INVESTIGATION OF SOIL-WATER PROPERTIES FOR RECLAIMED OIL SANDS, FIRE-DISTURBED, AND UNDISTURBED FORESTED SOILS IN NORTHERN ALBERTA, CANADA

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By

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ABSTRACT

Oil Sands mining operations in Northern Alberta, Canada generate large areas that contain marginal soil conditions and must be overlaid with reclamation substrate. In order to expedite revegetation efforts, salvaged peat is often incorporated with mineral subsoil to compose a peat:mineral mix (PMM) to act as a soil cover. However, the soil water characteristics and physical properties of these covers are poorly understood for reclamation. Therefore, the objective of this study was to determine the soil physical properties and soil water characteristics of reclaimed covers compared to naturally disturbed sites (i.e. fire) and undisturbed reference sites. Soil samples were collected in the summer of 2012 and 2013 from three reclaimed PMM soil covers, one recently fire-disturbed natural site and one undisturbed reference site. Of all the nutrients analyzed, soil phosphorous (PO_4^-) concentrations were significantly lower in the reclaimed soils compared to the disturbed and undisturbed natural sites.

Near-saturated hydraulic conductivity (K_{ns}) for water transmission through the soil were measured, along with soil water retention curves developed for describing moisture storage. Topsoil (0-20 cm) K_{ns} measurements revealed no statistical difference between reclaimed and natural sites and extremely high variation was detected at all sites. Three different models for estimating K_{ns} also revealed only minor differences between methods, although high variation within each site prevented conclusions on whether the mini-disc infiltrometer and associated K_{ns} models was an appropriate tool for measuring hydraulic conductivity in peat-dominated reclaimed soils.

Soil water retention curves were developed by tension table and pressure plate methods on intact soil cores. Five soil hydraulic models – three unimodal and two bimodal - were fit to the retention curves and parameterized. Bimodal models showed a superior fit compared to the unimodal models at all three reclaimed and one undisturbed sites. Bimodal trends are typically associated with natural soils exhibiting a high degree of soil aggregation and associated heterogeneous pore structure. The fire-burnt site showed a unimodal trend possibly as the result of its sandy texture and lack of aggregation. These model fits suggest that a juvenile PMM have similar soil water storage characteristics to certain highly-structured natural soil as provided by its peat additions. Available water holding capacity was determined by both soil core and Land Capability Classification System methods. No differences were detected between techniques and a mesic soil moisture regime was predicted at all sites.

This study found that juvenile PMM soil covers exhibited similar soil-water characteristics to a well-aggregated, undisturbed forested soil after only a few years post-placement. These results establish a comparative baseline for future soil research on reclaimed tailing ponds, as well as provide the necessary soil-water relationships for watershed and/or regional scale hydrological modelling.

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2°	Secondary Mineral Material
AEP	Alberta Environment and Parks
AOSR	Athabasca Oil Sands Region
AWHC	Available Water Holding Capacity
BD	Bulk density of Soil ($Mg\ m^{-3}$)
CEMA	Cumulative Environmental Management Association
CWD	Coarse Woody Debris
EPEA	Environmental Protection and Enhancement Act
FC	Field Capacity
FORWARD	Forest Watershed and Riparian Area Disturbance Project III
GCL	Geosynthetic Clay Liner
K_{ns}	Near-Saturated Hydraulic Conductivity
LCCS	Land Capacity Classification System
LFH	Litter, Fermented, Humic
MFT	Mature Fine Tailings
OC	Organic Carbon
PMM	Peat:Mineral Mix
PWP	Permanent Wilting Point
SOM	Soil Organic Matter
SSOB	Saline-Sodic Overburden
SWAT	Soil and Water Assessment Tool
VWC	Volumetric Water Content

1. Introduction

The current active footprint of Oil Sands developments in northern Alberta is greater than 80,000 ha (Government of Alberta, 2016). Per the Environmental Protection and Enhancement Act 1993 (Government of Alberta, 2010a), all disturbed land in Alberta is required to be reclaimed back to an equivalent productive capability to that of the pre-disturbance landscape before land ownership (and the associated responsibilities) can be transferred from the mining companies back to the Crown. Significant research has been done over the past 40 years to enable or expedite the reclamation processes necessary to establish these equivalent capabilities.

One reclamation technique used extensively in the Oil Sands region is the coarse combination of salvaged peat with relatively infertile subsoil mineral substrate. These Peat:Mineral Mixes (PMM) have been shown to benefit from the peat addition through improved soil microbial communities (Hahn and Quideau, 2012), greater propagule bank for native species establishment (Mackenzie and Naeth, 2010), as a source of soil nutrients (Hemstock et al., 2010), and can improve growth potential of possible long-term vegetation including trembling aspen (*Populus tremuloides* Michx.; Pinno et al., 2012) and jack pine (*Pinus banksiana* Lamb.; Farnden et al., 2013). Oil sand reclaimed sites utilizing PMM appear to have the ability to reach natural trajectories depending on soil cover prescriptions and fertilizer patterns (Rowland et al., 2009).

Of particular interest to researchers is the ability of peat to improve the soil-water relationship within reclamation soils, and improve its capabilities as a vegetation growth medium. Peat can enhance these conditions within the soil through both increased soil organic carbon and increased porosity (RRTAC, 1993; Moskal et al., 2001). When comparing these PMMs to adjacent undisturbed topsoils, Yarmuch (2003) detected little significant differences for soil hydraulic conductivity and other physical properties. These similarities were attributed to soil structure afforded by the peat component, although the author noted that “reclaimed soil structure per se is not truly equal to undisturbed soil structure”. For water storage and retention, previous research has suggested that the soil water retention characteristics of PMM follow a bimodal pattern (Shurniak, 2003), similar to that of structured aggregate loams (Sharma and Uehara, 1968; Smettem and Kirkby, 1990; Coppola, 2000). Examination of both soil water movement and retention are critical in new reclamation sites, as infiltration and storage of precipitation within the soil complex is the sole provider of water for all vegetation and accounts for nearly all ground-water recharge (Dingman, 2015).

In 2010, a decommissioned tailings pond completed its intended soil coverage and re-vegetation process; this is significant as it marks the first whole tailings pond to be successfully decommissioned, stabilized and reclaimed in the Oil Sands region. This event represents a major proof-of-scale for successful reclamation of the over 170 km^2 of tailing ponds within the Athabasca Oil Sands region (Government of Alberta, 2013). The same year an 85 ha overburden dump was also reclaimed. Both sites utilized PMM for the soil cover. Up to this point the majority of previous research has been conducted on singular hectare-scale experimental plots or laboratory testing. Examining these two sites and demonstrating that large-scale**,** non-experimental reclaimed soils align with the experimental reclamation paradigm enables reclamation planners to fill-in knowledge gaps with previous research, and ultimately have more confidence in long-term projections.

Earlier studies by the Forest Watershed and Riparian Disturbance (FORWARD) Project demonstrated that disturbing the surface soil conditions of Boreal Plains watersheds through either natural (forest fire) or anthropogenic (winter logging) processes can have a significant effect on water runoff and nutrient export (Whitson et al., 2003; Burke et al., 2005). The PMMs utilized in Oil Sands reclamation are another form of disturbed soil conditions. Characterizing soil physical properties in juvenile reclaimed sites and both fire-disturbed and undisturbed reference sites will assist in determining the efficacy of PMM soil covers in replicating natural conditions, comparison of known anthropogenic and natural disturbances, and provide baseline values to investigate soil structure development over time. Furthermore, future attempts at hydrologic modelling these reclaimed boreal watersheds (i.e. $SWAT_{BF}$ [Watson et al., 2008]) will require detailed understanding of soil-water relationships. Despite this need, no data regarding the soil physical characteristics of intact reclaimed tailing ponds or RA1 has been published. Therefore, the objectives of this study were to:

1. Characterize physical and chemical properties in large-scale PMM soil covers.

2. Determine whether quantitative similarities in soil-water properties exist between the natural disturbance of a forest fire and reclamation activities.

3. Investigate whether several common soil water tools used to determine soil water movement and retention in natural soils are applicable for reclaimed PMM soils.

To meet these objectives, both field and laboratory experiments were conducted. Hypotheses tested included whether reclaimed soil properties were quantitatively comparable to natural reference or fire-burned sites, and whether moisture retention data from reclaimed sites can be fitted to hydrological models used for natural soils. This document utilizes the traditional thesis format with chapters: 1. Introduction, 2. Literature Review, 3. Material and Methods, 4. Results, 5. Discussion, and 6. Conclusion.

2. Literature Review

2.1 Forest Soils in Northern Alberta

Upland mineral soils comprise roughly half of the Oil Sands region in the Fort McMurray area and are dominated by Luvisolic and Brunisolic soil orders in the northern and southern regions, respectively (Lindsay et al., 1962; Crown and Twardy, 1970). The soils are largely determined by their parent material, as the Luvisolic soils form on the medium- and fine- textured glacial till that supports trembling aspen (*Populus tremuloides*), balsam fir (*Abies Balsamea)*, and white spruce (*Picea glauca*) mixed wood forests on the drier upslopes and black spruce (*Picea mariana)* on the wet basal slopes; while Brunisols are restricted to the coarse-textured glacial fluvial and eolian deposits and whose drier and less nutrient-rich conditions support jack pine (*Pinus banksiana*) and black spruce on the depression (Johnson and Miyanishi, 2008). Both these soil types can produce commercially-viable forests (CEMA, 2009).

2.2 Effect of Fire Disturbances on Forest Soils

Forest fires are intrinsic natural disturbances that occur in large scope and frequency, and act as essential rejuvenators to the boreal landscape. On average, forest fires consumed 2.3 million ha a year across Canada (Natural Resources Canada, 2013). Larsen (1997) examined the temporal fire frequency in Wood Buffalo National Park, Northern Alberta and found that non-managed boreal forests have burn cycles ranging from 39 to 96 years depending on tree species. Many boreal plant species thrive under these conditions by adopting unique physiological adaptations to these frequent burn cycles (i.e. jack pine with serotinous cones). Despite the fundamental necessity of forest fires in the boreal plains ecosystem, many of its characteristics inherently alter the landscape and can be considered a natural soil disturbance.

There are significant negative effects on the chemical and physical properties of soils after a forest fire. Chemically, the loss of soil organic matter (SOM) and subsequent disruption of nutrient cycling have been well documented. The combustion of plant and soil organic biomass leads to the mass release of plant-available nutrients immediately following a fire; however, the ecosystem undergoes an overall net loss of nutrients. DeBano et al. (1998) summarised the mechanisms of nutrient loss - direct volatilization; particulate loss in smoke; transformation to ash; surface runoff and erosion losses; and downward leaching (Table 2.1). Soil physical properties are also affected by the intense fire temperatures (Table 2.1). From 200 to 500 ˚C organic compounds are combusted (DeBano et al., 1998), and temperatures exceeding 500 ˚C can begin to irreversibly damage clay minerals (Giovannini et al., 1988). Both organic matter and clay minerals are critical for the aggregation of soil particles – i.e. soil structure. Destruction of aggregates and overall soil structure leads to lower total porosity and a transformation of pore size distribution. At lower soil depths, water repellency can often be a measured effect. Organic matter that is vaporized close to the soil surface can migrate down the temperature gradient before condensing and coating soil particles lower in the soil profile. This hydrophobic effect can produce a water-repellent horizon (DeBano et al., 1998).

The similarities between naturally (fire) disturbed and reclaimed Oil Sands sites have recently been revealed in the restoration of aboveground ecology. An extensive review of differently-aged reclamation treatments was carried out by Rowland et al. (2009) to determine if similar ecosystems were being created to the surrounding natural sites. Across a range of ecosites on Oil Sands reclaimed sites (a1, b1, b3, d1, d2, and d3), plant diversity was found to decrease after canopy closure at about age 31 to 35, driven by a decline in understory plant species. Similar vegetation trends have been observed in reclaimed post-mining areas in the Czech Republic (Frouz et al., 2008). Interestingly, the decrease of understory biodiversity resulting from canopy closure is an established process in boreal forest stands recovering from a fire disturbance (Grandpre et al., 1993; Hart and Chen, 2008). Rowland et al. (2009) suggests that future long term monitoring programs should include fire-disturbed sites as a treatment to see whether ecosites development on naturally-disturbed soils mirror those observed on reclaimed soils.

Table 2.1 Chemical and physical effects of fire on forest soils. Summarized from DeBano et al. (1998).

Type	Effect	Description
Chemical	Direct Volatilization	Loss of gases nitrogen to the atmosphere
	Particulate Loss	Phosphorus and cations lost in smoke
	Ash Deposition	Highly plant available nutrients are released, can be lost through wind/water erosion
	Erosion Loss	Surface runoff and subsequent erosion can result in large watershed flushing events
	Soil Leaching	Loss of nutrients down through the soil profile
Physical	Soil Structure Loss	Decrease of total porosity in topmost soil layer due to destruction of soil aggregation
	Hydrophobicity	Development of water-repellant layer below and parallel to soil surface
	Reduced Infiltration rates	Clogging of pore network from pore deposition, contributes to erosion losses

2.3 Oil Sands Extraction and Processing

Bitumen is extracted from the Athabasca Oil Sands Region (AOSR) of northeastern Alberta for the production of synthetic crude oil. The AOSR covers approximately 140,000 km^2 – twice the size of New Brunswick – and is estimated to contain 178.7 billion barrels of initial established oil reserves (Government of Alberta, 2007). Since Oil Sands production was first started by the Great Canadian Oil Sands Limited (now Suncor Energy Inc.) in 1967, development has expanded exponentially and is forecasted to reach an estimated 3 million barrels of crude per year by 2018 (Government of Alberta, 2013).

The Oil Sands area is a mixture of a dense, heavily-viscous petroleum known as bitumen, clay, water and sand, and is found naturally occurring within largely disintegrated sedimentary deposits. In the Athabasca region of northern Alberta, these oil sand deposits can be found within 100 m of the surface, making it feasible for surface mining. To access the underlying Oil

Sands, the native forest is harvested, the land drained (if necessary), and the upper organic and mineral soil layers are scrapped and salvaged for post-mining reclamation. The additional material found between the surface layers and the Oil Sands is referred to as overburden (OB); excavated OB is either used as pit backfill or placed in dumps adjacent to the mining pits. Mine dumps are required to be reclaimed.

Once the bitumen ore have been exposed, the Oils Sands are excavated and transported to the extraction plant where the oil is separated via a variation of the Clarke Hot Water Extraction process (Clarke, 1980). Approximately 2 tonnes of Oil Sands are required to produce one barrel of synthetic crude (Government of Alberta, 2007). The slurry produced after bitumen extraction includes sand, clay, water and residual bitumen. When deposited into a tailings pond, the sand settles out fairly rapidly, and can be used as a structural component in dyke construction. The significantly smaller portion of remaining clay/water/bitumen mixture, coerced by the increased pH of extraction water, produces a stable suspension defined as mature fine tailings (MFT). With a solid content of 30-35%, MFT lacks the shear strength required to support reclamation material, and it is projected that it will take centuries to de-water to the required solid state (Mikula, 1996). At the end of the extraction process, two predominant waste products are created – overburden and tailing (Figure 2.1).

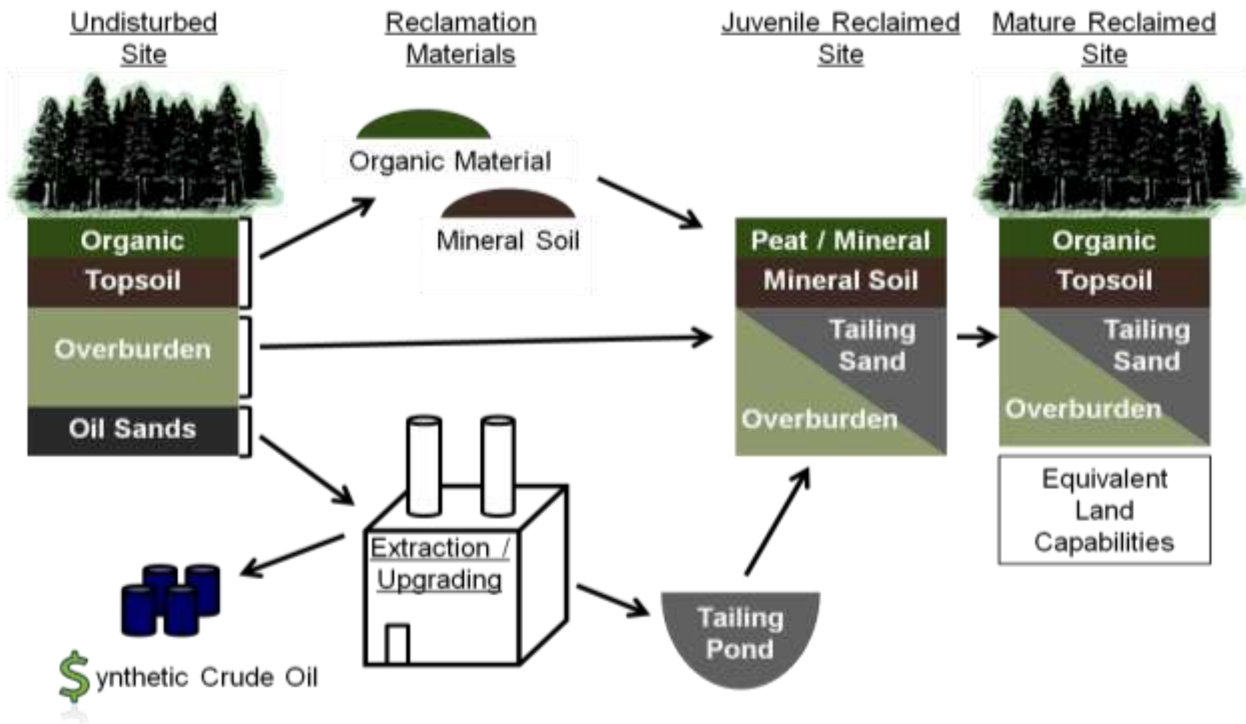

Figure 2.1 Diagram of Oil Sands extraction, processing and reclamation process. Modified from Hunter et al. (2011).

2.4 Reclamation in the Oil Sands Region

Reclamation, according to Alberta Environment and Parks (AEP), refers to the establishment of stable, non-hazardous, non-erodible, favourably drained soil conditions, which supports equivalent land capabilities to or better than pre-disturbance conditions (Alberta Environment, 2002). The total active Oil Sands footprint stands at roughly 90,000 ha (Government of Alberta, 2013). This includes mined-out pits, overburden dumps and tailing facilities. Of that disturbed land, roughly 6,500 ha is at some stage of active reclamation, including certified, permanent, temporary, and placed-soils sites (Government of Alberta, 2013). According to Alberta's Environmental Protection and Enhancement Act (EPEA), mining companies on government leases must conserve any specified land and reclaim all disturbed land prior to returning the lease to the Crown (Government of Alberta, 2010a). This document also lays out additional regulation that must be followed during reclamation planning:

- productive capability equivalent to that of the pre-disturbance landscape
- commercial forest viable on an area equivalent to the pre-disturbance condition
- upland reclamation landscapes have natural appearance characteristics of the region
- integration of landform, topography, and water bodies with adjacent undisturbed areas.

Successful reclamation does not try to manufacture a fully-functional landscape, but rather providing conditions such that the landscape can naturally redevelop towards an equivalent capability to that which existed prior to mining.

2.4.1 *Upland Boreal Reclamation*

Upland boreal reclamation is the leading form of reclamation prescription in the Oil Sands region. Compared to wetlands design, upland (also referred to as dryland) has been more widely adopted because it makes use of readily available materials (soil salvage), is less complicated to design, better understood, and takes significantly less time to regenerate to a natural state (Osko et al., 2010). Construction of more complicated peat-accumulating peatlands or fens is still in its infancy and has not reached the scale of upland reclamation (Price et al., 2010).

Through the cooperation of industry and non-government organization like the Cumulative Environmental Management Association (CEMA), the upland reclamation process has become fairly standardized throughout the region (Figure 2.1). First, the desired area is subjected to landform grading in order to develop the correct landscape and hydrology; heterogeneity and runoff performance are important characteristics to consider (MEND, 2007). Next, using the salvaged soil material from the mining process a soil cover of roughly 1 m depth is placed over either the overburden or tailings sand; the exact soil prescription varies with company and site. The objective of a soil cover is to act as an adequate growth medium for the vegetation prescription, as well as isolate the underlying materials from the biosphere (MEND, 2007). Vegetation is planted after the final grading of the placed soil. Barley was traditionally used as a nursery crop to provide soil stability against erosion without over-powering the desired long term woody species. Much of our knowledge regarding the conditions required for proper ecosite development has been synthesized in documents such as the 'Land Capacity Classification System (LCCS; CEMA, 2006) and the 'Guidelines for Reclamation to Forest Vegetation in the Athabasca Oil Sands Region (CEMA, 2009). In order to maximize the growth potential of the soil cover, peat inputs and textural layering have become universal techniques for upland reclamation.

Currently no structure exists to describe human-modified soils in the context of the Canadian System of Soil Classification. Naeth et al. (2012) highlights recent efforts made to introduce a new soil order - Anthroposols - that would allow the systematic description of anthropogenic soils dependent on factors such as intensity of disturbance and composition of anthropogenic materials.

The Land Capability Classification System for Forest Ecosystems (LCCS) manual was developed to help industry achieve the land capabilities required by Alberta's Environmental Protection and Enhancement Act for forest ecosystems on natural and reclaimed soils. Land capability is determined by assigning numerical values to soil and landscape parameters deemed plant growth limiting. Soil physical and chemical properties, as well as nutrient and moisture regimes are all considered, leading to a final aggregate rating. Five land capability classes are established, ordered from high to non-productive, along a 100-point scale – each class is divided into 20 point ranges. The resulting data can be used to tentatively project the mature ecosystem productivity of a juvenile reclaimed soil, or confirm the long-term vitality of an established reclaimed site for certification purposes. However, it is important to note that the correlation between LCCS-predicted and actual in-situ forest productivity is not clearly established at this time and caution must be used when extrapolating results.

2.4.2 ***Peat:Mineral Mix (PMM)***

The boreal plain landscape consists of roughly 50% peat-rich organic soils, broadly divided into marshes and fens (Bayley and Mewhort, 2004). This salvaged organic material represents a critical source of nutrients for a landscape. Simply placing peat in a landscape will not promote wetland development as organic soil growth is controlled by landscape hydrology as opposed to parent material. To keep this nutrient and carbon source, the salvaged peat is placed over secondary mineral soil then integrated by mechanical mixing (i.e. tilling) to create a suitable upland reclamation substrate. PMM have evolved as an effective and standardized practice for industry.

The SOM provided by peat has a positive relationship with soil aggregation, cation exchange capacity, pH buffering action, a critical source of mineralized nutrients, and an overall increase in plant productivity (Table 2.2; RRTAC, 1993; Bronick and Lal, 2005). Peat acts as an immediate SOM input until vegetation-derived organic matter is deposited as the soil matures. Initially it was predicted that due to microbial decomposition the benefits of peat were not permanent and would decrease over time (RRTAC, 1993); however, more recent measurements suggest that carbon inputs and outputs are nearly equal in the early years following revegetation (Drozdowski et al., 2010).

Table 2.2 Summary of organic amendments used in upland boreal reclamation in the Oil Sands region

Organic Amendment	Advantages	Disadvantages	Sources
Peat	• Soil tilth • Water holding capacity • Humus content • Nutrient Mineralization • Readily available	• Non-permanent • High application rates • Micro nutrients • Acidic • Limited microbial • propagation	➢ Larney and Angers, 2012 ➢ RRTAC, 1993
Forest Floor (LFH))	• Microbial and fauna propagation • Combination of SOM, nutrients and woody debris • Low-risk (developed and supported boreal forest vegetation)	• Non-permanent • Limited supply	➢ Alberta Environment and Water, 2012 ➢ Mackenzie and Naeth, 2010
Coarse Woody Material	• Increased woody species germination • Soil volumetric water content • Microsite heterogeneity • Erosion Control	• Non-permanent • Variable results	➢ Alberta Environment and Water, 2012 ➢ Brown and Neath, 2010

2.4.3 ***Layering***

The other technique utilized in soil cover construction is layering heterogenic-textured soil horizons to improve water storage conditions. It has been well-established that engineered soil profiles that contain strong vertical heterogeneity in soil texture can store greater amounts of water than vertically homogenous soils (Chaikowsky, 2003; Kelln et al., 2007; Hilderman, 2011; Naeth et al., 2011; Jung et al., 2014). By increasing water storage, layering assists in both objectives of the soil cover – adequate soil moisture and decreasing underlying material interaction with the hydrosphere through the reduction of downward water movement.

