NRC Research Press

ARTICLE

Reclaimed soils, fertilizer, and bioavailable nutrients: Determining similarity with natural benchmarks over time

D.M. Howell, S. Das Gupta, B.D. Pinno, and M.D. MacKenzie

Abstract: Comparing functional similarity in reconstructed ecosystems with natural benchmarks can provide ecologically meaningful information to measure reclamation success. We examined nutrient supply rate using ion-exchange resins as a measure of ecosystem function in two oil sands reclaimed soils, viz. peat mineral mix (PMM) and forest floor mineral mix (FFMM), and measured fertilization effect on nutrient supply rates in these soils for three consecutive years contrasted with young-fire-disturbed and mature forest stands. Results indicated that nutrient profiles of reclaimed soils were significantly different than natural benchmarks. Phosphorus and potassium supply rates in reclaimed soils were up to 91% lower, whereas S, Ca, and Mg were, respectively, up to 95%, 62%, and 74% higher than in benchmark soils. The expected nutrient flush postfertilization was only apparent in N and P, but the transient effect levelled off the year after fertilization in most cases. Fertilization aligned the temporal trajectory of the nutrient profile in PMM similar to benchmark conditions indicating greater ecological benefit of fertilization than in FFMM. The findings from this study suggest that fertilization focusing on P and K is likely more ecologically appropriate for establishing natural ecosystem function on reclaimed soils in this region of the boreal forest.

Key words: nutrient supply rates, fertilizer, oil sands reclamation, fire, functional similarity.

Résumé : Comparer les similitudes fonctionnelles entre les écosystèmes reconstitués et les écosystèmes naturels peut déboucher sur des informations d'ordre écologique utiles au succès des mesures de restauration. Les auteurs ont examiné l'apport d'oligoéléments en se servant de résines échangeuses d'ions pour reproduire le fonctionnement de l'écosystème sur deux sols issus de la restauration des sables bitumineux et le comparer à l'apport d'un mélange de tourbe et de minéraux (PMM) et à celui d'un mélange de litière forestière et de minéraux (FFMM). Ils ont mesuré l'effet de la fertilisation sur l'apport d'oligoéléments dans ces sols pendant trois années consécutives et l'ont comparé à celui observé sur des sols au peuplement forestier mature ou récemment ravagé par le feu. Les résultats indiquent que le profil minéral des sols restaurés diffère sensiblement de celui des sols naturels utilisés aux fins de comparaison. Ainsi, la quantité disponible de phosphore et de potassium était jusqu'à 91 % plus faible dans les sols restaurés, alors que celle de S, de Ca et de Mg était respectivement de 95 %, 62 % et 74 % plus élevée que dans les sols servant de point de comparaison. L'afflux prévu d'oligoéléments suivant la fertilisation n'a été manifeste que pour le N et le P, mais, dans la plupart des cas, cet effet n'a été que passager et s'est stabilisé à la baisse l'année suivant l'amendement. La fertilisation rapproche la trajectoire temporelle du profil minéral du PMM de celle des sols comparatifs, signe qu'elle a une plus grande incidence sur l'écologie de ce type de sol que sur celle du FFMM. Les constatations de cette étude donnent à penser qu'une fertilisation insistant davantage sur le P et le K permettrait de mieux rétablir l'écologie d'un écosystème naturel sur les sols restaurés dans cette partie de la forêt boréale. [Traduit par la Rédaction]

Mots-clés : apport d'oligoéléments, engrais, restauration des sables bitumineux, feu, similitude fonctionnell.

Received 24 June 2016. Accepted 4 October 2016.

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Abbreviations: PMM, peat mineral mix; **FFMM**, forest floor mineral mix; **TC**, total carbon; **TN**, total nitrogen; **VWC**, volumetric water content; **MRPP**, multiple response permutation procedures; **NMS**, non-metric multidimensional scaling; **PRS**, plant root simulator; **TIN**, total inorganic nitrogen; **AOSR**, Athabasca oil sands region.

Can. J. Soil Sci. **00:** 1–10 (0000) dx.doi.org/10.1139/cjss-2016-0069

Introduction

The current area disturbed by open-pit oil sands mining in the northern Alberta is approximately 895 km^2 (CAPP 2015). The disturbance includes clearing of vegetation and removal of topsoils, overburden, and geological materials to a maximum depth of 100 m to reach ore bodies (Johnson and Miyanishi 2008). Reclaiming the disturbed landscape is a legal mandate for the oil sands industry. The main objective is to create locally common, self-sustaining boreal forest with similar trajectories of vegetation development as in native ecosystems (Alberta Environment 2010). Current practice evaluates the success of reclaimed sites with measures of soil fertility and tree productivity (Cumulative Environmental Management Association 2006; Audet et al. 2014). However, the agronomic idea of "fertility" in soil might not fully apply to forested ecosystems where diverse species interact and compete for resources, and productivity is not the only end goal. This holistic approach to soil characterization has been described as soil quality, in contrast to soil fertility, in other forestland reclamation applications (Bendfeldt et al. 2001; Pietrzykowski 2014). In this regard, evaluation of land reclamation success should incorporate ecosystem functional traits and compare these to natural benchmarks (Chapin et al. 1996). Because soil is a key component in reconstructed ecosystems, an ecologically appropriate belowground functional trait could make this comparison traceable from the early site development phase. Nutrient availability is an obvious ecological requirement that can be used to track ecosystem recovery following disturbances (Bradshaw 1997; Bradshaw 2000; Bardgett et al. 2005). Profiles of bioavailable nutrients have been shown to produce an ecologically meaningful index in different natural (Huang and Schoenau 1996) and disturbed ecosystems (MacKenzie and Quideau 2012), which can be easily related to target ecosystem attributes (e.g., plant growth and soil microbial functions).

