Restoration and Reclamation of Boreal Ecosystems

Attaining Sustainable Development

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Initiatives in oil sand reclamation

Considerations for building a fen peatland in a post-mined oil sands landscape

INTRODUCTION

Originally, wetlands comprised over 50% of the land base in northeastern Alberta; over 90% of these were peatlands (Vitt et al., 1996). In the Athabasca oil sands region, the landscape is disturbed by either *in situ* or open-pit mining activities to recover bitumen below the surface. Open-pit mining removes entire landscapes, which oil companies are entrusted to reconstruct to the best of their abilities. By law, mining disturbances must be reclaimed to a state of "equivalent land capability" (OSWWG, 2000). As all wetland types and aquatic systems fall within the same land use capability class (Class 5) (CEMA, 2006), there is some latitude on reclamation target landscapes. However, provincial directives, developed in collaboration with industry and other stakeholders, aim to reclaim some of these areas to peatlands.

Although peatlands are the dominant wetland type in the Athabasca region, marshes have been the focus of reclamation projects, because they are hydrologically simpler than peatlands and may develop spontaneously in poorly drained sections of disturbed landscapes (Harris, 2007). Moreover, many marsh species are resistant to salt contamination present in post-mined oil sands landscapes (Daly and Ciborowksi, 2008; Hornung and Foote, 2007). Peatland vegetation, especially mosses, is not believed to be tolerant of saline conditions (Boerner and Forman, 1975); however, fen peatlands can be dominated by sedge and shrub vegetation, accumulate carbon (peat), and still fulfill several other ecological functions characteristic of marshes (Trites and Bayley, 2009).

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As fens were the dominant ecosystem in the pre-mined landscape, recent efforts have focused on fen reclamation. Fens have a peat layer of 40 cm or more and support brown mosses and graminoid vegetation (i.e., sedges, grasses) (National Wetlands Working Group, 1997). If fens were systematically replaced by marshes in the post-mined landscape, there would be a loss of habitat for diverse biota, such as amphibians (Mazerolle, 1999), birds (Lachance et al., 2005), moose, caribou (Berg, 1992), unique plants (*Sarracenia purpurea*) (Johnson et al., 1995), and rare plants (*Liparis loeselii, Cardamine dentata*) (Griffiths, 2007).

Peatlands are complex ecosystems that are difficult to construct as they take thousands of years to develop naturally (Clymo, 1983). Studies by Price et al. (2007; 2010) challenged this concept and present a conceptual model. This model (referred to as the fen model throughout this chapter) aims to create fen peatlands using peat from newly expanded oil sands mine operations and to support created fens with groundwater inflow from a constructed watershed.

The fen model was later adapted into Alberta Environmental Protection and Enhancement Act (AEPEA) approvals, which recommended testing this concept in the field. Hence, some oil sands mining companies are now mandated to attempt peatland reclamation. The goal of this chapter is to describe the peatland reclamation initiatives that are taking place in the Alberta oil sands, with a focus on the Suncor pilot fen watershed being constructed at Suncor Energy Inc. (Suncor).

SUNCOR PILOT FEN WATERSHED PROGRAM

The Suncor pilot fen (Suncor Fen) program commenced in 2008 in order to validate the fen model recommendations and to meet the terms and conditions of the AEPEA. The goal of the Suncor Fen program is to establish the hydrology necessary to maintain fen plant communities in a constructed fen. The objectives of the program are to construct a fen that: (1) is a self-sustaining ecosystem; (2) is capable of accumulating carbon; (3) is capable of supporting a variety of habitats and typical fen species; and (4) enables techniques for future fen creation to be tested and refined.

Several challenges were inherent to this project. First, fen watershed reclamation had not yet been attempted in boreal Canada when the program was initiated. Thus, there was a limited knowledge base upon which to build. Second, elevated concentration of sodium (Na) and naphthenic acids (NAs)[1] are present in tailings materials used to construct the

fen watershed. Both Na and NAs negatively affect the growth of typical fen plants, such as sedges and bryophytes, as both can be toxic to wetland plants (Apostol et al., 2004; Trites and Bayley, 2008). Elevated salinity causes toxic accumulation of ions in plants, which inhibits plant growth (Jacobs and Timmer, 2005; Timmer and Teng, 2004).

The design of a fen system in the post-mined landscape requires a broad range of understanding of the flows and stores of water to and within the system, the transport and fate of contaminants and their impact on the germination, growth, and survival of plants, and how these contribute to developing a self-sustaining, carbon accumulating system. This chapter outlines the theoretical, empirical, and procedural considerations undertaken in the design of the Suncor fen.

RESTORATION AND RECLAMATION HYDROLOGY

Wetlands are essentially a hydrological landscape. Although once commonly regarded as a nuisance, we now recognize the importance of wetland functions, and consequently, wetland restoration and reclamation have become important and often required activities. It is essential to distinguish between restoration and reclamation. Restoration takes advantage of the residual function of a degraded system situated in a landscape and aims to restore a site to its previous community structure or ecosystem functions (SER 2002). There have been many failures, which often arise from the inability to replicate the hydrological functions that drive the ecology (Mitsch and Wilson, 1996). Restoration of site hydrology may fail due to poor understanding of site-specific factors, which ultimately can compromise the local water budget, or when broader landscape changes have occurred, wetland restoration sites may no longer be suitable for supplying water at the same rate or volume as in the original system. In contrast to restoration, reclamation is the process of making land fit for a designated function. In the case of wetlands, this function can range from recreational wetlands (i.e., duck hunting, angling), to detention basins for hydrological and water quality control (Bishay et al., 1993), to more-or-less functional ecosystems (US EPA, 1993). In any of these, the design specifically accounts for the hydrology to achieve the desired function. However, to reclaim a fully functional wetland ecosystem, the hydrological design must foster the appropriate biogeochemical and ecological functions, which requires a detailed understanding of the abiotic and biotic processes. While great advances have been made in this regard (Mitsch and Wilson, 1996), each reclaimed wetland is unique, and there remains considerable uncertainty as to how the interdependent

