Trembling aspen seedling establishment, growth and response to fertilization on contrasting soils used in oil sands reclamation

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Pinno, B. D., Landhäusser, S. M., MacKenzie, M. D., Quideau, S. A. and Chow, P. S. 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. Trembling aspen (*Populus tremuloides*) is an important tree species for land reclamation. This study determined trembling aspen germination, establishment, initial growth and response to fertilizer on contrasting oil sands reclamation soils. In a greenhouse, eight soils varying in total nitrogen and available phosphorus were treated with no fertilizer (control), phosphorus and potassium (PK), nitrogen (N) and all three (NPK). Soil had the greatest impact on aspen growth when no fertilizer was applied with the best growth occurring on organic-mineral material soils where growth was positively correlated with extractable and foliar potassium but not to nitrogen or phosphorus. With PK and N fertilizer, growth increases were positively correlated with foliar phosphorus concentrations of the corresponding controls. NPK fertilizer caused greater growth, bud set and root:leaf mass ratio compared with PK or N fertilizer. Soil type had little impact on germination and establishment, indicating natural aspen seedlings can potentially regenerate on all of these soils. In oil sands mining reclamation where these soils are used as surface materials, organic-mineral mixes had the greatest potential without fertilizer. With fertilizer, NPK provided maximum growth and developmental benefits.

Key words: Land reclamation, boreal forest, peat-mineral mix, fertilizer, plant nutrition

Pinno, B. D., Landhäusser, S. M., MacKenzie, M. D., Quideau, S. A. et Chow, P. S. 2012. **Établissement, croissance et réaction à la fertilisation des plantules de tremble sur les sols contrastants employés pour la restauration des sables bitumineux**. Can. J. Soil Sci. **92**: 143–151. Le tremble (*Populus tremuloides*) est une espèce importante pour la restauration des terres. Les auteurs ont étudié la germination, l'établissement, la croissance initiale et la réaction aux engrais du tremble sur des sols contrastants servant à la restauration des sables bitumineux. Huit sols à concentration variable d'azote total ont subi les traitements que voici, en serre : aucun engrais (témoin), phosphore et potassium (PK), azote (N) et les trois amendements (NPK). La nature du sol exerce le plus grand impact sur la croissance du tremble quand il n'y a pas fertilisation, la meilleure croissance survenant sur les sols minéraux-organiques et étant positivement corrélée à la concentration de potassium extractible et foliaire, mais pas à celle d'azote ou de phosphore. Avec les amendements PK et N, la plus forte croissance présente une corrélation positive avec la concentration foliaire de potassium des témoins correspondants. L'amendement NPK engendre une plus forte croissance, l'apparition d'un plus grand nombre de bourgeons et un meilleur ratio entre la masse des racines et celle des feuilles que les amendements PK ou N. La nature du sol a peu d'incidence sur la levée et l'établissement de l'espèce, signe que les pousses naturelles de tremble peuvent se développer sur tous ces sols. Dans les opérations de restauration des sables bitumineux où l'on utilise ces sols comme matériaux de surface, ce sont les mélanges minéraux-organiques qui présentent les meilleures possibilités en l'absence d'engrais. Avec fertilisation, l'amendement NPK assure la meilleure croissance et engendre les plus grands avantages sur le plan du développement.

Mots clés: Restauration des terres, forêt boréale, mélange tourbe-minéral, engrais, nutrition des plantes

Trembling aspen (*Populus tremuloides* Michx.) is a common deciduous tree in the boreal mixedwood forests of Alberta, Canada, and is the most widespread tree in North America (Burns and Honkala 1990). There has been considerable recent interest in examining the impacts of differing levels of resource availability and environmental conditions on aspen seedling establishment and growth due to the increasing role of aspen in land reclamation and commercial forestry. Aspen has specific seed germination requirements (Fechner et al. 1981; McDonough 1985) and it was previously thought that seedlings were rare. Recent studies have shown, however, that aspen seedlings occur frequently in natural environments when the right seedbed conditions of exposed mineral soil in combination with moist

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conditions during seed dispersal are met (Romme et al. 2005; Landhäusser et al. 2010). Nonetheless, the relationship between aspen germination, seedling establishment and soil chemical properties has not been previously examined.