Fertilization immediately after soil placement is a common practice for oil sands reclamation in Alberta, which may be an option to "jumpstart" ecosystem function and create a bioavailable nutrient regime similar to the "assart" effect of fire (Kimmins 2004). In natural boreal forest stands, wildfires have demonstrated increased nutrient availability, especially inorganic N, which likely contributes to aggressive vegetative re-establishment following these disturbances (Driscoll et al. 1999). Nutrient availability generally recovers to the predisturbance levels within 1–10 yr after fire (Certini 2005). While application of inorganic fertilizer is commonly practiced in the young reclaimed sites, the fertilization scheme may not match to the inherent nutrient supply requirements in reclaimed soils, which can result in vigorous weed competition (Sloan and Jacobs 2013). Previous studies in the oil sands regions indicate that reclaimed soils have lower P and K supply rates and higher N and S supply rates than natural benchmarks, although most of these studies focused on only peat mineral mix (PMM; MacKenzie and Quideau 2012; Pinno et al. 2012; Quideau et al. 2013; Howell 2015). Some key questions remaining unanswered is whether or not fertilization can make nutrient supply rates in reclaimed soils more similar to natural benchmarks and if there is any long-lasting effect of fertilization on the reclamation trajectory.

The many studies examining temporal dynamics of nutrient supply profiles in reclaimed soils present variety of conclusions. For example, Rowland et al. (2009) found that fertilization renders available K and P concentrations in reclaimed soils closer to natural benchmarks within a timeframe of 25 yr than no fertilization. Inorganic N availability in reclaimed soils (both fertilized and unfertilized) in their study was higher than the natural range. However, Pinno and Hawkes (2015) found available inorganic N in peat-based reclaimed soils became similar to mature stands within 24 yr of reclamation, but P and K availability were consistently different from natural benchmarks. Although these studies presented data on nutrient supply rates in reclaimed soils, none compared these with the young naturally disturbed benchmarks. Moreover, general similarities or differences in nutrient supply rate between the two reclaimed soils, as reported in these studies, may not be appropriate, as the variability within these soils can be as large as between them due to the differences in their donor sites and extraction techniques. For example, PMM varies greatly depending on the amount and type of mineral soil or organic matter included in the mixture significantly influencing nutrient availability and associated biogeochemical processes (Rowland et al. 2009; Mackenzie and Naeth 2010).

This study aimed to (1) assess soil nutrient supply rates in reclaimed and natural benchmark soils, (2) test whether a fertilization treatment in reclaimed soils achieves nutrient supply rates similar to benchmarks in the short term, (3) characterize the early successional trend of nutrient supply profiles in reclaimed soils compared with natural benchmarks, and (4) determine if these data can be used as an estimate of ecosystem functional similarity. The operational goal of this research was to make recommendations on appropriate fertilization schemes for different reclaimed soil types based on their inherent ability to supply nutrients compared with natural benchmarks.

Materials and Methods

Study area and experimental design

The study area was located at an oil sands mine, 70 km north of Fort McMurray, AB, Canada (57°21′7″N, 111°49′49″W). Prior to site disturbance, upland mineral soil in this area was predominantly fine-textured Orthic Gray Luvisols (Golder Associates 2002) with trembling aspen (*Populus tremuloides*) and white spruce (*Picea glauca*) as dominant tree species, mostly classified as "d" ecosites (Beckingham and Archibald 1996). The target ecosite class for oil sands reclaimed sites using fine-textured capping soils is also "d". The current reclamation study site was constructed in 2011 on top of an 88.6 ha overburden dump consisting of saline/sodic materials and was capped with approximately 1.6 m of subsoil and 0.4 m of either forest floor mineral mix (FFMM), a mixture of upland forest floor organic materials and underlying mineral soil, or PMM, a lowland organic peat and mineral soil mixture (Canadian Natural Resources Ltd 2013). Benchmark natural sites included recently burnt stands (2011 Richardson burn; 57°23′56.14″N, 111°41′8.29″W) as young postdisturbed ecosystem and mature (62 yr old) mixedwood stands (near 57°20′51.69″N, 111°43′28.89″W) as the final target ecosystem along the trajectory. The stands were classified as "d" ecosites with mesic soil moisture and medium nutrient regimes, with Orthic Gray Luvisols as the predominant soil order (Beckingham and Archibald 1996). All the sites were within 10 km radius of each other and experienced similar weather conditions with annual precipitation (measured at Fort McMurray) of 458, 390, and 407 mm in 2012, 2013, and 2014, respectively.

The study was conducted in a 2 × 2 factorial design of soil type (FFMM and PMM) and fertilization (FFMF and PMMF). Fertilizer amendments of 100 kg N ha^{-1} of immediately available fertilizer (pellets; 29.9-9.1-9.1-9.1, N-P-K-S) were aerially broadcasted in June 2011 and 2012 on the FFMF and PMMF treatments. Immediately pursuant to fertilization in 2011, a barley (*Hordeum* sp.) nurse crop was seeded via fixed-wing aircraft at 60 kg ha^{-1}, and white spruce seedlings were planted at a density of 2000 stems ha^{-1}. Trembling aspen seedlings naturally recruited on the site mostly from wind-blown seeds (Pinno and Errington 2015).

