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ARTICLE

Species-specific responses to targeted fertilizer application on reconstructed soils in a reclaimed upland area

Shauna Stack, Marty Yarmuch, and Simon M. Landhäusser

Abstract: Forested reclamation of oil sand mines in northern Alberta often use peat salvaged from lowland organic soils as a coversoil during soil reconstruction of man-made landforms. Previous studies suggest that planted tree seedlings may be limited in part by low phosphorus (P) and potassium (K) availability in peat. Fertilization is commonly used to treat nutrient limitations on reclamation sites; however, broad spectrum applications can induce strong competition from colonizing vegetation. This study explores the ability of a targeted application of individual macronutrients to (1) reduce nutrient deficiencies in peat coversoils and improve tree growth, while (2) minimizing the colonizing competition. Liquid fertilizer was applied to 6-yr-old aspen, pine, and spruce trees in the field using five nutrient combinations: control (no fertilizer), NPK, PK, P, and K. Tree growth, foliar nutrient concentrations, vegetation cover, and environmental parameters were monitored over two growing seasons. Aspen responded the strongest to fertilization, particularly in the P treatment, whereas pine and spruce marginally responded to NPK. Competing vegetation increased in the NPK but did not respond to the P and K treatments, indicating targeted fertilization can reduce colonizing competition. Additional analyses of the soil conditions of the site suggest that other factors were potentially more limiting to the trees during the study. Targeted fertilization of forest reclamation sites at a later stand age can be an option to improve efficacy and cost savings; however, response will also depend on other site (e.g., soil pH, precipitation, and soil water content) and management (e.g., fertilizer application rate) factors.

Key words: peat, boreal forest, fertilizer, plant nutrition, soil–plant interactions.

Résumé : Lorsqu'on reboise les mines de sables bitumineux dans le nord de l'Alberta, on recourt souvent à de la mousse de sphaigne récupérée du sol organique des plaines basses pour l'utiliser comme couverture avant la reconstruction d'un relief anthropique. Des études antérieures laissent croire que les semis d'arbres ont du mal à pousser, en partie à cause d'une concentration de phosphore (P) et de potassium (K) trop faible dans la tourbe. Pour compenser ces carences en oligoéléments, on fertilise couramment les sites restaurés. Malheureusement, les applications d'engrais à spectre large peuvent renforcer la concurrence des plantes colonisatrices. Les auteurs ont tenté de voir si l'application ciblée de macronutriments distincts peut (1) atténuer les carences en oligoéléments dans la tourbe servant de couche de surface et améliorer la croissance des arbres (2) tout en minimisant la concurrence des plantes colonisatrices. À cette fin, ils ont épandu un engrais liquide dans un boisé de six ans composé de trembles, de pins et d'épinettes. Les traitements consistaient en l'absence d'engrais (témoin), du NPK, du PK, du P et du K. Ensuite, les auteurs ont surveillé la croissance des arbres, la concentration d'oligoéléments dans les feuilles, la couverture végétale et les paramètres environnementaux durant deux périodes végétatives. Le tremble répond le mieux à la fertilisation, surtout l'application de P, le pin et l'épinette ne réagissant que de façon marginale au mélange NPK. La concurrence de la végétation s'est intensifiée avec le traitement NPK, mais pas avec l'application de P ou de K, signe qu'une fertilisation ciblée peut la maîtriser. Des analyses supplémentaires du sol aux sites expérimentaux donnent à penser que d'autres facteurs ont pu freiner la croissance des arbres davantage. Quand les peuplements sont plus vieux, une fertilisation ciblée du site reboisé pourrait déboucher sur de meilleurs résultats et des économies. Toutefois, la réaction obtenue dépendra d'autre facteurs locaux (à savoir, pH du sol, précipitations, teneur en eau) et de paramètres associés à la gestion (taux d'application des engrais). [Traduit par la Rédaction]

Mots-clés : mousse de sphaigne, forêt boréale, engrais, nutrition des plantes, interactions sol–végétation.

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Introduction

For the successful afforestation of post-mined areas, the establishment of a forest plant community on these reclaimed lands is a critical step in the successful restoration of forest function (Burton and Macdonald 2011; Pickell et al. 2013; Jacobs et al. 2015). Creating a rooting medium that can support a diverse and dynamic forest cover can be challenging, particularly if there are limitations associated with the cover soil materials used and (or) with the underlying materials used for landform reconstruction (Zipper et al. 2013; Macdonald et al. 2015). Substrates that have chemical and (or) physical limitations require the placement of a suitable soil cover using coversoils placed over mineral subsoils salvaged prior to mining an area (Alberta Environment 2010). These soil reclamation materials must meet the demands of establishing and maintaining the plant communities equivalent to those found in the region (Oil Sands Vegetation Reclamation Committee 1998). The soil organic matter contained in coversoil material is important for initiating short-term nutrient cycling and providing water storage for early vegetation establishment and growth (McGill and Cole 1981; Berg and Laskowski 2005; Zhuang et al. 2008). Furthermore, the underlying subsoil materials provide long-term nutrient availability through weathering, as well as water storage and structural support for deep-rooted and long-lived plants (Strong and La Roi 1983; Jung et al. 2014).

In the oil sand mining area of northern Alberta, coversoil material available for upland forest reclamation is recovered from upland soils in the disturbance footprint, which is referred to as upland surface soil (often referred to as forest floor material). Forest floor material from upland forest soils is composed of a mixture of the surface leaf litter layer (LFH horizons), the A horizon, and potentially a portion of the B horizon. Surface peat salvaged from poorly drained bogs and fens is also used as coversoil in upland forest reclamation due to the abundance of bogs and fens in the mine development footprint and the increased proportion of uplands to lowlands in the closure reclaimed landscape. Therefore, the use of peat as coversoil reclamation material is common in oil sands mine reclamation activities. However, the soil chemical (e.g., nutrient availability and carbon content; Hemstock et al. 2009; Masse et al. 2016; Anderson et al. 2019) and physical (e.g., water-holding capacity and insulating effects; Barber et al. 2015) characteristics of the peat can differ from native upland forest floor materials and produce significantly different growth responses in trees (Stack et al. 2020).

Peat accumulation in bogs and fens is the result of slow organic matter decomposition rates caused by a combination of cold temperatures, prolonged water saturation, and anaerobic conditions (Aerts et al. 1999). However, when used as coversoil on an upland site, which is an aerobic environment with warmer soil temperatures, there is potential for these organic materials to decompose more quickly and initiate nutrient cycling processes that release important macronutrients such as nitrogen (N) and sulfur (S) for plant uptake (Kong et al. 1980; Quideau et al. 2017). Other macronutrients, however, such as phosphorus (P) and potassium (K), have been found to be limiting in peat coversoil when used in upland forest reclamation (Brown and Naeth 2014; Howell et al. 2016). The underlying subsoil materials may provide nutrients to plants (Quideau et al. 2013, 2017; Smith et al. 2011); therefore, the parent material type and characteristics (e.g., soil texture and chemical) of the subsoil material can also affect nutrient availability (Barnes et al. 2018; Stack et al. 2020). Subsoil is typically salvaged in a single lift, blending the soil horizons (e.g., B, BC, and C horizons) to produce a relatively homogenized material used for subsoil reconstruction (Stack et al. 2020). However, there is potential for elevated nutrient concentrations present in upper weathered horizons to be diluted with lower horizons, which potentially decreases the availability of nutrients like P and K in the soil root zone for tree uptake (Jung et al. 2014; Ojekanmi and Chang 2014).

Fertilization is a method that has been used for amending nutrient deficiencies in reclaimed soils, but it has produced varying levels of success. Many field-based studies are conducted on young reclamation sites that are dominated by bare soil materials with low native vegetation cover, which provides a substrate for other colonizing species to inhabit (Sloan and Jacobs 2013; Pinno and Errington 2015). When developing a fertilizer prescription that specifically targets the planted tree seedlings, a nutrient mixture containing proportions of all macronutrients and some micronutrients is often the easiest approach to ensure the different nutrient requirements of each species are supplemented and nutrient deficiencies of single nutrients are limited, especially when a variety of tree species are considered (Chapin III et al. 1986). However, the use of multi-nutrient fertilizers can introduce additional challenges by inducing a strong response from unwanted vegetation, particularly when broadcast applications are used on the bare reclaimed soils, rendering the fertilizer application as ineffective (Sloan and Jacobs 2013; Schott et al. 2016).

Nitrogen applied in the form of nitrate (NO_3^-) or ammonium (NH_4^+) is often the key nutrient driving competition from colonizing vegetation (Ramsey et al. 2003; Chang and Preston 2011), especially when applied in combination with P and K (Knecht and Göransson 2004). When treating nutrient limitations in peat materials, N is often less limiting than P and K because the high N pool that is retained in the soil organic matter is released through N mineralization as it decomposes (Hemstock et al. 2009; MacKenzie and Quideau 2012; Quideau et al. 2017). However, if the peat coversoil and mineral subsoil have low available P and K, these nutrients that may ultimately control tree seedling growth may need to be amended (Foster and Bhatti 2006). This study explores whether a targeted application of individual macronutrients rather than a combination of nutrients could (1) reduce nutrient deficiencies for a particular peat coversoil material and improve the growth response of the targeted tree seedlings, while (2) minimizing the competitive response of colonizing species that often renders an early application of broad-spectrum fertilizer ineffective.

