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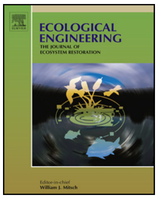

Typha latifolia plant performance and stand biomass in wetlands affected by surface oil sands mining

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ABSTRACT

Stand productivity of the dominant macrophyte *Typha latifolia* may be constrained by salinity and pollution in the oil sands wetlands of northern Alberta. We compared the performance and stand biomass of *T. latifolia* plants established in oil sands industrial wetlands (directly exposed to byproduct processed materials), on-site indirectly-affected, and off-site natural wetlands. We studied *T. latifolia* physiology (gas exchange, leaf fluorescence), morphology, leaf chemistry, and stand biomass. Oil sands plants had lower stomatal conductance than plants in natural wetlands resulting in lower transpiration but unaffected net photosynthesis rates. Oil sands plants had smaller and lower numbers of green leaves than natural wetlands plants. *T. latifolia* stands established in oil sands wetlands had lower aboveground and total biomass compared to natural wetlands. Despite water chemistry differences, *T. latifolia* plant performance did not differ between oil sands wetlands types. However, there was a lower total stand biomass in industrial than in indirectly-affected wetlands. *T. latifolia* had an unaltered photosynthetic activity in the oil sands wetlands allowing for the maintenance of persistent plant stands. However, *T. latifolia* growth restrictions and a lower stand biomass in the oil sands wetlands probably compromise long-term reclamation objectives focused on the accumulation of organic sediment and peat.

1. Introduction

Open pit bitumen mining in the oil sands region of Northeastern Alberta (Canada) involves the deep and complete removal of the vegetation, soil, and subsoil. This method of hydrocarbon extraction substantially transforms the landscape, erasing pre-existing freshwater wetlands – such as marshes and peatlands – from the mined area (Johnson and Miyanishi, 2008; Rooney et al., 2012). Reclamation of self-sustaining freshwater wetlands in oil sands landscapes is a particularly difficult challenge due to the high levels of salts released through tailings ponds seepage waters and weathering of exposed marine sediments (Harris, 2007; Trites and Bayley, 2009a,b; Rooney and Bayley, 2011). Large scale freshwater amendment is not considered as an economic solution to ameliorate wetland salinity due to provincial freshwater allocation policies and reclamation objectives focused on creating maintenance-free wetlands; thus, ongoing reclamation practices rely on the creation of watersheds according to detailed hydrogeologic designs (Daly, 2011). The outcome of integrated freshwater–saline systems will only be apparent in the future; yet, some more conservative, parsimonious alternatives are already under consideration: environmental researchers have pointed out that reclamation should consider replacing freshwater systems by means of the construction of oligosaline marshes (Purdy et al., 2005; Trites and Bayley, 2009a; Rooney and Bayley, 2011).

Oil sand wetlands are not uniformly exposed to the potential toxic constituents produced during bitumen extraction. Industrial wetlands are directly affected by salinity and miscellaneous hydrocarbon compounds (naphthenic acids [NAs], PAHs, residual bitumen) as the result of the use of tailings (mature fine tailings, MFT; consolidated tailings, CT) during their construction or their amendment with oil sands processed waters (OSPW) (Harris, 2007). Indirectly-affected wetlands are established on non-industrial sediments – yet may be chronically exposed to pollution from salts and other industrial byproducts that seep from tailings ponds or reclaimed upland areas at various but generally more moderate rates (Harris, 2007). Their chemical conditions are expected to be less stressful than those found in industrial wetlands as indirectly-affected wetlands are primarily fed with

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Abbreviations: CT, consolidated tailings; MFT, mature fine tailings; OSPM, oil sands processed materials; OSPW, oil sands processed waters.

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precipitation water. Even relatively recalcitrant, residual hydrocarbons in oil sands wetlands will eventually degrade through microbial activity and solar radiative energy (Allen, 2008), yet the water balance of the sub-humid regional climate contributes to salinity increases as salts continuously seep to wetlands (Harris, 2007).