Six circular plots ($n = 6$) of 10 m radius were established on each of the six treatments (two unfertilized soils, two fertilized soils, and two natural benchmarks). The reclamation plots were established across the entire area (approximately 20 ha each) of each treatment type whereas the natural plots were all located in different forest stands. Four smaller quadrats (1 m^2) were set up within each circular plot in each cardinal direction 10 m apart from the plot centre. In total, 36 plots and 144 quadrats were established and sampled across all the treatments in both 2013 and 2014. In 2012, the total number of plots sampled was 18 as part of a pilot study, which was then expanded in 2013 and 2014.

Soil characterization

Reported soil and site characteristics (Table 1) were derived from samples taken in August 2014. Mineral soil samples ($n = 4$) were collected at each plot from 0 to 15 cm depth using 88.7 cm^3 soil cores. Total carbon (TC) and total nitrogen (TN) were quantified using the Dumas method with a LECO C/N Analyzer (LECO Corporation, St. Joseph, MI, USA). Soil pH (0.01 mol L^{-1} $CaCl_2$) was measured from saturated pastes (Kalra and Maynard 1991). Soil volumetric water content (VWC) was measured at each plot during installation and retrieval of Plant Root Simulator (PRS) probes using a Field Scout TDR 300 equipped with 12 cm probes (Spectrum Technologies Inc., Aurora, IL, USA). Plant biomass was derived from dried aboveground vegetation in 50 cm × 50 cm quadrats ($n = 6$) of forest understory.

Supply rates of bioavailable nutrients were measured with ion-exchange resins (PRS™ Probes, Western Ag Innovations, Saskatoon, SK, Canada), which integrate soil temperature and moisture over the measurement period (Qian and Schoenau 2002; Johnson et al. 2005), providing a measure of soil nutrient bioavailability that is sensitive to many environmental factors. For all plots, a composite of four probe pair subsamples (cation and anion) was inserted such that the top of the probe was flush with the soil surface (0–10 cm). Resin probes were installed for a range of 39–43 d from June to August 2012, 2013, and 2014. Immediately after collection and cleaning, probes were returned to Western Ag Innovations for analysis. Nutrient concentrations were determined by colourimetry using a FIALab 2600 automated flow injection analysis system (FIAlab Instruments Inc., Bellevue, WA, USA) for NO_3^- and NH_4^+ [total inorganic N (TIN)] and an Optima 8300 inductively-coupled plasma optical emission spectrometry system (Perkin Elmer Inc., Woodbridge, ON, Canada) for P, K, S, Ca, Mg, Mn, Al, Fe, Cu, Zn, B, Cd, and Pb.

Statistical analyses

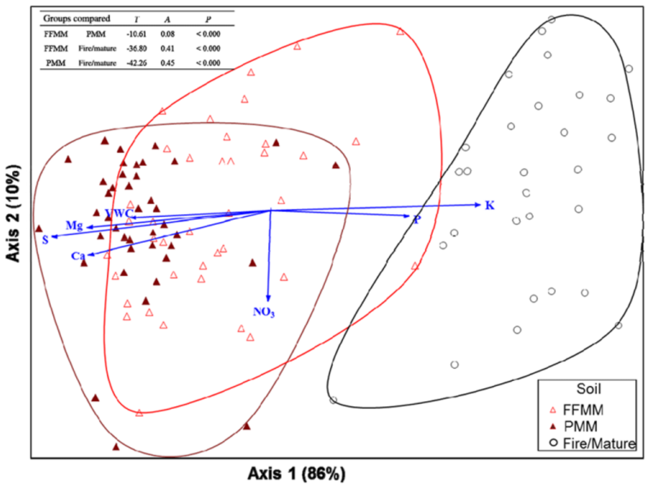
Nonmetric multidimensional scaling (NMS) was used to generate the profile of bioavailable nutrients using the Bray–Curtis dissimilarity matrix in ordination space with PC-ORD v. 6.0 (MjM Software Design, Gleneden Beach, OR, USA). Following $\log_{10}$ transformation, ordinations were run on the "slow-and-thorough" setting, completing 500 iterations per analysis. Associative joint plot vectors were cut off at $r^2 \leq 0.30$. Multiple response permutation procedures (MRPP) was selected as a nonparametric test to assess statistical differences within and between a priori groupings. Statistics reported from MRPP analysis includes probability value P, T value indicating separation among the groups (more negative values indicating greater separation), the A value representing the within-group homogeneity compared with random expectations (larger A indicates greater homogeneity), and the δ value representing the within-group variability (McCune et al. 2002). Non-metric multidimensional scaling ordination scores explaining >60% variability in nutrient supply rate was used as an index of overall nutrient supply rate in each soil type. Overall treatment effect on the supply rate of bioavailable nutrients was analyzed using

Table 1. Basic site and soil characteristics of oil sands reclaimed and natural benchmark plots, including total carbon (TC), total nitrogen (TN), pH, bulk density (D_b) at 5–10 cm, volumetric water content (VWC) at 12 cm and understory plant biomass; reporting means with standard error in brackets ($n = 6$).