Methodology

Study site

The Aurora Soil Capping Study (ASCS) is a large-scale reclamation experiment approximately 36 ha in size, located at the Syncrude Aurora North Mine lease, about 80 km north of Fort McMurray, AB, Canada (57°20′N, 111°31′W). The site is located within the central mixedwood natural subregion, which is characterized by a mixture of forested uplands and wetlands (e.g., bogs, fens, and marshes). Locally, the dominant upland forest species is jack pine (*Pinus banksiana* Lamb.) with trembling aspen (*Populus tremuloides* Michx.*)* and white spruce (*Picea glauca* Moench.) to a lesser degree (Natural Regions Committee 2006). The upland soils of the local area are predominantly coarse-textured (sandy loam and coarser) Brunisolic soils developed on Pleistocene glaciofluvial parent geologic material (Turchenek and Lindsay 1982). Bogs and fens dominate the lowlands, consisting of relatively sparse canopies of black spruce (*Picea mariana* Mill.) and tamarack [*Larix laricina* (Du Roi) K. Koch] tree species (Natural Regions Committee 2006). Soils are poorly to very poorly drained Organic and Gleysolic soils (Turchenek and Lindsay 1982). Growing season (May–September) climate normals (1981–2010) for the area have an average daily temperature of 13.4 °C and total precipitation of 284.3 mm (Government of Canada 2019). At the ASCS, average daily temperatures in 2017 and 2018 (May–August) were 16.9 and 16.5 °C, respectively. Total growing season precipitation was 191.8 mm in 2017 and 240.3 mm in 2018.

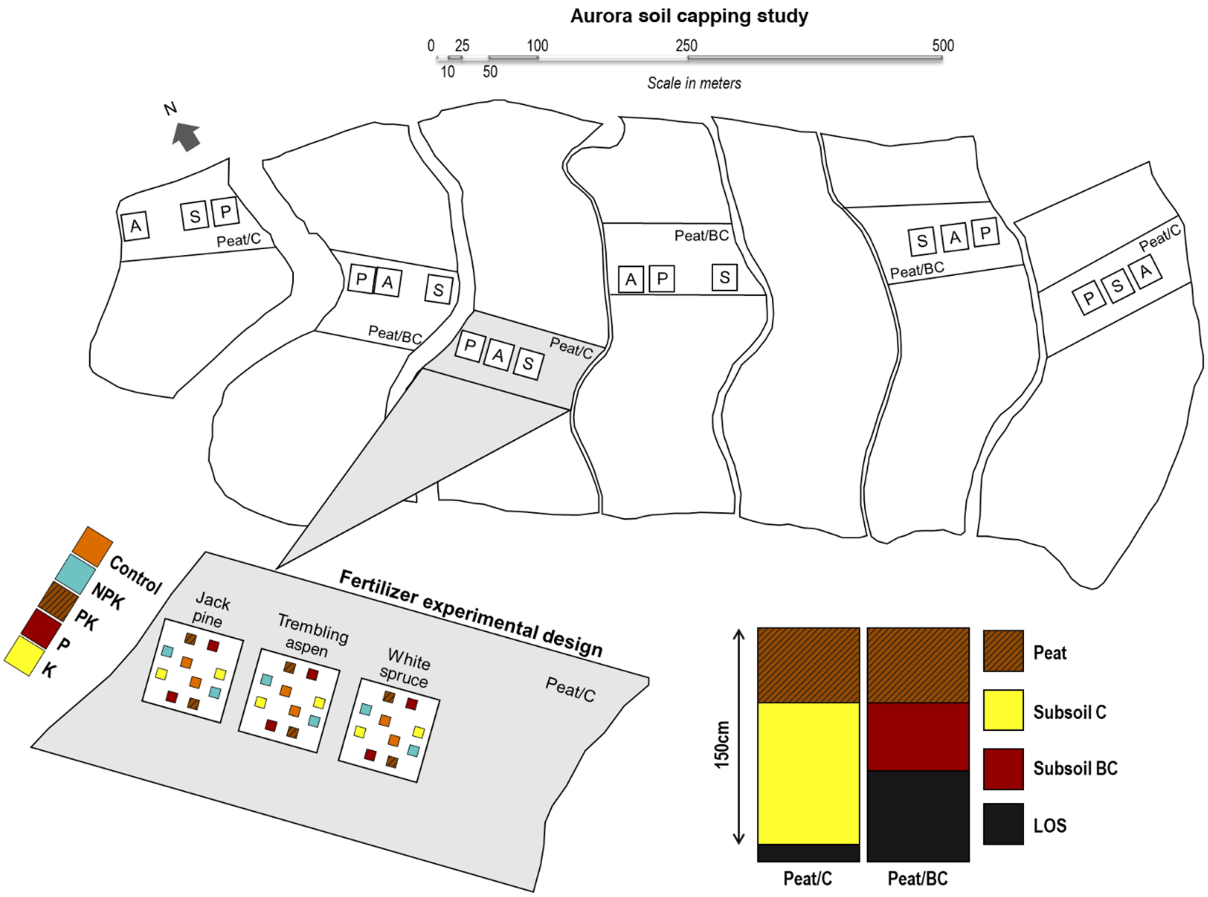
Experimental design

The ASCS is a research trial on an overburden disposal area that was constructed with materials that contain naturally occurring petroleum hydrocarbons referred to as lean oil sand. Thirteen different soil cover treatments were randomly assigned across the overburden, which ranged in the type of coversoil and subsoil materials and their placement depths. For this fertilizer study, soil cover treatments consisted of peat coversoil from the same source location, underlain by coarse-textured (i.e., loamy sand) subsoil materials salvaged from the same upland forest location at different salvage depths. One treatment consisted of 30 cm peat coversoil and 30 cm of subsoil BC (i.e., B, BC, and C horizons to approximately 100 cm depth), and the other consisted of 30 cm peat and 120 cm of subsoil C (i.e., B, BC, and C horizons to approximately 250 cm depth) (Fig. 1).

The peat was salvaged to the depth of mineral soil contact (up to 3–4 m in thickness) from a lowland black spruce and tamarack dominated forest. These soil treatments were selected based on initial data that showed poor tree seedling performance (Stack et al. 2020). Both treatments selected had a relatively thick peat coversoil layer, and it was hypothesized that P and K deficiencies could be associated with the poor seedling growth. For additional information on the ASCS field design, the reconstructed soil cover types and materials, how they were salvaged, and their profile configurations, see Stack et al. (2020).

All soil cover treatments were 1 ha in size and replicated three times. Tree plots (25 m × 25 m) were established within each soil cover replicate and planted at a density of 10 000 stems per hectare in 2012 with a single tree species of either trembling aspen, jack pine, or white spruce. None of the plots in the ASCS research trial received any fertilizer applications prior to this fertilization study. Tree seedlings at the ASCS were starting their sixth growing season when the fertilizer study was implemented (i.e., 2017), which ensured that seedlings had established root systems. Within each tree plot, 10 fertilizer plots (3 m × 3 m) each containing nine trees were selected. Plots were equally spaced and positioned to ensure a minimum distance of 5 m among plots (Fig. 1). Because this was a short-term study, and the longest lateral root length of trees in these soil materials did not exceed 3.5 m for each species (Bockstette 2017), we treated each fertilizer plot as independent (true replicate). The following five fertilizer treatments were assigned to the 3 m × 3 m fertilizer plots ($n = 6$): control (no fertilizer), NPK (nitrogen–phosphorus–potassium), PK (phosphorus–potassium), P (phosphorus), and K (potassium) (Fig. 1). Fertilizers were composed of pure compounds of ammonium nitrate (N), calcium phosphate (P), and potassium sulfate (K); these compounds were selected to ensure that no other macro- and micro-nutrients were inadvertently added, focusing only on N, P, and K. To apply P and K, calcium (Ca) and sulfate were present; however, we considered the potential confounding effects from their presence low, given their high levels already present in the soil material (Table 1). Compounds were dissolved in 4 L of tap water per fertilized plot to ensure the nutrients were readily available for the established trees upon application. Trees were fertilized once in early June 2017 with a dosage equivalent to 250 kg ha^{-1} of a 10N–30P–20K fertilizer, which is the same application rate used in a greenhouse study reported by Pinno et al. (2012) that tested similar reclamation materials near the ASCS study. The NPK treatment received 10–30–20, the PK received 0–30–20, the P received 0–30–0, and the K received 0–0–20 for a per nutrient equivalent of 25 kg N ha^{-1}, 75 kg P ha^{-1}, and 50 kg K ha^{-1}.

Fig. 1. Three single species tree plots planted with trembling aspen, jack pine, or white spruce were grown on two different soil covers from 2012 to 2017 at the Aurora Soil Capping Study: 150 cm of peat over subsoil C and 60 cm of peat over subsoil BC. Five fertilizer treatments were replicated twice within each 25 m × 25 m tree plot and applied in 2017: control (no fertilizer), nitrogen–phosphorus–potassium (NPK), phosphorus–potassium (PK), phosphorus (P), and potassium (K). Figure was adapted from map produced by O'Kane Consultants Inc. for Syncrude Canada Ltd. in 2011. [Colour online.]