Other reclamation objectives are expected to be achieved in oil sand wetlands besides self-sustainability over time: wetlands should produce, accumulate and sequester organic carbon and sustain a web of community diversity across trophic levels similar to those of the region's unaffected wetlands (Daly, 2011). Plant production by emergent macrophytes is critical in determining whole-wetland carbon stocks (Wetzel, 1993). In the oil sands wetlands, most organic matter production is concentrated in a relatively few species of emergent macrophytes (M.C. Roy, 2011, University of Alberta, Edmonton, AB, unpublished data, PhD in progress); with *Typha latifolia* L. (cattail) as the dominant species. In the natural wetlands of the boreal plain region of Canada, *T. latifolia* is found in stands of mixed vegetation but it occurs in near monospecific stands in the oil sands marshes. Clearly, *T. latifolia* could be a key species for the restoration of some important wetland functions (Wild et al., 2001) and also a valuable tool to mitigate nutrient enrichment in impacted wetlands (Chua et al., 2012; Zhao et al., 2012), yet, its competitive dominance may also negatively affect plant diversity and trophic assemblages. Reclamation scientists and practitioners are divided in their opinion on *T. latifolia* as a wetland reclamation plant. The existence of *T. latifolia* as an early succession dominant is suboptimal but in many cases may be better than the near absence of vegetation. Importantly, *T. latifolia* dominance must be planned as a stage of reclamation instead of an indication of success or an endpoint. An argument can be made to use *T. latifolia*'s weedy invasive nature, high standing crop and substantial production of detritus as a tool to pave the way for subsequent community development on problematic wetland soils and interstitial water.

T. latifolia performance was previously studied in plants exposed to oil sands processed materials and effluent (OSPM). Counter to early predictions, Bendell-Young et al. (2000) and Crowe et al. (2001) found that photosynthesis rates were higher in *T. latifolia* plants transplanted to OSPM than in plants cultivated on natural substrates with freshwater. The higher rates of photosynthetic performance of effluent-exposed plants, however, did not translate into increased plant growth (Bendell-Young et al., 2000). Moreover, differences in leaf lengths between exposed and non-exposed plants were not found despite the fact that effluent-exposed plants biochemically responded to osmotic stress (Bendell-Young et al., 2000; Crowe et al., 2001). On the other hand, Hornung and Foote (2006, University of Alberta, Edmonton, AB, unpublished data) found that although photosynthesis rates were similar between *T. latifolia* plants exposed to either effluent or freshwater, those plants exposed to effluent developed shorter leaves. The lack of consistency among studies and their narrow spatial and temporal scales prompted us to undertake a more comprehensive study. We used a larger suite of techniques (chlorophyll *a* fluorescence, gas exchange, morphology, leaf nutrient analyses) along a broader scale field approach (high number of wetlands across the oil sands region) to test for *T. latifolia* morphologic and physiologic performance across wetland types. Additionally, we studied *T. latifolia* biomass accumulation at the stand level to address potential stand productivity and carbon accrual.

Our main objective was to determine *T. latifolia* individual plant performance, carbon assimilation capability and potential stand productivity in the oil sands wetlands. Our working hypotheses were based on the chemical differences among wetlands and their degree of exposure to growth-affecting oil sands byproducts: (1) *T. latifolia* plants growing in oil sand wetlands have lower individual performance and stand biomass than plants growing in natural wetlands and (2) *T. latifolia* plants growing in oil sands industrial wetlands have lower individual performance and stand biomass compared to plants growing in indirectly-affected wetlands.

2. Materials and methods

2.1. Study site

This study was carried out in the Fort McMurray region of northeastern Alberta on two of the longest operating oil sands leases: Syncrude Canada Ltd. and Suncor Energy Inc. (Appendix 1). Vegetation in the area has been classified as Mid-boreal Mixedwood Ecoregion (Strong and Leggat, 1992). The climate is sub-humid with long cold winters and short cool summers. Mean July and January daily temperatures of the region are 16.8 and −18.8 °C, respectively (Environment Canada, 2013).