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[1] Strictly speaking, naphthenic acids are deprotonated naphthenate anions that are naturally present in bitumen, but become concentrated during oil sands extraction.

mechanisms of hydrology, biogeochemistry, and ecology will manifest in any particular instance. Because the oil sands open-pit mining process completely removes the original ecosystem, wetland reclamation rather than restoration has become a focus.

The climate of the Western Boreal Plain (WBP) near Fort McMurray, Alberta, is cool and dry, with average annual total precipitation (P) of 456 mm, with 34% as snow (Environment Canada, 2011; www.climate.weatheroffice.ec.gc.ca). Potential evapotranspiration (PET) in the WBP is approximately 517 mm (Bothe and Abraham, 1993), although actual evaporation (ET) is far less than PET. Carey (2008) reported average annual evapotranspiration as 251 mm/y (2003–2005) from reclaimed oil sands overburden materials. However, ET from open wetland areas where water is not generally limited will approach the potential rate (Lafleur, 1990; Price, 1994). The point is that evapotranspiration demand is high in this region and wetlands will only develop where surface and groundwater inflows are present, which may occur only sporadically during wet years.

Devito et al. (2005) noted that water availability coincides with the period of maximum evapotranspiration demand, and thus there is limited opportunity for overland flow and runoff to feed these systems. Given that fens comprise about half of the landscape in the oil sands region (Vitt and Chee, 1989), the upland area that could contribute to water fluxes is relatively small, of the order of 1:1. Furthermore, the connections between upland and fen are often transient. Significant recharge to fens of the WBP may therefore take place only during infrequent wet years that occur in a 10–15-year cycle (Ferone and Devito, 2004). In fact, flow reversal (peatland water supplies mineral upland) occurs because the water table of upland areas often drops sufficiently during dry periods due to the high water demand of poplars (Ferone and Devito, 2004; Smerdon et al. 2008). From a reclamation design point of view, however, there is sufficient uncertainty regarding the mechanisms of surface and groundwater inputs, as well as their frequency and magnitude of input, that a conservative approach is essential. The design must include appropriate consideration of hydrological processes beyond the wetland/upland boundary.

Many of the principles of peatland reclamation can be derived from peatland restoration research in Canada. This has focused mainly on bogs, for which a successful method has been developed (Rochefort et al., 2003). This approach uses a "moss transfer" method (see Chapter 14), whereby shredded material including *Sphagnum* mosses and rhizomes of vascular plants are milled from an undisturbed "donor" site, spread thinly onto prepared cutover peat surfaces of a rewetted bog (i.e., ditches blocked), and covered with a straw mulch to reduce ET losses (Price et al., 1998). A similar approach has been used for fen restoration in Quebec (Cobbaert et al., 2004; Graf and Rochefort, 2008), and direct plantings and seeding have also been used in small alpine fens in Colorado (Cooper and MacDonald, 2000). However, no critical moisture thresholds have been established for fen species reestablishment, as was done for bogs (Price and Whitehead, 2004). While vascular plants can extract moisture with considerable suction, *Sphagnum* mosses rely on capillary rise (Price et al., 2009) generated by the relatively weak tension in the large pores that form between the stems and leaves of individual plants clustered tightly together in a community (Price and Whittington, 2010).

The aforementioned hydrological research on mosses has been restricted to *Sphagnum* species and no similar work has been done on the brown mosses that occur in fens. However, Cobbaert et al. (2004) reported successful reestablishment of fen plants, excluding brown mosses, in a previously mined peatland where soil-water pressures temporarily dropped as low as −200 mb. However, given that fens typically have a higher water table than bogs (Ingram, 1983), it seems probable that non-vascular species (especially brown mosses) are poorly adapted to dry conditions. Indeed, Graf et al. (2008) found that on abandoned harvested fens in eastern Canada, Cyperaceae and Gramineae species were especially successful, but bryophytes did relatively poorly.

To date, fen reclamation over oil sands overburden and tailings sand structures is an untested concept. While fen peatlands are under construction at Suncor and Syncrude Canada Ltd. (Syncrude), we are far from being able to assess their long-term persistence in the landscape. These reclaimed fens aim to provide a peat substrate (imported from land clearance elsewhere on their leases) that can support fen vegetation, but they manipulate the hydrology in very different ways to achieve the target substrate conditions. The Syncrude fen relies on a managed water supply, whereas the Suncor fen incorporates an integral upland system intended to provide an adequate water supply, but is subject to the vagaries of weather. The fundamental problem for fen reclamation is to design a groundwater system that can provide the inflows required to sustain the hydrological, biogeochemical, and ecological processes and functions.

