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ARTICLE *in* ECOLOGICAL ENGINEERING · AUGUST 2015

Impact Factor: 3.04 · DOI: 10.1016/j.ecoleng.2015.04.038

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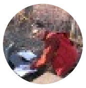

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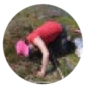

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Ecological Engineering 81 (2015) 471–480

Contents lists available at ScienceDirect

Ecological Engineering

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Impacts of donor-peat management practices on the functional characteristics of a constructed fen

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ARTICLE INFO

Article history:
Received 4 September 2014
Received in revised form 12 February 2015
Accepted 5 April 2015
Available online xxx

Keywords:
Alberta oil sands
Constructed fen
Biogeochemistry
Nutrient cycling
Peatland reclamation

ABSTRACT

The reclamation of fen peatlands on post-oil sand development landscapes involves the transfer of peat from a donor fen to form the upper 2 m of a sediments-filled pit resulting from open-pit mining. The placed peat serves two major functions of attenuating the upwelling of dissolved solutes from the underlying tailing sediments to the rooting zone, and as fen vegetation establishment substrate. However, the modifications (e.g., decomposition and fragmentation) resulting from salvage and transfer practices (e.g., dewatering and loading/placement with earth-moving equipment) could impact the potentials of the placed peat to support ecohydrological functions in the constructed fen. Thus, we conducted a study to evaluate the impact of these practices on the biogeochemical and hydrologic functioning of a constructed fen. Peat cores were extracted along transects in the donor fen before peat transfer, and after placement in the constructed fen. Cores were also taken from a natural reference site to serve as the nearest possible comparison to donor site conditions prior to dewatering. The cores were subsampled and analyzed for selected physicochemical and hydrophysical properties. Relative to the reference site, our results indicates a higher surface bulk density, and accelerated mineralization of organic-bound nutrients in the dewatered donor peat. Following transfer of peat to the constructed fen, changes in hydrophysical properties were reflected in a reduction of the horizontal/vertical anisotropy ratio from 1.5 to 1, which could impact the vertical fluxes of water. However this impact is likely less than that of the heterogeneity associated with the fragmentation of the placed peat. Hence, we recommend some management practices that can alleviate the modifications resulting from contemporary operational practices.

1. Introduction

The partially decomposed organic materials that form the peat layers in boreal forest peatlands are some of the vital resources impacted by oil sands development in Northeastern Alberta, Canada. In this region, the recovery of bituminous oil sands through open-pit mining presents a major threat to peatlands, as it involves the total stripping and stockpiling of peat layers that have accumulated over thousands of years (Yeh et al., 2010; Rooney et al., 2011). In an effort to foster environmental stewardship, oil sands operators are attempting the reclamation of functional peatland ecosystems on post-mining landscapes (Daly et al., 2012). One of the approaches currently under scientific investigation involves the transfer of salvaged peat from a donor peatland to a constructed landscape, where the peat serves as a vegetation establishment substrate, and also attenuates the upwelling of dissolved solutes from the underlying tailing sediments to the rooting zone (Price et al., 2007, 2010). The operational practice used in salvaging donor peat, which involves clearing of natural peatland vegetation, dewatering (i.e., the complete draining of a wetland) and transfer of fragmented peat with earth-moving equipment, may impact the residual peat quality relative to that of intact peat in natural analogues (Macyk and Drozdowski, 2008; Makenzie, 2012). It is well established that peat quality (i.e., the distinctive physicochemical properties of peat) controls major peatland functional characteristics such as; hydrologic regulation and water storage (Price and Schlotzhauer, 1999), biogeochemical transformations (Updegraff et al., 1995), vegetation establishment

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http://dx.doi.org/10.1016/j.ecoleng.2015.04.038

(Salonen, 1994) and organic matter turnover (Szumigalski and Bayley, 1996). Therefore, donor peat quality has the potential to influence the functional characteristic and development of constructed peatlands (Nwaishi et al., 2015), especially in the early stages of vegetation establishment.

Within the oils sands operation, conventional peat salvage practice involves the windrowing of peat as "peat-mineral mix", which is then stockpiled until it can be used as a reclamation cover-soil for upland and wetland sites (Kong et al., 1980; McMillan et al., 2007). Where practicable, peat is directly placed on a reclamation landscape rather than stockpiled. However, timing does not always allow for this, as the current rate of resource extraction far exceeds that of reclamation (Woynillowicz et al., 2005). Although best management practices (BMPs) have been developed for the conservation of stockpiled peat (peat-mineral mix) used as cover-soil in upland reclamation (Makenzie, 2012), these standards need to be updated to facilitate applicability to the conservation of donor peat slated for fen reclamation. For instance, Suncor's ongoing fen reclamation project eliminated the practice of windrowing, and adopted the *in situ* loading of donor peat and direct transfer to the constructed site. Verifying the appropriateness of this method raises the need to evaluate the potential effect on peat quality.

Before salvaging the donor peat used in the pilot fen, the peatland was also dewatered as part of the mine plan. The dewatered peat was transferred to the constructed site after about 2 years, which allowed enough time for peat decomposition. Previous studies have shown that dewatering of peatland leads to the aeration of formerly anoxic peat layers (Holden et al., 2004; Laiho et al., 1999), which reduces the microbial metabolic energy constraint that was dominant under anoxia (Freeman et al., 1996, 2004). With increased metabolic energy, heterotrophic micro-organisms become more efficient in decomposing the labile organic matter within the peat layers (Turetsky 2004; Laiho, 2006), which leads to structural collapse of large pores within the acrotelm, surface subsidence, compaction and shrinking of peat (Whittington and Price, 2006). The latter translates to increased bulk density, and subsequent decline in specific yield and hydraulic conductivity in the decomposed peat layers (Price et al., 2003; Petrone et al., 2008). Higher peat bulk density also increases the surface area of decomposed peat, enhancing the tendency for more nutrient adsorption (Hargrave 1972; Laiho et al., 1999; Sundström et al., 2000). Nutrient availability in drained peat is also altered by the re-oxidation of reduced inorganic compounds (e.g., NH_4^+ to NO_3^-) in the former anoxic layers.

The disturbance associated with earth-moving equipment used in *in situ* loading, transfer and placement of donor peat modifies physical structure of peat. It also leads to the fragmentation of the naturally stratified peat layers (acrotelm, mesotelm and catotelm), which control vital ecohydrological functions such as water-table regulation (Clymo et al., 1998; Clymo et al., 1998) and vertical stratification of microbially mediated biogeochemical processes in natural analogues (Andersen et al., 2013a, and references therein). The implication of this physical and biogeochemical disruption to the peat profile of a constructed fen has never been studied. Addressing this knowledge gap will require the evaluation of quantifiable measures of biogeochemical and hydrologic functioning in the constructed fen, following donor peat placement and vegetation establishment.

