Mine Closure 2011 — A.B. Fourie, M. Tibbett and A. Beersing (eds)

doi:10.36487/ACG_rep/1152_18_Leskiw

Comparison of soil quality and productivity of reclaimed and native oil sands soils

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Abstract

The primary target of land reclamation in the Athabasca Oil Sands (AOS) region of Canada is to re-create ecosystems which are similar to the pre-disturbance ecosystems. The main objective of this study was to determine if reclaimed soils of the AOS have comparable quality and productivity to native soils. Data collected from 49 natural and 39 reclaimed (6 to 24 years of age) plots were analysed and compared. Results showed that reclaimed tailing sand soils generally had higher total pools of nutrients and moisture storage capacity than natural coarse textured soils. Reclaimed overburden soils are similar to fine textured natural soils in terms of nutrients and moisture storage capacity. Available soil water holding capacity was observed as the primary factor determining productivity in both reclaimed ($R^2 = 0.61$; $p<0001$) and natural ($R^2 = 0.46$, $p<0001$) soils. We conclude that reclaimed soils of the AOS region have similar productivity to their comparable native soils. The interpretations and conclusions are made by the authors and are not endorsed by the Cumulative Effects Management Association, the funding agency.

1 Introduction

Provincial regulations require oil sand operators to reclaim disturbed lands and establish diverse and sustainable boreal forest ecosystems. They also require that the new ecosystems have equivalent capability to that which existed prior to disturbance.

A network of long-term soil and vegetation monitoring plots has been established and plots have been monitored since 2000. A huge dataset has been compiled on many aspects of soil quality and productivity. A comparison of these properties on reclaimed and natural soils is used to determine if reclaimed soils of the oil sands region have comparable quality and productivity to that of native soils.

2 Research methods

2.1 Site and plot description and sampling

The study area is located north of Fort McMurray, Alberta, Canada (56°39′ N, 111°13′ W). The area is characterised by a continental boreal climate where winters are typically long and cold, and summers are short and cool. Daily average temperatures range from –18.8°C in January to +16.8°C in July. Average annual precipitation is 455 mm of which 342 mm falls as rain during the summer period. The region is located within the boreal forest zone which has been further classified into *ecosite* classes based on soils, vegetation, landscape and drainage conditions. The *ecosite* classes that are included in this study are the *a-ecosite*, *b-ecosite*, *d-ecosite*, and *e-ecosite* (Beckingham and Archibald, 1996; Oil Sands Vegetation Reclamation Committee, 1998). The *a-ecosites* are characterised by Brunisolic soils with poor nutrient regime and *xeric* to *subxeric* moisture regime. The *b-ecosites* are characterised by poor to medium nutrient regime and *subxeric* to *sub-mesic* moisture regime. The *d-ecosite*s are characterised by medium nutrient regime and *sub-mesic* to *mesic* moisture regimes. The *e-ecosites* are characterised by a rich nutrient regime and *subhygric* moisture regime.

The long-term monitoring plots measure 10 × 40 m and the sampling design follows a Modified-Whittaker method consisting of nested subplots for vegetation measurement. In each plot, soil inspections and profile descriptions were conducted on ten points along plot boundaries to a depth of 100 cm. Total nutrients, salinity and metals were determined from samples collected from a hand-dug pit. Available nutrients, on the other hand, were determined from ten composite samples that were collected at 10 m intervals for discrete depths 0–20 and 20–50 cm, using a hand auger. Plots with similar reclamation materials were considered as spatial replicates of a given material type for the purpose of statistical analysis (Paragon Soil, 2010).

Site index was determined as the top height (or average height of the largest 100 trees/ha) at 50 years breast height age. Detail guidelines and measurement principles for both natural and reclaimed sites are described in Timberline (2008).

2.2 Comparison of soil properties of reclaimed and native soils

This study compares six commonly used reclamation prescriptions or 'Series' (A, B, H, E, F and I) that are characterised by their capping material types (PM, SEC, DP, OB, and TSS) and configurations relative to their comparable natural ecosites. PM (peat-mineral mix) is reclamation material which is a mixture of peat and mineral material obtained by over-stripping peat to include some underlying mineral soil. Typically PM contains 2/3 peat and 1/3 mineral per unit volume, hence rich in organic carbon. DP refers to direct placement and is a suitable quality soil (LFH, A, B horizons) taken from a natural deposit and placed directly on tailings sand or overburden. SEC (secondary material) is subsurface upland soil or surficial geological material of a suitable quality (B and C horizons). OB (overburden material) is reclamation material dominantly used as subsoil; it is obtained from below the soil profile and extends to the oil sand formations that are mined. TSS (tailing sand) is a fine sand which is one of the final products of the hydrocarbon removal process.