The improvement of available water is not restricted to engineered landscapes however, as similar phenomena have been measured in coarse undisturbed soils in the Ft. McMurray region. Zettl (2014) employed double-ring infiltrometers and real time volumetric water content readings to measure field capacity in coarse, undisturbed soils. She found that between 110 to 330 additional mm of water can be stored in a 1 m soil profile as a result of layering multiple textures in a simulation environment. Huang et al. (2013) used pedotransfer functions and numerical modelling to confirm that field capacity (and therefore available water) is the condition most positively affected by textural layering. Furthermore, the authors found that computer simulated jack pine and trembling aspen productivity and leaf area index increased on textural layered soils as oppose to uniform ones.

This hydrologic improvement is driven by two separate flow mechanisms known as hydraulic barrier and capillary barrier (Si et al., 2011). A hydraulic barrier occurs when water accumulates above the textural interface of a coarse texture soil due to the lower hydraulic conductivity of the underlying finer textured and/or compacted soil (Scott, 2000). Conversely, the water cohesion and capillary pressure in micropores of a fine-textured soil layer can prevent the percolation downwards into the predominantly macropores of an underlying sandy layer (Stormont and Anderson, 1999). The texture difference between layers can be relatively small - Huang et al. (2013) simulated this capillary barrier effect in the layering of fine and coarse sands. Depending on the textural difference of a given soil profile one or even both of these phenomena can be observed in a landscape.

2.5 Reclaimed Soil Physical Properties

Soil disturbance caused by mining has been shown to degrade the antecedent soil profile and associated chemical, biological, and physical properties. An anthropogenic soil formed by surface mining can attribute much of these losses to the necessary scale of the soil handling practices – the immense size and weight of the earth-moving equipment often leads to a breakdown of any antecedent soil structure. Higher bulk densities, massive soil structure, and lower water flow and storage rates are considered hallmarks of highly disturbed soils. Over the last 50 years, considerable research has been conducted to investigate the range of values that surface mining can impart on soil physical properties and how those values will affect revegetation. Much of this research has focused on the reclamation of coal minesoils (spoil) located in the eastern United States (Table 2.3).

Pederson et al. (1980) measured numerous soil physical characteristics of a reclaimed surface-coal mining operation in Western Pennsylvania. They found compacted soil conditions (average bulk density of 1.76 g cm^{-3}) and significant amounts of spatial variation in infiltration, water retention and hydraulic conductivity. When combined with evapotranspiration data, these properties would likely produce plant stress from drought conditions during periods of the growing season.

Expanding on previous research, Potter et al. (1988) investigated the physical properties of different aged (4- and 11-yr) reclaimed minesoils in North Dakota to those of surrounding natural, undisturbed soils. No significant differences in Field-Saturated hydraulic conductivity (Kfs) were detected between the reclaimed 4 yr and 11 yr treatments, suggesting that Ks development had stabilized by this point in time.

Table 2.3 Bulk density and field-saturated hydraulic conductivity (Kfs) of direct placement (DP) and peat:mineral mix (PMM) over secondary mineral material (2˚) reclamation prescriptions from two Oil Sands companies (SUN-Suncor, SYN and two other non-Oil Sands sites), in addition to natural Oil Sands region soils of varying texture . Depth of layers is (1) 0-20, (2) 20-50, and (3) 50-100 cm for each treatment.

Site	Age (yrs)	Layers	Bulk Density ($g\ cm^{-3}$)	Kfs ($cm\ s^{-1}$)	Source
SUN 31†	18	(1) DP	1.08	1.4E-04	Yarmuch (2003)
		(2) OB	1.62	1.4E-04	
		(3) OB	1.67	2.2E-05	
SUN 32†	16	(1) DP	0.72	7.6E-04	
		(2) OB	1.78	4.4E-05	
		(3) OB	1.73	2.8E-05	
SUN 33†	16	(1) DP	0.43	8.6E-04	
		(2) OB	1.57	1.9E-04	
		(3) OB	1.68	2.5E-06	
SYN 10†	3	(1) PMM	0.75	6.1E-04	
		(2) 2˚	1.42	6.1E-05	
		(3) OB	1.43	2.8E-06	
SYN 14†	9	(1) PMM	0.82	6.5E-04	
		(2) 2˚	1.51	5.0E-05	
		(3) OB	1.56	-	
SYN 15††	9	(1) PMM	1.09	3.1E-04	
		(2) 2˚	1.58	2.8E-04	
		(3) TSS	1.52	3.8E-04	
SYN 20††	5	(1) PMM	1.34	5.5E-04	
		(2) 2˚	1.68	2.5E-06	
		(3) TSS	1.61	2.2E-04	
South Bison Hills	1	(1) PMM	0.92	1.0E-03	Meiers et al. (2011)
		(2) 2˚	1.28	0.1E-05	
		(3) OB	1.47	0.1E-06	
South Bison Hills	5	(1) PMM	0.92	3.0E-03	-
		(2) 2˚	1.28	2.0E-04	
		(3) OB	1.47	0.3E-05	

Coal mine		(1) Ap	1.36	-	Pederson
(Pennsylvania)		(2) Ap	1.21	-	et al.
		(3) C1	1.61	-	(1980)
Coal mine	4	(1) DP	1.35	-	Potter
(North Dakota)		(2) 2˚	1.48	-	et al.
		(3) Spoil	1.31	-	(1988)
Coal mine	11	(1) DP	1.39	-	
(North Dakota)		(2) 2˚	1.59	-	
		(3) Spoil	1.39	-	
SV 1	Natural	(1) Ae	1.18	1.7E-03	Zettl et al.
(Coarse)		(2) Bm	1.49	2.2E-04	(2011)
		(3) BC1	1.63	2.7E-04	
CU 1	Natural	(1) Ae	1.59	3.6E-04	Yarmuch (2003)
(Medium)		(2) Bt	1.61	2.3E-04	
		(3) Ck	1.72	4.4E-05	
FU 5	Natural	(1) Ae	1.66	1.3E-04	
(Fine)		(2) Bt	1.61	2.6E-04	
		(2) Ck	1.66	3.5E-05	
FU 8	Natural	(1) Ae	1.12	3.7E-04	
(Fine)		(2) Bt	1.44	9.5E-04	
		(2) Bt	1.47	3.1E-05	

† Overlying overburden material (OB)
†† Overlying tailings sands (TSS)
††† m^3 of porosity per m^3 volume of soil

As coal-mining (and associated reclamation) has been ongoing in the United States for many decades, they are the basis of chronosequence studies investigating the long-term genesis of disturbed soils. Utilizing coal minesoils aged 1 to 50 years old, Schafer et al. (1980) compared morphological and physical characteristics of these reclaimed soils to those of adjacent natural lands and had three main conclusions:

1) Minesoils contain many unique properties. Revisions to the current soil taxonomy are required to reflect these properties.
2) Topsoil measurements of electrical conductivity, soil structure (10-50 years), and organic matter levels (30 years) can approach natural levels within decades.
3) Although disturbed soils have different properties, it does not necessarily make them inferior. Minesoils properly constructed with high-quality materials can surpass the potential of some natural soils.

Schafer et al. (1980) stated that newly-placed minesoils display massive soil structure throughout the profile; however, old minesoils (50 yrs old) exhibit structure nearly equivalent to natural soils both in grade and depth.

Despite the statistical difference found between reclaimed and natural soils in the coal mining industry, recent evidence suggests that this might not be applicable for anthropogenic soil in the Oil Sands region. Yarmuch et al. (2003) measured the soil physical properties of differently-aged reclaimed and natural sites in the Oil Sands to compare soil structure quality. The examination of bulk density, pore size distribution, and field-saturated hydraulic conductivity found no soil structure limitations in reclaimed soils compared to natural sites. In addition, soil structure measurements were consistent between different aged reclaimed soils. This suggests that oil sand reclaimed soils remain stable over time in terms of physical properties.

2.5.1 ***Reclamation Certification***

A key endpoint for Oil Sands reclamation is the handing over of land ownership from the mining company back to the Crown. In order for this to occur, the possessing Oil Sands company must apply and receive a reclamation certificate from the Alberta Government. The certification process is formatted into three parts – Landscape, Soils parameters and Vegetation parameters – from which the applied reclamation site is scrutinized for a particular set of standards (AE-SRD, 2011). A frequent requirement for the approval process is that “onsite properties must be comparable to offsite properties”, which is consistent with the emphasis placed on re-establishing native ecosystems and productivity (CEMA, 2006). Seven different professional regulatory organizations (i.e. Alberta Institute of Agrologists) are involved in the approval process (AE-SRD, 2012).

Many of the mentioned requirements, particularly within the vegetation parameters, need time after placement in order to be properly assessed and their long-term viability projected. Therefore, the reclamation certification process typically occurs decades after initial soil placement. To date only one Oil Sands site has been successfully reclaimed according to these requirements. In 2008, a 104-hectare parcel of land known as Gateway Hill was issued a reclamation certificate by the Alberta government, and possession was transferred back from Syncrude to the Crown as public land. Initially an overburden dump, Gateway Hill was decommissioned in the early 1980’s and overlaid with PMM topsoil and planted with shrubs and trees.

2.6 Hydraulic Conductivity

Darcy`s Law represents the basis for quantifying saturated flow through a porous medium (Darcy 1856). In the 19th century, Henri Darcy developed a simple proportional relationship between instantaneous volume discharge through a one-dimensional soil column to the column cross-sectional area, the fluid viscosity, and the total hydraulic head seen here:

$$Q = \frac{-kA}{\mu} \frac{(\Delta H)}{L} \tag{1}$$

Where the total discharge, Q ($m^3 s^{-1}$) is equal to the intrinsic permeability of the medium, k (m^2), the cross-sectional area to flow, A (m^2), and the total hydraulic head drop, ΔH (Pa), all divided by the fluid viscosity, μ (Pa·s) and the length, L (m) over which the change in hydraulic head is taking place. To simplify the equation for water flux proposes, both sides can be divided by the cross-sectional area (A) and fluid viscosity (μ) removed. This water-specific discharge rate is known as the flux density, q ($m^3 m^{-2} s^1$):

$$q = K \frac{(\Delta H)}{L} \tag{2}$$

Where K is a proportionality factor and is generally known as hydraulic conductivity ($m s^{-1}$). A measure of a soils ability to conduct water, hydraulic conductivity depends on the fluid permeability of the soil. K is designated as Ksat for saturated soils. It is important to note that K is not the velocity which the water is travelling through the soil. To determine flux velocity, q must be divided by porosity to account for the fact that only a portion of the total volume cross-sectional area is available for water movement (pore space).

The determination of soil water movement becomes significantly more difficult under non-saturated conditions. In these cases – representing the bulk of field conditions – the hydraulic conductivity of the soil is not a concrete value, but rather is responsive to the changes in soil water content. This phenomenon occurs as the water within the soil pores act as both the product and the conduit – as water is transported out from the soil matrix the soil loses its flow corridors and the K decreases. Adding to the complication, the K- θ relationship behaves non-linearly as the largest pores are the first to empty, leaving smaller and less efficient pores to transmit water. Unsaturated hydraulic conductivity can be presented as K(θ) and K(h), to illustrate the spectrum of K values depending on the specific volumetric water content or matric potential, respectively. Richards (1931) developed a foundational conceptual model that represents the movement of water in unsaturated soils:

$$\frac{\delta\theta_v}{\delta t} = \frac{\delta}{\delta z}\left[K(\theta_v)\left(\frac{\delta h}{\delta z} + 1\right)\right] \quad (3)$$

Where $K(\theta_v)$ is the hydraulic conductivity at any given moisture content (m s^{-1}), θ_v is the volumetric water content (m^3 m^{-3}), h is the matric potential (Pa), z is the elevation above a vertical datum (m), and t is time (s). The Richards formula is based in the saturated flow principals established in Darcy's law, with additional consideration to account for the dynamic soil moisture effects (K(θ)) and the matric 'suction' of the surrounding soil pores.

Soil hydraulic conductivity has been an area of study in the Alberta Oil Sands region. Field-saturated hydraulic conductivity (K_{fs}) is the most-frequently utilized measure of soil hydraulic conductivity in reclamation research – saturated conditions allow for the most straightforward comparisons between different treatments and the 'field' prefix acknowledges that full theoretical saturated is rarely achieved in the field due to air entrapment (Reynolds et al., 1983). Several trends are apparent when examining K_{fs} between natural and reclaimed treatments (Table 2.3). Yarmuch (2003) found no statistical difference between the K_{fs} of reclaimed and undisturbed soils and all sites exhibited hydraulic conductivities within the 10^{-4} cm s^{-1} range for the topsoil depths (0 – 20 cm). Examining the evolution of hydraulic conductivity of a peat mineral mix overlying overburden, reclaimed Oil Sands soils appear to experience the majority of hydraulic conductivity development early in the reclamation period. Meiers et al. (2011) found that K_{fs} increased significantly within the first three years post-placement before leveling off in the followings two years. The underlying shale overburden increased in K_{fs} by approximately a full order of magnitude. The authors attributed this improvement to the freeze/thaw cycle and its ability to promote soil structure development. As expected, coarse-textured soils produced relatively higher K_{fs} values in sandy, undisturbed forests (Table 2.3; Zettl et al., 2011).

On a landscape scale, Kelln et al. (2007) examined the balance between unsaturated (soil matrix) and preferential (macropore) flow of a PMM over OB reclaimed soil. The hydrologic data implies that frozen ground or lower matric potentials (wet conditions) are required prior to large precipitation events for preferential flow to occur. This is congruent with our understanding of the K_{fs}- θ_v relationship, as wet antecedent soil moisture conditions are required to fill the largest pores.

2.6.1 ***Mini-disc infiltrometer***

Due to the heterogeneity of macropores in a soil (cracks, wormholes, old root tunnels), Ksat is extremely spatially variable. This makes attaining an absolute Ksat value for a landscape a challenge. Soils rarely experience field conditions that are truly saturated; therefore, measuring infiltration under a tension prevents water transmission through the largest of the macropores (preferential flow). The resulting near-saturated K value is for the soil matrix, and is less spatially variable.

The minidisc infiltrometer (Decagon Devices Inc., 2012) is an attractive choice for measuring soil hydraulic properties. It combines low water requirements and a compact size to provide extreme transportability for any number of environments, with an ability to apply 0.5 to 6 cm suction heads. Soil hydraulic conductivity measured at a low suction head (i.e. 0.5 cm) can be reported as near-saturated hydraulic conductivity (K_{ns}) as the equivalent matric potential, -0.05 kPa, is nearly indistinguishable from saturation on soil moisture retention curves, however with the ’near’ prefix acknowledging that marcopore-dominated preferential flow is deterred due to the slight suction applied. It must be noted that K_{ns} would be theoretically lower than true saturated conditions due to this lack of marcopore flow. Since its introduction, minidisc infiltrometers have been used to measure in-situ K_{ns} (Johnson et al., 2006), water repellency (Lewis et al., 2006), and robustness at varying slope angles (Bodhinayake et al., 2004). Hunter et al. (2011) compared the effect of disc size had on water repellency for a mini-infiltrometer (4.5 cm) and standard sized infiltrometer (20 cm) - no statistical differences were found between disc sizes mainly due to the intrinsic variance that comes with infiltration tests. Despite examining different phenomena, both water repellency and hydraulic conductivity use cumulative water infiltration's (*i*) relationship with time (*t*) as a basis of their respective calculations.

2.7 Soil Water Retention Curves

Soil water retention curves (also known as soil water characteristic curves, soil water release curves, or soil moisture retention curves) examine the non-linear relationship between the matric potential and volumetric water content of a soil (Figure 2.2). Water retention in soils is controlled by two attracting forces: adhesion forces binding water to a soil particle's surface, and cohesion forces binding water to itself. The combined strength of these forces is referred to as the *matric potential* (Pa) of the soil. The water-soil adhesion forces, called soil sorption, decrease the further the distance away from the mineral surface, illustrating why larger pores are first to empty, as the sorption forces are weaker compared to a relatively smaller pore. Determining the effective pore diameter at a particular soil matric potential can be accomplished using the Kelvin equation (Carter and Gregorich, 2008):

$$d = \frac{4\gamma \cos \propto}{-pgh} \qquad (4)$$

Where d is the diameter (m) of the largest pores that remain full of water after a matric potential (*h*) in meters is applied, γ is the surface tension of water (kg s^{-2}), θ is the contact angle of the water held in the pore (assumed zero); p is the density of water (kg m^{-3}), and g is the gravity acceleration constant (m s^{-2}). The influence of soil texture on effective water-filled pores can be seen on retention curves. Hillel (1982) found that the greater the clay content, the greater the water content at any particular suction.

Soil texture and structure are the main physical influences of water retention. Soil structure plays a greater role at low matric suctions (or inversely high matric potentials) as water cohesion forces are dominant in the high water content environment. The proportional influence of soil texture on water retention has been shown to increase with matric suction. This is due to correlation between decreasing water content, soil-water sorption and the specific surface area of different sized soil particle (Hillel, 1982).

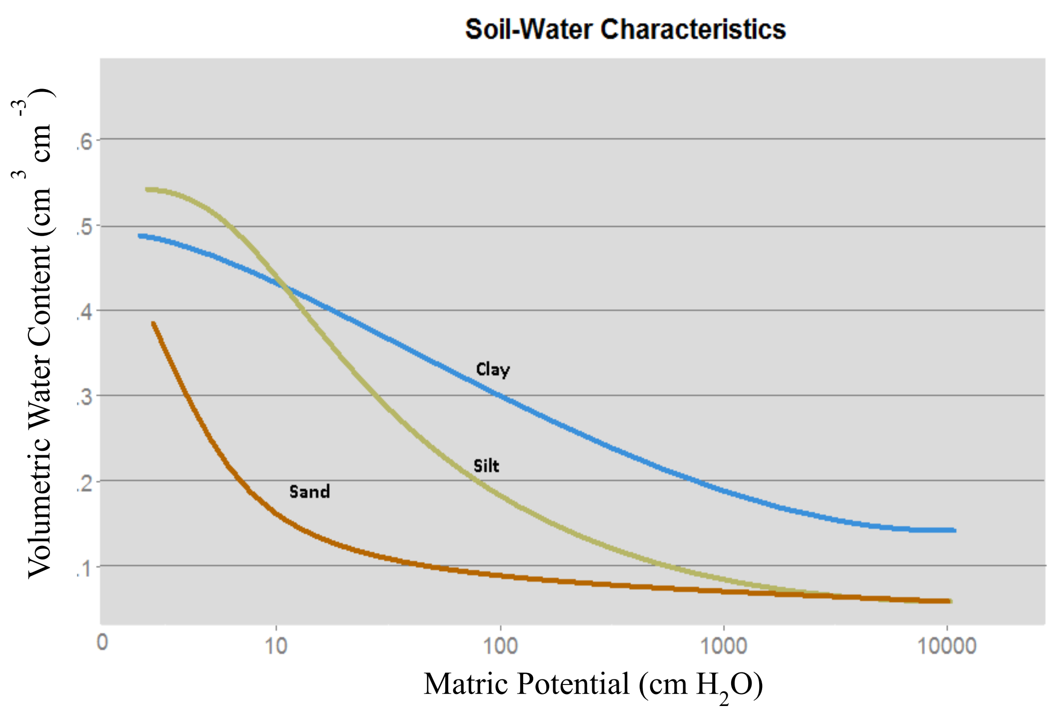

Figure 2.2 Example of moisture retention curve (i.e. soil-water characteristics curve, moisture release curve). Illustrates the relationship between volumetric water content and matric potential.

In recent times the numerical calculation of unsaturated soils has become a pressing issue, particularly in the environmental field. The exponential rise in computing power has led to the development of many soil assessment tools that enable the spatial modelling of water and toxicants (for example - Soil and Water Assessment Tool [SWAT], HYDRUS-3D). Despite the advances, being able to accurately express the water content-suction relationship (i.e. retention function) remains an important component to these models. Brooks and Corey (1964) developed a fitted parametrical model to express effective saturation of a porous media at different pressure heads based on laboratory measurements, with a theoretical pore size distribution. Building on this work, van Genuchten (1980) coupled his closed equation retention model with the earlier Mulaem (1976) equation to predict the unsaturated hydraulic conductivity from soil water retention data. The van Genuchten-Mulaem (1980) unsaturated hydraulic conductivity function is still prominently used in hydrology modelling. Many such parametrical retention models have been developed over the years (Brutsaert, 1996; Campbell, 1974; Ross and Smettem, 1993; Zhang and van Genuchten, 1994; Kosugi, 1996; Poulsen et al., 2002). Unlike the previous models that assume a homogeneous pore structure, some models have been specifically designed for soils that contain heterogeneous pore structures and exhibit bimodal retention characteristics by superimposing multiple unimodal models (Durner, 1994; Seki, 2007).

2.7.1 ***Available Water Holding Capacity***

Available Water Holding Capacity (AWHC) is the soil water that is considered available for plant growth and was initially developed as a tool for determining irrigation rates (Veihmeyer and Hendrickson, 1927). Characterized as the soil moisture content residing between the field capacity (FC) and permanent wilting point (PWP), AWHC can be used to estimate the ability of a soil to support specific vegetation through typical climatic conditions. The matric potential for field capacity is meant to represent the dryness at which water removal due to gravity has "materially decreased". To satisfy this somewhat vague criterion, soils of different textures use different matric potentials to represent field capacity - coarse-textured soils (sand, sandy loam, loamy sand) utilize a matric potential of -10 kPa whilst all other use -33 kPa (Cassel and Nielsen, 1986). The lower limit of AWHC, called the permanent wilting point (-1500 kPa), is the moisture content at which plant roots can no longer extract water from the soil pores.

The Alberta Government requires that reclaimed landscapes share equivalent land capabilities to pre-disturbed sites. To estimate these land capabilities, oil sand researchers have used AWHC as a comparative proxy for natural and reclaimed soils (

Table 2.4). From a water storage perspective, the incorporation of peat significantly enhances the water holding capacity of reclamation soils through the increase in organic carbon (OC). When examining reclamation sites of different ages and prescriptions, Leatherdale et al. (2012) found a positive relationship between AWHC and organic matter content. In a laboratory experiment, Moskal et al. (2001) found that % OC was significantly correlated with field capacity, wilting point, and available water holding capacity in prepared PMM. Textural layering of a reclaimed landscape also affects AWHC (see 2.4.3). A PMM over tailings sands prescription has been shown to consistently store additional water due to the capillary 'break' at the textural interface (Naeth et al., 2011; Chaikowsky, 2003; Leatherdale, 2012). Macyk et al. (2006) summarized that a PMM cap can considerably improve available water holding capacity, partially when placed over texturally heterogeneous substrates (i.e. tailings sands).

Table 2.4 Field Capacity (FC), Permanent Wilting Point (PWP), and Available Water Holding Capacity (AWHC) at different depths for reclaimed and natural soils in the Oil Sands region

Site	Layer†	Depth (cm)	Texture	FC‡	PWP§	AWHC	Source
					($m^3\ m^{-3}$)		
Site 1	PMM	0 - 20	Sandy Loam	0.228	0.097	0.131	Leatherdale et al. (2012)
	TSS	20 – 48	Sandy Loam	0.261	0.089	0.172	
	TSS	> 48	Sand	0.048	0.018	0.030	
Site 2	PMM	0 – 25	Sandy Loam	0.339	0.122	0.217	
	2˚	25 – 83	Sandy Loam	0.249	0.092	0.157	
	2˚	> 83	Sandy Loam	0.226	0.071	0.155	
Site 3	PMM	0-20	Sandy Loam	0.396	0.11	0.286	
	LOS	20 – 57	Sandy Loam	0.327	0.117	0.210	
	LOS	57 – 120	Sand	0.062	0.008	0.054	
Site 4	PMM	0 - 20	Clay Loam	0.23	0.125	0.105	
	2˚	20 - 50	Loam	0.252	0.140	0.112	
	2˚	50 - 100	Loam	0.274	0.150	0.124	
Syn-MLSB	PMM/TSS	0 - 100	-	0.311	0.106	0.205	Zettl (2014)
SV62 ‘b1 ecosite’	Natural	0 - 100	Sand	0.123	0.017	0.106	
SV 60 ‘d1 ecosite’	Natural	0 - 100	Sand	0.149	0.019	0.130	
Sand	Lab	-	Sand	0.11	0.03	0.08	Macyk et al. (2006)
Sandy Loam	Lab	-	Sandy Loam	0.22	0.08	0.14	
Loam	Lab	-	Loam	0.30	0.15	0.15	
Clay Loam	Lab	-	Clay Loam	0.34	0.17	0.17	
1:1 PMM	Lab	-	Sand	0.139	0.055	0.087	Moskal et al. (2001)
1:1 PMM	Lab	-	Sandy Loam	0.263	0.09	0.173	
3:1 PMM	Lab	-	Sandy Loam	0.432	0.207	0.226	

† TSS – Tailings Sands; 2˚ - Secondary Mineral Material; LOS – Lean Oil Sands
‡ Field Capacity of coarse-textured soils (sand - loamy sand) determined at 10 kPa; Fine-textured soils at 33 kPa
§ Permanent Wilting Point determined at 1500 kPa

AWHC measurements can be grouped into three categories: laboratory, field or LCCS. Laboratory experiments use instruments to exert a specific matric potential condition on soil cores (intact or packed) and measure the volumetric water content when equilibrium is reached. This can be done by creating either positive atmospheric pressure (pressure plate) or water suction (tension table) to 'push' or 'pull' water out of the soil pores, respectively (Carter and Gregorich, 2008). Laboratory methods generally underestimate the effective AWHC of a soil profile as they ignore the effects of layering (Elshorbagy and Barbour, 2007). Field approaches utilize excavated moisture content probes and tensiometers to measure water content and matric potential, respectively, in the field. Field measurements have the advantage of being temporally applicable across a whole season (Drozdowski et al., 2013). Finally, the Oil Sands-specific Land Capability Classification System (CEMA, 2006) uses key soil properties to estimate the AWHC of either a natural or reclaimed soil. To better capture the effective AWHC of a landscape, the LCCS uses layering (Table 2.5) and landscape 'multipliers' such as texture, slope %, aspect and water table depth. A comparison of these three methods by Macyk et al. (2006) found the following AWHC relationship: LCCS < Laboratory < Field. The LCCS estimation consistently underestimated the AWHC for PMMs. Compared to the two other techniques, the greater water content measured in-situ was partially attributed to the presence of a shallow water table (Macyk et al., 2006).

