Effect of soil cover system design on cover system performance and early tree establishment

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Abstract
Syncrude completed construction of a field-scale soil cover system trial at the Aurora North mine operations in Fort McMurray, Alberta, Canada in 2012. Syncrude, university researchers, and consultants developed the study design with an overall objective of determining appropriate soil cover system designs and capping depth(s) for overburden reclamation at the Aurora North mine operation. Specifically, the study was designed to address the uncertainty of reclaiming upland areas using coarse textured surficial soil materials that contain embedded naturally occurring oil sand that is comprised of petroleum hydrocarbons over lean oil sand overburden that also contains petroleum hydrocarbons. The trial consisted of 36 one hectare cells, made up of 12 treatment options varying in capping material thicknesses and types. All treatments were constructed in triplicate. The research cells were instrumented and planted with three native boreal forest tree species in varying densities.

Key mechanisms and processes that influence cover system performance and tree growth include freeze/thaw cycles and water retention characteristics. Instrumentation was installed to monitor water balance parameters and groundwater, and to collect pore-water. Initial results indicate that peat surface cover system materials had the lowest net percolation due to higher water storage capacity, and exhibited delayed soil warming and freezing. Tree mortality was 3% on salvaged forest floor soil capping treatments and 4% on peat capping treatments. Tree seedling growth after three growing seasons was up to 48% higher on treatments capped with mineral dominated forest floor material compared with treatments capped with organic peat material. The influence of lower subsoil material types and their arrangements on tree seedling performance is still unclear. This is a long-term study and results will serve to identify appropriate cover system configurations and guide future reclamation operations in oil sands mining.

1 Introduction
Syncrude Canada Ltd. (Syncrude) developed a field-scale soil capping study at their Aurora North mine operations in Fort McMurray, Alberta, Canada. The overall research objective of the Aurora Soil Capping Study (ASCS) was to determine appropriate soil cover system designs and capping depth(s) for reclamation using readily available surface materials, while understanding the risks and uncertainties associated with overburden and soil reclamation materials containing naturally occurring oil sand (petroleum hydrocarbons).

Syncrude has undertaken the study to examine alternative soil cover system designs for reclamation of their overburden at the Aurora North mine. Soil cover system designs must optimise the available reclamation materials to provide the foundation for re-emergence of sustainable, productive ecosystems. A wide range of land capability will be required within reclaimed areas and, as a result, reclamation treatments may change from one area to the next within the final landform. Consequently, the differences in performance between different surface and subsoil material types and their thickness and the influence of the underlying overburden waste material, needs to be defined.
Indicators of cover system performance include net percolation, the amount of water that moves from the base of the cover system to the waste material below, and health of vegetation, as indicated by growth and mortality rates. This paper primarily examines the hydrological performance of soil cover system design treatment alternatives. As soil water dynamics and vegetation health are interrelated, indirect indicators of vegetation performance such as plant available water and soil temperature are also considered.

2 Background

Oil sands mining is an open-pit operation. It involves the removal of surficial geologic materials within the mine footprint that are suitable for use later in reclamation, which primarily includes discrete salvage of upland surface topsoil, subsoil materials, and peat materials from lowland bogs and fens. Following reclamation soil salvage, overburden is removed to expose the oil sand ore body. The overburden is transported to a designated disposal area (generally above-grade or out of pit) where it is landform graded to a defined elevation and grade specifications and capped with previously salvaged soil reclamation materials.

The appropriate soil reclamation cover system design and capping depth is dependent on the underlying overburden quality and risk of environmental exposure to constituents of concern. For Syncrude’s Aurora North mine, there are a number of risks and uncertainties associated with overburden reclamation. The primary issue is one of naturally occurring petroleum hydrocarbons in both the overburden and soil reclamation materials. Naturally occurring hydrocarbons are generally present in the entire matrix of the overburden, and are present as discrete bands or chunks of varying size and proportion within the soil reclamation matrix. The removal, disruption, and spreading of these materials to a new setting poses a risk to the closure landscape, and the appropriate soil cover system design and thickness to alleviate any risks if present is also uncertain.