					VWC (%)			Understory plant biomass (g m^{-2})		
	TC (%)	TN (%)	pH	D_b (g cm^{-3})	2012	2013	2014	2012[a]	2013	2014
FFMM	2.61 (0.29)	0.12 (0.01)	7.59 (0.12)	1.18 (0.03)	11.31 (2.31)	29.02 (1.98)	18.76 (1.57)	—	241.39 (95.58)	472.35 (99.51)
PMM	8.07 (1.98)	0.25 (0.07)	6.01 (0.52)	0.94 (0.20)	21.78 (0.59)	52.27 (3.31)	33.56 (3.31)	—	55.77 (13.66)	78.43 (25.05)
Fire	1.07 (0.14)	0.07 (0.00)	5.40 (0.08)	1.13 (0.07)	6.21 (0.92)	16.29 (2.36)	10.80 (1.05)	—	196.25 (30.20)	244.74 (41.08)
Mature	1.32 (0.47)	0.09 (0.03)	5.40 (0.24)	0.90 (0.19)	5.80 (0.15)	9.53 (0.50)	5.71 (0.82)	—	148.87 (66.39)	158.74 (33.89)

[a] Understory plant biomass was not measured in 2012.

Fig. 1. Nonmetric multidimensional scaling ordination bi-plot of nutrient supply rates in oil sands reclaimed soils compared with natural benchmark soils (final stress = 10.18; cutoff r^2 = 0.30). Inset table shows group differences from MRPP analysis.



analysis of variance (ANOVA) and mixed-effect linear models, whereas year-to-year comparisons were assessed using repeated measures ANOVA in SAS v. 9.3 software (SAS Institute Inc., Cary, NC, USA). Due to the high variability in our data and to increase the power of analysis, alpha level of 0.1 was considered statistically significant for all the tests (Smith 1995).

Results

Effect of soil type

Contrasting differences were found among soil types in terms of physical and chemical properties (Table 1). Soil nutrient supply rates also significantly differed among FFMM, PMM, and benchmark soils (Fig. 1). Non-metric multidimensional scaling ordination generated a two-dimensional solution, and two axes explained 96% of the data variance. Ordination results and output from MRPP analysis indicate that reclaimed soil nutrient supply rates were closer to each other ($T = -10.38$; $A = 0.04$; $P < 0.0001$) than they were to benchmarks (FFMM; $T = -36.58$; $A = 0.30$; $P < 0.0001$ and PMM; -43.24; $A = 0.39$; $P < 0.0001$), although out of the reclaimed treatments, FFMM had less separation from benchmarks (Fig. 1). Ordination vectors showed that benchmark soils had strong positive correlation with P ($r^2 = 0.51$) and K ($r^2 = 0.85$) supply rates, whereas reclaimed soils were correlated with VWC ($r^2 = 0.58$), Ca ($r^2 = 0.80$), Mg ($r^2 = 0.77$), and S ($r^2 = 0.93$) supply rates (Fig. 1). Overall nutrient supply rate in FFMM showed significant positive relationship with VWC, whereas it was mostly nonsignificant in PMM.

Fertilization effect

Fertilization increased similarity in nutrient supply profiles between reclaimed and benchmark soils only

Table 2. Multiple response permutation procedure (MRPP) results comparing Bray–Curtis dissimilarity of fertilized and unfertilized oil sands reclaimed soils to natural benchmark soils in 2012, 2013, and 2014.

		2012			2013			2014		
Groups compared		*T*	*A*	*P*	*T*	*A*	*P*	*T*	*A*	*P*
FFMM	PMM	−2.2	0.20	0.029	−3.2	0.08	0.006	−6.4	0.27	0.001
FFMM	Fire	−3.0	0.60	0.022	−7.0	0.40	0.001	−6.3	0.44	0.001
PMM	Fire	−3.0	0.60	0.022	−7.3	0.42	<0.001	−6.5	0.56	0.001
Fire	Mature	−1.1	0.08	0.143	−0.2	0.01	0.364	0.0	0.00	0.481
FFMM	FFMF	−0.2	0.01	0.301	−1.6	0.03	0.074	−0.8	0.02	0.190
PMM	PMMF	−2.9	0.37	0.022	−2.5	0.04	0.020	−1.7	0.03	0.057
FFMF	Fire	−2.9	0.47	0.022	−8.0	0.33	<0.001	−7.4	0.33	<0.001
PMMF	Fire	−2.9	0.56	0.022	−9.6	0.41	<0.001	−8.9	0.45	<0.001

Note: *T* indicates separation among groups with more negative values indicating greater separation and *A* indicates within-group homogeneity with larger values indicating greater homogeneity.

Table 3. Multiple response permutation procedure (MRPP) results comparing Bray–Curtis dissimilarity in nutrient supply rate of oil sands reclaimed and natural benchmark soils between 2012–2013 and 2013–2014.

	δ			2012–2013			2013–2014		
	2012	2013	2014	*T*	*A*	*P*	*T*	*A*	*P*
FFMM	0.055	0.075	0.074	−3.3	0.12	0.005	−6.8	0.27	<0.001
FFMF	0.088	0.076	0.091	−3.1	0.08	0.005	−8.8	0.18	<0.001
PMM	0.058	0.077	0.073	−2.0	0.07	0.045	−3.1	0.09	0.010
PMMF	0.079	0.072	0.082	−7.5	0.25	<0.001	−6.2	0.10	<0.001
Fire	0.070	0.103	0.081	−2.2	0.12	0.037	−2.6	0.10	0.023
Mature	0.061	0.088	0.081	−3.7	0.19	0.005	−4.7	0.16	0.001

Note: *T* indicates separation among groups with more negative values indicating greater separation and *A* indicates within-group homogeneity with larger values indicating greater homogeneity. The δ test statistic is included as a measure of average within-group variability.

