FERTILIZATION TO OPTIMIZE GROWTH OF TREE SEEDLINGS ON RECLAIMED OIL SANDS SITES

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ABSTRACT

Successful establishment of boreal tree seedlings like trembling aspen (*Populus tremuloides* Michx) and white spruce (*Picea glauca* (Moench) Voss.) in reclaimed oil sands mining sites is often limited by low nutrient availability and competition from the ground cover vegetation like planted cover crops and weeds. Competing vegetation can adversely affect seedling establishment by augmenting the impacts of moisture and nutrient stress. Despite high potential of barley (*Hordeum vulgare* L.) and oats (*Avena sativa*) as cover crops in oil sands reclamation, it was not well known how these crops interact with fertilization to influence early survival and growth of tree seedlings. This study evaluated the potential of fertilization and other silvicultural practices to improve revegetation success in oil sands sites reclaimed with peat-mineral mixture. Fertilizer application significantly increased height and root collar diameter (RCD) of tree seedlings in controlled environment greenhouse conditions, but not at a field research site near Fort McMurray, Alberta. In a greenhouse study, alleviating soil moisture stress significantly increased height, RCD, and biomass of tree seedlings. Vigorous growth of ground cover vegetation stimulated by fertilizer addition in both the greenhouse and field, largely controlled survival and growth responses of tree seedlings. Survival rates of tree seedlings were significantly decreased with increased fertilizer application rates, and no positive growth responses were observed in the field. Maximum seedlings survival (92%) was recorded without fertilization. Trembling aspen was sensitive to ground cover competition, whereas white spruce was unaffected. The inherent fertility of the peat-mineral mixture appeared sufficient for establishment and early growth of planted tree seedlings in recently reclaimed oil sands sites. Fertilization appeared to increase competition between tree seedlings and cover vegetation by promoting increased growth and competition for other resources like water. Effects on growth over the longer term (several years) should be evaluated in future studies.

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1. GENERAL INTRODUCTION

Every year, oil sand extraction in northern Alberta results in a significant area of degraded land. Available surface mineable land in Alberta is approximately 4,800 km^2 out of which 715 km^2 has already been disturbed (Government of Alberta, 2013), and needs to be reclaimed. One of the sustainable reclamation strategies for a post-mining site is reforestation. This strategy is an optimal tool to rebuild the surface mining areas through stabilizing soils and restoring ecosystems functioning, especially nutrient cycling (Rowland et al., 2009; Macdonald et al., 2012). Rapid reforestation of reclaimed sites largely depends on the establishment success of planted tree seedlings. The success of reforestation is generally difficult in mine land areas. It greatly depends on early survival and growth of tree seedlings, which are often restricted by low soil fertility, soil compaction, and competition from weeds (Moffat, 2004; Casselman et al., 2006). Regardless of these limiting factors, studies suggest that it is possible to establish productive native vegetation and ecosystem processes similar to those of undisturbed conditions (Rodrigue and Burger, 2004; Rowland et al., 2009) when appropriate silvicultural treatments for mined sites are applied (Moffat, 2004; Rowland et al., 2009).

In addition to lower plant nutrient availability on recently reclaimed sites, use of different ground covers to minimize erosion rates may adversely affect outplanting success of tree seedlings by accentuating the impacts of moisture and nutrient stress. For example, alleviating competition through weed control and fertilizer additions has been found to significantly improve early survival and growth of tree seedlings in mined areas (Casselman et al., 2006). Competing vegetation in reclaimed mined sites can arise from ground cover, especially grasses, sown to control soil erosion (Renault et al., 2004). To minimize competition with tree seedlings tree compatible ground cover should be used. Barley (*Hordeum vulgare* L.) and oats (*Avena sativa*) are some of the ground cover types that are being tested in combination with native grass species to identify appropriate cover crops for stabilizing recently reclaimed oil sands sites and for protecting planted tree seedlings (OSVRC, 1998; Renault et al., 2003). Although barley is currently recommended for field operations (OSVRC, 1998), mechanisms of facilitative and competitive interactions of barley and oats with planted tree seedlings are not clearly understood. In particular, it is not well known how these cover crops interact with fertilizer to affect early survival and growth of tree seedlings.

The selection of suitable tree species is another important factor for the successful reforestation of reclaimed sites. Trembling aspen (*Populus tremuloides* Michx.) and white spruce (*Picea glauca* (Moench) Voss.) are the main species of mixedwood boreal forest and commercial uses of both tree species occur in Canada. Mixtures of these tree species produces higher wood volumes compared to single species (Man and Lieffers, 1999). The re-established mixedwood boreal ecosystem following natural disturbances are generally characterized with the mosaic vegetation pattern of fast-growing aspen as an overstory over slow-growing white spruce (Peterson and Peterson, 1992; Macdonald et al., 2012). Mined land in a state of arrested succession (Groninger et al., 2007) cannot provide the variety of ecosystem services similar to productive forests. Regeneration of trembling aspen and white spruce mixed stand is a complex process in post-disturbance areas considering the development phase, which is mainly regulated by the species ecological properties including growth rate, competition tolerance capability, and resources like moisture and nutrient use efficiency (Chen and Popadiouk, 2002; Dunabeitia et al., 2004; Macdonald et al., 2012).

Following industrial disturbance, nutrient loss and transformation predominantly from NH_4^+ to NO_3^- form, occurs in the salvaged soil materials (Sheoran et al., 2010) and it might be limiting for the seedlings establishment. For example, the use efficiency of NO_3^--N than NH_4^+-N was low in white spruce seedlings and this might have a critical impact on seedling establishment on disturbed sites (Kronzucker et al., 1997). Better growth of conifers was reported on NH_4^+-N than NO_3^--N dominated soil (Lavoie et al., 1992). Trembling aspen returns more nutrients to soil than coniferous species, although their requirement for nutrients is almost the same. The capacity for effective nutrients use is therefore important for dynamic forest establishment in successionally different sites. If unfavourable site conditions are limiting the establishment of pioneer trees, methods for reforestation of these sites may require intensive silvicultural management including control of competition and fertilization (Pinard et al., 1996; Van den Driessche et al., 2003; Balandier et al., 2006; Zhang et al., 2013).

Research results suggest that to build up a sustainable ecosystem on reclaimed oil sands sites, repeated fertilization may be an important consideration (Moffat, 2004; Casselman et al., 2006; McMillan et al., 2007; Rowland et al., 2009). Analysis of soils from reclaimed sites indicate both higher and lower soil NO_3^--N as well as lower plant available P and K in the fertilized stands (3 to 34 years) compared to natural forests (McMillan et al., 2007; Rowland et al., 2009). In addition, available plant nutrient content of different reclamation materials varies greatly along with their physico-chemical properties (Rowland et al., 2009; Turcotte et al., 2009; Pinno et al., 2012). These results reflect possible nutrient imbalances resulting from a wide range of fertilizer rates and/or organic matter amendments used for reclamation operations. Moreover these results do not provide required information to reduce operational cost as well as mitigate environmental impact. Therefore, it is necessary to optimize and standardize the fertilizer application rate.

Conventional approaches for fertilizer recommendation are based on matching application rates with the actual plant growth and nutrient uptake (Salifu and Jacob, 2006) or modeled plant growth and uptake based on soil nutrient analysis and simulations of plant root growth and nutrient demand (Qian and Schoenau, 2002) to identify the rate that optimizes plant growth. However, fertilization response studies and validation of recommendations are limited for the oil sands region. This study is undertaken to fill this gap by evaluating optimum fertilizer rate based on survival, growth and nutrient uptake of tree seedlings in the presence and absence of barley and oat cover crops.

This study was designed to address the following hypotheses:

- The peat-mineral mix used in reclamation operations does not provide sufficient nutrients to optimize growth and yield of tree seedlings and supplemental fertilizer additions will be beneficial
- Soil moisture and vegetative competition will control tree seedlings growth and the nutritional response of tree seedlings to fertilization

The primary objectives of this study were:

- to determine how cover crops interact with soil nitrogen, phosphorus, and potassium (NPK) fertilization and soil moisture to influence (improve or hamper) early survival and growth of tree seedlings
- to determine the fertilizer rate that optimizes early survival, growth (height and diameter), and nutrition of tree seedlings

Two studies are covered in this thesis. To fulfill the first objective a greenhouse study described in Chapter 3 was conducted to determine the tree seedling responses to fertilization as affected by cover crop competition. In this study, trembling aspen and white spruce tree seedlings were planted without and with cover crops (barley and oats) in a homogenized peat-mineral mix reclamation material, under controlled environmental conditions. Representation of actual field environmental conditions was achieved in a follow up study presented in chapter 4. The field study was conducted at a recently reclaimed oil sands site at Fort McMurray, Alberta, with a wide range of fertilizer rates that helped to develop a revised fertilizer prescription for oil sands reclamation.

2. LITERATURE REVIEW

2.1. Oil Sands Mining

The oil sands are an immense natural economic resource. Canadian oil sands represent a significant source of global energy supply for the future, mostly located within the boreal forest region of Northern Alberta (Fig. 2.1). Alberta's oil sands are the third largest recoverable oil reservoir in the world (Fig. 2.2) and contain 169.3 billion barrels of bitumen and 1.5 billion barrels of conventional oil (Government of Alberta, 2013). The majority of Alberta's oil sands deposits are found in the region of Athabasca, Peace River, and Cold Lake. Most of the deposits are not close enough to the surface and easily accessible by surface mining except the Athabasca region. Across the Athabasca river valley, Fort McMurray, with an area of 4,800 km^2 are shallow enough to use surface mining technology for oil recovery (Government of Alberta, 2013). Surface mining is possible where the overburden depth is less than 75 meters and by using this technology only 20% of the total oil can be recovered (Isaacs, 2007).

Industrial interest in Canadian oil sands first started in 1719, when Cree people brought oil sands samples to the fur traders of Hudson's Bay post at Fort Churchill (Syncrude, 2013). The european fur trader Peter Pond was the first visitor to the Athabasca oil sands in 1778. Decades later, the oil sands region was visited by Alexander Mackenzie, who wrote the first detailed description of oil sands in the Athabasca region. In 1875, the oil sands was registered by Geological Survey of Canada and in 1883, G.C. Hoffman, of the Geological Survey of Canada, tried to separate bitumen from the oil sands by using water. A commercially accepted oil sands extraction process was developed in 1920 by Dr. Karl Clark, who successfully separated bitumen from oil sands by mixing with hot water and aerating the floated slurry (Syncrude, 2013). Based on this hot-water extraction process, an oil sands separation plant was built near Fort McMurray in 1924, which led to first sale of commercially produced bitumen in Edmonton by Robert Fitzsimmons in 1930. For the development of oil sands extraction process, Dr. Clark and his associate Sidney M. Blair were awarded a Canadian patent in 1928 (Syncrude, 2013). This hot-water extraction process is still used today.

There are a number of companies involved in commercial oil production in Alberta, but three major consortiums such as Suncor Energy Inc. (Suncor), Syncrude Canada Ltd (Syncrude), and Albian Sands Energy Inc. are mainly dominating the field production. In 1967, Great Canadian Oil Sands (now Suncor) began the world's first oil sands mining in Athabasca, followed by Syncrude in 1978, and the third one in 2003 by the Albian Sands Energy Inc. which is a joint venture of Shell Canada, Chevron Corporation and Marathon Oil Corp. At the beginning, the oil production by Suncor and Syncrude was 120,000 and 129,000 barrels per day, respectively (Syncrude, 2013). In 2013, Suncor planned average production of 570,000 to 620,000 barrels of oil equivalent per day (Suncor, 2013) whereas production capability of Syncrude is 350,000 barrels per day (Syncrude, 2013). Canada's oil production is steadily expanding and oil sands production

Fig. 2.1. Map showing Alberta's boreal forest, oil sands regions and oil sand surface mineable area (Government of Alberta, 2013).

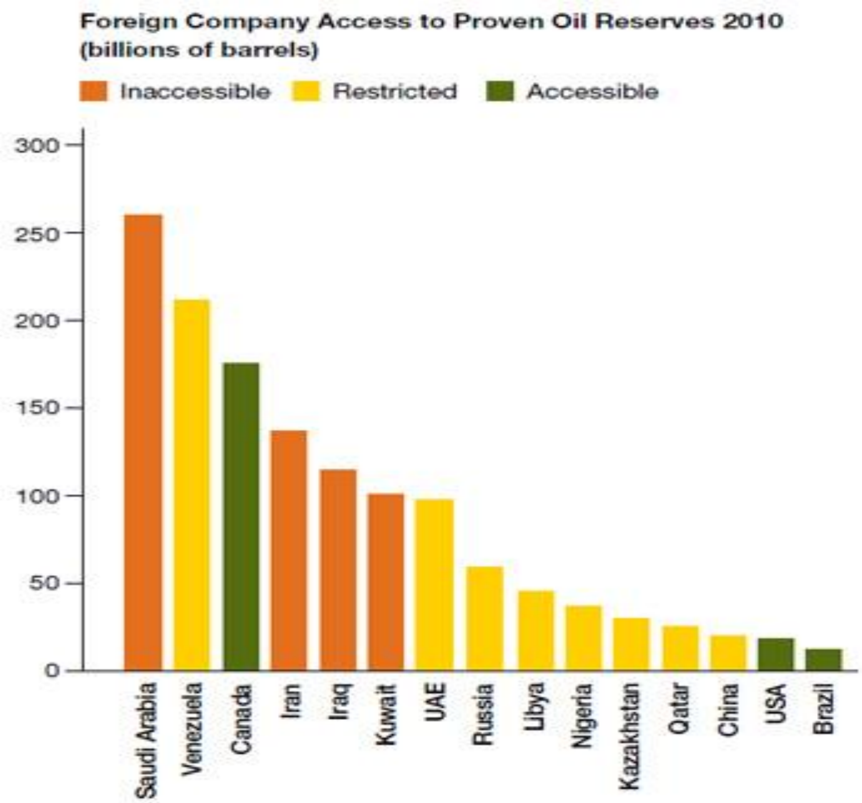


Fig. 2.2. Graph showing the ranking of oil producers with proven oil reserves in billions of barrels oil (Government of Alberta, 2013).

by 2030 is expected to double to 5.2 million per day, from 1.8 million per day in 2012 (Canadian Association of Petroleum Producers, 2013). As of June 2010, the number oil sands projects that are operating in Alberta are 91. Of these, four are involved with surface mining operations and the remainder uses in situ recovery methods (Government of Alberta, 2013). It is predicted that oil sands mining will result in the daily disturbance of 18.6 hectares of forest land by 2022 (Grant et al., 2013)

2.2. Surface Mining of Oil Sands

2.2.1. Geology

Oil sands are the natural mixture of sand or clay, water, and dense petroleum known as bitumen. Athabasca oil sands are primarily accumulated in the Lower Cretaceous McMurray Formation of Mannville group, formed by fluvial process and subsequently modified by the rising sea levels in the early Cretaceous period (Mellon and Wall, 1956; Gingras and Rokosh, 2004). The stratigraphic subdivision of the McMurray Formation was not formalized, but generally expressed as the upper, middle, and lower deposits (Carrigy, 1959; Gingras and Rokosh, 2004). These deposits reflect a continuum of aquatic environments that are fluvial in the lower groups, estuarine in the middle and marine shoreline at the upper unit (Gingras and Rokosh, 2004). In general, the McMurray Formation was distributed in the northeastern part of Alberta that directly overlies on a regional unconformity of Devonian carbonates and frequently covered by muskeg and overburden, Grand Rapids Formation and Clearwater Formation (Table 2.1). The thickness of McMurray Formation ranges from 45 m to 60 m that mainly varied due to uneven distribution of underlying Waterways limestone of Devonian Formation (Mellon and Wall 1956; Gingras and Rokosh, 2004). The McMurray Formation is within 75 m of the surface north of Fort McMurray, and suitable for surface mining (Conly et al., 2002). Due to the differences in depth of overburden, oil sands mining incorporate both surface mining and in-situ production methods. Mining of oil sands, bitumen extraction and upgrading are the three major activities of oil sands mining process.

Table 2.1. McMurray Formation in Athabaska oil sands region and their stratigraphy[‡].

Period	**Group or Formation**			**Lithology**	**Maximum thickness (m)**
Pleistocene and Recent				Glacial and post glacial deposit of till, silt, and sand	
Cretaceous	Mannville	Grand Rapids Formation		Lithic sands, sandstones, and some minor shale	110
		Clearwater Formation ----------------------------- Wabiskaw Member		Marine shale, glauconitic sandstone	84
		McMurray Formation	Upper	Argillaceous, very fine sand; usually saturated with bitumen	60
			Middle	Fine sand, lenticular beds of siltstone, shale and coal, well-saturated with bitumen	
			Lower	Conglomeratic sand , coarse-grained and barren in bitumen	
Devonian	Woodbend Group Beaverhill Lake group Elk Point Group			Fossiliferous limestone and shaley limestone	

Adopted from literature and tables presented by Mellon and Wall, 1956; Carrigy, 1959; Gingras and Rokosh, 2004.

2.2.2. Mining

Bitumen is extracted on a commercial basis from the Athabasca oil sands deposit mostly using the surface mining technique. Surface soil muskeg, along with all of the trees and overburden that overlies the oil sands, is excavated to gain access to the oil sands. Organic materials, surface soils and overburden are salvaged for later use in reclamation operation (Rowland et al., 2009; Pinno et al., 2012). The equipment used for surface mining is a combination of an excavation and on-site transportation system. Over time, different techniques such as draglines, conveyor-based systems, and truck and power shovels have been used for surface mining. At the beginning, Suncor used bucketwheel excavators and Syncrude started with draglines and bucketwheel reclaimer systems where conveyor belts were used for transporting oil sands to the extraction plants (Dunbar, 2010; Syncrude, 2013). Recently, most of the mining industries are using truck and shovel method due to operational flexibility. Oil sands mining, including the removal of the surface layer and overburden, are performed by power shovels, and huge trucks are used to transport oil sands to the crushers where it is prepared for extraction. Once the oil sands ore is crushed into small pieces, hot water is added to prepare a slurry and transferred (hydro-transport) to the extraction plant to begin the extraction process. To produce one barrel of crude oil it is necessary to mine about two tonnes of oil sands (Alberta Energy, 2013).

2.2.3. Extraction

Hot water extraction process is the commercial method of bitumen extraction from oil sands. This method was first developed by Clark in the 1920’s and accomplished by the Great Canadian Oil Sands in 1967 (now Suncor Energy Inc.) (Masliyah et al., 2004). At the processing plant hot water and caustic soda (NaOH) are added in tumblers and blended with the materials transported by the conveyor to form slurry (Syncrude, 2013). This slurry is then passed through different types of primary separation vessels (PSV) where settling time is provided to allow floating bitumen on the top. The PSV produces bitumen primary froth product, a middling stream and coarse tailing sands. The tailing sands are settled down and middlings are pumped to tailings oil recovery (TOR) vessels to recover the remaining bitumen. This recovered bitumen is then processed by a secondary floatation plant and mixed with PSV primary forth. To improve the quality of TOR vessels froth, it is also recycled through PSV. Before passing the froth to the froth treatment plant, it is deaerated and heated (Syncrude, 2013). To improve product quality the froth is diluted with naphtha and processed to remove water and tailings. Naphtha treatment helps to create suitable bitumen by decreasing its viscosity. Then bitumen is sent to the up-grader to convert it into synthetic crude oil.

2.2.4. Upgrading

Bitumen recovered in the extraction process contains higher amounts of sulphur and large molecules of hydrocarbon. The upgrading process converts bitumen into conventional light crude oil by adding hydrogen and/or removing carbon under high temperature and pressure (Canadian Centre for Energy Information, 2010). Removal of carbon is known as coking while addition of hydrogen is hydro-processing. Basically upgrading is a two-step process. In primary upgrading process, water and naphtha is removed from recovered bitumen by vacuum distillation unit (VDU). Then it is sent to hydrotreaters and cokers to breakdown the large molecules. Secondary upgrading process is used to remove impurities such as sulphur and nitrogen and to stabilize the products (Syncrude, 2013).

2.2.5. Waste materials

The surface mining process produces a significant amount of waste materials including overburden and tailing sands. Overburden is the geologic material (sand, gravel and shale) that overlies the mineable oil sands and must be removed during surface mining. Overburden along with surface soil materials are generally salvaged and stockpiled for future reclamation activities. Tailing sands that are produced during extraction process used to fill up the tailing ponds and mined pits.

2.3. Reclamation Process

Reclamation is the final step of the mining process and reclamation certification is mandatory for all participating industries for further exploration and extraction of new sites (Government of Alberta, 2013). Alberta's oil sand mining has significant impacts on land and environment. Public expectation and government requirements are that reclamation will return the disturbed areas to close to their pre-disturbance states. Therefore, oil sands mine companies are legally obligated to reclaim land that is disturbed by mining and the operation of related plants. Reclamation standards have been set by the Government of Alberta and change with time as new issues and technologies arise. Reclamation activities on different sites are following different procedures to meet the standards. Therefore, it can take different time periods to complete the process. At the present time, only 0.2% of the total disturbed land has been certified as reclaimed land by the Government of Alberta (Grant et al., 2008). The reclamation process involves site reconstruction that includes significant landform creation and contouring. It also involves cover soil salvaging and replacement, seed collection, seeding, planting trees, fertilization, monitoring, and certification (Syncrude, 2013).

2.3.1. Landform creation and design

Several materials are used to reconstruct sites that were previously mined. These materials include organic materials (i.e. forest floor, muskeg, and peat materials), upland surface soils, subsoils, tailings sand, overburden, saline-sodic Clearwater-formation shales and lean oil sand (Rowland et al., 2009). Less productive waste materials including tailings sands are used to fill in the mine pit, and subsoil are then placed and contoured to create a new landform. A stable landform with a self-sustaining productive surface ecosystem is the ultimate goal of the reclamation process (OSVRC, 1998). Therefore, replacement of reclamation materials and contouring are important concerns for site reconstruction as it will ultimately influence the native ecosystem development. Landscape planning and design is generally determined by the reclamation objectives. Several factors such as slope steepness and position, erosion control, stoniness, water movement, and drainage are major considerations for recreating a functional landscape as well as a productive forest ecosystem (OSVRC, 1998). A checklist with proposed landscape design and activities (CEMA-RWG Landscape Design Subgroup, 2005) can provide better understanding for appropriate landform creation in the oil sands region.

2.3.2. Top soil salvage and replacement

Surface materials including organic matter and mineral soil are important for land reclamation in oil sands mining areas. Organic materials such as forest floor (LFH), muskeg, and peat materials are generally mixed with mineral soil or directly used as cover soil in oil sands reclamation operation (OSVRC, 1998). These materials are salvaged from natural boreal forest during mining, which are stockpiled or directly replaced on top of the contoured areas as surface layer to promote vegetation establishment (Pinno et al., 2012). It also helps to improve plant emergence and establishment in tailing sands (Mackenzie and Naeth, 2010). Overall, cover soil materials must be supportive to develop native plant communities (Singh et al., 2002; Sheoran et al., 2010).

During the excavation of surface, peat is over-stripped along with mineral materials. Incorporation of peat-mineral at a 60:40 peat to soil volume ratio is considered as suitable cover soil material in oil sands reclamation (Alberta Environment and Water, 2012). Most recently, forest floor (LFH) and upland surface soil are also considered as valuable reclamation materials, and immediate placement of these materials as surface layer provides essential plant nutrients, soil microbes, and reproductive plant parts (viable seeds and roots) which helps in improving revegetation success (Mackenzie and Naeth, 2010; Alberta Environment and Water, 2012). However, peat-mineral mix is still preferable due to more available volume of peat than LFH, and long term moisture retention uncertainty with LFH and upland surface soil.

There are two techniques such as 'one-lift' or 'two-lift' used for replacement of cover soils. In general, the one-lift option includes mixing of 25 to 50% of mineral soil with peat on volume basis and the subsequent spreading over the contour site to a depth of 15 to 50 cm (OSVRC, 1998; BGC Engineering Inc., 2010). In two-lift operation, top layer is 15 to 25 cm of cover soil mix placed over 50 cm middle layer of sandy or clayey subsoil that generally overlies the tailings sand or suitable overburden (OSVRC, 1998). Historically, the use of peat as amendment started by mixing with coarse-textured overburden or fine textured tailing sands to improve moisture retention and facilitate drainage, nutrient availability and soil organic matter content (BGC Engineering Inc., 2010). It largely depends on the quality of the mineral component to be used as cover soils. Research results indicate that increasing peat ratio to mineral mix also increases moisture content but it is not significant when the ratio changes from 1:1 to 3:1 (BGC Engineering Inc., 2010). However, the overall quality of cover soil can be reduced by manipulations, or long term stockpiling which may led to substantial amount of nutrient transformation and loss (Ghose, 2001; Sheoran et al., 2010). In addition, the surface layers of newly reconstructed sites are maintained as "loosely compact" to provide effective rooting zone for newly planted tree seedlings, which may increase erosion susceptibility. Therefore, management of newly constructed sites may include seeding cover crops and fertilizer addition in the reclamation plan.

2.3.3. Revegetation

The primary objectives of revegetation are to provide a diverse plant community that will minimize soil erosion by stabilizing soil and create 'equivalent land capability' before disturbance. The current revegetation program includes seeding of annual grasses and shrubs as ground cover and understory vegetation, and plantation of boreal tree species. Different cover crops that are non-persistent and non-invasive such as annual cereal crops and grasses are recommended to be used on reclamation sites. Planting of native tree species is important for restoring original ecosystem function and structure. Vegetation establishment success generally depends on several factors such as micro-environment, landform design and structure, drainage, reclamation materials, soil type, and soil moisture level (OSVRC, 1998). Use of upland surface soil is helpful for developing understory species as it is an authentic propagule source of upland boreal forest communities (Mackenzie and Naeth, 2010). In general, effective vegetation management throughout the plantation development process will help to create a forest ecosystem with desired plant communities.

2.3.4. Fertilization

Fertilizer applications have been considered as a tool for oil sand reclamation due to insufficient plant nutrient content in cover soils. For reclamation, the use of cover crop is helpful for seedling growth and may also require fertilization. Establishment of desired plant community with increased nutrient availability could be achieved by a standard fertilization application rate. At present, fertilizer application strategies involve a high rate of starter application followed by annual maintenance applications (Alberta Environment and Water, 2012). Previous research has indicated that repeated fertilization is helpful for oil sand reclamation by encouraging native species to rapidly create a functional ecosite (Rowland et al., 2009). On the other hand, over fertilization and continuous high application rates may result in increased mortality of planted tree seedling due to increased competition from herbaceous species (Alberta Environment and Water, 2012), and can be a major environmental quality concern. It is necessary to reduce nutrient losses to surface water for maintaining sustainable environmental quality through sound nutrient management practices. Therefore, fertilizer applications should be based on expected vegetative responses and requirement, utilizing tools such as soil and plant nutrient analysis.