Measurements

In May 2017 and prior to fertilizer application, soil samples of the peat coversoil and mineral subsoil materials were taken from the center of each 25 m × 25 m tree plot, and in 2018, the peat coversoil layer from each 3 m × 3 m fertilizer plot was sampled. In both years, all soil samples were analyzed for salinity characteristics and plant-available nutrients. A saturated paste was made from each soil sample and vacuum filtered to remove the extract; thereafter, the extract was used to measure pH and EC with a pH/EC meter and analyzed by inductively coupled plasma – optical emission spectroscopy (ICP–OES) for sodium (Na), calcium (Ca), and magnesium (Mg) concentrations, which were later used to calculate SAR [Natural Resources Analytical Laboratory (NRAL), University of Alberta, Edmonton, AB, Canada]. NO_3^- and NH_4^+ were extracted using KCl and measured by a ThermoFisher Gallery Beermaster Plus (ThermoFisher Scientific, Waltham, MA, USA), whereas all other nutrients were extracted from saturated paste followed by ICP–OES (NRAL, University of Alberta, Edmonton, AB, Canada). Instrumentation installed following the initial construction of the ASCS to monitor vadose zone water dynamics were used for the 2017 and 2018 growing seasons in this study, and daily means from May through August were averaged to determine the average growing season soil volumetric water content (VWC). Time domain reflectometry sensors (model 616, Campbell Scientific Inc., Logan, UT, USA) were used to monitor in situ water content 15 cm below the soil surface, and these sensors were located at a single point outside of the 25 m × 25 m tree plots within each 1 ha soil treatment replicate.

Trees within each fertilizer plot were measured three times throughout the study for their height (from ground to bud tip) and root collar diameter (RCD; at ground level): May 2017 (prior to fertilization and spring flush; equivalent to 2016 fall height), August 2017 (first year measurement after fertilizer application), and August 2018 (second year measurement). To make comparisons among tree species and their responses to the fertilizer treatments, relative height and RCD in 2017 and 2018 were calculated in relation to the 2016 measurements (e.g., 2017height/2016height and

Table 1. Sodium adsorption ratio (SAR), electrical conductivity (EC), pH, and plant-available nutrients (±SE) in the peat and subsoil materials sampled in 2017.

	SAR	EC	pH	Plant-available nutrient (mg kg^{-1})						
	(dS m^{-1})			NO_3	NH_4	P	K	S	Ca	Mg
Peat	0.23 (0.03)	0.88 (0.11)b	8.22 (0.04)	18.06 (3.87)a	7.13 (0.50)a	0.15 (0.06)	6.35 (1.02)a	172.56 (33.54)b	240.56 (33.43)b	23.42 (3.96)b
Subsoil C	0.20 (0.01)	0.51 (0.04)c	8.08 (0.13)	0.81 (0.08)b	1.17 (0.12)b	0.04 (0.01)	1.07 (0.06)c	23.08 (2.75)d	28.21 (2.23)c	2.97 (0.35)c
Peat	0.27 (0.07)	1.32 (0.17)a	8.08 (0.05)	34.2 (10.9)a	6.90 (0.46)a	0.09 (0.04)	4.19 (0.50)b	347.55 (57.13)a	400.81 (57.84)a	40.19 (6.69)a
Subsoil BC	0.25 (0.05)	0.68 (0.08)bc	7.99 (0.07)	1.39 (0.45)b	1.39 (0.45)b	0.01 (0.01)	0.79 (0.07)d	33.70 (6.04)c	38.37 (5.22)c	4.28 (0.62)c

Note: Letters indicate statistically significant differences between means in the soil ($\alpha \leq 0.1$; $n = 9$), and if letters are absent, this indicates there were no significant differences between means. All plant available nutrients were logarithmically transformed prior to analysis.

2018height/2016height). Foliar samples were collected in August 2017 and July 2018 to assess foliar nutrient concentrations. Leaves or needles were taken from three trees and pooled per fertilizer plot. Samples were immediately cold stored in the field after collection and later frozen for future processing; thereafter, samples were dried at 100 °C for 1 h and then at 70 °C to constant weight, ground with a Wiley mill, sorted through a 0.4 mm mesh filter, and sent for nutrient analysis to assess for N, P, K, S, Ca, and Mg (NRAL, University of Alberta, Edmonton, AB, Canada). Nitrogen was measured by combustion, whereas all other nutrients were measured by microwave digestion followed by ICP–OES. Foliar nutrient concentrations were used to calculate N:P, N:K, and N:S ratios for each species and fertilizer treatment. To assess the levels of competition for nutrients between tree seedlings and colonizing vegetation, total vegetation cover was estimated in a 1 m^2 plot located in each fertilizer treatment plot (9 m^2) in August of 2017 and 2018.

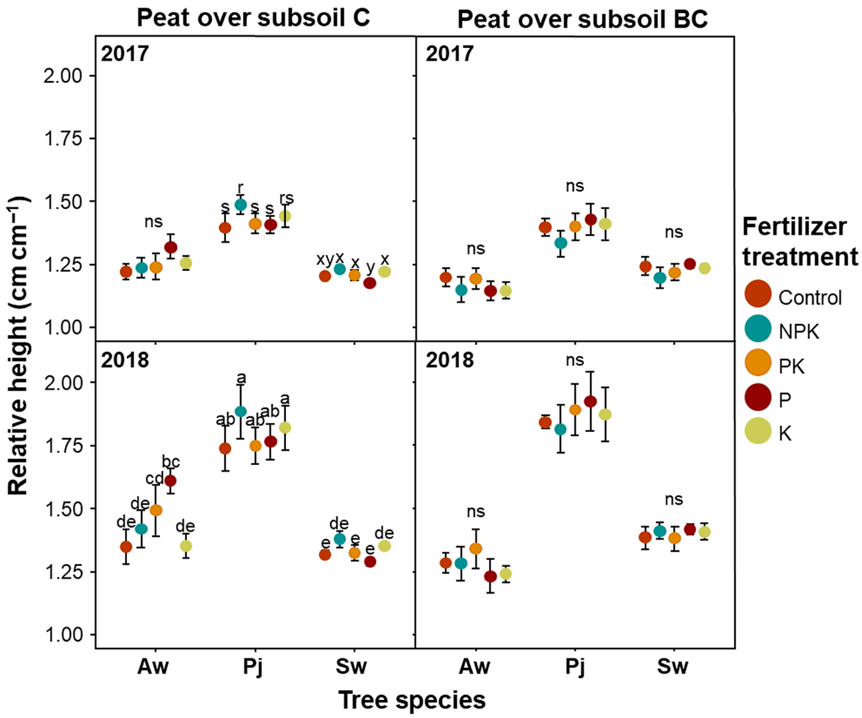
Statistical analysis

The experimental design of this study was a split-plot design, where tree plots served as the whole plot factor, and the fertilizer plots served as the subplot factor. The two soil cover treatments were analyzed separately due to the differences in tree performance observed in the initial 5 year study at the ASCS for these two subsoil treatments (Stack et al. 2020), and further investigation into these differences was not a focus of this study.

All analyses were executed using R software, version 3.4.3, 65 bit (R Core Team 2018*a*). Soil VWC is presented at the 1 ha soil cover level, soil chemistry data from 2017 are presented at the 25 m $\times$ 25 m tree plot level, whereas all other data (i.e., 2018 peat chemistry data, tree height and RCD, foliar nutrient concentrations and ratios, vegetation cover) are presented at the fertilizer plot level. Model residuals were tested for normality using the Shapiro–Wilk's test from the R *stats* package (version 3.6.0; R Core Team 2018*b*) and homogeneity of variance using Levene's test in the R *car* package (version 3.0-0; Fox and R Development Core Team. 2018); when data did not meet assumptions of normality or homogeneity, they were adjusted using transformations, or analyzed using a permutational test from the R *lmPerm* package (version 2.1.0; Wheeler et al. 2016) if transformations were inadequate. Due to the low replication necessitated by logistics of this large operational-scale study, a $p \leq 0.1$ was used in all analyses to reduce the risk of type II error (Stack et al. 2020).

Differences in soil nutrients and salinity characteristics between the peat and subsoil materials in 2017 and fertilizer treatments in 2018 were analyzed using a one-way analysis of variance (ANOVA). Comparisons of total tree height and RCD in May 2017 (i.e., 2016 height), August 2017, and August 2018, as well as total vegetation cover, were compared between fertilizer treatments and

Fig. 2. Relative height (±SE) of trembling aspen (Aw), jack pine (Pj), and white spruce (Sw) grown in peat over subsoil C (left panels) and peat over subsoil BC (right panels) post fertilization in 2017 and 2018. The effect of fertilizer, tree species, and their interaction was tested within each soil group and year. Letters indicate statistically significant differences between means in fertilizer treatments ($\alpha \leq 0.1$, $n = 6$). If a significant interaction was found, pairwise comparisons were conducted across all fertilizer treatment and tree species combinations. [Colour online.]



years using a repeated measures ANOVA. Relative height and RCD were compared among fertilizer treatments and tree species within each soil cover treatment and year in a two-way ANOVA. Foliar N:P, N:K, and N:S ratios of each species in 2018 were compared between fertilizer treatments within each soil cover treatment using a one-way ANOVA. When a significant effect or an interaction was detected, the Fisher's least significant difference test from the *agricolae* package was used to conduct post hoc pairwise comparisons ($\alpha \leq 0.1$; version 1.2-8; de Mendiburu and R Development Core Team 2017).