2.2. Wetland selection and chemical analysis

Nineteen wetlands were selected to study *T. latifolia* individual plant performance during 2010 and fifteen wetlands were used to study stand biomass during 2011 (Appendix 1). While randomization was the first criterion for wetland selection, accessibility and spatial distance among sites were also taken into account. Some wetlands studied in 2010 could not been studied in 2011 due to re-mining of sites (i.e. Mike's Pond and North Beaver) or lack of enough sampling area of *T. latifolia* stands (Appendix 1). Sites were classified as oil sands wetlands when situated inside leases or natural (off-site) wetlands, which were chosen within a 65 km radius from the center of mining activity (Appendix 1). In turn, on-site wetlands were classified as industrial (i.e. directly affected by OSPW, CT, or MFT) or indirectly-affected (i.e. wetlands which have not received any direct effluent input or were not created over CT, or MFT, Appendix 1). Industrial wetlands were created to study the effect of contaminants on biota (e.g.: Test Ponds) or to provide treatment for processed waters (e.g.: 4m-CT). Indirectly-affected wetlands have also diverse origins; some arose as the byproduct of landscape alteration that entrapped water while others were created as on-site controls to study the effects of freshwater and natural substrates amendments. Off-site natural wetlands showed no evident signs of being impacted by pollutants or anthropogenic disturbance, though we recognize that wetlands may be exposed to some low levels of airborne deposition.

The high levels of salinity, alkalinity, minerals, and potentially toxic constituents (NAs, PAHs, metals) in the oil sands wetlands have already been addressed by other authors (Purdy et al., 2005; Trites and Bayley, 2009a) but in this work we included data from the same wetlands in which plant measurements were carried out (Appendix 1). Electrical conductivity, salinity and dissolved oxygen (DO) were measured with a handheld YSI Model 85 (YSI Inc., Yellow Springs, OH, USA); pH and oxidative reductive potentials (ORP) were measured with a portable Hanna HI98121 (Hanna Instruments, Mauritius). Water samples were collected, frozen and immediately submitted for analysis of sodium, chloride, potassium and total nitrogen. Mature leaves of two plants per wetland were analyzed for sodium, chloride, potassium, calcium, magnesium, total phosphorus (TP), and total Kjeldahl nitrogen (TKN). After harvesting, leaf samples were rinsed, blotted and frozen at −20 °C. Chemical analyses of water and leaf samples were conducted in the Natural Resources Analytical Lab at the University of Alberta.

Table 1
Derivation of the OJIP-test parameters obtained from the recorded fluorescence transients.

Parameter	Derivation
F_0 (fluorescence at 50 μs; assumed to be initial)	F_0
F_M (maximal fluorescence intensity)	F_M
F_v (variable fluorescence)	$F_v = F_M – F_0$
F_V/F_M (maximum quantum yield of primary photochemistry)	$1 - F_0/F_M$
DI_0/ABS (maximum quantum yield of non photochemical deexcitation)	F_0/F_M
ABS/RC (calculated absorption per reaction center)	$(M_0/V_J)/(1 - F_0/F_M)$
RE_0/ET_0 (probability that an electron is transported from reduced PQ to the electron acceptor side of PSI)	$(F_M – F_{30\,ms})/(F_M - F_{2\,ms})$
Performance index	$(V_J/M_0)\,(F_v/F_M)\,(F_v/F_o)\,(ET_0/(dQ_A^-/dt_0))$

After Strasser et al. (2000) and Bussotti et al. (2010). V_J: relative variable fluorescence at 2 ms; V_I: relative variable fluorescence at 30 ms; $M_0 = (F_{300\,\mu s} - F_0)/(F_M - F_0)$.

2.3. Performance indicators and sampling procedures

Physiological measurements of *T. latifolia* plants were carried out near peak standing crop, during the second and third weeks of August 2010, near noon, on clear days. During all the sampling periods, gas exchange parameters were measured when photosynthetic photon flux density was above 1500 μmol m^{-2} s^{-1}. Leaf fluorescence was simultaneously measured. Morphological measurements were carried out immediately before peak standing crop period during the first week of August 2010. To reduce the likelihood of measuring genets from the same clones twice, different clumps were selected. When the emergent zone was evenly covered by *T. latifolia*, selected shoots were spaced more than one quarter of the stand length (typically more than 3 m between plants).