Aspen growth has been positively correlated with soil pH, nitrogen (N), potassium (K) and calcium (Ca) concentrations in the forest floor (Chen et al. 1998; Pinno et al. 2009). In mineral soils, pH, N, Ca, magnesium (Mg) and sulphur (S) concentrations have been positively correlated with aspen growth in natural stands and greenhouse experiments (Lu and Sucoff 2001; Paré et al. 2001; Pinno et al. 2009). Soil phosphorus (P) is the only major nutrient that has not been significantly correlated with aspen growth. However, certain ecosites in Alberta can have very high soil P in the B horizon (Lanoue 2003) and this may have an impact on vegetation development.

Only weak relationships have previously been found between foliar nutrient concentrations and growth in natural settings. For example, Jug et al. (1999) found only low correlations between foliar N concentration and growth of planted hybrid aspen but in this case foliar N was considered to be in the optimal range. In closely related hybrid poplars, growth in unfertilized conditions was positively correlated to foliar phosphorus (P) but not foliar N, Ca or K concentrations (Pinno and Bélanger 2009).

Aspen has shown varied growth in response to fertilizer. For example, in young planted aspen in Alberta, fertilizer only increased aspen growth when combined with irrigation with the main response to P fertilizer (Van den Driessche et al. 2003). In another study from Alaska, aspen height increased with N fertilizer but not P or K and there was no benefit to growth with NPK fertilizer compared with N fertilizer alone (Van Cleve 1973). These differences in response to fertilizer are likely related to soil chemical properties. To date, however, no studies have assessed aspen growth response to fertilizer on contrasting soils with a wide range of nutrient availabilities.

Reclamation of surface mining operations is a massive ecosystem rebuilding process in many areas of the world. Currently, oil sands operations in northern Alberta require large areas to be reclaimed after severe ground disturbance. During surface mining, organic matter, soil and geologic substrate (subsoil) are removed and stored for later use in reclamation with surface soils and organic matter placed on top of contoured subsoil before revegetating with native plant species. The areas are often treated with fertilizer for up to five years. A variety of soil types used as surface material in reclamation vary greatly in properties such as organic matter, pH and available N, P, K, S and Ca (Rowland et al. 2009; Turcotte et al. 2009). Therefore, there is interest in determining the differences in tree productivity on a variety of these materials and if selectively salvaged B horizons rich in P could potentially be used as a productive surface soil. This source of P may represent a pool that is less mobile than inorganic P applied as fertilizer, which can be a source of pollution to surface waters.

This study examines the complete cycle of aspen growth and development, from germination to fertilizer response, on a wide range of soils. Specifically, the goals of this study are to relate germination, establishment, growth and development of aspen seedlings to different soil types used as surface materials in oil sands reclamation and to examine any differential growth and development responses to fertilizer on contrasting soil types.

METHODS

Soils were collected in May 2009 from eight distinct salvaged stockpiles of soil used in oil sands reclamation. These stockpiles represent a range in fertility, specifically in P, pH and organic matter content (Table 1). The peat-mineral mix was a mixture of approximately 50% peat material from natural sphagnum bogs and 50% mineral material. The forest floor-mineral mix is a mixture of upland forest floor and the underlying mineral soil in a volume ratio of approximately 1:5. All of the soil materials used in this study are no longer natural soils but reclamation substrates, which have been stockpiled, mixed and will be redistributed across the landscape. The soils, all with greater than 80% sand content in the mineral component, were mixed and sieved through a 4 mm sieve to remove coarse

Table 1. Soil descriptions and properties

Soil description	Total carbon (%)	Total nitrogen (%)	Available phosphorus (PO_4 P mg kg^{-1})	Extractable potassium (mg g^{-1})	Cation exchange capacity (cmolc kg^{-1})	Electrical conductivity (dS m^{-1})	pH
Peat-mineral mix	9.52	0.38	1.26	0.60	59.250	1.41	7.06
Forest floor-mineral mix	1.22	0.04	20.64	0.93	6.066	0.07	6.60
B horizon-very high P	0.21	0.02	192.03	0.62	3.838	0.06	6.88
B horizon-low P, low pH	0.22	0.01	6.77	0.41	1.275	0.05	7.40
B horizon-high P, low pH	0.37	0.02	15.75	0.68	2.888	0.07	6.69
B horizon-low P, high pH	0.49	0.03	2.15	0.67	3.638	0.11	8.50
Subsoil greater than 1 m depth	0.20	0.004	1.74	0.40	0.595	0.06	7.11
Tailings sand	0.21	0.02	0.32	0.32	0.001	0.08	7.51