Using the first pilot project that used fragmented *in situ*-loaded peat to attempt fen reclamation on post-mining landscapes, we designed a field study which aimed to: (1) examine the impacts of dewatering on the physicochemical properties of the donor peat by comparing the dewatered peat and intact peat from a natural reference site; (2) evaluate the impact of *in situ* loading and fragmentation on peat quality by comparing the physicochemical and hydrophysical properties of the donor peat, before and after transfer to the constructed fen and; (3) discuss the potential effects of the residual peat quality on hydrologic and biogeochemical functioning of the constructed fen.

We hypothesize that; (1) the concentrations of bioavailable nutrients will be higher in the donor peat relative to natural analogues; (2) the disturbance associated with earth-moving equipment will affect the physical properties of the relocated donor peat, while the chemical properties will be influenced by rewetting with run-off water from surrounding slopes, which will likely lead to the leaching of essentials nutrients like NO_3^- and PO_4^{3-} due to increased mobility (Damman, 1978) and; (3) synthesizing the response of ecosystem processes to the modification of physicochemical properties will reveal the potential implication of altered peat quality on the ecohydrological functioning of constructed fen.

2. Materials and methods

2.1. Study sites description

The study was conducted at three different sites located within the oil sands development area, about 50 km north of Fort McMurray, Alberta. The area is characterized by a continental boreal climate with short summers and long cold winters. The mean annual temperature and total precipitation for the region was reported as 1 °C and 418.6 mm, respectively, based on 30-year monthly mean values (1981–2010) (Environment Canada, 2014). About 76% of the annual mean precipitation occurs as rainfall, which peaks during the growing season (May to August), and coincides with the warmest months of the year when evaporative demands are very high (Petrone et al., 2007). Based on comprehensive regional vegetation, soil, and tree production inventories, Beckingham and Archibald, (1996) classified this sub-region of the Boreal Forest as a Boreal Mixed-wood Ecological Area.

The first study site is a natural peatland (reference fen); located northwest of Fort McMurray Alberta (56°56.298′N 111°32.898′W). The reference fen is surrounded by a typical upland coniferous forest of poor to medium nutrient regime. A comprehensive vegetation survey characterized the site, which contains both treed poor fen and treed rich fen ecosite phases (A. Borkenhagen, unpublished, Colorado State University). Sampling for this study was conducted in the treed rich fen ecosites phase, with a tree cover of about 25% to 50%. The survey shows that this ecosite is dominated by the following shrubs, sedges, and moss species: *Larix laricina, Betula glandulosa,Equisetum fluviatile, Maianthemum trifolium, Carex prairea, Carex diandra, Stellaria longipe*, and numerous moss species (Crum and Anderson, 1981; Moss, 1983; Brodo et al., 2001). The peat depths at this site range between 0.6 and 1.6 m, and the geologic material underneath the peat is a thin layer (~5 m) of fluvial sand that overlay the McMurray lowland formation. The second study site is a dewatered peatland (donor fen), located in the southern end of Suncor's Millennium lease (56°54.258′N 111°19.610′W). The site was dewatered and cleared in early 2010 (January to March). Before clearing, the vegetation structure of the site was similar to that of the reference fen, but included more treed rich fen ecosites. Peat within the donor site ranged from a maximum thickness of 255 cm to a minimum of <10 cm at the periphery of the peatland (average peat thickness = 145 cm, $n = 14$ locations).

The third site is a 3 ha constructed fen located in an area known as the tailings line corridor (TLC) on Suncor's Millennium lease (56°55.944′N 111°25.035′W). The site is bounded by reclaimed slopes in the west and east corners, a patch of natural forest in the south, and an active mine haul-road in the northeast corner. The fen watershed was constructed between the spring of 2010 and winter of 2013. Details of the design, construction and revegetation approach were described earlier in Price et al. (2007, 2010) and Daly et al. (2012). To form the fen, peat from the donor fen was placed 2 m deep over a thin (0.5 m) petroleum coke layer designed to enhance the hydrological connection between the constructed upland aquifer and the fen.

2.2. Methods

The field study for this research was initiated in the fall of 2012 in the reference and donor sites. Two sets (side by side) of 100 cm deep triplicate peat cores (c. 10 m apart) were collected along transects in the reference and donor sites using a Russian peat corer (Eijkelkamp Agrisearch Equipment, Netherlands). Coring for the deeper peat layers (i.e., the first 50–100 cm depths) was executed following De Vleeschouwer et al. (2010) to avoid compression of the peat core. In the reference site, peat cores were collected at the interface of microforms (hummocks and hollows) to eliminate any micro-topographic influence and allow for relative comparison with fragmented donor peat. Selection of coring spots was targeted at capturing the vegetation assemblage representative of the ecosites. The intact cores collected were transferred to a semi-cylindrical PVC pipe (split lengthwise), and tightly sealed with plastic wrap before transportation to the Biogeochemistry Lab at the University of Waterloo for analysis.

In the laboratory, peat cores from the reference and donor fens were divided into the following depth categories; 0–5, 6–15, 16–45, 46–75, and 76–100 cm representing the upper acrotelm, lower acrotelm (or mesotelm), upper catotelm, middle catotelm, and lower catotelm respectively. The subsamples were analyzed for selected soil quality indices, which consists of bulk density, organic matter content, C/N ratio, gravimetric moisture content, soil pH, electrical conductivity (EC), and extractable nutrients. These soil properties were selected as candidate indices for peat quality assessment because of their key role in supporting biogeochemical functioning in peatlands. For the analysis, subsamples from the first sets of triplicate peat cores were oven-dried at 80 °C for 24 h to determine gravimetric moisture content and bulk density (g/cm^3). A known portion of the oven-dried peat samples were further analyzed for organic matter (OM) content, calculated by loss on ignition (LOI) following Rowell, (1995).