OIL SANDS PROCESS WATER, SODIUM AND NAPHTHENIC ACIDS TRANSPORT THROUGH PEAT, AND THE IMPACT ON FEN VEGETATION

It is not known whether fen plants can survive long-term exposure to oil sands process water (OSPW) containing sodium (Na) and naphthenic acids (NAs), naturally occurring substances in the oil sand deposit, or how these substances move through peat and interact with plant roots. A research program was initiated to address these challenges to reclaiming fens. In this program, laboratory and greenhouse mesocosm experiments were run to determine how OSPW is transported through peat driven by evapotranspiration from a moss and/or vascular plant cover, and how these plants and microbial communities react to OSPW contamination. The main objectives were to characterize: (1) the movement of process-affected water in peat substrate, and (2) survival and growth of common fen species native to the oil sands region.

Adsorption and dispersion of oil sands process-affected water in peat

Flow and transport in peat soils are dependent upon the chemical characteristics of the solute (Hill and Siegel, 1991), microbiological processes (Todorova et al., 2005), and the physical characteristics of the peat porous matrix (Ours et al., 1997; Price and Woo, 1988). Oil sands-derived aqueous mixtures of Na and NAs are readily transported through porous geological media (Gervais and Barker, 2005), but very little information is available in the literature on their transport through peat. Peat has a complex cell structure that results in a dual porosity comprising open, dead-end, and closed or partially closed pores that can delay the passage of nonreactive solutes (Hoag and Price, 1997). However, both Na and NAs are strongly adsorbed by organic matter (Ho and McKay, 2000; Janfada et al., 2006). Thus, an understanding of the migration and persistence of Na and NAs in the rooting zone of peat is needed, because these factors will control the critical toxicity levels in the reclaimed fen, where OSPW is expected to be present within the boundaries of the peatland as a result of the use of tailings sand as one of the construction materials.

To characterize the fate and transport of OSPW in peat, Rezanezhad et al. (2010) ran a series of experiments to determine the amount of adsorption and how the solute behaves in a solution flowing through the dual-porosity porous medium. Sorption of Na and NAs in OSPW on fen peat from Alberta was tested by mixing it at different concentrations with dried peat and measuring the concentration of the eluent. They found that approximately 94% of the 43.5 mg L^{-1} of NAs in OSPW was adsorbed by 1 kg of peat. For Na, ~84% sorption occurred with 382 mg L^{-1} kg^{-1} of peat. The adsorption of NAs and Na on peat fit Freundlich linear isotherms with distribution coefficients of 6.53 and 5.74 L kg^{-1}, respectively. This relationship is important to describe how much solute is removed from a flowing solution; for example, during transport modeling. This was done for Na through the fen peat by administering a step input of known concentration into a peat column and measuring the time for solute to break through to the outflow. Rezanezhad et al. (2010) showed the retardation of Na was $R = 1.92$ (i.e., 1.92 times slower than the average velocity of water molecules) using a two-region (mobile and immobile) non-equilibrium transport model to represent the dual porosity soil. The model confirmed that part of retardation is attributed to solute exchange between the mobile and immobile phases. Breakthrough tests were not performed on NAs due to poor analytical precision at low concentrations.

Rezanezhad et al. (2011) also examined OSPW migration in peat monoliths in the greenhouse, which were covered with either moss or vascular plants (see next section). Oil sands process water with concentrations representing field values (~40 mg L^{-1} NAs and 385 mg L^{-1} Na) was introduced to the base of the 76-cm thick mesocosms and drawn upward by evaporation from the mosses (0.5 to 1.6 mm d^{-1}) and evapotranspiration from the vascular plants (2.7 to 4.7 mm d^{-1}).

In the moss mesocosm, the increase in mass of Na and NAs in the liquid phase was sequentially delayed at higher elevations in the profile over 310 days of evapotranspiration. At a depth of −5 cm, the adsorption rate was 17.5% for Na and ~8% for NAs, respectively. In the vascular plant mesocosms, Na concentration of the −5-cm and −10-cm layer exceeded that of the −15- and −25-cm layer because of evapoconcentration. At a depth of −5 cm, the adsorption rate was 25% for Na and ~5% for NAs, respectively. In both mesocosms the amount of solute in the solid phase, due to sorption, was approximately one order of magnitude larger than in the liquid phase. These high concentrations, although considerably delayed, were detrimental to the moss health, but not the vascular plants (see next section).

Response of moss and vascular plants to oil sands process water

The effects of OSPW on fen vascular plants and mosses needs to be established to determine the target species for reclamation. Bryophytes are either absent or not prominent in saline conditions (Adam, 1976; Shacklette, 1961; Vitt, 1976) and salinity might be a driving factor in peatland distribution in the boreal plains (Vitt et al., 1996). Naturally, saline wetlands supporting salt tolerant plant communities are uncommon in the boreal region (Trites and Bayley, 2009) and only a few moss species appear in these saline fens (*Bryum pseudotriquetrum*, *Campylium* *stellatum*, and *Drepanocladus aduncus* [Vitt et al., 1993]). Salinity in OSPW may limit the development of peat mosses in oil sand post-mined areas due to low tolerances to salinity. Understanding the salinity thresholds of key peatland species is thus essential to peatland reclamation in a post-mined landscape. The type of salt is an important factor influencing plant growth (Franklin and Zwiazek, 2004) and NaCl seems to be the most harmful for boreal species (Nguyen et al., 2006). However, little research on salinity effects has been carried out on peatland mosses (Bloise and Vitt, 2011). Here, we summarize research funded by Suncor that addresses the tolerance of fen species to OSPW on two scales: (1) bryophytes in microcosms (Petri dishes); and (2) mesocosms experiment related to those described in the previous section.