fragments, debris and tar balls and then frozen until use. Total N and total organic carbon (C) was determined for each soil by dry combustion (McGill et al. 2007) using a Costech 4010 Elemental Analyzer System (Costech Analytical Technologies Inc., Valencia, CA). Available P was determined using the modified Kelowna technique with a soil to water ratio of 1:10 (Method SO23 Soil and Crop Diagnostic Centre, Alberta Agriculture, Edmonton, AB). Electrical conductivity and pH were measured in a soil to water ratio of 1:2 (Hendershot et al. 2007a) using a Fisher AR20 ph meter. Base saturation was determined using the saturated paste method with base cations extracted using a 0.1M $BaCl_2$ solution (Hendershot et al. 2007b) and then analyzed using an atomic absorption spectrophotometer (Varian 880). An equal volume of each soil was put into 50 pots, 20 cm in diameter and 8 cm deep, and then set inside the greenhouse at 20°C with a daily photoperiod of 16 h and watered before use in one of two experiments: (1) aspen seed germination and early establishment, and (2) aspen growth and response to fertilizer.

For the seed germination and establishment study, 120 trembling aspen seeds were sprinkled on the soil surface of 10 pots per soil type in a completely randomized design. The seeds were open-pollinated aspen collected in Edmonton, Alberta; 100 of the seeds per pot were collected in 1999 and 20 were collected in 2009. After sowing, pots were misted with water and covered with a clear plastic sheet. After 2 d, the plastic sheet was removed and the pots were misted with water daily. After 1 wk, the number of germinated seeds was counted and after 32 d the number of surviving seedlings was counted along with the number of seedlings that had developed primary and secondary leaves. At this time, the five seedlings with the best foliage development per pot were carefully extracted and the length of their longest root measured. The largest seedlings rather than the average sized seedlings were focused on, since these are the trees most likely to survive to form the next forest canopy.

For the growth and fertilization study, aspen seedlings were first established in peat mini-plugs (1.5 cm × 2.5 cm) from three to five seeds collected in 2009. The seeds were covered with a clear plastic sheet for 2 d and misted daily. After 25 d, seedlings were thinned to one seedling per plug and fertilized until mini-plug saturation with 1 g L^{-1} of 15-30-15 NPK fertilizer. Ten days later, the seedlings were transplanted to the pots of different soil types with 40 pots for each soil type and watered daily. Six days after transplanting, 10 pots from each soil type were assigned one of four fertilizer treatments: control (no fertilizer), PK, N and NPK. Trees were fertilized once per week for 5 wk with 50 mL of solution prepared based on a total dosage equivalent to 250 kg ha^{-1} of 10-30-20 summed over the 5 wk. The PK treatment received 0-30-20, the N treatment received 10-0-0 and the NPK treatment received 10-30-20 for a per nutrient equivalent of 25 kg N ha^{-1}, 75 kg P ha^{-1} and 50 kg K ha^{-1}, respectively. These fertilizer treatments represent fertilizer levels currently being used in oil sands reclamation. Fertilizer solutions were prepared using a mixture of ammonium nitrate solution and potassium phosphate (monobasic) solution. Every day between treatments, the pots were lightly watered to maintain moisture while minimizing runoff.

Seventy days after the fertilizer regime had started, seedlings were measured for height, root collar diameter and bud set, then harvested and oven dried at 70°C after which foliage, stem and root dry mass were determined. Foliar total N concentration was determined by Kjeldahl digestion (Kalra and Maynard 1991) while to determine other foliar nutrient concentrations, samples were subjected to microwave digestion (EPA Method 3051, US Environmental Protection Agency, Washington, DC.) and then analysis by inductively coupled plasma optical emission spectrometry (ICP-OES). Due to the small foliar mass of many of the trees, foliage samples of two seedlings were combined for each analysis resulting in a sample size of five for the foliar analysis of each soil-fertilizer treatment.

Statistical analyses for the germination study consisted of analysis of variance (ANOVA) comparing germination, survival, leaf development and root growth among soil types. Tukey's test was used to compare means across soil and fertilizer types. For the growth and fertilizer study, the analysis was divided into two stages. In the first stage, growth of the planted seedlings was analyzed in the control pots only, to determine the impact of soil type on aspen growth without fertilizer. This is warranted given the significant interaction between soil and fertilizer on aspen growth. Height growth was used as the standard growth response variable for all analyses and was highly related to seedling mass ($r^2 = 0.830$), foliar mass ($r^2 = 0.902$) and root collar diameter ($r^2 = 0.807$). This analysis involved one-way ANOVAs comparing seedling growth among soil types and linear regression relating tree growth to soil properties and foliar characteristics. Since soil properties were determined at the bulk scale for each soil type and not for each pot, response variables were averaged by soil type resulting in eight points for each regression.

