Assessing reclamation ready tailings materials using outdoor terrestrial mesocosms

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ABSTRACT

Current challenges in oil sands mine closure include the integration of tailings into reclaimed landscapes to ensure that materials are geotechnically stable; have acceptable soil; water and run-off quality; permit soil development consistent with regional soils; and, have ecological aspects of form and function consistent with the boreal forest. Infrastructure available in Alberta to facilitate feasible, controlled and replicated testing of tailings materials under realistic climate, environmental and exposure conditions is lacking. The Terrestrial Mesocosm Facility was designed to provide a relevant venue for testing engineered ecosystems, such as reconstructed soils. Mesocosms can include sufficient biotic and abiotic components to confer stability under replicated and controlled conditions; experiments can be conducted on time frames ranging from months to years. The facility represents an integrative scientific approach for investigating ecological and environmental systems by utilizing both laboratory and field data to develop complex assessments of indirect and synergistic ecosystem responses. Simultaneous testing of different scenarios can be completed as a feasible first step in identifying reclamation strategies to implement on-site; associated long-term monitoring may provide valuable information necessary for determining upland vegetation establishment success. This paper introduces a tool for testing tailings for reclamation planning and environmental effects assessment.

Key Words: Field mesocosm, tailings, reconstructed soils, environment

1 INTRODUCTION

1.1 Environmental Mesocosms

Environmental mesocosms are bound and partially enclosed physical models that permit detailed assessments of simulated ecosystems (Boyle & Fairchild 1997, Odum 1984). Mesocosms typically take the form of an impermeable vessel containing a substrate (e.g. soil, tailings, overburden, and process waters) and biotic community (plants, animals and microorganisms). This permits enclosed and secure testing of chemical constituents (e.g. hydrocarbons, salts, metals, organic acids) known to have harmful effects on aquatic and/or terrestrial environments.

Environmental mesocosms do not mimic specific ecosystems but reflect similar and specific structural and functional features and/or characteristics (Lagadic 2014, Shaw & Kennedy 1996). As simple engineered systems, mesocosms balance complexity and control to a degree rarely achievable in either laboratory or field based research (Solomon & Liber 1988) (Fig.1). Mesocosms are more representative of actual systems than laboratory studies due to their size and exposure to natural climatic and biological conditions when housed outdoors. Laboratory experiments tend to be reductionist, using only the minimum number of elements necessary to investigate relationships between independent and dependent variables. These experimental systems (e.g. bacteria in a petri dish, fish in an aquarium, potted plants) permit high degree of replication and control, but can generate simplistic conclusions that do not reflect the complexity of real world phenomena. In comparison, field studies lack control and replication.
Since no two field sites are identical, investigators must use a relatively large number of similar sites or plots to determine baseline responses and confer statistical weight to results. Field sites naturally change over time, either through ecological succession or uncontrollable events, increasing data variability; the collection of extensive baseline data at each site may not mitigate effects of confounding variables. The collection of field data can be time consuming and expensive; some sites require extensive training and supervision, making many long term investigations impractical. Conversely, if populations or ecosystems are targeted for investigation, laboratory or field-scale studies would more adequately represent the scientific study, depending on the research question.

![Diagram](https://via.placeholder.com/150)

**Figure 1.** Arbitrary distribution of the key properties distinguishing the types of environmental experiments. Mesocosms as engineered ecosystems fall between the extremes, incorporating a practical level of complexity while maintaining significant control and replication.

By incorporating the major structural and functional elements of a natural ecosystem, mesocosms provide sufficient complexity to improve our ability to holistically extrapolate from experimental work to understand and predict biotic/ecological and abiotic/environmental interactions and responses to perturbations at larger scales. The control afforded by mesocosm replication permits robust statistical analyses and the ability to identify parameters, such as early indicators, exposure thresholds and risk factors. This paper considers the design of a mesocosm facility and the potential studies for which it may be used in the testing of reclamation ready tailings.