Table 2.5 Estimates of increased available water holding capacity provided by textural layering of reclaimed soils from LCCS (2006). SCL - Sandy Clay Loam, Cl – Clay Loam, SL – Sandy Loam, S – Sand.

Soil cover Prescription	Moisture Enhancement (mm)
50 cm SCL-CL Secondary	20-30
20 cm Peat Mineral Mix /40 cm SCL-CL Secondary	30-40
80 CL Secondary	30-110
20, 35, 50 cm Peat Mineral Mix (SL-S)	32-47

Any of these measured and/or estimated AWHC can be used for ecosites prediction. The Guidelines for Reclamation to Forest Vegetation in the Athabasca Oil Sands Region (CEMA, 2009) uses the cumulative AWHC of soil horizons within the top 1 m of the soil profile to estimate the soil moisture regime (Table 2.6). Combined with the measured nutrient regime on an edatopic grid, one can develop an idea of potential ecosites that could be supported by a particular reclaimed site (Figure 2.3).

Table 2.6 Available water holding capacity (AWHC) of soil moisture regimes with associated boreal ecosites. Modified from LCCS (2006).

Soil Moisture Regime	AWHC Range	Ecosite
	mm H_20 per 1 m profile	
Xeric	56 - 85	a
Subxeric	86 - 115	a,b
Sub-Mesic	116 - 145	b,c,d
Mesic	146 - 175	d

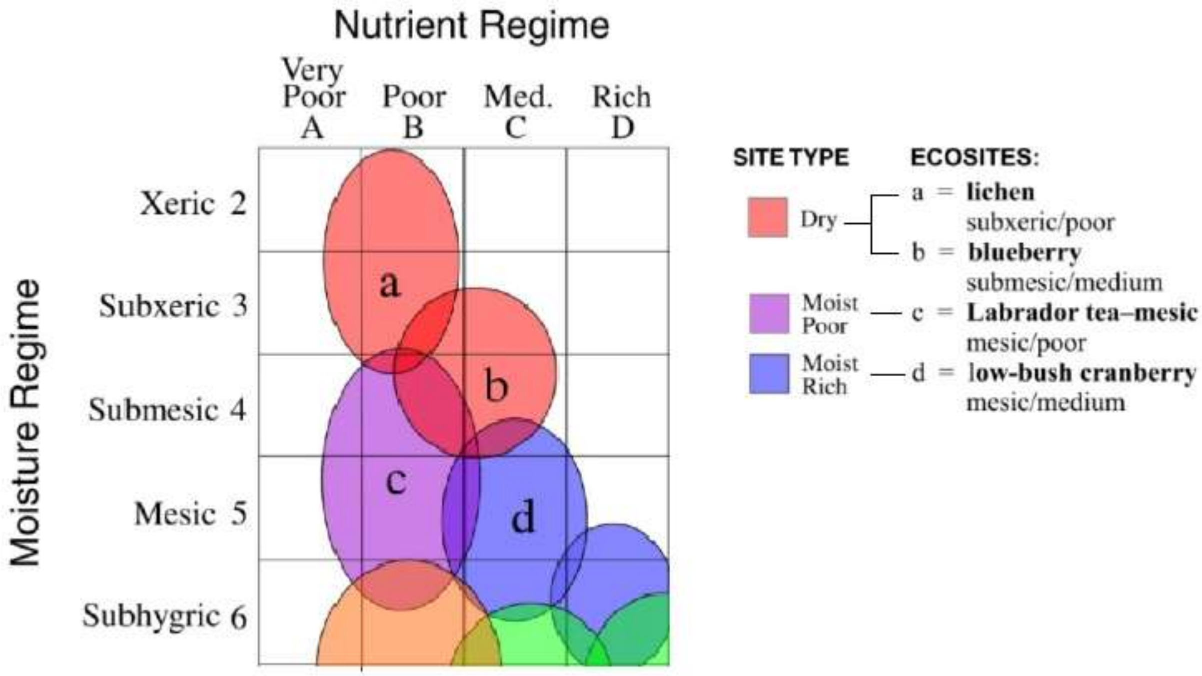

Figure 2.3 Edatopic grid of four ecosites (a, b, c, d) and three site types (dry, moist poor, moist rich) most commonly found in the boreal upland forests of Northern Alberta. Modified from CEMA (2009).

3. Materials and Methods

3.1 Research Sites

Five sites were selected for this study including three reclaimed sites, a fire-disturbed site in the Oil Sands region north of Fort McMurray and an undisturbed natural site near Whitecourt, AB (Figure 3.1). The two reclaimed tailing pond sites were sampled in summer of 2012, and the remaining sites in summer of 2013. Descriptions of the site locations are found in Table 3.1, and typical soil pits in Figure 3.2.

Table 3.1 Study sites with locations, date of establishment and/or disturbance, soil descriptions.

Sites Name	Site Description	Established	Soils Descriptions
WL1	Reclaimed Tailing Pond – Phase 2	2010	Peat Mineral Mix[a]
WL2	Reclaimed Tailing Pond – Phase 1	2009	Peat Mineral Mix[b,c]
RA1	Reclaimed Overburden Dump	2011	Peat Mineral Mix[d]
Burned	Oil Sands Lease	2011	Eluviated Dystic Brunisols
Reference	Forest Management Area	Natural	Orthic Gray Luvisols[e]

[a] 40 cm PMM / 10 cm mineral material / 100 cm densified tailings
[b] 40 cm PMM / 10 cm mineral material / 100 cm densified tailings
[c] Geosynthetic clay liner at 1.7 m
[d] 40 cm PMM/ 100 cm high quality overburden
[e] sporadic Eluviated Dystic Brunisols on knolls

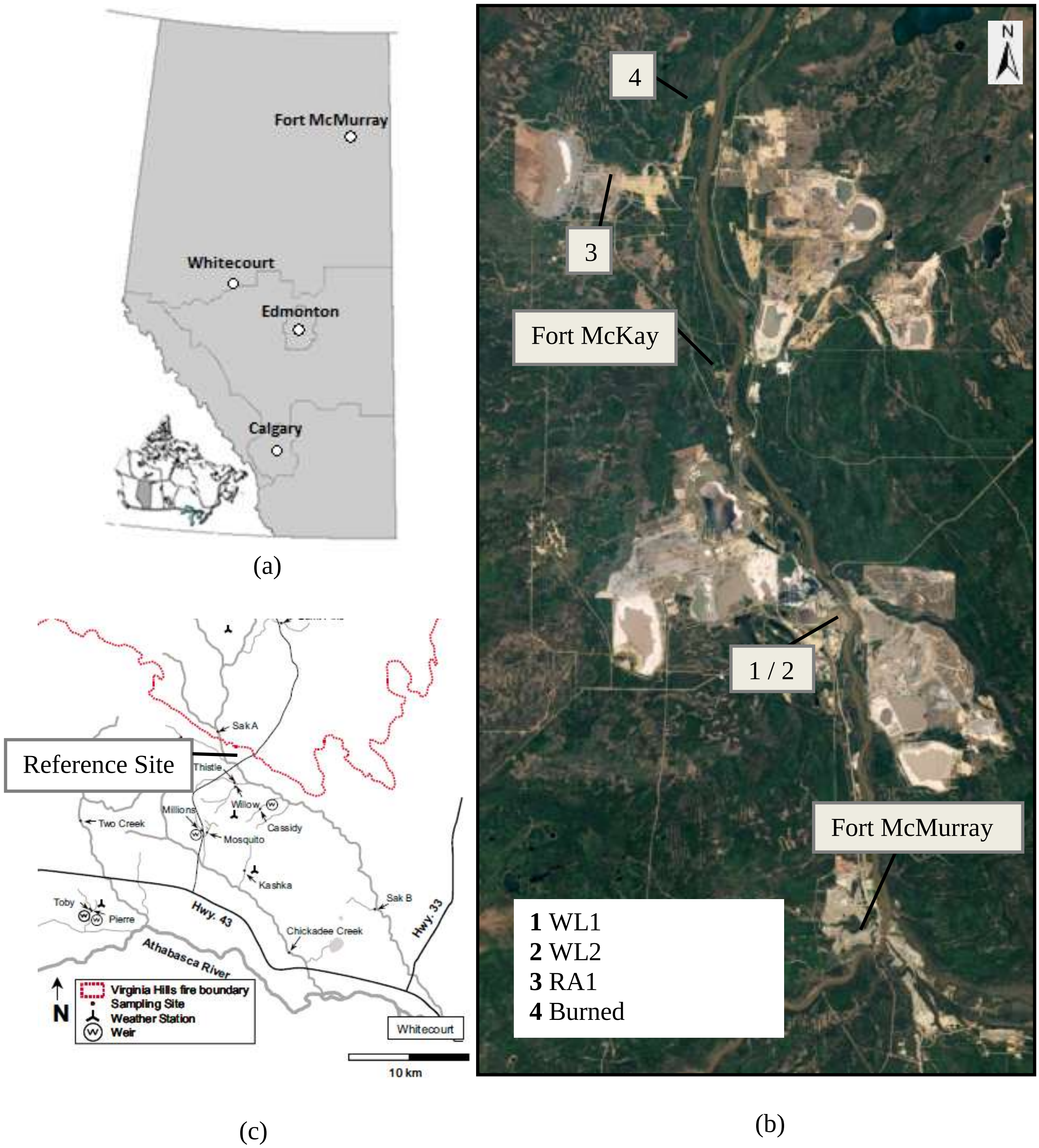

Figure 3.1 Maps of study sites (a) map of Alberta with map of Canada subset; (b) Map of Athabasca Oil Sands regions with study sites highlighted; (c) Map of FORWARD Research Watersheds near Whitecourt with the Reference study site highlighted.

Figure 3.2 Soil profiles of study sites (a) RA1 [PMM]; (b) WL1/WL2 Cover [PMM]; (c) Burned [Gleyed Eluviated Dystric Brunisol]; (d) Natural [Orthic Gray Luvisol].

3.2 Fort McMurray Area

The Fort McMurray area is part of the Mid Boreal Mixedwood Ecoregion (Strong and Leggat, 1992) with variable textured Gray Luvisol soils that support mixedwood forests of trembling aspen (*Populus tremuloides*) and white spruce (*Picea glauca*). Climatically, the region is characterized by long cold winters and short cool summers. At the Fort McMurray Airport from 1971-2000, the daily average temperature was 0.7 ˚C with an average daily maximum and minimum of 6.7 and -5.3 ˚C, respectively (Environment Canada, 2013). Mean annual precipitation was 413 mm with 316.3 mm as rainfall and 96.7 mm as snowfall (Environment Canada, 2013).

3.2.1 ***Reclaimed Sites***

This study specifically collaborates with two Oil Sands Mines located 40 and 75 km north of Fort McMurray, respectively (Figure 3.1). Three reclaimed sites were chosen for this project: A reclaimed tailings pond, with two different soil covers and a reclaimed overburden dump. No known soil characterization data has been published at either site.

The 220-hectare reclaimed tailings pond was the first operational pond in the Oil sands region and began construction in 1967. It demonstrates the technical and operational expertise to stabilize and reclaim large Oil Sands tailings ponds, as well as representing the first reclamation of a whole tailing pond in the Alberta Oil Sands industry. Reclamation first started in 2006 with the establishment of a trafficable surface. A multi-layered soil cover system was applied over the tailings sands to act as a growth medium. The overlying reclamation landscape and cover was designed to develop a sustainable, variable boreal plains ecosystem. During its operational years, Pond 1 received tailings sands as well as treatment water from numerous stages of the bitumen extraction process. Thus, the pond exhibits different physical and chemical characteristics determinant on the tailings source. Due to the heterogeneity of tailing sands quality within the pond, two different soil cover prescriptions were applied: Standard cover (WL1) and Engineered cover (WL2).

Following soil cover placement, a 23.5-25-8 (N-P-K) fertilizer mix was applied via aerial broadcast at a rate of 300 kg per hectare to each cover. Identified noxious weeds were treated with locally-applied herbicide during the summer months of subsequent growing years.

WL1 prescription, starting from the soil surface and moving downward, is as follows:

- 40 cm Peat/Mineral Mix (PMM)
- 10 cm Mineral subsoil material (Sandy Loam)

Winter placement of the cover occurred in 2009-2010 and occupies roughly two-thirds of the total tailing pond surface (
Figure **3.3**). Vegetation prescriptions, planted in the spring/summer following cover placement, can be found in Table 3.2.

WL 2 (Engineered cover) prescription, starting from the soil surface and moving downward, is as follows:

- 40 cm Peat/Mineral Mix (PMM)
- 10 cm Mineral subsoil material (Sandy Loam)
- 120 cm Densified (de-watered) tailings sand
- GCL with adhered High Density Polyethylene liner.

Winter placement of the cover occurred in 2008-2009. Vegetation prescriptions, planted in the spring/summer following cover placement, can be found in Table 3.2.

Figure 3.3 Two Sampling transects on a reclaimed tailing pond in Northern Alberta, Canada. 'S' 1-10 and 'E' 1-10 are the soil sampling points for WL1 and WL2 soil covers, respectively.

Table 3.2 Summary of Ecosite and Planting Prescription at WL and WL2. Taken from Suncor Energy (2011).

Cover	Ecosite	Description	Area (ha)	Estimated Number of Trees	Estimated Number of Shrubs
WL1	B1	Blueberry jack pine - aspen	8.2	16400	4100
	B4	Blueberry white spruce – jack pine	5.5	11000	2750
	B3	Blueberry aspen – white spruce	77.2	154400	38600
	F3	Horsetail white spruce	11.2	22400	5600
	H1/L1	Labrador tea/horsetail/black spruce marsh	2.4	4800	1200
	E1	Dogwood balsam poplar – aspen	0.7	1400	350
WL2	B1	Blueberry jack pine - aspen	10	20000	5000
	B2	Blueberry aspen – white birch	12	24000	6000
	B3	Blueberry aspen – white spruce	36	72000	18000
	B4	Blueberry white spruce – jack pine	9	18000	4500
	D2	Low bush cranberry aspen – white spruce	14	28000	7000
	E1	Dogwood balsam poplar – aspen	4	8000	2000

Reclamation Area One (RA1) is a 90-hectare reclaimed overburden dump (Figure 3.4). The majority of soil placement on this site occurred in the winter of 2010, and a five year research project was started in 2011 to examine the effects of nitrogen fertilization and coarse woody debris (CWD) placement on soil and vegetation quality. There are multiple soil cover x fertilization x CWD treatments present on RA1:

Peat-Mineral with N fertilization (100 kg N/ha)
Peat-Mineral without N fertilization
LFH with N fertilization (100 kg N/ha)
LFH without N fertilization
Peat-mineral with CWD amendment
Peat-mineral with no CWD amendment
LFH with CWD amendment
LFH with no CWD amendment

For this study, only one PMM section with no N fertilizer or CWD treatments (bolded) was selected. The PMM, starting from the soil surface and moving down the profile, consists of the following prescription:

- 40 cm of Peat/Mineral Mix (PMM)
- > 100 cm of subsoil overburden (high quality).

A post-construction soil survey conducted at RA1 measured the mean PMM and subsoil (OB) thickness at 42.7 cm and 160 cm, receptively (Canadian Natural Resources Limited, 2012).

Figure 3.4 Reclaimed overburden dump in Northern Alberta, Canada. Contains both PMM and forest floor soil covers, along with either fertilized or unfertilized treatments. Modified from Canadian Natural Resources Limited (2012).

3.2.2 ***Burned site***

The Fire-disturbed (Burned) site is a Boreal Plains forest located on the northern, undeveloped portion of the CNRL lease. Brunisolic soils have developed on coarse-textured fluvial deposits originating from the nearby Athabasca River (B. Sey, personal comm. 2014). In the summer of 2011, the Richardson forest fire burned over 700,000 ha and its southern extent reached the upgrader complex of CNRL's Horizon Mine (AE-SRD, 2011). Both the RA1 and Fire sites were 'disturbed' in 2011, presenting a unique opportunity to compare the soil properties of juvenile soils under both anthropogenic and natural disturbances within close geographical distance (Figure 3.1). Sampling points were chosen from wetter, finer-textured material ecosites in an attempt to minimize textural differences between study sites. Due to the wetter conditions and vegetation (i.e. trembling aspen) the fire appeared to have fairly low intensity which is traditionally associated with aspen forest burns (Forestry Canada, 1992).

3.3 Whitecourt Area

3.3.1 ***FORWARD Reference Site***

The FORWARD research watersheds near Whitecourt, Alberta were selected as the undisturbed forested sampling sites. Located approximately 200 km southwest of Ft. McMurray in the Forest Management Area of Millar Western Forest Products Ltd., these watersheds were initially instrumented in the early 2000's to develop models that link water quantity, water quality and disturbance indicators to management practices on the Boreal Plains of western Canada (Smith et al., 2003). This site is classified as a Gray Luvisolic-dominated (Figure 3.2) Boreal Mixedwood Ecoregion, with lodgepole pine (*Pinus contorta*), white spruce, balsam poplar (*Populus balsamifera*) trembling aspen, jack pine (*Pinus banksiana*), and black spruce (*Picea mariana*) found in varying stands (Strong and Leggat, 1992). At Whitecourt from 1981-2000, the daily average temperature was 2.6 ˚C with an average daily maximum and minimum of 8.3 and -3.0 ˚C, respectively. Mean annual precipitation was 544 mm, with 410 mm as rainfall and 134 mm as snowfall (Environment Canada, 2015). The FORWARD watershed was deemed an appropriate natural analogue due to its representative ecosites (b,d), and immense database of historical measurements and intimate site knowledge within the FORWARD project. In addition, within the watershed exists undisturbed, fire-disturbed, and numerous harvested treatments which could fit into future research opportunities.

3.4 Experimental Design

3.4.1 *Transect Design*

Sampling followed a stratified random transect design, with 10 points being sampled along a linear transect at each site (
Figure 3.3 and Figure 3.4). Sampling points selected along the transect were of non-uniform distance and selected to represent the relative proportion of depression, toe slope, midslope and knoll positions within each landscape. Localized randomized was achieved by choosing soil pit locations by tossing a pin flag over a shoulder. This technique was used to prevent site selection bias at the local scale. At the Burned site some deviation from the transect was due to the heterogeneity of fire-disturbed conditions.

The Land Capability Classification System (CEMA, 2006) recommends a minimum post-disturbance sampling density of 10 to 50 ha per sample for selectively handled materials. The largest area examined was WL1 at approximately 160 ha; therefore, the sampling density (160 ha / 10 samples = 16 ha $sample^{-1}$) was appropriate for the study.

3.4.2 *Soil Pit Excavation and Field Measurements*

At each sample point, a 0.5 m x 0.5m soil pit was dug (using shovels) in the soil cover until overburden/tailings sands/C Horizon was reached. Ground disturbance permits were obtained prior to excavation for on-lease sites. If a suitable surface vegetation layer was present, a 'vegetation mat' was cut first, removed and set aside for backfilling in order to minimize disturbance. Next, a bricklayers' trowel was used to cut shallow shelves into one face of the soil pit in a descending pattern, allowing for sampling at each layer. The LCCS (2006) categorized the soil profiles into three consolidated layers: Topsoil (TS) from 0-20 cm, Upper Subsoil (USS) from 20-50 cm, and Lower Subsoil (LSS) from 50 – 100 cm (Figure 3.5). Sampling for each shelf included: near-saturated hydraulic conductivity (K_{ns}) measurement using a mini-disc infiltrometer, soil strength measurements and a soil core (~5 cm dia. x 7 cm long) for determining Bulk Density (BD) and Available Water Holding Content (AWHC). These sampling selves were cut at approximately 5 cm, 30 cm and 55 cm depth and applied to 0-20 cm, 20-50 cm, 50-100 cm soil layers, respectively. At each soil layer, a soil sample was hand-collected from three faces of the soil pit to form a composite sample. These bulk soil samples were air-dried, sieved (2 mm) and put into vials for laboratory analysis. Intact soil cores were required for laboratory analysis of moisture retention curve and bulk density measurements. The 141 cm^3 aluminium soil core (60 mm dia. x 5 mm long) was placed on the cut sampling shelf and driven down using a rubber mallet. Next, the core was removed, covered on both ends, secured and properly labelled. Both the bulk soil samples and cores (BD and moisture release curve) were stored at 4˚C until analysis could be completed. In addition, a complete soil pit and site description was completed for each sample point. Once sampling was completed, the pit was filled back in and the vegetation mat replaced.

In the first year of fieldwork, the initial sampling scheme had samples taken at each prescription layer within the reclamation cover ie. PMM (0-20 cm) and secondary mineral material (50 - 100 cm). However, after the first field season it was decided that this sampling scheme may by neglecting the undeveloped lower portion of the PMM. Therefore, it was decided that the sampling at the remaining sites should emulate the LCCS (CEMA, 2006) technique: Topsoil (TS) from 0-20 cm, Upper Subsoil (USS) from 20-50 cm, and Lower Subsoil (LSS) from 50 – 100 cm. Due to this modification, the two sites sample during the first field season (WL 1 and WL2) consist of two sampling depths (0-20 cm and 50-100 cm), while the following three study sites (RA1, Burned, Reference) have three sampling depths (0-20 cm, 20-50 cm, 50-100 cm).

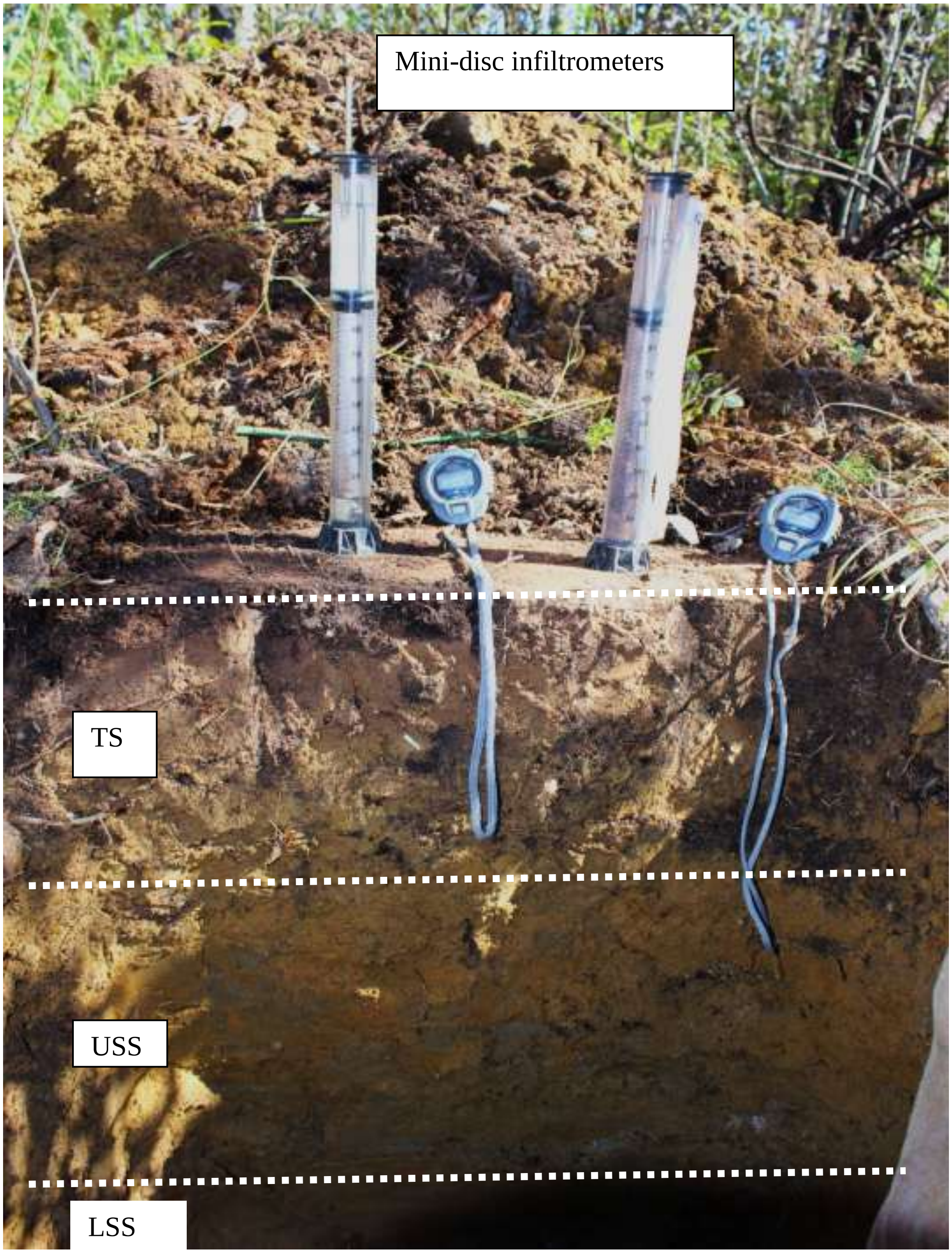

Figure 3.5 Mini-disc infiltrometers measuring cumulative infiltration over time in a Burned Brunisol. Dashed lines represent boundaries between samplings depths - TS, Topsoil (0-20 cm); USS, Upper subsoil (20-50 cm); LSS, Lower Subsoil (50-100 cm).