Subsamples from the second set of the triplicate peat cores were homogenized individually in a Ziploc bag before removing two aliquots (∼5 g in dry weight). The first aliquot was leached in 50 ml of 2 M KCl to extract NO_3^- and NH_4^+, while the second aliquot was extracted in 50 ml distilled-deionized water for the

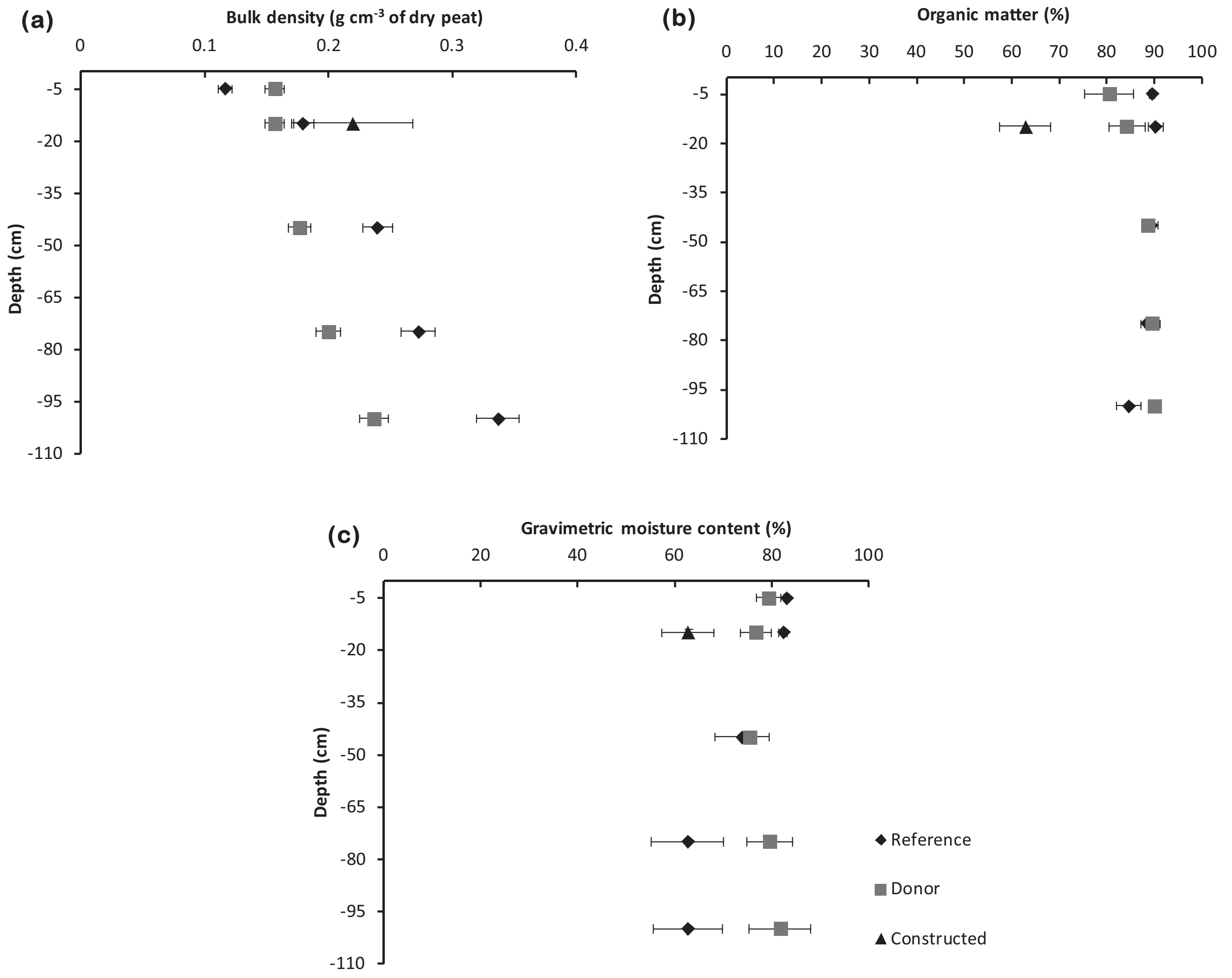

Fig. 1. Mean and standard deviations (error bars) of peat bulk density (a), organic matter (b) and gravimetric mositure content (c). The mean values for Reference (dark diamond shape) and Donor sites (grey square shape) were measured along the peat profile (0–100 cm dpth, $n = 3$), while that of the Constructed fen (dark triangle shape) was measured in the near-surface depth (0–15 cm depth $n = 12$).

determination of soluble reactive phosphorous (SRP). These extracts were analyzed using a colorimetric technique (Bran Luebbe AA3 autoanalyzer, Seal Analytical, USA). Electrical conductivity (EC) and pH were also measured in peat-deionized water slurry (1:5 ratios) with an Accumet^{TM} AP85 pH/Conductivity meter (Thermo Fisher Scientific Inc. Canada).

The constructed fen was sampled in the summer of 2013 after the re-deposited donor peat (which was transferred to the constructed site between December 2012 and January 2013) has undergone consolidation and rewetting through winter freezing and spring thaw cycles, respectively. Prior to *in situ* loading of the donor peat, the upper 30 cm was removed to avoid weed seedbank transfer from the donor to the constructed fen, which would complicate vegetation establishment experiments. Accordingly, for consistent comparison and illustrative purposes, the new “0 cm depth” of the donor peat presented in this paper was actually peat located at 30 cm depth in the donor site. Two sets of shallow (15 cm deep) cores were collected side by side from 4 points located along each of the 3 east-west running transects (c. 5 m apart) in the constructed fen ($n = 12$). The first set of these samples was processed for nutrient extraction within 12 h of collection in the Chemistry Lab at Keyano College, Fort McMurray Alberta, and later the nutrient extracts were sent to the Biogeochemistry Lab at University of Waterloo for analysis. The second set was analysed for bulk density, OM, C/N ratio, gravimetric moisture content, soil pH, electrical conductivity (EC) and extractable nutrients using the methods described earlier.

The carbon to nitrogen (C/N) ratio of peat was quantified as the ratio of ^{13}C and ^{15}N in different sets of shallow peat cores (15 cm deep) collected from the three sites. Peat samples for C/N ratio analysis were processed in the Environmental Isotope Lab (EIL) at the University of Waterloo, following the approach described in Krüger et al. (2014). Stable C and N isotope analyses were measured in processed peat samples using the Delta Plus Continuous Flow Stable Isotope Ratio Mass Spectrometer (Thermo Finnigan, Bremen-Germany) coupled to a Carlo Erba Elemental Analyzer (CHNS-O EA1108 - Italy). C and N Isotope signatures are expressed in the common δ-notation $\delta\text{-‰} = ((R_{\text{sample}}/R_{\text{standard}}) - 1) \times 1000$, relative to the Vienna PeeDee Belemnite (V-PDB) standard or N_2 in ambient air for ^{13}C and ^{15}N data respectively. The analytical precision for ^{13}C and ^{15}N were below ±0.5‰; deviation between duplicate samples was $< \pm 0.1$‰. A standard was analyzed for $\delta^{13}C$ and $\delta^{15}N$ following every 5 peat samples ($n = 15$).