Microscale experiments (Pouliot et al, unpublished) determined the effect of OSPW salts on the growth of mosses by immersing selected species in solutions of NaCl and Na_2SO_4. This includes *B. pseudotriquetrum* and *C. stellatum*, which are found in saline Alberta fens (Vitt et al., 1993); and *Sphagnum warnstorfii* and *Tomenthypnum nitens*, which are common in non-saline fens in the Athabasca region (Chee and Vitt, 1989). Differences between the number of innovations (i.e., new shoots emerging from a moss fragment) counted on ten moss fragments at the beginning and at the end of each experiment, or the number of capitula (for *S. warnstorfii*), used to compare treatments.

First, *C. stellatum*, *S. warnstorfii*, and *T. nitens* were immersed in a saline solution (0, 100, 300, or 500 mg L^{-1} of NaCl) for ¼, 1, 3, or 7 days before being placed in Petri dishes and watered with rainwater for 65 (*C. stellatum* and *S. warnstorfii*) or 100 days (*T. nitens*). Moss species tolerated their immersion in saline conditions and, in some cases, showed an increase in the number of innovations or capitula. For *S. warnstorfii*, the situation was different; a longer immersion time increased the number of capitula when salt concentrations were equal to 0 or 100 mg L^{-1} (higher for 0 mg L^{-1}), but peaks were observed around three days (300 mg L^{-1}) and one day (500 mg L^{-1}).

In a second experiment, *B. pseudotriquetrum*, *C. stellatum*, and *T. nitens* were watered with different saline solutions (NaCl, Na_2SO_4, and a combination of both) for approximately 100 days, at concentrations of 0, 30, 50, or 70% of the concentrations found in OSPW, which contains around 500 mg L^{-1} of NaCl and 600 mg L^{-1} of Na_2SO_4 (in OSPW samples taken by Suncor in 2009). Bryophyte growth was not stimulated when they were watered with saline solutions. Salt type had no effect; an increase of salt concentration of either solution inhibited the development of new innovations for two of the three species (*B. pseudotriquetrum* and *T. nitens*).

These data show that the tested moss species common to northeastern Alberta may be tolerant to salt concentrations typical of post-mined oil sands landscapes (Trites and Bailey, 2008). Furthermore, salt concentrations in OSPW were probably not high enough to disrupt photosynthesis (Wilcox, 1984). Contrary to the findings of Nguyen et al. (2006), sodium chloride (NaCl) did not have a stronger effect than Na_2SO_4 on mosses. Thus, all tested species would likely survive periodic inundations in OSPW as may occur during spring snowmelt or after heavy rains. Furthermore, as immersion time had a positive effect on the number of initiations, punctual saline stress perhaps prompted mosses to be more productive. However, constant growth in salt concentration, even at only 30% of concentration in OSPW, was sufficient to reduce the number of new innovations and would be detrimental for mosses. Hence, persistent inundation with OSPW should be avoided if the restoration of a moss carpet is an objective. Our experiment showed that threshold levels for salt tolerance of the species tested were possibly not reached. However, evapoconcentration of Na (and other salts) has been shown to reach 1.2 to 23.5 g L^{-1}, in moss and vascular plant experiments, respectively (Rezanezhad et al. 2011). Therefore, under field conditions the stress on mosses (and many vascular species) will be high. We conclude that *B. pseudotriquetrum* and *C. stellatum* already found in saline fens (Vitt et al., 1993) seem to be the best choice in fen creation following oil sands exploitation. The sensitivity to NAs was not tested.

In fen reclamation, it is necessary to understand the ability of candidate plant species to survive and grow on a peat substrate receiving OSPW. A greenhouse experiment with five replicates was conducted to test the response of whole plant transplants of five vascular plants (*Calamagrostis stricta*, *Carex atherodes*, *C. utriculata*, *Trichophorum cespitosum*, and *Triglochin maritima*) growing in peat and receiving varying concentrations of OSPW (Pouliot et al., in press). The OSPW effect was tested at different concentrations: (a) nondiluted OSPW (approximately 54 mg L^{-1} of naphthenic acid and 569 mg L^{-1} of Na); (b) diluted OSPW (approximately 40 mg L^{-1} NAs and 400 mg L^{-1} Na); and (c) rain water (control treatment). All these species are common in rich fens of the oil sands region (Chee and Vitt, 1989). The experiment was run over two growing seasons, where the first was wetter than the second. A plant health index was noted for all species, ranging from 7 (100% healthy) to 1 (100% dead). Over both growing seasons there was no significant decrease between the OSPW treatments for plant health for vascular plants (health index averaged 5.3), although at the end of each season there were signs of senescence (health index averaged 4.1). Similar results were observed in another experiment where only one OSPW concentration was tested for *C. aquatilis* and *C. stricta* (approximately 54 mg L^{-1} of naphthenic acid and 569 mg L^{-1} of Na) (Rezanezhad et al., 2011). The increase in Na and NAs in the rooting zone (see previous section), especially during the relatively dry second growing season, had little apparent effect on vascular plant health.