Reclamation Series A is comprised of 20 cm PM over 30 cm of SEC material over TSS substrate; Series B contains DP of salvaged upland soils over 50 cm TSS; Series H has 20 cm of PM over TSS; Series E contains 20 cm PM over 30 cm of SEC material on OB; Series F has 50 cm DP over OB material; and Series I has 20 cm of PM over OB material.

Natural soils from *a*- and *b-ecosites* are coarse-textured; whereas, those from *d*- and *e-ecosites* have medium to fine-textured soils. Reclaimed soils with dominantly coarse textured substrates (Series H) are expected to develop into *a*- and *b-ecosites*. Similarly, reclaimed soils with dominantly fine textured substrates (A, B, E, F and I) are expected to develop into the *d*- or e-e*cosites*. Consequently, reclamation Series H is compared to the *a*- and *b-ecosites,* and A, B, E, F and I are compared to the natural *d*- and *e-ecosites*.

2.3 Soil chemical and physical analyses

Soil pH was determined on a saturated paste extract (water) for reclaimed soils and natural C horizons, and pH for natural LFH, A and B horizons was determined on $CaCl_2$ extract. Soil EC was measured on saturated paste extract (water). Available N (NH_4-N and NO_3-N) analysis was performed on soil samples with a 2 M KCl extract and available P (PO_4) (Carter, 1993), and K was determined using the Modified Kelowna method (Ashworth and Mrazek, 1995). Soil total C and N concentrations were determined by dry combustion method using a CNS elemental analyser on air-dried samples. Hot water soluble boron was determined using Azomethine-H method (McKeague, 1978). Bulk density of each horizon was determined from undisturbed samples collected in duplicates using metal core rings of 72 mm (inside) diameter and 75 mm height. Particle size analysis was conducted using the Hydrometer Method (Carter, 1993). Available water holding capacity (AWHC), defined as the difference between field capacity and permanent wilting point, was modified for textural discontinuity (i.e. coarse over fine or fine over coarse material stratification) (CEMA, 2006). Plots with similar reclamation prescription were treated as spatial replicates of a given series. This resulted in 9 replicates for Series A, 6 each for B and H, 7 for E, 3 for F and 8 for Series I. Similarly, for natural soils there were 5, 20, 15 and 10 replicates, respectively, for *ecosites a, b, d* and *e*. Analysis of variance (ANOVA) with multiple comparisons was used to determine if soil properties differed among the six Series (at $p = 0.05$).

3 Results and discussion

3.1 Bulk density and textural distribution

In order to facilitate direct comparison, data from reclaimed and natural plots were grouped based on type of the main substrate as tailing sand or overburden material. In the surface 0–20 cm soil depth, mean bulk densities of all coarse textured natural soils (*a- and b- ecosites*) were significantly higher (1.36 and 1.44 Mg.m^{-3} respectively) than mean bulk density of reclaimed Series A and H (1.11 and 1.10 Mg.m^{-3} respectively). Similarly, the mean bulk density of the fine textured *d- ecosite* (1.51 Mg.m^{-3}) was higher than both Series E and I. This difference is attributed to peat mix having lower bulk density than mineral soils. In the 20–50 cm depth, mean bulk densities of all reclaimed soils were similar to those of upland natural soils regardless of texture. Bulk density is generally not excessively high and is not limiting to rooting and air and water movement in most reclaimed soils, except the lower subsoil of Series I soils. The overburden in I Series contains oil and often has a massive structure and very firm consistence which is restricting to rooting and water movement.

Mean clay contents (over all plots) of reclamation and capping materials were 100, 160, 220 and 300 g.kg^{-1} soil, respectively, in TSS, PM, OB and DP materials. Whereas, mean clay content of natural plots (measured at the 20–50 cm depth) were 45, 80, 380 and 210 g.kg^{-1} soil, respectively, in *a-*, *b-*, *d-*, and *e-ecosites*. In the top 0–20 cm depth, clay content decreased in the order [Series with DP topsoil] > [natural *d-* and *e-ecosites*] > [reclamation Series with PM topsoil] > [natural *a-* and *b-ecosites*]. In the 20–50 cm depth texture of the natural coarse textured soils was reflected only in the H Series.