Gas exchange rates (net CO_2 exchange and transpiration) and stomatal conductance were measured in mature fully-exposed leaves in a similar position on each *T. latifolia* vegetative shoot (seven sub-samples per population) using a recently purchased and calibrated infrared gas analyzer provided with a narrow leaf chamber (LCi, ADC Bioscientific Ltd., Herts, UK).

Chlorophyll *a* fluorescence transients were measured in dark-adapted leaves on ten *T. latifolia* vegetative shoots per population with a Hansatech Pocket PEA (Hansatech Instruments Ltd., King's Lynn, Norfolk, UK). Measured leaves were dark-adapted with leaf clips for 20 min prior to fluorescence measurements. The transients were induced by a light pulse of 3500 μmol m^{-2} s^{-1} with a peak wavelength of 627 nm provided by a high intensity LED. The fast polyphasic fluorescence rise (OJIP rise) until F_M was recorded from 10 μs to 1 s. The fluorescence intensity at 50 μs was considered as F_0. The photosynthetic capacity of different plant samples can be related to the first steps of the sunlight energy transduction and the associated fluorescence OJIP rise (Strasser et al., 2000). In this way, a suite of basic leaf fluorescence parameters were selected to cover each of the main experimental signals, fluxes, quantum yields, and vitality indices related to the structure and function of the photosystem 2 (PSII) (Bussotti et al., 2010). Table 1 summarizes the definitions and derivations of the fluorescence transient parameters (for further details see Strasser et al., 2000).

Seven reproductive plants (seed heads visible) per population were chosen to measure leaf number and shoot height, i.e. the height of plants taken from the rooted sediment level to the apex of the inflorescence. Leaf length and width were measured in fully expanded leaves on the nearest vegetative shoot. Different measurements were made in vegetative and reproductive shoots because shoots neither change in height during the growing season nor develop new leaves after the appearance of the reproductive organs (Grace and Harrison, 1986), so leaves from reproductive shoots are generally shorter than those from vegetative shoots.

2.4. Stand biomass measurements

T. latifolia stand biomass was studied trough two methods: a harvesting technique for above and belowground biomass and a non-destructive technique for aboveground biomass. Plant aboveground biomass was estimated non-destructively by regression-based allometric relationships following the method outlined by Lieffers (1983) for *T. latifolia* stands in the Fort McMurray region. A non-destructive technique was used as a way to estimate seasonal biomass differences among wetlands as well as a method of aboveground production comparisons less prone to be affected for biomass losses than the harvesting technique (Dickerman et al., 1986).

Harvesting sites and permanent plots were systematically chosen in stands with the highest density of preceding year stems to get an idea of the maximum potential of biomass accumulation for each of the 15 wetlands and to avoid bias due to sampling. For measurements of belowground biomass, two 0.5 m × 0.5 m stands per wetland were dug out from the sediment–water interface to a 25 cm depth in mid May 2011, before noticeable *T. latifolia* regrowth. Likewise, two adjacent 0.5 m × 0.5 m permanent quadrats were staked out for both the non-destructive biomass determination and the end of the season destructive biomass measurement in late August (time of peak biomass).

Harvested plants for the destructive method were washed to remove sediment and divided into above and belowground biomass. Belowground biomass was separated into live and dead components and the dead component was discarded. Plant material was oven dried at 90 °C until a constant weight before biomass determination. The ash content of above and belowground organs was determined after combustion and the proportion of ash was rested from dry biomass (Dickerman et al., 1986). In each of the wetlands, heights of seven reproductive and seven vegetative stems growing outside permanent plots were measured to the nearest centimeter; height was measured from the sediment–water interface to either the tip of the inflorescence in reproductive stems or the tip of the longest leaf in vegetative stems (Lieffers, 1983). Then, stems were clipped at ground level and dried as mentioned above to establish the allometric relationship between stem height and biomass. Data from the different wetlands were pooled to find the allometric equations. The relationship of biomass to height was regressed with and without logarithmic transformations to find the best fit to the data. There was a linear relationship between reproductive stem heights and the natural logarithm of weights [ln biomass = 0.015 (stem height) + 1.35; $r^2 = 0.81$; $p < 0.0001$] and plant heights and the natural logarithm weights of vegetative stems [ln biomass = 0.016 (stem height) + 0.226; $r^2 = 0.78$; $p < 0.0001$]. Biases in the estimates due to logarithmic transformation were corrected following the method described by Baskerville (1972). Stems were tagged and measured starting with the first monitoring date (second week of June). The second monitoring date was in the fourth week of July and the third monitoring date was carried out during the last week of August 2011. Final aboveground biomass was estimated from the sum of the increment in biomass of tagged and new reproductive and vegetative stems over successive monitoring dates.