2.3.5. Monitoring and certification

Monitoring activities starts after landform creation and vegetation establishment. Monitoring activities of the completed reclamation sites continues up to 15 or more years to ensure that the land is in stable condition (Government of Alberta, 2013). Mining operators are continuing research and conducting annual monitoring programs in reclaimed sites particularly on changes in soil properties, understory vegetation establishment as well as survival and growth assessment of trees and shrubs (OSVRC, 1998).

Reclamation certificates can only achieved by rebuilding the pre-disturbance conditions. If the site meet or exceeds the reclamation standards set by the government, the operators can apply for certification.

2.4. Re-establishment of Boreal Forest Ecosystem

The boreal ecosystem is influenced by a combination of several factors including local climate, landform, topography, soil characteristics, and natural disturbance, which also determined the vegetation pattern, stand productivity and successional development (Bonan and Shugart, 1989; Bridge and Johnson, 2000). Therefore, a better understanding on the natural boreal forest ecosystem can led to developing sustainable restoration approaches for the mined areas.

2.4.1. Natural boreal forest ecosystem in Canadian region

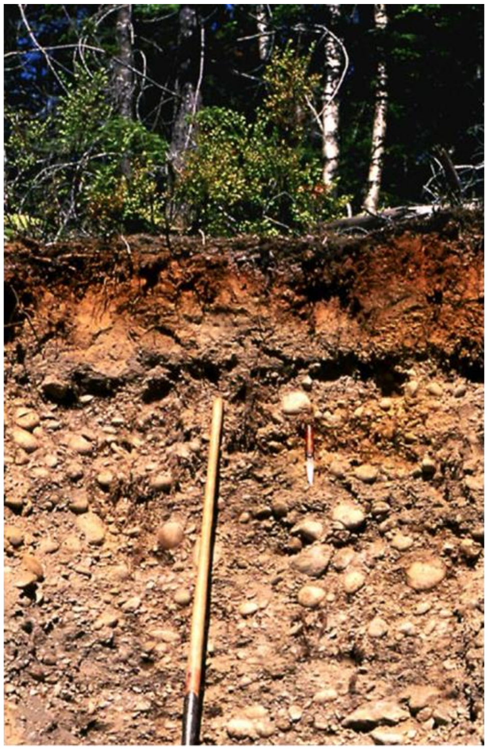
2.4.1.1. Extent

The circumpolar boreal forest is a globally important ecosystem covering approximately 11% of the earth's surface (Bonan and Shugart, 1989). The Canadian boreal region extends in a northwesterly direction from British Columbia and the Yukon Territory to Newfoundland and Labrador (Fig. 2.3). It covers seven out of fifteen Canadian eco-zones (Canadian Boreal Initiative, 2005) and is distributed across the boreal shield to boreal plain regions (Macdonald et al., 2012). One third of the world's boreal forest is within the Canadian region that covers 58% of the Canadian land area and contains diverse ecological and economic resources (Anielski and Wilson, 2005; Canadian Boreal Initiative, 2005). This region is rich in variety of natural resources that include minerals, coal, conventional and nonconventional oil and gas deposits (Macdonald et al., 2012). The number of industries and resource extraction activities in this region are rapidly expanding and subsequently results in large scale disturbance of the natural landscape (Schneider et al., 2003). In addition to anthropogenic disturbance, natural disturbance including forest fires, extreme weather, and insect infestations are frequent in these regions and affects vegetation structure, function, and forest ecosystem (Rich et al., 2010; Carlson et al., 2011).

Fig. 2.3. Map showing boreal forest distribution across the Canadian landscape (http://www.borealbirds.org/images/map-boreal-general.png).

2.4.1.2. Soils

In general, vegetation composition across the Canadian boreal landscape is mainly associated with the soil type and topographic conditions. Most common soils in the natural boreal forest are typically Podzols and Luvisols (Fig. 2.4). The majority of these soils are found in Canadian Shield along with the coastal area of Appalachican and western Cordilleran region (Macdonald et al., 2012). The soils found in oil sands regions include:Brunisols, Regosols, Solonetzic, Cryosols, Gleysols, and Organics (Macdonald et al., 2012). Brunisols are formed on sand, whereas medium- to fine-textured parent materials allow Luvisolic soil formation. Most of the upland mineral soils are Gleysols and Organic soils are found in low-lying areas. Saline-sodic parent materials are related to Solonetzic soils development, whereas permafrost influenced organic deposits result in formation of Cryosolic soils. About 30% of Canada's boreal landscapes are wetlands or peatlands, which also referred to as bogs, fens, marshes, swamps and shallow water (National Wetlands Working Group, 1997). Most of these peatlands usually developed on poorly drained, flat terrain or in depressions in the landscape. The peatland formation in boreal forest region is generally favoured by cool and wet soil conditions (Maltby and Proctor, 1996).




Podzol **Luvisol**

Fig. 2.4. Figure showing soil profile of the Podzol and Luvisol order (http://sis.agr.gc.ca/cansis/images/pr/index.html).

2.4.1.3. Climate

The Canadian boreal forest climate is characterized by strong seasonal variation that includes long, extremely cold winters and short, moderately warm summers. Average annual precipitation in the Fort MacMurray area is 455 mm, of which 342 mm is rainfall in summer and 155 mm is snowfall in winter (Environment Canada, 2013). According to Köppen-Geiger climate classification system the boreal forest is in *Dfc* climate category, where *D* indicates cold and snowy, *f* represents moist, and *c* for summer without dry season (Peel et al., 2007).

2.4.1.4. Vegetation

Naturally, black spruce (*Picea glauca* (Moench) Voss.) and tamarack (*Larix laricina*) are common tree species in in low-lying organic soils whereas coniferous-deciduous mixture is observed in upland sites. Fine-textured upland mineral soils are dominated by mosaic stands of trembling aspen (*Populus tremuloides* Michx.), balsam poplar (*Populus balsamifera* L.) and white spruce (*Picea glauca* (Moench) Voss.) and coarser soil covers jack pine (*Pinus banksiana*) forest

(Fung and Macyk, 2000) (Fig. 2.5). The understory vegetation of boreal forests are shrubs, herbs (forbs), grasses, mosses and lichens. Characteristic understory shrubs include *Rosa acicularis* (prickly wild Rose), *Alnus crispa* (green alder), *Viburnum edule* (low bush cranberry), *Vaccinium vitis-idaea* (lingonberry/bog cranberry), *Ribes triste* (wild red currant), *Linnea borealis* (twinflower), *Amelanchier bartramiana* (mountain juneberry), *Lonicera involucrata* (*twinberry* honeysuckle), *Rubus idaeus* (wild red raspberry), *Rubus parviflorus* (thimbleberry), *Rubus pubescens* (dwarf raspberry), *Ribes lacustre* (bristly black currant), and *Salix bebbiana* (bebb's willow/beaked willow) (Strong et al., 1991; Macdonald and Fenniak, 2007). Common herbaceous species include *Aster ciliolatus* (ciliolate aster), *Actaea rubra* (red baneberry), *Vicia americana* (american vetch), *Pyrola asarifolia* (pink pyrola), *Fragaria virginiana* (common strawberry), *Lathyrus ochroleucus* (creamy ceavine/pale vetchling), *Epilobium angustifolium* (fireweed), *Osmorhiza depauperata* (bluntseed sweetroot), *Orthilia secunda* (one-sided pyrola), *Equisetum sylvaticum* (horsetail), *Pyrola chlorantha* (green-flowered pyrola), *Goodyera repens* (dwarf rattlesnake plantain), *Aralia nudicaulis* (wild sasparilla), *Achillea millefolium* (common yarrow), *Arnica cordifolia* (heartleaf arnica), *Calypso bulbosa* (fairy slipper), *Cornus canadensis* (bunchberry), *Coptis trifolia* (goldthread), *Delphinium glaucum* (sierra larkspur), *Draba breweri* **(c**ushion draba**),** *Equisetum pratense* (meadow horsetail), *Galium triflorum* (*fragrant bedstraw*), *Heracleum maximum* (common cowparsnip), *Lathyrus ochroleucus* (cream pea), *Ledum groenlandicum* (*bog labrador tea*), *Maianthemum canadense* (*Canada mayflower*), *Mertensia paniculata* (northern bluebell), *Mitella nuda* (*naked mitrewort*), *Viola renifolia* (kidney-leaved violet), *Vaccinium myrtilloides* (Canada blueberry), *Streptopus roseus* (rose twisted stalk); *Streptopus amplexifolius* (claspleaf twistedstalk), *Petasites palmatus* (sweet coltsfoot), *Maianthemum racemosum* (treacleberry, false solomon's seal**)** (Strong et al., 1991; Macdonald and Fenniak, 2007). Common Graminoids are *Calamagrostis canadensis* (blue-joint grass) and *Elymus innovatus* (hairy wildrye) (Strong et al., 1991; Macdonald and Fenniak, 2007). Mosses, lichens and saprophytic fungi are often abundant on wetter areas. Common species include *Lycopodium annotinum* (stiff clubmoss), *L. clavatum* (running ground pine), *L. obscurum* (ground pine), *Athyrium filix-femina* (lady fern), *Gymnocarpium dryopteris* (western oakfern) (Strong et al., 1991; Macdonald and Fenniak, 2007). The diversity of understory plant communities is much greater than tree species in the boreal region and is mainly due to wide range of ecological tolerance capability (Rowe, 1956; Macdonald et al., 2012).

Fig. 2.5. Vegetation of boreal forest showing mosaic of stands dominant by conifer and broadleaf trees (http://spaceinimages.esa.int/Images/2008/10/Boreal_forest).

2.4.1.5. Ecological succession

The temporal dynamics of boreal forest, particularly post-disturbance successional development is important for understanding the ecosystem function and sustainable resource management. The species composition and structure of boreal forest is often influenced by anthropogenic and frequent natural disturbance, where many of the species have shown better adaptability to post-disturbance environment (Chen and Popadiouk, 2002). The shade-intolerant tree species such as aspen, poplar and pine are found to establish first, while shade-tolerant conifers are prominent in the next stage (Chen and Popadiouk, 2002; Macdonald et al., 2012). Following natural disturbance, the re-established mixedwood boreal forests are showing the vegetation pattern of fast-growing aspen as an overstory over slow-growing white spruce (Peterson and Peterson, 1992; Macdonald et al., 2012). Similar to tree species, herbaceous species of understory vegetation with fast-growing and shade-intolerant properties are found to first dominate post-disturbance boreal forest sites (Archibold, 1979; Macdonald et al., 2012). In addition, re-established understory species have wide ecological tolerance, greater seed viability and dispersal capability, and reproductive vegetative propagules, thus immediately regenerates on post-disturbance sites (Archibold, 1979; Lee, 2004). However, post-disturbance regeneration and vegetation dynamics in boreal forest is a complex process that may be influenced by several factors including disturbance severity, relative abundance and ecological properties of species, soil resource (light, moisture and nutrients) availability and environmental conditions (Chen and Popadiouk, 2002; Frelich et al., 2003; Macdonald and Fenniak, 2007; Macdonald et al., 2012).

2.4.2. Restoration of boreal ecosystem on reclaimed sites

Plantation of native tree species is currently practiced in reestablishing the boreal forest ecosystem on reclaimed sites. Mixed plantation of early and late successional tree species is considered to be a productive approach to ensure an induced forest ecosystem similar to native forest (Macdonald et al., 2012). Direct seeding of understory vegetation species is extremely limited on reclaimed sites due to lack of appropriate seed source, growing medium and microclimates for seed germination (Macdonald et al., 2012). As tree seedlings are planted on reconstructed sites, soil-vegetation relationship is therefore important for accelerating reestablishment success (Macdonald et al., 2012). In oil sands region, reclamation begins with site reconstruction where suitable cover soil materials are used to cap the reconstructed mineral soils to ensure effective rooting zone for planted tree seedlings, which is an important consideration for forest reestablishment (Burger et al., 2005; Macdonald et al., 2012). In addition, establishment of newly planted tree seedlings is largely influenced by initial soil moisture and nutrients content (Nilsson and Allen, 2003; Van den Driessche et al., 2005; Guillemette and DesRochers, 2008; du Toit et al., 2010) that could be improve by mixing peat or forest floor materials with mineral soils (Alberta Environment and Water, 2012). Considering the availability, peat is frequently used in oil sands reclamation. Forest floor materials stripping from pre-mining upland areas is considered as a rich source of native plant seeds and propagules that will help understory vegetation development (Mackenzie and Naeth, 2010) and also effective to stimulate soil microbial activity in reclaimed sites (McMillan et al., 2007). Once site reconstruction is completed, annual grasses are seeded as a part of site management and revegetation process, which helps in stabilizing soil, control erosion, and tree seedling protection.

Early establishment of tree seedlings is often affected by limited growth resources including light, temperature, moisture, and nutrients that are affected by vegetative cover competition (Nilsson and Allen, 2003; Moffat, 2004; Van den Driessche et al., 2005; Casselman et al., 2006; Guillemette and DesRochers, 2008; du Toit et al., 2010). Moreover, differences in growth habit and competition sensitivity of different tree species may play an important role in establishing forest dynamics similar to the natural boreal forest. Oil sands reclamation is still progressing, therefore, considering the challenging factors, long-term planning is required to ensure restoration success in reclaimed sites.

2.5. Possible Factors Affecting Tree Seedling Establishment

Forest plantation development following disturbance is a complex process that largely depends on successful establishment of newly planted tree seedlings. Several biotic and abiotic factors are found to affect the early establishment and growth of tree seedlings when assembling a forest stand by planting or natural regeneration. However, in reclaimed sites, the identifiable abiotic factors include soil moisture and nutrient availability, while ground cover vegetation is abiotic factor that can restrict availability of the previously mentioned resources available for the planted tree seedlings.

2.5.1. Effect of soil moisture

Soil moisture is an important resource for the growth and establishment of newly planted tree seedlings. Planted tree seedlings are often exposed to soil moisture stress due to limited contact between roots and soil, and subsequent reduced root growth immediately after planting (Grossnickle, 2005; Van den Driessche et al., 2005). Moisture stress that can occur after transplantation is serious as it may not only decrease plant growth but also increases mortality of recently planted tree seedlings. In addition, several physiological processes including photosynthesis, stomatal conductance, and transpiration are reduced by increased soil moisture stress (Jacobs et al., 2009; Xu et al., 2010). A recent study conducted by Man and Greenway (2013) in Alberta reported that the early growth of aspen and white spruce is decreased greatly by increased moisture stress.

Soil moisture stress can be influenced by different soil properties like soil texture, salinity and hydraulic conductivity. Competition from other vegetation with planted tree seedlings is also another cause of water depletion (Passioura, 1996). During seedling establishment, grass competition is the main biotic cause of water stress (Lamhamedi et al., 1998; Picon-Cochard et al.,

2001) that can decrease soil water availability (Löf and Welander, 2004; Picon-Cochard et al., 2006; Dinger and Rose, 2009; Dinger and Rose, 2010). Improved establishment and early growth of tree seedlings can be achieved by efficient moisture management techniques including irrigation and controlling competing vegetation (Strong and Hansen, 1991; Nilsson and Allen, 2003; Van den Driessche et al., 2003).

2.5.2. Effect of ground cover vegetation

Vegetation cover and grasses that are similar to that found on the adjacent undisturbed ground are helpful in managing reconstructed mine sites and re-creating functional ecosystem (Rowland et al., 2009). Cover crops such as annual cereals are also helpful in absorbing and recycling soil nutrients (Sundermeier, 2010). Due to high adaptability on disturbed sites, native grasses are potentially used for mine land reclamation and restoration (Burton and Burton, 2003). The fibrous root system of grasses generally helps soil aggregation in the surface layer. Considering the saline-sodic nature of some reclamation materials (tailing sands and overburden), barley (*Hordeum vulgare*) is being used as a pioneer species to provide vegetation cover as it shows some salt tolerance capability (Renault et al., 2003). In addition, a mixture of annual grasses and shrub species are planted in reconstructed mine sites to develop an understory boreal community and to provide protective cover for surface soil and tree seedlings, but interaction with planted tree seedlings is still unknown.

Balandier et al., (2006) reviewed different interaction mechanisms of planted tree seedlings with surrounding vegetation including graminoids, forbs and shrubs, and reported that, tree seedling survival and growth are most often negatively affected due to competition for resources. Different physiological attributes like rapid growth, dense root system and ecological tolerance capability of competing vegetation are allowing them to dominate over the newly planted tree seedlings (Balandier et al., 2006). For example, perennial grasses have a shallow, fibrous, and dense root system that usually localized within the same soil horizon of tree roots during establishment, and therefore strongly restricts tree seedling root proliferation and nutrient uptake (Hangs et al., 2003; Balandier et al., 2006). In high resource environments, fast-growing herbaceous species are very effective competitors to reduce tree growth by limiting available space and light as they can shadow tree seedlings (Richardson et al., 1999; Grime, 2001). Survival of fast-growing tree species is also reduced in low light environments (Balandier et al., 2006).

The negative effects of competing vegetation on tree seedling establishment and early growth are well documented in the forestry literature (e.g., Morris et al., 1993; Hangs et al., 2003; Coll et al., 2003; Balandier et al., 2006). Therefore, competing vegetation management by applying herbicide or mechanical site preparation is widely practiced for plantation forest (Allen et al., 1990; Allen and Albaugh, 2000; Albaugh et al., 2012), but undesirable for reclaimed site. Moreover, the benefits of controlling competition often vary by tree species (Lanini and Radosevich, 1986; Wagner et al., 1996; Zutter et al., 1997), site quality (Powers and Reynolds, 1999; Zhang et al., 2006; Devine et al., 2011) and silvicultural treatments (Haywood et al., 1997; Van den Driessche et al., 2003). Thus, this project aims to develop efficient vegetation management techniques in improving plantation establishment on reclaimed sites.

2.5.3. Effect of soil fertility and nutrient management

Vegetation re-establishment on disturbed mine sites is often difficult due to reduced plant performance in low fertility soil (Classen and Zasoski, 1993; Renault et al., 2003). In newly constructed mine sites, peat and forest floors are commonly used reclamation materials that help to create a functional soil surface layer to promote vegetation growth (Macdonald et al., 2012). The physico-chemical properties including essential plant nutrient content of different reclamation materials are different (Rowland et al., 2009; Turcotte et al., 2009; Pinno et al., 2012). These properties largely depend on the preexisting forest type, peat, and mineral soil from where they are stripped out. For example, most of the boreal forest soils in Alberta regions are naturally deficient in phosphorus (Strong and La Roi, 1985). Peat-mineral mix is sometimes found to be deficit in phosphorus, potassium and some micronutrients (Alberta Environment and Water, 2012). Furthermore, nitrogen can be a major limiting nutrient in salvaged soil materials due to disturbance, long-term stockpiling and manipulation, which favours substantial amount of nitrogen transformation and subsequent losses (Sheoran et al., 2010). Therefore, nutrient is recommended to be added in the form of fertilizer to maintain healthy growth and establishment of vegetation.

Fertilization is one of the key tools to improve a forest plantation by addressing limitations in available plant nutrients. Several studies (Nilsson and Allen, 2003; Van den Driessche et al., 2003; Van den Driessche et al., 2005; Jacobs et al., 2005; Guillemette and DesRochers, 2008; du Toit et al., 2010) reported that survival and early growth of planted tree seedlings were increased by fertilizer addition. In addition, nutrient availability to planted tree seedlings can be achieved by the control of competing vegetation (Allen et al., 1990; Allen and Albaugh, 2000; Albaugh et al., 2012). However, the positive response of fertilization may vary with site characteristics, tree species, and control of competing vegetation (Brockley 1988; Rose and Ketchum, 2001). Increased growth of aspen seedlings with fertilizer addition was observed in different reclamation soils (Pinno et al., 2012). Another fertilization study conducted in oil sands region of northern Alberta reported that white spruce seedling growth significantly increased by fertilization, while aspen did not respond effectively (Sloan and Jacobs, 2013). In reclaimed site, field fertilization is helpful in developing native vegetation's to recreate functional ecosystem (Rowland et al., 2009), but the interaction of planted tree seedlings with planted cover crops is still unknown.

3. The Effect of Cover Crop Species on Growth and Yield Response of Tree Seedlings to Fertilizer and Soil Moisture on Reclaimed Sites

3.1. Preface

Alberta's oil sands are primarily located within the boreal forest region. Establishment and early growth of newly planted tree seedlings in reclaimed oil sands sites are thought to be restricted by low soil fertility, and competition from weeds and planted cover crops that are generally used to stabilize soil and control erosion. Field fertilization with a single rate and blend of fertilizer is currently practiced in oil sands reclamation, under the assumption that it will alleviate nutrient competition and accelerate tree seedling growth. This study was conducted to determine the response of tree seedlings (aspen and white spruce) grown on reclaimed oil sands soil to fertilization and moisture, without and with competition from commonly used cover crop species (barley and oats), under controlled environment conditions. Conducting this study under controlled environment (greenhouse) conditions allowed the nature of intra and interspecific competition to be evaluated under known, controlled conditions of temperature, moisture, and homogenized soil and with complete weed control, so as to reduce variability and allow treatment effects to be clearly elucidated. This assessment will allow to compare potential effects of oats and barley on survival and growth of tree seedlings on reclaimed oil sands to guide future field operations. The greenhouse study was followed by a similar set of treatments evaluated at the oil sands and described in Chapter 4, which allowed evaluation under field conditions.

3.2. Abstract

Several grass species are being screened to identify appropriate cover crops for stabilizing recently reclaimed oil sands sites and for nursing newly planted tree seedlings on these sites. Besides soil erosion control, cover crops can influence the establishment success of tree seedlings by regulating the impacts of nutrients, moisture, and light on early survival and growth. However, interspecific interactions determining the net effects of these resources on tree seedling establishment in the oil sands region are not clearly understood. This study evaluated growth and yield responses of trembling aspen (*Populus tremuloides* Michx.) and white spruce (*Picea glauca* (Moench) Voss.) seedlings to fertilizer, soil moisture, and cover crop species using a bioassay factorial experiment. The objective was to characterise the effects of intra and interspecific

interactions on growth of tree seedlings as related to fertilization and soil moisture. Barley (*Hordeum vulgare*) and oats (*Avena sativa*) were used as cover crops because these herbaceous species are being recommended for oil sands reclamation operations.

Significant differences in height and root collar diameter (RCD) growth increments after fertilization were attributed to differential growth rates between tree species. Overall, fertilization had limited impact on tree seedling growth and biomass yield. In contrast, increasing soil moisture to optimal conditions stimulated height, shoot and root biomass yields of tree seedlings. Cover crop species largely controlled growth and yield responses of tree seedlings to fertilizer and soil moisture. Even with fertilization, RCD increment and shoot biomass yield were reduced by 26–51% and 36–68%, respectively by the cover crops relative to the no vegetation treatment. Comparatively the suppressive effect of barley was higher than that of oats. Competition from ground cover vegetation may adversely affect early growth and yield of tree seedlings on reclaimed oil sands sites by inducing or augmenting the effects of nutrient limitation and moisture stress. However, revisiting fertilizer recommendations to account for nutrient uptake by the competing vegetation may be the appropriate approach for enhancing tree seedling growth in the oil sands region because cover crops are planted for stabilizing recently reclaimed sites. This approach, however, needs to consider the observed species-specific response to weed competition, and responses to fertilization may be overshadowed by induced water consumption by the ground cover vegetation, especially under water limited (drought) conditions.

3.3. Introduction

A key component of successful land reclamation is re-vegetation to stabilize soils and restore ecosystems functions equivalent to the productive forest. A common re-vegetation technique in reclaimed sites is planting of native tree species along with ground cover vegetation (OSVRC, 1998), and its success largely depends on how well the newly planted tree seedlings are able to survive and grow. These sites however, are generally difficult to regenerate successfully since the early survival and growth of planted tree seedlings is often restricted by several factors including poor soil fertility status, and competition from ground cover vegetation (Moffat, 2004; Casselman et al., 2006). As well, newly planted tree seedlings may be exposed to potential soil moisture and nutritional stresses due to a confined root system in the planting hole and limited root growth just after planting (Grossnickle, 2005; Van den Driessche et al., 2005). Nambiar and Sands (1993) reported that water and nutrient deficiencies can arise from vegetation competition even in sites not limited in resources. In recently reclaimed sites, competition between cover crops and planted tree seedlings for allocated resources might have adverse effects on outplanting success. However, these limitations could be overcome by efficient resource management and adopting appropriate silvicultural practices.

Addition of supplemental nutrients and water through fertilization and irrigation are forest management practices that have been used to improve plantation establishment as well as early growth of trees. Several researchers (Allen et al., 1990; Nilsson and Allen, 2003; Van den Driessche et al., 2005; Guillemette and DesRochers, 2008; du Toit et al., 2010) reported that soil nutrient availability and tree seedling growth were increased by fertilization at planting. Increased growth of tree seedlings was also observed in an irrigation study in Wisconsin, USA (Strong and Hansen, 1991). Furthermore, fertilization in combination with irrigation was most effective in promoting tree seedlings growth (Sands and Mulligan, 1990; Van den Driessche et al., 2005). However, in forests of western Canada, irrigation is generally not practically feasible. In addition, overall resource reallocation to the target tree seedlings can be accomplished by controlling competing vegetation, such as through herbicide application or mechanical removal (Allen et al., 1990; Allen and Albaugh, 2000; Albaugh et al., 2012). Still, access, cost and labor considerations likely limit widespread application of vegetation control practices in native forests.

Although the benefits of eliminating competing vegetation in establishing plantations are well recognized (Wagner et al., 2006), in reclaimed sites the presence of competing vegetation like native and/or planted cover crops is of interest and of potential benefit due to the impact on stabilizing soils and minimizing erosion (OSVRC, 1998; Renault et al., 2003). Along with some native grass species, barley (*Hordeum vulgare*) and oats (*Avena sativa*) are the recommended cover crops for surface mining site reconstruction (OSVRC, 1998), where the beneficial or detrimental effects of cover crops on planted tree seedlings are not clearly understood.