It appears that peat has a high buffering capacity which adsorbs many substances found in OSPW, and the transport of Na and NAs in peat substrates is highly retarded (see the previous section). In addition, peat affected the concentration of potentially toxic compounds in the rooting zone. Vascular plants that received OSPW did not show signs of stress. This is consistent with the results of Trites and Bayley (2008), which showed that whole plant transplants of vascular wetland species were able to grow in oil sands wetlands. Here, the concentrations are low enough that Gramineae and Cyperaceae, for example, do not require adaptations such as maintaining high potassium concentrations in their tissue to block the entry of sodium (Albert and Popp, 1977; Cooper, 1982; Gorham et al., 1980). Peat thicknesses in the Suncor pilot fen currently under construction will be much greater (~2 m) than in the tested experimental units. This suggests that several years may pass before any effect of OSPW on plants is detectable, potentially allowing a healthy cover of graminoid vegetation to establish. Moreover, normal precipitation in the oil sands district is higher than was simulated in the greenhouse, and potentials for leaching, horizontal transport, and surface runoff losses are present in the field. Some plants regenerated better and began reproducing more quickly than others. These plants also produced much more biomass, indicating that they might be better peat-accumulating species. *Carex aquatilis*, *C. atherodes*, *C. utriculata*, and *T. maritima* produced more aboveground biomass than *C. stricta* or *T. cespitosum*, making them more useful species for restoring a vegetative cover quickly and, potentially, creating a peat-accumulating system.

In the greenhouse experiment described in the previous section, mosses were not affected during the first growing season when watering was more similar to the amount of precipitation that historically falls each summer in the oil sands region (plant health index of 6.6), but they rapidly declined in the second growing season (dropping to a plant health index of 1.5). We interpret that decline in moss health in the OSPW-affected mesocosms to toxicity coupled with water stress (in the drier second season). Contrary to the Petri dish experiment, where mosses grew in the presence of OSPW in a closed environment with high humidity, OSPW treatments in the greenhouse were detrimental for mosses in situations of water stress, indicating that water control should be a crucial step in fen creation following oil sands exploitation.

SUNCOR FEN SITE INVESTIGATION, DESIGN, CONSTRUCTION, REVEGETATION, AND MONITORING

The Suncor fen design uses an upland linked to fen peat placed at the base of a slope designed to provide the requisite amount of water to keep peat sufficiently wet to support fen vegetation. The simulations of Price et al. (2007; 2010) tested a range of material types (by varying hydraulic properties) and geometric arrangements (slope, upland contributing area, layer thickness, etc.), under: (1) severe drought, and (2) climatic conditions characteristic of the Fort McMurray area. The simulations were examined to determine the ability of the system to sustain a critical threshold pressure in the peat during drought conditions. Price et al. (2007; 2010) caution, however, that the threshold condition (soil water pressure at 10 cm depth $\geq$100 mb) was set for *Sphagnum* mosses in drained cutover bogs (Price and Whitehead, 2004), and as previously noted, has not been tested for fen species.

The final design for the Suncor fen (unpublished) was based on the fen model recommendations using materials meeting the hydraulic requirements they specified. However, the final design was modified in consultation with geotechnical engineers to accommodate the specific morphological and hydrogeological conditions of the site. It will rely on a thick peat layer (~2 m) to delay and disperse transport of contaminants to the rooting zone.

Moving from concept to design began by establishing the goals and objectives of the program, as previously outlined. The program was then divided into five parts: (1) site investigation, (2) watershed design, (3) vegetation strategies, (4) construction, and (5) research and monitoring.

Site investigation

First, an appropriate location for the constructed fen watershed was required. Site selection was based on the following criteria: (1) Suncor had no future plans to disturb the location; (2) the sediments were geotechnically stable and capable of supporting a wet environment; (3) the location's topography contained gentle slopes, which facilitated the fen model recommendations outlined by Price et al. (2010); (4) the region was large enough to enable all fen dimensions to be a minimum of 100 m to minimize edge effects; (5) close proximity to natural areas that may

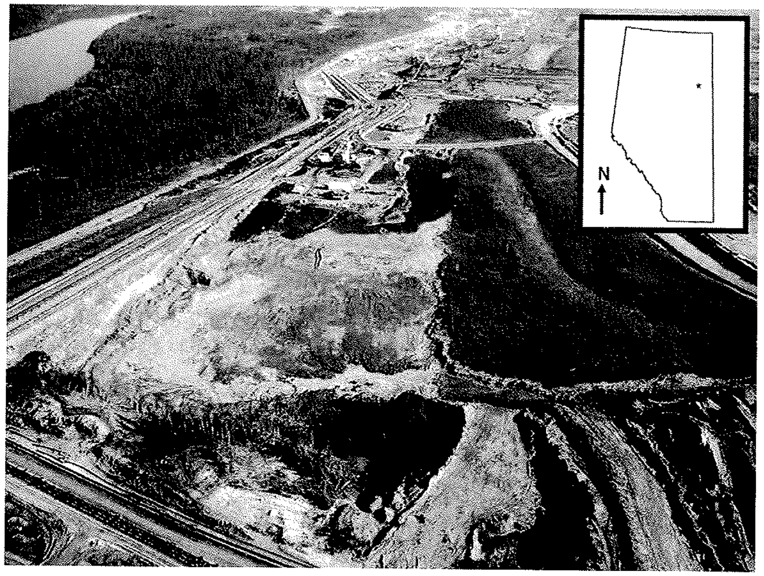

Figure 9.1. Looking north at the Suncor Fen site known as the TLC, pre-construction, on Suncor's lease in Fort McMurray, AB. The site approximates 675 m at its widest extent near the south end. (Photo credit: Gord McKenna.) (See color plate section for colored image.)

act as natural seed banks and wildlife corridors; (6) materials planned for use in construction were nearby, so as to minimize haul route costs; and (7) the area was in an easily accessible, low mine traffic area, safe for researchers and tours. Suncor reclamation staff compiled a list of all available areas on Suncor's open-pit mining leases and compared each potential site to the site selection criteria. An area known as the tailings line corridor (TLC) met all of these criteria and was selected as the optimal site for fen reclamation. The TLC is located on Suncor's Millennium lease in the southwest corner of the active Millennium mine and east of the wildlife corridor, a parcel of natural forest over 100 m wide along the Athabasca River (Figure 9.1). The TLC was a pit previously mined for bitumen and later filled in with overburden. Part of an intact natural ravine with wildlife habitat (i.e., birds and small mammals) at the south end of the construction site was incorporated into the design.