Results

Tree responses

Compared among all species, the strongest response to the targeted fertilizer application was observed in trembling aspen (fertilizer × species: $p = 0.004$), where the relative height of aspen in the peat/C was 26% higher in the P treatment compared with the control in 2018 (Fig. 2). This difference corresponds to absolute growth of 28.1 cm compared with the control (15.8 cm) ($p = 0.05$; Table A1). Relative RCD of aspen in the same soil cover was at least 5% higher in the NPK, PK, and K treatments in 2017 and 10% higher in the NPK, P, and K treatments in 2018 when compared with the control (2017: $p = 0.07$; 2018: $p = 0.06$; Fig. 3). In the peat/BC soil cover, only relative RCD responded to the NPK and PK fertilizer treatments which was 10% higher than the control in 2018 ($p = 0.08$; Fig. 3).

Foliar N concentrations of aspen leaf samples from the peat/C soil cover in 2017 increased in the NPK and K treatments compared with the controls ($p = 0.01$; Table A2). In the peat/BC soil cover, foliar N in the NPK, PK, and P treatments from 2018 had decreased below the concentrations observed in the control and K treatments ($p = 0.02$; Table A2). Foliar K concentrations in the peat/C soil cover increased in the K treatment in 2017 but were not different in 2018 ($p = 0.08$; Table A2). In the peat/BC soil cover, foliar K increased in the PK and K treatments compared with the controls in 2017, and by 2018, K concentrations were higher in the NPK and PK treatments ($p = 0.02$ for both years; Table A2). Foliar N:P ratios in aspen decreased in response to all P fertilizer treatments on the peat/BC soil cover ($p = 0.001$; Table 2). Similarly, N:K ratios decreased in all P fertilizer treatments in the peat/BC ($p = 0.03$), whereas a decrease was only observed in the P treatment on peat/C ($p = 0.06$; Table 2). Interestingly, N:K ratios in the K treatment did not change relative to the control on either soil cover (Table 2).

Relative height of jack pine grown on peat/C marginally responded to the NPK treatment in 2017 ($p = 0.08$; Fig. 2). However, absolute height of pine in the peat/BC soil cover responded positively to the P and PK treatments in 2018 ($p = 0.02$; Table A1), where pine growth

Fig. 3. Relative root collar diameter (RCD) (±SE) of trembling aspen (Aw), jack pine (Pj), and white spruce (Sw) grown in peat over subsoil C (left panels) and peat over subsoil BC (right panels) post fertilizer in 2017 and 2018. The effect of fertilizer, tree species, and their interaction was tested within each soil group and year. Letters indicate statistically significant differences between means in fertilizer treatments ($\alpha \leq 0.1$, $n = 6$). [Colour online.]

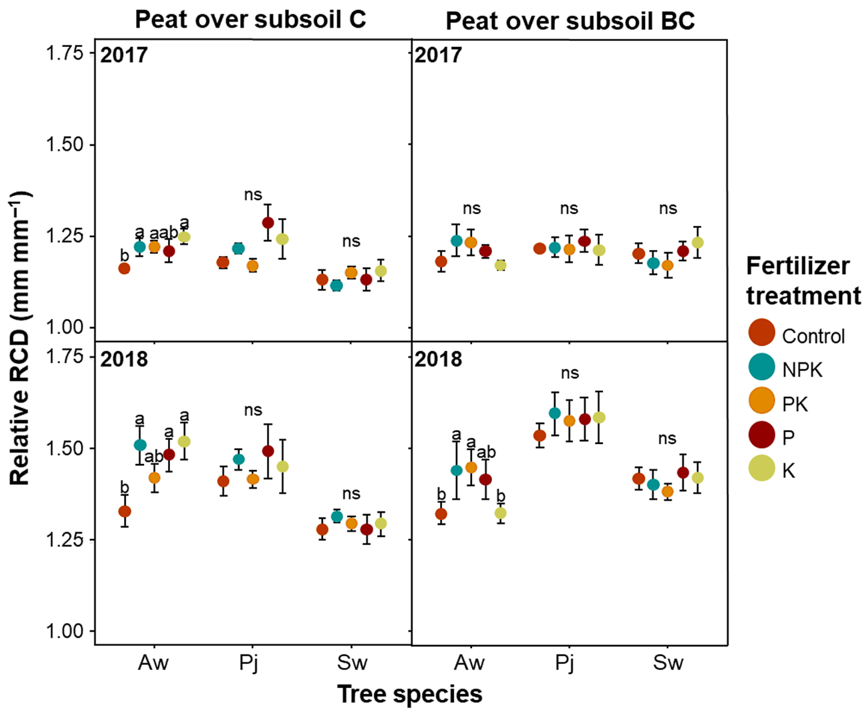


Table 2. Foliar N:P, N:K, and N:S ratios (±SE) of trembling aspen, jack pine, and white spruce grown in either peat over subsoil C or peat over subsoil BC in 2018.

Soil cover	Ratio type	Tree species	Control	NPK	PK	P	K
Peat over subsoil C	N:P	Trembling aspen	29.24 (2.29)	26.04 (1.97)	26.60 (2.04)	24.08 (1.72)	30.86 (1.51)
		Jack pine	11.66 (1.40)	9.23 (1.41)	10.58 (1.60)	9.94 (1.14)	11.34 (1.22)
		White spruce	9.69 (1.05)	8.94 (1.66)	8.63 (1.52)	10.17 (1.69)	10.70 (2.04)
	N:K	Trembling aspen	2.45 (0.09)ab	2.43 (0.12)abc	2.36 (0.12)bc	2.21 (0.06)c	2.64 (0.08)a
		Jack pine	1.79 (0.32)	1.68 (0.23)	1.89 (0.32)	1.84 (0.27)	1.70 (0.27)
		White spruce	1.42 (0.32)	1.48 (0.39)	1.34 (0.30)	1.59 (0.40)	1.41 (0.36)
	N:S	Trembling aspen	7.98 (0.27)	8.14 (0.38)	8.26 (0.43)	7.87 (0.32)	8.20 (0.29)
		Jack pine	8.98 (0.37)	8.74 (0.26)	9.19 (0.18)	9.21 (0.06)	9.03 (0.18)
		White spruce	8.78 (0.32)	8.59 (0.41)	8.25 (0.27)	9.13 (0.42)	8.24 (0.26)
Peat over subsoil BC	N:P	Trembling aspen	34.36 (1.18)x	26.68 (1.72)y	27.33 (1.15)y	27.87 (1.62)y	34.31 (1.81)x
		Jack pine	15.82 (1.39)x	12.01 (0.94)y	12.25 (0.82)y	11.94 (1.09)y	14.35 (1.13)xy
		White spruce	11.22 (0.27)wx	10.29 (0.47)xy	8.97 (0.61)z	9.86 (0.68)yz	12.17 (0.43)w
	N:K	Trembling aspen	2.90 (0.18)x	2.31 (0.18)y	2.18 (0.13)y	2.37 (0.13)y	2.80 (0.12)x
		Jack pine	2.54 (0.20)x	2.34 (0.16)xy	1.99 (0.09)y	2.26 (0.16)xy	2.12 (0.15)y
		White spruce	1.18 (0.05)	1.29 (0.09)	1.15 (0.08)	1.30 (0.10)	1.16 (0.06)
	N:S	Trembling aspen	7.67 (0.47)	7.32 (0.57)	7.07 (0.51)	7.25 (0.73)	8.30 (0.96)
		Jack pine	9.34 (0.43)	8.98 (0.53)	8.87 (0.33)	8.79 (0.23)	8.92 (0.47)
		White spruce	10.43 (0.37)y	11.74 (0.54)x	10.80 (0.42)xy	11.71 (0.53)x	10.83 (0.44)xy

Note: Letters indicate statistically significant differences between foliar ratio means in fertilizer treatments within each tree species ($\alpha \leq 0.1$; $n = 6$), and if letters are absent, this indicates there were no significant differences between means.

was 9.3 and 6.9 cm greater in the P and PK treatments, respectively, compared with the control. A similar response was observed in absolute RCD ($p = 0.02$; Table A1). Foliar K concentrations in the peat/BC increased in the PK and K treatments in 2018 ($p = 0.01$; Table A2). Foliar N:P ratios in pine in the peat/BC soil

Fig. 4. Total understorey vegetation cover (%) (±SE) for each fertilizer treatment in 2017 and 2018 on both subsoil treatments combined. Letters indicate statistically significant differences between vegetation cover means in fertilizer treatments across both years ($\alpha \leq 0.1$, $n = 36$). [Colour online.]