The next stage of analysis involved all treatments from the fertilizer study. Two-way ANOVA was used to determine the impact of soil type and fertilizer regime on aspen growth and foliar nutrient concentrations. Regression was used to examine incremental growth of the trees due to fertilizer treatment, i.e., fertilizer treatment growth minus control growth. Differential growth was regressed against soil characteristics and foliar nutrient concentrations of control trees. Regression was used to relate absolute growth of each fertilizer treatment to the treatment foliar characteristics and general soil properties. All statistical analyses were completed using JMP 8.0 (SAS Institute, Inc. 2008).

RESULTS

Germination was not significantly different among soil types with average germination rate ranging from 89 to 95% (Table 2). Seedling survival and early establishment differed among soil types ($F=4.29$, $P=0.001$) (Table 2), but seedling survival was still greater than 50% on all soils. The number of seedlings bearing secondary leaves also differed among soil types ($F=4.87$, $P<0.001$) with only the forest floor-mineral mix having a greater number of seedlings with secondary leaves than the other soils (Table 2). Root growth of the best five seedlings in each pot varied significantly with soil type ($F=2.59$, $P=0.019$) from 33 mm (peat-mineral mix) to 50 mm (B horizon with low P, high pH) with the other soil types having an average of 45 mm of root growth (Table 2).

Aspen height varied with soil type and fertilizer (Fig. 1) with all fertilizer regimes significantly different from each other, thereby justifying the individual analysis of each fertilizer regime. Without fertilizer, aspen height from the planted mini-plug seedlings varied significantly among soil types (Fig. 1). The best growth occurred in organic matter-mineral soil mixes followed by the B horizon with very high P, while the poorest growth was in the subsoil and tailings sand. In relation to soil properties, aspen height was positively related to extractable K but was not related to any other measured soil variable (Table 3). In the unfertilized pots (Table 4), aspen height was positively related to foliar K concentration, while the root:leaf mass ratio was negatively related to foliar K (Fig. 2). No other measured foliar nutrient concentrations or ratios were significantly related to above-ground aspen growth in controls.

With fertilizer, the general response pattern for aspen height was NPK > N > PK > Control, which held true for all lower productivity soils, but not for the three soils with the best growth in the control treatment (peat-mineral mix, forest floor-mineral mix and B horizon with very high P) (Fig. 1). For the peat-mineral mix, there was no response to PK or N fertilizer but a very large response to NPK fertilizer while, for the forest floor-mineral mix and B horizon with very high P, NPK fertilizer did not result in greater aspen growth than N fertilizer. Root:leaf mass ratio response to fertilizer was different from the growth response to fertilizer with the general pattern of root:leaf mass being, NPK > Control > N = PK (Fig. 3). Root mass was positively related to above-ground mass ($P<0.001$, $r^2=0.940$) and height ($P<0.001$, $r^2=0.750$) across all fertilizer treatments, but was not related to any other soil or foliar characteristics. Bud set was similar across all soil types ($P=0.076$) but varied significantly with fertilizer ($P<0.001$) and there was a soil × fertilizer interaction ($P<0.001$). Across all soil types, bud set occurred on 91% of seedlings with NPK, 59% for the control, 45% with N and 39% with PK.

PK fertilizer resulted in an average height increase of only 2–10 cm over that of controls and this response was positively related to foliar P concentration of the controls (Fig. 4a). N fertilizer increased aspen height 1–17 cm over that of the controls and was positively related to foliar P concentration of the controls (Fig. 4b). No other soil or foliar variables could explain the growth increase from PK or N fertilizer.

NPK fertilizer increased aspen height 6–22 cm over that of the controls and was negatively related to soil extractable K ($P=0.002$, $r^2=0.804$) indicating that the poorest soils benefitted the most from NPK fertilizer. Average height of the NPK fertilized trees ranged from 19 to 32 cm and was not related to control height ($P=0.466$). The tallest aspen with NPK were the peat-mineral mix and low pH, low P B horizon, while the shortest aspen were in the forest floor-mineral mix (Fig. 1). Height of NPK trees was positively related to foliar S concentration of the fertilized trees ($P=0.003$, $r^2=0.772$, data not shown).