The effect of surrounding vegetation on plantation establishment are dependent of several factors such as tree species (Wagner et al., 1996; Zutter et al., 1997), site quality (Powers and Reynolds, 1999; Zhang et al., 2006), silvicultural treatments (Haywood et al., 1997; Van den Driessche et al., 2003), and vegetation composition (Coll et al., 2003; Balandier et al., 2006). For example, the competitive effect of grasses is extremely high in the first year of seedling establishment, and the competition is reported to be mainly for water and nutrient resources (Balandier et al., 2006). The shallow and dense root system of grasses strongly hampers root growth of newly planted tree seedlings within the same soil horizon, and subsequently restricts growth and resource uptake (Hangs et al., 2003; Balandier et al., 2006). However, resources like nutrients and moisture may modify plant interaction mechanisms that are reflected in the survival and growth of tree seedlings that are planted in reclamation sites. To the best of our knowledge, such studies are lacking for the oil sands region.

To address these limitations in our understanding, a bioassay experiment was conducted in a greenhouse under controlled conditions with the following objectives: 1) to evaluate how cover crops interact with nitrogen, phosphorus, and potassium (NPK) fertilizer amendment to influence (improve or hamper) early growth of tree seedlings, and 2) determine if soil moisture influences such interactions. In addition, this study is part of a major research effort directed towards improving fertilizer prescriptions for the successful establishment of tree seedlings, in order to minimise operation and environmental costs associated with high inputs of mineral fertilizers and/or organic amendments on reclaimed sites.

3.4. Materials and Methods

3.4.1. Experimental design, treatments and management

This study adopted a 2 x 2 x 3 x 3 factorial experiment laid out in a randomized complete block (RCB) design with four replicates in a greenhouse. Factors tested include tree species (trembling aspen and white spruce), soil moisture at different levels (with and without moisture stress), the addition of NPK fertiliser at 0, 700 (half rate), and 1400 kg ha^{-1} (full rate); and cover crop grass species (control, barley, oats). Barley and oats were used as test crops because these species are recommended for oil sands reclamation operations. Fertilizer rates are based on Suncor's typical field application rates of NPK (23.5-25-8) fertilizer. Considering the low fertility status of the reclamation materials, anticipated competition between tree seedlings and cover crops, and restricted root growth in pots, we used comparatively higher fertilizer rates than the current field application rates (in the range of 300 kg ha^{-1}) in oil sands reclamation. A commercial water soluble fertilizer (plant-prod 20–20–20); containing 20, 9, and 17% of N, P, and K respectively was used for this study. The materials and proportions of N,P,K in the fertilizer blend were urea nitrogen (10.25%), ammoniacal nitrogen (3.85%), nitrate nitrogen (5.90%) available phosphoric acid (20% P_2O_5), and soluble potash (20% K_2O). The fertilizer mixture was applied in solution as three equal splits on week 1, 4, and 8 after planting throughout the experimental period. Soil moisture was maintained at 80% and 40% of field capacity for the no water stress and water stress treatments, respectively. Equal amounts (12 ± 1 kg) of the peat-mineral mix cover soils used for Suncor's reclamation operations was placed in each plastic pot (30 cm diameter and 24 cm depth). Some important properties of peat-mineral mixture are presented in Table 3.1.

Table 3.1. Some selected characteristics of peat-mineral mixture used in greenhouse study.

Bulk density	**FC¶**	**pH**	**EC†**	**OC‡**	**Available N**		**Available P**	**Extractable K**
					NO_3^--N	**NH_4^+-N**		
(g cm^{-3})	(%)		(mS cm^{-1})	(%)	----------------------(mg kg^{-1})---------------------			
0.57	60.0	6.95	0.61	11.25	18.69	42.01	3.65	118

¶FC, field capacity on volume basis; †EC, electrical conductivity; ‡OC, organic carbon

Soil moisture content at field capacity was determined prior to planting seedlings by watering the pots with distilled water and draining the pots for 24 hours. The process was repeated for three days to achieve full saturation (Salifu and Timmer, 2003). On each day, containers were weighed and soil samples collected for gravimetric moisture content determination at 105 °C. Then the volume of water at field capacity was calculated and used as a basis for determining the volume of water required to maintain soil moisture at 80% and 40% field capacity. Moisture stress was induced by withholding irrigation until soil water content declined to 40% field capacity. This treatment was initiated two weeks after establishing the experiment to allow roots of tree seedlings and grass to develop initially. Thereafter, a hand held Time Domain Reflectrometry (TDR) meter (TDR 100) was used to monitor volumetric soil moisture content in pots at the predetermined moisture levels (40% and 80%) throughout the experimental period.

Tree seedlings and grass seeds were planted on October 30, 2010 and grown until February 20, 2011 (for 16 weeks) corresponding to one growing season. Tree seedlings used for this study were one-year-old nursery-grown and winter-stored seedlings, which were supplied as 1+0 container planting stock. For each treatment, two tree seedlings were planted in the middle of each pot and assigned grass seeds were symmetrically placed around the tree seedlings. Six grass plants in each pot with at least 8 cm distance between tree seedlings and grass was maintained throughout the experimental period. Four racks, each containing 36 pots with all treatment combinations were placed side by side under the lights in a greenhouse chamber. Plants were grown under an 18 hours photoperiod where photon flux density ranged from 42 to 498 µmol m^{-2} s^{-1}. Throughout the experimental period average day and night temperature was 22 °C and 20 °C, respectively and relative humidity was approximately 31%.

3.4.2. Seedling growth data collection

Tree seedlings were measured for height and root collar diameter (RCD) at two week intervals using a tape and digital vernier caliper. To account for the variation of tree seedling size, initial measurements were taken immediately after planting and used for calculating height and RCD growth increments. At the termination of the experiment, all tree seedlings and grass plants were harvested and partitioned into shoot and root biomass components for oven-dry weight determination at 70 ^{o}C. Prior to oven drying, root samples were washed under a 0.5 mm sieve to remove soil materials. Plant components were then ground and plant tissue nutrient analysis was performed in the laboratory. Post-harvest soil samples were air dried, ground to < 2 mm particle size and analyzed for residual available nutrients.

3.4.3. Analytical methods

Electrical conductivity (EC) and soil pH were measured in a soil-water suspension with a ratio of 1 part soil:2 parts water using a Fisher AP85 pH/conductivity meter (Hendershot et al., 2007a; Miller and Curtin, 2007). Organic carbon (OC) content was determined using the LECO-C632 carbon analyzer (LECO© Corporation, 1987) set at 813 ^{o}C (Skjemstad and Baldock, 2007). Bulk density was measured using the core sampling method. Soil available N (NH_4^+ and NO_3^-) was determined using 2.0 *M* KCl extractant (Keeney and Nelson, 1982), and modified Kelowna extraction method was used for available P determination (Qian et al., 1994), followed by automated colorimetry using Technicon Autoanalyzer II to determine ion concentration in the extract. For K extraction NH_4OAC extraction was performed (Hendershot et al., 2007b). Plant tissue digestion was completed for total N and P determination by following a standard H_2SO_4-H_2O_2 digestion method (Thomas et al., 1967). Soil and plant extracts were then analyzed colorimetrically for N and P concentrations using a Technicon II autoanalyzer (Technicon Instruments Corp. NY, USA). Extractable K concentration in soil samples was analyzed using Atomic Absorption spectrometry (SpectrAA 220, Varian).

3.4.4. Statistical analysis

Testing of the assumption of homogeneity of variance and normality distribution were conducted on all data prior to conducting the analysis of variance (ANOVA). No data transformations were required as all data were homogeneous and normally distributed. Data were analyzed according to experimental design using the mixed-model procedure in the statistical analysis system (SAS Institute Inc., 2010). Fertilizer rate, soil moisture, tree and grass species, and interactions of these factors were fixed effects variables, while block and block-by-treatment interaction were random effects variables in the model. Following ANOVA significant treatments were compared using Tukey's studentised range test at 5% probability levels.

3.5. Results

3.5.1. Height and diameter growth

Fertilizer and soil moisture significantly interacted with tree species and increased seedling height and RCD growth (Fig. 3.1). With and without fertilization, height ($p = 0.0009$) and RCD ($p = 0.0253$) growth of trembling aspen seedlings were significantly higher than corresponding growth of white spruce seedlings (Fig. 3.1a and 3.1b). Apparently, significant fertilizer-by-species interactions on height and RCD increments largely reflect rapid initial growth of trembling aspen seedlings because white spruce seedlings showed little response to fertilization over the entire experimental period (Fig. 3.1a and 3.1b). Height and RCD growth of trembling aspen seedlings increased by 18–29 cm and 1.7–3.2 mm, respectively and by 2.8–3.1 cm and 1.7–3.2 mm for white spruce seedlings. Soil moisture stress also reduced growth of tree seedlings, especially height increments of trembling aspen (Fig. 3.1c and 3.1d). On the other hand, height and RCD growth of white spruce seedlings were generally little affected by fertilizer inputs and soil moisture availability (Fig. 3.1a to 3.1d), possibly reflecting low resource demand due to slow initial growth rate.

Apparently, interspecific competition modified seedling response to fertilizer and soil moisture (Fig. 3.2). With and without fertilizer addition, barley and oats suppressed height growth of tree seedlings by 50% (Fig. 3.2a and 3.2b). The effects were significant for RCD at half and full rates, indicating that suppressive effects of these cover crop grass species could not be overcome by fertilization. Fertilization of cover crops may further increase demand for moisture and uptake of other nutrients not supplied in the fertilizer. Cover crop grass species reduced both height ($p = 0.0007$) and RCD ($p = 0.0018$) of tree seedlings at 40% and 80% field capacity (Fig. 3.2c and 3.2d).

The overall effects of grass competition for nutrients and soil moisture were more pronounced in trembling aspen seedlings than for white spruce seedlings (Fig. 3.2e and 3.2f). Both RCD ($p < 0.001$) and height ($p < 0.001$) of trembling aspen seedlings in mixture were reduced by 54% and 63% in barley treatments compared to 47% and 46% in oats treatments. These results indicate that trembling aspen seedlings were more sensitive to interspecific competition and barley competed more strongly for growth resources than oats.

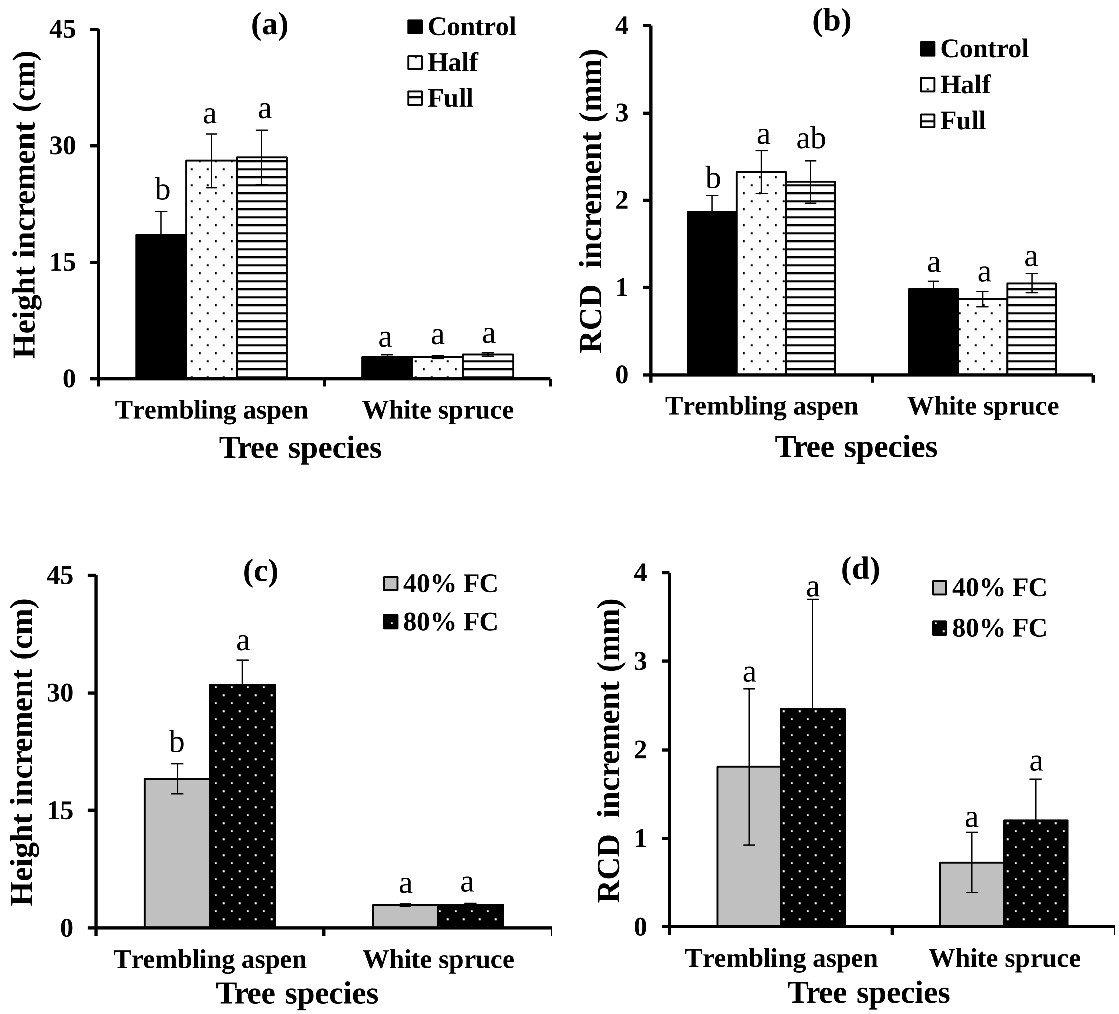


Fig. 3.1. Height and root collar diameter (RCD) growth response of tree seedlings to NPK fertilizer (a–b) and soil moisture at different levels (c–d) after 16 weeks growth in a greenhouse bioassay experiment. Application rates of the 20–20–20 NPK fertilizer were: control = no fertilizer, half = 700 kg ha^{-1} and full = 1400 kg ha^{-1}. Vertical bars indicate standard error of means (n = 4). Columns in each treatment followed by the same letter are not significantly different ($p > 0.05$).

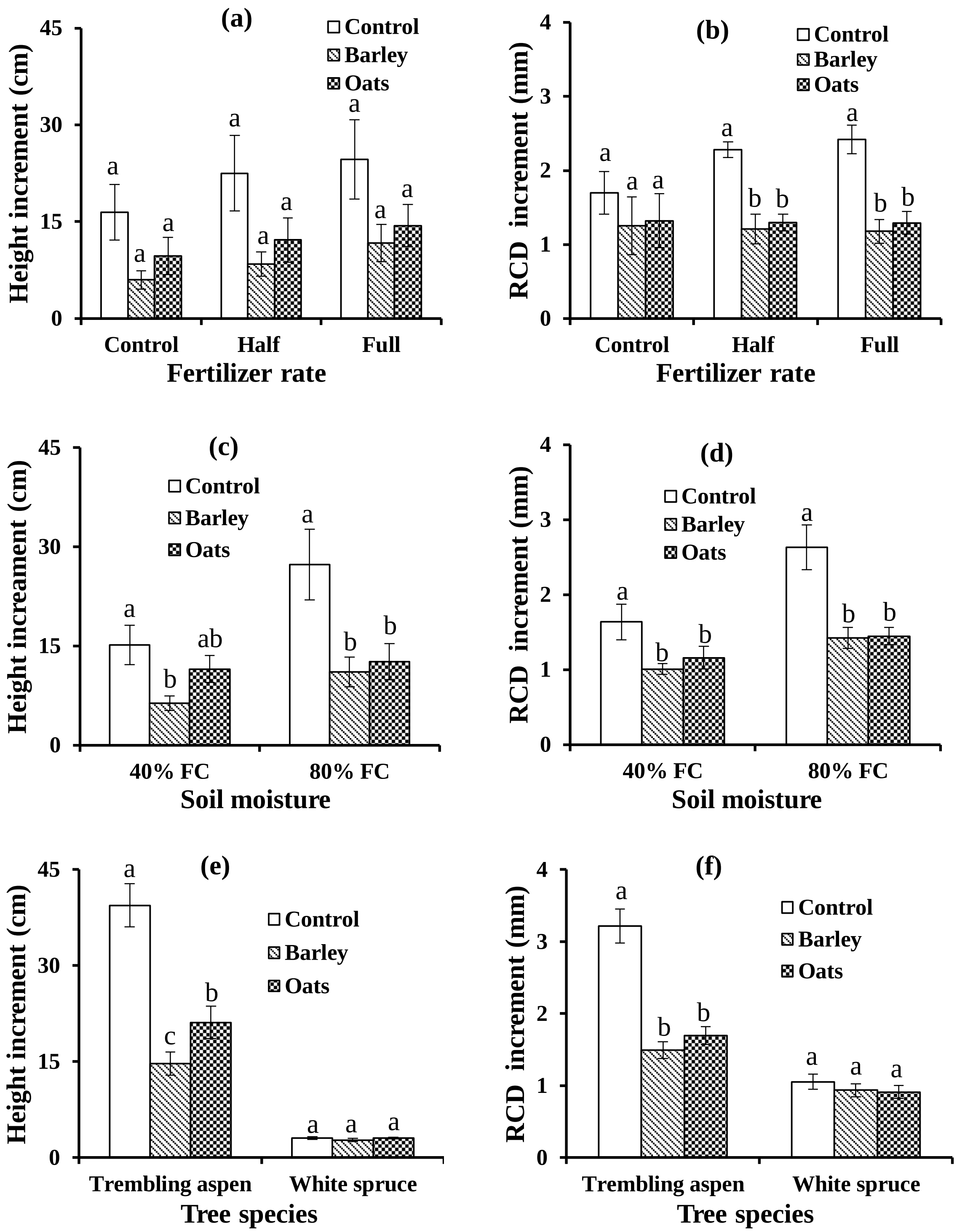


Fig. 3.2. Height and root collar diameter (RCD) increments of tree seedlings for the interactions between cover crops and fertilizer (a–b) or soil moisture at different levels (c–d) or tree species (e–f) after 16 weeks growth in a greenhouse bioassay experiment. Application rates of the 20–20–20 NPK fertilizer were: control = no fertilizer, half = 700 kg ha^{-1} and full = 1400 kg ha^{-1}. Vertical bars indicate standard error of means (n = 4). Columns in each treatment followed by the same letter are not significantly different (p > 0.05).

3.5.2. Biomass yield of tree seedlings

Fertilizer application did not significantly increase shoot and root biomass yields of trembling aspen and white spruce seedlings (Fig. 3.3a and 3.3b). Trembling aspen seedlings exhibited a 30 % decrease in root biomass ($p = 0.0123$) and a 50% decrease in shoot biomass ($p < 0.0001$) at 40% field capacity compared to 80% field capacity (Fig. 3.3c and 3.3d). These yield reductions corroborate earlier results that soil moisture was probably the main factor driving seedlings growth (Fig. 3.1c and 3.1d).

Fertilization doubled shoot biomass ($p = 0.0191$) and root biomass ($p = 0.0101$) yields of tree seedlings in the no grass treatment relative to barley and oats treatments (Fig. 3.4a and 3.4b). Similar results were also noted for shoot and root biomass at 40% and 80% field capacity (Fig. 3.4c and 3.4d). As mentioned earlier, the increase indicates that cover crops suppressed yield response of tree seedlings to fertilizer and soil moisture. This effect was more pronounced for trembling aspen seedlings compared to white spruce seedlings (Fig. 3.4e and 3.4f).

3.5.3. Biomass yield of cover crops

Biomass yield of barley interplanted with tree seedlings was higher than that of oats (Table 3.2). This is consistent with the greater negative effect of barley on aspen growth parameters compared to oats as noted in the previous section. Overall, fertilization doubled biomass yield relative to unfertilized control. Yields of cover crops were also increased by 50% at 80% field capacity relative to the moisture stressed 40% of field capacity condition. These results indicate that fertilizer addition can benefit cover crop growth and protective surface cover in recently reclaimed sites, but as noted may have little impact on enhancing tree seedling growth or reduce it due to competitive effects. Trembling aspen reduced yields of cover crop species by 14% compared to white spruce, possibly due to high resource demand associated with the rapid initial growth of this species. Unlike tree seedlings, biomass yields of barley and oats were not affected by treatment interactions ($p > 0.05$), indicating that these cover crops accessed sufficient amount of resources, especially at the vegetative growth periods, because of initial faster growth rates compared to the tree component.

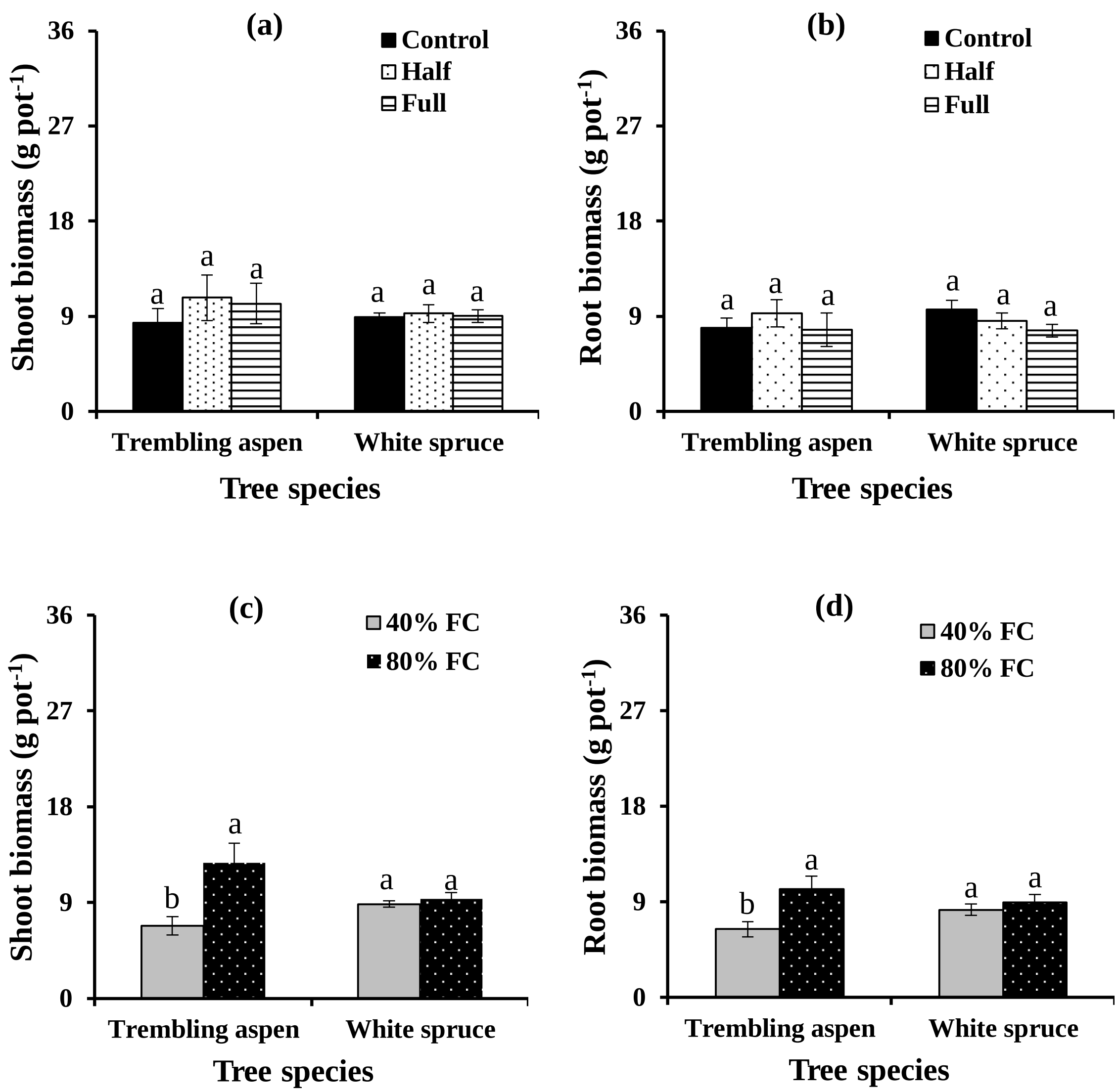


Fig. 3.3. Shoot and root biomass yield response of tree seedlings to NPK fertilizer (a–b) and soil moisture at different levels (c–d) after 16 weeks growth in a greenhouse bioassay experiment. Application rates of the 20–20–20 NPK fertilizer were: control = no fertilizer, half = 700 kg ha^{-1} and full = 1400 kg ha^{-1}. Vertical bars indicate standard error of means (n = 4). Columns in each treatment followed by the same letter are not significantly different ($p > 0.05$).