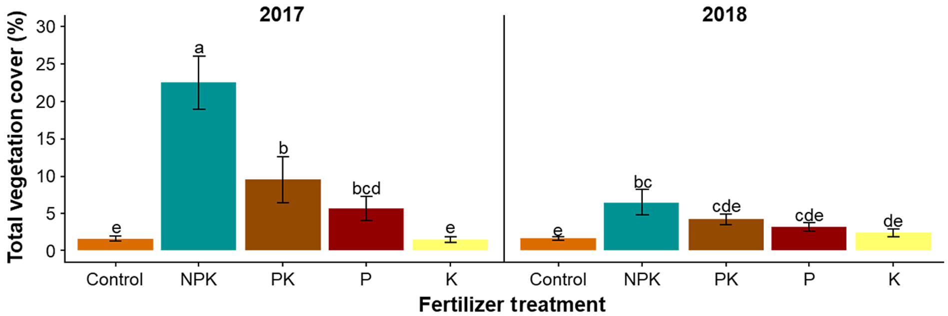
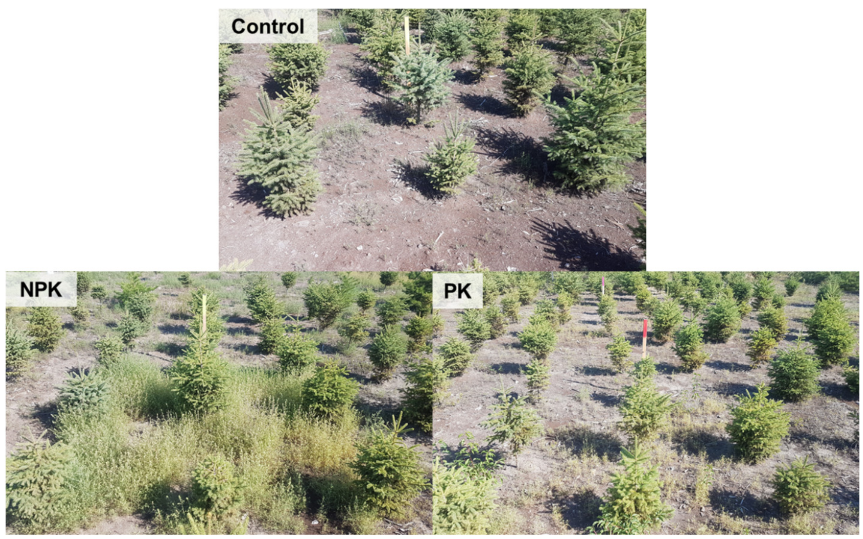


Fig. 5. Photos show understorey vegetation response, specifically of *Salsola pestifer* A. Nels., in the control, NPK, and PK fertilizer plots in 2017. [Colour online.]



cover decreased in all treatments containing P ($p = 0.07$; Table 2). Foliar N:K ratios of pine grown in the peat/BC decreased in the PK and K treatments but not the NPK ($p = 0.03$; Table 2).

The response of white spruce to fertilizer application was the weakest of the three species, regardless of the soil cover. The P treatment was the only treatment to show a response, where absolute height was 5.6 cm higher than in the control in 2018 in the peat/BC treatment ($p = 0.002$) (Table A1). Foliar N concentrations of spruce needles grown in peat/C increased by 27% relative to the control in the NPK treatment in 2017, and this response disappeared by 2018 (fertilizer × year: $p = 0.16$; Table A2). In the peat/BC, foliar N:P ratios decreased in the PK and P treatments compared with the control ($p = 0.002$; Table 2). Unlike the first two tree species, foliar N:S of spruce in the peat/BC responded positively to a NPK and P application compared with the control ($p = 0.003$; Table 2).

Colonizing vegetation

Total colonizing vegetation cover in 2017 increased by 21%, 8%, and 4%, in the NPK, PK, and P treatments, respectively, compared with the control ($p < 0.001$; Fig. 4). The NPK continued to have the greatest cover in the second growing season; however, the total cover (6%) was lower than in the previous year (22%) (fertilizer × year interaction: $p < 0.001$; Fig. 4). The response of the colonizing vegetation to the fertilizer application was primarily driven by one species, *Salsola pestifer* A. Nels. (Russian Thistle), an annual species that was already present at the study site and represented 90% of the total cover (Fig. 5).

Edaphic and climatic factors

The 2017 growing season was drier than 2018 at the ASCS, receiving 191.8 mm of precipitation in 2017 compared with 240.3 mm in 2018 (Section 2.1). A draw-down in VWC to approximately 25% was evident in both soil

Table 3. Sodium adsorption ratio (SAR), electrical conductivity (EC), pH, and plant-available nutrients (±SE) sampled from the peat coversoil 15 cm below the surface in 2018.

Soil cover	Fertilizer treatment	SAR	EC (dS m^{-1})	pH	Plant-available nutrient (mg kg^{-1})						
					NO_3	NH_4	P	K	S	Ca	Mg
Peat over subsoil C	Control	0.24 (0.05)	0.87 (0.13)	7.99 (0.05)	5.7 (0.7)bc	11.0 (0.5)	<0.015	13.3 (1.5)c	152.9 (44.0)	338.0 (35.6)	34.5 (5.0)
	NPK	0.31 (0.06)	0.97 (0.11)	7.97 (0.03)	7.6 (1.8)ab	11.4 (0.9)	<0.015	40.1 (3.3)a	203.6 (38.0)	358.2 (29.7)	37.2 (4.1)
	PK	0.29 (0.07)	0.92 (0.15)	8.03 (0.04)	4.3 (0.3)c	10.9 (0.7)	<0.015	36.4 (3.4)ab	151.1 (48.8)	308.8 (38.7)	31.9 (5.1)
	P	0.27 (0.05)	1.07 (0.09)	8.02 (0.02)	4.9 (0.5)c	12.0 (0.7)	<0.015	15.1 (1.4)c	232.5 (46.6)	392.5 (58.8)	39.8 (4.7)
	K	0.27 (0.04)	1.05 (0.10)	8.02 (0.02)	8.2 (1.3)a	12.2 (1.1)	<0.015	31.4 (4.1)b	214.8 (44.5)	381.6 (33.2)	38.3 (3.7)
Peat over subsoil BC	Control	0.19 (0.03)	1.18 (0.24)	7.91 (0.05)	5.6 (1.0)	10.7 (0.8)	<0.015	13.5 (2.4)y	377.0 (113.0)	572.5 (101.4)	67.3 (21.7)
	NPK	0.20 (0.03)	1.01 (0.14)	7.87 (0.04)	6.1 (1.1)	10.2 (0.8)	<0.015	36.7 (4.1)x	284.5 (85.4)	456.8 (92.2)	46.1 (8.7)
	PK	0.24 (0.06)	1.00 (0.09)	7.94 (0.04)	9.5 (2.8)	9.9 (0.6)	<0.015	43.1 (8.6)x	295.9 (74.6)	452.5 (80.5)	50.1 (10.2)
	P	0.19 (0.04)	1.08 (0.21)	7.92 (0.06)	9.6 (2.5)	11.3 (0.9)	<0.015	14.9 (5.7)y	356.9 (139.4)	558.6 (151.3)	51.9 (15.0)
	K	0.21 (0.03)	1.24 (0.22)	7.93 (0.03)	4.3 (0.5)	10.0 (0.6)	<0.015	37.7 (4.1)x	353.7 (120.2)	557.2 (132.7)	51.0 (10.7)

Note: Letters indicate statistically significant differences between means in fertilizer treatments within each soil cover ($\alpha \leq 0.1$; $n = 9$), and if letters are absent, this indicates there were no significant differences between means.

covers near the end of the 2017 growing season (Fig. A1), which represents the approximate wilting point of peat (Ojekanmi and Chang 2014). In 2018, there were two large precipitation events, as noted by the arrows in Fig. A1, that maintained a VWC above 30% throughout the summer.

The soils sampled in 2017 reported a slightly alkaline pH of approximately 8 in all soil materials (Table 1). Plant-available nutrients (except P) were higher in the peat materials compared with the subsoils, whereas the peat coversoil placed over the subsoil BC material had higher K, S, Ca, and Mg than the peat on subsoil C ($p < 0.001$ for all; Table 1). Phosphorus concentrations were low and undetectable in several subsamples used in the analysis (Table 1), and these levels were comparatively lower than levels found in the surface litter layer (LFH horizon) and Bm horizons of natural upland soils that were sampled within the same locale as the soils of the ASCS (32–40 mg kg^{-1} of P; Table A3). Similarly, K concentrations were low when compared with the natural upland soils (387 mg kg^{-1} of K; Table A3), but K concentrations were higher and more available than P in the ASCS soil materials (Table 1).

All plant-available nutrients, except for NO_3^- and K, did not differ across the fertilizer treatments. Available K was more than 170% higher in the NPK, PK, and K treatments relative to the control ($p < 0.001$), indicating that K fertilizer infiltrated at least 15 cm below the soil surface where the soil samples were taken (Table 3). However, P was not detectable at the same sample depth of 15 cm (Table 3). Available NO_3^- was 44% higher in the K treatment relative to the control in the peat placed over the subsoil C material ($p = 0.05$).