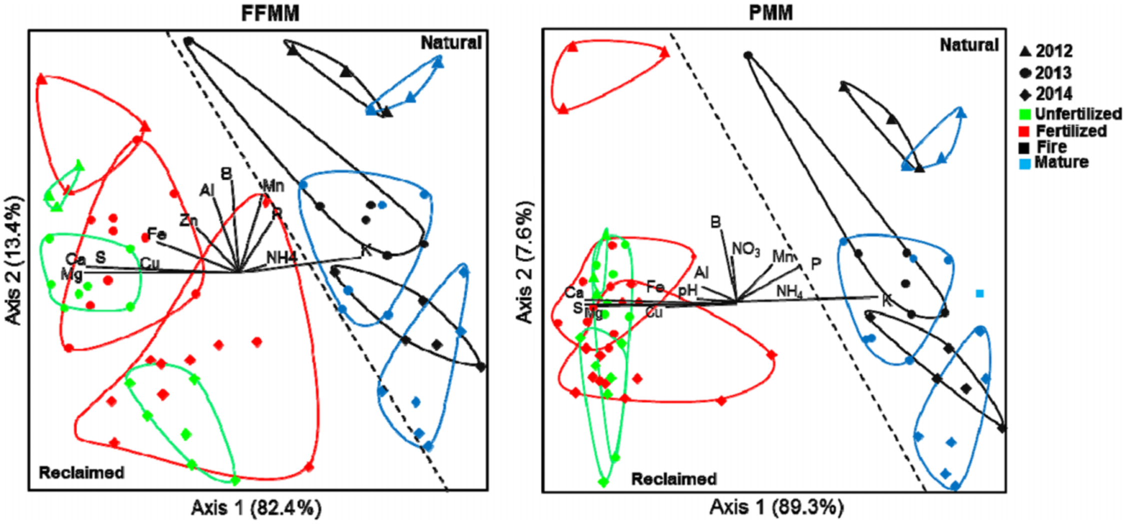
in 2012 (Table 2). Although no significant increase in similarity was detected for subsequent years, the nutrient supply profile of fertilizer-reclaimed soils seems shifted toward natural benchmark in ordination space. However, an increase in variability was detected in fertilized soils as indicated by the higher δ statistic, which was also the case in fire sites (natural fertilization effect; Table 3). Fertilization effect on the variability of nutrient profile was most evident with FFMM in all measured years (Fig. 2).

Fertilization produced variable effects on the supply rates of individual macronutrients except for TIN. Total inorganic nitrogen was increased by 1–2 orders of magnitude for both soil types in 2012 ($P < 0.01$; Fig. 3) and was predominantly due to increased NO_3^- (Fig. 4). This effect was greatest in PMM, demonstrated by a significant separation in ordination space between years (Table 2; Fig. 2). The similar spike in nutrient supply rate immediately after fertilization was also evident for P in PMM and K in FFMM (Fig. 3). Irrespective of fertilization, reclaimed soils had significantly lower P and K ($P < 0.10$) and higher S, Ca, and Mg supply rate than the benchmark soils (Fig. 3). Fertilization effect on overall nutrient supply rate (NMS ordination score) was significant only in PMM.

Temporal pattern

A clear trend was found in the annual variability pattern of nutrient profiles of reclaimed and benchmark soils (Fig. 2; Table 3). The temporal pattern of reclaimed soils followed a similar pattern to benchmark soils. The within-soil variability of nutrient supply rates (δ value) increased in 2013 and then decreased the year after (2014) in both reclaimed and benchmark soils (Table 3). The *T* value (group separation) from MRPP analysis indicates that the variability between 2012 and 2013 is much smaller than the variability between 2013 and 2014, and this pattern was also similar in both reclaimed (except PMMF) and benchmark soils. Forest floor mineral mix followed a similar trajectory to benchmark soils whereas the PMM did not. Fertilization aligned the trajectory of PMM nutrient supply profiles similar to that of benchmark conditions, although convergence toward those conditions did not happen (Table 3). A fertilization effect on the temporal trajectory of the FFMM nutrient supply

Fig. 2. Nonmetric multidimensional scaling ordination bi-plot of nutrient supply rates in oil sands reclaimed soils compared with natural benchmark soils in 2012–2014 (final stress FFMM = 9.01, final stress PMM = 8.40; cutoff r^2 = 0.10).



profile was less evident (Fig. 2), but also did not converge toward benchmark conditions. Interannual variability was found to be significant for overall nutrient supply in all the reclaimed and benchmark sites; however, the time-treatment interaction effect (fertilization × year) was only significant in PMM (data not shown). Soil moisture appeared as a significant factor along with the annual variability for the supply rate of the key macronutrients except for TIN in reclaimed sites. Total inorganic N supply rate in benchmark fire sites, however, showed a significant association with soil moisture and interannual variability ($P < 0.001$).