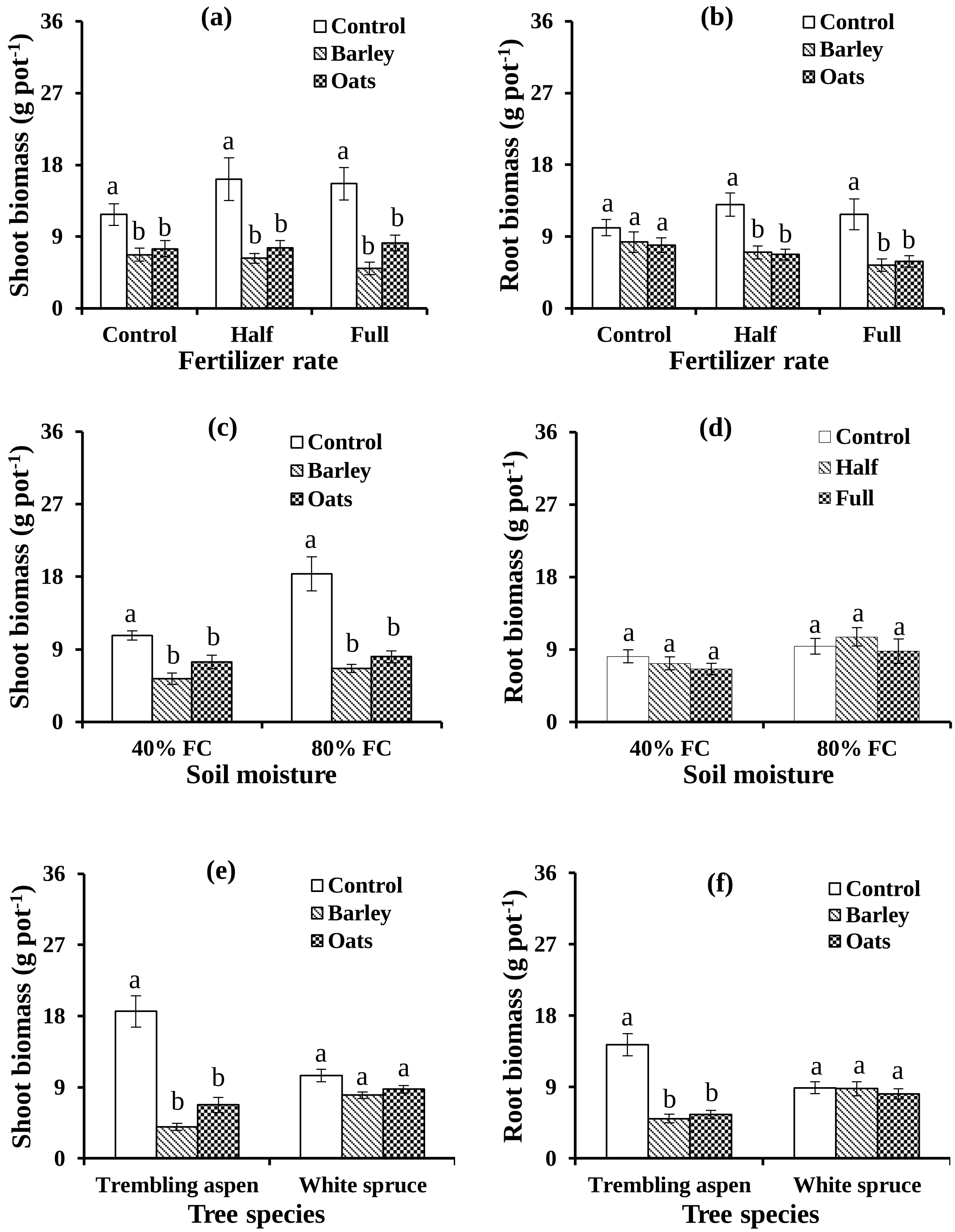


Fig. 3.4. Shoot and root biomass yield response of tree seedlings for the interactions between cover crops and fertilizer (a–b) or soil moisture at different levels (c–d) or tree species (e–f) after 16 weeks growth in a greenhouse bioassay experiment. Application rates of the 20–20–20 NPK fertilizer were: control = no fertilizer, half = 700 kg ha^{-1} and full = 1400 kg ha^{-1}. Vertical bars indicate standard error of means ($n = 4$). Columns in each treatment followed by the same letter are not significantly different ($p > 0.05$).

Table 3.2. Biomass yield of cover crop grass species after 16 weeks growth in the greenhouse as affected by different factors.

Factor	Biomass Yield (g pot^{-1})		
	Shoot	Root	Total
Fertilizer			
Control	17.63c	1.13c	18.76c
Half	31.12b	2.36b	33.48b
Full	36.33a	3.31a	39.64a
MSD	2.98	0.9407	3.3216
p-values	<.0001	<.0001	<.0001
Grass species			
Barley	31.13a	3.13a	34.27a
Oats	25.58b	1.40b	26.98b
MSD	1.94	0.6125	2.1628
p-values	<.0001	<.0001	<.0001
Tree species			
Trembling aspen	26.56b	1.99b	28.54b
White spruce	30.16a	2.54a	32.71a
MSD	1.94	0.6125	2.1628
p-values	0.0081	0.0143	0.0037
Soil moisture			
40% FC	22.81b	1.54b	24.35b
80% FC	33.91a	3.00a	36.90a
MSD	1.94	0.6125	2.1628
p-values	<.0001	<.0001	<.0001

Mean of four replicates (n = 4). Means followed by the same letter in a column under each factor are not statistically significant ($p > 0.05$). MSD = Minimum significant difference.

3.5.4. Nutrient uptake

Fertilization significantly increased the N and P concentrations and uptake by both the tree seedlings and the two cover crop species (Tables 3.3 and 3.4). In the presence of cover crops, N and P uptake were significantly reduced compared to the control, confirming the competition for nutrients with the tree seedlings induced by the presence of the cover crop grass species, especially barley. Apart from tree seedling roots, N concentration in tree seedlings and grasses was not significantly different between the two different tree species, but N uptake was significantly higher for white spruce treatment with the exception of tree shoots (Table 3.3). Phosphorus concentration and uptake were not significantly different between tree species except shoot concentration in trees and root uptake in cover crops (Table 3.4). Nitrogen concentration was higher under soil moisture stress condition where tree and cover crops shoot N uptake were significantly lower than no stress condition. Significantly lower P uptake by tree seedlings and cover crops was also observed under water stress (Table 3.4). Overall nutrient accumulation pattern in tree seedlings and cover crops indicates that the added nutrients were mostly used by non-target cover crop grass species rather than target tree seedlings.

Table 3.3. Nitrogen accumulation in shoots and roots of tree seedlings and cover crop grass species after 16 weeks growth in the greenhouse.

Factor	N concentration (mg g^{-1})				N uptake (mg pot^{-1})			
	Tree seedlings		Cover crops		Tree seedlings		Cover crops	
	Shoot	Root	Shoot	Root	Shoot	Root	Shoot	Root
Fertilizer								
Control	14.0b	8.2b	9.7c	5.4c	127b	71b	185c	6c
Half	15.1b	11.7a	13.5b	7.9b	155ab	99a	413b	18b
Full	17.9a	12.7a	17.4a	10.1a	188a	91a	591a	34a
MSD	1.46	1.06	2.69	1.04	41.6	17.1	98.4	6.4
p-values	<.0001	<.0001	<.0001	<.0001	0.0001	0.0005	<.0001	<.0001
Grass species								
Control	18.6a	11.1a	-	-	274a	119a	-	-
Barley	13.7b	10.6a	13.5a	7.9a	82b	70b	437a	28a
Oats	14.8b	10.8a	13.5a	7.8a	114b	72b	355b	11b
MSD	1.46	1.06	1.83	0.71	41.6	17.1	66.9	4.4
p-values	<.0001	0.3994	0.9727	0.4407	<.0001	<.0001	0.0201	<.0001
Tree species								
T. aspen	15.3a	10.0b	13.0a	7.8a	167a	76b	358b	16b
W. spruce	16.1a	11.7a	14.1a	7.7a	146a	98a	434a	22a
MSD	0.99	0.72	1.83	0.71	28.3	11.7	66.9	4.4
p-values	0.052	<.0001	0.2191	0.7496	0.0661	0.0032	0.0034	0.0084
Soil moisture								
40% FC	16.0a	11.5a	14.8a	8.4a	129b	83a	369a	16b
80% FC	15.3a	10.2b	12.2b	7.2b	184a	91a	423a	23a
MSD	0.99	0.72	1.83	0.71	28.3	11.7	66.9	4.4
p-values	0.1134	0.0002	0.0045	0.0004	<.0001	0.1341	0.1259	0.0013

Mean of four replicates (n = 4). Means followed by the same letter in a column under each factor are not statistically significant ($p > 0.05$). MSD = Minimum significant difference.

Table 3.4. Phosphorus accumulation in shoots and roots of tree seedlings and cover crop grass species after 16 weeks growth in the greenhouse.

Factor	P concentration (mg g^{-1})				P uptake (mg pot^{-1})			
	Tree seedlings		Cover crops		Tree seedlings		Cover crops	
	Shoot	Root	Shoot	Root	Shoot	Root	Shoot	Root
Fertilizer								
Control	1.3b	0.9c	1.4c	0.5c	12.2b	7.5b	28.1c	0.6c
Half	1.8a	1.2b	2.4b	1.0b	17.6a	10.0a	74.1b	2.3b
Full	1.9a	1.6a	3.1a	1.9a	18.8a	11.7a	107a	5.9a
MSD	0.17	0.20	0.41	0.23	3.69	2.10	17.6	0.91
p-values	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
Grass species								
Control	1.8a	1.2a	-	-	26.4a	13.4a	-	-
Barley	1.6b	1.3a	2.2a	1.0b	9.7b	7.9b	73.0a	3.9a
Oats	1.7b	1.2a	2.4a	1.3a	12.5b	7.7b	66.6a	1.9b
MSD	0.17	0.20	0.28	0.16	3.69	2.10	12.0	0.62
p-values	0.0011	0.9509	0.0539	<.0001	<.0001	<.0001	0.2875	<.0001
Tree species								
T. aspen	1.6b	1.2a	2.3a	1.2a	16.4a	9.8a	65.4a	2.4b
W. spruce	1.8a	1.2a	2.3a	1.2a	16.0a	9.7a	74.2a	3.4a
MSD	0.11	0.13	0.28	0.16	2.52	1.43	12.0	0.62
p-values	0.0074	0.2740	0.7784	0.7459	0.7178	0.8683	0.1449	0.0009
Soil moisture								
40% FC	1.7a	1.3a	2.3a	1.2a	13.4b	9.1a	59.8b	2.4b
80% FC	1.7a	1.2b	2.3a	1.1a	18.8a	10.3a	79.8a	3.5a
MSD	0.11	0.13	0.28	0.16	2.52	1.43	12.0	0.62
p-values	0.1429	0.0298	0.5666	0.0669	<.0001	0.0766	0.0013	0.0002

Mean of four replicates (n = 4). Means followed by the same letter in a column under each factor are not statistically significant ($p > 0.05$). MSD = Minimum significant difference.

3.5.5. Residual soil nutrient

Soil residual N, P, and K were higher in fertilized treatments as expected (Table 3.5). Cover crop grass species reduced residual NO_3^--N but did not significantly reduce residual P and K, suggesting that competitive effects may be most pronounced for N. Trembling aspen also had lower residual NO_3^--N than white spruce, consistent with a higher nutrient demand of aspen for NO_3^--N. Soil residual N and P were not affected by soil moisture treatment. Organic carbon levels in the post-harvest soil were not significantly different among treatments (Table 3.5).

Table 3.5. Mean soil organic carbon, available nitrogen (NO_3^--N and NH_4^+-N), available P and extractable K in post-harvest soil.

Factor	Organic carbon	Available N		Available P	Extractable K
		NO_3^--N	NH_4^+-N		
	(%)	------------------------(mg kg^{-1})------------------------			
Fertilizer					
Control	8.24a	9.78b	38.32b	4.04c	129b
Half	8.72a	15.22b	45.32ab	10.72b	169a
Full	8.21a	30.10a	55.75a	20.53a	173a
MSD	0.872	14.204	17.364	2.118	35.6
p	0.4445	0.0005	0.0202	<.0001	0.0041
Grass species					
Control	8.08a	32.37a	50.23a	12.99a	146a
Barley	8.93a	6.39b	41.43a	10.92a	160a
Oats	8.18a	16.34b	47.72a	11.36a	165a
MSD	0.872	14.204	17.364	2.118	35.6
p-values	0.1099	<.0001	0.3405	0.1251	0.3846
Tree Species					
Trembling aspen	8.37a	11.29b	45.85a	11.10a	153a
White spruce	8.42a	25.44a	47.07a	12.41a	161a
MSD	0.715	8.814	10.628	1.649	24.3
p-values	0.899	0.0012	0.8084	0.1234	0.5407
Soil moisture					
40% FC	8.44a	20.46a	47.01a	12.56a	155a
80% FC	8.39a	16.27a	45.92a	10.96a	159a
MSD	0.715	8.814	10.628	1.649	24.3
p-values	0.8084	0.3254	0.8282	0.0624	0.7205

Mean of four replicates (n = 4). Means followed by the same letter in a column under each factor are not statistically significant ($p > 0.05$).

3.6. Discussion

Growth, biomass yield, and nutrition of tree seedlings were affected by the fertilizer and moisture management treatments tested in this study. Moreover, these silvicultural treatments interacted with cover crops in important ways to modify the impact of cover crops on tree seedlings establishment and early growth. This discussion considers each silvicultural treatment along with their appropriate interactions to accomplish re-vegetation success in oil sands region.

3.6.1. Fertilization

Previous studies (Nilsson and Allen, 2003; Van den Driessche et al., 2003; Jacobs et al., 2005; Van den Driessche et al., 2005; Guillemette and DesRochers, 2008; du Toit et al., 2010) revealed the effectiveness of fertilization at planting to promote growth and establishment of tree seedlings. In this study, fertilizer additions did not result in increased growth of white spruce but there were effects for trembling aspen, indicating a species specific response to fertilization. Moreover, increased growth and yields of cover crop grasses from fertilization also indicates that added benefits of fertilization were mostly utilized by cover crops which may lead to potential competition for other resources like moisture, space and light in fields (Allen and Albaugh, 2000; Nilsson and Allen, 2003; Balandier et al., 2006).

Several materials (i.e., peat-mineral mixture, litter, fibric, humic (LFH), and upland surface) that are used as surface soil layers in oil sands reclamation vary greatly according to their fertility status (Rowland et al., 2009; Turcotte et al., 2009; Pinno et al., 2012). For example, soils of boreal forest zone in Alberta are sometimes deficient in P (Strong and La Roi, 1985) and aspen growth in Alberta was noted in one study to respond to P fertilization (Van den Driessche et al., 2003). Another study with different reclamation soil was conducted in Alberta to evaluate N, P, and K fertilizer effects on aspen seedling growth and it was reported that peat-mineral mix and LFH gave maximum aspen growth without any nutrient addition (Pinno et al., 2012). Rowland et al. (2009) also considered peat-mineral mix as a potential reclamation material that could provide sufficient plant nutrients for native ecosystem development in recently reclaimed sites. Therefore, fertilizer addition in reclaimed sites might be adjusted or eliminated according to plant community composition and nutrient status of reclamation material.

3.6.2. Moisture management

Adequate growth resources including soil moisture are important for newly planted tree seedlings to overcome the transplant shock and to facilitate successful establishment. In this study, seedling growth and biomass yield were reduced by moisture stress indicating soil moisture was probably the driving factor in seedling establishment and growth. Similar growth reduction of aspen and white spruce was observed in Alberta due to increased moisture stress (Man and Greenway, 2013). Our results showed that soil moisture effect was more apparent for trembling aspen than white spruce. It might be due to the rapid growth of aspen that requires greater resource acquisition early on (Peterson and Peterson, 1992; Hangs et al., 2003). Increased growth of different *Populus* species was observed in Wisconsin, USA with enhanced soil moisture conditions by irrigation (Strong and Hansen, 1991). In addition, adequate soil moisture could increase the efficiency of fertilizer and plant nutrient uptake. Van den Driessche et al. (2003) reported that fertilizer response of aspen seedling in Drayton Valley, Canada was greatly influenced by soil moisture. Likewise, soil moisture status can be increased by controlling competing vegetation. Annual grass competitors like barley and oats generally will utilize moisture from same soil layer where the tree seedlings are planted, which in turn might have a strong negative effect on early establishment and growth of trees especially in limited moisture conditions (Balandier et al., 2006).

3.6.3. Vegetation management

Vegetation management is an integral part of reforestation that accelerates tree growth and ensures successful stand development (Thompson and Pitt, 2003; Wagner et al., 2004). Although vegetation management can be used throughout the life cycle of a forest stand for better tree growth, it may be most appropriate and easily applicable in early establishment period. Numerous studies have been conducted in the US and Canada that have documented the benefits of controlling competing vegetation during the plantation establishment phase (Balandier et al., 2006; Wagner et al., 2006; Pinno and Belanger, 2009). Control of competition can modify resource allocation to the target tree seedlings and subsequently increase establishment and growth (Allen et al., 1990; Allen and Albaugh, 2000; Nilsson and Allen, 2003), as was observed in this research.

Competing vegetation can influence the effectiveness of applied silvicultural practices intended to increase tree seedlings establishment and growth (Wagner et al., 2004). If the competing vegetation benefits from the applied silvicultural practices then the growth of preferred crop trees might be lower (Allen and Lein, 1998; Nilson and Allen, 2003). It was reflected in this study, where early growth and biomass yield of tree seedlings were adversely affected by cover crops, and that competition could not be reduced by silvicultural interventions like nutrient and moisture management. Barley and oats as cover crops are very effective resource competitors and users compared to tree seedlings. Rapid growth and tolerance to a wide range of soil and environmental conditions are key attributes associated with superior competition of these cover crops for space, soil nutrients and moisture (Bowman et al., 1998; Grime, 2001; Kremer and Ben-Hammouda, 2009).

3.7. Conclusion

Both trembling aspen and white spruce seedlings responded poorly to fertilizer additions. Despite rapid initial growth rates of trembling aspen seedlings, shoot and root biomass yields after a 16 week growth period did not differ. In contrast, reducing soil moisture stress stimulated height, shoot and root biomass yields of tree seedlings, implying that availability of soil moisture was probably the most limiting factor for growth. Grass species competition largely determined growth and yield responses of tree seedlings to fertilizer inputs and soil moisture availability. Even with fertilization, RCD growth and shoot biomass yield of tree seedlings were reduced by 45–50% and 50–65%, relative to no grass cover. The effects increased with increasing fertilizer application rates. Similar effects were also found for soil moisture both with (40% FC) and without (80% FC) soil moisture stress. Apparently, competition from any companion vegetation, including planted cover crop and/or weeds, may adversely affect early growth and yield of tree seedlings on reclaimed oil sands sites by inducing or augmenting the effects of competition for resources.

Controlling weeds along with fertilizer addition may help to improve establishment success of tree seedlings. However, revising fertilizer recommendations to account for nutrient uptake by the competing vegetation may be the appropriate approach for enhancing seedling growth in the oil sands region because cover crops are planted for controlling soil erosion on recently reclaimed sites. This approach, however, needs to consider the observed species-specific response to weed competition.

Comparatively, the suppressive effect of barley was higher than that of oats. A follow up field study is recommended to examine if these interactions will persistent in subsequent years and to provide further information on appropriate recommended fertilizer rates for optimizing growth and yield of both grass and tree seedlings under field conditions.

4. RESPONSE OF ASPEN AND WHITE SPRUCE SEEDLINGS TO FERTILIZATION ON A RECONSTRUCTED OIL SANDS FIELD SITE IN ALBERTA, CANADA

4.1. Preface

In chapter 3, under controlled environment conditions we observed a species-specific response of tree seedlings to competition from cover crops that was not overcome by amendment with fertilizer or water. Trembling aspen was most affected. Horizontally spreading of the lateral root system at the early growth stages is a characteristic feature of aspen, and the root growth might have been restricted in pots due to confined space. Moreover, in the controlled environment study, the effect of cover crops was compared with a control treatment in which it was possible to eliminate all competitive vegetation by hand weeding, which is not possible under field conditions. Thus, the field study described in this chapter was designed to verify greenhouse results and to develop an effective prescription for fertilizer and vegetation management for oil sands reclamation.

4.2. Abstract

Oil sands reclamation following surface extraction involves extensive site reconstruction, with planting of ground cover vegetation and native tree species, and addition of fertilizers to establish an equivalent ecosystem that existed prior to disturbance. In reconstructed mine sites, establishment of mixed-wood boreal tree seedlings like trembling aspen (*Populus tremuloides* Michx) and white spruce (*Picea glauca* (Moench) Voss.) along with ground cover is helpful to stabilize soil, minimize erosion, and promote native vegetation restoration. Barley (*Hordeum vulgare* L.) and oats (*Avena sativa*) are the ground cover species that have been recommended for oil sands reclamation operations, but interactions of planted tree seedlings with ground cover and the growth response to fertilization are not clearly understood. This study evaluated the effect of different rates of nitrogen (N), phosphorus (P), and potassium (K) fertilizer on survival and early growth of tree seedlings that were planted with seeded annual cover crops: barley and oats. In the field study, significantly reduced survival of tree seedlings was observed with increased rates of fertilizer addition compared to without fertilization. Trembling aspen was more sensitive than white spruce to ground cover competition and was negatively affected by barley and oats, especially with added fertilizer. Survival, early growth, and biomass yield of trembling aspen were

significantly reduced by barley and oats in comparison to native ground cover vegetation, whereas white spruce was not affected. In general, adding fertilizer to the peat-mineral mixture reclaimed sites appears to be of very little benefit in enhancing the early establishment and growth of tree seedlings. Longer term (after several years) effects of the practices on forest growth and regeneration deserve attention in future research work.

4.3. Introduction

Oil sands in the Cold Lake, Peace River and Athabasca regions of northern Alberta, Canada, are one of the greatest petroleum reservoirs in the world (Government of Alberta, 2013). In the Athabasca boreal region, a small fraction of the deposited oil sands is closer to the surface which is suitable for surface mining. During surface mining, vegetation covers are cleared, organic matter and overburden are stripped out for accessing deposited bitumen. Therefore, the surface mining process is involved with severe ground disturbance and ecosystem destruction. Reclamation following oil sands surface mining is considered to be a massive ecosystem rebuilding process (Pinno et al., 2012), and is mostly focused on promoting native vegetation establishment.

In reclamation operations, several organic materials such as litter, fibric, humic (LFH), peat-mineral mix, and upland surface soils are generally used to construct a surface layer on top of recontoured overburden and subsoil that will support vegetative growth. These materials are salvaged and stockpiled during mining. The physico-chemical properties including available plant nutrient contents of these materials are usually different (Rowland et al., 2009; Turcotte et al., 2009; Pinno et al., 2012). Soil properties are important considerations in establishing a productive forest in reclaimed mined sites (Torbert et al., 1988; Torbert et al., 1990; Ashby, 1997). Another potentially important consideration is the ground cover vegetation, specifically as it affects competition with newly planted tree seedlings. Early establishment and growth of tree seedlings in post-disturbance mine sites is critical and is usually affected by vegetation competition (Moffat, 2004; Casselman et al., 2006; Harrington, 2006). Native, and planted species such as barley and oats are currently used in reconstructed sites to provide protective cover that will stabilize soils and help to minimize erosion (OSVRC, 1998; Renault et al., 2004).

In addition to vegetation competition, outplanting success of tree seedlings is often hindered by inadequate nutrient supply (Van den Driessche et al., 2003). Alberta's boreal forest soil is inherently deficient in phosphorus (Strong and La Roi, 1985) and phosphorus (P) may be the limiting factor for tree seedling growth. A peat-mineral mix is widely used as a reclamation material (Fung and Macyk, 2000) and also contains low amounts of phosphorus and potassium (K) (Alberta Environment and Water, 2012). Furthermore, nitrogen (N) transformations, particularly NH_4^+-N to NO_3^--N (nitrification) and subsequent loss is an overall feature in mine sites which is mainly due to soil disturbance, long-time stockpiling and manipulation of reclamation materials (Kronzuchker et al., 1997; Sheoran et al., 2010). Many forest tree species are adapted to high NH_4^+-N and prefer this form of inorganic N (Huang and Schoenau, 1996; Yao et al., 2011). For example, in comparison to deciduous species such as aspen, conifers such as spruce and pine are reported to prefer conditions with high NH_4^+-N abundance (Nadelhoffer et al., 1984; Lavoie et al., 1992). Aspen has shown lower P use efficiency than that of several other boreal tree species (Van Cleve et al., 1983). Therefore, one may anticipate that different tree species will respond differently to fertilization practices.

Trembling aspen (*Populus tremuloides* Michx.) and white spruce (*Picea glauca* (Moench) Voss.) are the most common tree species of boreal mixedwood forest in Canada (Peterson and Peterson, 1992; Lieffers and Beck, 1994). There has been increasing interest in commercial plantations of these species in Alberta, largely for their value in the forest product industry and in oil sands reclamation (Archibold et al., 2000; Macdonald et al., 2012). Moreover, these species are naturally found on mesic sites of northern Alberta and also can grow on saline sodic overburden with adequate resources including available plant nutrients management (Khasa et al., 2003; Lilles et al., 2010; Lillies et al., 2012; Lazorko and Van Rees, 2012).

Fertilization is the optimum silvicultural tool for supplying nutrient resources especially under nutrient deficient conditions to newly planted tree seedlings. Positive response of tree seedlings to early fertilization (Van den Driessche, 1988; Van den Driessche et al., 2003) depends on several factors such as fertilizer application method and rate, plant stock type, site characteristics and vegetation control (Brockley 1988; Rose and Ketchum, 2001). Successful establishment and better growth of trees is also acheived by controlling competitive vegetation (Rose and Ketchum, 2001) but use of ground cover vegetation is of interest in reconstructed sites. Therefore, it is appropriate to investigate the response of tree seedlings to fertilization in presence of ground cover vegetation. This study was conducted on a reconstructed oil sands site with the objective to evaluate the effect of different fertilizer rates on survival and early growth of trembling aspen and white spruce tree seedlings planted without and with barley and oats as ground cover grass species.

4.4. Materials and Methods

4.4.1. The study area and site description

The study area is within the Wood Buffalo region of northeastern Alberta, Canada. The climatic conditions of this region are described as continental humid, where winters are usually long and cold, with warm and short summers. Thirty-year annual averages of daily minimum temperatures of this area are -18.8 ^{o}C in January (coldest month) and maximum +16.8 ^{o}C in July (warmest month) (Environment Canada, 2013). Overall annual average of precipitation is 455 mm, including a predominance of rainfall in summer (342 mm) and snowfall in winter (155 cm). The experiment was conducted at the capping site of Suncor Energy Inc. (MD8). It is located 40 km north of Fort McMurray (56°39′N, 111°13′W). The site was designed and reconstructed in 2010, where a 50cm thick layer of peat-mineral mix was placed as a cover soil on top of overburden. The peat-mineral mix contains approximately 60% peat and 40% mineral material. Selected results from initial soil analyses of the cover soil are summarized in Table 4.1. A weather station was placed at the field research site and total monthly precipitation throughout the experimental period is summarized in Table 4.2.

4.4.2. Experimental design, treatments and managements

The study was designed as a 2 tree species × 3 cover crops × 8 fertilizer dose rate factorial experiment, laid out in a randomized complete block design (RCBD) with three replication, giving a total of 144 plots. The tree species treatments were trembling aspen and white spruce, and planted with three cover crops treatments of: 1) control/vegetation that regenerated naturally and was comprised of invasive weeds including lamb's quarters (*Chenopodium album*), wild oats (*Avena fatua*), creeping thistle (*Cirsium arvense*), common dandelion (*Taraxacum officinale*); 2) barley (*Hordeum vulgare*); and 3) oats (*Avena sativa*). The fertilizer treatments were 0,150, 300, 600, 750, 900, 1200 and 1500 kg ha^{-1} of a NPK blend 20-20-20 water soluble fertilizer. Fertilizer was applied by using a manual fertilizer spreader prior to seeding the cover crops and tree seedlings. The fertilizer blend was comprised of urea, ammonium phosphate and potassium nitrate with the proportions of urea nitrogen (10.25%), ammoniacal nitrogen (3.85%), nitrate nitrogen (5.90%) available phosphoric acid (20% P_2O_5), and soluble potash (20% K_2O). The seeding rate of barley and oats was 25 kg ha^{-1} and the seed was broadcasted and incorporated after fertilizer application. The individual experimental plot size was 10 m × 10 m. In spring 2011, sixteen tree seedlings were transplanted in each plot to obtain a spacing of 2 m × 2.5 m (2000 stems ha^{-1}) that is used in Suncor's field operations. The tree seedlings were transplanted in the same day of fertilization and cover crops plantation. Buffer width was maintained by leaving 3 m distance between blocks and 1 m for plots.