DISCUSSION

The largest impact of soil type was on aspen growth when no fertilizer was applied. In contrast to this, soil type had less impact on aspen germination and establishment and aspen growth when combined with NPK fertilizer. The best aspen growth without fertilizer was in the organic matter-mineral mix soils, while the poorest growth was in the subsoil and tailings sands, which had the lowest organic matter, confirming the importance of organic matter on aspen growth (Stone and Elioff 1998; Wolken et al. 2010). Aspen growth was

Table 2. Aspen seed germination, survival and establishment

Soil	Germination (%)	Survival (%)	True leaves (%)	Root length (mm)
Peat-mineral mix	89.4 (2.33)	62.8*ab* (4.68)	16.2*b* (2.26)	33.4*b* (3.24)
Forest floor-mineral mix	94.1 (1.36)	72.0*ab* (6.17)	23.0*a* (1.71)	44.9*ab* (3.29)
B horizon-very high P	94.8 (1.25)	76.5*a* (6.99)	12.2*b* (1.42)	36.1*ab* (3.30)
B horizon-low P, low pH	90.7 (1.31)	78.4*a* (2.37)	16.8*b* (0.77)	46.3*ab* (3.87)
B horizon-high P, low pH	94.8 (1.13)	77.2*a* (4.04)	17.3*ab* (1.31)	43.7*ab* (3.86)
B horizon-low P, high pH	89.9 (1.65)	53.7*b* (3.91)	16.1*b* (0.51)	50.9*a* (4.15)
Subsoil greater than 1 m depth	94.9 (1.71)	80.1*a* (2.61)	16.7*b* (0.54)	47.7*ab* (3.85)
Tailings sand	90.5 (1.60)	77.4*a* (2.85)	16.9*b* (1.20)	42.8*ab* (3.41)

Values are mean and standard error ($n=10$).
a, *b* Different letters represent significant differences among soil types.

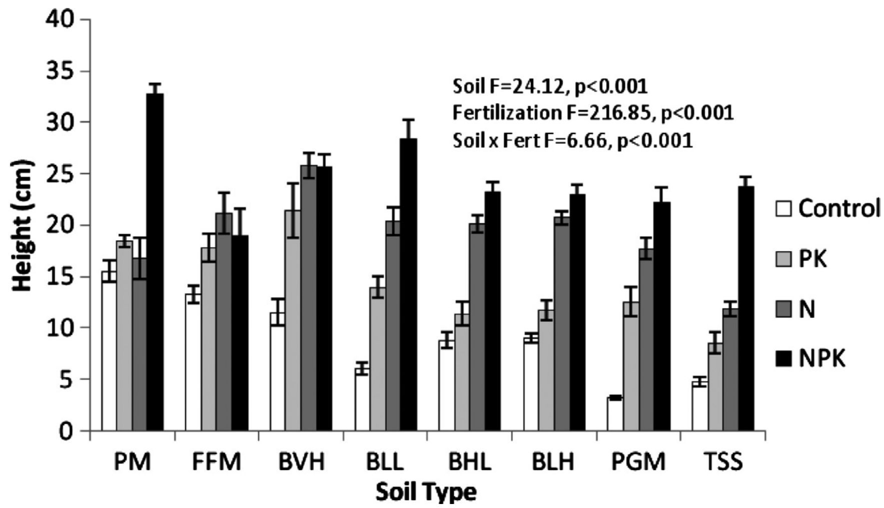

Fig. 1. Aspen height for each soil type and fertilizer treatment. Values are mean and standard error ($n = 10$). PM, peat-mineral mix; FFM, forest floor-mineral mix; BVH, B horizon with very high P; BLL, B horizon with low P and low pH; BHL, B horizon with high P and low pH; BLH, B horizon with low P and high pH; PGM, subsoil greater than 1 m depth; TSS, tailings sand.

positively related to soil extractable K and foliar K concentration. In comparison to optimal foliar nutrient concentrations for closely related hybrid poplar (*Populus* ×) growing in similar environments, all of our aspen trees had below the critical foliar concentration of 15 mg g^{-1} K (Hansen 1994) and therefore should have responded positively to increasing K availability. However, foliar N and P concentrations were also all well below the optimal foliar concentrations of 33 mg g^{-1} for N (Hansen 1994) and 2.5 mg g^{-1} for P (Van den Driessche 2000), but aspen growth was not positively related to these values. This could be due to large imbalances in internal N:P ratios. For example, the peat-mineral mix had the highest foliar N concentration but lowest foliar P concentration indicating that N may not have been the nutrient most limiting growth even though foliar N concentration was well below optimum.