3.4.3 ***Tension Infiltrometer***

Near-saturated hydraulic conductivity (K_{ns}) was measured with a mini-disc infiltrometer (Figure 3.5) at 0.5 cm tension (Decagon Devices Inc., 2012). The term 'near-saturated' reflects that even a slight tension will prevent preferential flow in the widest of marcopore. In true saturated conditions this preferential flow mechanism accounts for a large portion of the overall water movement. Limiting preferential flow – hence restricting water movement through the soil matrix only – significant decreases the spatial variability of K values and allows site differences to be more easily determined. A trade-off of the K_{ns} technique is it does not represent the true saturated hydraulic conductivity at each site.

The starting water volume was recorded at time zero, and the infiltrometer was placed (assuring good contact) on the soil surface. Water volume was documented every 30 s as the water infiltrated from the water reservoir into the soil until a steady infiltration-state was observed over several minutes. Decagon Device, Inc. (2012) recommends a minimum of 15 ml of water needs to infiltrate in order to accurately calculated K_{ns}. Two K_{ns} measurement were taken at each sampling depth (with the exception of WL1 and WL2, where only one measurement per depth was taken).

The K_{ns} estimation method proposed by Zhang (1997) uses cumulative infiltration (*I*) data to determine near-saturated hydraulic conductivity in a wide-range of dry soils. This method begins with the first two terms of Philip's (1957) one-dimensional infiltration equation:

$$I = C_1 t + C_2 \sqrt{t} \tag{5}$$

Where C_1 (m s^{-1}) and C_2 (m $s^{-1/2}$) are coefficients that are related to soil sorption (S) and hydraulic conductivity, respectively. Both coefficients are determined by fitting the cumulative infiltration data to time (*t*) using a maximum neighborhood method (Marquardt, 1963). Zhang

(1997) suggested that C_2 could be related to the near-saturated hydraulic conductivity of the soils surface through simple linear expressions:

$$K_{h0} = \frac{C_2}{A_2} \tag{6}$$

Where A_2 is a unit-less value representing the sorption properties of a given soil. Using van Genuchten (1980) water retention model, A_2 is closely related to the parameters α (cm^{-1}), and *n* (dimensionless) which represent air entry suction and pore-size distribution, respectively. Zhang (1997) performed numerical experiments to estimate the empirical relationship between A_2 and soil retention parameters, physical infiltrometer parameters and initial water content. Depending on the value of *n*, two A_2 equations were derived:

$$A_2 = \frac{11.65(n^{0.1} - 1) \exp[2.92(n - 1.9)\alpha \mathrm{h}_0}{(\alpha r_0)^{0.91}} \qquad n \geq \; 1.9 \tag{7}$$

$$A_2 = \frac{11.65(n^{0.1} - 1) \exp[7.5(n - 1.9)\alpha \mathrm{h}_0}{(\alpha r_0)^{0.91}} \qquad n < \; 1.9 \tag{8}$$

Where h_0 is the negative infiltrometer suction value at the disk surface (cm), and r_0 the disc radius (cm). These empirical relationships allow A_2 to be estimated using only soil texture class and suction values for a mini-disc infiltrometer.

To validate the robustness of the empirical estimations used by the Zhang (1997) method, Dohnal et al. (2010) ran three-dimensional axisymmetric flow simulations on a wider range of soils. The original Zhang (1997) simulations were performed on two hypothetical soils and four real soils, while the Dohnal et al. (2010) simulations included 12 soils of different soils textures, modelled using the ROSETTA pedotransfer function (Schaap et al., 2001), as well as two intact field soils. Assessing K_{h0} accuracy using relative error, the Zhang (1997) estimations were found to be insufficient for soils with an $n < 1.35$. The following modified A_2 equation was optimized by Dohnal et al. (2010) utilizing a new dataset of 16 soils:

$$A_2 = \frac{11.65(n^{0.82} - 1)\exp[34.65(n - 1.19)\alpha h_0}{(\alpha r_0)^{0.6}} \qquad n < 1.35 \qquad (9)$$

As this study encountered a large number of soils with $n < 1.35$ (ie. Clayey soils), the three different A_2 equations devised by Donhal et al. (2010) were used to determine near-saturated hydraulic conductivity. The A_2 equation used was dependent on the *n* value of the soil: $n \geq 1.9$ = Eq. [7]; $1.9 > n \geq 1.35$ = Eq. [8]; $n < 1.35$ = Eq. [9].

Both Zhang (1997) and Dohnal et al. (2010) require the *n* value for each individual infiltration reading to be estimated based on soil texture class. Table 3.3 illustrates the soil texture class/van Genuchten parameter relationships used by Zhang (1997) and recommended by Decagon Devices Inc. (2012). As previously mentioned, the Dohnal et al. (2010) values were used in this section of the study.

Table 3.3 Summary of van Genuchten parameters (α,*n*) estimated for each soil texture class in both Zhang (1997) and Dohnal et al. (2010).

Soil texture Class	**Zhang (1997)**		**Dohnal et al. (2010)**	
	Estimated α	**Estimated *n***	**Estimated α**	**Estimated *n***
Sand	0.145	2.68	0.035	3.18
Loamy Sand	0.124	2.28	0.035	1.75
Sandy Loam	0.075	1.89	0.027	1.45
Loam	0.036	1.56	0.011	1.47
Silt	0.016	1.37	0.007	1.68
Silt Loam	0.020	1.41	0.005	1.66
Sandy Clay Loam	0.059	1.48	0.021	1.33
Clay Loam	0.019	1.31	0.016	1.41
Silty Clay Loam	0.010	1.23	0.008	1.52
Sandy Clay	0.027	1.23	0.033	1.21
Silty Clay	0.005	1.09	0.016	1.32
Clay	0.008	1.09	0.015	1.25

3.4.3.1 ***K_{ns}* Equation Comparison**

Soil texture tables are used to estimate the α and *n* van Genuchten parameters in both Zhang (1997) and Dohnal et al. (2010) equations (Table 3.3). This presents a problem - the significant hydraulic influence of the peat component within our studied PMM are ignored. Hillel (1982) states that organic carbon imparts similar characteristics as the clay fraction within a soil. Not accounting for the peat component may lead to assuming a ‘coarser’ behaviour within our reclaimed soils than actually exist. To explore this problem, an additional hydraulic conductivity calculation was completed replacing the soil-texture estimated parameters with the intact soil core-measured α and *n* van Genuchten parameters from this study’s soil water retention models (Section 3.4.4.2), and inserted into Dohnal et al. (2010) equation. The original Zhang (1997) model was also included. In total, three K_{ns} models were developed – Zhang (1997), original Dohnal et al. (2010), and Dohnal et al. (2010) with calculated α and *n* parameters from this study. A list of parameters used for each unique calculation is located in APPENDIX A.

3.4.4 ***Laboratory Analysis***

A total of 1,322 discrete laboratory measurements were collected. A list of laboratory analysis sample size and mean values can be found in APPENDIX B and APPENDIX C, respectively.

3.4.4.1 ***Bulk Density***

Within the soil moisture retention curve experiments the intact soil cores needed to be destructively reduced in size between the low and high tension measurements (Section 3.4.4.4). At this time the bulk density was measured. Samples were dried at 100˚C for 48 hours and bulk density determined by dividing the dry sample mass by the core volume (141 cm^3). Coarse fragments (>2 mm) were found to be greater than 5% total soil volume for the WL1 and WL2 sites; therefore, bulk densities were adjusted by separating coarse fragments (2 mm sieve) and measuring their dry weight and volume (water displacement method).

3.4.4.2 ***Particle Size Analysis***

The modified pipette method was utilized to determine relative proportions of sand, silt, and clay of each soil sample (Indorante et al., 1990). Clay, silt and sand particles range from <0.002 mm, 0.002 – 0.05 mm and 0.05 - 2 mm respectively. Briefly, 20 g samples were pre-treated with hydrogen peroxide to remove organic matter. Calgon® solution was added and shaken overnight to assist in clay dispersion. Standardizing for the air temperature within the lab, the samples were left to settle for approximately four hours, and then a 10 mL subsample was extracted with a vacuum-connected pipette from a 5 cm depth. This subsample was oven-dried, weighed, and then extrapolated based on liquid volume to determine soil clay content. The sand-sized fraction was measured via 50 μm sieving. Finally, the silt fraction was considered the unaccounted weight remaining after considering the clay and sand fractions from the total weight.

3.4.4.3 ***Chemistry***

Soil chemical analyses of soil samples included pH, electrical conductivity (EC), total carbon, organic carbon (OC) and extractable Nitrogen (N) and Phosphorus (P). A 2:1 water-to-soil dilution slurry was made to determine pH and EC on a pH/EC glass electrode meter (Model FG2, Mettler Toledo). Organic carbon samples were first pre-treated with a HCL fumigation to remove carbonates (Harris et al., 2001) and measured using a dry combustion Carbonator (Model CR-12, LECO). Extractable N as nitrate (NO_3) and ammonium (NH_4), and extractable P (PO_4) were measured using a 2M KCl extract and Modified Kelowna extraction, respectively (Soon and Hendershot, 2008). Both extracts were analyzed on a Technicon AutoAnalyzer II (SEAL Analytical. Mequon, WI).

3.4.4.4 ***Soil Moisture Retention Curves***

The soil water retention relationship between soil matric potential (h) and volumetric water content (θ) was examined by tension table and pressure plate methods on intact soil cores. Both devices operate by applying suction/pressure conditions to a saturated, cored soil sample and allowing excess water to be expelled. At equilibrium, all soil water is considered held at a tension lower than the applied tension. Tension tables are generally chosen for the $0 < h < -1$ m range due to its stability at lower matric potentials and higher sample capacity (Reynolds and Topp, 2008). The tension tables used in this study were custom-built acrylic boxes measuring approximately 75 x 45 cm, with perpendicular grooves milled into the base to allow water drainage. To ensure good hydraulic contact with the cores, a layer of silt-sized (25 – 50 μm) tension medium was poured onto the bottom of the table with a piece of filter paper separating the tension medium from the underlying drainage grooves. The tension of the table was achieved with a constant head.

Saturating the core without creating air pockets involved a series of steps (Reynolds and Topp, 2008). First, both ends of the core were covered with cheesecloth and placed in water approximately half the core's height. After 24 hours, the core was flipped and left to saturate for an additional 24 hours. The water level was then raised to submerge the whole core for a final 24 hours. Once fully saturated, the cores were placed on the table/plate at prescribed tensions and the cores were measured daily for total weight. Equilibrium was achieved when < 0.1 g daily variation was measured and the tension was then increased to the next highest setting. From these measurements, volumetric water content was determined by the following calculation:

$$\theta = \frac{Wet\ soil\ wt. - Dry\ soil\ wt.}{Density\ of\ Water * Core\ Volume} \tag{10}$$

For tensions greater than 100 cm, both 5 and 15 bar pressure plate extractors (Soil Moisture Equipment Corp. Santa Barbara, CA) were used to determine equilibrium weight (Figure 3.6). At the highest two tensions (5000 cm and 15000 cm), the cores were repacked into smaller, 1.5 cm tall sleeves at the same bulk density as the taller intact cores. The total core volume was reduced to improve equilibrium times and water retention at these higher tensions is dominated by soil particle size and not structure in these disturbed cores (Hillel, 1982).

Table 3.4 Tensions, methods and pore-size classification used to calculate moisture retention curve.

Method	Cores	Set Tensions				Pore Size Class	Pore-size
		cm	kPa	psi	bar		um
Tension Table	Intact ($141\ cm^3$)	3	0.29	0.04	0.003	Macropores	1000
		30	2.93	0.43	0.03		100
		70	6.85	1.00	0.07	Mesopores	42
Pressure Plates		100	9.78	1.42	0.1		30
		300	29.3	4.27	0.29		9.85
		700	68.5	9.95	0.69	Micropores	4.22
		1500	146.7	21.33	1.47		2
	Disturbed ($18\ cm^3$)	5000	489	71.1	4.90		0.6
		15000	1467	213.3	14.7		0.2

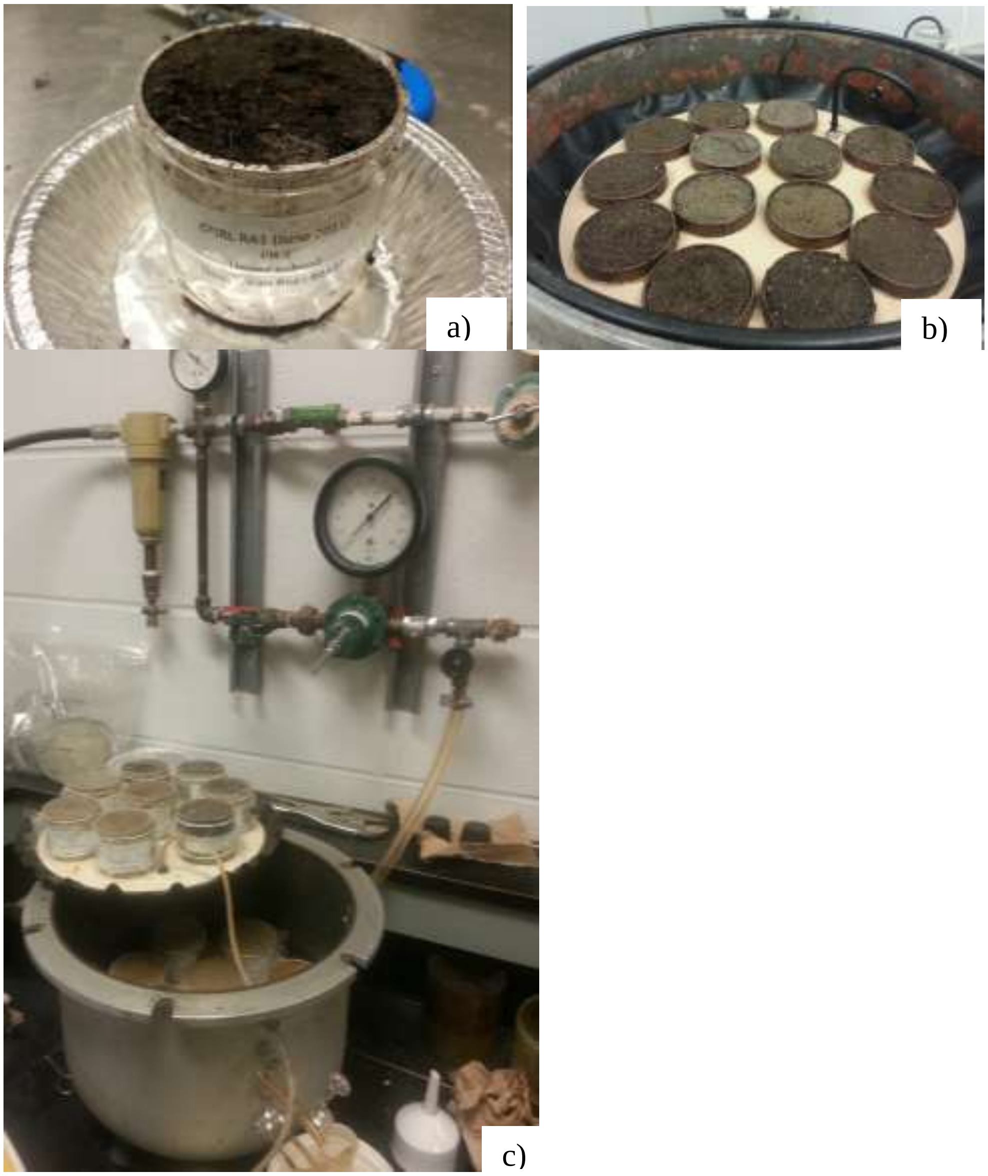

Figure 3.6 Photos of a) 141 cm^3 intact soil core filled with PMM, b) 18 cm^3 disturbed soil cores, and c) pressure chamber with two ceramics plates of intact soil cores.

Originally it was intended for this study to complete retention curves on all 130 soil cores sampled from the five sites (2 sites [WL1, WL2] x 10 pits x 2 depths + 3 sites [RA1, Burned, Reference] x 10 pits x 3 depths). However, due to extremely long equilibrium times and high instrument demand the sample size was reduced to 50 samples (5 sites x 5 pits x 2 depths [0-20 cm, 50-100 cm]). Cores were selected based primarily on core intactness and site representativeness.

3.4.4.1 ***Available Water Holding Capacity***

Available Water Holding Capacity (AWHC) is the mathematical difference between the water held at field capacity and permanent wilting point. This study defined field capacity as 10 kPa for coarse-textured soils (sand, sandy loam, loamy sand) and 33 kPa for fine-textured soils (remaining soil texture classes). The lower limit, permanent wilting point, was established at 1500 kPa for all samples.

Laboratory-derived AWHC was calculated as the difference between texture-appropriate FC and PWP values measured in the soil moisture retention curves study (Section 3.4.4.4). Using intact soil cores allows for discrete, tangible AWHC values to be measured; however, it does not account for field conditions effects such as landforms or water tables on the real in-situ water availability.

Land Capability Classification System (LCCS; CEMA, 2006) is an Oil Sands-specific tool developed to more easily estimate the AWHC of either a natural or reclaimed soil without the time consuming process of determining water retentions. As shown in Table 3.5, soil texture is the key device used to determine the AWHC of each soil horizon – the sum of 1 m depth is considered the total soil profile AWHC. Furthermore, LCCS uses layering (Table 2.5) and landscape ‘multipliers’ such as texture, slope %, aspect and water table depth to better represent the in-situ water availability that a core-based method cannot capture.

Table 3.5 Available water (mm H_2O) per thickness of soil horizon (cm^{-1}) as determined by soil texture and parent material. Modified from Land Capability Classification System (LCCS; CEMA, 2006).

Field Capacity Soil Suction	**Description**			**Texture class**	**mm H_2O cm^{-1} Soil**
n/a	Organic material	Surface	Natural	n/a	0.0
	(> 17% TOC)		Reclaimed	n/a	0.0
		Buried	Reclaimed	n/a	1.0
10 kPa	PMM			LS, S	1.2
				SL or finer	1.7
	Tailing sands			LS or S	1.0
	Sand			S	0.8
	Loamy sand			LS	1.1
	Sandy loam			SL	1.4
33 kPa	Loam, sandy clay, sandy clay loam			L, SC, SCL,	1.5
	Clay loam			CL	1.7
	Silty loam, silt, silty sand			SiL, Si, SiS	1.8
	Clay, silty clay loam, silty clay			C, SiCL, SiC	1.6

3.4.4.2 ***Soil Hydraulic Models***

The SWRC Fit Program (Seki, 2007) was used to fit different soil hydraulic models to the soil water retention curves by the Levenberg-Marquardt method. Initial parameters were internally estimated based on soil texture and then nonlinear-fitting of each model was performed.
Five equations for modelling soil water retention were tested, shown in their effective saturation (S_e) derivatives:

1. The unimodal equation proposed by Brooks and Corey (1964):

$$S_e = \begin{cases} \left(\frac{h}{h_b}\right)^{-\lambda} & (h > h_b) \\ 1 & (h \leq h_b) \end{cases} \tag{11}$$

2. The unimodal equation proposed by van Genuchten (1980):

$$S_e = \left[\frac{1}{1 + (\propto h)^n}\right]^m \quad (\propto > 0, n > 1, 0 < m < 1) \tag{12}$$

3. The unimodal equation proposed by Kosugi (1996) employing a log-normal pore size distribution:

$$S_e = Q\left[\frac{\ln(\frac{h}{h_m})}{\sigma}\right] \tag{13}$$

4. The bimodal equation proposed by Durner (1994) which obtained the flexibility necessary to describe multimodal retention features by superimposing van Genuchten (1980) models. For this study, k=2:

$$S_e = \sum_{i=1}^{k} w_i \left[\frac{1}{1 + (\alpha_i \propto h)^{ni}}\right]^{mi} \quad (0 < w_i < 1, \sum w_i = 1) \tag{14}$$

5. The bimodal equation proposed by Seki (2007) that used the log-normal pore size distribution function of Kosugi (1996) with the multi-curve feature of Durner (1994) to achieve a bimodal fit. For this study, k=2:

$$S_e = \sum_{i=1}^{k} w_i \, Q \left[\frac{\ln(\frac{h}{h_{mi}})}{\sigma_i} \right] (0 < w_i < 1, \sum w_i = 1) \qquad (15)$$

Where *h* is the suction head; λ is the pore-size distribution index of the medium (dimensionless); h_b, α, n and m are calculated fitting parameters (dimensionless), where m=1-1/n; σ is a dimensionless parameter (σ > 0) of the standard deviation of the log-normal pore size distribution; Q is the complementary normal distribution function; *wi* is the weighing factor used for the subcurves of the multimodal models.

3.4.5 ***Statistical Analysis***

Statistical analysis was conducted using R (R project. v 3.1.1). Data exploration investigated normality of distribution and possible transformations. Results were visually inspected for normality using Quantile-Quantile plots, histograms, and box-and-whisker plots. The vast majority of unique treatments (site x depth x soil property) exhibited normal distribution. To correct for non-normal skewing, outliers were removed in order of intensity to determine if they were affecting normality. If the removal of an outlier did not improved normality, it was preserved; if deemed an enhancement of normality, it was removed. These corrected data sets were further verified with a Shapiro-Wilk test to ensure normality was within an adequate p value < 0.1 (Royston, 1995). In total, eleven of the 1,530 unique samples were removed to ensure normality and a note of caution was added to the analysis. Due to the extreme spatial variability of near-saturated hydraulic conductivity, those measurements were log-transformed and presented as box-and-whisker plots to illustrate a range of naturally-occurring values.

An analysis of variance within the general linear model framework was used to determine significant parameters for each soil property tested. To further compare between levels within a parameter (i.e. different depths), a Tukey's multiple comparisons of means Post-hoc test was performed (R package: *multicomp*). For both the ANOVA and Tukey's tests a significance level of $p = 0.05$ was used.

Pseudo-replication was present within this study as each sampling transect was located within a single, confined field. This attribute is caused by the exclusivity of sites; only one intact reclaimed tailings pond in the Oil Sands region exists. Due to the uniqueness of these sites, there was no corresponding sampling locations that would mitigate the errors afforded by pseudo-replication. Therefore, the scope of inference of this analysis is directly limited to the sites sampled within the project.

4. Results

4.1 Characterization of Research Sites

4.1.1 *Soil Profile Descriptions*

The type and depth of soil horizons measured at both the reclaimed and natural soil profiles are presented in Figure 4.1. The mean total soil cap thickness of WL1 and WL2 soil covers was 79 ± 26 and 64 ± 17 cm, respectively (Table 4.1). RA1's mean total soil cap thickness was determined to be ≥ 100 cm as the soil cover was too thick to measure with non-mechanical equipment. CNRL measured mean subsoil cap thickness on RA1 is approximately 1.6 m (CNRL, RA1 Research Project, 2012). The peat mineral mix accounted for 65 %, 67 % and ≤ 39 % of the soil cover for the three reclaimed sites WL1, WL2, and RA1, respectively.

4.1.2 *Soil Particle Size Distribution*

The particle size distribution of the five study sites can be separated into two distinct texture categories. WL1, WL2 and Burned have statistically (p-value = 2.4×10^{-6}) coarser material than the other sites and have sand fractions that are 54-66 %, silt 11-25 %, and clay within 18-27 % ranges, with a majority of sandy loam and/or sandy clay loam soil texture (Table 4.2 and Table 4.3). Conversely, RA1 and the Reference sites consist of a larger proportion of finer materials that range from 22-30 % sand, 26-46 % silt and 25-48 % clay (Table 4.2). The RA1 and References sites are dominated by silt and clay loams textures (Table 4.3).