A second issue Syncrude faces with overburden reclamation at the Aurora North mine is the large abundance of coarse textured (sandy loam to sand) mineral reclamation materials. Although Syncrude has over 30 years of reclamation experience in the region, the Aurora North mine coarse textured surficial geological materials differ from previous mining locations. The appropriate use of available soil reclamation materials to re-establish similar vegetation present prior to the disturbance has not been determined.

The ASCS was constructed to address the risks and uncertainties with overburden reclamation at the Aurora North mine. The objective of the study was to evaluate the environmental risks and provide an appropriate soil cover system design and depth to mitigate these risks. This paper focuses on cover system design performance. The ASCS is a large-scale, replicated multi-disciplinary study that encompasses key disciplines such as soil physics, soil chemistry, geochemistry, hydrology, plant growth, and soil microbiology.

3 Methodology

Twelve treatment options (Figure 1) were constructed in triplicate to facilitate scientifically rigorous comparisons, resulting in a total of 36 cells (Figure 2). Surface layer materials included peat (a material of high organic content, salvaged from bogs and fens with no underlying mineral material), LFH (forest floor material which includes all of the L-F-H, A horizon plus a portion of the B horizon of an upland natural soil), and a split-plot treatment with no cover soil additions, with half consisting entirely of a Bm soil salvage and the other a subsoil salvage of approximately 15 to 200 cm. Instrumentation for measurement of groundwater and various parameters of the water balance was installed in the cells (Figure 2). In each treatment cell four 25 × 25 m tree planting plots were established and assigned to one of the four vegetation treatments; single species plots with Populus tremuloides Michx., Pinus banksiana Lamb. and Picea glauca (Moench) Voss and a plot with an even mix of the three species. All plots were planted in the spring of 2012 with one-year-old containerised planting stock at a 1 × 1 m spacing (equivalent to a density of 10,000 seedlings per hectare (sph)). Average tree height per year and mortality rate was used as performance indicator. Therefore, seedling height and mortality was measured at the end of each growing season (2012 to 2014). Seedling mortality and seedling height after three growing seasons (2012 to 2014) are presented.
Figure 1 Twelve treatment options applied at the Aurora Soil Capping Study. Treatment twelve was split into two separate subsoil treatments. Each treatment overlies overburden (OB), but only treatments with a capping depth <150 cm show OB in the figure.

**Note:** Subsoil (>1m) is a 1 Lift salvage to approximately 2 m after removal of the forest floor material (FFM; top 15 cm); Bm is a 15 to 50 cm salvage after removal of the FFM; B/C is a B and C horizon salvage from 50 to 100 cm. LFH is the FFM salvaged to a depth of 15 cm, which consists of the LFH horizon, plus A and a portion of the B horizon; peat is the salvaged organic soil layer of lowland bogs and fens with no underlying mineral material.

Figure 2 Study layout including tree plots and instrumentation installed at the Aurora Soil Capping Study

3.1 Water balance method

Analytical water balances were calculated for cells on the perimeter of the ASCS to quantify the volume of water percolating through the cover systems in the 2012 to 2013 water year (1 November 2012 to 31 October 2013). Water balances use inputs that are field measured, calculated, or estimated from the residual
to solve the water balance equation (1) on a daily basis during frost-free periods. In this way, the water dynamics of the various cover system treatments, and the hydrology of the system as a whole, can be characterised.

\[ PPT = RO/S + AET + NP + dS \]  

Where:
- \( PPT \) = precipitation (rainfall plus snow water equivalent (SWE)),
- \( RO/S \) = runoff and sublimation,
- \( AET \) = actual evapotranspiration,
- \( NP \) = net percolation, and
- \( dS \) = change in water storage.