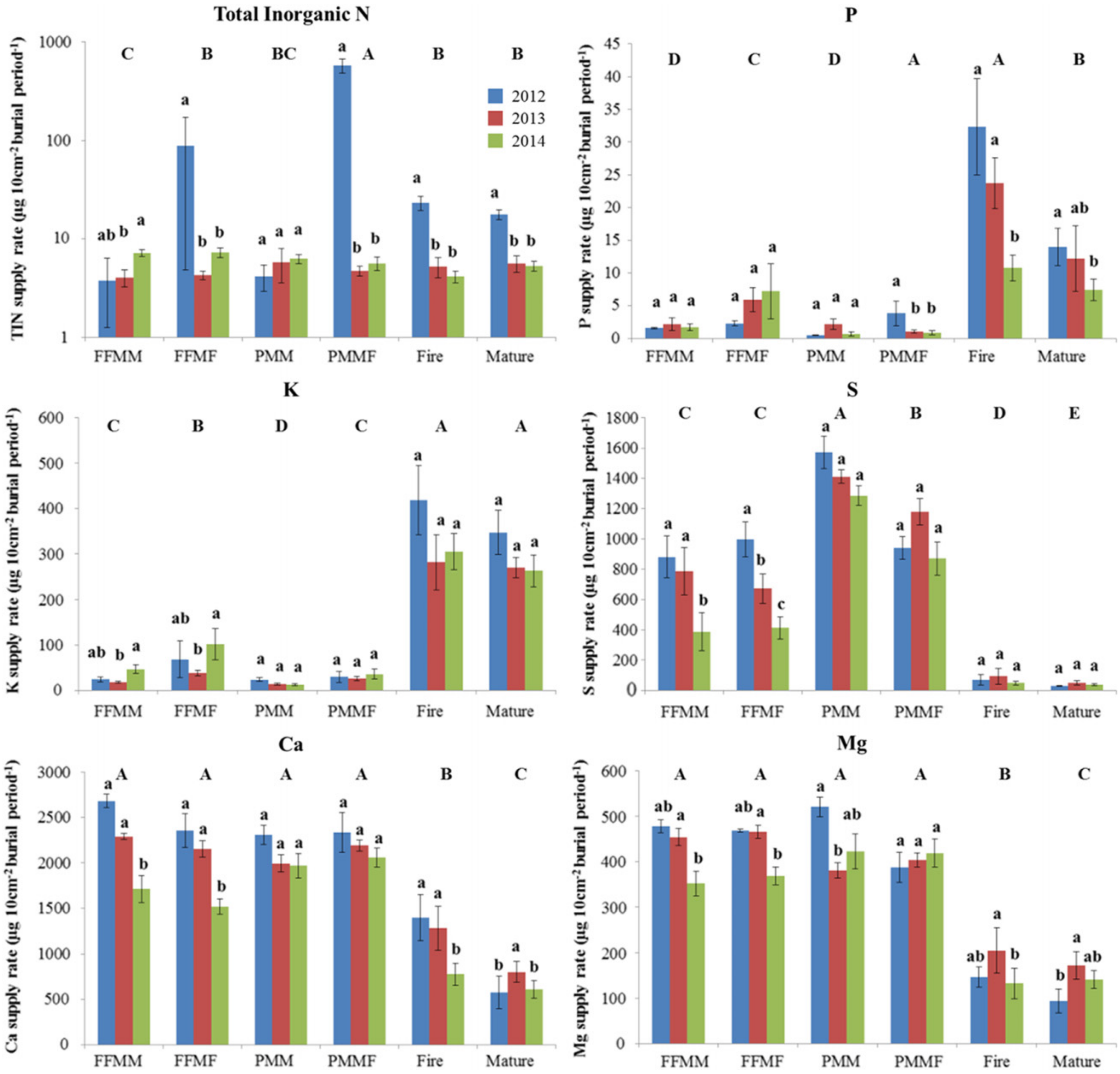
Similarity between the temporal patterns of individual nutrient supply rates in fertilized reclaimed and benchmark soils were only observed for TIN, P (in PMM), and Ca supply rates (Fig. 3). Total inorganic N supply rate decreased to unfertilized levels after 2012 and maintained a consistent pattern similar to the benchmark soils. Proportions of NO_3^- to NH_4^+ were similar in benchmark soils in all years, whereas NO_3^- was the dominant form of inorganic N in reclaimed soils during the fertilization year (2012), but became consistent with benchmark soils by 2014 (Fig. 4). Increased P in PMM from fertilization was only measured in 2012, with no carryover into subsequent years; however, a similar pulse was measured in FFMF in 2013 and 2014, although not significantly different from 2012. Soil S, Ca, Mg all decreased over the three year period in FFMM but not in PMM. Wildfire soils were either consistent with mature soils (TIN, K, and Mg) or returned to comparable concentrations by 2014 (P, S, and Ca) after the initial pulse (Fig. 3).