For the hydrophysical analyses, four additional cores (∼90 cm deep) were extracted from separate locations within the donor site in the summer of 2012 using a Wardenaar box corer (10 cm × 10 cm). Four cores were also extracted from the constructed fen for comparison; however, issues with the Wardenaar corer in the fragmented peat limited extraction to a depth of 60 cm. All cores were carefully transported back to the Wetlands Hydrology Laboratory at University of Waterloo. In the laboratory, the upper 30 cm of each peat cores extracted from the donor site was discarded for accurate comparison with the donor peat layers, as described previously. The cores were subsampled at 10 cm intervals below the “new 0 cm depth”, and each subsample was analyzed for specific yield and porosity following standard methods (Price, 1996) and both vertical (K_V) and horizontal (K_H) saturated hydraulic conductivity (K_{SAT}) using the constant head method described by Freeze and Cherry (1979).

2.3. Statistical analyses

The data sets obtained from laboratory studies were subjected to a normality test prior to statistical analyses, and appropriate transformations were applied when necessary. Statistical analyses were performed using SPSS Software Version 22 (IBM Corporation, USA). Since peat decomposition increases with depth, we expected the effect of donor peat dewatering to vary with depth. We ran a two-way factorial analysis of variance (ANOVAs) to test the effect of dewatering on peat quality indices, while controlling for site (reference and donor) and depth categories in each of the sites, and also the interaction between both. We also used ANOVAs to test the effect of peat salvage and placement practices on residual peat quality and potentials to support fen vegetation establishment, by comparing rhizosphere peat (0–15 cm depth) from the three study sites. Post hoc analyses (Tukey) were performed using SPSS. Correlation analyses were also performed to evaluate the interrelations among peat properties and nutrient transformation processes in the constructed fen. The significant level for all statistical tests was $p \leq 0.05$.

3. Results

3.1. Peat physical properties

Generally, our results showed that the physical properties of peat varied among the three sites (Fig. 1a–c). Since peat for physiochemical analysis of the constructed fen was collected from the rhizosphere depth (0–15 cm), the data reported as “near-surface value” for the donor and reference sites are averages for 0–5 cm and 6–15 cm from these sites. In the intact cores from the reference and donor fens, bulk density increased with depth (Fig. 1a), and the near-surface value was similar ($p > 0.05$) between the reference (0.149 g/cm^3) and donor (0.157 g/cm^3) peat. Bulk density varied significantly with depth ($p < 0.001$), and between the reference and donor fens ($p < 0.05$). In the constructed fen, the near-surface bulk density (0.193 g/cm^3–0.359 g/cm^3) was within the range observed in subsurface layers of the intact reference and donor peat (Fig. 1a). Hence, it was significantly higher ($p < 0.05$) than that of the reference and donor fens. Correlation analysis indicated that bulk density was negatively correlated ($p < 0.05$, Table 2) with organic matter (OM) and moisture content.

Near-surface OM content was significantly lower ($p < 0.05$) in the donor (82% ± 4.46) than in the reference fen (90% ± 1.05). In the subsurface layers of both sites, OM did not vary with depth ($p > 0.05$, Fig. 1b). Following donor peat transfer and placement in the constructed fen, there was a significant reduction in OM ($p < 0.05$) to about 63% ± 5.36. Moisture content in the near-

Table 1
Stable isotope compositions and elemental C/N ratios of surface (0–15 cm) peat samples from the three study sites, mean values ($n = 5$) of peat sub-samples (±standard deviation).

Sites	$\delta^{13}C$ (‰)	$\delta^{15}N$ (‰)	% Weight Carbon	% Weight Nitrogen	C/N Ratio
Reference	−28.38(0.40)	0.31(0.37)	33.63(16.3)	1.25(0.64)	26.00(5.24)
Donor	−27.43(1.51)	−1.34(1.63)	37.44(2.64)	1.13(0.18)	34.02(7.04)
Constructed	−26.53(0.20)	−0.06(0.41)	29.33(3.48)	1.30(0.16)	22.54(0.98)

Table 2
Correlation coefficients matrix (Spearman's ρ) between the selected peat quality indices along the peat profile. Significant correlations are shown in bold.

Characteristics	BD	OM	MC	pH	EC	NO_3-N	NH_4-N	TIN
OM (%)	**−0.929****							
MC (%)	**−0.786***	**0.714***						
pH	**0.946****	**−0.946****	**−0.778***					
EC ($\mu S\,cm^{-1}$)	**0.833***	**−0.905***	**−0.810***	**0.826***				
NO_3-N ($\mu g\,g^{-1}$)	**−802****	0.492	**0.806****	0.382	0.236			
NH_4-N ($\mu g\,g^{-1}$)	−0.395	-0.073	**0.830****	**0.830****	−0.152	0.588		
TIN ($\mu g\,g^{-1}$)	−0.480	0.018	**0.879****	**0.794****	−0.115	**0.721***	**0.964****	
SRP($\mu g\,g^{-1}$)	**−0.675***	0.529	0.479	0.321	−0.503	0.467	0.527	0.576

$N = 10$; BD = bulk density; OM = organic matter; MC = moisture content; EC = electrical conductivity.
[*] $P \leq 0.05$.
[**] $P \leq 0.01$.

surface layer was higher ($p < 0.05$) in the reference fen than in the donor and constructed fen (Fig. 1c). Moisture content correlated positively with organic matter and water extractable nutrients, but was negatively correlated with EC and pH (Table 2).

For peat hydrophysical properties, porosity showed no discernable difference between the donor and constructed fen peats; however, there was a slight increase in porosity with depth in both sites (Fig. 2). Likewise, K_H of the donor and constructed fen peats were similar, ranging from 3×10^{-3} to $3 \times 10^{-2}\,cm\,s^{-1}$. Interestingly, K_V of the constructed fen peat was consistently higher than that of the donor peat with depth (Fig. 2c), which is a consequence of the large changes to the peat structure during the extraction–transportation–placement process. Consequently, the horizontal/vertical anisotropy ratio was reduced from 1.5 (donor peat) to 1 (constructed fen peat).