Discussion

A targeted fertilizer application produced different responses among trembling aspen, jack pine, and white spruce, and the strength of these responses appear to be strongly influenced by the nutritional requirements of the targeted species, the chemistry of the peat layer, and the environmental conditions of each growing season. Analysis of soil nutrient availability prior to fertilization reported low levels of K, and at times, undetectable levels of P in all peat and subsoil materials, suggesting a limited availability of these nutrients for plant uptake compared with levels found in natural upland forest soils (Lanoue 2003; Foster and Bhatti 2006). Because the most limiting nutrient(s) will likely have the most impact on plant growth (Liebig 1840), we expected to have the greatest increase in plant response to an addition of P and (or) K in the three tree species tested. In our study, the strongest response to fertilization was observed in aspen grown in the peat/C soil cover, particularly when only P was applied, whereas both conifers responded minimally to any of the fertilizer treatments. The root systems of the planted seedlings had been developing for five growing seasons prior to fertilizer application, and we expected that the efficacy of nutrient uptake from these expanding root systems would be greater and height growth rates would significantly improve, particularly for aspen which is known for allocating more carbon to root system development during early establishment (Landhäusser and Lieffers 2001; Landhäusser et al. 2012). Although growth rates of aspen with P addition in the peat/C reached levels that were similar to those in aspen growing in salvaged forest floor material (average 27.9 cm yr^{-1}; Stack et al. 2020), the same was not observed in the P only treatment on the peat/BC, and when considering neither conifer species responded as strongly as expected to the targeted fertilizer treatments, the varied responses suggest that there were other variables that may have limited growth in these reconstructed soils.

The abundance of nutrients and their relation to each other (i.e., their ratios) in the peat material may have influenced the internal nutrient balance within the trees and subsequently their physiological processes and growth (Garten 1976; Diem and Godbold 1993). Phosphorus is particularly important for plant growth given its major role in forming nucleic acids, phospholipids and adenosine triphosphate (Schachtman et al. 1998), and this nutrient can be the most limiting to tree growth, particularly for a relatively fast-growing species like aspen (Chapin III et al. 1983; Chen et al. 1998). Foliar P concentrations sampled in all three species from both soil covers were below the optimal levels published for related *Populus* species (<0.33%; Hansen 1994; Kopinga and Van den Burg 1995), white spruce (<0.14%; Ballard and Carter 1986; Allen 1987), and the closely related lodgepole pine (<0.16%; Weetman et al. 1985), supporting our prediction that P was a limiting nutrient for trees grown in these soil materials. The addition of P improved this limitation for aspen in the peat/C and resulted in greater growth; however, the aspen grown in the peat/BC only showed a response in the foliar N:P ratio and not growth. Foliar N:P ratios of aspen in the controls were considerably higher than 15 on both soil covers, where a value of 15 indicates an approximate ratio where N and P are considered balanced within the plant (Güsewell et al. 2003). Ratios higher than this value indicate a deficiency in P, and in 2018, P fertilization significantly lowered the foliar N:P ratio of aspen in the peat/BC closer to this balance value of 15.

The addition of P had the same effect on the foliar N:P ratios of both conifer species in the peat/BC; however, P addition lowered the ratios below the value of 15, potentially indicating a need for more N. This was further supported by the foliar N concentrations that were below the suggested optimum level of 1.55% for both conifer species (Weetman et al. 1985; Allan 1987; Ballard and Carter 1986), suggesting N may have been more limiting for pine and spruce than P and may be partly responsible for the lack of response in the conifers. Although NPK was applied in this study, the application rate of nitrogen (25 kg ha^{-1}) was low compared with other operational application rates (85–200 kg ha^{-1} of N; Lanoue 2003; Rowland et al. 2009; Pinno and Errington 2015), and P and K (the focus of this study) were applied proportionally at a higher rate than N. Furthermore, pine and spruce will preferentially use ammonium over nitrate (Lavoie et al. 1992; Kronzucker et al. 1997; Duan et al. 2015), and given the higher availability of nitrate compared with ammonium in the peat prior to fertilization, it is likely ammonium was the limiting form of N for the conifer species in the study, and a higher application rate of this nutrient was required.

Potassium is more mobile than P (Chapin III et al. 1986), and trees are able to regulate the uptake of K when other nutrients like N and P are less available (Clarkson 1985). Targeting P rather than K may have improved the internal balance of K as observed in the N:K ratios of aspen and to a lesser extent in jack pine, suggesting there was an increase in K uptake relative to N within the foliar pool as P became more available after fertilization. Furthermore, K availability was likely not as limiting as originally predicted from the soil samples in 2017 based on the foliar K concentrations that were within the range considered optimal for each species (aspen: 1.6% (Hansen 1994; Kopinga and Van den Burg 1995); pine and spruce: 0.5% (Weetman et al. 1985; Ballard and Carter 1986; Allen 1987).

Soil nutrient concentrations of S, Ca, and Mg were substantially higher in the soil materials compared with the levels found in natural upland sites, which is common for reclaimed soils in the region (Howat 2000; Howell et al. 2016). These nutrients play an important role in plant metabolism, photosynthesis, and cell structure (Fromm 2010; Garten 1976); however, when the abundance of these nutrients is higher than N, P, and K, it could create nutrient imbalances that may negatively impact growth (Diem and Godbold 1993). Phosphorus fertilization increased the foliar N:S ratios of spruce, suggesting the increased availability of P improved the uptake of N in relation to the high concentrations of S in the peat. Nutrients like Ca are considered less mobile than S and are unregulated during uptake, which can lead to an accumulation of Ca within the tree (Knecht and Göransson 2004). Foliar concentrations of Ca in our study supports this accumulation, which were higher than optimal levels in aspen (0.63%, Hansen 1994) and the conifer species (0.1%–0.2%, Weetman et al. 1985; Ballard and Carter 1986) on both soil covers.

An important consideration in this study that will require further investigation is the interaction between the alkalinity (pH 8) and highly available Ca in the peat materials. This is likely a legacy effect from the salvage site where calcium carbonate was present in the peat and underlying mineral soil. Studies on the effect of high pH and Ca availability have been linked to reduced water uptake, and with that transpiration and photosynthesis, in pH-sensitive species like aspen and pine, whereas late successional species like spruce are more tolerable of these conditions (Zhang et al. 2013; Zhang et al. 2015). Furthermore, phosphorus sorption in organic matter is negatively related to pH because in high pH soils, the organic acids, which inhibit the sorption of P, decrease (Guppy et al. 2005). As a result, the competition for sorption sites decrease and cations, particularly Ca, can attach to the P ions and reduce their availability for plant use (Bell and Black 1970; Bolan et al. 1988; Tunesi et al. 1999; Vetterlein et al. 1999). This mechanism is supported by our observation that P levels did not increase 15 cm below the peat surface in 2018, whereas the added K was clearly present and detectable at that same depth. Furthermore, Ca concentrations were substantially higher in the peat placed over the subsoil BC material, which may further explain why overall tree growth was not responsive with P addition compared with the peat/C which had lower Ca levels.

Soil moisture availability in the first growing season may also partly explain the limited growth responses observed in 2017. Soil water content steadily decreased following fertilizer application in early June, a result of the low precipitation throughout the 2017 growing season. Consequently, this may have slowed the infiltration rate of the applied nutrients, and combined with immobilization, could have reduced the rate of nutrient uptake by the tree roots (van den Driessche et al. 2005, 2003). The weak growth responses observed in the first growing season corresponded with these conditions and has been observed in other studies. However, climatic conditions improved by the second year when the ASCS received higher total rainfall and a spring snow melt that would have assisted with infiltration of the nutrients at the beginning of that year when trees were emerging from winter dormancy. Evidence of this deeper infiltration is supported by the elevated K levels in all K fertilized treatments that indicate K had infiltrated to the root zone by 2018.

Lastly, the strong response of the competing colonizing vegetation to the application of nutrients could have also had an impact on tree growth. Peat materials used in reclamation generally lack a source of propagules associated with natural forest upland areas, resulting in the potential development of a vegetation cover dominated by non-native species that have migrated onto the site in the early years after reclamation (Mackenzie and Naeth 2010; Brown and Naeth 2014; Jones and Landhäusser 2018). In this study, fertilized plots were dominated by a weedy early colonizer known as *S. pestifer*, which was already present on the ASCS prior to fertilization (Jones and Landhäusser 2018). Germination of this annual species occurs when soil temperatures increase above 15 °C (Crompton and Bassett 1985), and temperatures reached this threshold in the upper layers of the peat by the end of May in 2017, which was shortly before the fertilizer treatments were applied. Considering the low rainfall of that year, *S. pestifer* was likely able to utilize the liquid fertilizer that remained near the soil surface, and as a result, a significant portion of the applied nutrients intended for the trees was taken-up by *S. pestifer* in the first year, particularly in the NPK treatment where N appears to be the strongest driver of growth in this species (Beckie and Francis 2010). A targeted fertilization with P and K successfully limited the competition of this species, which highlights the possibility of targeting individual nutrients during broadcast applications and limiting N application that would otherwise support the establishment of ruderal species adapted to environments requiring strong competition for essential resources (Grime 1977).