3.2 Soil organic carbon and total nitrogen content of reclaimed and natural soils

Soil OC in 0–20 cm depth of the A and H Series (reclaimed tailing sand) was significantly higher than OC in the natural *a-* and *b-ecosites* (Figure 1a). For instance, organic carbon in topsoil of A Series (131 Mg.ha^{-1}) was more than six times OC in *a- ecosite* (21 Mg.ha^{-1}). In the 20–50 cm depth of the coarse textured groups, soil OC in Series B was significantly higher than OC in natural *a-* and *b-ecosite*. In general, except in the upper subsoil layer of Series H (tailing sand), the reclaimed soils had higher soil OC than the natural *a-* and *b-ecosite* soils.

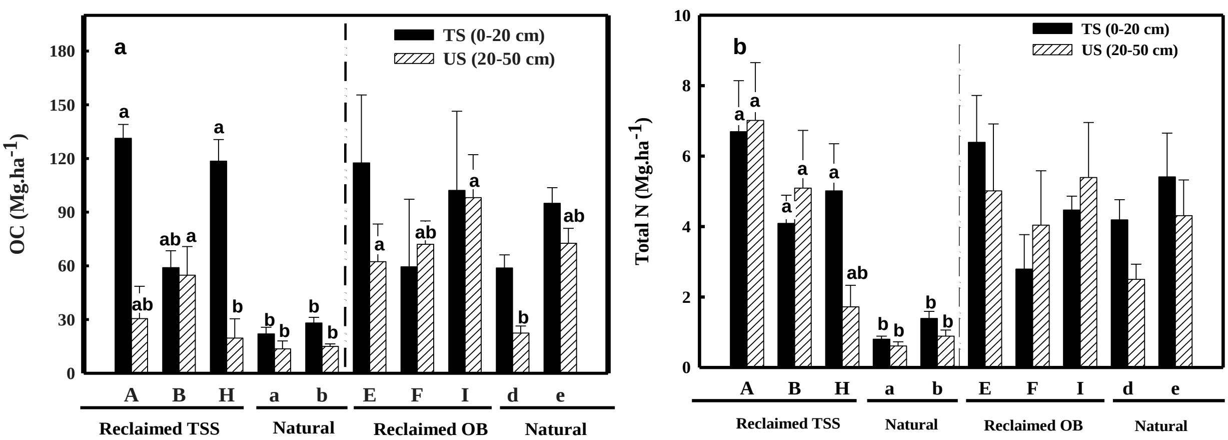

Figure 1 a) Organic carbon content (Mg.ha^{-1}) and b) total nitrogen (Mg.ha^{-1}) in topsoil (0–20 cm) and upper subsoil (20–50 cm) of reclaimed and natural soils. Common letters within the same soil horizon are not significant at p = 0.05

In the 0–20 cm depth of fine textured groups, there were no significant differences between natural and reclaimed soils in terms of soil OC content. However, in the 20–50 cm depth, Series E and I had higher OC content than the natural *d-ecosites*. Soil OC content of fine textured reclaimed soils (Series E, F, and I) were comparable to natural fine textured soils (*d-* and *e-ecosites*). In other words, it is likely that Series H may develop initially into richer soils (both in terms of nutrient and moisture regime) than the *a-* and *b-ecosites*.

Total N in the top soils of all reclamation Series and upper subsoil of Series A and B was significantly higher than total N in natural *a-* and *b-ecosites* (Figure 1b). The PM and DP materials in the reclaimed plots provided total N which is much higher than total N in the *a-* and *b- ecosites*. For instance, total N content in the 0–20 cm depth of Series H was more than six times higher than in the natural *a-ecosite*. In general, total N in the reclaimed soils with TSS subsoil was significantly higher than total N in the *a-* and *b-ecosites*. In the fine textured groups, however, there were no significant differences in total N content between reclaimed and natural soils. Total N distribution in both fine and coarse textured reclaimed soils followed a similar pattern to that of soil OC distribution. Hence, as discussed in the soil OC section, land reclamation guidelines need to reconsider the amount of peat material applied when the target is *a*- and *b*- *ecosite* soils. Unlike soil OC content, however, total N content in the 0–20 and 20–50 cm depths of reclaimed soils were comparable, resulting in lower C/N ratio in the 20–50 cm depth.

