Casselman et al., 2006). Rapid response to weed control has been seen for other fast-growing tree species such as loblolly pine (*Pinus taeda* L.) (Perry et al., 1993) and *Populus* spp. (Pinno and Bélanger, 2009), but slower growing species with determinate growth patterns, such as Engelmann spruce (*Picea engelmannii* Parry ex Engelm.), may require up to three years after repeated competition control to show any growth response (Biring et al., 2003). Despite the benefits of herbicide application for reducing vegetative competition, there is increasing public sentiment against its use due to negative effects on the environment and on biodiversity (Löf et al., 2012; Thiffault and Roy, 2010).

Fertilization at the time of planting has also been shown to increase early growth rates, allowing trees to overtop competing vegetation and accelerate stand establishment (Miller, 1981; Rowland et al., 2000). Current reclamation practices include applying various fertilizer prescriptions based on perceived needs for nutritional supplements, frequently with broadcast applications of traditional (agronomic), immediately available fertilizers (IAF) for up to 5 years after planting (MacKenzie, 2011; Pinno et al., 2012). However, IAF has generally shown low recovery rates and may stimulate growth and nutrient uptake of competing vegetation more than outplanted seedlings (Chang and Preston, 2000; Chang et al., 1996; Imo and Timmer, 1998; Ramsey et al., 2003; Staples et al., 1999). Excessive nutrient supply, commonly resulting from an application of conventional, water-soluble fertilizers, may result in a high concentration of soluble salts in the root zone (Shaviv and Mikkelsen, 1993; Trenkel, 1997). Furthermore, detection of relatively high or low nitrate levels in some fertilized stands in the oil sands region (Rowland et al., 2000) suggests the need to optimize fertilization operations to improve cost efficiency and decrease the risk of nutrient leaching to surface and underground water bodies (McMillan et al., 2007).

Steady-state nutrition theory (Ingestad and Lund, 1986) suggests that seedling growth and nutrient uptake can be maximized and leaching losses minimized by supplying nutrient quantities in proportion to plant requirements. Controlled-release fertilizers (CRF) allow nutrients to be released slowly over time to better match plant demand and are expected to improve use efficiency (UE) and minimize adverse effects on the environment (Donald, 1991; Shaviv, 2005). Polymer-coated CRFs provide especially good control over release rates because they tend to be less sensitive to soil conditions (Shaviv, 2005). This allows for directed application of fertilizer to the seedling root zone at planting, with relatively low risk of root damage compared to IAF (Jacobs and Timmer, 2005). A single application of CRF can maintain nutrient availability at the levels of plant demand over an extended period of time, as they can release nutrients for up to two years (Fan et al., 2002; Hangs et al., 2003; Jacobs et al., 2005). Controlled-release fertilizer has been shown to improve plant growth and quality, increase nutrient use efficiency, reduce the cost of maintenance associated with repeated fertilizations, and decrease nutrient losses to surface water (Hangs et al., 2003; Shaviv and Mikkelsen, 1993; Shaviv, 2001). Nutrient release of CRF begins when a critical volume of saturated solution is formed inside the fertilizer prill. Thus, when fertilization occurs at the time of outplanting in late winter or spring, nutrient release generally occurs after the onset of competing vegetation, reducing its negative effect on seedling performance (Shaviv, 2005). Although there are different methods of applying CRF, application directly (or immediately adjacent) to the seedling root zone at planting has relatively low risk of root damage compared to IAF (Jacobs and Timmer, 2005). Application of CRF at planting has stimulated growth of newly planted forest trees across a variety of ecotypes in North America (e.g., Arnott and Burdett, 1988; Carlson and Preisig, 1981; Carlson, 1981; Fan et al., 2002; Jacobs et al., 2005).

Despite the demonstrated potential to improve UE of fertilizer operations on reforestation and afforestation sites, most studies investigating the use of CRF in field plantings have not directly compared CRF and IAF (and their corresponding application methods) in terms of seedling development and nutrient uptake dynamics. Additionally, while there are many examples of applied fertilizer studies in forest regeneration, relatively few of these have assessed the recovery of N for varying fertilization methods using ^{15}N tracing techniques. Past fertilizer recovery studies have also generally been conducted on reforestation sites following logging, while our study was focused on reclamation of a heavily disturbed post-mining site, which represents an important new ecosystem for this type of research given the increasing significance of these sites as restoration targets (MacDonald et al., 2015).

Sloan and Jacobs (2013) recently examined seedling responses to a wide range of CRF and IAF rates on a boreal post-mining reclamation site, reporting improved seedling growth for both fertilizer types relative to controls. They noted that responses to CRF application were similar or better to those achieved using IAF, despite using 90–95% lower N application rates. These results, implying wide discrepancies in UE between the two fertilizer systems, indicate the need for more detailed examination of relative rates of recovery of fertilizer N within planted seedlings or in adjacent competing vegetation and soil. To help address these knowledge gaps, we conducted a field trial on a mine reclamation site in the Canadian oil sands region to examine use of CRF in comparison to IAF. Our objectives were to: (1) characterize and quantify the recovery of ^{15}N-enriched fertilizer during the first post-planting growing season using different application methods (i.e. planting hole fertilization for CRF and broadcast for IAF); (2) examine responses of competing vegetation among fertilizer treatments; and (3) compare seedling growth and nutrient uptake between CRF and IAF.

2. Materials and methods

2.1. Study site and plantation establishment

The study site was located on a level portion of a reclamation area of an oil sands mine located north of Fort McMurray, Alberta, Canada (56°56.495′N, 111°16.443′W, 369 m ASL). Substrate on the site consisted of a peat-mineral mix (PMM) capping material (excavated from low-lying peatland sites, in which the layer of organic soil and some underlying mineral soil were salvaged) averaging 50 cm in depth placed atop an overburden substrate. Soil analysis of this PMM material from adjacent plots on the same mine reclamation site showed 52.3% sand, 14.2% clay, 6.67 pH, and electrical conductivity of 0.125 dS m^{-1} (Schott et al., 2015). Historical mean summer/winter (May–August/September–April) air temperatures in the area are 14.3/−6.0 °C and seasonal precipitation is 265.7/190.0 mm (Environment Canada: National Climate Data and Information Archive 2013).

On 9 June 2011, 30 seedlings per species of white spruce (*P. glauca* (Moench) Voss) and trembling aspen (*P. tremuloides* Michx.) were randomly arranged and planted at 3 m × 3 m spacing. All seedlings of both species were grown in 615A styroblock containers (336 cm^3 volume, 15.1 cm depth × 5.9 cm top diameter, Beaver Plastics, Ltd., Acheson, Alberta, Canada) and produced operationally at the Smoky Lake Forest Nursery of Coast to Coast Refor-