The intent of targeted fertilization in forest reclamation is to improve nutrient-specific deficiencies in the soil necessary for the establishment and growth of planted species that have relatively low nutrient requirements (particularly for N), while avoiding excess nutrients being available for undesirable species and (or) leaching from the root zone to other parts of the landscape. In that case, targeted application of the nutrients could limit the development of competing ruderal vegetation cover that requires high resource availability. Evidence collected in this study suggests that the success of this method goes beyond just the nutrient type and application and is also dependent on such things as the type of species that is targeted, the chemistry of reconstructed materials, the soil conditions at the time of fertilizer application, and the nutrient application method. The targeted fertilization of peat successfully increased the growth rates of aspen similar to those observed in the more productive mineral coversoils during the initial ASCS 5 yr study; however, this response was not observed in pine and spruce most likely due to their own set of unique nutrient requirements. Limitations associated with the type of soil materials on site and their condition prior to fertilization may further limit nutrient availability, even when these nutrients are present in the soil. The soluble calcium and elevated pH of the peat in this study created chemical limitations that likely reduced the availability of the applied fertilizers. Higher application rates in combination with greater water availability could have possibly overcome these soil limitations. Although targeted fertilization has the potential to improve the efficacy and cost savings of nutrient applications on reclaimed sites as compared with conventional fertilization methods, this study highlights the potential limitations with this approach, and showcases that the success of targeted fertilization is dependent on external factors, some of which can be controlled while others cannot.

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Appendix

Fig. A1. Daily average volumetric water content (VWC) measured 15 cm below the soil surface (i.e., within the peat coversoil layer) for the 2017 and 2018 growing seasons (1 May to 31 Aug.) in the peat/subsoil C and peat/BC soil covers. Bars shown in the background represent total daily rainfall. Red arrow in the 2017 graph shows point when fertilizer was applied, and arrows in the 2018 graph indicate important precipitation events that maintained water content levels above the wilting point of plants (25%; Ojekanmi and Chang 2014) in the Peatmateria. [Colour online.]

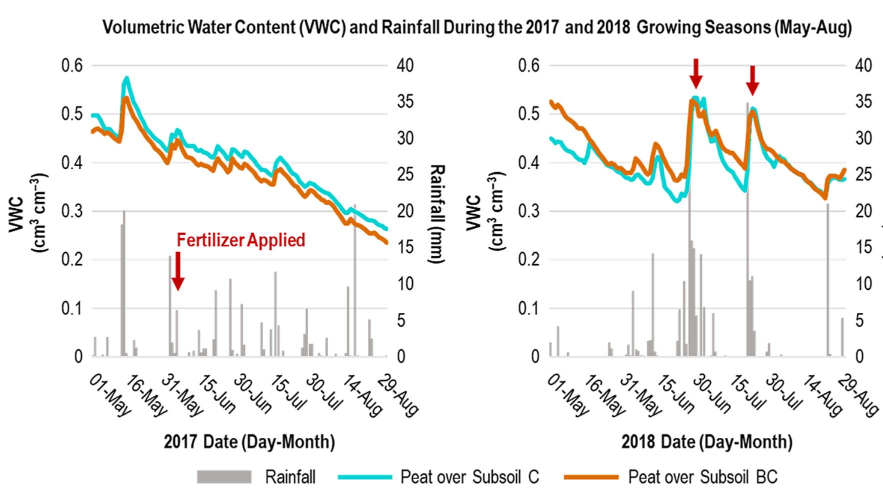

Table A1. Average height and root collar diameter (RCD) (±SE) of trembling aspen, jack pine, and white spruce grown in peat over subsoil C and peat over subsoil BC from 2016 to 2018 ($n = 6$).

			Peat/subsoil C					Peat/subsoil BC				
Species	Growth parameter	Year	Control	NPK	PK	P	K	Control	NPK	PK	P	K
Trembling aspen	Height (cm)	2016	94.8 (5.6)	88.1 (9.8)	97.1 (11.7)	98.2 (12.2)	90.1 (8.9)	90.1 (10.7)	105.1 (6.5)	92.3 (9.3)	94.0 (9.1)	109.2 (5.4)
		2017	114.2 (7.5)	106.8 (10.8)	117.7 (11.8)	124.7 (13.7)	113.9 (12.2)	106.0 (10.6)	119.4 (5.0)	109.4 (10.7)	108.2 (13.7)	125.0 (4.4)
		2018	125.7 (11.8)	125.3 (14.1)	137.7 (13.8)	151.8 (18.8)	123.8 (12.1)	113.0 (11.7)	133.8 (6.9)	122.4 (11.9)	119.9 (15.8)	136.1 (6.8)
	RCD (mm)	2016	14.5 (1.3)	13.4 (1.3)	16.0 (1.7)	14.9 (1.2)	13.7 (0.9)	14.1 (1.1)	14.5 (0.7)	13.5 (0.9)	13.6 (1.3)	15.6 (0.6)
		2017	16.8 (1.4)	16.3 (1.4)	17.8 (1.8)	17.9 (1.5)	17.2 (1.3)	16.4 (1.4)	17.8 (0.5)	16.5 (1.2)	16.7 (1.8)	18.3 (0.7)
		2018	19.1 (1.7)	20.1 (1.7)	20.8 (1.9)	21.7 (1.5)	20.8 (1.7)	18.6 (1.8)	20.7 (0.9)	19.5 (1.4)	19.5 (1.9)	20.9 (0.8)
Jack pine	Height (cm)	2016	116.7 (12.0)	113.4 (9.8)	117.6 (7.7)	113.3 (10.1)	114.3 (8.4)	83.3 (13.1)	84.9 (15.0)	90.3 (10.8)	91.6 (9.4)	84.3 (11.9)
		2017	159.9 (15.3)	166.8 (11.9)	164.0 (9.3)	158.7 (14.8)	161.9 (9.6)	118.1 (19.5)	111.1 (16.8)	124.0 (11.9)	127.8 (8.7)	114.8 (11.0)
		2018	196.7 (15.3)	208.1 (11.5)	201.5 (11.7)	196.5 (16.9)	202.0 (10.3)	151.0 (21.8)	146.3 (18.3)	163.8 (13.3)	169.9 (9.1)	149.0 (13.5)
	RCD (mm)	2016	29.0 (2.3)	29.9 (1.3)	29.9 (1.1)	27.6 (2.5)	28.4 (2.0)	22.9 (2.7)	21.8 (3.1)	24.4 (2.1)	24.3 (1.5)	22.6 (1.9)
		2017	33.8 (2.5)	36.4 (1.7)	34.8 (1.5)	34.4 (2.2)	34.8 (1.9)	27.6 (3.2)	26.5 (3.5)	29.3 (2.0)	29.7 (1.5)	27.0 (1.4)
		2018	40.1 (2.4)	43.7 (1.5)	42.0 (1.6)	39.6 (3.0)	40.5 (2.3)	34.3 (3.5)	34.0 (3.8)	37.7 (2.2)	37.8 (1.4)	34.8 (1.6)
White spruce	Height (cm)	2016	71.1 (5.2)	71.2 (3.9)	70.0 (4.7)	70.8 (5.2)	74.2 (7.0)	70.8 (4.4)	71.9 (5.0)	70.0 (3.8)	79.2 (3.5)	74.2 (4.1)
		2017	85.7 (6.1)	87.4 (4.4)	84.3 (6.4)	83.1 (5.6)	90.4 (7.6)	85.4 (3.4)	85.6 (7.2)	84.8 (4.3)	99.0 (4.1)	91.5 (4.8)
		2018	93.9 (6.8)	98.1 (5.3)	92.7 (7.6)	91.2 (5.9)	99.9 (8.4)	94.4 (3.6)	101.8 (7.5)	95.9 (4.3)	112.0 (3.6)	104.3 (5.5)
	RCD (mm)	2016	21.6 (0.7)	22.5 (0.8)	21.4 (1.2)	21.6 (1.3)	22.6 (1.0)	21.7 (1.0)	22.6 (1.6)	21.5 (0.9)	23.0 (0.9)	22.1 (1.0)
		2017	24.2 (0.6)	24.9 (0.8)	24.4 (1.4)	24.3 (1.5)	26.0 (0.9)	25.9 (1.0)	26.3 (1.7)	25.1 (1.5)	27.4 (1.2)	26.9 (1.1)
		2018	27.3 (0.7)	29.3 (1.3)	27.6 (1.6)	27.4 (1.6)	29.0 (1.4)	30.4 (1.0)	31.4 (1.8)	29.6 (1.8)	32.8 (1.7)	31.2 (1.6)

Note: Five fertilizer treatments (i.e., control, NPK, PK, P, and K) were applied after the 2016 measurement.

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Table A2. Foliar nutrient concentrations (±SE) of trembling aspen, jack pine, and white spruce grown in five fertilizer treatments in the peat over subsoil C and peat over subsoil BC soil covers during the 2017 and 2018 growing seasons ($n = 6$).