Series B, H, E, and I had similar C/N ratios to that of natural soils in both 0–20 and 20–50 cm depths. The C/N ratio in the 20–50 cm depth of Series A (C/N = 3) was significantly lower than the C/N in natural *a*- and *b*-*ecosites*; whereas, the ratio in Series F was significantly higher (C/N = 46–47) than the C/N in natural *d*- and *e*-*ecosite* soils.

There were no significant differences in available N content between reclaimed and natural coarse textured soils (data not shown). However, NO_3-N content in younger plots with DP and secondary upper subsoil horizons were significantly higher than those of natural *d*-*ecosite* soils and lower than the *e*-*ecosite* soils.

3.3 Phosphorus and potassium

Reclaimed soils had a slightly higher total P content to 50 cm depth (537 and 844 kg.ha^{-1}, respectively, in the coarse and fine groups) than their natural comparable *ecosites* (442 and 813 kg.ha^{-1}, respectively, in the coarse and fine groups) (Figure 2a). This higher P content is very valuable as it offsets the extremely low P levels of TSS material (Lanoue, 2003; Barbour et al., 2007). The disproportion in P levels between Series H and I (both with PM as a topsoil material) shows the huge difference between TSS and OB material in terms of total P content.

Reclamation and capping materials (other than TSS) generally had higher total K content than in the topsoil and upper subsoil of natural soils (Figure 2b). Total K content in both 0–20 and 20–50 cm depths of Series A and B were significantly higher than total K in respective depths of *a*- and *b*-*ecosites*. In the OB subsoil and fine textured natural groups, total K in both 0–20 and 20–50 cm depths of Series F, and 20–50 cm depths of Series E and I were significantly higher than total K in respective depths of *d*- and *e*-*ecosites*. The relatively high total K levels in Series B and F (both topsoil and upper subsoil) reflects higher total K content in the initial reclamation materials (mineral soil contains more K than peat).

Available P was higher in the topsoil of both coarse and fine textured natural soils than reclaimed soils (Table 2). On the other hand, available K was only higher in the topsoil of fine textured natural soils than reclaimed soils. In other words, while available K in the TSS material was comparable to available K in sandy natural soils, available K in the OB material was significantly lower than available K in fine textured natural soils.

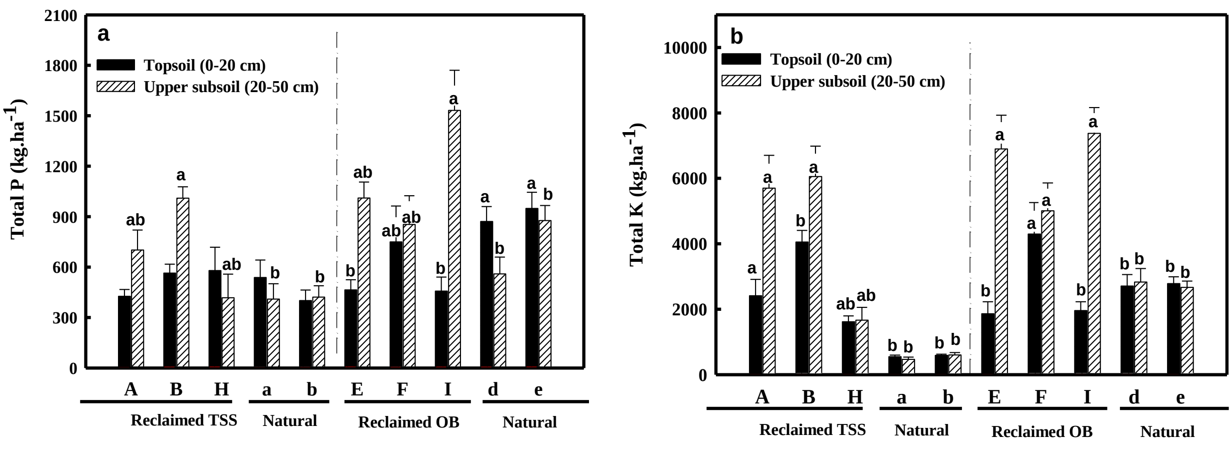

Figure 2 Total a) phosphorus and b) potassium contents (kg.ha^{-1}) in topsoil (0–20 cm) and upper subsoil (20–50 cm) of reclaimed and natural soils. Common letters within the same soil horizon are not significant at p = 0.05