### 1.2 Existing Mesocosm Facilities

Terrestrial mesocosms have been used to identify short term measures of ecological processes and validate field survey data (Fay et al. 2008, Hu et al. 2005, Moore et al. 2007, Nippert et al. 2007). North American mesocosm facilities range from large complexes to small tanks, depending on the intended application. The majority of previous experiments have either been small in scale (< 2600 L), utilizing soil core samples from the field, or highly instrumented open air terraces (e.g. Ecotron chambers) (Stewart et al. 2013). Of the existing mesocosm facilities in North America, there are no terrestrial facilities within the Great Plains and Northern Boreal Forest ecoregions of Canada to adequately represent environmental conditions of the prairie provinces (Fig. 2), thus restricting this type of research to the USA, Germany, France, Norway and Belgium (Stewart et al. 2013).
Figure 2. Distribution of mesocosm facilities across North America and location of the Alberta Innovates - Technology Futures and University of Alberta Terrestrial Mesocosm Facility in Vegreville, AB (yellow). The facilities highlighted include aquatic mesocosms (blue), terrestrial mesocosms (green) and riparian mesocosms (orange). Note the absence of mesocosm facilities in the Western inland of North America. Photo is adapted from GoogleEarth (2014).

1.3 Alberta Innovates - Technology Futures Mesocosm Facility

Alberta Innovates - Technology Futures (AITF) and the University of Alberta (through the Helmholtz-Alberta Initiative) are constructing an outdoor mesocosm research facility. The complete facility will contain both terrestrial and aquatic mesocosms, providing a secure, controlled, professionally operated and ecologically relevant venue for a range of investigations, leveraged by support, expertise and funding from participating organizations and industries. The mesocosm facility will provide unique physical infrastructure and a new model for strategic collaboration for research and development surrounding some of Alberta’s most pressing environmental challenges. The first phase of construction is the development and construction of the terrestrial mesocosms.

2 MATERIALS AND METHODS

2.1 Site

The Terrestrial Mesocosm Facility (TMF) is located in Vegreville, Alberta on 22,000 m² of land adjacent to a major transportation corridor. The area is undeveloped agricultural land since prior to 1949, used as pasture since at least 1976. The area is generally flat and at grade. This site has been considered for the testing of oil sands related materials, currently produced in the Athabasca oil sands region (Fort McMurray, Alberta).

Similar to Fort McMurray, maximum average monthly air temperatures in Vegreville occur from June through July (21 to 23 °C); minimum average monthly temperatures occur from December through February (-19 to -23 °C). There is little regional variation in temperature. The average number of frost free days is 106 days. Average annual precipitation is 404 mm, comparable to 435 mm in Fort McMurray; greatest during the summer months (Environment Canada 2015, McClay 1996, NHC 2005).

2.2 Spill Containment

Wastes generated at oil sands mine sites and processing plants are subject to the Waste Control Regulation and must be classified as hazardous or non-hazardous by the generator (AQP 1996). This includes wastes that result from construction, operation or reclamation of well sites, heavy
oil sites, oil sands sites or related facilities. As per the Waste Classification Guide, mining overburden, soil contaminated with crude petroleum hydrocarbons, tailings pond sludge and delayed/fluid petroleum cokes are not regulated as hazardous wastes (AEP 1995). However, due to the current lack of stakeholder and public understanding of these materials and their associated chemical components, secondary containment was incorporated into the TMF. This additionally permits outdoor testing of toxic materials (e.g. materials containing chemical constituents above Alberta Tier 1 and/or Canadian Council of the Ministers of Environment (CCME) guidelines or defined as such by material safety data sheets (MSDS), and materials governed by the zero discharge policy (e.g. oil sands process water, recycle water in full strength, or process/recycle water diluted to any concentration).

Incorporating secondary containment at the TMF permits identification and mitigation of spills; prevention of soil and groundwater contamination; and, maintains public and stakeholder approval based on due diligence and control over materials that are not well understood. As a result, long term outdoor research can be conducted using a wide range of oil and gas related materials without safety and liability concerns.

Secondary containment was designed and constructed (September 2015) as per guidelines for above ground storage tanks containing industrial waste and wastewater (AEP 1997). The total staged area is approximately 640 m², consisting of a lined and dyked area (500 mm earthen berms) graded (2%) to a catchment with a volumetric capacity of 100% of the largest tank, 10% of the aggregate capacity of all other tanks, and 1/100 year 24 hour rainfall (~74 mm). The underlying clay (compacted to 98% standard proctor density at optimum moisture content) was lined with the following liner materials: geotextile LP 8 (overlain on top of the underlying clay layer), double textured synthetic liner (overlain on top of the geotextile) and a geocomposite. Gravel was placed and compacted to 100% on top of the liner materials, graded and swaled to create positive drainage. The area containing the mesocosm tanks was leveled. The design permits spills to be contained before treatment and disposal, if necessary (Fig. 3).