Soil cover	Tree species	Foliar nutrient (%)	2017					2018				
			Control	NPK	PK	P	K	Control	NPK	PK	P	K
Peat over subsoil C	Trembling aspen	N	2.41(0.10)	2.52 (0.12)	2.41 (0.08)	2.33 (0.07)	2.67 (0.10)	2.05 (0.04)	2.05 (0.08)	2.06 (0.09)	1.98 (0.06)	2.18 (0.07)
		P	0.30 (0.03)	0.31 (0.03)	0.28 (0.02)	0.28 (0.03)	0.31 (0.02)	0.07 (0.00)	0.08 (0.00)	0.08 (0.00)	0.09 (0.01)	0.07 (0.00)
		K	1.12 (0.05)	1.11 (0.03)	1.12 (0.06)	1.17 (0.06)	1.27 (0.05)	0.84 (0.03)	0.85 (0.03)	0.87 (0.02)	0.90 (0.02)	0.83 (0.02)
		S	0.06 (0.00)	0.07 (0.00)	0.07 (0.00)	0.06 (0.00)	0.06 (0.00)	0.26 (0.01)	0.25 (0.01)	0.25 (0.01)	0.25 (0.00)	0.27 (0.01)
		Ca	1.30 (0.07)	1.38 (0.08)	1.33 (0.12)	1.32 (0.05)	1.31 (0.10)	0.98 (0.05)	1.09 (0.06)	1.07 (0.04)	1.06 (0.03)	1.06 (0.05)
		Mg	0.21 (0.01)	0.19 (0.01)	0.17 (0.01)	0.21 (0.02)	0.16 (0.01)	0.18 (0.00)	0.17 (0.01)	0.17 (0.01)	0.18 (0.01)	0.18 (0.01)
	Jack pine	N	1.35 (0.11)	1.29 (0.09)	1.18 (0.13)	1.31 (0.09)	1.32 (0.11)	1.03 (0.14)	0.97 (0.10)	1.03 (0.13)	1.06 (0.13)	1.06 (0.14)
		P	0.10 (0.00)	0.12 (0.01)	0.11 (0.00)	0.11 (0.00)	0.12 (0.01)	0.09 (0.00)	0.11 (0.01)	0.10 (0.01)	0.11 (0.01)	0.09 (0.01)
		K	0.51 (0.01)	0.54 (0.03)	0.56 (0.03)	0.52 (0.03)	0.60 (0.05)	0.61 (0.05)	0.60 (0.03)	0.58 (0.05)	0.59 (0.03)	0.64 (0.04)
		S	0.07 (0.00)	0.08 (0.00)	0.07 (0.01)	0.07 (0.00)	0.08 (0.01)	0.11 (0.01)	0.11 (0.01)	0.11 (0.01)	0.11 (0.01)	0.12 (0.01)
		Ca	0.21 (0.01)	0.20 (0.01)	0.19 (0.01)	0.20 (0.01)	0.19 (0.01)	0.30 (0.06)	0.31 (0.07)	0.31 (0.06)	0.29 (0.07)	0.27 (0.04)
		Mg	0.10 (0.00)	0.11 (0.00)	0.10 (0.00)	0.10 (0.00)	0.10 (0.00)	0.10 (0.00)	0.10 (0.00)	0.10 (0.01)	0.09 (0.01)	0.10 (0.01)
	White spruce	N	0.92 (0.01)	1.17 (0.11)	0.84 (0.09)	0.93 (0.09)	0.96 (0.06)	0.81 (0.11)	0.77 (0.10)	0.75 (0.08)	0.80 (0.10)	0.75 (0.08)
		P	0.08 (0.00)	0.09 (0.00)	0.08 (0.01)	0.08 (0.00)	0.09 (0.00)	0.08 (0.01)	0.09 (0.01)	0.09 (0.01)	0.08 (0.01)	0.08 (0.01)
		K	0.41 (0.02)	0.42 (0.02)	0.40 (0.03)	0.39 (0.03)	0.41 (0.02)	0.63 (0.06)	0.60 (0.06)	0.63 (0.07)	0.60 (0.07)	0.63 (0.08)
		S	0.05 (0.00)	0.06 (0.00)	0.06 (0.00)	0.06 (0.00)	0.06 (0.00)	0.09 (0.01)	0.09 (0.01)	0.09 (0.01)	0.09 (0.01)	0.09 (0.01)
		Ca	0.58 (0.04)	0.61 (0.04)	0.51 (0.02)	0.54 (0.04)	0.63 (0.03)	0.36 (0.05)	0.41 (0.03)	0.37 (0.02)	0.41 (0.03)	0.40 (0.03)
		Mg	0.08 (0.00)	0.09 (0.00)	0.08 (0.00)	0.07 (0.00)	0.08 (0.00)	0.09 (0.00)	0.09 (0.01)	0.09 (0.01)	0.09 (0.01)	0.09 (0.01)
Peat over subsoil BC	Trembling aspen	N	2.19 (0.19)	2.52 (0.09)	2.18 (0.14)	2.45 (0.09)	2.32 (0.06)	2.16(0.11)	1.97(0.08)	1.96(0.08)	1.95(0.08)	2.18(0.04)
		P	0.36 (0.01)	0.35 (0.03)	0.34 (0.02)	0.36 (0.02)	0.34 (0.04)	0.06 (0.00)	0.07 (0.00)	0.07 (0.00)	0.07 (0.00)	0.06 (0.00)
		K	0.96 (0.09)	0.98 (0.06)	1.16 (0.05)	1.07 (0.09)	1.11 (0.05)	0.75 (0.01)	0.87 (0.05)	0.90 (0.04)	0.83 (0.04)	0.78(0.02)
		S	0.06 (0.00)	0.07 (0.01)	0.06 (0.00)	0.06 (0.01)	0.06 (0.00)	0.28 (0.01)	0.28 (0.02)	0.28 (0.01)	0.28 (0.02)	0.28 (0.03)
		Ca	1.30 (0.08)	1.35 (0.11)	1.30 (0.11)	1.36 (0.13)	1.23 (0.08)	0.94 (0.04)	1.05 (0.05)	1.11 (0.08)	1.06 (0.05)	0.95 (0.06)
		Mg	0.23 (0.02)	0.22 (0.02)	0.20 (0.01)	0.23 (0.01)	0.22 (0.01)	0.20 (0.01)	0.20 (0.01)	0.19 (0.01)	0.20 (0.01)	0.20 (0.00)
	Jack pine	N	1.41 (0.20)	1.53 (0.15)	1.36 (0.19)	1.51 (0.13)	1.35 (0.19)	1.30 (0.03)	1.31 (0.05)	1.22 (0.03)	1.21 (0.05)	1.33 (0.03)
		P	0.12 (0.01)	0.12 (0.01)	0.12 (0.00)	0.12 (0.01)	0.12 (0.01)	0.08 (0.01)	0.11 (0.01)	0.10 (0.01)	0.11 (0.01)	0.09(0.01)
		K	0.42 (0.04)	0.46 (0.06)	0.49 (0.03)	0.46 (0.04)	0.47 (0.04)	0.52 (0.03)	0.57 (0.02)	0.62 (0.02)	0.54 (0.02)	0.64 (0.04)
		S	0.06 (0.00)	0.06 (0.00)	0.06 (0.00)	0.06 (0.00)	0.06 (0.00)	0.14 (0.00)	0.15 (0.01)	0.14 (0.00)	0.14 (0.01)	0.15 (0.01)
		Ca	0.32 (0.06)	0.33 (0.05)	0.31 (0.03)	0.31 (0.05)	0.32 (0.03)	0.26 (0.02)	0.25 (0.02)	0.23 (0.01)	0.23 (0.01)	0.24 (0.02)
		Mg	0.11 (0.00)	0.11 (0.01)	0.11 (0.00)	0.11 (0.00)	0.11 (0.01)	0.10 (0.00)	0.10 (0.00)	0.09 (0.00)	0.10 (0.00)	0.10 (0.00)
	White spruce	N	1.15 (0.09)	1.18 (0.17)	1.10 (0.20)	1.06 (0.19)	1.09 (0.16)	0.74 (0.02)	0.79 (0.01)	0.73 (0.02)	0.77 (0.02)	0.79 (0.02)
		P	0.09 (0.01)	0.08 (0.00)	0.08 (0.00)	0.08 (0.00)	0.09 (0.01)	0.07 (0.00)	0.08 (0.00)	0.07 (0.01)	0.08 (0.00)	0.06 (0.00)
		K	0.33 (0.03)	0.29 (0.01)	0.31 (0.03)	0.26 (0.02)	0.34 (0.03)	0.63 (0.02)	0.62 (0.03)	0.65 (0.02)	0.61 (0.04)	0.68 (0.03)
		S	0.05 (0.00)	0.06 (0.00)	0.05 (0.00)	0.05 (0.00)	0.05 (0.00)	0.07 (0.00)	0.07 (0.00)	0.06 (0.01)	0.07 (0.00)	0.07 (0.00)
		Ca	0.62 (0.05)	0.68 (0.03)	0.61 (0.03)	0.58 (0.05)	0.62 (0.04)	0.41 (0.02)	0.45 (0.03)	0.44 (0.02)	0.47 (0.05)	0.45 (0.04)
		Mg	0.08 (0.00)	0.08 (0.00)	0.08 (0.01)	0.07 (0.00)	0.08 (0.01)	0.07 (0.00)	0.07 (0.00)	0.07 (0.00)	0.07 (0.00)	0.07 (0.00)

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Table A3. Plant-available nutrients in undisturbed Brunisolic soils sampled from three natural sites near the ASCS in 2011 ($n = 3$).

Soil horizon	Average thickness (cm)	Kelowna method (mg kg^{-1})			KCl extract (mg kg^{-1})	Saturated paste (mg kg^{-1})			
		NO_3	P	K	NH_4	K	SO_4	Ca	Mg
LFH	3	<10	40	387	10	—	—	—	—
Bm	24	<2	32	<20	<0.3	<1	0.8	1.4	0.2
BC	39	—	—	—	—	<1	0.5	0.2	0.1
C	17	—	—	—	—	<1	0.6	0.4	0.1

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