Table 4.1. Selected characteristics of cover soil at the study site.

Depth (cm)	Bulk density	pH	EC†	OC‡	Available N		Available P	Exchangeable Cations			
					NO_3^--N	NH_4^+-N		K	Ca	Mg	Na
	g cm^{-3}		(mS cm^{-1})	(%)	------------(kg ha^{-1})-----------			------------cmol[+]kg^{-1}-----------			
0-30	0.55	6.9	0.76	7.7	15.0	65.2	6.4	0.1	33.2	4.5	0.2
30-50	0.62	7.1	0.64	5.5	7.9	82.4	6.6	0.1	29.0	3.7	0.2

†EC, electrical conductivity; ‡OC, organic carbon

Table 4.2. Total precipitation for summer months of 2011-2012 at study site, and 30-year (1971–2000) normal values from Fort McMurray Airport, Alberta, Canada.

Year	Total monthly precipitation (mm)					Total summer precipitation (mm)
	May	June	July	August	September	
2011	23.5	31.5	55.1	51.3	30.5	191.9
2012	27.4	52.6	91.2	39.6	127.8	338.6
Normal	34.2	74.8	81.3	72.6	45.0	307.9

4.4.3. Measurements

Height and root collar diameter (RCD) of the tree seedlings were measured at planting and in the following two growing seasons to obtain growth increments. Height and RCD growth were measured by using a measuring tape and digital slide calipers respectively, and during measurement the ground surface was considered the base line. Survival was recorded after first growing season in September, 2011 and again in the second growing season in September, 2012. After second growing season, four tree seedlings and soil samples at two different depths (0 to 30 cm and 30 to 60 cm) were randomly collected from the center of each plot. Samples were transported to the laboratory in the Department of Soil Science, University of Saskatchewan. Plant samples were partitioned into shoots and roots upon returning from the field. Before washing, root samples were frozen at -5 ^{o}C. After thawing, the root samples were gently washed within a 1-mm mesh screen that was immersed in a bucket full of water and slightly agitated to remove the soil (Lazorko and Van Rees, 2012). To recover fine roots, the washing process was repeated with dislodged materials from the bucket. Plant samples were dried at 50 ^{o}C to constant weight and then weighed to obtain shoot and root dry biomass. Plant samples were then ground, homogenized and sub-samples taken for nutrient analysis. The soil samples were air-dried at 25 ^{o}C by spreading on paper. Large components like stones were removed, then the remaining soil was ground to pass through 2-mm sieve and stored at room temperature for laboratory analysis.

4.4.4. Chemical analysis

Soil and plant samples were analyzed for selected soil characteristics and plant tissue nutrient concentration. Soil pH and electrical conductivity (EC) were measured in a suspension with a soil to water ratio of 1:2 (Hendershot et al., 2007a; Miller and Curtin, 2007) using a Fisher AP85 pH/conductivity meter. Organic carbon (OC) was determined by the dry combustion method (Skjemstad and Baldock, 2007) at a temperature of 813 ^{o}C using LECO-C632 carbon analyzer (LECO© Corporation, 1987). Soil available N (NH_4^+-N and NO_3^--N) was determined by KCl extraction (Keeney and Nelson, 1982), and available P was determined by a modified Kelowna method (Qian et al., 1994). Calcium chloride extraction was used for available S analysis (Grimmett and Kowalenko, 2007) and NH_4OAC extraction was performed for exchangeable cations (Hendershot et al., 2007b). Plant available nutrient supply rate was measured by a sandwich method using ion exchange resin membrane strips (Qian et al., 2007). Plant samples were analyzed for total tissue N, P, K, Ca and Mg concentrations following the extraction by a standard H_2SO_4-H_2O_2 digestion method (Thomas et al., 1967). The N and P concentrations were determined colorimetrically by Technicon Autoanalyzer II, and a 4100 MP-AES [Microwave Plasma-Atomic

Emission Spectrometer (Agilent Technologies)] was used for S analysis. Concentrations of K, Ca, Mg and Na were analyzed using Atomic Absorption spectrometry (SpectrAA 220, Varian).

4.4.5. Statistical analysis

Statistical analyses was performed using the MIXED procedure, SAS 9.2 software (SAS Institute Inc., 2010). A three-way ANOVA was used to determine the impact of fertilizer rates, ground cover and tree species on survival, growth, plant tissue nutrient concentrations and residual soil nutrients. Prior to ANOVA, data distribution were tested for normality using the Shapiro-Wilk test. The survival rate data were not normally distributed, so a square root transformation was performed before analysis. Means are reported on untransformed data. All other data exhibited homogeneity and no transformations were required. Differences among significant treatment means were tested using Tukey's HSD test at a 0.05 alpha value.

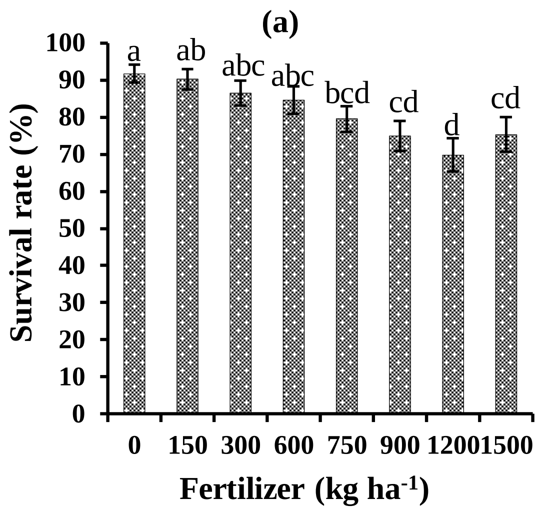
4.5. Results

4.5.1. Survival of tree seedlings

Survival of tree seedlings after one growing season was significantly affected by fertilizer addition ($p < .0001$) and tree species ($p < .0001$). (Appendix B, Table B.1). A significant interaction was also observed between cover crops and tree species ($p = 0.0075$). The highest survival of tree seedlings (92%) was observed in the 0 kg ha^{-1} fertilizer treatment, and was identical up to 600 kg ha^{-1} application rate (85% survival). Surprisingly, there was a trend of decreasing tree seedling survival with further fertilizer addition, and significantly reduced survival was observed with higher rates of application which ranged from 79% survival (750 kg ha^{-1}) to 75% survival (1500 kg ha^{-1}) (Fig. 4.1a). From the cover crops and tree species interaction it was observed that barley and oats had significant negative effect on trembling aspen survival (68% and 69% survival, respectively) as compared to native vegetation (78% average survival), while white spruce was not affected by cover crop vegetation (Fig. 4.1b). Overall, the presence of cover crops significantly lowered the survival of trembling aspen tree seedlings (71%) compared to white spruce (92%) (Table 4.3). At the end of second growing season, it was observed that survival rate of tree seedlings was not further affected by the different treatments (data not shown).

4.5.2. Height, RCD growth, and biomass yield of tree seedlings

Growth and biomass yield response of tree seedlings after two growing seasons were significantly affected by tree species, cover crops, and tree species and cover crops interactions (Appendix B, Table B.2). Different rates of fertilizer addition had non-significant effects on height ($p = 0.0773$), and root collar diameter (RCD) ($p = 0.4464$) incremental increase of the tree seedlings (Fig. 4.2a and 4.3a). Shoot ($p = 0.0576$) and root ($p = 0.0593$) biomass yield of the tree



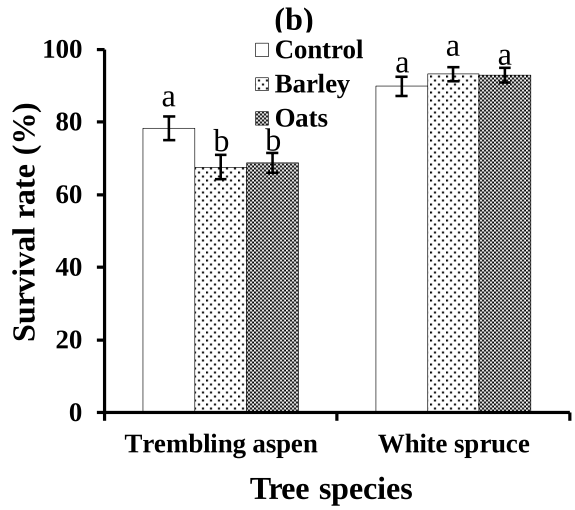


Fig. 4.1. Survival of trembling aspen and white spruce tree seedlings combined for (a) fertilization and (b) tree species and cover crops [control (native vegetation), barley and oats] after one growing season in a reconstructed oil sands site. Vertical bars indicate standard error of means (n = 3). Columns in (a) and for a tree species in (b) followed by the same letter are not significantly different ($p > 0.05$).

seedlings were also not significantly different among the different rates of fertilizer addition (Fig. 4.4a and 4.5a). For tree species treatment, comparatively higher height increment and root biomass yield was recorded from trembling aspen, whereas RCD increment and shoot biomass was higher in the white spruce treatment (Table 4.3). Overall, trembling aspen growth and biomass yields were adversely affected by seeded cover crops. Height and RCD increment of trembling aspen were reduced by 40% and 31% respectively, when planted with barley, and by 33% and 26% when oats were the cover crop, as compared to native vegetation (control) treatment (Fig. 4.2b and 4.3b). Trembling aspen shoot and root biomass yield were also reduced by barley (40% and 32%, respectively) and oats (38% and 30%, respectively) (Fig. 4.4b and 4.5b). White spruce growth and biomass yields were not affected by different cover crops. Overall, there was no significant height, RCD or biomass yield response of tree seedlings to added fertilizer in presence of native vegetation or planted cover crops like barley and oats (Table 4.4).

Table 4.3. Survival, growth and biomass yield response of tree seedlings.

Tree species	Survival rate (%)	Height increment (cm)	RCD increment (mm)	Shoot biomass (g plant^{-1})	Root biomass (g plant^{-1})
Trembling aspen	71b	35.6a	4.3b	22.8b	14.7a
White spruce	92a	15.0b	5.5a	34.8a	10.7b
p-values	<.0001	<.0001	<.0001	<.0001	<.0001

Mean of three replicates (n = 3). Means followed by the same letter in a column are not significantly different ($p > 0.05$).

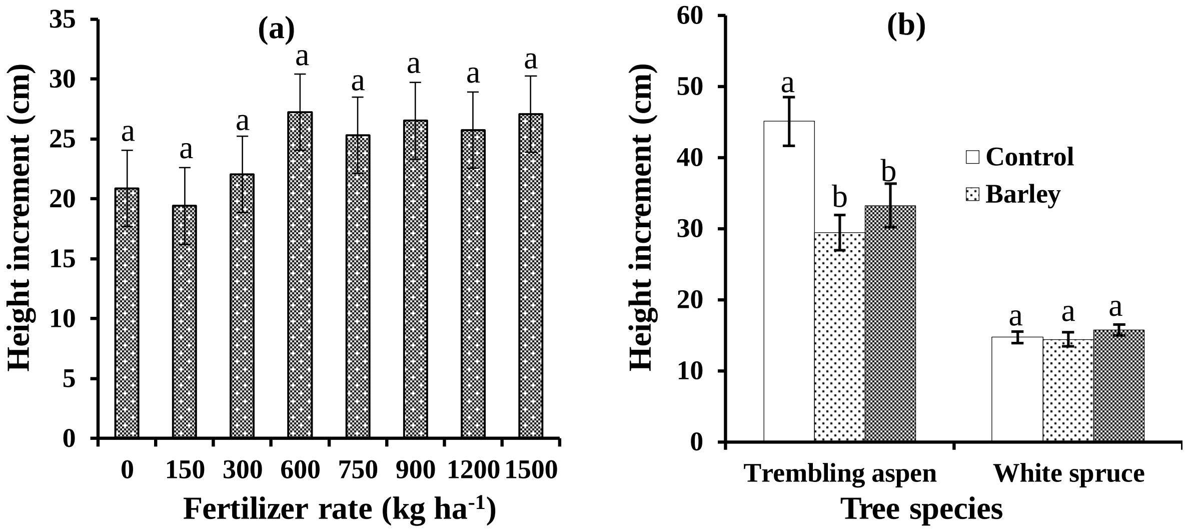


Fig. 4.2. Height incremental increase (cm) of trembling aspen and white spruce tree seedlings combined for (a) fertilization and (b) tree species and cover crops [control (native vegetation), barley and oats] after two growing seasons in a reconstructed oil sands site. Vertical bars indicate standard error of means (n = 3). Columns in (a) and for a tree species in (b) followed by the same letter are not significantly different ($p > 0.05$).

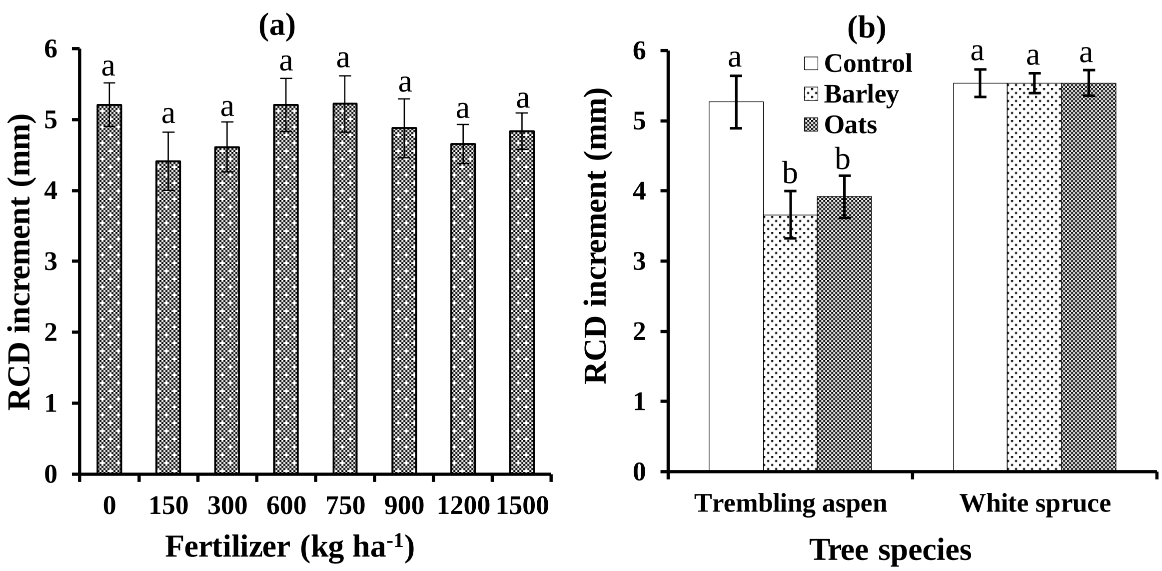


Fig. 4.3. Root collar diameter (RCD) incremental increase (mm) of trembling aspen and white spruce tree seedlings combined for (a) fertilization and (b) tree species and cover crops [control (native vegetation), barley and oats] after two growing seasons in a reconstructed oil sands site. Vertical bars indicate standard error of means (n = 3). Columns in (a) and for a tree species in (b) followed by the same letter are not significantly different ($p > 0.05$).

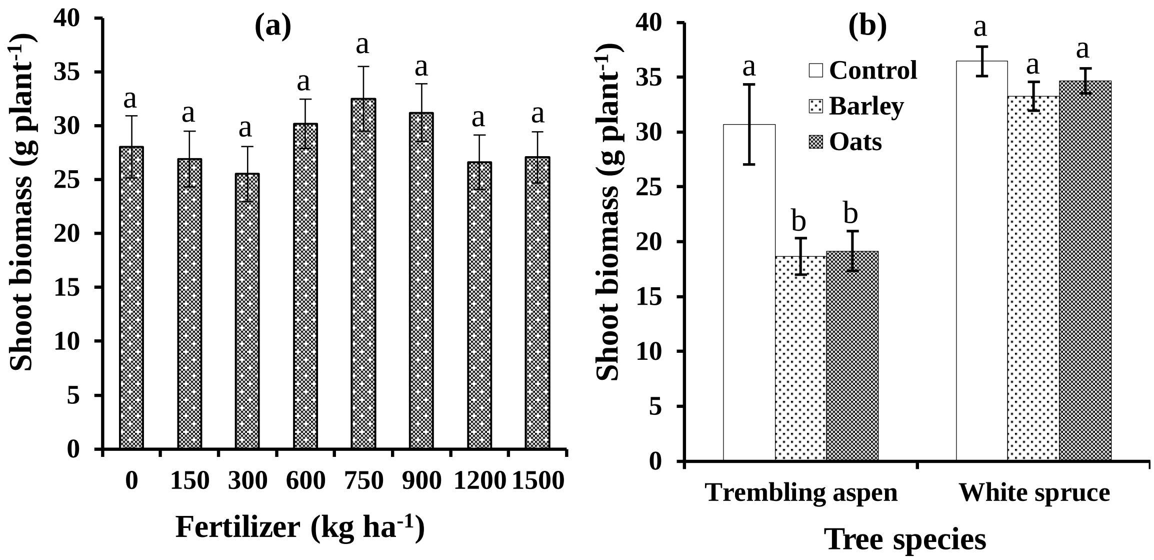


Fig. 4.4. Shoot biomass of trembling aspen and white spruce tree seedlings combined for (a) fertilization and (b) tree species and cover crops [control (native vegetation), barley and oats] after two growing seasons in a reconstructed oil sands site. Vertical bars indicate standard error of means (n = 3). Columns in (a) and for a tree species in (b) followed by the same letter are not significantly different ($p > 0.05$).

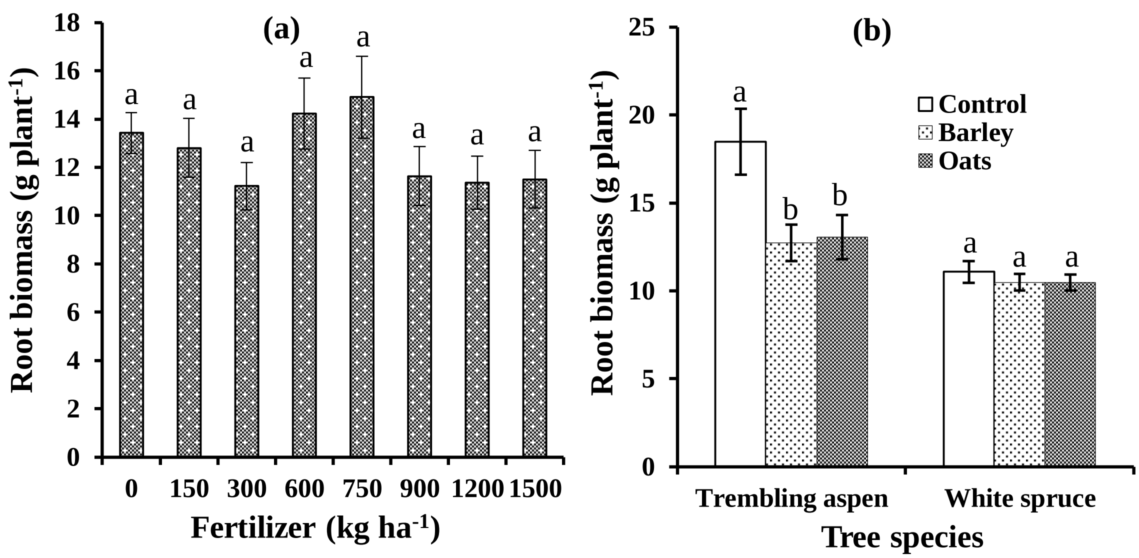


Fig. 4.5. Root biomass of trembling aspen and white spruce tree seedlings combined for (a) fertilization and (b) tree species and cover crops [control (native vegetation), barley and oats] after two growing seasons in a reconstructed oil sands site. Vertical bars indicate standard error of means (n = 3). Columns in (a) and for a tree species in (b) followed by the same letter are not significantly different ($p > 0.05$).

Table 4.4. Effect of cover crops and fertilizer combinations on the growth and yield response of tree seedlings.

Factor		Survival Rate (%)	Height increment (cm)	RCD increment (mm)	Shoot biomass (g $plant^{-1}$)	Root biomass (g $plant^{-1}$)
Cover crops	**Fertilizer**					
Control	0	96.8a	21.58a	5.41a	27.84a	14.69a
	150	91.4a	21.22a	4.91a	29.96a	13.82a
	300	86.1a	23.17a	4.72a	25.89a	11.20a
	600	82.5a	39.69a	6.43a	37.10a	17.47a
	750	75.1a	29.27a	6.18a	40.67a	18.95a
	900	83.0a	29.21a	5.65a	38.42a	14.40a
	1,200	71.1a	24.93a	4.33a	24.97a	10.72a
	1,500	87.1a	36.54a	5.76a	36.40a	14.94a
Barley	0	90.3a	18.20a	5.12a	28.51a	13.19a
	150	93.6a	17.83a	3.94a	23.07a	11.72a
	300	87.7a	21.14a	4.18a	22.76a	10.04a
	600	83.9a	20.90a	5.05a	28.97a	14.33a
	750	76.6a	19.85a	4.50a	26.71a	11.38a
	900	69.1a	23.52a	3.97a	25.97a	9.35a
	1,200	71.9a	29.83a	5.41a	30.51a	12.51a
	1,500	68.3a	19.94a	4.37a	21.01a	10.16a
Oats	0	88.1a	23.02a	5.10a	27.73a	12.39a
	150	85.8a	19.26a	4.42a	27.67a	12.88a
	300	85.5a	21.90a	4.97a	27.94a	12.45a
	600	87.3a	22.91a	4.25a	24.51a	10.85a
	750	87.2a	27.35a	5.05a	30.06a	14.41a
	900	73.0a	27.01a	5.10a	29.23a	11.16a
	1,200	66.5a	22.69a	4.27a	24.34a	10.90a
	1,500	71.2a	25.99a	4.44a	23.74a	9.05a
p-values		0.2374	0.2225	0.2766	0.0539	0.4894

Mean of three replicates (n = 3). Means followed by the same letter in a column under each treatment are not statistically significant ($p > 0.05$).

4.5.3. Nutrient accumulation in shoots and roots of tree seedlings

Fertilizer application rate had a significant effect on N, P, and K concentrations of tree seedling shoots and roots, and concentrations of these three elements increased with higher rates of fertilizer application (Table 4.5) whereas Ca and Mg concentrations were not affected (Table 4.6). Uptake of all the measured nutrients was significantly different among the different fertilizer rates, except N and K uptake in roots and Mg uptake in shoots and roots (Tables 4.5 and 4.6). For tree species, nutrient concentrations in trembling aspen were significantly higher than that of white spruce with the exception of K in shoots and Ca in roots (Tables 4.5 and 4.6). However, with nutrient uptake, apart from Ca uptake in shoots, there were significant differences in the uptake of all the nutrients between the two tree species. The nutrient uptake trend in roots followed the pattern of trembling aspen being greater than white spruce, while in white spruce shoots, nutrient uptake was greater than trembling aspen (Tables 4.5 and 4.6). In the presence of cover crops, higher nutrient concentrations and uptake were observed in the control treatment with native vegetation compared to barley and oats. Apart from concentrations of N in roots, and Ca and Mg in both shoots and roots, all the concentrations values were significantly different among the cover crop treatments. The general trend was that nutrient uptake was reduced in presence of barley and oats compared to native vegetation (control).

Table 4.5. Effect of fertilization and vegetation on total N, P and K uptake accumulation in shoots and roots of tree seedlings after two growing seasons.

Factor	N (mg g^{-1})		N uptake (mg plant^{-1})		P (mg g^{-1})		P uptake (mg plant^{-1})		K (mg g^{-1})		K uptake (mg plant^{-1})	
	Shoot	**Root**	**Shoot**	**Root**	**Shoot**	**Root**	**Shoot**	**Root**	**Shoot**	**Root**	**Shoot**	**Root**
Fertilizer												
0	8.6c	6.5bc	236.9b	88.6a	0.9c	0.7d	24.7b	9.5b	3.9c	3.1b	114.0ab	43.1a
150	9.1c	6.1bc	224.4b	79.8a	1.1ab	0.9cd	28.4ab	11.3ab	4.0bc	3.2ab	109.0ab	44.2a
300	9.1c	6.0c	220.1b	72.1a	1.0bc	0.8cd	23.6b	9.8b	3.9c	3.2b	100.8b	36.9a
600	9.2bc	6.5bc	279.7ab	98.4a	1.1ab	0.9bc	33.1ab	14.7ab	4.1abc	3.2ab	124.5ab	47.6a
750	9.2bc	6.8bc	296.7ab	110.3a	1.1ab	1.0abc	37.1a	15.6a	4.2abc	3.7a	139.5a	59.3a
900	10.4ab	6.9bc	322.4a	80.6a	1.2a	1.1ab	35.7a	12.4ab	4.3abc	3.6ab	133.7ab	46.4a
1,200	10.5ab	7.3ab	265.8ab	83.9a	1.1ab	1.0ab	29.7ab	12.0ab	4.4ab	3.4ab	117.0ab	40.9a
1,500	10.7a	8.3a	288.5ab	101.1a	1.2a	1.1a	32.3ab	13.2ab	4.5a	3.3ab	126.2ab	40.1a
p-values	<.0001	<.0001	0.0008	0.1207	<.0001	<.0001	0.0003	0.0091	0.0002	0.0038	0.0096	0.1483
Tree species												
Trembling aspen	11.0a	8.2a	248.1b	121.0a	1.1a	1.2a	25.3b	16.9a	3.8b	4.5a	85.5b	66.3a
White spruce	8.2b	5.4b	285.6a	57.6b	1.0b	0.7b	35.8a	7.7b	4.5a	2.2b	155.7a	23.4b
p-values	<.0001	<.0001	0.0054	<.0001	0.0047	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
Cover crops												
Control	10.5a	6.9a	339.5a	108.5a	1.2a	1.0a	38.1a	15.5a	4.4a	3.5a	144.4a	55.5a
Barley	9.0b	6.7a	221.7b	77.3b	1.0b	0.9b	25.6b	10.3b	4.0b	3.1b	106.4b	37.4b
Oats	9.4b	6.9a	239.3b	82.2b	1.1ab	0.9b	28.0b	11.2b	4.1b	3.5a	111.0b	41.5b
p-values	<.0001	0.5276	<.0001	0.0008	0.0049	0.017	<.0001	<.0001	<.0001	0.0002	<.0001	0.0006

Mean of three replicates (n = 3). Means followed by the same letter in a column under each treatment are not significantly different ($p > 0.05$).