A meteorological station was erected at the ASCS on Cell 22 to measure site-specific climatic parameters (Figure 2). The station included instrumentation to monitor air temperature, relative humidity, net radiation, wind speed and direction, rainfall, snow depth, and air pressure.

Potential evapotranspiration (PE) was estimated using the modified Penman-Monteith method (Vanderborght et al., 2010) and site meteorological data collected by the meteorological station. Actual evapotranspiration was calculated based on climate data and rates of PE, while AET/PE ratios were based upon soil saturation levels, available water holding capacity, and adjusted to match the calculated storage to the measured storage in the water balance.

Vadose zone water dynamics in the cover systems and overburden at the ASCS were monitored by Campbell Scientific (CS) model 616-L volumetric water content sensors and CS229-L matric suction sensors. Data from these sensors was used to determine the measured change in storage for the water balance. Pairs of soil water sensors were installed by hand in all layers of cover materials and in overburden, with a focus on material interfaces.

Soil temperatures were measured using CS229-L matric suction sensors. Soil temperature data were used to determine the frost-free period, and assist with the interpretation of water content data. In addition, the season when vegetation on the test cells is active is heavily influenced by soil temperatures.

Net percolation through the cover system treatments was monitored by large-scale lysimeters (Figure 2). The large-scale lysimeters were installed in the upper overburden profile of 12 test cells on the perimeter of the study area. Smaller scale Gee drain gauges were installed to assist in the characterisation of water flow dynamics. Water balance net percolation was estimated using lysimeter and Gee gauge data, and the change in water storage at the base of the cover system.

Runoff was not directly measured at the site. Runoff and sublimation from the snowpack were estimated from the water balance.

4 Results and discussion

Two cells with surface treatment types of 20 cm LFH (Cell 18) and 30 cm peat (Cell 30) were selected for presentation of results. Trends for research cells with large scale lysimeters located on the perimeter of the study area are also discussed. Cell 18 and Cell 30 were selected for presentation as they have the same subsoil treatment, and have the most common surface material thickness.

4.1 Temperature

Cells with peat as a surface material did not freeze as quickly as cells with LFH as a surface material. Freezing was more gradual for Cell 30 (Figure 3) than for Cell 18 (Figure 4), which quickly froze to approximately 50 cm depth in both years.
The number of days that soil temperatures at 10 cm depth exceeded 5°C was determined for the four major surface treatment types for 2013 and 2014 growing seasons (Figure 5). The criterion of 5°C at 10 cm depth was used as a rough indicator for when vegetation becomes active (Novak, 2005). The cells with 20 cm LFH at the surface had a greater number of days with active vegetation than cells with 30 cm of surface peat. Peat is an excellent thermal insulator and has a high resistance to temperature change. Resistance to temperature change is manifested as lower mean temperatures and smaller temperature amplitudes in the material underlying the peat. Conversely, the sandy textured LFH has a very high capacity for transmitting energy, resulting in faster, deeper freezing in the winter, and higher subsoil temperatures in the summer. If soil-water is present to meet vegetation demand, increased soil temperature will likely translate into increased tree growth.

Figure 3 In situ soil temperature contours measured at Cell #30 (30 cm peat cover treatment) from 2012 to 2014
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Figure 4  In situ soil temperature contours measured at Cell #18 (20 cm LFH cover treatment) from 2012 to 2014

Figure 5  Number of days soil temperature at 10 cm depth was greater than 5°C for surface materials during the 2013 and 2014 growing seasons