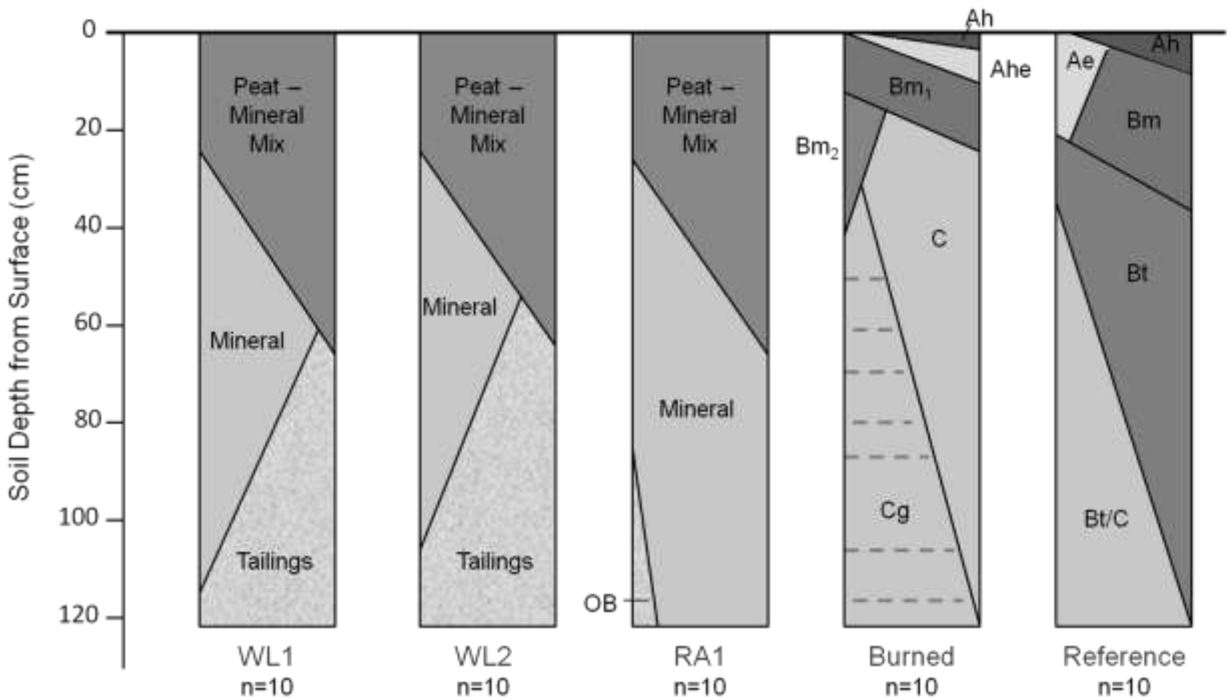

Figure 4.1 Soil profiles of three reclaimed Oil Sands soils (WL1, WL2, RA1), one fire-disturbed forested soil (Burned), and one undisturbed forested soil (Reference). Natural horizons were designated by the Canadian Soils Classification System.

Table 4.1 Mean thickness (cm) and standard deviation of soil cover measured on three reclaimed Oil Sands sites (WL1, WL2, RA1) in northern Alberta, Canada (n= 10).

Site	Peat mineral Mix	Mineral Subsoil	Total Soil cover
		cm	
WL1	50.9±22.0	28.3±26.7†	79.2±26.3
WL2	42.8±12.4	21.6±17.1†	64.4±16.8
RA1	39.0±12.4	61.0±5.8‡	+100‡

† No discernible mineral subsoil horizon present at some points

‡ Soil cover was greater than 1m in thickness and final depth was undetermined at majority of sample points

Table 4.2 Particle Size Analysis of three reclaimed Oil Sands soils (WL1, WL2, RA1), one fire-disturbed soil (Burned), and one undisturbed soil (Reference) determined by pipette method (n=10).

Soil	Reclaimed			Natural	
Depth	WL1	WL2	RA1	Burned	Reference
			Sand (%)		
0-20 cm	57±13a†	66±7a	25±11b	57±15a	30±8b
20-50 cm	-‡	-	25±8b	56±14a	27±12b
50-100 cm	54±16ab	62±10a	26±15b	65±18a	22±8b
			Silt (%)		
0-20 cm	17±5b	15±6b	41±19a	25±12ab	46±9a
20-50 cm	-	-	40±19a	17±8b	41±12a
50-100 cm	22±8ab	18±9ab	26±13ab	11±10b	38±20a
			Clay (%)		
0-20 cm	26±10ab	19±2b	34±15a	18±12b	25±7ab
20-50 cm	-	-	35±20a	27±8a	32±2a
50-100 cm	24±12b	21±6b	48±12a	24±13b	39±19a

† Values in a row with the same letter are not significantly different at a $p < 0.05$.
‡ not sampled

Table 4.3 Soil texture class of ten sampling points (n=10) at three reclaimed Oil Sands soils (WL1, WL2, RA1), one fire-disturbed soil (Burned), and one undisturbed soil (Reference). Number in parentheses represents number of sampling points of that soil texture class at that site x depth. Particle size determined by pipette method.

Depth (cm)	Reclaimed			Natural	
	WL1	WL2	RA1	Burned	Reference
0-20	Sandy Loam (1) SCL† (7) Clay (2)	Sandy Loam (5) SCL (5)	Loam (1) Clay (3) SiL (2) Clay Loam (2) Silty Clay (1) Silty Clay Loam (1)	Sandy Loam (8) Loam (1) Clay (1)	Loam (4) Silty Loam (3) Clay Loam (2) Clay (1)
20-50	-‡	-	Clay (4) Clay Loam (3) Silty Loam (3)	SCL (8) Sandy Loam (1) C (1)	Loam (2) Clay Loam (2) Clay (2) Silty Clay (1) SCL (1) Silty Loam (1) Silty Clay (1)
50-100	SCL (5) Sandy Loam (3) Clay Loam (1) Clay (1)	Sandy Loam (5) SCL (5)	Clay (6) Clay Loam (2) Sandy Clay (1) Silty Clay (1)	SCL (4) Sand (2) Sandy Loam (2) Clay Loam (1) Clay (1)	Clay (5) Loam (2) Clay Loam (2) Silt (1)

† Sandy Clay Loam
‡ Not sampled

4.1.3 ***Physical and Chemical Properties for the Sites***

Mean soil BD for topsoil (0-20 cm) at the WL2 (0.88 g cm^{-3}), RA1 (0.60 g cm^{-3}) and Reference (0.99 g cm^{-3}) sites was significantly lower compared to the Burned (1.25 g cm^{-3}) site (Table 4.4). RA1 upper subsoil (20-50 cm) exhibited the greatest variability in BD amongst all site/depth combinations, which may be a result of the coarse mixing of its two dissimilar substrates – fibric peat and clayey subsoil – leading to a 'mosaic' of high density and low density pockets. The lower subsoil (50-100 cm) in WL2 was significantly less dense at 1.12 g cm^{-3}, (p-value = 0.00011) compared to the other sites, with the exception of WL1 (Table 4.4).

Organic carbon for all sites showed a decreasing trend down the soil profile (Table 4.4). The highest mean OC % in the topsoil was found at RA1 (11.67 %), followed closely by WL2 (9.09 %). Burned topsoil (4.49 %) had similar OC % content to the peat-infused reclaimed sites (Table 4.4). Additionally, topsoil within two reclaimed sites – WL2 and RA1 – had significantly (p-value = 6.3×10^{-5}) higher OC % content than the Reference soil (1.16 %). At the 50-100 cm depth, both reclaimed tailings sites - WL1, WL2 - had significantly higher OC than the natural sites (Burned, Reference).

Extractable soil NH_4^+ levels were the dominant form of extractable soil N at the sites. The other three sites (WL1, WL2, Burned) still had larger proportions of NH_4^+ compared to NO_3^-, but not at the same proportions. The WL1 and WL2 sites had the highest mean NO_3^- concentration at 2.20 ± 3.64 mg kg^{-1} and 3.44 ± 4.11 mg kg^{-1}, respectively (Table 4.4).

Within the top 20 cm, extractable PO_4^- was significantly higher (p-value = 4.2×10^{-7}) at both natural sites (Burned (34.1 mg kg^{-1}) and Reference (22.9 mg kg^{-1})) compared to the three reclaimed sites. At the 50-100 cm soil depth the natural sites (Burned and Referenced) had significantly more extractable PO_4^- compared to WL1 and WL2. The majority of extractable PO_4^- within the natural sites was located within the 0-20 cm layer, while reclaimed sites tended to exhibit a more even distribution throughout the soil profile (Table 4.4).

Table 4.4 Mean and standard deviation of soil nutrients in three reclaimed Oil Sands soils (WL1, WL2, RA1), one fire-disturbed soil (Burned), and one undisturbed soil (Reference).

Soil Depth	Reclaimed			Natural	
	WL1	WL2	RA1	Burned	Reference
			Bulk Density (g cm^{-3})		
0-20	1.13±0.29ab†	0.88±0.18b	0.60±0.26b	1.25±0.18a	0.99±0.25b
20-50	-‡	-	1.08±0.52a	1.53±0.06a	1.48±0.10a
50-100	1.47±0.19ab	1.12±0.22b	1.64±0.17a	1.54±0.07a	1.52±0.06a
			Organic Carbon (% wt.)		
0-20 cm	5.62±2.83ab	9.09±4.79a	11.67±10.11a	4.49±4.27ab	1.16±0.47b
20-50 cm	-	-	3.89±3.90a	0.69±0.13b	0.56±007b
50-100 cm	4.16±1.96a	5.71±4.57a	1.35±0.31ab	0.63±0.07b	0.58±0.19b
			pH		
0-20 cm	8.0±0.15a	7.8±0.24a	7.0±1.04ab	5.3±0.62b	5.2±0.41b
20-50 cm	-	-	7.5±0.27a	5.8±0.65b	5.4±0.36b
50-100 cm	8.1±0.14a	7.8±0.22ab	7.6±0.19ab	6.1±0.73bc	5.5±0.47c
			NO_3^- (mg kg^{-1})		
0-20 cm	2.20±3.64ab	3.44±4.11ab	0.94±0.91b	1.72±1.31a	0.23±0.18b
20-50 cm	-	-	0.59±0.15b	1.72±1.50a	0.17±0.05ab
50-100 cm	1.04±0.13ab	1.38±0.89ab	0.83±0.49ab	1.86±1.33b	0.16±0.06a
			NH_4^+ (mg kg^{-1})		
0-20 cm	6.2±3.19ab	5.8±3.05ab	7.5±2.40a	3.2±0.89b	9.9±9.66a
20-50 cm	-	-	5.0±2.12a	2.9±0.70b	3.4±0.85ab
50-100 cm	4.5±3.06ab	4.4±3.00ab	4.2±1.59ab	2.7±0.57b	4.8±1.42a
			PO_4^- (mg kg^{-1})		
0-20 cm	1.9±1.44b	1.8±0.14b	2.5±1.20b	34.1±23.98a	22.9±18.38a
20-50 cm	-	-	2.1±0.77b	11.4±12.29a	5.1±3.42ab
50-100 cm	1.0±0.47b	1.3±0.39b	2.5±1.45ab	5.6±2.53a	7.0±4.50a
			Electrical Conductivity (dS m^{-2})		
0-20 cm	0.77±0.18b	0.71±0.37b	1.45±0.43a	0.12±0.05c	0.09±0.04c
20-50 cm	-	-	1.62±0.62a	0.13±0.08b	0.04±0.01b
50-100 cm	0.75±0.36bc	0.93±0.32b	1.82±0.90a	0.19±0.17cd	0.04±0.01d

† Values in a row with the same letter are not significantly different at $p < 0.05$
‡ not sampled

Conversion of nutrient levels to volumetric totals (Mg ha^{-1}) can be found in APPENDIX D.

Both WL1 (8.0 ± 0.15) and WL2 (7.8 ± 0.24) had significantly (p-value = 2.3 x 10^{-7}) higher soil pH (more basic topsoil) than the natural Burned (5.3 ± 0.62) and Reference (5.2 ± 0.41) sites. The Reference site demonstrated the lowest pH means at each of the three depths. Both the RA1 and Burned sites had a slight increase in pH with increasing soil depth (Table 4.4). Reclaimed sites had higher mean topsoil electrical conductivity (EC) than either natural sites (Table 4.4). RA1 was measured as having the highest mean EC values with a trend of increasing salts deeper into the profile. Hill slope and aspect at each sampling point were also analysed for correlations with chemical and physical properties, however no significant results were revealed. Data not shown.

4.2 Near-Saturated Hydraulic Conductivity

No significant differences in near-saturated hydraulic conductivity were found between sites within the topsoil (Figure 4.2, p-value = 0.94) or upper subsoil depths (data not shown, p-value = 0.065). However, significant treatment differences (p-value = 0.0012) were detected at the lower subsoil depth where the RA1 and Reference sites had significantly lower near-saturated hydraulic conductivity compared to the Burned site. With the exception of the Burned site, all sites exhibited a decreasing trend of K_{ns} with increasing depth in the soil profile. Outliers indicated by the box-and-whisker plots in Figure 4.2 were deemed valid based on the accompanying soil characteristics of that individual sample point (i.e. soil texture).

The comparison of K_{ns} results derived from utilizing three different K_{ns} models (Zhang, 1997; Dohnal et al., 2010; this Study) on the same infiltration data yielded minor difference between sites x methods (Figure 4.3). Applying different models resulted in both increasing and decreasing means, with no common trend between models. Only singular visual improvements of outliers were seen within the boxplot plotting program.

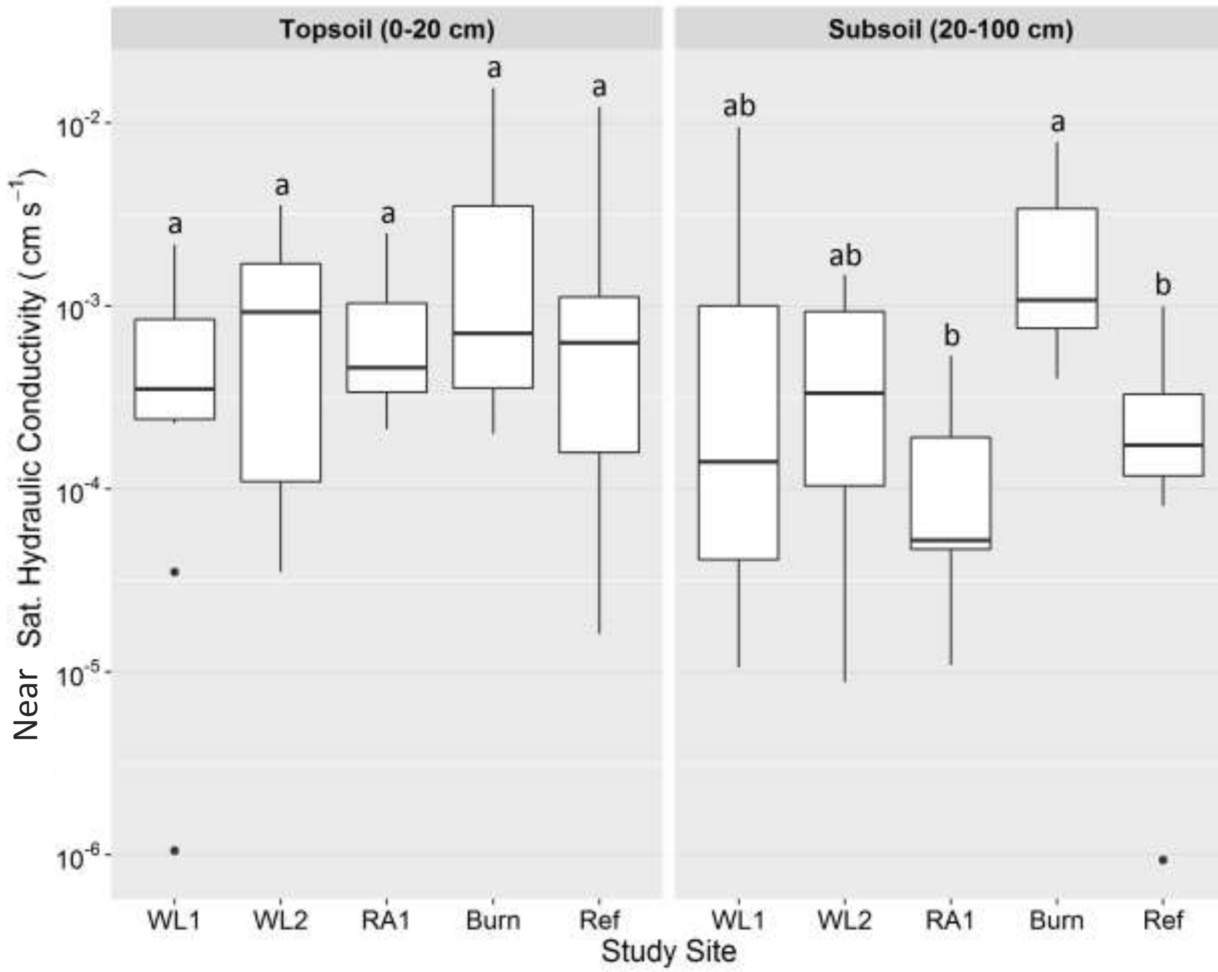

Figure 4.2 Boxplots of near-saturated hydraulic conductivity (cm s^{-1}) of three reclaimed Oil Sands soils (WL1, WL2, RA1), one fire-disturbed soil (Burn), and one undisturbed soil (Ref) by mini-disc infiltrometers on a log-transformed scale. Measurements taken at -0.5 cm tension at approximately 5 cm (0-20 cm) and 50 cm (20-100 cm) depths, at 10 sample points per treatment. RA1, Burned and Reference used two measurements per depth x sample point and results were averaged; WL1 and WL2 used one measurement per depth x sample point. Boxplots with the same letter fo reach depth are not significantly different at $p<0.05$.

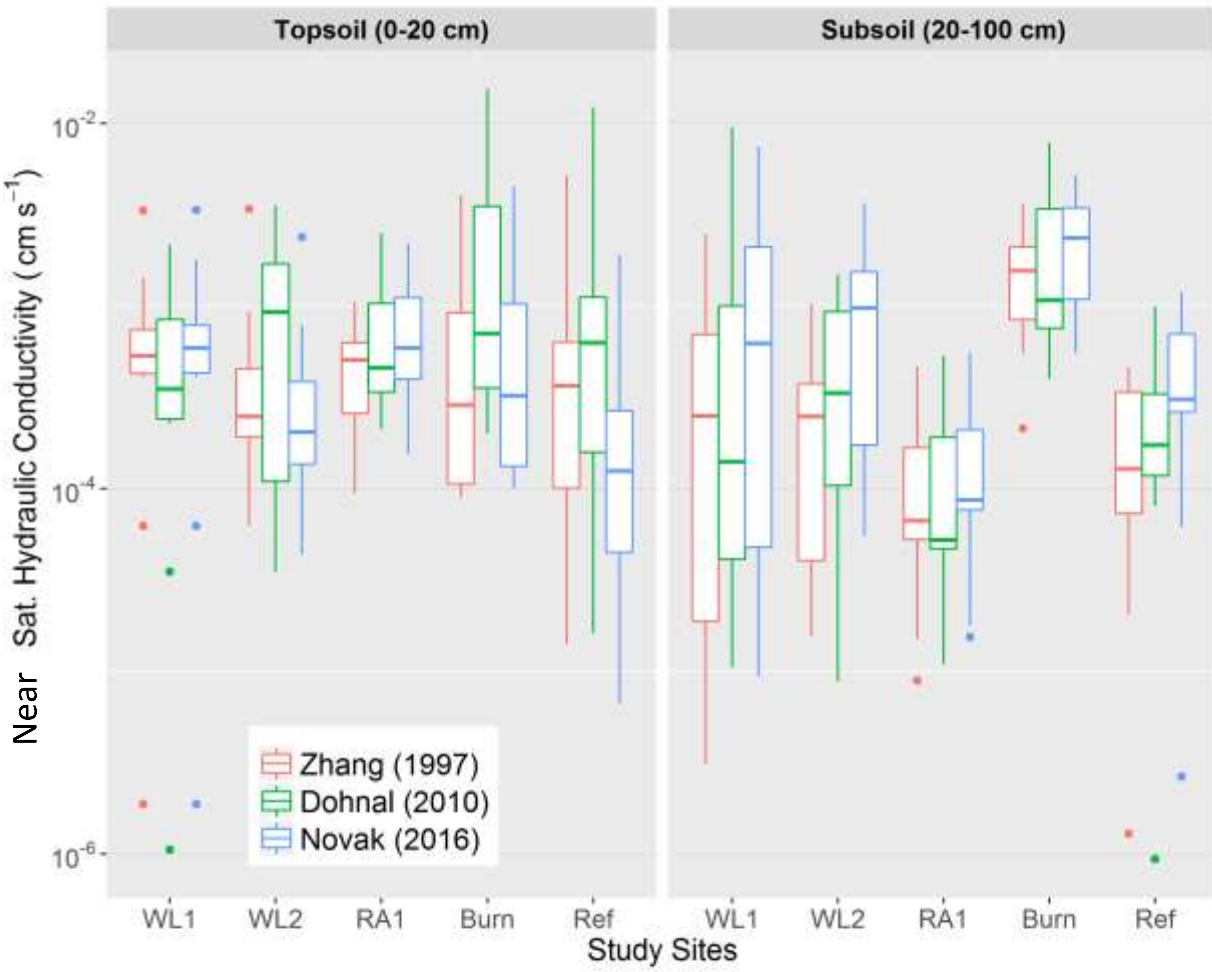

Figure 4.3 Boxplots illustrating near-saturated hydraulic conductivity (cm s^{-1}) outputs from three different models on a log-transformed scale. Zhang (1997) and Dohnal et al. (2010) utilized literature-based soil hydraulic parameters based on the soil texture of each site. Novak 2016 (this study) used van Genuchten soil parameters calculated from the intact soil core results in Table A**.0.1**. Infiltration data was collected from three reclaimed Oil Sands soils (WL1, WL2, RA1), one fire-disturbed soil (Burned), and one undisturbed soil (Ref).

4.3 Soil Water Retention Curves (SWRC)

The VWC of the topsoil layer at the Burned site was lower than all the other sites (Figure 4.4) at all matric potentials excluding the last two potentials (5000 and 15,000 cm H_2O). RA1 had the highest mean water content at all matric potentials for the topsoil. Examining the lower portion (higher tension) of the subsoil SWRC, the order in terms of volumetric water content is Reference > RA1 > WL2 > WL1 > Burned.

Full saturation of the cores was verified by comparing the measured volumetric water content with the theoretical saturated water content based on a 2.65 g cm^{-3} particle density. All samples were within 10% of the theoretical saturated water content (data not shown) with the exception of several samples with high clay content at the RA1 and Reference sites where measured volumetric water content was up to 18% higher (data not shown).

4.3.1 *Soil Hydraulic Models*

Fitting multiple soil hydraulic models to the raw SRWC data resulted in different trends depending on the hydraulic model and soil depth (ie. topsoil vs. subsoil; Figure 4.5). The unimodal-designed models by Brooks and Corey (1964), van Genuchten (1980) and Kosugi (1996) generally performed more poorly compared to the bimodal models of Durner (1994) and Seki (2007). This contrast was especially prominent within the 0-20 cm topsoil SWRCs, where the unimodal models commonly over or under estimated the saturated water content of the SWRC (Figure 4.5), and expressed considerably lower r^2 values (Table 4.5). In addition, unimodal models were unable to calculate non-zero residual water content values for the vast majority of samples at both depths (Table 4.5). The success of the bimodal models within the 0-20 cm depth may be largely due to the inherent bimodal shape of the topsoil SWRCs at four sites – the topsoil at the Burned site was the only site not to exhibit a bimodal shape. Subsoil SWRCs and associated models revealed the expected unimodal trends at all sites. Interestingly, despite the archetypal contours of the subsoil SWRCs, the Brooks and Corey (1964) and van Genuchten (1980) models still extrapolated residual water contents to be essentially zero (Table 4.5).