With PK fertilization, there was a relatively small growth increase, which was positively related to foliar P concentration in the controls. This small growth response was surprising given the very low P availability in some soils and the positive relationship between K and growth in the controls. It was expected that soils high in N but low in P such as the peat-mineral mix would benefit the most from this fertilizer treatment but this was not the case. Phosphorus fertilizer has been shown to increase height and stem volume of aspen and hybrid poplars (DesRochers et al. 2006; Van den Driessche et al. 2005). Another study showed that P fertilization of aspen only increased height when applied with S, indicating the importance of balanced P and S nutrition (Liang and Chang 2004), however, we did not find any relationships between P:S ratio and aspen growth.

The growth response to N fertilizer was as expected with aspen with greater access to P benefitting the most from increased N availability so that aspen growing in the B horizon with very high P had the greatest total growth in this fertilizer treatment. However, aspen growing in the peat-mineral mix did not respond to N fertilizer but they already had relatively high foliar N concentrations and very low P. This is similar to the response found in poplar plantations established on soils with high organic matter (Pinno and Bélanger 2009) or pH (DesRochers et al. 2006) where an increase in available N resulted in very little growth benefit, likely because tree growth was not limited by N on these soils. Other studies have documented increased growth rates of aspen with N fertilizer (DesRochers et al. 2003; Van Cleve 1973) so identifying this differential growth response based on soil type is the first step in refining

Table 3. Correlation (*r*) between measured soil properties and aspen height for each of the fertilizer treatments

	Total carbon	Total nitrogen	Available phosphorus	Extractable potassium	Cation exchange capacity	Electrical conductivity	pH
Control	0.671	0.672	0.273	**0.711**[z]	0.687	0.620	−0.306
PK	0.404	0.399	0.674	0.505	0.435	0.362	−0.448
N	−0.282	−0.293	0.659	0.536	−0.241	−0.310	−0.219
NPK	**0.717**	**0.736**	0.027	−0.364	**0.737**	**0.762**	0.062

[z]Bold values represent significant relationships ($P < 0.05$).

Table 4. Average foliar nutrient concentrations ($n = 5$) and growth ($n = 10$) of aspen in the controls. Letters represent significant differences between soil types

Soil	N (mg g^{-1})	P (mg g^{-1})	K (mg g^{-1})	S (mg g^{-1})	Height (cm)	Foliage mass (g)	Seedling mass (g)	Root:Leaf mass ratio
Peat-mineral mix	22.7*a*	0.72*d*	11.06*a*	5.20*a*	15.5*a*	0.44*a*	0.72*ab*	0.36*c*
Forest floor-mineral mix	10.2*c*	1.36*bcd*	9.36*ab*	2.34*b*	13.3*a*	0.41*a*	0.92*a*	0.82*b*
B horizon-very high P	12.0*b*	2.18*a*	10.17*ab*	3.05*b*	11.5*a*	0.34*ab*	0.67*ab*	0.69*bc*
B horizon-low P, low pH	12.9*b*	1.85*ab*	10.72*ab*	3.47*b*	6.0bc	0.12*cd*	0.26*c*	0.86*b*
B horizon-high P, low pH	11.0*b*	1.44*bc*	8.50*bc*	2.64*b*	8.8*b*	0.20*bc*	0.40*bc*	0.71*bc*
B horizon-low P, high pH	11.6*b*	1.42*bc*	10.01*ab*	2.64*b*	9.0*b*	0.21*bc*	0.39*bc*	0.63*bc*
Subsoil greater than 1 m depth	12.2*b*	1.96*ab*	5.38*d*	3.57*b*	3.2*c*	0.06*d*	0.14*c*	1.32*a*
Tailings sand	10.1*c*	1.09*cd*	6.62*cd*	3.55*b*	4.8*c*	0.10*cd*	0.22*c*	0.90*b*

fertilizer prescriptions that better meet the demands of aspen on each soil type.