2.5. Statistical analysis

Plant performance and biomass data were analyzed using one-way ANOVAs and a priori orthogonal contrasts to compare: (1) plant performance and biomass accumulation of *T. latifolia* stands established in oil sands wetlands to that of stands established in natural wetlands and (2) plant performance and biomass accumulation of *T. latifolia* stands established in industrial wetlands to that of stands established in indirectly-affected wetlands. Differences in water quality parameters between wetlands were also examined by using ANOVAs and orthogonal contrasts. All datasets were checked to ensure normality and homogeneity of variances. If heteroscedasticity was detected, datasets were transformed to meet ANOVA assumptions. All results are presented as non-transformed means ± S.E. All statistical analyses were made using STATISTICA version 10 (StatSoft Inc., Tulsa, OK).

3. Results

3.1. Water chemistry

The statistical analysis of the water chemistry data revealed significant differences among wetlands types (Table 2). Oil sands wetlands had higher salinity, electrical conductivity (EC), pH ($p < 0.05$ for all cases; Table 2) but lower oxidative reductive potentials (ORP) ($p = 0.005$; Table 2) than natural wetlands in both 2010 and 2011. Additionally, water chemistry data of 2010 indicated that oil sands wetlands were richer in sodium and chloride than natural wetlands ($p < 0.05$; Table 2). Industrial wetlands studied in 2010 had higher salinity, electrical conductivity, pH, and chloride concentrations but lower ORP values than indirectly-affected wetlands ($p < 0.05$; Table 2). Indirectly-affected wetlands studied in 2011 were on average higher in salinity and EC that those of 2010 (Table 2) so there were not statistical differences in terms of salinity or EC with industrial wetlands yet showed lower pH values ($p < 0.05$; Table 2).

3.2. Plant nutritional and ionic status

There were large differences in leaf mineral content between *T. latifolia* plants established in the oil sands and those growing in natural wetlands (wetlands studied in 2010, Table 3). Leaves of plants growing in the oil sands had a significantly lower N, P, K, and Ca contents on a dry weight basis than plants established in natural wetlands ($p < 0.05$ for all cases, Table 3). Plants in the oil sands had higher leaf Na concentrations and, consequently, significantly lower cation to Na ratios than plants established in the natural wetlands ($p < 0.05$, Table 3). On the other hand, there were not differences in NPK nutritional status between *T. latifolia* plants established in industrial wetlands when compared to those growing in indirectly-affected wetlands ($p > 0.05$, Table 3). Industrial wetland plants had higher Na but lower Ca contents than plants in indirectly-affected wetlands ($p < 0.005$, Table 3). Cation to Na ratios were one order of magnitude lower in industrial wetlands plants compared to plants sampled in indirectly-affected wetlands ($p < 0.005$ both cases, Table 3). There were not differences in Cl and Mg contents among all wetland types ($p > 0.05$, Table 3).

3.3. Physiology

Chlorophyll *a* fluorescence statistical analysis results indicated significant differences in basic fluorescence parameters for wetlands studied in 2010: maximum and variable leaf fluorescence (F_M, F_V) were lower in oil sands wetlands than in the natural wetlands ($p < 0.01$ both cases, Table 4). *T. latifolia* photochemical efficiency of PSII (F_V/F_M) was also lower in oil sands wetlands ($p = 0.036$, Table 4). Marginally significant differences ($p = 0.068$, Table 4) were found between oil sands and natural wetlands in maximum quantum yield of non-photochemical de-excitation (DI_0/ABS), suggesting that leaves of oil sands plants may dissipate more sunlight energy than plants established in natural wetlands. However, no other chlorophyll *a* fluorescence parameters showed significant variations between plants established in oil sands or natural wetlands (Table 4).