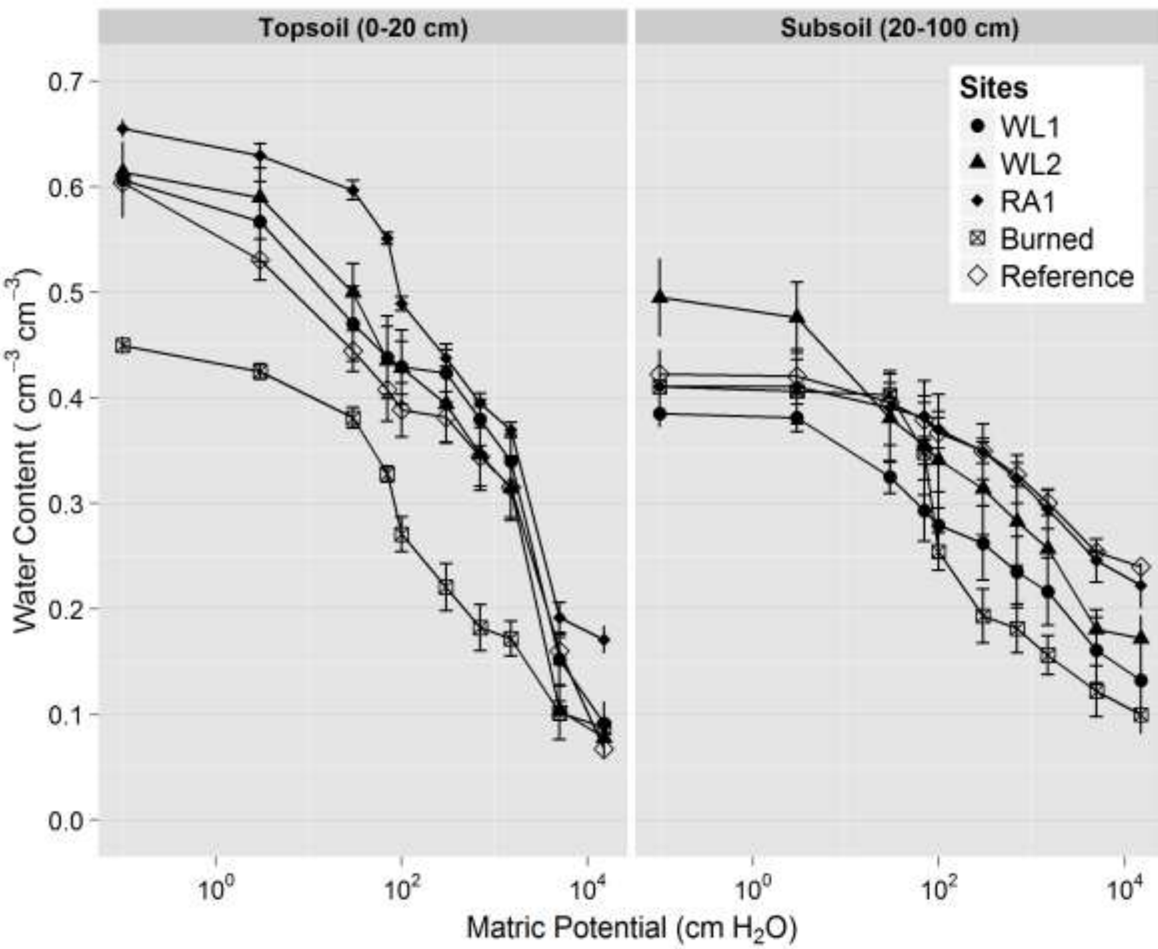

Figure 4.4 Soil moisture retention curves determined by tension table and pressure plate methods for three reclaimed Oil Sands soils (WL1, WL2, RA1), one fire-disturbed soil (Burned), and one undisturbed soil (Reference) at two depths. Symbol point are mean volumetric water content (cm^{-3} cm^{-3}) with standard error bars (n=5).

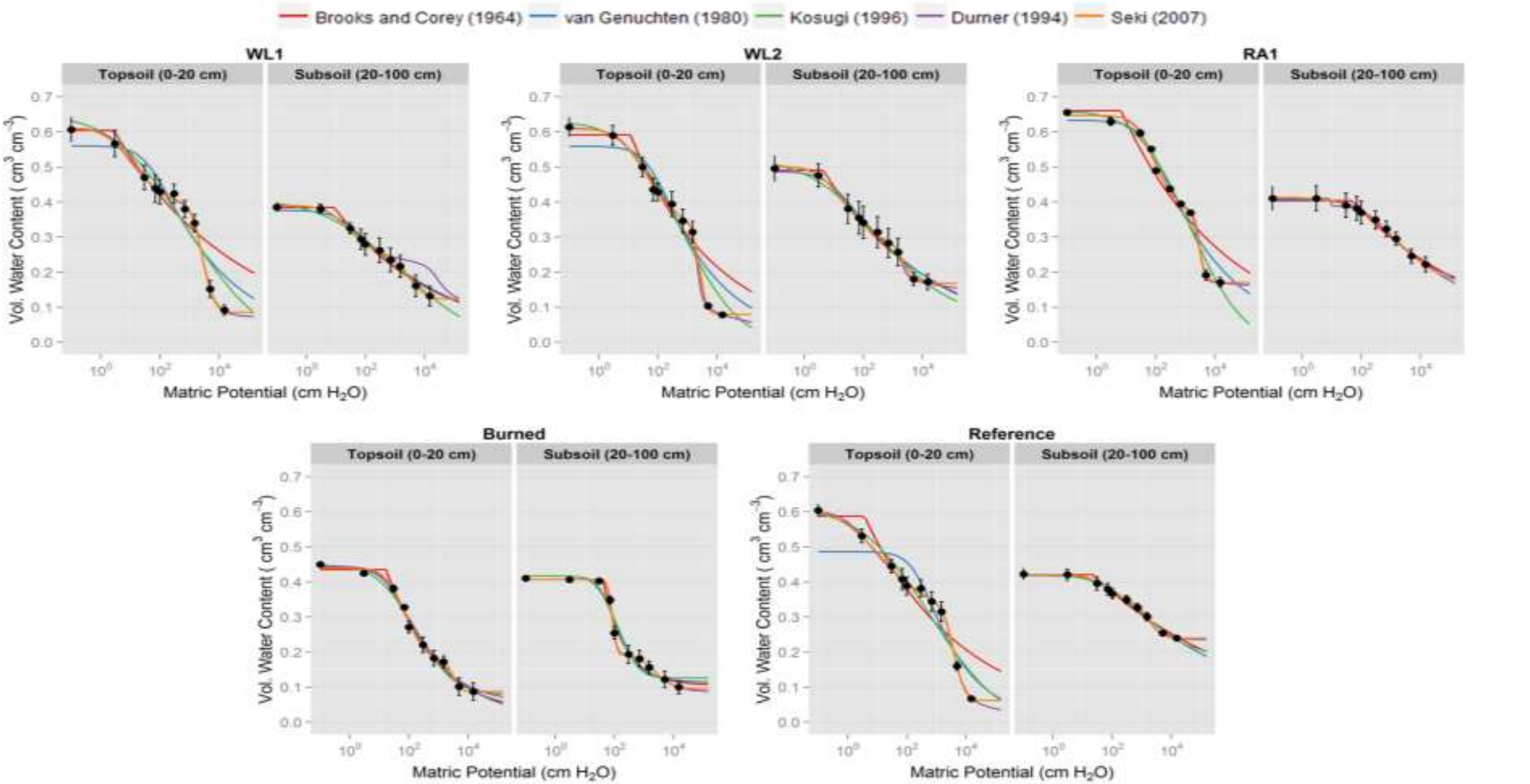

Figure 4.5 Fitting of soil moisture retention data with five soil hydraulic models – three unimodal (Brooks and Corey (1964), van Genuchten (1980), Kosugi (1996)) and two bimodal (Durner (1994), Seki (2007)) for three reclaimed Oil Sands soils (WL1, WL2, RA1), one fire-disturbed soil (Burned), and one undisturbed soil (Reference) at two depths (0-20, 20-100 cm). Solid points and standard error bars show measured volumetric water content (cm^3 cm^{-3}) at 10 matric potentials.

Table 4.5 Calculated model parameters output for five soil hydraulic models. BC = Brooks and Corey (1964), VG = van Genuchten (1980), LN = Kosugi (1994), BD = Durner (1994), BL = Seki (2007). Soil cores collected from three reclaimed Oil Sands soils (WL1, WL2, RA1), one fire-disturbed soil (Burned), and one undisturbed soil (Reference) at two depths (0-20, 20-100 cm). All treatments n=5.

Hydraulic model w/ parameters	**WL1**	**WL2**	**RA1**	**Burned**	**Reference**
			Topsoil (0-20 cm)		
BC					
θs	0.60404	0.59136	0.66015	0.4348	0.58792
θr	7.67E-05	6.22E-04	1.89E-06	1.06E-06	1.66E-05
hb	2.8037	11.913	6.7108	16.971	3.6471
λ	0.10266	0.14998	0.12041	0.23279	0.13164
r2	0.803	0.87249	0.8974	0.98936	0.8568
VG					
θs	0.56	0.56	0.63	0.44	0.49
θr	6.57E-05	1.43E-05	1.62E-05	2.70E-02	4.00E-04
α	0.02	0.02	0.02	0.04	0.00
m	0.16	0.18	0.16	0.23	0.24
n	1.18	1.22	1.19	1.30	1.31
r2	0.88	0.90	0.96	0.99	0.86
LN					
θs	0.65	0.63	0.66	0.45	0.61
θr	0.00	0.00	0.00	0.08	0.00
hm	842.21	684.69	1452.40	170.28	630.38
σ	4.62	3.57	3.29	2.40	4.32
r2	0.92	0.95	0.98	0.99	0.94
BD					
θs	0.61	0.61	0.65	0.44	0.60
r	0.07	0.03	0.16	0.05	0.00
w1	0.46	0.63	0.63	0.97	0.59
α1	0.33	0.11	0.02	0.04	0.83
n1	1.36	1.27	1.62	1.32	1.20
α2	0.00	0.00	0.00	0.00	0.00
n2	2.74	5.65	5.75	42.25	2.82
r2	1.00	1.00	1.00	0.99	1.00
BL					
θs	0.61	0.61	0.65	0.42	0.61

θr	0.09	0.08	0.17	0.11	0.06
w1	0.40	0.52	0.57	0.79	0.52
hm1	14.27	45.49	97.23	75.33	14.79
σ1	1.87	1.94	1.32	0.96	2.87
hm2	2753.80	2516.50	2902.80	0.00	3861.90
σ2	0.74	0.47	0.42	10.59	0.68
r2	1.00	1.00	1.00	0.99	1.00
			Subsoil (20-100 cm)		
BC					
θs	0.38442	0.4905	0.40342	0.40667	0.42
θr	5.23E-06	2.12E-07	2.93E-06	0.1048	1.46E-05
hb	8.7061	4.429	48.07	40.859	22.327
λ	0.1249	0.12058	0.09861	0.5833	0.0834
r2	0.9744	0.98084	0.981	0.9801	0.9792
VG					
θs	0.38	0.49	0.41	0.42	0.4186
θr	7.98E-06	1.12E-04	3.28E-06	1.14E-01	1.65E-06
α	0.07	0.13	0.01	0.02	0.0204
m	0.11	0.11	0.11	0.43	0.09
n	1.13	1.13	1.12	1.76	1.0998
r2	0.97	0.98	1.00	0.97	0.9888
LN					
θs	0.41	0.52	0.41	0.42	0.4213
θr	0.00	0.08	0.17	0.13	0.19415
hm	1695.70	328.50	1659.50	127.99	1101
σ	4.92	4.44	2.76	1.31	2.8355
r2	0.99	0.98	1.00	0.96	0.9923
BD					
θs	0.39148	0.50	0.41	0.41	0.4204
θr	0.11052	0.14	0.15	0.09	0.2346
w1	0.63894	0.80	0.08	0.67	0.5349
α1	0.11656	0.20	0.11	0.01	0.0312
n1	1.3822	1.28	25.97	5.99	1.5557
α2	4.44E-04	0.00	0.00	0.00	0.0007
n2	2.2686	6.16	1.28	1.82	2.6711
r2	1.00	1.00	1.00	1.00	0.9998
BL					
θs	0.39	0.50	0.41	0.41	0.4202
θr	0.12	0.17	0.17	0.10	0.2391

w1	0.53	0.66	1.00	0.69	0.4216
hm1	30.00	26.86	1567.00	83.76	63.574
σ1	1.57	1.90	2.86	0.29	1.1928
hm2	2921.40	2301.10	0.00	2392.40	1750.8
σ2	1.00	0.64	17.33	1.11	0.84892
r2	1.00	1.00	1.00	1.00	0.9999

4.3.2 ***Available Soil Water Holding Capacity***

Soil cores taken from the topsoil layer (0-20 cm) had both higher Field Capacity (FC) and lower Permanent Wilting Point (PWP) water contents than the subsoil, resulting in a greater Available Water Holding Capacity (AWHC) (Table 4.6). The RA1 sites had the highest water contents at both FC and PWP, while the Burned site showed the lowest WC at FC and the Reference site had the lowest WC at PWP. The Burned site had a significantly lower (p-value < 0.01) AWHC compared to the WL1, WL2, and Reference sites. There were no significant differences for subsoil AWHCs between the different sites (p-value = 0.61).

When applying the topsoil (0-20 cm) and subsoil (20-100 cm) lab-derived AWHCs values to a whole 1 m soil profile to calculate a total AWHC value (Table 4.7), no statistical differences were found between study sites (p-value = 0.96). All the soil-core derived AWHCs fell within the 'mesic' soil moisture regime of 146 - 175 mm H_20 per 1 m profile as predicted by the Land Capability Classification System (2006). Conversely, the LCCS-Derived AWHC found significant differences with WL2 having lower values than both the RA1 and Burned sites (p-value = 0.00014).

Table 4.6 Soil core-measured Field Capacity (FC), Permanent Wilting Point (PWP) and Available Water Holding Capacity (AWHC) of three reclaimed Oil Sands soils (WL1, WL2, RA1), one fire-disturbed soil (Burned), and one undisturbed soil (Reference) at two depths (0-20, 20-100 cm).

Site	FC	PWP	AWHC	Dominant Layer
	mm H_20 per mm soil			
			Topsoil (0 – 20 cm)	
WL1	0.423±0.06ab†	0.103±0.04ab	0.320±0.06a	PMM
WL2	0.394±0.08ab	0.078±0.01ab	0.316±0.08a	PMM
RA1	0.438±0.02a	0.171±0.03a	0.267±0.02ab	PMM
Burned	0.271±0.04b	0.088±0.06ab	0.183±0.03b	Ahe
Reference	0.382±0.05ab	0.067±0.02b	0.314±0.05a	Ae
			Subsoil (20 – 100 cm)	
WL1	0.262±0.08a	0.132±0.06ab	0.130±0.04a	PMM/Mineral
WL2	0.314±0.10a	0.172±0.05ab	0.142±0.10a	PMM/Mineral
RA1	0.349±0.06a	0.222±0.05a	0.127±0.03a	PMM/Mineral
Burned	0.254±0.04a	0.100±0.04b	0.154±0.04a	B/C
Reference	0.350±0.03a	0.240±0.04a	0.110±0.03a	B/C

† Values in a column and soil depth with the same letter are not significantly different at a $p < 0.05$

Table 4.7 Comparison of Available Water Holding Capacity (AWHC [mm H_20 per cm]) by laboratory measurements and LCCS (Land Capability Classification System)-derived methods for three reclaimed Oil Sands soils (WL1, WL2, RA1), one fire-disturbed soil (Burned), and one undisturbed soil (Reference) over a 1 m soil profile.

Site	**Lab-Derived AWHC**	**LCCS-Derived AWHC**
	mm H_20 per 1 m profile	
WL1	164±27a†‡	155±17ab
WL2	166±52a	140±10a
RA1	155±26a	167±3b
Burned	160±41a	173±25b
Reference	151±31a	161±5ab

† Values in a column with the same letter are not significantly different at a $p < 0.05$
‡ Subsoil values for reclaimed sites were used for soil cap only. If the soil cap did not reach to 1m depth, literature values of underlying materials (tailing sands = 1 mm H_2O cm^{-1} soil, overburden = 1.6 mm H_2O cm soil) were used for the remaining portion of the 1 m profile.

5. Discussion

5.1 Characterization of Soil covers

5.1.1 *Soil cover Thickness*

The soil covers at the reclaimed tailings pond and overburden dump were designed differently to accommodate the underlying waste material. The reclamation prescription at WL1 and WL2's reclaimed tailing pond called for a total soil cover thickness of 50 cm (Suncor Energy, 2011) as required by the EPEA's Mining Approval (Government of Alberta, 2010b). Both WL1 and WL2 were measured to be slightly greater than the required prescription. This is noteworthy as PMM possesses greater moisture retention per unit of volume than unmodified tailing sand (Moskal et al., 2001; Chaikowsky, 2003). The Land Classification Capability System (CEMA, 2006) recommends tailings sands are given an available water holding capacity value of 1.0 mm available H_2O per cm of material – this value amplifies to 1.7 mm available H_2O per cm of material for a fine-textured PMM. Therefore, an increase in cover thickness will impart greater long-term drought resistance and overall soil moisture into the reclaimed site, as seen in cover thickness modelling (Keshta et al., 2010). However, it is worth noting that this retention growth has the potential to change the water balance of the reclamation site. For example, in a 1 m soil cover overlaying tailing sands, increasing the PMM portion from 50 cm (135 mm available H_2O) to 70 cm (149 mm available H_2O) would hypothetically convert the moisture regimes from submesic to mesic, according to the Land Classification Capability System (CEMA, 2006). Climatic precipitation inputs have not changed in this scenario, therefore this increase in soil moisture availability results from less water leaving the system due to deep percolation, runoff, evapotranspiration, etc. In a reclamation context this is important and will need to be accounted for when auditing the water needs of downstream watersheds.

The mineral subsoil thickness at RA1 was undetermined at nine of the ten sampling points due to the restrictions of augering through clayey subsoil material; a minimum depth of 1 m was reached at all sampling points. Only at one sampling site was the underlying overburden reached with the hand auger (80 cm; Figure 4.1). The RA1 site was previously measured as having a mean PMM thickness of 40 cm and a mean subsoil depth of 1.6 m (Canadian Natural Resources Ltd., 2012). Subsoil thickness was designed to be greater at RA1 than the reclaimed tailing pond due to the risk of salt migration upwards from the underlying saline-sodic overburden into the soil cover. Examining different soil cover prescriptions over saline sodic overburden, Kessler et al. (2010) found elevated electrical conductivity and sodium absorption ratio within 15 to 20 cm above the overburden-soil cover interface within four years of placement. The upwards movement of salts was attributed to diffusion gradients and was not significantly related to cover thickness or slope position. Placing 1.6 m of non-saline subsoil above the saline sodic overburden at RA1 hopes to establish a sizeable 'buffer' zone to help prevent diffusing salts from reaching the above rooting zone and effecting vegetative growth.

5.1.2 ***Particle Size Analysis***

The five research sites can be roughly grouped into two texture classes: Sand-dominated (S > 50% wt.) soils found at WL1, WL2, and Burned; and the fine-textured soils (C/Si > 70% wt.) at RA1 and Reference (Table 4.2). This bimodal trend in particle sizes between the three overarching sites– reclaimed, burned and undisturbed – make comparisons difficult for soil texture-sensitive analysis. For example, the Burned and RA1 reclamation sites present an unique opportunity to directly compare natural and anthropogenic disturbances that are spatially adjacent (< 10 km) and temporally related (2011). The dichotomy expressed by the particle size analysis of the sites did however allow comparisons between fine- and coarse-textured treatments, which was useful in explaining soil water characteristics between treatments.

5.1.3 ***Physical and Chemical Properties***

The physical and chemical properties of all three reclaimed sites reflected an archetypical consistency for PMM over tailings sands and overburden, respectively, and suggest that these intact sites fit within the established reclamation paradigm.

Generally, the measurement of higher peat proportions within the PMM is indicated by higher soil organic carbon along with lower bulk densities at the reclamation sites (Table 4.4). Peat:mineral mixes exhibit lower soil bulk densities due to the relative lower densities of its peat component (Moskal, 2001). Over time, the predicted decomposition of this peat element will be offset by organic inputs from the developing vegetation, and SOC stocks are expected to remain stable in the long-term (Drozdowski et al., 2010). However, The FORWARD Reference Forested sites had the lowest SOC at the 0-20 cm layer across all sites (1.16 %), but the mean bulk density was not different compared to any of the reclaimed sites (Table 4.4). This lack of relationship between SOC and bulk density when comparing all five study sites is somewhat unexpected. A possible explanation is that the reclaimed, fire-burned, and forested reference sites all have unique mechanisms within their topsoil development that overrides a potential SOC- bulk density positive relationship. In reclaimed sites, the antecedent plant structures from the peat component of the PMM produce high SOC, low bulk density topsoils that mimic a well-develop natural soil. In the silty topsoil of the forested reference sites, highly-structured Ae horizons developed by the pedogenic eluviation of organic matter downwards create a platy-structured, high porosity and a SOC-void layer (Soil Classification Working Group, 1998). These are commonly encountered throughout the boreal region (Lavkulich and Arocena, 2011) and produce mean bulk densities less than 1.0 g cm^{-3} (Nyborg et al., 1991). Interestingly, the Burned soils exhibited the highest SOC trends that closely resemble the Reclaimed soils and yet yielded the highest 0-20 cm bulk densities (Table 4.4). Forest fires have been shown to increase topsoil SOC in the years following a burn due to volatile organic matter precipitating down the soil profile, carbon transformation into recalcitrant forms, increased residue incorporation, and reduced mineralization (Certini, 2005; DeBano et al., 1998). Conversely, a lack of strong topsoil structure might be responsible for the greater bulk densities, as the coarser soil textures of the area's Brunisolic soils do not promote structure development as well as the fine textured Reference soils (Figure 3.2; Bronick and Lal, 2005; Smith et al., 2011).

Nitrogen speciation varied across sites. Mean extractable soil N concentrations illustrated a strong $NH_4^+ > NO_3^-$ trend at both the RA1 and Reference sites while WL1, WL2 and Burned sites had more balanced proportions. The only two sites that were significantly different at all depths were the two natural sites. Rowland et al. (2009) found that Oil Sands reclaimed soils have N levels equal to or greater than natural sites, regardless of fertilization practices. However, these N concentrations were typically much more skewed towards available NO_3^- and the authors proposed a reduction in nitrate fertilizers to help better mimic natural ecosites. In this study, the section of RA1 sampled received no fertilization treatment and yielded statistically-similar N results to the natural Reference site, while the fertilized WL1 & WL2 did not (Table 4.4). Comparison of the two reclaimed soil covers in this study reveals that a reduction of nitrate fertilizing practices may indeed promote N-speciation more akin to natural boreal forests.

Extractable soil phosphorous levels were significantly lower in Reclaimed sites compared to either natural sites (Table 4.4). Neither the peat nor mineral components appear to be a ready source of available P as the levels vary little throughout the soil profile, despite the change in the peat:mineral ratio. Although soil N concentrations are typically regarded as the main-driver of boreal forest productivity (Vitousek and Howarth, 1991; Attwill and Adams, 1993; Reich et al., 1997), some studies have shown that soil P appear to be significantly lower or non-detectable in OS peat:mineral mix soils (Rowland et al., 2009; Naeth et al., 2011; Pinno et al., 2012;2015). This P deficiency appears to carry over to vegetation grown on PMM soils. When comparing different Oil Sands reclamation materials, Pinno et al. (2012) noted that trembling aspen established on PMM had the highest foliar N concentration of any material but also the lowest foliar P concentrations. A similar investigation found that foliar P concentrations in RA1 vegetation were significantly lower than adjacent natural stands, contrasting foliar N concentrations which showed no difference (Li et al., 2015). As questions have been raised regarding insufficient phosphorous stores in both reclaimed soil and vegetation, it should continue to be examined closely for its long-term effect on ecosite development.

The inherent alkalinity of the salvaged mineral materials is the reason for the > 7.0 pH of the reclaimed soils (Table 4.4), as peat itself is typically highly acidic (Fung and Macyk, 2000). These pH differences are not extreme enough to have an effect on growing conditions. Electrical conductivity at RA1 approached the 2 dS m^{-2} limit for slight salt tolerance (CEMA, 2006). Table 4.4 shows that RA1 has SOC % decreases strongly with soil depth, which can be associated with decreasing peat proportion within the PMM. Assuming that peat contributes relatively smaller proportions of salts than the mineral subsoil, the increase of EC with depth seen at RA1 may be an artifact of decreasing peat:mineral ratios, rather than an upward movement of salts from the underlying overburden. The overburden directly under the PMM cover is 1 m of non-saline sodic overburden to act as an additional buffer for upward salt migration from the farther underlying waste products.

5.2 Near-Saturated Hydraulic Conductivity

5.2.1 ***Comparison of Sites***

No differences in topsoil K_{ns} values were found between any of the Reclaimed, Burned, or Reference sites. Across all sites K_{ns} showed a decreasing trend with sampling depth, with the exception of the Burned site (Figure 4.2). As discussed in Section 5.3, the well-structured topsoil horizons (Reference) or the residue plant structure in the salvaged peat (WL1, WL2, RA1) are plausible causes of the increased porosity and corresponding water transmission in the topsoil at these sites, as this effect was lost at soil depth. The Burned site lacked the topsoil aggregation of the Reference site due to its coarse soil texture, hence K_{ns} was more consistent throughout the soil profile.