Table 1 Plant available phosphorus and potassium ($kg.ha^{-1}$) in topsoil (0–20 cm) and upper subsoil (20–50 cm) horizons of reclaimed and natural plots

	Available P	Available K	Available P	Available K
	$kg.ha^{-1}$		$kg.ha^{-1}$	
	Topsoil (0–20 cm)		Upper Subsoil (20–50 cm)	
	Reclaimed TSS and coarse natural		*Reclaimed TSS and coarse natural*	
A (n=9) [z]	10 (1.3)[y]b[x]	158 (20)	23 (0.61)	244 (51)
B (n=6)	19 (4.2)b	259 (32)	24 (1.4)	265 (34)
H (n=6)	22 (4.0)b	115 (21)	29 (2.4)	108 (20)
a (n=5)	61 (12.2)a	166 (30)	57 (13.6)	113 (39)
b (n=20)	56 (7.7)a	147 (15)	52 (9.3)	107 (13)
	Reclaimed OB and fine natural		*Reclaimed OB and fine natural*	
E (n=7)	8 (1.4)b	141 (25)b	24 (0.63)	351 (104)
F (n=3)	18 (6.5)b	261 (77)b	23 (2.9)	320 (71)
I (n=8)	12 (2.5)b	191 (22)b	24 (0.64)	276 (36)
d (n=15)	73 (12.7)a	610 (118)a	44 (10)	434 (101)
e (n=9)	25 (9.8)b	517 (87)a	22 (9.7)	459 (78)

zNumber of plots in each reclaimed Series or natural ecosite soils. yStandard error of the mean (SE). xMeans with common letters are not significantly different at p = 0.05

3.4 Soil reaction and salinity

Five of the six reclamation Series (other than H) had mean pH levels between 7.0 and 7.5; whereas, mean pH in natural soils (both coarse and fine) were between 6.3 and 6.9 (Table 2). The observed differences, however, were not significant in the topsoil of all horizons and in subsoil of the fine textured soils. In the upper subsoil horizon of the fine textured groups, pH in Series A (SEC material) was significantly higher than pH in the natural *b-ecosite* soils. In most cases, high variability in plot data (resulting from site conditions) appears to mask differences in pH levels among reclamation Series and natural soils.

The pH ranges observed in most reclamation Series are outside ranges considered optimal for the topsoils (McMillan et al., 2007). In Series A, E and I (SEC and OB materials), the observed high pH appears to be the result of trace carbonates (alkaline materials) in the salvaged secondary and overburden materials. The high pH of TSS material is attributed to oil extraction processes that use alkaline products which later end up in the TSS material. Haering et al. (2004) also found high pH in younger reclaimed soils, which they attributed to traces of carbonates (1 to 2%) in fresh overburden materials that buffer the pH to > 7.0 in young mine soils. Soil pH in some reclaimed soils is likely to decline with time as the carbonates break down and acidic inputs from LFH increases with vegetation development. A decreasing trend has been observed in pH of the TSS material (data reported in annual report). If high pH values persisted (e.g. as observed for OB material), it is worth considering management intervention to reduce the pH levels (e.g. sulphur application) as high pH levels may reduce availability of essential nutrients such as phosphorus.

Table 2 Soil pH, electrical conductivity (EC), and sodium adsorption ratio (SAR) in topsoil (0–20 cm) and upper subsoil (20–50 cm) horizons of reclaimed and natural plots