Table 4.6. Effect of fertilization and vegetation on total Ca and Mg uptake accumulation in shoots and roots of tree seedlings after two growing seasons.

Factor	Ca ($mg\ g^{-1}$)		Ca uptake ($mg\ plant^{-1}$)		Mg ($mg\ g^{-1}$)		Mg uptake ($mg\ plant^{-1}$)	
	Shoot	**Root**	**Shoot**	**Root**	**Shoot**	**Root**	**Shoot**	**Root**
Fertilizer								
0	12.9a	8.3a	328.6ab	110.3ab	1.7a	1.2a	43.4a	15.7a
150	13.0a	8.5a	308.4ab	107.0ab	1.8a	1.1a	43.0a	14.9a
300	12.5a	8.3a	293.4b	96.1b	1.9a	1.1a	43.2a	13.1a
600	13.6a	9.7a	411.9a	131.6ab	1.8a	1.3a	51.9a	18.0a
750	11.9a	9.6a	374.6ab	143.3a	1.7a	1.3a	52.8a	19.1a
900	12.4a	8.4a	371.1ab	101.4ab	1.6a	1.2a	48.6a	14.2a
1,200	12.0a	8.8a	292.1b	101.8ab	1.6a	1.2a	39.2a	13.4a
1,500	12.1a	9.2a	312.9ab	107.2ab	1.6a	1.1a	42.5a	13.5a
p-values	0.0826	0.2439	0.0127	0.0283	0.0695	0.3177	0.0840	0.0597
Tree species								
Trembling aspen	15.9a	8.9a	353.4a	130.1a	2.2a	1.3a	48.6a	18.6a
White spruce	9.2b	8.8a	319.9a	94.6b	1.2b	1.1b	42.6b	11.9b
p-values	<.0001	0.7435	0.076	<.0001	<.0001	<.0001	0.0204	<.0001
Cover crops								
Control	13.0a	8.9a	417.3a	129.0a	1.7a	1.2a	54.1a	17.8a
Barley	12.3a	9.1a	294.8b	103.8b	1.7a	1.2a	39.8b	13.3b
Oats	12.3a	8.6a	297.8b	104.2b	1.7a	1.2a	42.8b	14.6b
p-values	0.1668	0.6256	<.0001	0.0107	0.348	0.4477	<.0001	0.002

Mean of three replicates (n = 3). Means followed by the same letter in a column under each treatment are not significantly different ($p > 0.05$).

4.5.4. Soil fertility status

4.5.4.1. Soil extractable nutrients

Extractable nutrients in post-harvest soil measured after two seasons of growth did not show strong patterns related to fertilizer addition, tree species or cover crop treatments (Tables 4.7 and 4.8). Soil NO_3^--N levels were generally low and only significantly elevated at the highest fertilizer rate addition treatment (1500 kg ha^{-1}). Similar results were observed for phosphorus and potassium (Tables 4.7 and 4.8). Soil sulphur level was significantly affected by N,P,K fertilizer application and cover crops treatment. There was a decreasing trend of soil sulphur levels with increased rates of fertilizer application (Table 4.7), indicating initial soil sulphur may have been used by the cover crops. In addition, amounts of calcium, magnesium and sodium were not significantly affected by treatment factors (Table 4.8). Overall, there appears to be a relatively large amount of added N that was added but which is unaccounted for in the post-harvest soil. This nutrient may have been lost from the system or may still be present in the system immobilized in dead biomass residue of the native vegetation and cover crops. Available N (NO_3^--N and NH_4^+-N) in post-harvest soil was lower than in the initial soil (Tables 4.1 and 4.7).

4.5.4.2. Nutrient supply rate

Soil inorganic nutrient supply rate measured in the post-harvest soil (Table 4.9) showed similar trends to soil extractable nutrients. Supply rates of NO_3^--N, PO_4^{3-}-P, and K^+ were only significantly higher at the highest level of fertilizer addition. Soil nitrate and potassium supply rate were also affected by tree species and a significantly lower supply rate of nitrate was recorded from trembling aspen, whereas potassium supply rate from white spruce soil was lower than trembling aspen (Table 4.9). Soil sulphate supply rate was significantly affected by fertilization and cover crops treatment, and there was a decreasing trend of sulphate supply rate with increased rates of fertilizer addition (Table 4.9). Soil ammonium, calcium, and magnesium supply rates were not affected by fertilizer, tree species or cover crop treatments (Table 4.9).

Table 4.7. Mean soil extractable available nitrogen (NO_3^--N and NH_4^+-N), phosphorus (PO_4^{3-}-P) and sulphur (SO_4^{2-}-S) at different depths after two growing seasons as affected by fertilizer application and vegetation growth.

Factor	**NO_3^--N Soil depth (cm)**			**NH_4^+-N Soil depth (cm)**			**PO_4^{3-}-P Soil depth (cm)**			**SO_4^{2-}-S Soil depth (cm)**		
	0-30	**30-60**	**0-60**	**0-30**	**30-60**	**0-60**	**0-30**	**30-60**	**0-60**	**0-30**	**30-60**	**0-60**
Fertilizer	---kg ha^{-1}---											
0	2.5b	2.2a	4.7b	22.9a	33.8a	56.7b	5.8c	6.6a	12.4ab	189a	234ab	424a
150	2.6b	2.3a	4.9b	22.7a	37.4a	60.1ab	6.2bc	6.8a	13.0ab	166ab	214ab	381a
300	2.8b	2.4a	5.2b	22.0a	32.4a	54.4b	6.4bc	5.7a	12.1b	149ab	181b	331a
600	2.6b	2.2a	4.8b	22.8a	32.0a	54.8b	6.6bc	6.0a	12.6b	162ab	249ab	411a
750	3.2b	2.4a	5.6b	23.2a	39.8a	63.0ab	8.9ab	7.1a	16.0ab	121ab	175b	296a
900	3.5b	2.6a	6.1b	27.0a	38.2a	65.2ab	8.6abc	6.1a	14.7ab	130ab	238ab	369a
1,200	2.9b	2.7a	5.6b	23.5a	32.2a	55.7b	8.3abc	7.3a	15.6ab	104b	211ab	313a
1,500	5.8a	3.1a	8.9a	32.7a	39.5a	72.2a	10.0a	8.2a	18.2a	108b	308a	416a
p-values	<.0001	0.0511	<.0001	0.1001	0.0728	0.0041	0.0002	0.1814	0.0016	0.0028	0.0202	0.1932
Tree species												
Trembling aspen	2.8b	2.3b	5.1b	26.8a	34.1a	60.9a	8.0a	6.7a	14.9a	143a	194b	337a
White spruce	3.6a	2.6a	6.2a	22.4b	37.2a	59.6a	7.2a	6.5a	13.7a	139a	259a	398a
p-values	0.0006	0.0096	0.0007	0.0248	0.0814	0.5405	0.0892	0.2663	0.0907	0.7471	0.0010	0.0598
Cover crops												
Control	3.5a	2.5a	6.0a	25.8a	38.2a	64.0a	8.6a	7.1a	15.7a	129b	184b	314b
Barley	3.0a	2.4a	5.4b	24.7a	34.4a	59.1a	7.2ab	6.7a	13.9ab	124b	225ab	350b
Oats	3.1a	2.5a	5.6ab	23.3a	34.3a	57.6a	7.0b	6.4a	13.4b	170a	269a	440a
p-values	<.0001	0.0660	0.0328	0.8540	0.1828	0.6839	0.2957	0.5745	0.5517	0.0128	0.0001	0.0002

Mean of three replicates (n = 3). Means followed by the same letter in a column under each treatment are not significantly different ($p > 0.05$).

Table 4.8. Mean soil exchangeable base cations at different depths after two growing seasons as affected by fertilizer application and vegetation growth.

Factor	**K^+ Soil depth (cm)**			**Ca^{2+} Soil depth (cm)**			**Mg^{2+} Soil depth (cm)**			**Na^+ Soil depth (cm)**		
	0-30	**30-60**	**0-60**	**0-30**	**30-60**	**0-60**	**0-30**	**30-60**	**0-60**	**0-30**	**30-60**	**0-60**
Fertilizer	---cmol[+]kg^{-1}---											
0	0.2b	0.2b	0.4b	34.6a	30.0a	64.6a	5.3a	4.5a	9.8a	0.2a	0.2a	0.4a
150	0.2b	0.2b	0.4b	30.7a	29.9a	60.6a	4.5a	4.7a	9.2a	0.2a	0.2a	0.4a
300	0.2b	0.2b	0.4b	35.7a	35.9a	71.6a	4.7a	5.0a	9.7a	0.2a	0.2a	0.4a
600	0.2b	0.2b	0.4b	36.4a	35.1a	71.5a	4.8a	4.6a	9.4a	0.2a	0.2a	0.4a
750	0.2b	0.2b	0.4b	32.3a	25.7a	58.0a	4.9a	3.8a	8.7a	0.2a	0.2a	0.4a
900	0.2b	0.2b	0.4b	35.3a	33.4a	68.7a	4.9a	4.7a	9.6a	0.2a	0.2a	0.4a
1,200	0.2b	0.2b	0.4b	30.8a	35.2a	66.0a	4.4a	4.6a	9.0a	0.2a	0.2a	0.4a
1,500	0.3a	0.4a	0.7a	32.8a	27.5a	60.3a	5.0a	3.9a	8.9a	0.2a	0.2a	0.4a
p-values	<.0001	0.0007	<.0001	0.2355	0.0541	0.0601	0.6493	0.1966	0.7539	0.1553	0.2105	0.1244
Tree species												
Trembling aspen	0.2a	0.2a	0.4a	32.6a	31.8a	64.4a	4.7a	4.6a	9.3a	0.2a	0.2a	0.4a
White spruce	0.2a	0.3a	0.5a	34.6a	31.4a	66.0a	4.9a	4.4a	9.3a	0.2a	0.2a	0.4a
p-values	0.1578	0.3192	0.8051	0.1340	0.8139	0.5267	0.4247	0.5797	0.8775	0.2282	0.2137	0.1144
Cover crops												
Control	0.2a	0.2b	0.4b	33.8a	30.9a	64.7a	4.8a	4.4a	9.2a	0.2a	0.2a	0.4a
Barley	0.2a	0.2b	0.4b	31.8a	31.0a	62.8a	4.7a	4.6a	9.3a	0.2a	0.2a	0.4a
Oats	0.2a	0.3a	0.5a	35.1a	32.9a	68.0a	4.9a	4.5a	9.4a	0.2a	0.2a	0.4a
p-values	0.0524	0.0456	0.0485	0.2499	0.1201	0.2024	0.1650	0.1045	0.0978	0.6902	0.0609	0.0516

Mean of three replicates (n = 3). Means followed by the same letter in a column under each treatment are not significantly different ($p > 0.05$).

Table 4.9. Nutrient supply rate as measured by ion exchange membranes after 24 hours sorption from initial and post-harvest soils at 0-30 cm depth.

Factor	NO_3^--N	NH_4^+-N	PO_4^{3-}-P	SO_4^{2-}-S	K^+	Ca^{2+}	Mg^{2+}
	---------------$\mu g\ cm^{-2}$---------------						
Initial soil	5.5	0.9	0.2	98.9	1.4	397.3	49.3
Post-harvest soil							
Fertilizer							
0	0.6b	1.5a	0.2b	64.7ab	0.8b	344.4a	38.7a
150	0.4b	1.6a	0.2b	74.3a	1.0b	343.7a	39.2a
300	0.4b	1.5a	0.2b	51.3ab	1.6b	384.1a	41.1a
600	0.3b	1.9a	0.2b	50.8ab	1.1b	384.0a	39.6a
750	1.1b	1.7a	0.3b	40.6b	1.4b	360.4a	41.6a
900	0.6b	1.9a	0.4b	48.9b	1.7b	346.9a	38.1a
1,200	0.6b	2.1a	0.3b	41.1b	1.5b	344.5a	39.7a
1,500	2.7a	2.3a	1.5a	42.6b	6.0a	393.0a	45.8a
p-values	<.0001	0.0664	0.0011	0.0003	<.0001	0.0920	0.1014
Tree species							
Trembling aspen	0.6b	1.8a	0.6a	52.8a	2.4a	357.6a	40.2a
White spruce	1.1a	1.9a	0.3a	50.8a	1.4b	367.6a	40.7a
p-values	0.0091	0.5497	0.0631	0.6195	<.0001	0.2196	0.6891
Cover crops							
Control	0.6a	1.7a	0.3a	44.7b	1.7a	366.6a	40.3a
Barley	1.1a	1.8a	0.3a	50.5ab	2.0a	351.1a	41.1a
Oats	0.8a	2.0a	0.6a	60.1a	2.0a	370.3a	40.0a
p-values	0.1295	0.1056	0.1135	0.0112	0.5765	0.1270	0.7487

Mean of three replicates (n = 3). Means followed by the same letter in a column under each treatment are not significantly different ($p > 0.05$).

4.6. Discussion

4.6.1. Seedling establishment and growth

An important outcome of this experiment was the observed interaction between tree species and cover crops, with different response of the two different tree species to cover crops, especially with added fertilizer. Visual observations were that fertilizer additions greatly enhanced the growth of ground cover crops (Appendix B, Fig. B.1) as was measured in the controlled environment experiment described in chapter 3. In the field this subsequently reduced survival and growth of the tree seedlings. This reflects enhanced competition between tree seedlings and cover crops for other available resources such as soil moisture and sunlight (Morris et al., 1993; Nambiar and Sands, 1993; Thevathasan et al., 2000). In general, the results indicate that trembling aspen was more sensitive than white spruce to ground cover crop competition which was stimulated by fertilization. Trembling aspen is a very shade-intolerantspecies and full sunlight is a pre-requisite for survival and optimum growth (DeByle and Winokur, 1985; Perala, 1990; Puettmann and Reich, 1995). During the early stages of growth, horizontally spreading lateral roots near the surface is a prominent feature of aspen (Strong and La Roi, 1983), such that direct competition for available resources with planted cover crops like barley and oats with a shallow and fibrous rooting system will be a major issue. Rapid growth of annual crops like barley and oats would deplete water in the same region of the soil profile, restricting root proliferation and thereby reducing growth and biomass yield of aspen.

Van den Driessche et al. (2003) reported that aspen survival in Alberta was reduced by fertilization without irrigation and might be due to additional soil moisture stress developed by soluble fertilizer addition in dry soil. In this study, native weeds as a competing vegetation grew invasively only with added fertilizer, and also were observed to accelerate soil moisture stress (Van den Driessche et al., 2005) and lower biomass yield and plant nutrient uptake (Guswa, 2005). On the other hand, white spruce is considered as a shade tolerant and slow growing species (Sims et al., 1990), but reduced seedlings survival and early growth from vegetation competition was also observed in a study in Alaska (Cole et al., 2003). Moreover, as a slow growing species, the early growth of white spruce as expressed in height increase is generally not responsive to fertilization (Sims et al., 1990), which agrees with the results of this study. Overall, fertilization adversely affected the establishment success and growth of planted tree seedlings by stimulating competition from native vegetation/weeds and planted cover crops, as the added benefits were mostly obtained by those non-targeted plants. This finding agrees with others (Allen and Nien, 1998; Allen and Albaugh, 2000; Nilsson and Allen, 2003).

4.6.2. Tree seedling nutritional status

Tree seedlings that have adequate supplies of mineral nutrients are considered to perform better in field in terms of establishment and early growth (Jacobs et al., 2005, Salifu et al., 2009). From results of this study, comparatively higher nutrient concentrations in trembling aspen are an indication that aspen is a more nutrient demanding tree species than white spruce. This finding is in agreement with the observation that early successional tree species like aspen are more nutrient demanding than climax species like white spruce (Strong and La Roi, 1985; Van Rees, 1997). In general, increased N, P, and K concentration in shoots and roots of tree seedlings with fertilizer addition is an expected trend of enhanced nutrient acquisition under favourable conditions. On the other hand, limited nutrient uptake enhancement with increased fertilizer application may be explained by non-crop vegetation competition. Several researchers (Jacobs et al., 2005; Casselman et al., 2006; Salifu et al., 2009) reported that growth and nutrient uptake of competing vegetation rather than planted tree seedlings was increased with broadcast fertilization with mineral fertilizers. Compared to native vegetation, competition for nutrients is greater with cover crop grass species like barley and oats due to their fibrous root system and rapid growth characteristics (Clark, 2007). On contrary, the immobilization of nutrient in cover crop biomass may be beneficial in reducing leaching loss and enhance nutrient cycling in subsequent years as cover crop residues undergo decomposition in the following years.

4.6.3. Soil nutrient availability

Observed differences in exchangeable nutrients and their supply rate in initial and post-harvest soils are useful in explaining the fertility status and suitability of peat-mineral mixture as reclamation materials. Many researchers (Fung and Macyk, 2002; Rowland et al., 2009; Pinno et al., 2012) reported that organic-mineral mixtures (forest floor or peat mixed with mineral soils) can create a surface layer that supports plant growth in reconstructed oil sands site and aid in re-establishing the native ecosystem. Better growth of aspen seedlings was observed in organic-mineral mixtures compared to different types of sub-surface soil used for reclamation in a study in Alberta (Pinno et al., 2012). It might be due to the comparatively higher available nutrient content in the organic-mineral mixture that supplied nutrient in sufficient amounts for early aspen growth.

The amount of N in reclaimed soil is often higher than natural soils (Rowland et al., 2009), therefore, added N may also accelerate leaching and denitrification losses from the field. In this study, elevated soil available N with increased fertilization was not observed in deeper soil layers, thus indicating denitrification might be the major process of N loss in this system. Research results on denitrification losses in fertilized boreal forest systems are not available. However, it was reported that annual N loss in an unfertilized boreal forest ecosystem by denitrification ranged from <0.01 to 42 kg N ha^{-1} $year^{-1}$ (Vermes and Myrold, 1992). Furthermore, the denitrification process is highly correlated with soil NO_3^- levels and can be aggravated by nitrogenous fertilizer addition (Vermes and Myrold, 1992; Barton et al., 1999). Similarly, addition of P in excess of plant requirements often results in higher buildup of total P and available P in surface soil (Chang et al., 2005) and/or increased P losses which promotes eutrophication of surface water bodies (Pote et al., 1996; Andraski et al., 2003). However, the increased risk of P loss from fertilization is dependent on several factors including soil pH, initial soil P levels and soil P-retention capacities (Kleinman et al., 2003). The study site soil pH was favourable for total P buildup, as under high soil pH, P reacts with Ca or Mg to form less soluble Ca or Mg-phosphates compounds (Havlin et al., 2005) that are not easily available for plants. It is also possible that some of the added fertilizer nutrient remains immobilized in the dead biomass of the native vegetation and cover crops in organic forms. Extractions and supply rate measurements that were made in this study included only the inorganic, ionic forms of the nutrient. It is suggested that future work on fate of fertilizers added to these reclaimed soils focus on organic as well as inorganic forms in which nutrient may be accumulating.

4.7. Conclusion

The establishment and early growth of the aspen and white spruce tree seedlings planted for reclamation were greatly affected by current re-vegetation programs that includes planting of cover crops and application of mineral fertilizer to reconstructed oil sands sites. In general, a species-specific response of tree seedlings to cover crops and fertilization was observed in this oil sands site reconstructed with a peat-mineral mixture. Survival of trembling aspen was comparatively lower than white spruce, and growth and biomass yields of trembling aspen were adversely affected by cover crops with added fertilizer. Compare to native vegetation, seeded cover crops like barley and oats had negative effects on survival and growth of trembling aspen due to resource competition, whereas white spruce was unaffected. Added benefits of fertilization were mostly capitalized on by cover crops, with their subsequent vigorous growth affecting the survival and growth of tree seedlings. Considering the soil fertility status of this study site, it is concluded that the peat-mineral mixture can supply sufficient nutrients for early seedling growth, and fertilization is not necessary for the establishment and early growth of tree seedlings. Benefits of fertilization and cover crops may appear after a few years, and it is recommended that future work consider the longer term (several years) effects.

5. SYNTHESIS AND RECOMMENDATION

5.1. Summary

Reclamation following open-pit surface mining in the oil sands region of northern Alberta, Canada, has focused on reconstruction of disturbed sites and re-establishment of native vegetation. A mixture of soils salvaged from existing boreal forest and peat lands are used as the surface layer in reclaimed sites to promote vegetation establishment. Seeded ground cover vegetation is also used in recently reclaimed sites for soil stabilization, to prevent erosion, and to provide protective cover for the newly planted boreal tree seedlings. Considering the potential low fertility of reclamation materials and potential competition by the vegetation cover for nutrients and water, it was hypothesized that fertilization will compensate for the additional nutrient demand by cover crops, and improve establishment success (survival and growth) of tree seedlings.

In this thesis, two approaches were used to investigate the effect of fertilization on survival and growth of trembling aspen and white spruce tree seedlings planted without and with barley and oats as cover crops. The first approach was a greenhouse experiment to determine the interspecific competition for key growth resources like nutrients and moisture to improve revegetation success, conducted under controlled conditions to reduce variability in soil and environmental conditions. An important consideration is to also verify the greenhouse results in the field under natural growth environment where the native plant community may develop along with planted cover crops without restricted root volume and may impact the reclamation success. Therefore, a fertilizer dose response trial was conducted under field conditions at Fort McMurray, Alberta to determine what fertilization practices are needed to optimize survival, early growth, and nutrition of tree seedlings in the oil sands region.

In the greenhouse study described in Chapter 3, tree seedlings responded more to variation in soil moisture status than to alteration of soil nutrient availability through fertilizer addition. Alleviating moisture stress produced consistent significant increases in height, RCD growth, and biomass yield of tree seedlings, whereas fertilizer effects were less and sometimes not significant for the parameters measured. Overall, the effects of different treatment combinations on tree seedling growth and biomass yield differed between the tree species, with trembling aspen being responsive while white spruce generally was not. For trembling aspen, fertilization significantly increased height and RCD growth, with a significant effect of soil moisture observed for height, shoot and root biomass yield.

Tree seedling responses to cover crops were adverse due to interspecific competition between the tree seedlings and the cover crops. Negative effects on the tree seedlings from the cover crops were not overcome with fertilizer addition. The barley and oats cover crops benefitted from the added resources, grew vigorously, and suppressed the growth of tree seedlings. Growth and biomass yield of trembling aspen was significantly reduced by barley and oats in comparison to control (no grass), while white spruce was unaffected.

Similar findings to the controlled environment greenhouse study described in Chapter 3 were observed under field conditions in the study covered in Chapter 4. It is important to recognize that in the greenhouse study, the competitive effects of barley and oats cover crops were compared with a control treatment that was kept completely weed free, but in the field study, annual weeds and native vegetation also grew invasively, and visually their growth was observed to increase with higher rates of fertilizer application. Thus, similar competitive effects occurred in both the field study and in the greenhouse study with seeded cover crops. In the field study, the overall effect of fertilization was negative for tree seedling survival. Moreover, nutrient content of tree seedlings after two growing seasons in the field and available nutrient supplying capacity of peat-mineral mixture at the beginning and after two growing seasons were only affected by the higher rates of fertilizer application. Therefore, it may be concluded that the peat-mineral mixture may supply adequate nutrients for initial tree seedling growth and that the added fertilizer is utilized by cover crops and/or invasive vegetation rather than the tree seedlings such that the associated increased ground cover growth inhibits tree seedling survival and growth.

5.2. Reclamation application and significance

Results from this study suggest that broadcast application of high rates of immediately available fertilizer may not be beneficial in enhancing early establishment and growth of tree seedlings in reclaimed sites capped with peat-mineral mixture. In fact, fertilization may have a negative effect by enhancing seeded cover crop and/or invasive species growth, thereby increasing competition for other resources like water. Planted cover crops like barley and oats compete with newly planted tree seedlings for resources, therefore, tree seedling plantation could be performed in the year after site development and planting of cover crops. This would provide time for the residues of the annual crops like barley and oat that were planted the previous years to undergo decomposition and release of nutrient. Furthermore, it would be anticipated that these annual species would not regenerate to a great extent and that the straw mulch could be beneficial for moisture retention and protection of the site from erosion.

5.3. Future research

This study was conducted with a peat-mineral mixture that is usually used as top capping layer in restructuring mined sites to promote vegetation growth. Growth data on the tree seedlings were collected for two growing seasons following planting, but stored nutrient in tree seedlings and that retained in the residue of the decomposing cover crop residues could be helpful in promoting better growth in subsequent years. Therefore, an evaluation of the effects of fertilization five, ten or even more years following fertilizer application would be beneficial. As well, using other reclamation materials like upland surface and sub-surface soil would be rewarding to evaluate, as these materials likely have different nutrient supplying power and moisture retention capabilities compared to the peat-mineral mixture used in the reclamation site evaluated in this study.

6. References

Albaugh, T.J., J.L.Stape, T.R. Fox, R.A. Rubilar, and H.L. Allen. 2012. Midrotation vegetation control and fertilization response in *Pinus taeda* and *Pinus elliottii* across the southeastern United States. Southern J. Appl. For. 36:44-53.

Alberta Energy. 2013. Alberta energy: facts and statistics. http://www.energy.alberta.ca /OilSands/791.asp (accessed on 1 Nov., 2013).

Alberta Environment and Water. 2012. Best Management practices for conservation of reclamation materials in the mineable oil sands region of Alberta. Prepared by MacKenzie, D. for the terrestrial subgroup, Best management practices task Group of the Reclamation Working Group of the Cumulative Environmental management association, Fort McMurray, Alberta. http://environment.gov.ab.ca/info/library/ 8431.pdf.

Allen, H.L., P.M. Dougherty, and R.G. Campbell. 1990. Manipulation of water and nutrients - Practice and opportunity in southern U.S. pine forests. For. Ecol. Manage. 30:437-453.

Allen, H.L., and S. Lein. 1998. Effects of site preparation, early fertilization, and weed control on 14-year old loblolly pine. Proc. South. Weed Sci. Soc. 51:104-110.