Discussion

Differences between soil types

Using the profile of nutrient supply, we were clearly able to distinguish between reclaimed and natural soils, and we found reclaimed soils were more similar to each other than to the benchmark soils, yet remained significantly different. Our results corroborate other findings from laboratory-based analyses (MacKenzie and Quideau 2012) and field analyses (McMillan et al. 2007; Rowland et al. 2009; Howell 2015), suggesting differences in biogeochemical performance between FFMM and PMM, although in our study, these differences were less pronounced. Organic matter quality has been shown to greatly influence nutrient availability in soils, and variability is largely determined by botanical inputs (Turcotte et al. 2009). Therefore, we expect to find differences between FFMM and PMM soil types due to profound differences in their origin and chemical composition. Peat mineral mix was significantly different from FFMM; however, the degree of separation was much less than expected, and plant macronutrient supply rates exhibited recurring similarities. The discrepancy between our study and others in the region (Mackenzie and Naeth 2010; MacKenzie and Quideau 2012) highlights the differences inherent to reclaimed soil quality based on its provenance. Rich fens with near neutral pH and greater nutrient inputs will likely create a different quality PMM than materials derived from bogs possessing low pH and nutrient contents (Aerts et al. 1999). Similarly, differences in soil texture and litter inputs will influence the quality of FFMM produced from aspen versus jack pine ecosystems (Sorenson et al. 2011). In the future, assessing and classifying reclaimed soils according to their chemical composition or their biotic legacy prior to salvage could explain some of the variability observed within PMM or FFMM reclaimed environments. Additionally, mixing rates of organic to mineral material are highly variable site to site, which will influence the organic matter content and therefore nutrient supply rate in the reclaimed soils.

Fig. 3. Nutrient supply rates of oil sands reclaimed and natural benchmark soils in 2012–2014. Significant differences between treatments are represented by uppercase letters from a repeated measures ANOVA, while between year comparisons are defined by lowercase letters from ANOVA ($P < 0.1$).

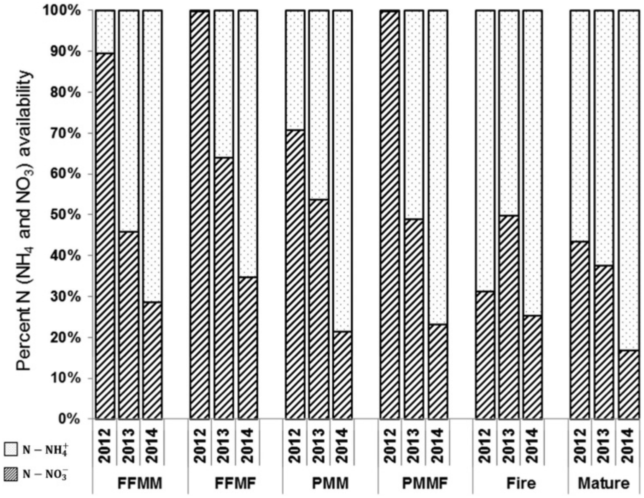


The greatest separation in nutrient supply rate between reclaimed and benchmark soils is expected because the soil disturbance (salvaging and placement) during reclamation exposes soil particles to aerobic condition, thereby increasing nutrient mineralization potentials, which may result in altered nutrient conditions. Major differences were attributable to higher P and K availability in natural soils, similar to the findings of Rowland et al. (2009), and higher S, Ca, and Mg availability in reclaimed soils. This can be explained by soil admixing during salvage and placement, which homogenizes soil horizons from the entire salvage depth, effectively diluting nutrient stratification (Yarmuch 2004; Das Gupta et al. 2015). Therefore, nutrients concentrated in undisturbed surficial soil horizons from uptake and deposition (K and P) will be measured in lower concentrations in reclaimed soils, but may still be present in similar total quantities across the entire soil profile depth. Similarly, higher levels of Ca, Mg, and S present in Luvisolic Bt horizons (Lavkulich and Arocena 2011) will be present in greater quantities at the reclaimed soil surface.

Fertilization effects

Fertilization as a reclamation practice aims to provide an initial pulse of nutrition for planted and naturally recruited species because it is assumed that soils may be deficient in macronutrients. We also asked whether fertilization could be done to create a nutrient profile in reclaimed soils, which is more similar to that in the benchmark soils. Wildfire is well-documented to generate a pulse of available nutrition that contributes to resource opportunities for emergent vegetation (Rokich et al. 2000; Choromanska and DeLuca 2001; Ball et al. 2010). However, in highly disturbed environments, such as reclamation areas, this pulse of nutrients provided by fertilization has the potential to benefit undesirable

Fig. 4. Forms of available inorganic N (%) in oil sands reclaimed and natural benchmark soils in 2012–2014.



weedy species at the expense of trees (Sloan and Jacobs 2013; Pinno and Errington 2015). In our study, fertilization produced significantly different nutrient profiles compared with unfertilized reclaimed soils; however, similarity to benchmark conditions was not achieved except for a slight increase during the fertilization year (Table 2). It is possible that fertilizer application to reclaimed soils might be a solution in generating similar nutrient conditions as benchmark soils, but the fertilizer prescription must be created with a priori knowledge of nutrient bioavailability in natural ecosystems. However, another important aspect is the efficiency of nutrient cycling with natural forests having established cycles. Fertilization alone will not replace this cycling on reclaimed sites, which will develop over time as the forest matures.