Series	Soil pH	EC (dSm^{-1})	SAR	Soil pH	EC (dSm^{-1})	SAR
	Topsoil (0–20 cm)			Upper subsoil (20–50 cm)		
Reclaimed TSS and coarse natural				*Reclaimed TSS and coarse natural*		
A (n=9)[z]	7.3 (0.2)[y]	0.7 (0.1)b[x]	0.2 (0.0)	7.4 (0.1)b	1.3 (0.4)b	1.1 (0.2)b
B (n=6)	7.4 (0.2)	0.6 (0.1)b	0.3 (0.1)	7.1 (0.2)ab	1.0 (0.4)b	0.9 (0.3)b
H (n=6)	6.8 (0.3)	1.1 (0.4)b	0.1 (0.0)	6.9 (0.3)ab	0.7 (0.2)b	0.1 (0.0)a
a (n=5)	6.5 (0.2)	0.2 (0.1)a	0.5 (0.2)	6.4 (0.1)ab	0.1 (0.1)a	0.4 (0.1)a
b (n=20)	6.5 (0.2)	0.2 (0.0)a	0.4 (0.1)	6.3 (0.1)a	0.1 (0.0)a	0.5 (0.1)a
Reclaimed OB and fine natural				*Reclaimed OB and fine natural*		
E (n=7)	7.1 (0.2)	1.2 (0.3)a	0.2 (0.0)b	7.5 (0.1)	1.3 (0.4)b	1.0 (0.2)b
F (n=3)	7.3 (0.2)	1.2 (0.4)a	0.2 (0.1)b	7.3 (0.1)	0.9 (0.1)b	0.2 (0.1)a
I (n=8)	7.1 (0.1)	1.2 (0.2)a	1.0 (0.4)a	7.3 (0.3)	1.5 (0.3)b	1.9 (1.0)b
d (n=15)	6.7 (0.3)	0.9 (0.4)ab	0.9 (0.4)a	6.7 (0.3)	0.7 (0.3)ab	1.0 (0.4)b
e (n=9)	6.8 (0.4)	0.4 (0.2)b	0.4 (0.1)b	6.9 (0.3)	0.5 (0.2)a	0.3 (0.1)a

[z]Number of plots in each reclaimed Series or natural ecosite soils. [y]Standard error of the mean (SE). [x]Means with similar letters are not significantly different (one-way ANOVA with Holm-Sidak multiple comparisons, $p<0.05$).

Soil EC in TS and US of all reclaimed soils was between 0.5 and 1.5 dS m^{-1}; whereas, EC in natural soils was between 0.2 and 0.9 dS m^{-1}(Table 2). Comparing reclaimed and natural soils, reclaimed soils with TSS subsoil had a significantly higher ($p<0.05$) EC than coarse textured natural soils. Soil EC in reclaimed soils with OB subsoil was not statistically different than EC in natural fine textured soils. Nonetheless, current levels of EC in all reclaimed soils are well below levels known to adversely affect forest productivity (Purdy et al., 2005; Lilles et al., 2010). The SAR values of reclamation Series containing secondary material were consistently higher than others by an order of magnitude (not statistically significant). Nonetheless, in terms of soil quality all SAR values are within optimal ranges for forest soils.

3.5 Water holding capacity

Adjusted available water holding capacity ($AWHC_{adj}$) of the coarse textured reclaimed soil (Series H) was significantly higher than $AWHC_{adj}$ of coarse textured natural soils (Table 3). The mean $AWHC_{adj}$ decreased in the order H (136 mm) > > *b-ecosite* (88 mm) > *a-ecosite* (80 mm). In the fine textured group, $AWHC_{adj}$ in I and E Series were not significantly different from that of natural soils. However, the F Series had a significantly lower $AWHC_{adj}$ than fine textured natural soils.

Comparison of natural *a- ecosite* soils to that of reclaimed H Series showed that the reclaimed profile had higher $AHWC_{adj}$ and site index value (Table 3). Comparison of the *d-ecosite* to that of I, F, B and E reclamation Series also showed comparable $AWHC_{adj}$ (136 mm/m to 146 mm/m) and tree site indices. Similarly, natural *e-ecosite* soils and reclamation Series A had similar $AWHC_{adj}$ (143 mm/m versus 144 mm/m) and site indices. Note that the *e-ecosite* soils also receive some seepage water.

Table 3 Comparison of productivity and available water holding capacity among natural and reclaimed sites

Natural					Reclaimed				
Ecosite	$AWHC_{adj}$	Site index (m at 50 y)			Series	$AWHC_{adj}$	Site index (m at 50y)		
		Pine[z]	Spruce	Aspen			Pine	Spruce	Aspen
a - ecosite	80	15.7			H	136	16.6	17.6	13
b - ecosite	88	17.1	17.3	14.6					
d - ecosite	136		18.4	19.6	I	146	16.3	20.9	19.1
					F	97		21.5	19.5
					B	127	15.9	23.4	20.4
					E	118	18.7	22	20.4
					A	144	18.8	20.4	21.1
e - ecosite	143		20.7	21.6					

[z] CEMA 2006 Report.