Allen, H.L., and T.J. Albaugh. 2000. Understanding the interactions between vegetation control and fertilization in young plantations: Southern pine plantations in the southeast USA. p. 1-14 in Proc. conf. on II Seminario sobre Manejo de Plantas Infestantes em Areas Florestais. Department of Forest Soils at ESALQ, Univ. of San Paulo, Brazil.

Andraski, T.W., L.G. Bundy, and K.C. Kilian. 2003. Manure history and long-term tillage effects on soil properties and phosphorus losses in runoff. J. Environ. Qual. 32:1782-1789.

Anielski, M., and S. Wilson. 2005. Counting Canada’s natural capital: assessing the real value of Canada’s boreal ecosystems. Canadian Boreal Initiative and the Pembina Institute. Canadian Boreal Initiative. Ottawa, ON. p. 78.

Archibold, O.W. 1979. Buried viable propagules as a factor in postfire regeneration in northern Saskatchewan. Can. J. Bot. 57:54-58.

Archibold, O.W., C. Acton, and E.A. Ripley. 2000. Effect of site preparation on soil properties and vegetation cover, and the growth and survival of white spruce (*Picea glauca*) seedlings, in Saskatchewan. For. Ecol. Manage. 131:127-141.

Ashby, W.C. 1997. Soil ripping and herbicides enhance tree and shrub restoration on stripmines. Restor. Ecol. 5:169-177.

Balandier, P., C. Collet, J.H. Miller, P.E. Reynolds, and S.M. Zedaker. 2006. Designing forest vegetation management strategies based on the mechanisms and dynamics of crop tree competition by neighbouring vegetation. Forestry. 79:3-27. doi:10.1093/forestry/cpi056.

Barton, L., C.D.A. McLay, L.A. Schipper, and C.T. Smith. 1999. Annual denitrification rates in agricultural and forest soils: a review. Soil Res. 37:1073-1094.

BGC Engineering Inc. 2010. Review of reclamation options for oil sands tailings substrates. Oil Sands Research and Information Network, University of Alberta, School of Energy and the Environment, Edmonton, Alberta. OSRIN Report No. TR-2. p.59.

Bonan, G.B., and H.H. Shugart. 1989. Environmental factors and ecological processes in boreal forests. Annu. Rev. Ecol. Syst. 20:1-28.

Bowman, G., C. Shirley, and C. Cramer. 1998. Managing cover crops profitably, 2nd edition, Sustainable Agriculture Publications, Burlington, VT. p. 212.

Bridge, S.R.J., and E.A. Johnson. 2000. Geomorphic principles of terrain organization and vegetation gradients. J. Veg. Sci.11:57-70.

Brockley, R.P. 1988. The effects of fertilization on the early growth of planted seedlings: a problem analysis. For. Canada and B.C. Min. For. Res. Br., FRDA Report 011, Victoria, B.C.

Burger, J., D. Graves, P. Angel, V. Davis, and C. Zipper. 2005. The forestry reclamation approach. For. Reclamation Advisory, 2.

Burton, C.M., and P.J. Burton. 2003. A manual for growing and using seed from herbaceous plants native to the interior of northern British Columbia. Symbios Research and Restoration, Smithers, BC. p.168.

Canadian Boreal Initiative. 2005. The boreal in balance: Securing the future of Canada's boreal region. Canadian Boreal Initiative, Ottawa, Ontario. p. 1-72. http://www.borealcanada.ca/documents/Boreal_in_the_Balance_Full.pdf.

Canadian Centre for Energy Information. 2010. Canada's oil sands. Third Edition. p.16. http://www.centreforenergy.com/ (accessed on 1 March, 2012).

Canadian Association of Petroleum Producers (CAPP). 2013. Crude oil forecast, markets and transportation report. p. 1-48. http://www.capp.ca/getdoc.aspx? DocId=227308&DT =NTV (accessed on 25 Oct., 2013).

Carlson, D., P.B. Reich, and L.E. Frelich. 2011. Fine-scale heterogeneity in overstory composition contributes to heterogeneity of wildfire severity in southern boreal forest. J. For. Res. 16:203-214. doi:10.1007/s10310-011-0251-z.

Carrigy, M.A. 1959. Geology of the McMurray formation, Part III, General geology of the McMurray area. Alberta Res. Counc. Mem. p. 130.

Casselman, C.N., T.R. Fox, J.A. Burger, A.T. Jones, and J.M. Galbraith. 2006. Effects of silvicultural treatments on survival and growth of trees planted on reclaimed mine lands in the Appalachians. For. Ecol. Manage. 223:403-414.

CEMA-RWG Landscape Design Subgroup. 2005. Landscape Design Checklist, Revised RSDS government regulator version, May 2005. Cumulative Environmental Management Association. Fort McMurray, AB. http://www.cemaonline.ca/ (accessed on 25 March, 2012).

Chang, C., J.K. Whalen, and X. Hao. 2005. Increase in phosphorus concentration of a clay loam surface soil receiving repeated annual feedlot cattle manure applications in southern Alberta. Can. J. Soil Sci. 85:589-597.

Chen, H.Y., and R.V. Popadiouk. 2002. Dynamics of North American boreal mixedwoods. Environ. Rev. 10:137-166.

Clark, A. 2007. Managing Cover Crops Profitably. 3rd edition. Sustainable Agriculture Network Handbook Series 9. Beltsville, MD: Sustainable Agriculture Network.

Classen, V. P., and R. J. Zasoski. 1993. Enhancement of revegetation on construction fill by fertilizer and topsoil application: effect on mycorrhizal infection. Land Degrad. Rehab. 4:45-57.

Cole, E.C., A. Youngblood, and M. Newton, M. 2003. Effects of competing vegetation on juvenile white spruce (*Picea glauca* (Moench) Voss.) growth in Alaska. Ann. For. Sci. 60:573-583. doi:10.1051/forest:2003049.

Coll, L., P. Balandier, C. Picon-Cochard, B. Prevosto, and T. Curt. 2003. Competition for water between beech seedlings and surrounding vegetation in different light and vegetation composition conditions. Ann. For. Sci. 60:593-600.

Conly, F.M., R.W. Crosley, and J.V. Headley. 2002. Characterizing sediment sources and natural hydrocarbon inputs in the lower Athabasca River, Canada. J. Environ. Eng. Sci. 1:187-199.

DeByle, N.V., and R.P. Winokur, editors. 1985. Aspen: Ecology and management in the western United States. USDA forest service, General technical report RM-119. Rocky mountain forest and range experiment station, Fort Collins, CO. p. 283.

Devine, W.D., T.B. Harrington, T.A. Terry, R.B. Harrison, R.A. Slesak, D.H. Peter, C.A. Harrington, C.J. Shilling, and S.H. Schoenholtz. 2011. Five-year vegetation control effects on aboveground biomass and nitrogen content and allocation in Douglasfir plantations on three contrasting sites. For. Ecol. Manage. 262:2187-2198.

Dinger, E., and R. Rose. 2009. Integration of soil moisture, xylem water potential, and fallspring herbicide treatments to achieve the maximum growth response in newly planted Douglass-fir seedlings. Can. J. For. Res. 39:1401-1414.

Dinger, E., and R. Rose. 2010. Initial fall-spring vegetation management regimes improve moisture conditions and maximize third-year Douglass-fir seedling growth in a Pacific Northwest plantation. New Zealand J. For. Sci. 40:93-108.

du Toit, B., C.W. Smith, K.M. Little, G. Boreham, and R.N. Pallett. 2010. Intensive, site- specific silviculture: manipulating resource availability at establishment for improved stand productivity. A review of South African research. Forest Ecol. Manage. 259:1836-1845.

Dunabeitia, M.K., S. Hormilla, I. Jose, K. Txarterina, U. Arteche and J.M. Becerril. 2004. Differential responses of three fungal species to environmental factors and their role in the mycorrhization of *Pinus radiata* D. Don. Mycorrhiza. 14:11-18.

Dunbar, R.B. 2010. Canada's oil sands, A world-scale hydrocarbon resource, Strategy West Inc., Calgary, AB. p. 23. http://www.strategywest.com/downloads/StratWest_OilSands_2011.pdf.

Environment Canada. 2013. Canadian climate normals 1971–2000. Fort McMurray Airport Alberta.http://www.climate.weatheroffice.gc.ca/climate_normals/ results_e.html?stnID=2519&lang=e&dCode=1&province=ALTA&provBut=Search&month1=0&month2=12 (accessed on 15 April, 2013).

Frelich, L.E., J.L. Machado, and P.B. Reich. 2003. Fine-scale environmental variation and structure of understorey plant communities in two old-growth pine forests. J. Ecol. 91:283-293.

Fung, M.Y.P., and T.M. Macyk. 2000. Reclamation of oil sands mining areas. In: R.I. Barnhisel, R.G. Darmody, and W.L. Daniels, editors, Reclamation of drastically disturbed lands. ASA, Madison, WI. p. 755-774.

Ghose, M.K. 2001. Management of topsoil for geo-environmental reclamation of coal mining areas. Env. Geol. 40:1405-1410.

Gingras, M., and D. Rokosh. 2004. A brief overview of the geology of heavy oil, bitumen and oil sand deposits. Can. Soc. Explor. Geophysicists (CSEG) Conf. Abstr. www. Csegconvention.org/2004abstracts/122S0227ingras_M_heavy_oil_bitumen_oil_sands.pdf.

Government of Alberta. 2013. Oil sands reclamation. http://oilsands.alberta.ca/ reclamation.html (accessed on 10 Oct., 2013).

Grant, J., S. Dyer, and D. Woynillowicz. 2008. Fact or fiction? Oil sands reclamation. The pembina institute: Drayton Valley, Alberta.

Grant, J., E. Angen, and S. Dyer. 2013. Forecasting the impacts of oilsands expansion. Pembina Institute. http://pubs.pembina.org/reports/oilsands-metrics.pdf. (accessed on 12 Oct., 2013)

Grime, J.P. 2001. Plant Strategies, vegetation processes, and ecosystem properties, 2nd edition, John Wiley and Sons, New York, NY.

Grimmett, M., and C.G. Kowalenko. 2007. Chemical characterization of sulfur. In: M.R. Carter and E.G. Gregorich, editors, Soil sampling and methods of analysis. 2nd edition, Chapter 23. CRC Press, Boca Raton, FL, p. 173-178.

Groninger, J.W., J. Skousen, P. Angel, C. Barton, J. Burger, and C. Zipper. 2007. Mine reclamation practices to enhance forest development through natural succession. USDOI Office of Surface Mining. Forest Reclamation Advisory No. 5. http://arri.osmre.gov/fra.htm.

Grossnickle, S.C. 2005. Importance of root growth in overcoming planting stress. New Forests. 30:273-294.

Guillemette, T., and A. DesRochers. 2008. Early growth and nutrition of hybrid poplars fertilized at planting in the boreal forest of western Quebec. For. Ecol. Manage. 255: 2981-2989.

Guswa, A.J. 2005. Soil-moisture limits on plant uptake: An upscaled relationship for water-limited ecosystems. Adv. Water Resour. 28:543-552.

Hangs, R.D., J.D. Knight, and C.J. Van Rees. 2003. Nitrogen uptake characteristics for roots of conifer seedlings and common boreal forest competitor species. Can. J. For. Res. 33:156-163.

Harrington, T.B. 2006. Five-year growth responses of douglas-fir, western hemlock, and western redcedar seedlings to manipulated levels of overstory and understory competition. Can. J. For. Res. 36:2439-2453.

Havlin, J.L., J.D. Beaton., S.L. Tisdale, and W.L. Nelson. 2005. Soil fertility and fertilizers, 7th edition, Pearson Education. Upper Saddle River, N.J.

Haywood, J.D., A.E. Tiarks, and M.A. Sword. 1997. Fertilization, weed control, and pine litter influence loblolly pine stem productivity and root development. New Forests 14:233-249.

Hendershot, W.H., H. Lalande, and M. Duquette. 2007a. Soil reaction and exchangeable acidity. In: M.R. Carter and E.G. Gregorich, editors, Soil sampling and methods of analysis. 2nd edition, Chapter 16. CRC Press, Boca Raton, FL, p. 173-178.

Hendershot, W.H., H. Lalande, and M. Duquette. 2007b. Ion exchange and exchangeable cations. In: M.R. Carter and E.G. Gregorich, editors, Soil sampling and methods of analysis. 2nd edition, Chapter 18. CRC Press, Boca Raton, FL, p. 197-206.

Huang, W.Z., and J.J. Schoenau. 1997. Seasonal and spatial variations in soil nitrogen and phosphorus supply rates in a boreal aspen forest. Can. J. Soil Sci. 77:597-612.

Isaacs, E. 2007. The Canadian oil sands in the context of the global energy demand. Extended abstract for 17th convocation of the international council of academics of engineering and technological sciences (CAETS), Tokyo, Japan.

Jacobs, D.F., F.K. Salifu, and J.R. Seifert. 2005. Growth and nutritional response of hardwood seedlings to controlled-release fertilization at outplanting. For. Ecol. Manage. 214:28-39.

Jacobs, D.F., K.F. Salifu, and A.S. Davis. 2009. Drought susceptibility and recovery of transplanted *Quercus rubra* seedlings in relation to root system morphology. Ann. For. Sci. 66:504-515.

Keeney, D.R., and D.W. Nelson. 1982. Nitrogen-inorganic forms. In: A.L. Page, R.H. Miller, and D.R. Keeney, editors, Methods of soil analysis. Part 2. 2nd edition, ASA and SSSA, Madison, p. 643-698.

Khasa, D.P., M. Fung, and B. Logan. 2005. Early growth response of container-grown selected woody boreal seedlings in amended composite tailings and tailings sand. Bioresource Technology. 96:857-864.

Kleinman, P.J.A., B.A. Needelman, A.N. Sharpley, and R.W. McDowell. 2003. Using soil profile data to assess phosphorus leaching potential in manured soils. Soil Sci. Soc. Am. J. 67:215-224.

Kremer, R.J., and M. Ben-Hammounda. 2009. Allelopathic plants, Barley (*Hordeum vulgare* L), Allelopathy J. 24:225-242.

Kronzucher, H.J., M.H. Siddiqi, and A.D.M. Glass. 1997. Conifer root discrimination against soil nitrate and the ecology of forest succession. Nature. 385:59-61.

Lamhamedi, M.S., P. Bernier, C. Hebert, and R. Jobdon. 1998. Physiological and growth responses of three sizes of containerized *Picea Mariana* seedlings out planted with and without vegetation control. For. Ecol. Manage. 110:13-23.

Lanini,W.T., and S.R. Radosevich. 1986. Response of three conifers to site preparation and shrub control. For. Sci. 32:61-77.

Lavoie, N., L.P. Vézina, and H. Margolis. 1992. Absorption and assimilation of nitrate and ammonium ions by jack pine seedlings. Tree Physiol. 11:171-183.

Lazorko, H., and K.C.J. Van Rees. 2012. Root Distributions of planted boreal mixedwood species on reclaimed saline–sodic overburden. Water Air and Soil Pollut. 223:215-231.

Lee, P. 2004. The impact of burn intensity from wildfires on seed and vegetative banks, and emergent understory in aspen-dominated boreal forests. Can. J. Bot. 82:1468-1480.

Lieffers, V.J., and J.A. Beck. 1994. A semi-natural approach to mixedwood management in the prairie provinces. For. Chron. 70:260-264.

Lilles, E.B., B.G. Purdy, S.X. Chang, and S.E. Macdonald. 2010. Soil and ground water characteristics of saline sites supporting boreal mixedwood forests in northern Alberta. Can. J. Soil Sci. 90:1-14.

Lilles, E.B., B.G. Purdy, S.E. Macdonald, and S.X. Chang. 2012. Growth of aspen and white spruce on naturally saline sites in northern Alberta: Implications for development of boreal forest vegetation on reclaimed saline soils. Can. J. Soil Sci. 92:213-227.

Löf, M., and N. Welander. 2004. Influence of herbaceous competitors on early growth in direct seeded *Fagus sylvatica* L. and *Quercus robur* L. Ann. For. Sci. 61:781-788.

Macdonald, S.E., and T.E. Fenniak. 2007. Understory plant communities of boreal mixedwood forests in western Canada: Natural patterns and response to variable-retention harvesting. For. Ecol. Manage. 242:34-48.

Macdonald, S.E., S.A. Quideau, and S. Landhausser. 2012. Rebuilding boreal forest ecosystems after industrial disturbance. In: D. Vitt and J. Bhatti, editors, Restoration and reclamation of boreal ecosystems. Cambridge Univ. Press, Cambridge, UK. p. 123-160.

Mackenzie, D.D., and M.A. Naeth. 2010. The role of forest soil propagule bank in assisted natural recovery after oil sands mining. Rest. Ecol. 18:418-427.

Maltby, E., and M.C.F. Proctor. 1996. Peatlands: their nature and role in the biosphere. In: E. Lappalainen, editor, Global Peat Resources. International Peat Society and Geological Survey of Finland, Jyska, Finland. p. 11-19.

Man, R., and K.J. Greenway. 2013. Effects of soil moisture and species composition on growth and productivity of trembling aspen and white spruce in planted mixtures: 5-year results. New Forests. 44:23-38.

Man, R., and V.J. Lieffers. 1999. Are mixtures of aspen and white spruce more productive than single species stands? For. Chron. 75:505-513.

Masliyah, J., Z.J. Zhou, Z. Xu, J. Czarnecki, and H. Hamza. 2004. Understanding water-based bitumen extraction from Athabasca oil sands. Can. J. Chemi. Eng. 82:628-654. Doi: 10.1002/cjce.5450820403.

McMillan, R., S.A. Quideau, M.D. MacKenzie, and O. Biryukova. 2007. Nitrogen mineralization and microbial activity in oil sands reclaimed boreal forest soils. J. Environ. Qual. 36:1470-1478.

Mellon, G.B., and J.H. Wall. 1956. Geology of the McMurray formation, Part 1, Foraminifera of the upper McMurray and basal Clearwater formations. Alberta Res. Counc. Rep. 72:1-29.

Miller, J.J., and D. Curtin. 2007. Electrical conductivity and soluble ions. In: M.R. Carter and E.G. Gregorich, editors, Soil sampling and methods of analysis. 2nd edition, Chapter 15. CRC Press, Boca Raton, FL, p. 161-164.

Moffat, A.J. 2004. Silviculture: reclamation of mining lands. In: Burley, J., J. Evans, and J. Youngqvist, editors, Encyclopedia of Forest Sciences. Academic Press, London. p. 1078-1085.

Morris, L.A., S.A. Moss, and W.S. Garbett. 1993. Competitive interference between selected herbaceous and woody plants and *Pinus taeda* L. during two growing seasons following planting. For. Sci. 39:166-187.

Nadelhoffer, K.J., J.D. Aber, and J.M. Melillo. 1984. Seasonal patterns of ammonium and nitrate uptake in nine temperate forest ecosystems. Plant Soil. 80:321-335.

Nambiar, E.K.S., and R. Sands. 1993. Competition for water and nutrients in forests. Can. J. For. Res. 23:1955-1968.

National Wetlands Working Group (NWWG). 1997. The Canadian wetland classification system, second edition, by B.G. Warner and C.D.A. Rubec, editors. Wetlands Research Centre, University of Waterloo, Waterloo. p. 68.

Nilsson, U., and H.L. Allen. 2003. Short- and long-term effects of site preparation, fertilization and vegetation control on growth and stand development of planted loblolly pine. For. Ecol. Manage. 175:367-377.

OSVRC. 1998. Guidelines for reclamation to forest vegetation in the Athabasca oil sands region. Oil Sands Vegetation Reclamation Committee. Alberta Environmental Protection Report #ESD/LM/99-1. http://environment.gov.ab.ca/info/library/6869. pdf.

Passioura, J.B. 1996. Drought and drought tolerance. Plant Growth Regul. 20:79-83.

Peel, M.C., B.L. Finlayson, and T.A. McMahon. 2007. Updated world map of the Köppen-Geiger climate classification. Hydrol. Earth Syst. Sci. 11:1633-1644.

Perala, D.A. 1990. *Populus tremuloides* Michx. - Quaking aspen. In: Burns, R.M., and B.H. Honkala, editors, Silvics of North America – Volume 2, Hardwoods, USDA forest service, Washington, DC, Agriculture handbook. p. 1081-1184. http://www.na.fs.fed.us/pubs/silvics_manual/volume_2/silvics_v2.pdf

Peterson, E.B., and N.M. Petersen. 1992. Ecology, management and use of aspen and balsam poplar in the prairie provinces, Canada. Special Report 1. Forestry Canada, Northern Forestry Centre, Edmonton. p. 252.

Picon-Cochard, C., A. Nsourou-Obame, C. Collet, J. Guehl, and A. Ferhi. 2001. Competition for water between walnut seedlings (*Juglans regia*) and rye grass (*Lolium perenne*) assessed by carbon isotope discrimination and δ18O enrichment. Tree Physiol. 21:183-191.

Picon-Cochard, C., L. Coll, and P. Balandier. 2006. The role of below-ground competition during early stages of secondary succession: the case of 3-year-old Scots pine (*Pinus sylvestris* L.) seedlings in an abandoned grassland. Oecologia. 148:373-383.

Pinard, M., B. Howlett, and D. Davidson. 1996. Site conditions limit pioneer tree recruitment after logging of dipterocarp forests in Sabah, Malaysia. Biotropica. 28:2-12. doi: 10.1111/j.1744-7429.2007.00386.x

Pinno, B.D., and N. Bélanger. 2009. Competition control in juvenile hybrid poplar plantations across a range of site productivities in central Saskatchewan, Canada. New Forests. 37:213-225.

Pinno, B.D., S.M. Landhausser, M.D. MacKenzie, S.A. Quideau, and P.S. Chow. 2012. Trembling aspen seedling establishment, growth, and response to fertilization on contrasting soils used in oil sands reclamation. Can. J. Soil Sci. 92:143-151.

Pote, D.H., T.C. Daniel, A.N. Sharpley, P.A Moore, D.R. Edwards, and D.J. Nichols. 1996. Relating extractable soil phosphorus to phosphorus losses in runoff. Soil Sci. Soc. Am. J. 60:855-859.

Powers, R.F., and P.E. Reynolds. 1999. Ten-year responses of ponderosa pine plantations to repeated vegetation and nutrient control along an environmental gradient. Can. J. For. Res. 29:1027-1038.

Puettmann, K.J., and P.B. Reich. 1995. The differential sensitivity of red pine and quaking aspen to competition. Can. J. For. Res. 25:1731-1737.

Qian, P., J.J. Schoenau, and R.E. Karamanos. 1994. Simultaneous extraction of available phosphorus and potassium with a new soil test-a modification of Kelowna extraction. Commun. Soil Sci. Plant Anal. 25:627-635.

Qian, P., and J.J. Schoenau. 2002. Practical applications of ion exchange resins in agriculture and environmental soil research. Can. J. Soil Sci. 82:9-21.

Qian, P., J.J. Schoenau, and N. Ziadi. 2007. Ion supply rate using ion-exchange resins. In: M.R. Carter and E.G. Gregorich, editors, Soil sampling and methods of analysis, 2nd edition, Chapter 13.2. CRC Press, Boca Raton, FL, p. 137-140.

Renault, S., M. MacKinnon, and C. Qualizza. 2003. Barley, a potential species for initial reclamation of saline composite tailings of oil sands. J. Environ. Qual. 32:2245-2253.

Renault, S., C. Qualizza, and M.C. MacKinnon. 2004. Suitability of altai wildrye (*Elymus angustus*) and slender wheatgrass (*Agropyron trachycaulum*) for initial reclamation of saline composite tailings of oil sands. Environ. Pollut. 128:339-349.

Rich, R., L. Frelich, P. Reich, and M. Bauer. 2010. Detecting wind-disturbance severity and canopy heterogeneity in boreal forest by coupling high-spatial resolution satellite imagery and field data. Remote Sens. Environ. 114:299-308.

Richardson, B., M.O. Kimberley, J.W. Ray, and G. Coker. 1999. Indices of interspecific plant competition for *Pinus radiata* in the central north island of New Zealand. Can. J. For. Res. 29:898-905.

Rodrigue, J.A., and J.A. Burger. 2004. Forest soil productivity of mined land in the midwestern and eastern coalfield regions. Soil Sci. Soc. Am. J. 68:833-844.

Rose, R., and J.S. Ketchum. 2002. Interaction of vegetation control and fertilization on conifer species across the Pacific Northwest. Can. J. For. Res. 32:136-152.

Rowe, J.S. 1956. Uses of undergrowth plant species in forestry. Ecol. 37:461-473.

Rowland, S.M., C.E. Prescott, S.J. Grayston, S.A. Quideau, and G.E. Bradfield. 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.

Salifu, K.F., and V.R. Timmer. 2003. Optimizing nitrogen loading in *Picea mariana* seedlings during nursery culture. Can. J. For. Res. 33:1287-1294.

Salifu K.F., and D.F. Jacobs. 2006. Characterizing fertility targets and multi-element interactions in nursery culture of *Quercus rubra* seedlings. Ann. For. Sci. 63:231-237.

Salifu, K.F., D.F. Jacobs, and Z.K.D. Birge. 2009. Nursery nitrogen loading improves field performance of bareroot oak seedlings planted on abandoned mine lands. Restor. Ecol. 17:339-349.

Sands, R., and D.R. Mulligan. 1990. Water and nutrient dynamics and tree growth. For. Ecol. Manage. 30:91-111.

SAS Institute, Inc. 2010. SAS 9.2 Intelligence platform: Application server administration guide. Cary, NC.

Schneider, R.R., J.B. Stelfox, S. Boutin, and S. Wasel. 2003. Managing the cumulative impacts of land uses in the Western Canadian Sedimentary Basin: a modeling approach. Conserv. Ecol. 7:8.

Sheoran, V., A.S. Sheoran, and P. Poonia. 2010. Soil reclamation of abandoned mine land by revegetation: A Review," Int. J. Soil Sediment Water. 3(2):13.

Sims, R.A., H.M. Kershaw, and G.M. Wickware. 1990. The autecology of major tree species in the north central region of Ontario. Ont. Min. Nat. Resour., N.W. Ont. For. Tech. Dev. Unit, Tech. Rep. No. 48 / COFRDA Rep. No. 3302. p. 126.

Singh, A.N., A.S. Raghubanshi, and J.S. Singh. 2002. Plantations as a tool for mine spoil restoration. Curr. Sci. 82:1436-1441.