3.2. Peat chemical properties

The pH of the donor peat (7.2–7.8) was significantly higher than that of the reference peat (6.5–6.8) ($p < 0.05$, Fig. 3a), but did not vary with depth at either site. Fragmentation of donor peat did not have any significant effect ($p > 0.05$) on the near-surface pH of the constructed fen peat (7.7–0.1). pH correlated positively with EC, NH_4-N and TIN (Table 2). EC was significantly lower ($p < 0.001$) in the reference fen (37–129 μS/cm) compared with the donor fen (145–184 μS/cm) peat. We also observed an abrupt increase in EC

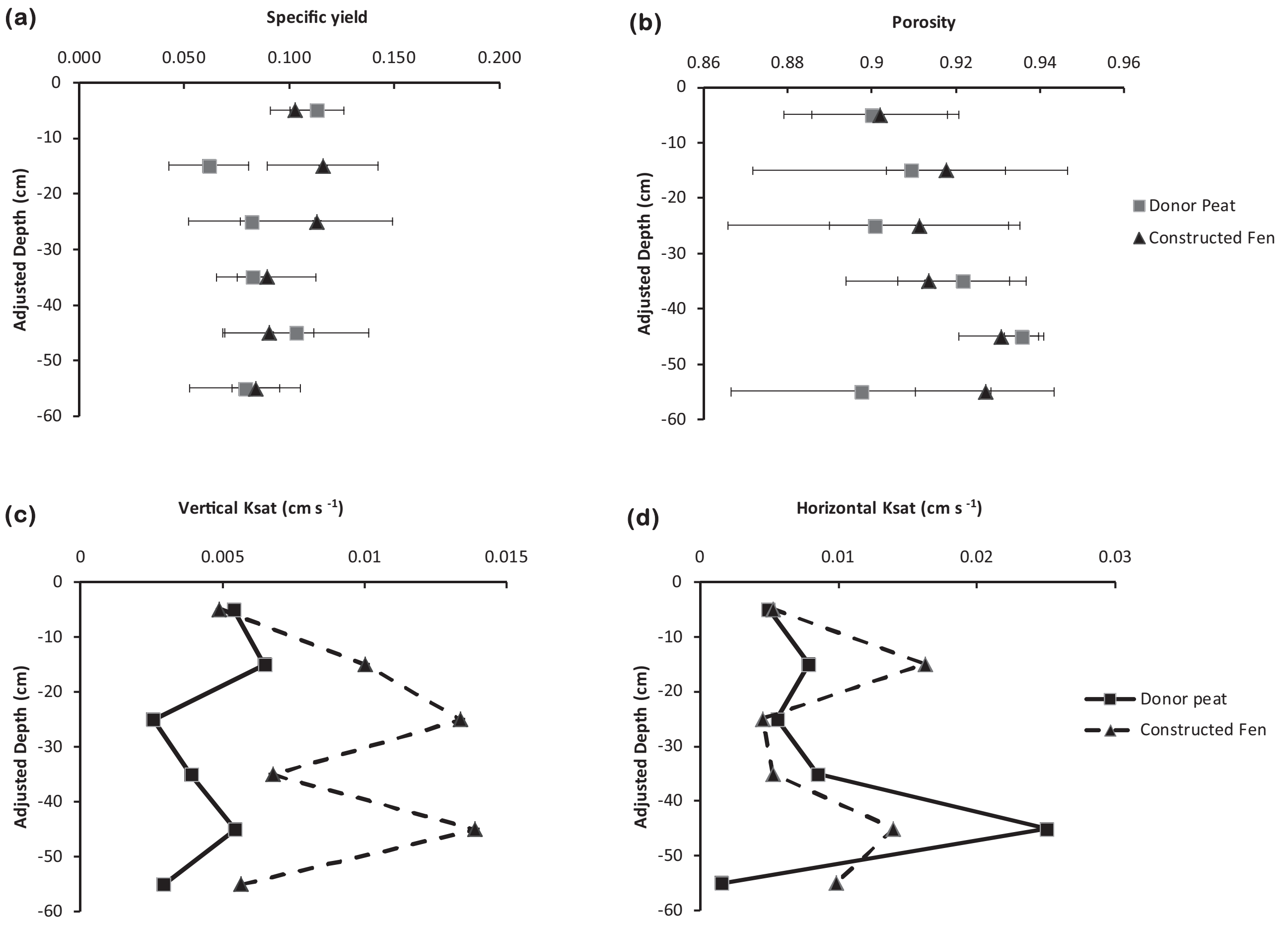

Fig. 2. Hydrophysical properties of Donor and Constructed fens' peat: (a) specific yield, (b) porosity, (c) vertical saturated hydraulic conductivity, and (d) horizontal saturated hydraulic conductivity.