![Figure 3. Secondary containment design for the staging of the terrestrial mesocosms (Vegreville, Alberta).](image)

### 2.3 Terrestrial Mesocosm Construction

Terrestrial mesocosms were constructed from open top polyethylene tanks (2.2 m width x 1.3 m height; 5000 L), connected to source and drainage tanks (0.6 m width x 1.3 m height) (Fig. 4). Construction of the TMF was completed on September 30, 2015; full scale operation will begin spring 2016.
Figure 4: Schematic of a terrestrial mesocosm designed for the Terrestrial Mesocosm Facility.

Water table depth is regulated by hydraulic head from the source tanks, providing a simulated groundwater source, based on gravity flow. Water is introduced to the base of the mesocosm tank at three points through slotted pipes to permit a relatively even distribution of water through the soil profile. Valves are placed near the top and center of the mesocosm tank to aid in maintaining groundwater level, under simulated drought, perched water table or flooding conditions. Additional water added to the tank by precipitation is directed to a drainage tank via screened sand pack pipes. A suite of instrumentation is incorporated into the design to aid investigation of environmental perturbations (Table 1).

Table 1: Instrumentation and equipment currently incorporated into the terrestrial mesocosms.

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Description</th>
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</thead>
<tbody>
<tr>
<td>Standpipe</td>
<td>Installed to capture, confirm and monitor intended water table depth within the soil profile.</td>
</tr>
<tr>
<td>Piezometers</td>
<td>Installed into each soil horizon to collect groundwater samples for chemical analyses. Used to document changes in pore water chemistry, evaluate transport and fate of chemical compounds (inorganic and organic) and evaluate chemical and/or biological condition of the rooting zone.</td>
</tr>
<tr>
<td>Lysimeters</td>
<td>Installed into each soil horizon (or at the soil horizon interfaces) to measure and monitor soil temperature, pH and electrical conductivity.</td>
</tr>
<tr>
<td>Soil Sensors</td>
<td>Specialized tube and camera that permit visualization of root development throughout the soil during plant growth and development.</td>
</tr>
<tr>
<td>Rhizotron Tubes/Camera</td>
<td>Installed adjacent to the terrestrial mesocosms to record soil sensor data and capture local meteorological data. Includes: air temperature, relative humidity, solar radiation, rainfall and wind speed and direction.</td>
</tr>
<tr>
<td>Weather Station</td>
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For experimentation, soil materials can be shipped from any site or location and layered in the mesocosm tanks to produce various soil profiles to meet independent experimental objectives. Other materials typically used in reclamation scenarios, such as amendments (e.g. biochar, humalite and sludge), litter, and woody debris can be incorporated and investigated in the mesocosms. Soils can be planted with various grasses, forbs, shrubs and juvenile trees in a
suitable planting density. Sampling is not restricted to water, soil and plants, as soil microbiota (e.g. bacteria and fungi) and soil dwelling arthropods can also be investigated.

2.4 Experimental Design

Variability is expected to increase with experimental complexity of the mesocosms. The literature suggests that 4 to 7 replicate treatment and control mesocosms be used to statistically detect a 50% deviation from the control, with an acceptable 20 to 30% coefficient of variation for monitored biological endpoints (Kraufvelin 1998). This corresponds with literature reporting that most field studies rely on 4 replicates per treatment (Kennedy et al. 1999, Voshell et al. 1989). Basic experimental designs typically include a minimum of 3 treatment groups (e.g. high, medium and low dose) along with a control group. This permits identification and quantification of trends in observable responses. Using the replication and experimental guidelines, individual experiments will be based on a maximum of 16 terrestrial tanks (e.g. 4 groups of 4 tanks each). However, experimental designs will be determined by individual research questions and parameters to be analysed. For more complex experimental designs with increased biotic components, fewer treatments and increased replicates may be used.

3 PILOT TERRESTRIAL MESOCOSMS

Pilot terrestrial mesocosms were constructed in September 2013 to verify the design and methods for construction. These pilots have been in operation for 2 years, permitting testing of the infrastructure and instrumentation over multiple seasons. Pilots were set up in individual leveled excavated pits of 1 m depth without secondary containment.

The intention of the pilots was to test a current oil sands capping soil prescription using reclaimed soils from the Athabasca oil sands region, to test the effectiveness of the soil capping process within the mesocosms; evaluate effectiveness of the hydraulic head method for maintaining suitable and consistent water table levels; and, determine natural seasonal effects from precipitation, drought, freezing and snow cover.