Fen watershed design

After site selection was complete, an investigation of the construction site was initiated to provide an understanding of the site-specific hydrogeological setting and how the fen model recommendations could be incorporated. Specifically, the site investigation examined the stratigraphic profile, geotechnical stability, groundwater hydrology, and water quality.

The geologic formations present include Devonian limestone below a thin layer (~5 m) of fluvial sands. The Middle and Lower McMurray formations overlay the fluvial sands and were capped with overburden material containing a mixture of lean oil sand, glacial material, clay, shale, and loamy sand (Kessler et al., 2010). In general, the overburden materials varied from uniform sand, consisting of approximately 85% sand and 15% silt and clay-sized particles to a well-graded material consisting of 40% sand and 60% silt and clay-sized particles, based on the Unified Soil Classification System (Kessler et al., 2010).

Once the site investigation was complete, the fen watershed design phase commenced. Both the site investigation and fen watershed designs were completed by BGC Engineering Inc. and O'Kane Consultants Inc. The Suncor pilot fen designs were modified from the Price et al. (2007; 2010) fen watershed design recommendations to meet site-specific conditions, and were as follows (Figure 9.2):

1. Construct the base of the fen watershed with a liner that has a relatively uniform hydraulic conductivity (*K*) less than or equal to 1×10^{-10} m s^{-1}. For the site-specific conditions, a synthetic liner is suggested because it more than meets the minimum hydraulic requirements and minimizes cut and fill volumes, thus cost.
2. Use a liner slope of 3%, which provides a sufficient hydraulic gradient to move water downslope (i.e., without excessive seepage or ET loss).
3. Construct the upland aquifer of tailings sand with $K = 1 \times 10^{-4}$ m s^{-1}, which enables groundwater to flow relatively rapidly toward the fen. The recommended thickness of the sandy aquifer is 3 m near the fen to 2 m at the upland end of the system. This is intended to keep the water table a relatively constant 2 m below the surface, given a wedge-shaped saturated zone expected to develop over the liner. Otherwise a shallow water table in the upland near the fen boundary would be susceptible to salinization.
4. Construct the system with an upland:fen area ratio of ~3:1.
5. Strategically place a series of gentle swales and hummocks on the upland to intercept and recharge surface water (i.e., snowmelt) from adjacent slopes.
6. Use a relatively thin (20 cm depth) LFH (boreal forest) soil acquired from newly cleared lease areas over the upland aquifer to promote

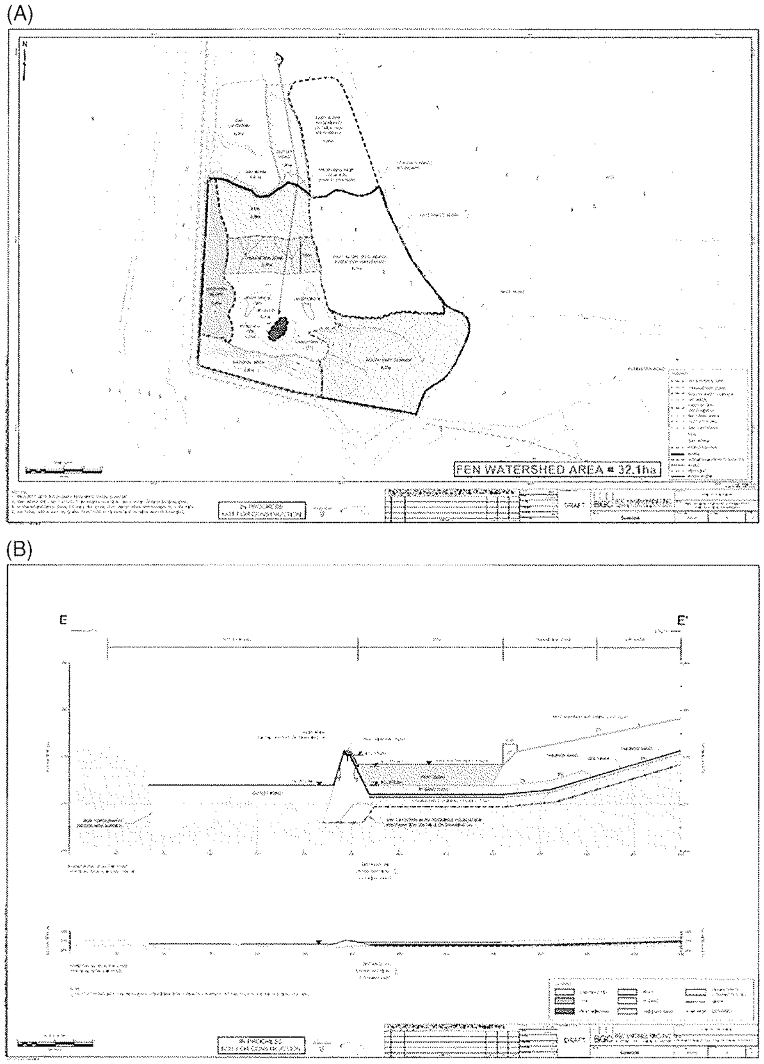

Figure 9.2. (A) Plan view and (B) cross-section of the Suncor Fen watershed conceptual-level designs.

infiltration while maintaining an adequate moisture content to support plant growth.