Gas exchange measurements indicated that *T. latifolia* plants in oil sands and natural wetlands assimilated CO_2 at a similar rate ($p > 0.05$, Table 5) in spite of the significantly lower stomatal conductance (g_s) of plants established in the oil sands ($p = 0.007$, Table 5). Changes were detected in g_s which affected transpiration rates (E): oil sands plants had lower E than plants growing in natural wetlands ($p = 0.022$, Table 5).

Neither chlorophyll *a* fluorescence nor gas exchange measurements indicated differences in physiology between plants growing in industrial sites and those established in indirectly-affected wetlands ($p > 0.05$, Tables 4 and 5).

3.4. Morphology

Morphological data indicated substantial differences between oil sands and natural habitats for those wetlands studied in 2010. *T. latifolia* plants in oil sands wetlands had shorter and narrower leaves ($p < 0.05$ for both cases, Table 5). Although total leaf numbers per shoot were similar ($p > 0.05$, Table 5), oil sands plants had fewer green leaves per shoot and lower green to total leaf numbers than plants in natural wetlands ($p < 0.01$ for both cases, Table 5) indicating dissimilar senescence rates between wetland types. Marginal statistical differences were detected for leaf length between plants growing in the two types of oil sands wetlands ($p = 0.083$), resulting in shorter leaves in the industrial wetlands compared with the indirectly-affected wetlands (Table 5). None of the other orthogonal comparisons between the industrial and indirectly-affected wetlands showed statistical differences in terms of morphological features ($p > 0.05$, Table 5).

3.5. Stand biomass

The harvesting method showed contrasting results in terms of belowground biomass of *T. latifolia* stands immediately before and at the end of the growing season: while belowground biomass was not significantly different among wetland types before the growing season ($p = 0.32$, Fig. 1a), in nearby stands, it showed higher biomass amounts and statistical differences among wetland types in late August ($p = 0.007$, Fig. 1b). According to the a priori orthogonal contrasts, oil sands wetlands accumulated less rhizome and root biomass than natural wetlands at the end of the growing season ($p = 0.017$, Fig. 1b). On the other hand, industrial wetlands showed lower *T. latifolia* belowground biomass than indirectly-affected wetlands ($p = 0.020$, Fig. 1b). Aboveground biomass comparisons based on the harvesting method showed that natural wetlands had higher amounts of shoot biomass per stand than oil sands wetlands ($p < 0.001$, Fig. 1c); however, both industrial and indirectly-affected wetlands had statistically similar aboveground biomass values ($p = 0.17$, Fig. 1c). The harvesting method showed that, by the end

Table 2
Water chemistry and results of the orthogonal contrasts for the industrial, indirectly-affected, and natural (off-site) wetlands studied in the oil sands region in years 2010 and 2011.

	Year	Industrial	Indirectly-affected	Natural	*p*-Values a priori contrasts	
					OS vs. natural	Industrial vs. affected
Salinity (ppt)	2010	1.66 ± 0.42	0.31 ± 0.09	0.17 ± 0.04	**0.004**	**0.001**
	2011	1.28 ± 0.45	0.58 ± 0.13	0.12 ± 0.02	**0.000**	0.081
EC (μs cm^{-1})	2010	3435 ± 782	607 ± 166	347 ± 99	**0.003**	**0.001**
	2011	2401 ± 814	1174 ± 248	234 ± 52	**0.000**	0.126
pH	2010	8.8 ± 0.2	7.9 ± 0.2	7.4 ± 0.3	**0.008**	**0.005**
	2011	8.7 ± 0.2	7.8 ± 0.2	7.6 ± 0.5	**0.040**	**0.012**
DO (mg L^{-1})	2010	5.4 ± 0.7	5.4 ± 0.6	4.1 ± 0.6	0.161	0.967
	2011	4.7 ± 0.5	4.8 ± 0.3	4.9 ± 1.3	0.849	0.922
ORP (mV)	2010	60 ± 12	100 ± 14	128 ± 7	**0.005**	**0.048**
	2011	125 ± 27	121 ± 10	119 ± 19	0.880	0.903
Na (mg L^{-1})	2010	271 ± 141	100 ± 65	17.7 ± 7.7	**0.035**	0.154
Cl (mg L^{-1})	2010	111 ± 53	10.0 ± 4.4	13.1 ± 6.6	**0.047**	**0.003**
K (mg L^{-1})	2010	5.1 ± 2.2	5.4 ± 3.0	0.9 ± 0.4	0.192	0.958
K/Na	2010	0.09 ± 0.07	0.07 ± 0.01	0.07 ± 0.02	0.827	0.554
TDN (ppm)	2010	1.4 ± 0.3	1.9 ± 0.9	2.7 ± 1.3	0.688	0.914