With NPK fertilizer, soil type played a much smaller role in determining aspen growth in our study. All soils, including the B horizons, subsoil and tailings sands, showed reasonably good growth with NPK fertilizer with all soils having average aspen height over 19 cm with the poorest growth in the forest floor-mineral mix, which was the second best growing environment in the controls. In this greenhouse environment with adequate water and nutrients, it is not surprising that aspen growth is unrelated to soil properties, since the soil is now less important in providing water and nutrients to

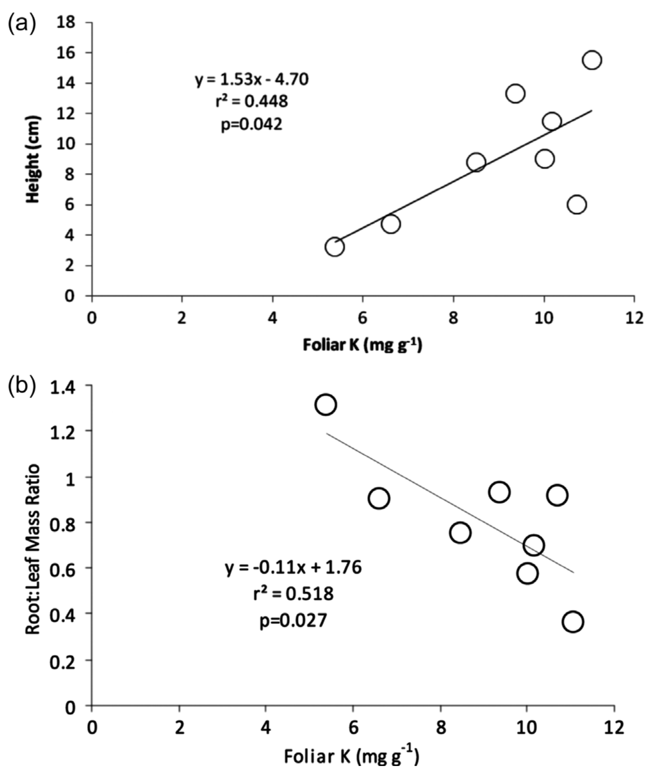

Fig. 2. Foliar K concentration of aspen in the controls of eight different soil types in relation to (a) height and (b) root:leaf mass ratio.

the growing trees. However, our results do indicate that S may be the limiting nutrient once the demands for N, P and K are met. This is similar to what has been found previously for trembling aspen (Liang and Chang 2004) and lodgepole pine (Brockley 2000) and indicates that S fertilizer should be considered as an option to help establish these aspen forests.

Soil type had relatively little impact on seed germination and seedling establishment. Aspen seeds require specific environmental conditions including a consistent water supply to germinate (Fechner et al. 1981; McDonough 1985). This is most often met in nature by a concave mineral seedbed exposed after human activities such as timber harvesting (Landhäusser et al. 2010). It appears that when these exacting environmental conditions are met, as they were in our greenhouse setting, very high rates of aspen germination and establishment are possible on all soil types, including the organic matter-mineral mixes. Our average germination rate of 92% and survival rate of 72% is very similar to another recent greenhouse study examining aspen germination and survival on different soil horizons, which found a germination rate of 90% and a survival rate of 81% (Wolken et al. 2010). Germinant root growth varied slightly among soil types with the peat-mineral mix having the least root growth, while the B horizon with low pH and high P had the greatest root growth with most soil types showing approximately the same root growth. This contrasts with Wolken et al. (2010), who found that aspen germinants growing on B horizons had poorer secondary root growth. Overall, it appears that although soil properties differed significantly among the types compared here, they did not limit aspen germination and establishment. It may therefore be possible to provide the appropriate seedbeds during reclamation to encourage natural aspen seedling establishment.

Rapid root growth after planting is a desired characteristic of planted trees, enabling uptake of water and nutrients to meet the demands of the growing shoot and avoid planting shock (Grossnickle 2005). This is particularly important in the relatively harsh growing environment of reclaimed sites in northern Alberta, which lack a forest floor to aid in nutrient cycling