7. Peat should be placed 2 m deep in the fen, overlying a 50 cm layer of glaciofluvial sand that extends part-way upslope, with the intent of precluding a discharge zone at the upland–fen interface, and instead, distributing the water (and salts) more uniformly beneath the fen.

The Suncor fen watershed designs covered 32.1 hectares (Figure 9.2). Fen peat (2 m deep) from a new lease being opened for development is to be placed at the base of the upland aquifer system. This system is designed to supply groundwater and surface runoff. The benefit of using a relatively thick peat layer is that: (1) it can dampen water table drawdown (Price, 2003; Whittington and Price, 2006); and (2) it will increase dispersion of contaminants and delay their passage to the rooting zone (Rezanezhad et al., 2010). The upland:fen ratio will be 2.7:1 for the constructed system; however, the ratio increases to 10.1:1 when the surrounding slopes (western slope, east slope, southeast corner, and natural area) are included.

Some settlement of basal sediments is anticipated within the site as it was previously mined out (2001–2004) and later in-filled with overburden (2005–2006). Consequently, geogrid and 1 m-thick engineered compacted clay underlay were placed under a thin layer of tailings sand (0.3-m deep) beneath a geosynthetic clay liner, to protect against localized, uneven settlement that could challenge the integrity of the liner. A geosynthetic clay liner was selected because it went beyond the optimal requirement of 1×10^{-10} m s^{-1} to sustain a perched water table. A berm has been constructed around the entire watershed to ensure that surface water flows, spills, etc. from nearby operations cannot enter the system. Excess water in the fen will discharge over an adjustable weir into an outlet pond that is directed northward via an engineered stream channel to a containment pond designed to contain OSPW water within Suncor's lease. The adjustable weir allows for fine-tuning of the water level in the fen following construction–it is not intended to be used (adjusted frequently) for long-term management but only to allow flexibility as the system comes to equilibrium and until we determine the optimal weir setting. A small (0.2 ha) perched fen with 0.3-m deep fen peat will be placed above tailings sand in the upland area adjacent to a hummock at a 1:1 hummock to fen ratio. This will be a small scale study within the Suncor pilot fen program to investigate whether perched fens can develop over sand within a small watershed in a similar manner to the natural perched fens present within the regional landscape (Devito et al., 2011).

Fen watershed construction

Construction of the fen watershed commenced in 2010 and is planned to continue through 2012. Construction is managed by Suncor Reclamation Operations, carried out by local contractors, and monitored by a third party contractor and surveyor.

Revegetating the Suncor fen watershed

The Suncor fen watershed fell within the boreal mixedwood ecological area (Beckingham and Archibald, 1996). Plants characteristic of this region were selected for planting within the watershed. Planting strategies were divided between fen and upland regions.

Fen planting strategies

Based on the significant volume of peat (2-m depth) within the constructed fen, the nutrient rich coversoils (forest soils and mixed organic and mineral soils) overlaying the surrounding upland watershed and the underlying tailings sand, the Suncor pilot fen is expected to receive alkaline nutrient-rich water, which is characteristic of a moderate-to-extreme rich fen. Trees will not be planted in the fen itself, although they will be planted on upland slopes. Target plant communities for the fen include shrub, forb, grass, sedge, and moss species. Therefore, the Suncor fen is expected to develop into either a shrubby or, if the shrubs do not adapt well, a graminoid moderate rich to rich fen. Target species were selected using the following criteria: (1) rich fen plant; (2) shrub, sedge, grass, forb, or moss species; (3) shows some sign of saline tolerance; (4) good peat accumulator; and (5) present in local fens. The target species are: sage-leaved willow (*Salix candida*), diamondleaf willow (*S. planifolia*), dwarf birch (*Betula pumila*), water sedge (*C. aquatilis*), beaked sedge (*C. utriculata*), slender sedge (*C. lasiocarpa*), two-stamened sedge (*C. diandra*), marsh reed grass (*Calamogrostis canadensis*), seaside arrow grass (*T. maritima*), northern reedgrass (*C. stricta*), golden moss (*T. nitens*), drepanocladus moss (*Drepanocladus aduncus*), scorpidium moss (*Scorpidium scorpioides*), tufted moss (*Aulacomnium palustre*), and Warnstorf's peat moss (*S. warnstorfii*). The selected species met most if not all of the criteria. There were a few exceptions. A few species were added to the target species list for their ecological or cultural significance to local aboriginal peoples, even though they only met a few of the target species criteria. Such species included: cloudberry (*Rubus chamaemorus*), round-leafed sundew (*Drosera rotundifolia*), pitcher plant (*Sarracenia purpurea*), and small bog cranberry (*Oxycoccos microcarpus*).

Although poor water quality may occur shortly after fen watershed construction due to the presence of salt ions and some organics (i.e., NAs), water quality is expected to improve over time as rainwater flushes the sand aquifer with fresh water. Consequently, many salt tolerant species were selected for revegetating the constructed fen. However, it will likely evolve into a freshwater system over the long-term.

Four vegetation strategies will be tested in the Suncor pilot fen to determine the optimal strategy for vegetating oil sands constructed fens. The strategies are as follows: (1) moss transfer; (2) seedlings plantation; (3) direct seeding; and (4) the control or spontaneous revegetation (i.e., seedbank within the fen peat; aerial seed rain).