4.2  Water balances

Water balances were completed for all research cells with large scale lysimeters of the study. Water balances for the 2012 to 2013 water year are provided as examples. Calculated and measured storages matched well for Cell 30 (Figure 6) and Cell 18 (Figure 7) for the 2012 to 2013 water year. Runoff and sublimation were higher for Cell 30, as well as for the majority of cells with peat as a surface material. Rates of AET were similar for Cell 18 and Cell 30, and ranged from 61% to 76% for all estimated water balances. Rates of AET did not have a discernible pattern based on material type. Rainfall for the year was above average, with two major rainfall events resulting in the majority of net percolation events through the cover systems.
The rate of net percolation will affect plant available water and groundwater recharge rates. The net percolation rate for Cell 30 for the 2012 to 2013 water year, at 12% of annual precipitation, was lower than the rate for Cell 18, at 25%. On average, cells with 30 cm of peat as a surface material had lower net percolation rates (14%), than cells with LFH as a surface material (23%) (Figure 8). This is attributed to the higher water storage capacity of peat, which allows for a greater period of time over which water can be removed from the soil surface via AET. In addition, it is possible that textural discontinuity between peat and subsurface materials inhibits drainage from peat to subsurface materials.
4.3 Seedling mortality

Overall seedling mortality after three growing seasons was low for all species (Figure 9). When all species are combined, cover material did not affect seedling mortality (p=0.2). However, analysis of variance (ANOVA) indicated that mortality was significantly higher in the 30 cm peat compared to the 10 cm peat cover (p=0.019).

![Figure 9](image.png)

Figure 9 Mortality over three years for three tree species (2012 to 2014). Error bars are one standard error of the mean (n=3)

4.4 Tree growth performance

The three tree species showed similar responses in total height (growth over three growing seasons) to the cover soil materials; however responses of *P. tremuloides* and *P. banksiana* to capping materials appear to be more pronounced than in *P. glauca*. All three species grew better in the treatments which were capped with LFH compared with peat materials (across both thicknesses). For example after three growing seasons the average height of *P. tremuloides* seedlings was 125 cm in the LFH material compared to 90 cm in the peat (p=0.012). For *P. banksiana* the difference between LFH and peat was 28 cm (p<0.001) and in *P. glauca* the difference was 10 cm in height (p<0.001). At 30 cm peat capping depth *P. banksiana* seedling height was reduced by 20 cm (p<0.001) and 25 cm in *P. tremuloides* (p=0.04) compared to a peat thickness of 10 cm, while *P. glauca* did not show a significant reduction in height (p=0.19). *Populus tremuloides* seedlings growing in the selectively salvaged Bm material performed better than when planted in subsoil (p=0.03), while *P. banksiana* and *P. glauca* did not show a difference in growth (p=0.29; p=0.77, respectively).
Conclusion

The influence of cover system treatments on soil temperature and water content were measured at an oil sands reclamation research study referred to as the Aurora Soil Capping Study. Net percolation rates for the 2012 to 2013 monitoring year for treatments with 30 cm of peat at the surface were 14% of annual precipitation, which was lower than treatments with LFH (23% of annual precipitation) at the surface. The greater soil-water content of the treatments with peat at the surface is attributed to peat having a higher water storage capacity. In addition, textural discontinuity between peat and underlying sandy subsurface materials potentially inhibits drainage. Peat also had an influence on soil temperature. Due to the ability of peat to insulate the soil from large changes in temperature, the number of active growing days was lower in the peat cover treatments relative to the LFH cover treatment. Although peat may improve vegetation performance in terms of water storage, it has the potential to reduce effective growing season length and might also limit nutrient availability. Indications of these limitations are reflected in the response of seedlings heights to a change in thickness of the peat cap, while the thickness of a salvaged mineral soil dominated LFH was not a factor in seedlings performance. Overall seedlings growing in LFH had a much better performance over the first three growing seasons. The relative advantages and disadvantages of peat over a range of wet-dry conditions and whether they persist as the site matures may shape the preferred reclamation soil cover system design strategy.

The initial monitoring of the dynamics of the overburden disposal area at the ASCS have shown the interactions of the vegetation, cover materials, and climate are complex and further study is required to determine the preferred cover system design(s) for closure of the area. Data collected so far was sufficient to provide a comparison of cover system performance and identify key trends that will affect long-term performance such as net percolation, and the length of the vegetation growing season.

References