Values represent means ± S.E. OS: oil sands wetlands, EC: electrical conductivity, DO: dissolved oxygen, ORP: oxidative reductive potentials, TDN: total dissolved nitrogen.
Bold values signify $\alpha = 0.05$.

Table 3
Mineral contents of *Typha latifolia* leaves on a dry weight basis and results of the ANOVAs and orthogonal contrasts for plants established in industrial, indirectly-affected, and natural wetlands in the oil sands region.

	Industrial	Indirectly-affected	Natural	*F*-Value	*p*-Value	*p*-Values a priori contrasts	
						OS vs. natural	Industrial vs. affected
TKN (ppm)	24.8 ± 1.7	25.6 ± 1.7	31.6 ± 2.5	3.16	0.0700	**0.023**	0.803
TP (ppm)	1.51 ± 0.09	1.67 ± 0.19	3.12 ± 0.35	12.74	**0.0005**	**<0.001**	0.685
Na$^+$ (μmol g^{-1})	419.4 ± 87.9	100.4 ± 48.1	71.3 ± 19.3	10.40	**0.0013**	**0.022**	**0.001**
Cl$^-$ (μmol g^{-1})	368.1 ± 24.2	392.2 ± 50.7	386.7 ± 45.6	0.09	0.9188	0.899	0.701
K$^+$ (ppm)	43.9 ± 3.5	54.7 ± 5.9	64.3 ± 5.0	4.31	**0.0319**	**0.022**	0.153
Ca^{2+} (ppm)	22.7 ± 2.6	35.6 ± 2.1	37.4 ± 2.5	10.49	**0.0012**	**0.012**	**0.002**
Mg^{2+} (ppm)	8.23 ± 1.39	6.68 ± 0.45	8.81 ± 0.88	1.27	0.3089	0.263	0.291
K$^+$/Na$^+$	1.8 ± 0.5	23.5 ± 12.0	25.1 ± 8.5	10.35	**0.0013**	**0.013**	**0.002**
Ca^{2+}/Na$^+$	0.99 ± 0.30	12.58 ± 5.09	12.56 ± 3.55	17.49	**0.0001**	**0.004**	**<0.001**

Values represent means ± S.E. calculated from 6 industrial and indirectly-affected wetlands and 7 natural wetlands studied in 2010. $df = 2$, $df_{\text{error}} = 16$. OS: oil sands wetlands, TKN: total Kjeldahl nitrogen, TP: total phosphorous.
Bold values signify $\alpha = 0.05$.

of August, total *T. latifolia* standing crop was significantly different among wetland types ($p = 0.001$, Fig. 1d): orthogonal contrasts indicated that natural wetlands had higher total biomass than oil sands wetlands ($p = 0.001$, Fig. 1d), while industrial wetlands showed lower amounts of total biomass than indirectly-affected wetlands ($p = 0.033$, Fig. 1d). Despite the previously mentioned significant differences in *T. latifolia* standing crop at the end of the growing season, there were no statistical differences among wetland types in above to belowground biomass ratio ($p = 0.215$, Fig. 1e) or shoot density ($p = 0.748$, shoot number/m^{-2} = 48 ± 3, data not shown).

The non-destructive method of biomass calculation indicated that natural wetlands accumulated higher amounts of aboveground biomass than oil sands wetlands ($p = 0.046$, Fig. 1f). The second round of biomass assessment, which included growth from June 9–12 to July 19–22, was the only individual round which showed significant biomass differences among wetland

Table 4
Chlorophyll *a* fluorescence results of *Typha latifolia* leaves. ANOVA and orthogonal contrast statistics of the analyzed parameters for plants established in industrial, indirectly-affected, and natural wetlands in the oil sands region.