Skjemstad, J.O., and J.A. Baldock. 2007. Total and organic carbon. In: M.R. Carter and E.G. Gregorich, editors, Soil sampling and methods of analysis. 2nd edition, Chapter 21. CRC Press, Boca Raton, FL, p. 225-227.

Sloan, J.L., and D.F. Jacobs. 2013. Fertilization at planting influences seedling growth and vegetative competition on a post-mining boreal reclamation site. New Forests. 44:687-701.

Strong, T., and E.A. Hansen. 1991. Response of three *Populus* species to drought. Research Paper NC-302. USDA, Forest Service. North Central Forest Experiment Station, St. Paul, MN. p. 9.

Strong, T., and G.H. La Roi. 1985. Root density–soil relationships in selected boreal forests of central Alberta Canada. For. Ecol. Manage. 12:233-251.

Strong, W.L., and G.H. La Roi. 1983. Root-system morphology of common boreal forest trees in Alberta, Canada. Can. J. For. Res. 13:1164-1173.

Strong, W.L., D.J. Pluth, G.L. Roi, and I.G.W Corns. 1991. Forest understory plants as predictors of lodgepole pine and white spruce site quality in west-central Alberta. Can. J. For. Res. 21:1675-1683.

Suncor. 2013. Suncor Energy Inc. web pages, Suncor Energy announces 2013 capital spending plan and production outlook. http://www.suncor.com/en/newsroom/ 2418.aspx?id=1700109 (accessed on 10 Oct., 2013).

Sundermeier, A.P. 2010. Nutrient management with cover crops. Journal of NACAA. 3.

Syncrude (Syncrude Canada Ltd.). 2013. Syncrude Canada Ltd. web pages. http://www.syncrude.ca / (accessed on 30 Oct., 2013).

Thevathasan, N.V., P.E. Reynolds, R. Kuessner, and W.F. Bell. 2000. Effects of controlled weed densities and soil types on soil nitrate accumulation, spruce growth, and weed growth. For. Ecol. Manage. 133:135-144.

Thomas, R.L., R.W. Sheard, and J.R. Moyer. 1967. Comparison of conventional and automated procedures for nitrogen, phosphorus, and potassium analysis of plant material using a single digestion. Agron. J. 59:240-243.

Thompson, D.G., and D.G. Pitt. 2003. A review of Canadian forest vegetation management research and practice. Ann. For. Sci. 60:559-572.

Torbert, J.L., A.R. Tuladhar, J.A. Burger, and J.C. Bell. 1988. Minesoil property effects on the height of ten-year-old white pine. J. Environ. Qual. 17:189-192.

Torbert, J.L., J.A. Burger, and W.L. Daniels. 1990. Pine growth variation associated with overburden rock type on a reclaimed surface mine in Virginia. J. Environ. Qual. 19:88-92.

Turcotte, I., S.A. Quideau, and S.W. Oh. 2009. Organic matter quality in reclaimed boreal forest soils following oil sands mining. Org. Geochem. 40:510-519.

Van Cleve, K., L. Oliver, R. Schlentner, L.A. Viereck, and C.T. Dyrness. 1983. Productivity and nutrient cycling in a taiga forest ecosystem. Can. J. For. Res. 13:747-766.

Van den Driessche, R. 1988. Response of Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) to some different fertilizers applied at planting, New Forests 2:89-110.

Van den Driessche, R., F. Niemi, and L. Charleson. 2005. Fourth year response of aspen seedlings to lime, nitrogen and phosphorus applied at planting and 1 year after planting. For. Ecol. Manage. 219:216-228.

Van den Driessche, R., W. Rude, and L. Martens. 2003. Effect of fertilization and irrigation on growth of aspen (*Populus tremuloides* Michx.) seedlings over three seasons. For. Ecol. Manage. 186:381-389.

Van Rees, K.C.J. 1997. Rooting patterns of boreal tree species. Prince Albert Model Forest Association, Inc. Prince Albert, SK.

Vermes, J.F., and D.D. Myrold. 1992. Denitrification in forest soils of Oregon. Can. J. For. Res. 22:504-512.

Wagner, R.G., T.L. Noland, and G.H. Mohammed. 1996. Timing and duration of herbaceous vegetation control around four northern coniferous species. New Zealand J. For. Sci. 26:39-52.

Wagner, R.G., K.M. Little, B. Richardson, and K. McNabb. 2006. The role of vegetation management for enhancing productivity of the world's forests. Forestry. 79:57-79.

Wagner, R.G., M. Newton, E.C. Cole, J.H. Miller, and B.D. Shiver. 2004. The role of herbicides for enhancing forest productivity and conserving land for biodiversity in North America. Wildlife Soc. Bull. 32:1028-1041.

Xu, Z., G. Zhou, and H. Shimizu. 2010. Plant responses to drought and rewatering. Plant Signal. Behav. 5:649-654.

Yao, B., J. Cao, C. Zhao, and Z. Rengel. 2011. Influence of ammonium and nitrate supply on growth, nitrate reductase activity and N-use efficiency in a natural hybrid pine and its parents. J. Plant Ecol. 4:275-282.

Zhang, J., R.F. Powers, W.W. Oliver, and D.H. Young. 2013. Response of ponderosa pine plantations to competing vegetation control in Northern California, USA: a meta-analysis. Forestry. 86:3-11.

Zhang, J.W., W.W. Oliver, and M.D. Busse. 2006. Growth and development of ponderosa pine on sites of contrasting productivities: relative importance of stand density and shrub competition effects. Can. J. For. Res. 36:2426-2438.

Zutter, B.R., G.R. Glover, R.J. Mitchell, and D.H. Gjerstad. 1997. Response of loblolly pine and sweetgum to intra- and inter-specific competition and influence of soil organic matter. Can. J. For. Res. 27:882-899.

7. APPENDICES

7.1. Appendix A: Analysis of variance (ANOVA) tables for all data reported in the greenhouse experiment (chapter 3).

Table A.1. Analysis of variance (ANOVA) showing degrees of freedom (df) and probability level (*p*) of effect of source of variation on growth and biomass yields of tree seedlings after 16 weeks growth in a greenhouse bioassay experiment.

Source of variation		**Height increment (cm)**	**RCD increment (mm)**	**Shoot biomass (g pot^{-1})**	**Root biomass (g pot^{-1})**
	df	--------------------Probability (*p*)†			---------------------------
Fertilizer (F)	2	**0.0005**	0.1102	0.1933	0.1881
Grass species (G)	2	**<.0001**	**<.0001**	**<.0001**	**<.0001**
F x G	4	0.3090	**0.0101**	**0.0191**	0.0565
Tree species (T)	1	**<.0001**	**<.0001**	0.2604	0.6188
F x T	2	**0.0009**	**0.0253**	0.3394	0.2391
G x T	2	**<.0001**	**<.0001**	**<.0001**	**<.0001**
F x G x T	4	0.1496	0.3828	0.2191	0.4327
Soil moisture (M)	1	**<.0001**	**<.0001**	**<.0001**	**0.003**
F x M	2	0.5562	0.4495	0.1294	0.3843
G x M	2	**0.0007**	**0.0018**	**<.0001**	0.1860
F x G x M	4	0.3951	0.2151	0.2856	0.8079
T x M	1	**<.0001**	0.2824	**<.0001**	**0.0123**
F x T x M	2	0.5367	0.0928	0.5817	0.6200
G x T x M	2	**0.0017**	**0.0030**	**0.0003**	**0.0283**
F x G x T x M	4	0.2830	0.0741	0.1245	0.3927

† Bolded values indicate statistically significant at 5% level of probability ($p \leq 0.05$).

Table A.2. Analysis of variance (ANOVA) showing degrees of freedom (df) and probability level (*p*) of effect of source of variation on biomass yield of grasses after 16 weeks growth in a greenhouse bioassay experiment.

Source of variation		**Biomass Yield (g pot^{-1})**		
		Shoot	**Root**	**Total**
	df	-------------------Probability (*p*)†	-----------------	
Fertilizer (F)	2	**<.0001**	**<.0001**	**<.0001**
Grass species (G)	1	**<.0001**	**<.0001**	**<.0001**
F x G	2	**0.0019**	**<.0001**	**0.0001**
Tree species (T)	1	**0.0081**	**0.0143**	**0.0037**
F x T	2	0.5888	0.2042	0.4524
G x T	1	0.1214	0.6571	0.1589
F x G x T	2	0.7575	0.1995	0.7661
Soil moisture (M)	1	**<.0001**	**<.0001**	**<.0001**
F x M	2	0.1629	0.7168	0.1838
G x M	1	0.9527	**0.0142**	0.6496
F x G x M	2	0.8371	0.1213	0.6778
T x M	1	0.1111	0.2165	0.0869
F x T x M	2	0.2857	0.2013	0.2223
G x T x M	1	0.2452	0.6422	0.2376
F x G x T x M	2	0.2464	0.0504	0.1739

† Bolded values indicate statistically significant at 5% level of probability ($p \leq 0.05$).

Table A.3. Analysis of variance (ANOVA) showing probability level (*p*) of effect of source of variation on nitrogen concentration and uptake by tree seedlings and grass species after 16 weeks growth in a greenhouse bioassay experiment.

Source of variation	N concentration (mg g^{-1})				N uptake (mg pot^{-1})			
	Tree seedlings		Cover crops		Tree seedlings		Cover crops	
	Shoot	Root	Shoot	Root	Shoot	Root	Shoot	Root
	---------------------Probability (*p*)[†]---------------------------							
Fertilizer (F)	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**0.0001**	**0.0005**	**<.0001**	**<.0001**
Grass species (G)	**<.0001**	0.3994	0.9727	0.4407	**<.0001**	**<.0001**	**0.0201**	**<.0001**
F x G	**0.0036**	0.7109	0.7973	0.5075	**0.0028**	**0.0032**	0.0888	**<.0001**
Tree species (T)	0.0523	**<.0001**	0.2191	0.7496	0.0661	**0.0002**	0.0334	**0.0084**
F x T	**0.0220**	**0.0013**	0.9901	0.2751	**0.0176**	**0.0172**	0.5441	0.1421
G x T	**<.0001**	**<.0001**	0.7237	0.6569	**<.0001**	**0.0005**	0.8158	0.3262
F x G x T	**0.0398**	0.3431	0.8174	0.2716	**0.0026**	**0.0207**	0.8810	0.5137
Soil moisture (M)	0.1134	**0.0002**	**0.0045**	**0.0004**	**<.0001**	0.1341	0.1259	**0.0013**
F x M	0.5331	**0.0188**	0.2584	0.1283	0.3301	0.2135	0.8520	0.2041
G x M	0.5641	0.1294	0.2399	0.3553	**<.0001**	0.9026	0.2501	0.2431
F x G x M	**0.0005**	0.4175	0.8817	**0.0150**	0.5301	0.4050	0.9383	0.2691
T x M	0.1658	0.1134	0.7171	0.0541	**<.0001**	0.3218	0.3891	0.5424
F x T x M	0.7158	0.6563	0.4574	0.1886	0.1932	0.8080	0.9165	0.6164
G x T x M	**<.0001**	0.9043	0.4818	0.0974	**<.0001**	0.3134	0.4306	0.2779
F x G x T x M	**0.0232**	0.1804	0.8541	0.7777	0.8578	0.6294	0.4115	0.1138

† Bolded values indicate statistically significant at 5% level of probability ($p \leq 0.05$).

Table A.4. Analysis of variance (ANOVA) showing probability level (*p*) of effect of source of variation on phosphorus concentration and uptake by tree seedlings and grass species after 16 weeks growth in a greenhouse bioassay experiment.

Source of variation	P concentration (mg g^{-1})				P uptake (mg pot^{-1})			
	Tree seedlings		Cover crops		Tree seedlings		Cover crops	
	Shoot	Root	Shoot	Root	Shoot	Root	Shoot	Root
	--Probability (*p*)† --							
Fertilizer (F)	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**
Grass species (G)	**0.0011**	0.9509	0.0539	**<.0001**	**<.0001**	**<.0001**	0.2875	**<.0001**
F x G	**0.0041**	0.9050	0.6795	0.0502	**0.0032**	**0.0024**	0.3080	**<.0001**
Tree species (T)	**0.0074**	0.2740	0.7784	0.7459	0.7178	0.8683	0.1449	**0.0009**
F x T	**0.0038**	0.7240	0.9235	0.1884	**0.0381**	0.0968	0.5272	**0.0010**
G x T	0.6690	0.2336	0.9938	0.0550	**<.0001**	**<.0001**	0.8907	**0.0375**
F x G x T	0.2904	0.6053	0.8437	0.6199	**0.0398**	**0.0029**	0.9470	**0.0338**
Soil moisture (M)	0.1429	**0.0298**	0.5666	0.0669	**<.0001**	0.0766	**0.0013**	**0.0002**
F x M	0.5263	0.0718	0.2147	**0.0094**	0.5228	0.4258	0.3667	0.0698
G x M	0.2017	0.3788	0.4298	0.2539	**<.0001**	0.9851	0.4331	0.1870
F x G x M	**<.0001**	0.6595	0.4931	0.0952	0.8327	0.7578	0.5000	0.4074
T x M	0.9633	0.5338	0.4743	0.1579	**<.0001**	**0.0112**	0.3567	0.3333
F x T x M	**0.0104**	0.4234	0.2247	0.5269	0.7408	0.6942	0.7220	0.6753
G x T x M	**0.0006**	0.9925	0.0506	**0.0078**	**<.0001**	0.0636	0.1954	0.0848
F x G x T x M	0.1977	0.4077	0.4499	0.1473	0.1346	0.6472	0.3265	**0.0161**

† Bolded values indicate statistically significant at 5% level of probability ($p \leq 0.05$).

Table A.5. Analysis of variance (ANOVA) showing probability level (*p*) of effect of source of variation on soil organic carbon, available nitrogen (NO_3^--N and NH_4^+-N), available P and extractable K in post-harvest soil.

Source of variation	Organic carbon	Available N		Available P	Extractable K
		NO_3^--N	NH_4^+-N		
	(%)	(mg kg^{-1})			
	Probability (p)†				
Fertilizer (F)	0.4445	**0.0005**	**0.0202**	**<.0001**	**0.0041**
Grass species (G)	0.1099	**<.0001**	0.3405	0.1251	0.3846
F x G	**0.0009**	**0.0236**	0.0665	0.0823	0.0949
Tree species (T)	0.8990	**0.0012**	0.8084	0.1234	0.5407
F x T	0.2123	0.5622	0.8395	**0.0351**	0.9063
G x T	0.5253	**0.0357**	0.2414	0.0833	0.9761
F x G x T	0.1283	0.0510	0.4874	0.5445	0.7381
Soil moisture (M)	0.8084	0.3254	0.8282	0.0624	0.7205
F x M	0.5202	0.6016	0.7398	**0.0390**	0.3238
G x M	0.8367	0.4797	0.6820	0.8200	0.8272
F x G x M	0.6504	0.5379	0.9296	0.9836	0.7380
T x M	0.9973	0.3745	0.2969	0.1012	0.4364
F x T x M	0.9498	0.7682	0.2600	0.3459	0.8488
G x T x M	0.7923	0.4756	0.2128	0.9311	0.3988
F x G x T x M	0.6074	0.9427	0.1559	0.7911	0.3693

† Bolded values indicate statistically significant at 5% level of probability ($p \leq 0.05$).

7.2. Appendix B: Photograph showing the growth of tree seedlings and cover crops in the greenhouse experiment.

Fig. B.1. Effect of fertilization on growth responses of tree seedlings and cover crops in the greenhouse experiment.

7.3. Appendix C: Analysis of variance (ANOVA) tables for all data collected from the field study.

Table C.1. Analysis of variance (ANOVA) showing degrees of freedom (df) and probability level (*p*) of effect of source of variation on survival and growth of tree seedlings after one growing season in field.

Source of variation		Survival rate (%)	Height increment (cm)	RCD increment (mm)
	df	---------------Probability (*p*)†	---------------	
Fertilizer (F)	7	**<.0001**	0.2880	0.3149
Tree (T)	1	**<.0001**	**<.0001**	**<.0001**
F x T	7	0.2826	0.8843	0.2320
Cover crop (C)	2	0.2071	0.1533	0.2031
F x C	14	0.2374	0.0574	0.0972
T x C	2	**0.0075**	0.6600	0.8895
F x T x C	14	0.2622	0.8550	0.0533

† Bolded values indicate statistically significant at 5% level of probability ($p \leq 0.05$).

Table C.2. Analysis of variance (ANOVA) showing degrees of freedom (df) and probability level (*p*) of effect of source of variation on growth and biomass yield of tree seedlings after two growing seasons in field.

Source of variation		Height increment (cm)	RCD increment (mm)	Shoot biomass (g plant^{-1})	Root biomass (g plant^{-1})
	df		----------------------Probability (*p*)†	------------------	
Fertilizer (F)	7	0.0773	0.4464	0.0576	**0.0317**
Tree (T)	1	**<.0001**	**<.0001**	**<.0001**	**<.0001**
F x T	7	0.2975	0.0803	**0.0121**	0.3343
Cover crop (C)	2	**0.0008**	**0.0045**	**<.0001**	**0.0018**
F x C	14	0.2225	0.2766	0.0539	0.4894
T x C	2	**0.0004**	**0.0054**	**0.0094**	**0.0152**
F x T x C	14	0.3720	0.2870	0.0847	0.0653

† Bolded values indicate statistically significant at 5% level of probability ($p \leq 0.05$).

Table C.3. Analysis of variance (ANOVA) showing probability level (*p*) of effect of source of variation on total N, P and K concentration and uptake by tree seedlings after two growing seasons in field.

Source of variation	N ($mg\ g^{-1}$)		N uptake ($mg\ plant^{-1}$)		P ($mg\ g^{-1}$)		P uptake ($mg\ plant^{-1}$)		K ($mg\ g^{-1}$)		K uptake ($mg\ plant^{-1}$)	
	Shoot	**Root**	**Shoot**	**Root**	**Shoot**	**Root**	**Shoot**	**Root**	**Shoot**	**Root**	**Shoot**	**Root**
	Probability (*p*)†											
Fertilizer (F)	**<.0001**	**<.0001**	**0.0008**	0.1207	**<.0001**	**<.0001**	**0.0003**	**0.0091**	**0.0002**	**0.0038**	**0.0096**	0.1483
Tree (T)	**<.0001**	**<.0001**	**0.0054**	**<.0001**	**0.0047**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**
F x T	**0.0038**	**0.0124**	**0.0002**	0.3779	**0.0452**	**0.0010**	**0.0026**	0.0583	0.1607	0.5668	0.1226	0.7574
Cover crop (C)	**<.0001**	0.5276	**<.0001**	**0.0008**	**0.0049**	**0.0170**	**<.0001**	**<.0001**	**<.0001**	**0.0002**	**<.0001**	**0.0006**
F x C	0.6295	**<.0001**	0.0562	0.1360	0.0663	**0.0004**	**0.0158**	0.1237	**0.0037**	**0.0036**	**0.0096**	0.4024
T x C	0.9789	0.9038	**0.0184**	**0.0129**	0.5455	0.8265	0.0505	**0.0033**	0.7016	0.4636	0.0774	**0.0265**
F x T x C	**<.0001**	**<.0001**	**0.0010**	0.2594	**0.0246**	0.1114	**0.0053**	0.1952	**0.0423**	**0.0354**	0.0502	0.6278

† Bolded values indicate statistically significant at 5% level of probability ($p \leq 0.05$).

Table C.4. Analysis of variance (ANOVA) showing probability level (*p*) of effect of source of variation on total Ca and Mg concentration and uptake by shoots and roots of tree seedlings after two growing seasons in field.

Source of variation	**Ca ($mg\ g^{-1}$)**		**Ca uptake ($mg\ plant^{-1}$)**		**Mg ($mg\ g^{-1}$)**		**Mg uptake ($mg\ plant^{-1}$)**	
	Shoot	**Root**	**Shoot**	**Root**	**Shoot**	**Root**	**Shoot**	**Root**
	---Probability (*p*)† ---							
Fertilizer (F)	0.0826	0.2439	**0.0127**	**0.0283**	0.0695	0.3177	0.0840	0.0597
Tree (T)	**<.0001**	0.7435	0.0760	**<.0001**	**<.0001**	**<.0001**	**0.0204**	**<.0001**
F x T	**0.0333**	0.3882	0.0513	0.8655	**0.0097**	**0.0111**	0.1503	0.5881
Cover crop (C)	0.1668	0.6256	**<.0001**	**0.0107**	0.3480	0.4477	**<.0001**	**0.0020**
F x C	0.0671	**0.0211**	**0.0028**	0.2566	**0.0275**	**0.0217**	**0.0021**	0.2296
T x C	0.6580	0.1082	**0.0048**	**0.0061**	0.0738	0.3770	**0.0003**	**0.0077**
F x T x C	**0.0055**	0.4166	**0.0048**	0.3442	**0.0048**	0.2196	**0.0116**	0.4400

† Bolded values indicate statistically significant at 5% level of probability ($p \leq 0.05$).

Table C.5. Analysis of variance (ANOVA) showing probability level (*p*) of effect of source of variation on soil extractable available nitrogen (NO_3^--N and NH_4^+-N), phosphorus (PO_4^{3-}-P) and sulphur (SO_4^{2-}-S) at different depths after two growing seasons in field.

Source of variation	**NO_3^--N Soil depth (cm)**			**NH_4^+-N Soil depth (cm)**			**PO_4^{3-}-P Soil depth (cm)**			**SO_4^{2-}-S Soil depth (cm)**		
	0-30	**30-60**	**0-60**	**0-30**	**30-60**	**0-60**	**0-30**	**30-60**	**0-60**	**0-30**	**30-60**	**0-60**
	--- Probability (*p*)[†] ---											
Fertilizer (F)	**<.0001**	0.0511	**<.0001**	0.1001	0.0728	**0.0041**	**0.0002**	0.1814	**0.0016**	**0.0028**	**0.0202**	0.1932
Tree (T)	**0.0006**	**0.0096**	**0.0007**	**0.0248**	0.0814	0.5405	0.0892	0.2663	0.0907	0.7471	**0.0010**	0.0598
F x T	**<.0001**	0.0660	**0.0328**	0.8540	0.1828	0.6839	0.2957	0.5745	0.5517	**0.0128**	**0.0001**	**0.0002**
Cover crop (C)	0.1203	0.5423	**0.0157**	0.5634	0.1089	0.1151	**0.0198**	0.4401	**0.0172**	**0.0028**	**0.0025**	**0.0025**
F x C	0.6982	0.8437	0.5599	0.1770	0.0871	0.1271	0.4658	0.2660	0.5286	**0.0204**	**0.0480**	0.2388
T x C	0.5441	0.3670	0.0701	0.4813	0.7747	0.3288	0.1525	0.5944	0.0951	**0.0003**	**0.0242**	**0.0047**
F x T x C	0.9358	0.5790	0.9110	0.0634	**0.0257**	0.2801	**0.0053**	0.0934	0.2203	**0.0032**	**0.0099**	**0.0413**

† Bolded values indicate statistically significant at 5% level of probability ($p \leq 0.05$).

Table C.6. Analysis of variance (ANOVA) showing probability level (*p*) of effect of source of variation soil exchangeable base cations at different depths after two growing seasons in field.

Source of variation	**K^{+} Soil depth (cm)**			**Ca^{2+} Soil depth (cm)**			**Mg^{2+} Soil depth (cm)**			**Na^{+} Soil depth (cm)**		
	0-30	**30-60**	**0-60**	**0-30**	**30-60**	**0-60**	**0-30**	**30-60**	**0-60**	**0-30**	**30-60**	**0-60**
	---------- Probability (p)† ----------											
Fertilizer (F)	<.0001	0.0007	<.0001	0.2355	0.0541	0.0601	0.6493	0.1966	0.7539	0.1553	0.2105	0.1244
Tree (T)	0.1578	0.3192	0.8051	0.1340	0.8139	0.5267	0.4247	0.5797	0.8775	0.2282	0.2137	0.1144
F x T	0.0524	0.0456	0.0485	0.2499	0.1201	0.2024	0.1650	0.1045	0.0978	0.6902	0.0609	0.0516
Cover crop (C)	0.3013	0.0160	0.0051	0.1456	0.6022	0.2157	0.7029	0.7906	0.7929	0.8335	0.8751	0.7994
F x C	0.0004	0.0007	0.0003	0.0005	0.0865	0.0008	0.0069	0.2143	0.0417	0.0847	0.0481	0.0240
T x C	0.4782	0.6294	0.4476	0.2374	0.9943	0.7066	0.9094	0.9736	0.9832	0.2441	0.6517	0.4649
F x T x C	0.3705	0.9222	0.9107	0.0012	0.0038	0.0065	0.0306	0.0098	0.0252	0.0158	0.0055	0.0013

† Bolded values indicate statistically significant at 5% level of probability ($p \leq 0.05$).

Table C.7. Analysis of variance (ANOVA) showing probability level (*p*) of effect of source of variation on nutrient supply rate of post-harvest soil from 0-30 cm depth after two growing seasons in field.

Source of variation	**NO_3^--N**	**NH_4^+-N**	**PO_4^{3-}-P**	**SO_4^{2-}-S**	**K^+**	**Ca^{2+}**	**Mg^{2+}**
	----------------------	----------------------	----------------------	----------$\mu g\ cm^{-2}$----------	----------------------	----------------------	----------------------
Fertilizer (F)	0.0664	**<.0001**	**0.0011**	**0.0003**	**<.0001**	**0.0029**	0.1014
Tree (T)	0.5497	**0.0091**	0.0631	0.6195	**<.0001**	0.2196	0.6891
F x T	0.1399	**<.0001**	**0.0053**	**0.0004**	**<.0001**	**0.0037**	0.4060
Cover crop (C)	0.1056	0.1295	0.1135	**0.0112**	0.5765	0.1270	0.7487
F x C	**0.0308**	0.6079	**0.0005**	**0.0324**	**<.0001**	0.1058	**0.0337**
T x C	0.3058	0.0992	0.1580	**0.0016**	0.0965	0.2987	0.0650
F x T x C	0.4647	0.0559	**0.0055**	**0.0155**	**0.0004**	**0.0449**	**0.0049**

† Bolded values indicate statistically significant at 5% level of probability ($p \leq 0.05$).

7.4. Appendix D: Photograph showing growth of native weeds and planted cover crops in response to fertilization in field.

Fig. D.1. Vigorous growth of planted cover crops and native weeds with high rates of fertilizer addition in a reconstructed oil sands site (MD 8, Suncore site) at Fort McMurray, Alberta.