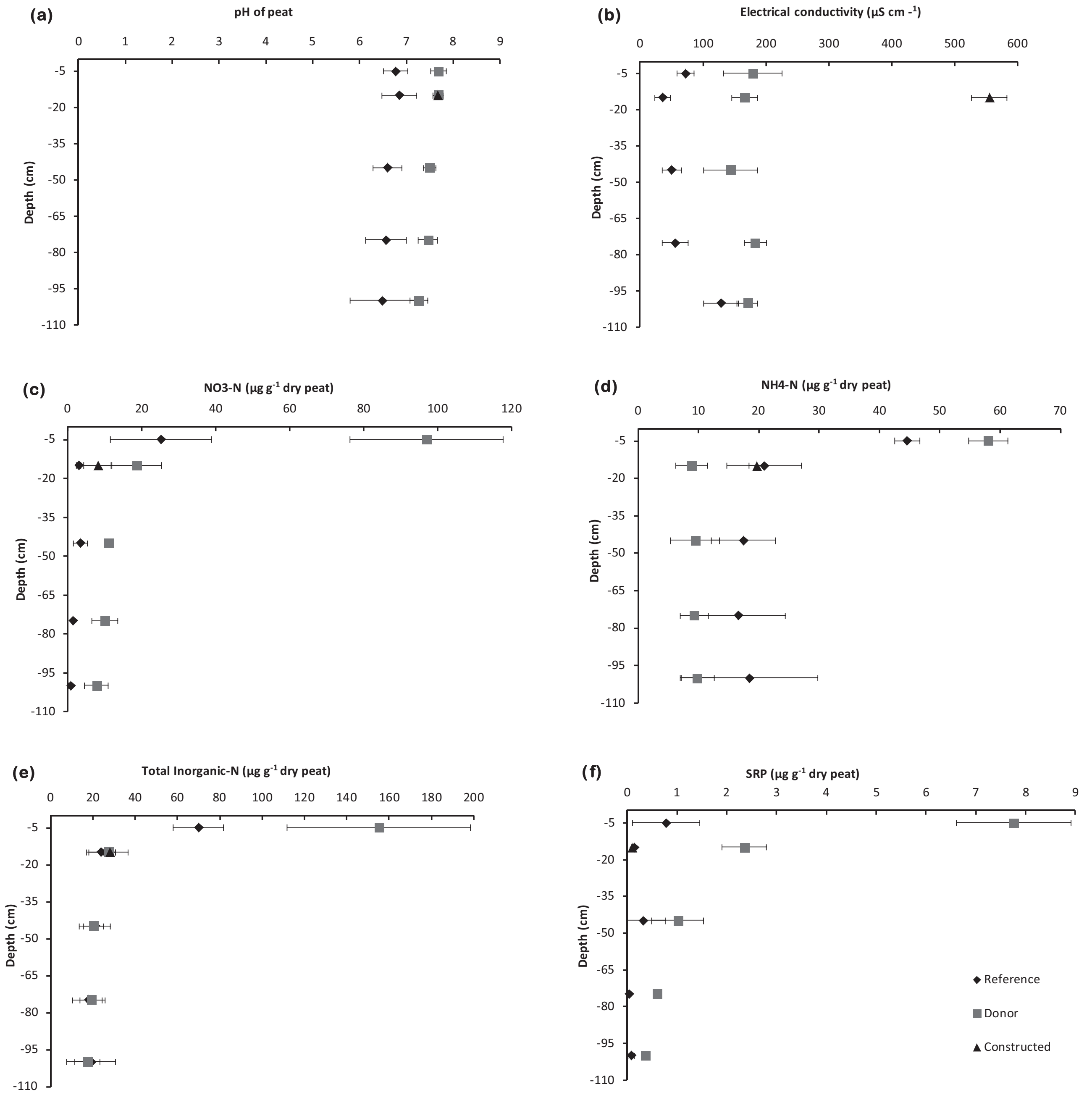

Fig. 3. Mean and standard deviations (error bars) of peat pH (a), electrical conductivity (b), NO_3-N (c), NH_4-N (d), TIN (e) and SRP (f). The mean values for Reference (dark diamond shape) and Donor sites (grey square shape) were measured along the peat profile (0–100 cm dpth, $n = 3$), while that of Constructed fen (dark triangle shape) was measured in the near-surface depth (0–15 cm depth $n = 12$).

(from 169 µS/cm ± 15–556 µS/cm ± 88) after donor peat transfer to the constructed fen, which was thus significantly higher than in the two other sites ($p < 0.001$, Fig. 3b).

The concentrations of NO_3^- and NH_4^+ decreased with depth in both reference and donor peat profiles (Fig. 3c). In the reference peat, total inorganic nitrogen (TIN, i.e., the sum of NO_3^- and NH_4^+) was dominated by NH_4^+ (~76% of TIN). Conversely, in the dewatered donor peat, the contribution of NH_4^+ to TIN dropped to ~39%, making NO_3^- the dominant form of TIN (~61%). The major differences in the N concentration of both sites were observed in the near-surface layers ($p < 0.001$, Fig. 3c–e). Relative to the donor peat, NO_3^- concentration decreased significantly ($p < 0.001$) in the near-surface layers of the constructed fen (8.23 µg g^{-1} ± 3.8); reinstating NH_4^+ as the dominant source to TIN (~70%). SRP was low within the reference peat layers and decreased with depth (0.78–0.09 µg g^{-1}). Higher concentrations of SRP (7.77–2.36 µg g^{-1}) were observed in the near-surface layers of the donor peat, but concentrations decreased (0.11 µg g^{-1} ± 0.04, $p < 0.001$) in the constructed fen (Fig. 3f).

Carbon isotopic signature ($\delta^{13}C$) in the near-surface layers ranged between −28.95‰ and −25.56‰ across the three sites. The constructed fen peat was more $\delta^{13}C$ enriched than the other two sites, with the lowest enrichement observed in the reference fen (Table 1). Post-hoc analyses (Tukey) showed that there was no significant difference between the mean $\delta^{13}C$ enrichement of the reference and donor peat, but the higher mean $\delta^{13}C$

(−26.53 ± 0.20) observed in the constructed fen was significantly different from the other sites ($p < 0.05$). A significant negative correlation ($\rho = -0.794$; $p = 0.006$) was found between δ^{13}C and % C content of peat using Spearman ranked correlation. The δ^{15}N signatures in the peat samples ranged between −3.66‰ and 0.68‰ across all the sites. Relative to δ^{15}N signatures in the reference fen peat (Table 1), lower values were observed in the donor fen peat (∼−1.34‰ ± 1.63). There was no significant difference ($p > 0.05$) in δ^{15}N signatures across the three sites, but a post hoc test showed that it differed significantly ($p < 0.05$) between the reference and donor fen peat. C/N ratio ranges between 18.9–31, 26.4–44 and 20.9–23 in the reference, donor and constructed fen respectively. The mean C/N ratio was significantly different ($p < 0.05$) across the three sites. We observed a strong negative correlation between δ^{15}N signatures and C/N ratio across the sites ($\rho = -0.706$; $P = 0.003$).

4. Discussion

4.1. Donor fen dewatering and potential impacts on peat properties

Given that there was only one donor and one reference site in this study, it is impossible to differentiate between the effect of dewatering and the inherent differences between two sites. However, the donor site, prior to drainage, supported the same vegetation assemblages as the reference fen site and this gives us more confidence in attributing the observed differences to dewatering. Dewatering of peatlands generally alters peat physical characteristics, which feedback on biogeochemical processes such as organic matter decomposition and nutrient cycling (Silins and Rothwell, 1998; Prévost et al., 1999; Holden et al., 2004). Our results suggest that the effects of dewatering on peat properties varies with depth. Kong et al. (1980) observed a similar pattern of variation in the physical properties of stockpiled peat in the Alberta Oil Sands Region (AOSR). Studies have shown that well-decomposed peat generally displays high bulk densities (Boelter, 1968; Clymo, 1983). Thus, given the increased aeration (decomposition) associated with donor fen drainage, we expected a resultant higher mean bulk density in the donor fen relative to the reference fen, but this was not the case. However, relative to the reference fen, we observed a significantly lower bulk density in the subsurface layers of the donor peat. One possibility is that the donor site initially had a lower bulk density than the reference site, which has now increased in the near-surface layers following the dewatered donor peat as a consequence of surface subsidence (Price and Schlotzhauer, 1999).

Accelerated decomposition in the dewatered peat could lead to lower organic matter content, especially in the near-surface layers, which was observed here and supported by a strong negative correlation between bulk density and organic matter content (Table 2). Kong et al. (1980) reported similar results for stockpiled peat, as organic matter content decreased following peat decomposition and increase in bulk density. High bulk density is generally associated with smaller pore size distribution (Price, 1997; Silins and Rothwell, 1998; Petrone et al., 2008), which explains the observed significant negative correlation between moisture content and bulk density. Similar to findings reported by Stapanian et al. (2013), our results confirmed the positive correlation between moisture content and organic matter, which is critical to peat water-holding capacity in the constructed fen. Overall, the effect of donor peat dewatering on peat physical characteristics seems to be tightly coupled with the alteration of peat physical structure.