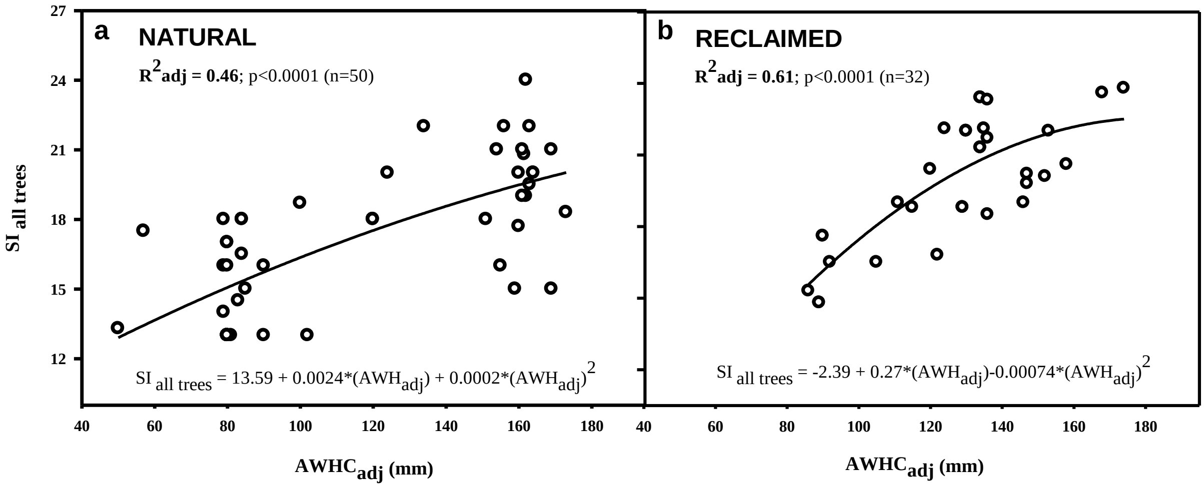

Figure 3 Relationship between adjusted available water holding capacity and site index values of a) natural and b) reclaimed soils (both fine and coarse) modelled as a second order polynomial

Multiple linear and non-linear regression analysis was performed on different soil chemical and physical properties to identify those factors that were most strongly related to tree productivity. In the natural soils, tree productivity was determined by a multitude of factors (soil OC, total and available N, soil texture, and $AWHC_{adj}$), with $AWHC_{adj}$ explaining 46% of the variability (Figure 3a). In the reclaimed soils, however, only $AWHC_{adj}$ was significantly correlated to SI and explained more than 61% of the variation in tree productivity (Figure 3b). None of the measured soil chemical and physical properties (bulk density, soil texture, soil nutrient, salinity, pH, etc.) were significantly related to tree productivity in reclaimed soils. In other words, in all the reclaimed plots soil moisture was the most critical factor determining tree productivity. This observation is consistent with several other studies that reported significant relationships between site index and soil water holding capacity in similar soils (e.g. Wang, 1995).

The results showed that reclamation prescriptions designed to reclaim tailing sand materials (Series A, B, and H) generally had higher soil moisture and nutrient regimes than natural coarse textured soils. The higher soil moisture and nutrient regime, in turn, could result in higher tree productivity.

4 Conclusions

Key findings of this study were: (a) Reclaimed soils that were expected to be comparable to coarse textured native soils generally had higher total pools of nutrients and moisture storage capacity than native coarse textured soils. (b) Reclaimed soils that were expected to be comparable to fine textured native soils had similar nutrient levels and moisture storage capacity to natural fine textured soils. (c) In all reclaimed and natural soils, available soil water holding capacity was the primary factor determining tree productivity. Overall, from a soils standpoint, current productivity status of all reclaimed soils is satisfactory and we conclude that reclaimed soils of the AOS region have similar productivity to their comparable native soils of the region.

Acknowledgements

This work was funded by the Cumulative Environmental Management Association (CEMA), with site access, technical collaboration and field support provided by Suncor Energy Inc., Syncrude Canada Ltd and Albian Sands Energy Inc. The authors gratefully acknowledge valuable assistance and input from personnel with the Terrestrial Subgroup (TSG) of CEMA, Suncor Energy Inc., Syncrude Canada Ltd, Albian Sands Energy Inc. and Paragon Soil and Environmental Consulting Inc.

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