However, a contrarian (or possibly additive) explanation of the Burned sites K_{ns} trend is the Burned site topsoil is being suppressed by fire-derived water repellency. This appears unlikely as both the low burn intensity and sampling depth suggest a relatively minimal treatment effect on the soil. A low intensity burn is mostly likely due to the moist soil conditions and subsequent deciduous vegetation. The Land Classification Capability System (CEMA, 2006) rated seven of the 10 sampling points as a subhygric moisture regime due to the presence of mottling greater than 20 cm down the soil profile. The moisture content of both the LFH and mineral soils are major determinates of fire severity (Bergeron et al., 2002; Certini, 2005), and the black spruce and trembling aspen inhabiting these moister soils typically produce lower severity fires (Larsen, 1997; Forestry Canada, 2002). Secondly, the 5 cm soil temperatures rarely exceed 150°C even in high severity fires (Certini, 2005). This is significant as samples and measurements for the topsoil horizon were taken from about the 5 cm depth of the soil profile and therefore theoretically had relatively little fire effects. Visually the trees appeared burnt only at the base of the bole, and crown combustion was not apparent which would be indicative of hotter burns.

Only one interaction was statistically significant, with the Burned soil exhibiting higher K_{ns} than both the Reference and RA1 soils at the 50-100 cm depth (Figure 4.2). The two aforementioned causes of K_{ns} enhancement are eliminated at this depth as the RA1 soil cover is mineral only (Table 4.1) and soil structure is rare, making it an almost direct comparison of fine (Reference and RA1) and coarse (Burned) soil textures. It is encouraging that the mini-infiltrometer method was able to successfully distinguished between fine and coarse soil textures; however, the extreme spatial variability seen in the K_{ns} results - even with removal of preferential flow (Section 3.4.3) – does raise concerns regarding this method's ability to consistently differentiate between more subtle treatments. That said, these results are comparable with the OS reclamation literature. Yarmuch (2003) detected little to no significant differences between topsoil K_{fs} values of Undisturbed and PMM soils, with both means falling in the 10^{-4} cm s^{-1} order of magnitude, as did this study.

The evolution of these sites should also be a point of interest. On an acute timescale, reclaimed OS soils have been shown to increase in K_{fs} for up to five years' post-placement (Meiers et al., 2011). As the reclaimed sites in this study were between 2-3 years of age at time of measurement, the values of K_{ns} may not yet have reached their equilibrium endpoint. Over longer periods of time the peat is thought to decompose in upland settings without the hydrology necessary to preserve it, suggesting that the benefits of the peat additions will be only temporary (RRTAC, 1993). However, Yarmuch (2003) found no difference in K_{fs} or other significant physical properties between young (5-7 yr.) and older (17-19 yr.) reclaimed soils. Also, the measured carbon inputs and outputs of reclaimed soils appear to be relatively equal up to 25 years post-placement (Drozdowski et al., 2010). Both studies attribute the offsetting of peat decomposing with litter inputs from the established vegetation.

5.2.2 ***Comparison of K_{ns} calculation methods***

While differences in sample K_{ns} values can be seen between methods, the experimental variability is relatively minor compared to the intrinsic spatial variability (Figure 4.3). Therefore, conclusions and trends derived from the shared dataset would be independent of which method is utilized. The lack of significant difference in calculated K_{ns} was surprising considering the relative differences in equations and van Genutchen parameters used as input in each method. This suggests that the Zhang (1997) method and its derivatives are fairly robust to changes in van Genuchten parameters (α and n) and the key-driver of treatment differences is actually the calculated cumulative infiltration (I). Furthermore, these results seem to validate using the literature values of the mineral component in PMM to determine van Genuchten parameters for the whole substrate, such as required in Zhang (1997) and Dohnal et al. (2010) methods; hence, avoiding the time consuming process of measuring and modelling soil moisture retention curves for each unique reclaimed soils.

5.2.3 *Mini-Disc Infiltrometer*

Hydraulic conductivity is a heterogeneric measurement and prone to extreme spatial variation (Scott, 2000). This trait can be exacerbated when working in a coarse mixture of buoyant peat material and dense mineral substrate, leading to a mosaic of contrary soil properties. A tension infiltrometer allows the user to moderate preferential flow by preventing water transmission in pores greater than a certain size through the application of negative tension on the infiltrating water, thus smoothing spatial variability (Reynolds and Elrick, 1991). The mini-disc infiltrometer (Decagon Devices. Pullman, WA) is a miniaturized version of the common tension infiltrometer with a 4.5 cm diameter ring. It substitutes inference size for ease-of-use, and theoretically allows a greater number of measurements to be taken with the purpose of overcoming greater spatial variability with superior sample size. The mini-disc infiltrometer was chosen for its ease of operation, low water consumption and transportability into numerous remote sites in this study.

The majority of previous research have utilized constant head well permeameter methods (ie. Guelph Permeameters [GP]) to determine the saturated hydraulic conductivity in OS reclaimed soils (Yarmuch, 2003; Meiers et al., 2011). Given the number of different K_{fs} measurement methods available, studies have tried to identify the differences and applicability between methods (Huang et al., 2016; Reynolds et al., 2000; Hunter et al., 2011; Gupta et al., 1993) – most have been unable to prove statistically that any method is significantly different due to high coefficients of variation.

Rather than measuring saturated hydraulic conductivity like many previous studies, this study measured near-saturated hydraulic conductivity (K_{ns}) at - 0.5 cm tension in an attempt to reduce macropore-derived spatial variability. The resulting K_{ns} range-of-values were still prominent – often across four orders of magnitude. Any variance reduction by the applied negative tension appear to have been overridden by the relatively small contact area. In addition, the true saturated hydraulic conductivity of these soils would be higher – perhaps significantly – than the measured K_{ns} results due to the inclusion of macropore water transmission. This makes comparison between these K_{ns} results and saturated hydraulic conductivity values from the literature incomplete.

Mini-disc infiltrometers have a limited number of studies in the Oil Sands as it is a relatively new instrument. Overall, the K_{ns} values derived in this study with the mini-disc infiltrometer were able to statistically detected soil texture differences and validated the methodology for peat:mineral mixes. On the downside, variation was still significant within site x depth treatments. As mentioned previously, spatial variation is an inherent feature of soil hydraulic conductivity, and measurement of such should not be necessarily seen as a failure of the measurement system. However, given that measuring at K_{ns} did not seem to improve site variability, and that it limits the literature comparables, it could be suggested that traditional saturated hydraulic conductivity methods might be a better fit for site-to-site comparisons. Upon review, measurement variability may have been improved by using a contact sand to ensure good hydraulic contact (Reynolds and Zebchuk, 1996) and is recommended for similar measurements.

5.3 Soil Water Retention Curves

5.3.1 *Soil Water Retention Measurements*

Similar to the K_{ns} analysis, comparison of soil texture classes assists in solidifying effects of the soil origins. If the study sites are categorized into two distinct texture groups – coarse (WL1, WL2, Burned) and fine (RA1, Reference) – then the effects of the peat additions become apparent. For this analysis to take place, the Burned site could be treated as the natural analogue to the similarly textured WL1 and WL2 sites. This assumption, explained in Section 5.2.1, is feasible as the 2011 forest fire was of low intensity due to antecedent moist soil conditions and had relatively little effect on soil characteristics. When examining the coarse textured soils, the volumetric water contents on the topsoil SWRCs (Figure 4.4) at the reclaimed

WL1 and WL2 have significantly higher values compared to the similarly textured Burned soil. In addition, both WL1 and WL2 have bimodal tendencies while the Burned site had a unimodal distribution. These differences in both shape and moisture values can be attributed to peat additions. Moskal et al. (2001) found that in-situ peat additions to course-texture soils can increase field capacity moisture content, and the bimodal characteristics of peat are well established (Loxham, 1980; Dettman et al., 2014; Shurniak, 2003). It would appear that the peat additions in coarse-textured WL1 and WL2 are allowing the site to behave similar to a fine-textured natural soil, as opposed to a comparably-textured natural soil (Burned). The same cannot be said for fine-textured reclaimed soils. Little difference was seen in SWRC shape and value between the fine-textured RA1 and Reference sites, but it is impossible to separate the peat and/or clay effects at these sites. The combination of these comparisons provide evidence that a coarse-textured substrate, if given the proper amount of peat additives, can exhibit moisture retention characteristics y similar to that of a structured, fine-textured natural soil.

As discussed in Ball and Hunter (1988), intact soil cores are often destructively sampled and re-packed into smaller cores to assist in reducing prohibitively long equilibrium times. At high tensions moisture retention is independent of soil structure therefore reducing core volumes should have no effect. The low density and structured nature of many samples made packing the smaller cores difficult as often the required mass would not entirely fill the necessary volume. In addition, the more fibric peat was broken apart using a mortar and pestle in order to better fit the smaller core. The effect of this packing may be noticeable in the moisture content drop between the 1500 and 5000 cm H_2O tensions in some sites – the point at which the soil cores were converted from the intact to the packed configurations. This theory is supported by the fact that the highest SOC and lowest bulk density sites in RA1 and WL2 seem to have the most significant drop in volumetric water content post -1500 cm H_2O tensions (Figure 4.4). Trends related to SWRC shape are revealed prior to 5000 cm H_2O tension; however, it should be noted that at least a portion of the bimodal curve shape might be an artifact of the SWRC method.

5.3.2 ***SWRC Model Comparison***

The topsoil SWRC calculated by the unimodal models were inferior to the bimodal models in two regards: 1) the r^2 values were consistently lower in unimodal models signifying a poorer relationship with the retention data, and 2) unimodals predicted residual water contents (θres) that were essentially zero (Table 4.5). Based on the soil textures for the sites it would be expected that θres be in the range of 0.06 to 0.10 cm^3 cm^{-3} water content (Nemes et al., 2001). The bimodal models more accurately predicted θres with a range from 0.00 to 0.17 cm^3 cm^{-3} Table 4.5). The inability of the unimodal models to predict residual water contents also makes them less desirable for extrapolating in extremely dry conditions beyond the final 15,000 cm H_2O measurement, as well as raising questions on the interpolated data within the measured tension range.

Durner (1994) summarized four different situations in which a traditional unimodal model will fail to accurately capture the moisture retention trend of a soil: 1) near-saturation conditions in undisturbed soils, 2) linear near-saturated trends in morainic and solifluction soils, 3) significant drop in water content very close to saturation in unconsolidated sands, and 4) multiple sigmoid-shaped (bimodal) retention curves in the mid-pore range of aggregated loams. The last situation described by Durner (1994) can be observed in the SWRC results (Figure 4.4) for the Reclaimed (WL1, WL2, RA1) and Reference soils.

Two different sources can be responsible for this bimodal phenomenon. For undisturbed natural soils, bimodal forms are usually associated with silty loams that promote strong peds development and two distinct pore sizes: meso-pores in the pore network surrounding the peds, and micro-pores within the ped structure itself (Sharma and Uehara, 1968; Smettem and Kirkby, 1990; Coppola, 2000). The Reference soils fit within these criteria both quantitatively and qualitatively as silt was the dominate particle size at all depths (Table 4.2), and strong structure was visually observed at most sites. The second possible catalyst is the peat component of reclaimed soils providing the secondary structure needed for heterogeneous pore systems. Organic soils contain a large macropore network derived from its partially-decomposed plant origins, as well as a great number of smaller pores that enable dual porosity and corresponding bimodal retention characteristics (Loxham, 1980). Dettman et al. (2014) found that bimodal models typically had a stronger fit compared to typical unimodal models, particularly in the near-saturated zone for organic (peaty) soils. In an Oil Sands setting, these peat characteristics confirm the findings of Shurniak (2003) who found that a multimodal Fredlund and Xing (1994) model created a superb fit for soil water retention data from a peaty soil cover at Syncrude's South Hill. It is important to note that Shurniak (2003) did not have a natural reference soil to directly compare the bimodal trends seen in the peaty reclamation soil. The consistent multimodal pattern seen in previous research and across all three different reclaimed soils in this study strongly suggest that the addition of peat within a reclamation cover is an effective method for replicating effective soil structure over a short time period.

5.3.3 *Available Soil Water Holding Capacity*

The Land Capability Classification assigns an AWHC value to a soil layer based on soil texture and soil origin (i.e. natural or reclaimed; CEMA, 2006). Overall, the topsoil AWHC measured by the soil core method had significantly higher values than those predicted by the LCCS literature. For example, a sandy loam PMM at WL2 had a value from the Land Capability Classification of 1.7 mm H_2O per cm of soil, yet was measured at 3.16 mm H_2O per cm of soil. This trend was true for all five sites. The most realistic explanation is that the low bulk densities (Table 4.4) in the topsoil added significant macroporosity and increased water content within the field capacity section of the retention curve (Figure 4.4), leading to greater water holding capacity. This is buoyed by the fact that the greatest discrepancy was found in sites with the lowest bulk densities, and that the relatively high topsoil bulk density at the Burned site (1.25 g cm^{-3}) had the most similar AWHC values (1.4 vs. 1.8 mm H_2O per cm of soil) between methods. Furthermore, subsoil AWHC profile totals by the soil core method had a much greater correlation with LCCS literature values (Table 4.6). While the tension table/pressure plate method has been shown to inflate retention water contents (Schelle et al., 2013), it would not explain the greater AWHC as both field capacity and permanent wilting point would be affected. These findings seem to suggest that the LCCS available water holding capacity values are more appropriate for soils within a more typical bulk density range (i.e. 1.45 to 1.55 g cm^{-3}).

Available water holding capacity values appears to be strongly dependant on bulk density in both this study and the literature (Scott, 2000). Caution should be used when interpolating these AWHC results as using one sampling point for a 20 cm thick layer (0-20 cm), and one more for an 80 cm thick layer (20-100 cm) assumes a lot about the homogeneity of those layers. Due to the prohibiting long extraction times in SWRC measurements, the number of samples available for any study is fairly limited. That said, extracting only two soil cores per sampling location will not fully capture the multiple depositions or pedogenic processes that could be represent in the soil profile. This caution is somewhat lessened for the reclaimed soils however, as the number of prescribed layers is known and substrates are fairly vertically homogeneous.

With that in mind, comparing the full 1 m profile AWCH measured by the soil core method and those predicted by the Land Capability Classification System reveals that both techniques predict a Mesic soil moisture regime (146 to 175 mm H_2O per 1 m profile) at all sites (Table 4.7). The LCCS is largely a texture-based method; however, the coarser-textured sites of WL1, WL2 and Burned had AWHC modifiers that raised the predicted water holding capacity of their soils leading to designations in the mesic regime. In the reclaimed soils, the peat additions added another 30 mm H_2O per 1 m profile to sandy loam or finer soils (LCCS, 2006). In addition, a fine-over-coarse layering addition of 15 mm H_2O per 1 m profile was added to three WL1 sampling sites due to the capillary barrier effect noted in Chaikowsky (2003) and Naeth et al. (2012). In the fire-disturbed soils, evidence of mottles greater than 20 cm from the soils surface was an indication of subhygric moisture conditions and a profile AWHC value of 190 mm H_2O per 1 m profile was given to that particular site (CEMA, 2006). Subhygric values were specified for seven of the 10 Burned sampling locations (Figure 4.1). Without these mottling effects, the mean profile AWHC value would have been approximately 140 mm H_2O per 1 m profile and firmly in the submesic range. The advantage of the LCCS is that it accounts for landscape and other interactions allowing for a more ‘in-situ’ prediction which the soil core method cannot accomplish.

6. Conclusion

Examination of WL1, WL2, and RA1 soil covers was completed in order to: I) characterize physical and chemical properties in large-scale PMM soil covers, II) determine whether quantitative similarities in soil-water properties exist between the natural disturbance of a forest fire and reclamation activities, and III) investigate whether several common soil water tools used to determine soil water movement and retention in natural soils are applicable for reclaimed PMM soils. WL1 and WL2 were particularly significant as they compose the first and only fully reclaimed tailing pond in the Oil Sands region. Additionally, until this study, no known soil characterization data has been published for all three reclaimed sites.

An interesting observation from the site characterization is the significantly lower phosphorus concentrations found in the reclaimed soils compared to either natural soil. While this is not uncommon in the Oil Sands region, it does present an interesting opportunity to observe whether the vegetation communities would face a nutrient stress with future stand development.

Comparisons between similar-textured natural and reclaimed sites gave indications of the effect of peat additions in soil-water relationships. Near-saturated hydraulic conductivity was found to be not statistically different within the topsoil at any of the reclaimed sites, despite having both fine- and coarse-textured soils. This non-significance was attributed to the reduced bulk density and pseudo structure afforded by the residue plant material in the peat, which replicates the aggregate-based soil structure found in some natural soils. K_{ns} differences were measured between fine- and coarse-textured soils at subsoil depths. For water storage, the soil water retention curves exhibited a bimodal release pattern accredited to its peat origins and documented in earlier work. The comparison of PMM soils and contrasting textured natural soils did however suggest bimodal similarities between the SWRC of peaty reclaimed soils and a structured fine-textured natural soil, which had not previously been studied.

Hydraulic conductivity and soil water retention curves are two important aspects of the soil-water relationship, and therefore common parameterized models were tested for robustness on the non-typical peat:mineral soils. Mini-disc infiltrometers, a miniaturized version of the popular full-size infiltrometers, did not appear to smooth spatial variability when used at a -0.5 cm tension. However, a key assumption in the recommended K_{ns} equation by Zhang (1997) that requires retention parameters to be estimated based on the soil texture of the mineral soil – which only makes up a portion of the peat:mineral mix – was tested against parameters directly calculated from intact soil cores. Only minor differences were found between estimated or calculated K_{ns} values. The experimental variability between methods was not large enough to change conclusions drawn from the data, and was largely masked by the extreme spatial variation measured within each site. This suggests that the recommended K_{ns} equation may be suitable for all soil types studied, including PMM; although additional techniques should be utilized to reduce variability (i.e. contact sand to improve disc-soil connectivity). For the soil water retention curves, a number of different hydraulic models were applied to the curves to determine the best fit. Bimodal models (Durner, 1994; Seki, 2007) proved to be the most appropriate in terms of both r^2 and estimated θres values. An area of interest might be the difference in field-scale hydrology modelling results when a bimodal model is used as oppose to a typical unimodal module, and how sensitive these models are to retention curve distinctions. AWHC derived from soil core measurement and the LCCS were compared. Both methods predicted a mesic moisture regime at all sites.

There are several limitations in this study that should be noted. Due to the pseudo replication necessitated by the limited number of reclaimed watersheds that currently exist, results and outcomes brought forth by this study should not be applied to all reclaimed soils. The experimental design was chosen to allow a higher sampling resolution at a select few sites, with the trade-off being a narrower scope of interference. These limitations should also be extended to the temporal range of the sites. Each reclaimed sites, in addition to the Burned site, were juvenile soils that were within 5 years of their initial placement/disturbance. Extrapolating data beyond that time frame should be done with caution.

This study hopes to provide a groundwork for future research on WL1, WL2 and RA1, as well as related Oil Sands reclamation. Having creditable soils characterization data from the initial years of each site will grant forthcoming studies a compatible ‘time zero’ to investigate soil properties over time. This is buoyed by WL1 and WL2 composing the first reclaimed intact tailings pond; these soil covers and its self-contained landscape will continue to be oldest treatment in any future studies of the eventually numerous reclaimed tailing ponds in the region. Finally, the Forest Watershed and Riparian Disturbance Project III (FORWARD III) will utilize the assembled soil properties, hydraulic conductivity, and soil retention data to assist in the development of water-shed scale hydrological models and hopes to provide recommendations for benchmarks and recovery trajectories of engineered soils.

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8. APPENDIX A

Table A.0.1 Van Genutchen parameters (α, n) utilized in Kns calculations of three reclaimed Oil Sands soils (WL1, WL2, RA1), one fire-disturbed forested soil (Burned), and one undisturbed forested soil (Reference). LAYER CODE: TS (Topsoil) 0-20 cm, USS (Upper Subsoil) 20-50 cm, LSS (Lower Subsoil) 50-100 cm.

SAMPLE ID	SITE	PIT ID	LAYER CODE	van Genuchten Parameters [Zhang]		van Genuchten Parameters [Dohnal]		van Genuchten Parameters [Novak]	
				α	n	α	n	α	n
1	WL1	1	TS	0.008	1.09	0.015	1.25	0.023	1.18
2	WL1	1	LSS	0.019	1.31	0.016	1.41	0.066	1.13
3	WL1	2	TS	0.059	1.48	0.021	1.33	0.023	1.18
4	WL1	2	LSS	0.075	1.89	0.027	1.45	0.066	1.13
5	WL1	3	TS	0.059	1.48	0.021	1.33	0.023	1.18
6	WL1	3	LSS	0.059	1.48	0.021	1.33	0.066	1.13
7	WL1	4	TS	0.059	1.48	0.021	1.33	0.023	1.18
8	WL1	4	LSS	NA	NA	NA	NA	NA	NA
9	WL1	5	TS	0.075	1.89	0.027	1.45	0.023	1.18
10	WL1	5	LSS	0.075	1.89	0.027	1.45	0.066	1.13
11	WL1	6	TS	0.059	1.48	0.021	1.33	0.023	1.18
12	WL1	6	LSS	0.059	1.48	0.021	1.33	0.066	1.13
13	WL1	7	TS	0.059	1.48	0.021	1.33	0.023	1.18
14	WL1	7	LSS	0.059	1.48	0.021	1.33	0.066	1.13
15	WL1	8	TS	0.008	1.09	0.015	1.25	0.023	1.18
16	WL1	8	LSS	0.008	1.09	0.015	1.25	0.066	1.13
17	WL1	9	TS	0.059	1.48	0.021	1.33	0.023	1.18
18	WL1	9	LSS	0.075	1.89	0.027	1.45	0.066	1.13
19	WL1	10	TS	0.059	1.48	0.021	1.33	0.023	1.18
20	WL1	10	LSS	0.059	1.48	0.021	1.33	0.066	1.13

Table A.0.1 (Continued)

SAMPLE ID	SITE	PIT ID	LAYER CODE	van Genuchten Parameters [Zhang]		van Genuchten Parameters [Dohnal]		van Genuchten Parameters [Novak]	
				α	n	α	n	α	n
21	WL2	1	TS	0.059	1.48	0.021	1.33	0.017	1.22
22	WL2	1	LSS	0.075	1.89	0.027	1.45	0.133	1.13
23	WL2	2	TS	0.075	1.89	0.027	1.45	0.017	1.22
24	WL2	2	LSS	0.075	1.89	0.027	1.45	0.133	1.13
25	WL2	3	TS	0.059	1.48	0.021	1.33	0.017	1.22
26	WL2	3	LSS	0.059	1.48	0.021	1.33	0.133	1.13
27	WL2	4	TS	0.075	1.89	0.027	1.45	0.017	1.22
28	WL2	4	LSS	0.075	1.89	0.027	1.45	0.133	1.13
29	WL2	5	TS	0.059	1.48	0.021	1.33	0.017	1.22
30	WL2	5	LSS	0.075	1.89	0.027	1.45	0.133	1.13
31	WL2	6	TS	0.059	1.48	0.021	1.33	0.017	1.22
32	WL2	6	LSS	0.075	1.89	0.027	1.45	0.133	1.13
33	WL2	7	TS	0.075	1.89	0.027	1.45	0.017	1.22
34	WL2	7	LSS	0.059	1.48	0.021	1.33	0.133	1.13
35	WL2	8	TS	0.075	1.89	0.027	1.45	0.017	1.22
36	WL2	8	LSS	0.059	1.48	0.021	1.33	0.133	1.13
37	WL2	9	TS	0.059	1.48	0.021	1.33	0.017	1.22
38	WL2	9	LSS	0.059	1.48	0.021	1.33	0.133	1.13
39	WL2	10	TS	0.075	1.89	0.027	1.45	0.017	1.22
40	WL2	10	LSS	0.059	1.48	0.021	1.33	0.133	1.13

Table A.0.1 (Continued)

SAMPLE ID	SITE	PIT ID	LAYER CODE	van Genuchten Parameters [Zhang]		van Genuchten Parameters [Dohnal]		van Genuchten Parameters [Novak]	
				α	**n**	**α**	**n**	**α**	**n**
41	RA1	1	TS	0.019	1.31	0.016	1.41	0.020	1.19
42	RA1	1	USS	0.020	1.41	0.005	1.66	0.011	1.12
43	RA1	1	LSS	0.008	1.09	0.015	1.25	0.011	1.12
44	RA1	2	TS	0.020	1.41	0.005	1.66	0.020	1.19
45	RA1	2	USS	0.020	1.41	0.005	1.66	0.011	1.12
46	RA1	2	LSS	0.008	1.09	0.015	1.25	0.011	1.12
47	RA1	3	TS	0.020	1.41	0.005	1.66	0.020	1.19
48	RA1	3	USS	0.008	1.09	0.015	1.25	0.011	1.12
49	RA1	3	LSS	0.008	1.09	0.015	1.25	0.011	1.12
50	RA1	4	TS	0.020	1.41	0.008	1.52	0.020	1.19
51	RA1	4	USS	0.008	1.09	0.015	1.25	0.011	1.12
52	RA1	4	LSS	0.027	1.23	0.033	1.21	0.011	1.12
53	RA1	5	TS	0.008	1.09	0.015	1.25	0.020	1.19
54	RA1	5	USS	0.019	1.31	0.016	1.41	0.011	1.12
55	RA1	5	LSS	0.008	1.09	0.015	1.25	0.011	1.12
56	RA1	6	TS	0.036	1.56	0.011	1.47	0.020	1.19
57	RA1	6	USS	0.008	1.09	0.015	1.25	0.011	1.12
58	RA1	6	LSS	0.008	1.09	0.015	1.25	0.011	1.12
59	RA1	7	TS	0.008	1.09	0.015	1.25	0.020	1.19
60	RA1	7	USS	0.008	1.09	0.015	1.25	0.011	1.12
61	RA1	7	LSS	0.008	1.09	0.015	1.25	0.011	1.12
62	RA1	8	TS	0.008	1.09	0.015	1.25	0.020	1.19
63	RA1	8	USS	0.019	1.31	0.016	1.41	0.011	1.12
64	RA1	8	LSS	0.019	1.31	0.016	1.41	0.011	1.12
65	RA1	9	TS	0.005	1.09	0.016	1.32	0.020	1.19