Coarse and fine soil materials, consisting of salvaged peat mix, secondary clay and tailings sand were placed into the mesocosms in 40 cm lifts (or vertical sections) and compacted, by hand, to achieve targeted bulk densities typical of reclaimed landscapes. Once completed, 6 plugs of balsam poplar, jack pine and black spruce and 3 plugs of trembling aspen were planted. Other plants included dogwood, fireweed and hairy wild rye. Coarse woody debris was added to create microsites for vegetation establishment. Tap water was added to the source tanks on September 27, 2013. The drains were confirmed to work immediately, suggesting that the desirable water table level was achieved (further confirmed through piezometer water table levels and soil moisture sensors). Soil samples obtained from each mesocosm, taken in 10 cm increments to 70 cm in depth confirmed saturation conditions.

Prior to seasonal freezing, the source water was removed, hoses were drained and the valves were closed. Soil pore water remained in the mesocosms over the winter months for evaluation of mesocosm performance under freezing conditions. After two winter seasons, the terrestrial mesocosm infrastructure withstood and supported vegetation through repeated freeze-thaw conditions. After two growth seasons, vegetation was well established in the soil prescription, suggesting initial suitability of the capping strategy (Fig. 5). Overall, the design and configuration of the terrestrial mesocosms was confirmed, based on successful instrumentation use and preliminary results (data not shown; Woosaree et al. 2013), hereby reducing the risk of failure in future planned mesocosm experiments.

Learnings from the pilot mesocosms included slight modifications to the design, including the placement of the tanks above ground to permit greater ease of accessibility and control of valves and pipes. Individual mesocosms now contain one drain and one fill tank, connected to the main tank via manifolds (Fig. 4), instead of three drain and fills tanks, minimizing maintenance, potential leakage, and overall costs.
4 TESTING RECLAMATION READY TAILINGS IN TERRESTRIAL MESOCOSMS

Alberta industries are currently dealing with some of the largest environmental issues in Canada including the establishment of reclaimed landscapes. One of the standing features of mesocosms is that they permit proactive assessment of potential environmental and ecological impacts of many industrial materials.

4.1 Reclamation Ready Tailings

Oil sands tailings are a waste by-product of bitumen mining and extraction processes, made up of various quantities of water, dissolved inorganic and organic chemical constituents, sand, clay and residual bitumen (Allen 2008). It is estimated that the volume of tailings stored within the 22 tailings ponds (covering 167 km²) spread across the Athabasca oil sands region, exceeds 840 million m³ (Government of Alberta 2014, Pembina 2007). The main issues are that the clay/fine slurry portion of tailings is often held in suspension, taking years to settle (RAMP 2014); and the water fraction can be acutely toxic, containing high concentrations of salts and organic acids (Allen 2008). Therefore, reclamation of tailings to former and/or productive uses requires either long term storage (incorporated into dry or wet capping strategies) or treatment (RAMP 2014). New tailings technologies are expected to speed up the transformation of tailings into reclamation ready deposits (or deposits ready for transformation into reclaimed lands). These technologies are different for each oil sands operator (COSIA 2015, Government of Alberta 2011) and the various tailings materials are expected to behave differently as soils, due to the different processes, polymers, etc. used during tailings treatment.

The new tailings management framework (Government of Alberta 2015) focuses on faster tailings pond remediation, or reclamation ready tailings (i.e. tailings that meet ready-to-reclaim criteria), thus slowing tailings pond growth. This includes both tailings treatment and on-site direct placement of tailings. Reclamation ready tailings include those that once integrated into
the closure landscape, have functional drainage systems; have acceptable water quality (in shallow soil and runoff); are geotechnically stable; have natural appearances consistent with the boreal region; have soil process development consistent with regional soils; and/or, have functional and structural aspects (i.e. ecological communities) consistent with the boreal forest (Government of Alberta 2015). Under this scenario, placed treated tailings require monitoring, and physical and chemical characteristics of the materials must be managed to achieve specific performance criteria. Previous research has found that the natural drying of some treated tailings types, as one method for on-site treatment and placement, is limited beyond 0.5 m in depth for achieving 5 kPa strength in a reasonable period (Caldwell et al. 2014, Masala & Dhadli 2012). Individual operators have conducted significant work in assessing deposition methods and strengths of treated tailings. As a result, Suncor’s tailings reduction process trials have achieved a strength profile greater than that required by Directive 074, proving the validity of optimised seasonal deposition (Caldwell et al. 2014). However, there are still uncertainties in the quantity and placement of dried tailings in soil profile reconstruction. Focused trials are required to determine methods and impacts of placed tailings for progressive reclamation, to achieve landform stability and ecosystem sustainability. Such tests can be done in the terrestrial mesocosms to help identify adequate treatments to apply at larger field scales.