Studies looking at the impact of drainage on peat chemistry have reported an increase in the concentration of some essential elements with increasing bulk density (Heathwaite, 1990; Laiho et al., 1999; Sundström et al., 2000). This relationship could be due to an increase in the surface area of decomposed organic materials (humus) associated with high peat bulk density (Hargrave, 1972). Hence, the saturation of base cations (e.g. Ca^{2+} and Na^{+}) in pore water translates to increased alkalinity and EC (Bragazza and Gerdol, 2002). The significant positive correlation between pH and EC ($p < 0.05$, Table 2) could be explained by the tight coupling between alkalinity and the accumulation of salts forming cations.

Donor fen dewatering could feedback on the interactions between peat chemical and physical properties. For instance, the surface area available for ion adsorption is known to increase in well-degraded organic matter (Hargrave, 1972; Crist et al., 1996). This implies that the further degradation of donor peat could exacerbate the displacement of nutrient anions (e.g., NO_3^- and PO_4^{3-}) due to higher affinity for base cations on the surface layers, therefore creating a greater tendency for base saturation and salinity in the constructed fen, which is supported by the significant negative correlation between bulk density and nutrient anions (Table 2).

The higher concentrations of extractable NO_3^- and SRP in the near-surface layers of the donor peat relative to the reference peat may also reflect site-specific differences associated with groundwater influence or could be an effect of dewatering, since previous studies have shown that increased areation in dewatered peatland accelerates nutrient mineralization and subsequent release to porewater (Laiho et al., 1999; Macrae et al., 2013). A shift in the proportional contribution of NO_3^- and NH_4^+ towards TIN can be used to assess the effect of dewatering on net N-mineralization. Based on this concept, studies looking at N-mineralization in northern peatlands have shown that most of the TIN in undrained peat are present as NH_4^+ (Verhoeven et al., 1990; Westbrook and Devito, 2004; Bayley et al., 2005), whereas in drained peatlands, NO_3^- comprises a larger proportion of TIN (Macrae et al., 2013). Our results agree with these studies: a larger proportion of TIN in the donor fen was present as NO_3^- while the opposite was true for the reference fen. This explains the observed difference in the dominant form of TIN between the reference and donor peat and supports our argument that N-mineralization in the donor fen was altered by peat dewatering effects. Considering the decreasing tendency for anion adsorption with increasing surface area in decomposed organic materials, the larger contribution of NO_3^- to TIN may decline with further degradation of peat, making NH_4^+ the dominant form of TIN, especially under anoxic alkaline conditions (Bragazza and Gerdol, 2002).

As observed in previous studies, SRP is usually a limiting nutrient in peatlands, especially in the subsurface layers of peat (Boeye et al., 1999; Andersen et al., 2013a,b). Due to the redox sensitivity of SRP, changes in the hydrologic regimes of wetlands often affects the mobilization of SRP through chemical precipitation (Shenker et al., 2005). This suggests that the significantly higher concentration of SRP ($p < 0.05$) observed in the donor peat, especially in the near-surface layers, maybe a consequence of dewatering effects such as oxygen-induced iron (Fe) precipitation (Zak et al., 2010).

The use of ^{13}C and ^{15}N isotope signatures as a surrogate for assessing organic matter quality in the near-surface layers of the study sites is explored here. Based on these analysis, the observed δ^{13}C enrichment in the donor peat, suggests that the organic matter quality was reduced as a result of changes in microbial metabolic pathways following donor peat aeration (Alewell et al., 2011). This coincides with a significant decrease in δ^{15}N and subsequently, a higher C/N ratio in the donor peat. The significant negative correlation between δ^{13}C and % C supports the notion that the total C component of the donor peat's C/N ratio may be dominated by lignin-derived C compounds (Benner et al., 1987; Esmeijer-Liu et al., 2012). Lignin-derived C compounds are less easily metabolised by microbial communities due to the energy constraints associated with the metabolism of these compounds (Andersen et al., 2010). Hence the dominance of lignin-derived C compounds associated with donor peat degradation could have a negative impact on microbially mediated biogeochemical processes in the constructed fen.

4.2. Impact of donor peats' post-tranfer modifications on the functional characteristics of the constructed fen

Discernible differences in near-surface peat properties were observed following the transfer of peat to the constructed fen. Our analysis suggests that the modifications resulting from peat transfer and placement had additional effect on peat properties. However, considering that the constructed fen is prone to sediments and solutes loading from surrounding slopes, these effects cannot be solely attributed to the operational practices associated with donor peat transfer and placement. For instance, a closer look at bulk density results (data not shown) reveals that plots nearest to the slopes had the highest bulk density values. Although high surface bulk density was expected due to the removal of the upper 30 cm layer prior to donor peat transfer, the relationship between high bulk density and proximity to sediment-rich slopes attributes highest surface bulk density values to sediment loading (edge effect). Consequently, the mean surface bulk density of the constructed fen was similar to those measured in the subsurface layers (75–100 cm deep) of stratified reference peat (Fig. 1a).

The observed degradation in peat physical properties along the periphery of the constructed fen is important as it may compromise ecohydrological functioning of the constructed fen. For instance, the increased surface bulk density will result in a subsequent decline in specific yield and hydraulic conductivity of the upper peat layer (Price et al., 2003; Whittington and Price, 2006). The outcome is poor infiltration capacity, and subsequent enhacement of overland flow along the margins. Recent site observations identified the formation of sediment crust lense beneath ponds along the fens's margins, which exacerbates the competitive advantage of invasive vascular plants such as *Typha spp* over peat-forming mosses, as the latter are incapable of sustaining efficient water retention capacity under degraded peat substrates (McCarter and Price, 2013). The invasion niche created at the margins of the constructed fen could extend into other parts of the fen where conditions are similar, undermining the establishment of fen vegetations.

The variability in hydrophysical properties with depth also suggests that random placement and fragmentation of the donor peat is partly responsible for inconsistencies between the surface and subsurface properties of the placed peat. For instance, higher degree of variability in K_V of the constructed fen (Fig. 2c) could cause percolating water to follow preferential flow paths in the unsaturated zone during precipitation events. Over time, there is potential for more permanent preferential flow paths to be sustained within the fragmented peat column. These would extend either vertically or horizontally with the development and extention of vascular plants' root architecture, which tends to shift towards the direction of water and nutrient sources (Rydin and Jeglum, 2006). Such preferential flow paths could represent a substantial mechanism of water transport within the constructed fen if they become incorporated into the saturated zone with a rise in water table.