Effects of fertilization on the supply rates of individual macronutrients was significant, especially for TIN, P, and K. Inorganic N supply rates were increased up to two orders of magnitude greater than other treatments in the year immediately following fertilization, with no additional N supply increase apparent in subsequent years. Volatilization could be one potential means of loss for TIN, given the open canopy structure of the reclaimed sites; however currently, there is no confirmatory study to account for this loss. In fire-disturbed benchmark ecosystems, TIN losses are predominantly due to volatilization and increased availability that lasts at least for few years after fire (Maynard et al. 2014). A small but significant overall increase in P supply rate was found in both reclaimed soils after fertilization and K supply rate in only in fertilized FFMM. Interestingly, P inputs from fertilization in FFMM were not apparent until 2013 and 2014. Therefore, fertilization does not necessarily mean immediate increase in nutrient availability indicating that there might be a mechanism initially inhibiting the cycling of these nutrients. Higher plant biomass in FFMM than in PMM might indicate an uptake-recycle mechanism responsible for the late increase in the supply of these nutrients through decomposition process. However, chemical process such as adsorption might also be an important mechanism for certain nutrient ions (PO_4^- and SO_4^{2-}) to be removed from the soil solution. Such potentials have been previously evaluated in oil sands reclaimed soils (Jung et al. 2011). High concentrations of calcium (Ca), magnesium (Mg), and iron (Fe) in FFMM could also lead to P complexation and thus immobilization across a range of pH values (Vetterlein et al. 1999; Wang et al. 2012). Greater P and K supply rates in fertilized treatments would at least partially explain the greater variability observed and their closer proximity in ordination space to benchmark soils than in unfertilized treatments.

Our study indicated that fertilizer application in the reclaimed soils might not have a long-lasting effect on the inherent supply rate of macronutrients other than P and K; therefore, soil amendments that increase overall retention in macronutrients should be examined. In this context, fertilizing reclaimed soils with P and K might be more appropriate than fertilizing with N.

Reclamation trajectory

By comparing reclaimed with mature and recently disturbed wildfire sites, we can show whether the reclaimed sites are recovering ecosystem function in a short time frame and with what level of similarity. Although we concur that reclaimed sites will likely be novel ecosystems (Quideau et al. 2013; Audet et al. 2014), the goal of reclamation should be to create a developmental trajectory similar to the natural ecosystems. Reclaimed and benchmark soils shared similar interannual variability in nutrient supply profiles, although unfertilized PMM failed to generate a similar temporal trajectory. Fertilized PMM in 2012 expressed strong separation from subsequent years; however, this was probably due to the elevated TIN supply rates from fertilization, exacerbated by a lack of vegetation. This indicates that fertilization in PMM could be more ecologically beneficial than fertilization in FFMM to create similar benchmark conditions.

Similar to wildfire effects, we expected variation in nutrient supply rates in reclaimed soils to be greatest in the initial years following fertilization and levelling off over time (Miyanishi and Johnson 2002; Johnstone and Chapin 2006). This was observed up to 2013 after which the within group variability increased, which could be due to the interannual variability in soil moisture as indicated by the significant effect on overall and individual nutrient availability, but might also indicate variations due to plant (e.g., uptake) and soil processes (e.g., adsorption) (Jung et al. 2011). The absence of a significant moisture effect on TIN supply in FFMM could be attributed to the high vegetative demand for this nutrient, which probably superimposed the moisture effect through plant uptake. Supply rate of other macronutrients, however, showed dependency on soil moisture in reclaimed soils suggesting a difference between benchmark soils in terms of nutrient acquisition mechanism. Virtually, all TIN in the fertilized reclaimed soils was present as NO_3^- in the first year of fertilization, indicating a potential disconnect between nutrient supply and plant uptake (MacKenzie and Quideau 2010). By 2014, proportions of each N species in reclaimed soils became similar to benchmark, which suggests that N cycling might have some common drivers in both PMM and FFMM.

The fertilization effect of converging the temporal trajectory of reclaimed soil nutrient profiles toward benchmark conditions was not clearly achieved in the short timeframe measured by this study. This convergence may begin to occur as forest litter layers from native boreal tree, and shrub species develop and begin cycling nutrients (Sorenson et al. 2011). It has been suggested in the literature that this might take 25–30 yr using the conventional reclamation techniques of the Athabasca oil sands region (AOSR) (Rowland et al. 2009; Quideau et al. 2013). We suggest that by using a priori specific fertilizer knowledge and functional similarity tracking with benchmarks over time, reclamations goals may be achieved sooner.

Conclusions and Recommendations

Our findings suggest that nutrient profiles can be used to compare functional similarity in oil sands reclaimed ecosystems with natural benchmarks, as they are more characteristic of the soil environment that plant roots experience. Typical N-dominated fertilizer application in reclaimed soils might not generate a nutrient pattern similar to the benchmark conditions. Phosphorus and potassium are the two major nutrients that could be more meaningful to manage on reclaimed sites, due to their low supply rate compared with benchmark soils and apparent low retention or bioavailability. Specific fertilizer prescriptions with these nutrients may create nutrient conditions more similar to natural benchmarks than unfertilized treatments. Our results also indicated that fertilization in PMM might be more ecologically beneficial than in FFMM, given its effects on the temporal dynamics of nutrient supply rates. Temporal trajectory of nutrient supply rates is therefore another ecological cue that can be useful in measuring reclamation success. Finally, inherent variability within reclaimed soils must be considered while evaluating nutrient status for fertilizer prescription as this can strongly influence nutrient supply rates. Therefore, better characterization of reclamation soils, including physical characteristics such as water holding capacity and chemical characteristics such as pH and nutrient supply rates, would be appropriate rather than generally classifying them all as PMM or FFMM.

Acknowledgements

We thank Paul Hazlett and Ira Sherr for their constructive and insightful comments on the previous version of this manuscript. We also thank Edith Li and Ruth Errington who coordinated and led the fieldwork of many summer students. Funding for this project was provided by Canadian Natural Resources Ltd.

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