Geotechnical stability can be assessed within individual mesocosms, depending on the type of tailings used, during and after tailings placement to evaluate strength and consolidation of the soil profile. Once placed tailings meet strength requirements, tailings can be capped with a variety of materials for soil profile reconstruction (such as overburden clay, tailings sand, peat mineral mix, LFH). Wolter & Naeth (2014) identified that dried mature fine tailings (MFT) could be used as capping materials if placed underneath overburden sand (OS) and peat mineral mix (PMM). The presence of OS and PMM was suggested to dilute hydrocarbons and salts originating from the tailings materials prior to reaching the rooting zone. Thus, there may be strategic advantages to the placement of treated fluid tailings with other oil sands materials.

It is still unknown whether reclamation ready tailings provide adequate rooting material for developing plant communities. This will affect the placement location of tailings in reconstructed soil profiles. For soil reconstruction to be successful, placed soils must provide sufficient nutrients to sustain developing plant communities and promote and re-establish biotic nutrient cycling within the soil (Barbour et al. 2007). This is based on the re-establishment of ecosystems that naturally occur in the region, classified as ecosites with defined soil (chemical and physical nature of the root zone) and landscape (plant species composition and abundance) characteristics (OSVRC 1998). Within the terrestrial mesocosms, treated tailings can be placed on top or below oil sands materials, such as tailings sands, and even near the soil surface to further investigate the suitability of different placement strategies and impacts on plant root establishment and development.

4.2 Effects of the Chemical Composition of Tailings

It is known that fine tailings are enriched in total organic carbon, due to the high percentage of fine clays that bind hydrocarbons to their surfaces; some organic components found in MFT drying cells are resistant to biological processes (Noah et al. 2014). Chemical and biological assays conducted on pore water from Syncrude’s Mildred Lake Settling Basin MFT were identified as acutely toxic, relating to the organic acid fraction in one study; however, toxicity dissipated rapidly with biodegradation and mutagenic activity was negligible (Madill et al. 2001). Composite tailings pore water at another pond contained adamantane-type carboxylic acids; toxicity was not determined (Bowman et al. 2014). Hydrocarbons within soils can affect photosynthesis because of their ability to accumulate in plant cell chloroplasts, distancing chlorophyll molecules and disrupting sub-microscopic structures required for photosynthesis (Baker 1970). Organic acids, such as napthenic acids, are most likely to adsorb to and accumulate in plant roots, injuring root membranes by preventing nutrient and water uptake (Apostol et al. 2004, Kamaluddin & Zwiazek 2002). Due to their surfactant-like properties,
naphthenic acids adsorbed to plant roots may also inhibit essential nutrient uptake, adversely affecting chlorophyll formation and photosynthetic processes (Kamaluddin & Zwiazek 2002).

Other environmental concerns of MFT include phytotoxic organic compounds (e.g. benzene, toluene, ethylbenzene and xylenes) and inorganic ions (salts) of high concentration (e.g. sodium, chloride and sulfate) (Wolter & Naeth 2014). Natural salt tolerant plant communities within the boreal region are uncommon (Daly et al. 2012), and the magnitude of the potential ecological impacts of salts could be as great as those of naphthenic acids (Allen 2008). This is due to the osmotic action and direct ionic toxicity of salts on plant morphology and physiology (Volkmar et al. 1998). The accumulation of sodium within plant roots can interfere with the uptake of essential major ions, resulting in reduced cell membrane permeability, osmotic imbalance and diminished cell enzyme activity (Nguyen et al. 2006). Ultimately, this can affect physiological mechanisms such as transpiration (Apostol et al. 2002, Asraf & Wu 2011). Plant root injury can also lead to the accumulation of absorbed salt ions within plant shoots and leaf tissue, resulting in reduced photosynthesis (Apostol et al. 2004).