The "moss transfer" method was a technique developed to restore harvested peatlands in Canada, mainly bogs (Rochefort et al., 2003). This approach has been used for fen restoration in Quebec (Cobbaert et al., 2004; Graf and Rochefort, 2008). Direct plantings and seeding have been used successfully in small alpine fens in Colorado (Cooper and MacDonald, 2000). Shrub, sedge, grass, and forb seed was collected from natural fens and marshes on Suncor's lease starting in July 2010 and is ongoing. Seed will be used to produce seedlings in a local greenhouse for the seedling planting method and to sow directly into the fen as per the seed planting method. Both methods focus only on vascular plant introduction and exclude bryophytes. However, in some cases bryophytes have been known to colonize restored fens spontaneously. For example, bryophytes colonized sloping fen restoration sites in Colorado, as early as seven years after restoration, where only vascular plants had been introduced (D. Cooper, personal communication). Revegetation of the fen is planned for 2012.

Upland planting prescriptions

The planting prescriptions for the upland regions in the system were developed using the *Revegetation Manual* (CEMA, 2010), which categorizes planting prescriptions according to soil characteristics and the position of the site on the reclaimed landscape. Aspect, slope, and soil type and texture were derived from the fen watershed designs and used to predict moisture and nutrient regimes. The upland, southeast corner and western slopes, referred to in Figure 9.1, were prescribed the following site types: moist poor site, dry site, and moist rich site, respectively. The dominant vegetation in the moist poor site type is jack pine (*Pinus banksiana*), black spruce (*Picea mariana*), labrador tea (*Ledum groenlandicum*), and an assortment of other shrubs. The dominant vegetation in the dry site type is jack pine (*P. banksiana*), white spruce (*P. glauca*), blueberry (*Vaccinium myrtilloides*), and an assortment of other shrubs. The dominant vegetation in the moist rich site type is white spruce (*P. glauca*), aspen (*Populus tremuloides*), and an assortment of shrubs. Because the *Revegetation Manual* only focuses on developing planting prescription for upland forests, the *Field Guide to Ecosites of Northern Alberta* (Beckingham and Archibald,

1996) was used to develop planting prescriptions for the wetter transition zone. Moisture and nutrient regimes were predicted from the watershed designs. The transition zone, referred to in Figure 9.1, will be planted to a tree-rich fen (k1) ecosite as it represents the lagg zone (periphery of a peatland). The dominant vegetation will be tamarack (*Larix laricina*), black spruce (*P. mariana*), willow (*Salix spp.*), dwarf birch (*Betula pumula*), and an assortment of other shrubs, grasses, sedges, and forbs.

Research and monitoring in the Suncor fen watershed

Research and monitoring of the Suncor pilot fen is viewed as an important step in the reclamation process because it will determine success with the program's goals of creating a self-sustaining ecosystem that is carbon-accumulating, capable of supporting a representative assemblage of species, and resilient to normal periodic stresses. Furthermore, it is essential to understanding design implications and to the development of more optimal designs and cost-effective protocols.

A five-year integrated hydrological, biogeochemical, and ecological research program was developed by Dr. Jonathan Price (University of Waterloo), in collaboration with Drs. David Cooper (Colorado State University), Rich Petrone (Wilfrid Laurier University), and Maria Strack (University of Calgary). Research funded by the Environmental Reclamation Research Group (ERRG) of the Canadian Oil Sands Network for Research and Development (CONRAD ERRG) focuses on hydrology, water quality, revegetation, carbon dynamics, plant establishment success, and microbial communities in the constructed fen and in nearby reference fens. Reference fens in the region will be analyzed to determine natural vegetation composition, above- and belowground production by species where possible, microbial processes, and other factors relevant to judging the success of fen reclamation in the oil sands region. Finally, wildlife monitoring cameras will be established in the watershed to determine whether wildlife is returning to the region after the construction and revegetation of the program is completed.

LOOKING FORWARD

Although marshes have been a major focus of oil sands research and reclamation, considerable effort has been put into constructing fen peatlands as they are the dominant wetland type in the Athabasca oil sands region. To date, some uncertainty exists with regard to whether the hydrogeological, biogeochemical, and ecological attributes of a natural fen peatland can be engineered. Detailed research and monitoring will provide answers to optimize future reclaimed peatlands and provide best management practices, such as habitat design and revegetation strategies.

To date, laboratory and greenhouse fen mesocosm experiments have revealed that fen graminoid plants native to the Athabasca oil sands region are capable of tolerating a realistic contamination scenario (~385 mg L^{-1} of Na salts and ~40 mg L^{-1} of NAs) and probably do not need particular management actions to counteract OSPW additions. However, mosses appeared to have a lower tolerance threshold to OSPW, especially under drier conditions when they acquire water by capillarity from OSPW. Further experiments are needed to clearly identify those thresholds and to test the resistance of mosses to OSPW or salts, because they are an important part of fen vegetation and should be included in reclamation of the oil sands region.

Program results also indicate that transport of Na and NAs in peat substrates becomes delayed due to adsorption onto peat and dispersion in the dual porosity medium, thereby affecting the concentration of potentially toxic compounds in the plant rooting zone. This is expected to reduce the stress on plants growing on peat containing OSPW. This lag time before reaching full contamination potential may provide sufficient time for the reintroduced plant communities to form a good litter layer that could further isolate it from the belowground contaminants.

The lessons from the Suncor pilot fen program and similar fen reclamation programs in the region are expected to shape the future of wetland reclamation in the Athabasca oil sands region. Success will be measured in the ability to understand the implications of design choices in a way that guides future restoration efforts. The process of designing, building, and studying the system challenges our theoretical understanding of fen peatlands.

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