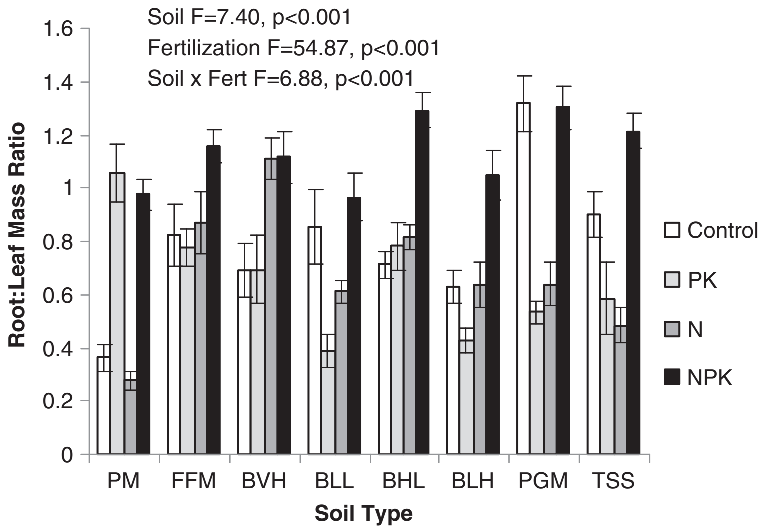

Fig. 3. Root:leaf mass ratio by soil type and fertilizer treatment. Values are mean and standard error ($n = 10$). PM, peat-mineral mix; FFM, forest floor-mineral mix; BVH, B horizon with very high P; BLL, B horizon with low P and low pH; BHL, B horizon with high P and low pH; BLH, B horizon with low P and high pH; PGM, subsoil greater than 1 m depth; TSS, tailings sand.

and water retention. In our study, root growth was positively related to above-ground biomass across all treatments. However, the root:leaf mass ratio declined as above-ground productivity increased in the controls indicating that on poorer soils relatively more energy is allocated below ground. This confirms the finding of another aspen growth experiment with greater allocation to roots with lower fertilizer rates (Coleman et al. 1998). However, other studies have found that aspen root:shoot ratios are under strong genetic control rather than environmental control (King et al. 1999; DesRochers et al. 2003) indicating that the root response to soil properties may vary among aspen clones.

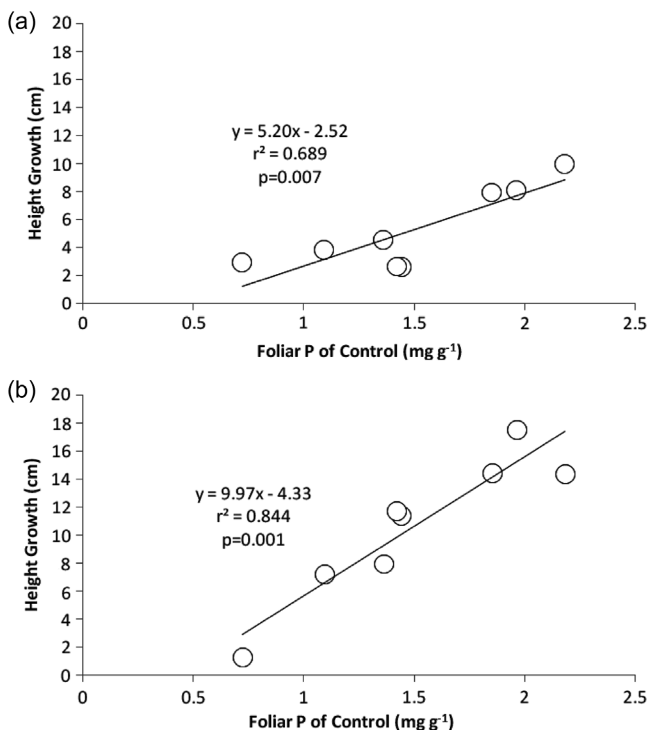

Fig. 4. Aspen height differential (fertilizer height minus control height) due to (a) PK and (b) N fertilizer treatment related to foliar P concentration of aspen in the controls.

Another important developmental measure is bud set since, if the trees do not set bud early in the fall, they are prone to frost damage. Bud set is generally controlled by day length and associated hormone levels, but this can be manipulated by fertilizer. We found that PK and N fertilizer treatments had lower bud set than either the control or NPK treatments indicating the potential for increased frost damage with incomplete fertilization.

CONCLUSIONS

Caution must be taken when extrapolating these results from a controlled greenhouse environment to the environment of forest land reclamation since the trees grown in our experiment had no water limitations and were not subjected to competition. However, there are some general recommendations that can be made from this study based solely on plant growth response. If fertilizer is going to be applied, NPK fertilizer offers the greatest aspen development benefit for root:leaf mass ratio and bud set above that of the increased growth benefits. It also appears that B horizons potentially offer a viable surface soil when combined with NPK fertilizer. However, caution should be taken when applying fertilizers since reclaimed soils are known to have higher N than natural soils (Rowland et al. 2009); thus adding more nutrients could lead to increased leaching into the surrounding environment. If fertilizer is not going to be applied, the organic matter-mineral mixes offer the best aspen growth. This divergence is likely to become greater in operational reclamation projects exposed to periodic water shortages since lack of organic matter in the B horizons of these sandy soils may result in lower water holding capacity and increased drought stress.

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