In addition to chemical constituents, temperature sensitive polymer flocculants are soluble in water at low temperatures (Vedoy & Soares 2015). These compounds may be present in oil sands process waters and MFT pore water and capable of contributing to species toxicity despite residence times of two decades (Anderson et al. 2012). Cationic polymers have been identified to be more toxic than anionic polymers (Liber et al. 2005), as anionic polymers are readily biodegradable in soil environments (Barvenik 1994). However, there is limited information on the long term fate of polymers in tailings deposits. It is important to investigate the long term fate of both chemical constituents and flocculants within tailings materials to evaluate their potential impact and effect on microbiota and vegetation during direct long term contact with the material. This can be done using the terrestrial mesocosms.

4.3 Oil Sands Waters in the Soil Profile

To investigate the effects of oil sands process water (straight, diluted, treated) and saline source water, waters can be introduced to the mesocosms through the source tanks before or after planting. Since the chemical composition of these waters differs among oil sands operators, water, soils and tailings can be characterized before addition to the mesocosms for physical and chemical properties (e.g. solids content, pH, naphtha, bitumen, dissolved organic carbon, naphthenic acids, major ions, trace metals, polymers). The same components can be analyzed in the different soil layers, pore water and plant tissues at the end of the experiment to determine how chemical components interact with plant roots and soil materials over time. It is assumed that different effects may be experienced by plants growing in different tailings types, and the associated effects observed will be primarily attributed to the chemical and physical composition of the water and tailings used for in mesocosm set up. As the tested waters migrate along the pathway from the source water tank, through the tailings sand, clay and peat layers it may change in composition due to ion-exchange, precipitation, dissolution, adsorption, and degradation reactions. The resulting water that reaches the surface soils or plant roots may have a different composition than the original source. As a result, it is important to understand the long term fate of polymers and chemical constituents within tailings material, how they degrade over time, and whether their transport into soil and/or groundwater may come into contact with active terrestrial systems; results from mesocosms can be used to develop more accurate models.

It is unknown how the breakdown and transport of organics, inorganics and polymers in novel treated tailings materials impact root development during times of water table fluctuation (e.g. spring thaw, flooding, drought). The permeability of fine tailings materials may also decrease with consolidation, slowing the rate of water migration (Wang et al. 2014). Dried tailings undergoing continual freeze and thaw consolidation may limit natural water table movement and fluctuation, affecting soil water availability. This may force plant roots to grow to greater depths to access water sources, causing direct plant root interaction with the tailings materials and residual polymer and/or chemical constituents. Consolidation and limited water movement could
create a bog-like environment, influencing native plant growth and succession. As a result, the behaviour of tailings in a soil profile will ultimately influence ecosystem sustainability in designed and reclaimed landforms.

5 CONCLUSIONS

The TMF (Vegreville, Alberta) is a research venue that can be used by academic researchers and industry to model and evaluate structural and functional elements of natural ecosystems. These systems can be used to examine a range of ecological responses to different reclamation, mine closure and management scenarios. The design of the venue permits safe testing of materials reputed to have harmful effects on environments. Pilot terrestrial mesocosms have shown that the infrastructure can support and maintain biota over the winter months and multiple growth seasons, under climatic conditions typical of the prairie provinces. Mesocosms can be used for the controlled and replicated testing of reclamation ready tailings as a feasible first step in identifying suitable reclamation strategies to implement at the field scale. Various soil capping prescriptions can be used incorporating treated and dried tailings. AITF researchers can work directly with industrial tailings teams to ensure that soil profiles incorporate the wealth of expertise available and strategies likely to be incorporated into reclamation plans. The following components can be evaluated simultaneously to better understand and model ecosystem effects: water balance and water quality monitoring, soil physical and chemical properties and processes, vegetation monitoring and characterization, microbial characterization, and more. In doing so, the long term transport and fate of inorganic and organic chemical constituents can be evaluated to determine how the behaviour of tailings in a soil profile will ultimately influence ecosystem sustainability and reclamation trajectories in the Athabasca oil sands region.

6 ACKNOWLEDGEMENTS

The authors acknowledge the funding provided by Total E&P Ltd. to establish the terrestrial mesocosm pilots, and Canadian Natural Resources Ltd. for providing the soils materials used in the pilot soil capping prescription. For the construction of the TMF, including mesocosms, secondary containment and instrumentation, the authors acknowledge the University of Alberta and the Helmholtz-Alberta Initiative in addition to leveraged funding and support from Alberta Innovates - Technology Futures. The authors would also like to acknowledge Jim Davies for aid in the development of mesocosm facility design.

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