Although in-situ loading, tranfer and placement process did not have an appreciable impact on the porosity or K_H of the peat (Fig. 2d), changes to the peat structure resulted in substantial differences to the K_V of the placed peat within the constructed fen. During the accumulation of peat in natural fen peatlands, dead vegetation materials (especially forbes and sedges) are typically oriented in a horizontal direction within the peat profile, as these plant materials die and bend over 90 degrees to the vertical direction of growth (Dai and Sparling, 1973). Although often complicated relationships, peatlands typically have horizontal/vertical anisotropy ratios greater than 1 (Beckwith et al., 2003) (indicates that $K_H > K_V$) and ratios as high as 4 have been documented (Schlotzhauer and Price, 1999). The reduction in anisotropy in the placed peat (from 1.5 to 1) indicates that the layered structure of natural sedge peat deposits was largely disrupted during the transfer and placement process. This will result in greater vertical groundwater fluxes than would be observed in a more anisotropic system with lower K_V, which will inevitably influence (increase) the vertical fluxes of solutes through the placed peat deposit as well. Nonetheless, the influence of this change to the peat structure, albeit important, will likely have less of an impact on water stores and fluxes than the level of heterogeneity encountered within the placed peat deposit.

As in cutover (harvested) peatlands in other parts of Canada (Price and Ketcheson, 2009), the hydrologic self-regulatory function intrinsic in intact peatlands is compromised in a peatland constructed with fragmented donor peat. The consequential persistence of anoxic conditions will affect biogeochemical transformation functions such as the loss of NO_3^- and mobilization of P through redox processes and leaching (Shenker et al., 2005; Seitzinger et al., 2006; Niedermeier and Robinson, 2007). Although this could explain in part, the lower concentration of NO_3^- and SRP observed in the surface layers of the constructed fen, it is more likely a consequence of the removal of the upper peat layers where most of these nutrients accumulate (Damman, 1978). In any case, the loss of nutrients through removal of upper layer and/or rewetting of the donor peat resulted to nutrient concentrations similar to those of the reference site, which was necessary to reinstate the "optimum nutrient concentration" present in natural analogues (Kleimeier et al., 2014).

Consequentially, the removal of upper peat would result in the decline of near-surface microbial biomass, similar to conditions observed in bogs exploited for horticultural peat (Andersen et al., 2006). Reduced microbial biomass would be exacerbated by the high surface bulk density of humified donor peat, and could lead to microbial energy conservation (starvation–survival state) and low nutrient transformation rate in the developing acrotelm (Fisk et al., 2003). Since the addition of fresh substrates through plant litter and root exudates can promote microbial activity (Zak et al., 2003), practices such as moss-transfer for vegetation establishment maybe important for restoring the lost active microbial biomass in the upper peat layer of constructed fen. Following reclamation, active microbial groups could facilitate microbial biomass build-up by retaining mineralized nutrients in the microbial loop (Andersen et al., 2013a,b,b), leading to nutrient immobilization. Hence monitoring the evolution of microbial activies in relation to nutrients transformation and recovery of nutrient pools will be essential to understanding the constructed fens' trajectory.

The limited infiltration capacity of fragmented donor peat will abet the accumulation of solutes on the peat surface. Consequently, the high EC observed in the surface layers of the constructed fen could be associated with the accumulation of sodic solutes from advective transport and flushing of tailing-enriched sediments used in the reclamation of adjacent slopes. The significant negative correlation between moisture content and EC (Table 2) suggests a dilution effect of water on sodic solutes. This also indicated that practices like mulching, which supports moisture conservation will also reduce salinity stress in the constructed fen. Although we expected the C/N ratio of the constructed fen peat to be higher because of the high bulk density and low organic matter, we observed that it was lower than both the reference and donor fen peat C/N ratios (Table 1). N addition from atmospheric deposition at the site could have led to higher δ^{15}N and percentage total N and a subsequent decrease in C/N ratio (Esmeijer-Liu et al., 2012). This is possible since the constructed fen is sited in the hub of industrial activities, where atmospheric N deposition has been recently reported (Proemse et al., 2013).

5. Conclusion and recommendations for future fen reclamation projects in the Alberta oil sands region

The comparison in this study was limited by site-specific differences such as peat depth and the influence of underlying geologic materials. To eliminate the effect of such differences in the interpretation of results, we suggest that future peatland reclamation projects should conduct a comprehensive analysis of the donor peat before the commencement of dewatering and, immediately before transfer to the constructed landscape. This is crucial to improve our understanding of the functional characteristics and anticipated trajectory of a constructed fen in the AOSR. Hence, at the pilot stage of fen creation in the AOSR, analysis of key indicators of donor peat quality should be incorporated and adopted as part of the mine commissioning procedures for mine sites located on prospective donor peatlands.

The ecohydrological functions supported by peatlands are controlled by the natural stratification observed in intact peat layers (Graft et al., 2009). Our results showed that current peat placement practices, which result in fragmentation and inversion of the peat layers, will modify the trajectory to recovery of ecohydrological conditions required to support biogeochemcial and hydrological functions in the constructed fen. Based on the findings of this study, future reclamation projects can work towards improving the quality of reclamation substrate by reducing the timeframe between donor peat dewatering and transfer to the constructed landscape. Also, a timeline that eliminates accelerated growing season decomposition should be considered when selecting the timing for donor peat dewatering. For instance, dewatering can be commenced towards the end of fall season, then followed by donor peat transfer by mid-winter, when trafficability over the dewatered site is more feasible.

Since our results also shows that major alterations to peat physical structure occurred after peat transfer to the constructed fen, reclamation stakeholders should explore efficient means of improving the resultant poor surface properties. This can be achieved by ensuring the strict adherence to environmental regulatory guidelines when selecting cover materials for construction of surrounding upland and slopes. The installation of fine wire mesh at the margins of the constructed fen, would check the loading of mineral sediments from surrounding slopes. Heterogienity in surface structure of the placed peat can be minimized by implementing appropriate surface reconfiguration techniques such as ploughing and harrowing. Surface reconfiguration could improve physical structure of peat, hydrologic conditions and also enhance the successful establishment of peat-forming vegetation, which is essential for reclaiming the carbon sequestration potential of a constructed fen.

Aknowledgements

We acknowledge that funding for this project was provided through an NSERC Collaborative Research and Development Grant (CRD), # 418,557-2011, entitled “Evaluating the success of fen creation in the post oil sands landscape” with funding from Suncor Energy Inc., Shell Canada Ltd., and Imperial Oil Resources Ltd. This initiative is a part of a Joint Industry Project convened under Canada’s Oil Sands Innovation Alliance (COSIA), Land Environmental Priority Area (EPA) led by Suncor Energy with Shell Canada and Imperial Oil. Special thanks to Dr. Merrin Macrea and Vito Lam for assistance with nutrient analyses, William Mark for CN Isotope analyses, Sarah Scarlett for assistance with the hydrophysical analyses, and Adam Green for field assistance.

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