66	RA1	9	USS	0.020	1.41	0.005	1.66	0.011	1.12
67	RA1	9	LSS	0.019	1.31	0.016	1.41	0.011	1.12
68	RA1	10	TS	0.019	1.31	0.016	1.41	0.020	1.19
69	RA1	10	USS	0.019	1.31	0.016	1.41	0.011	1.12
70	RA1	10	LSS	0.005	1.09	0.016	1.32	0.011	1.12

Table A.0.1 (Continued)

SAMPLE ID	SITE	PIT ID	LAYER CODE	van Genuchten Parameters [Zhang]		van Genuchten Parameters [Dohnal]		van Genuchten Parameters [Novak]	
				α	n	α	n	α	n
71	Burned	1	TS	0.075	1.89	0.027	1.45	0.039	1.30
72	Burned	1	USS	0.059	1.48	0.021	1.33	0.017	1.76
73	Burned	1	LSS	0.075	1.89	0.027	1.45	0.017	1.76
74	Burned	2	TS	0.075	1.89	0.027	1.45	0.039	1.30
75	Burned	2	USS	0.059	1.48	0.021	1.33	0.017	1.76
76	Burned	2	LSS	0.145	2.68	0.035	3.18	0.017	1.76
77	Burned	3	TS	0.075	1.89	0.027	1.45	0.039	1.30
78	Burned	3	USS	0.059	1.48	0.021	1.33	0.017	1.76
79	Burned	3	LSS	0.145	2.68	0.035	3.18	0.017	1.76
80	Burned	4	TS	0.075	1.89	0.027	1.45	0.039	1.30
81	Burned	4	USS	0.059	1.48	0.021	1.33	0.017	1.76
82	Burned	4	LSS	0.075	1.89	0.027	1.45	0.017	1.76
83	Burned	5	TS	0.075	1.89	0.027	1.45	0.039	1.30
84	Burned	5	USS	0.059	1.48	0.021	1.33	0.017	1.76
85	Burned	5	LSS	0.059	1.48	0.021	1.33	0.017	1.76
86	Burned	6	TS	0.036	1.56	0.011	1.47	0.039	1.30
87	Burned	6	USS	0.008	1.09	0.015	1.25	0.017	1.76
88	Burned	6	LSS	0.008	1.09	0.015	1.25	0.017	1.76
89	Burned	7	TS	0.075	1.89	0.027	1.45	0.039	1.30
90	Burned	7	USS	0.059	1.48	0.021	1.33	0.017	1.76
91	Burned	7	LSS	0.019	1.31	0.016	1.41	0.017	1.76
92	Burned	8	TS	0.075	1.89	0.027	1.45	0.039	1.30
93	Burned	8	USS	0.059	1.48	0.021	1.33	0.017	1.76
94	Burned	8	LSS	0.059	1.48	0.021	1.33	0.017	1.76
95	Burned	9	TS	0.075	1.89	0.027	1.45	0.039	1.30

96	Burned	9	USS	0.059	1.48	0.021	1.33	0.017	1.76
97	Burned	9	LSS	0.059	1.48	0.021	1.33	0.017	1.76
98	Burned	10	TS	0.008	1.09	0.015	1.25	0.039	1.30
99	Burned	10	USS	0.075	1.89	0.027	1.45	0.017	1.76
100	Burned	10	LSS	0.059	1.48	0.021	1.33	0.017	1.76

Table A.0.1 (Continued)

SAMPLE ID	SITE	PIT ID	LAYER CODE	van Genuchten Parameters [Zhang]		van Genuchten Parameters [Dohnal]		van Genuchten Parameters [Novak]	
				α	n	α	n	α	n
101	Reference	1	TS	0.019	1.31	0.016	1.41	0.004	1.31
102	Reference	1	USS	0.010	1.23	0.008	1.52	0.020	1.10
103	Reference	1	LSS	0.019	1.31	0.016	1.41	0.020	1.10
104	Reference	2	TS	0.019	1.31	0.016	1.41	0.004	1.31
105	Reference	2	USS	0.008	1.09	0.015	1.25	0.020	1.10
106	Reference	2	LSS	0.008	1.09	0.015	1.25	0.020	1.10
107	Reference	3	TS	0.036	1.56	0.011	1.47	0.004	1.31
108	Reference	3	USS	0.036	1.56	0.011	1.47	0.020	1.10
109	Reference	3	LSS	0.019	1.31	0.016	1.41	0.020	1.10
110	Reference	4	TS	0.036	1.56	0.011	1.47	0.004	1.31
111	Reference	4	USS	0.005	1.09	0.016	1.32	0.020	1.10
112	Reference	4	LSS	0.008	1.09	0.015	1.25	0.020	1.10
113	Reference	5	TS	0.036	1.56	0.011	1.47	0.004	1.31
114	Reference	5	USS	0.019	1.31	0.016	1.41	0.020	1.10
115	Reference	5	LSS	0.036	1.56	0.011	1.47	0.020	1.10
116	Reference	6	TS	0.008	1.09	0.015	1.25	0.004	1.31
117	Reference	6	USS	0.020	1.41	0.005	1.66	0.020	1.10
118	Reference	6	LSS	0.008	1.09	0.015	1.25	0.020	1.10
119	Reference	7	TS	0.036	1.56	0.011	1.47	0.004	1.31
120	Reference	7	USS	0.008	1.09	0.015	1.25	0.020	1.10
121	Reference	7	LSS	0.016	1.37	0.007	1.68	0.020	1.10
122	Reference	8	TS	0.020	1.41	0.005	1.66	0.004	1.31
123	Reference	8	USS	0.036	1.56	0.011	1.47	0.020	1.10
124	Reference	8	LSS	0.008	1.09	0.015	1.25	0.020	1.10
125	Reference	9	TS	0.020	1.41	0.005	1.66	0.004	1.31

126	Reference	9	USS	0.059	1.48	0.021	1.33	0.020	1.10
127	Reference	9	LSS	0.008	1.09	0.015	1.25	0.020	1.10
128	Reference	10	TS	0.020	1.41	0.005	1.66	0.004	1.31
129	Reference	10	USS	0.019	1.31	0.016	1.41	0.020	1.10
130	Reference	10	LSS	0.036	1.56	0.011	1.47	0.020	1.10

9. APPENDIX B

Table B.0.1 Number of samples (*n*) analyzed for each physical and chemical test performed in this study. Analysis divided into field and laboratory components with total numbers in final row. Kns = Field-Saturated Hydraulic Conductivity. MRC = Moisture Retention Curves. PSA = Particale Size Analysis. BD= Bulk Density.

Sites	**Sample Pits**	**Kns**	**MRC**	**PSA**	**Vol. Water Content**	**BD**	**OC**	**NO_3^-**	**NH_4^+**	**PO_4^-**	**pH**	**EC**
	Field		**Laboratory**									
WL1	10	19	90	19	19	19	19	19	19	19	19	19
WL2	10	20	90	20	20	20	19	20	20	20	20	20
RA1	10	59	90	30	30	27	30	29	29	29	29	29
Burned	10	60	90	30	30	30	30	30	30	30	30	30
Reference	10	60	90	30	30	30	30	29	29	29	28	29
Total	50	218	50	129	129	126	128	127	127	127	126	127

10. APPENDIX C

Table C.0.1 Soil physical properties of three reclaimed Oil Sands soils (WL1, WL2, RA1), one fire-disturbed forested soil (Burned), and one undisturbed forested soil (Reference). LAYER CODE: TS (Topsoil) 0-20 cm, USS (Upper Subsoil) 20-50 cm, LSS (Lower Subsoil) 50-100 cm. SLOPE: 0 = 0°, 2 = 2-4°, 5 = 5-9°.

SAMPLE ID	SITE	PIT ID	LAYER CODE	SLOPE	BD (g cm^{-3})	OC (%)	NO_3^- (mg kg^{-1})	NH_4^+ (mg kg^{-1})	PO_4^- (mg kg^{-1})	pH	EC (dS m^{-2})
1	WL1	1	TS	2	1.16	5.62	1.1	6.9	5.3	8.17	0.60
2	WL1	1	LSS	2	1.82	3.74	1.0	4.1	0.9	8.1	0.72
3	WL1	2	TS	2	1.03	9.37	1.2	5.0	1.2	8.08	1.18
4	WL1	2	LSS	2	1.31	5.40	1.0	1.8	0.6	8.27	0.34
5	WL1	3	TS	0	1.01	7.78	0.9	2.3	1.1	7.83	0.87
6	WL1	3	LSS	0	1.59	6.09	1.0	2.7	1.0	8.27	1.01
7	WL1	4	TS	2	1.08	5.50	1.0	7.9	0.5	7.98	0.65
8	WL1	4	LSS	2	NA	NA	NA	NA	NA	NA	NA
9	WL1	5	TS	0	1.35	7.03	1.0	6.3	3.5	8	0.60
10	WL1	5	LSS	0	1.29	4.33	1.3	5.8	1.7	7.91	0.47
11	WL1	6	TS	0	1.40	3.54	1.0	4.0	1.9	7.92	0.79
12	WL1	6	LSS	0	1.42	3.52	1.0	4.4	0.8	8.07	0.72
13	WL1	7	TS	2	1.37	3.70	1.0	4.3	1.2	8.02	0.78
14	WL1	7	LSS	2	1.47	3.59	1.0	4.5	0.8	8.04	0.92
15	WL1	8	TS	2	0.99	9.68	1.2	12.4	1.5	7.82	0.60
16	WL1	8	LSS	2	1.28	2.65	1.2	11.6	1.6	8.04	1.00
17	WL1	9	TS	0	1.73	2.49	1.00	2.96	1.17	8.17	0.93
18	WL1	9	LSS	0	1.76	0.73	0.95	0.97	0.34	8.14	0.23
19	WL1	10	TS	2	0.72	1.52	12.55	10.26	1.23	7.77	0.73
20	WL1	10	LSS	2	1.75	7.39	0.98	4.72	1.49	7.80	1.36

Table C.0.1 **(**Continued)

SAMPLE ID	SITE	PIT ID	LAYER CODE	SLOPE	BD (g cm^{-3})	OC (%)	NO_3^- (mg kg^{-1})	NH_4^+ (mg kg^{-1})	PO_4^- (mg kg^{-1})	pH	EC (dS m^{-2})
21	WL2	1	TS	0	0.72	15.11	13.13	12.81	1.69	7.71	0.46
22	WL2	1	LSS	0	0.92	14.74	3.65	11.32	1.53	NA	NA
23	WL2	2	TS	0	0.91	8.17	7.76	6.37	0.53	7.64	1.66
24	WL2	2	LSS	0	1.24	3.72	2.26	0.91	0.91	7.76	0.60
25	WL2	3	TS	2	0.29	11.47	1.13	5.74	1.27	7.69	0.65
26	WL2	3	LSS	2	1.02	11.36	1.01	7.35	1.03	7.66	1.16
27	WL2	4	TS	5	1.23	6.88	0.93	3.45	1.56	7.80	0.60
28	WL2	4	LSS	5	1.23	5.95	1.03	4.45	1.87	7.75	0.67
29	WL2	5	TS	0	1.14	4.88	1.43	4.22	3.04	7.74	0.60
30	WL2	5	LSS	0	1.07	5.46	0.98	4.07	1.54	7.49	0.97
31	WL2	6	TS	2	1.12	5.34	1.01	3.72	1.50	7.39	0.77
32	WL2	6	LSS	2	1.19	5.12	0.98	4.38	1.33	7.59	1.06
33	WL2	7	TS	5	0.99	6.41	1.57	6.64	2.10	7.64	0.53
34	WL2	7	LSS	5	1.52	NA	0.97	2.58	1.76	NA	NA
35	WL2	8	TS	0	0.82	12.35	1.18	7.54	0.63	7.80	0.81
36	WL2	8	LSS	0	1.44	2.00	0.96	2.50	1.06	7.98	0.78
37	WL2	9	TS	0	0.83	17.49	5.29	6.41	1.05	8.30	0.78
38	WL2	9	LSS	0	1.43	1.30	1.02	2.27	0.65	8.03	1.54
39	WL2	10	TS	0	1.10	2.83	0.94	1.59	4.25	7.94	0.25
40	WL2	10	LSS	0		1.74	0.95	3.70	1.32	8.09	0.69

Table C.0.1 **(**Continued)

SAMPLE ID	**SITE**	**PIT ID**	**LAYER CODE**	**SLOPE**	**BD ($g\ cm^{-3}$)**	**OC (%)**	**NO_3^- ($mg\ kg^{-1}$)**	**NH_4^+ ($mg\ kg^{-1}$)**	**PO_4^- ($mg\ kg^{-1}$)**	**pH**	**EC ($dS\ m^{-2}$)**
41	RA1	1	TS	2	0.33	7.52	2.11	5.82	3.04	7.86	1.74
42	RA1	1	USS	2	0.52	12.04	0.73	7.43	1.28	7.85	2.15
43	RA1	1	LSS	2	1.59	1.14	0.69	3.45	3.38	7.92	1.72
44	RA1	2	TS	2	0.28	9.54	3.07	9.71	0.80	6.10	1.90
45	RA1	2	USS	2	1.78	7.97	0.67	9.25	1.44	6.84	2.28
46	RA1	2	LSS	2	NA	1.18	1.51	3.30	2.62	7.62	1.49
47	RA1	3	TS	0	1.07	16.56	0.59	10.57	1.98	6.10	1.88
48	RA1	3	USS	0	1.58	1.52	0.46	2.91	2.75	7.55	1.34
49	RA1	3	LSS	0	1.69	1.86	1.84	6.65	0.96	7.50	3.12
50	RA1	4	TS	0	0.59	5.97	0.61	6.12	1.64	7.68	0.99
51	RA1	4	USS	0	1.56	1.12	0.49	3.56	2.04	7.61	0.74
52	RA1	4	LSS	0	1.79	1.39	0.47	3.20	0.92	7.46	1.96
53	RA1	5	TS	0	0.25	3.95	0.51	4.85	2.06	7.68	1.44
54	RA1	5	USS	0	0.72		0.53	6.67	2.83	7.46	0.86
55	RA1	5	LSS	0	1.35	1.05	0.53	4.17	5.09	7.83	0.64
56	RA1	6	TS	0	0.88	16.90	0.46	8.12	3.50	6.59	0.88
57	RA1	6	USS	0	1.61	0.86	0.50	3.32	2.89	7.50	2.29
58	RA1	6	LSS	0	NA	1.21	0.49	3.80	2.71	7.41	2.75
59	RA1	7	TS	0	0.77	3.08	0.55	6.37	3.55	7.82	0.99
60	RA1	7	USS	0	0.86	0.77	0.50	3.26	3.04	7.73	1.28
61	RA1	7	LSS	0	NA	NA	NA	NA	NA	NA	NA
62	RA1	8	TS	0	0.56	36.93	0.13	11.58	1.81	4.80	1.88
63	RA1	8	USS	0	0.46	3.63	0.49	4.32	1.33	7.33	1.46
64	RA1	8	LSS	0	1.80	1.15	0.65	2.62	1.62	7.85	0.72
65	RA1	9	TS	0	0.68	5.13	0.63	6.39	4.77	7.46	1.04
66	RA1	9	USS	0	0.57	1.80	0.95	5.23	2.63	7.52	1.40

67	RA1	9	LSS	0	1.75		0.71	7.10	3.91	7.50	1.26
68	RA1	10	TS	2	0.58	11.15	0.77	4.97	1.55	7.69	1.73
69	RA1	10	USS	2	1.17	5.33	0.60	4.03	1.15	7.52	2.43
70	RA1	10	LSS	2	1.49	1.80	0.62	3.31	1.19	7.51	2.72

Table C.0.1 **(**Continued)

SAMPLE ID	**SITE**	**PIT ID**	**LAYER CODE**	**SLOPE**	**BD (g cm^{-3})**	**OC (%)**	**NO_3^- (mg kg^{-1})**	**NH_4^+ (mg kg^{-1})**	**PO_4^- (mg kg^{-1})**	**pH**	**EC (dS m^{-2})**
71	Burned	1	TS	0	0.94	1.09	0.65	4.74	75.92	6.71	0.11
72	Burned	1	USS	0	1.49	0.65	0.27	2.98	5.73	5.45	0.06
73	Burned	1	LSS	0	1.54	0.61	0.32	3.23	6.62	5.82	0.05
74	Burned	2	TS	0	1.34	7.45	0.19	3.25	22.80	4.80	0.08
75	Burned	2	USS	0	1.59	0.74	2.37	2.54	7.75	5.83	0.06
76	Burned	2	LSS	0	1.59	0.74	2.49	2.50	5.96	6.05	0.03
77	Burned	3	TS	0	1.31	14.40	2.56	2.65	47.48	4.94	0.05
78	Burned	3	USS	0	1.50	0.67	2.45	3.40	11.61	5.12	0.05
79	Burned	3	LSS	0	1.63	0.65	3.07	1.90	7.83	5.75	0.06
80	Burned	4	TS	0	1.37	3.78	3.19	2.59	12.63	5.15	0.19
81	Burned	4	USS	0	1.58	0.73	3.22	2.32	2.19	7.26	0.32
82	Burned	4	LSS	0	1.62	0.64	2.93	2.24	1.51	7.18	0.30
83	Burned	5	TS	0	1.26	3.61	2.33	2.11	29.08	6.00	0.09
84	Burned	5	USS	0	1.52	0.98	3.36	3.05	11.34	6.11	0.18
85	Burned	5	LSS	0	1.53	0.53	2.96	2.71	5.04	6.35	0.14
86	Burned	6	TS	0	1.07	3.38	2.67	4.07	20.78	4.78	0.17
87	Burned	6	USS	0	1.50	0.63	3.97	4.06	4.66	5.02	0.08
88	Burned	6	LSS	0	1.39	0.71	2.45	3.66	8.90	5.18	0.10
89	Burned	7	TS	0	1.31	1.21	2.55	3.31	14.13	5.02	0.12
90	Burned	7	USS	0	1.56	0.71	0.48	3.46	6.13	5.70	0.15
91	Burned	7	LSS	0	1.54	0.54	3.30	2.93	3.22	5.76	0.29
92	Burned	8	TS	0	1.60		2.95	2.03	48.57	5.45	0.14
93	Burned	8	USS	0	1.48	0.75	0.34	3.15	18.59	5.60	0.17
94	Burned	8	LSS	0	1.52	0.66	0.21	2.64	4.71	5.66	0.15
95	Burned	9	TS	0	1.18	4.74	0.07	2.82	65.44	4.83	0.11
96	Burned	9	USS	0	1.44	0.47	0.24	2.63	43.35	5.65	0.14

97	Burned	9	LSS	0	1.55	0.62	0.24	3.32	8.92	5.94	0.20
98	Burned	10	TS	0	1.11	0.74	0.04	4.00	4.65	5.09	0.18
99	Burned	10	USS	0	1.61	0.58	0.46	1.52	2.19	6.40	0.11
100	Burned	10	LSS	0	1.47	0.56	0.65	2.08	3.11	7.60	0.60

Table C.0.1 **(**Continued)

SAMPLE ID	SITE	PIT ID	LAYER CODE	SLOPE	BD (g cm^{-3})	OC (%)	NO_3^- (mg kg^{-1})	NH_4^+ (mg kg^{-1})	PO_4^- (mg kg^{-1})	pH	EC (dS m^{-2})
101	Reference	1	TS	0	0.87	2.17	0.28	5.54	14.54	6.11	0.14
102	Reference	1	USS	0	1.51	0.53	0.29	2.84	2.31	6.41	0.07
103	Reference	1	LSS	0	1.50	0.44	0.26	1.53	1.53	6.73	0.05
104	Reference	2	TS	5	0.60	1.22	0.20	12.94	64.54	5.28	0.11
105	Reference	2	USS	5	1.45	0.54	0.16	3.84	6.47	5.52	0.06
106	Reference	2	LSS	5	1.46	0.77	0.19	6.28	7.15	5.42	0.05
107	Reference	3	TS	5	0.97	0.92	0.63	34.46	42.83	5.44	0.15
108	Reference	3	USS	5	1.55	0.75	0.19	2.00	4.35	5.18	0.06
109	Reference	3	LSS	5	1.51	0.27	0.18	3.64	3.86	5.22	0.04
110	Reference	4	TS	2	1.36	1.02	0.21	4.51	10.35	5.02	0.07
111	Reference	4	USS	2	1.46	0.55	0.21	4.72	2.59	5.33	0.04
112	Reference	4	LSS	2	1.47	0.41	0.23	6.19	4.50	5.33	0.05
113	Reference	5	TS	0	0.92	0.57	0.01	8.24	14.51	4.77	0.09
114	Reference	5	USS	0	1.26	0.53	0.14	2.79	9.32	5.25	0.05
115	Reference	5	LSS	0	1.60	0.43	0.13	4.27	16.51	5.28	0.04
116	Reference	6	TS	0	0.75	1.34	0.13	5.92	11.88	5.05	0.08
117	Reference	6	USS	0	1.45	0.52	0.17	3.44	5.21	5.31	0.03
118	Reference	6	LSS	0	1.61	0.80	0.12	4.77	5.65	5.28	0.04
119	Reference	7	TS	0	1.08	0.93	0.24	4.03	14.85	5.17	0.05
120	Reference	7	USS	0	1.45	0.59	0.13	3.85	4.58	5.36	0.04
121	Reference	7	LSS	0	1.57	0.78	0.17	5.97	6.80	NA	0.03
122	Reference	8	TS	2	1.35	0.81	NA	NA	NA	NA	NA
123	Reference	8	USS	2	1.53	0.52	0.09	4.01	2.39	5.38	0.03
124	Reference	8	LSS	2	1.54	0.58	0.04	4.84	3.55	5.44	0.03
125	Reference	9	TS	0	0.86	NA	NA	9.38	16.92	4.75	0.06
126	Reference	9	USS	0	1.58	0.48	0.16	2.50	1.35	5.22	0.02

127	Reference	9	LSS	0	1.41	0.52	0.11	5.25	7.66	5.30	0.03
128	Reference	10	TS	0	1.18	1.45	0.17	4.19	15.60	5.06	0.05
129	Reference	10	USS	0	1.60	0.59	0.17	4.12	12.10	5.28	0.04
130	Reference	10	LSS	0	1.56	0.77	0.18	4.97	12.61	5.44	0.02

11. APPENDIX D

Table D.0.1 Mean and standard deviation of soil nutrients in three reclaimed Oil Sands soils (WL1, WL2, RA1), one fire-disturbed soil (Burned), and one undisturbed soil (Reference) by total amounts per hectare. Bulk densities included to see multiplier effect from concentrations.

Soil Depth	Reclaimed			Natural	
	WL1	WL2	RA1	Burned	Reference
			Bulk Density (g cm^{-3})		
0-20 cm	1.13±0.29ab†	0.88±0.18b	0.60±0.26b	1.25±0.18a	0.99±0.25b
20-50 cm	-‡	-	1.08±0.52a	1.53±0.06a	1.48±0.10a
50-100 cm	1.47±0.19ab	1.12±0.22b	1.64±0.17a	1.54±0.07a	1.52±0.06a
			Organic Carbon (Mg ha^{-1})		
0-20 cm	123±53	148±159	150±146	102±113	23±9
20-50 cm	-	-	107±129	32±6	25±4
50-100 cm	305±159	275±178	97±52	48±6	44±15
			NO_3^- (Mg ha^{-1})		
0-20 cm	39±46	53±55	9±5	45±36	5±4
20-50 cm	-	-	18±8	79±69	9±2
50-100 cm	76±7	75±42	65±41	144±104	12±5
			NH_4^+ (Mg ha^{-1})		
0-20 cm	130±50	95±34	93±60	76±13	181±186
20-50 cm	-	-	159±122	133±30	152±39
50-100 cm	318±188	223±119	358±161	208±39	363±105
			PO_4^- (Mg ha^{-1})		
0-20 cm	43±34	33±26	31±22	837±552	396±237
20-50 cm	-	-	71±42	507±528	223±154
50-100 cm	74±31	73±26	193±121	428±192	536±360