Parameters	Industrial	Indirectly-affected	Natural	*F*-Value	*p*-Value	*p*-Values a priori contrasts	
						OS vs. natural	Industrial vs. affected
F_0	5418 ± 122	5205 ± 175	5488 ± 83	1.25	0.3141	0.292	0.270
F_M	$2.4 \times 10^4 \pm 1 \times 10^3$	$2.4 \times 10^4 \pm 1 \times 10^3$	$2.8 \times 10^4 \pm 1 \times 10^3$	5.02	**0.0214**	**0.006**	0.985
F_V	$1.8 \times 10^4 \pm 1 \times 10^3$	$1.9 \times 10^4 \pm 1 \times 10^3$	$2.2 \times 10^4 \pm 1 \times 10^3$	4.75	**0.0252**	**0.008**	0.870
F_V/F_M	0.77 ± 0.01	0.78 ± 0.01	0.80 ± 0.01	3.02	0.0792	**0.036**	0.408
DI_0/ABS	0.23 ± 0.01	0.22 ± 0.01	0.20 ± 0.01	2.24	0.1412	0.068	0.439
ABS/RC	0.84 ± 0.06	0.76 ± 0.06	0.73 ± 0.06	0.54	0.5909	0.466	0.477
RE_0/ET_0	0.50 ± 0.02	0.51 ± 0.02	0.52 ± 0.05	0.70	0.9338	0.797	0.796
PI	2.69 ± 0.40	3.11 ± 0.32	4.00 ± 0.79	1.53	0.2484	0.117	0.589

Values represent means ± S.E. calculated from 6 wetlands from each wetland type. $df = 2$, $df_{\text{error}} = 15$. Significance levels are presented. OS: oil sands wetlands. Wetlands studied in 2010.
Bold values signify $\alpha = 0.05$.

Table 5
Values of gas exchange parameters, morphological variables. ANOVA and orthogonal contrasts statistics of *Typha latifolia* plants established in industrial, indirectly-affected, and natural wetlands in the oil sands region.

	Industrial	Indirectly-affected	Natural	*F*-Value	*p*-Value	*p*-Values a priori contrasts	
						OS vs. natural	Industrial vs. affected
A (μmol m^{-2} s^{-1})	2.41 ± 0.17	2.40 ± 0.28	2.48 ± 0.37	0.02	0.9798	0.844	0.978
E (mmol m^{-2} s^{-1})	4.88 ± 0.43	5.67 ± 0.61	6.79 ± 0.38	3.93	**0.0425**	**0.022**	0.269
g_s (mol m^{-2} s^{-1})	0.58 ± 0.08	0.64 ± 0.07	0.90 ± 0.07	6.63	**0.0226**	**0.007**	0.559
Shoot height (cm)	137.2 ± 5.6	151.0 ± 8.09	157.3 ± 7.66	2.12	0.1521	0.137	0.197
Leaf length (cm)	139.3 ± 8.5	168.7 ± 14.60	181.9 ± 11.05	3.72	**0.0471**	**0.046**	0.083
Leaf width (mm)	12.82 ± 0.44	13.51 ± 0.47	14.76 ± 0.77	3.03	0.0766	**0.034**	0.418
Total leaves/shoot	16.29 ± 0.43	15.50 ± 0.47	15.21 ± 1.11	0.55	0.5871	0.458	0.479
Green leaves/shoot	7.79 ± 0.46	7.98 ± 0.45	9.60 ± 0.48	5.07	**0.0197**	**0.006**	0.775
Green/total leaves	0.48 ± 0.03	0.52 ± 0.03	0.64 ± 0.03	7.64	**0.0047**	**0.001**	0.419

Values represent the means ± S.E. $df = 2$, $df_{\mathrm{error}} = 15$. OS: oil sands wetlands. A = net photosynthesis rate; E: transpiration rate; g_s: stomatal conductance. Wetlands studied in 2010.
Bold values signify $\alpha = 0.05$.

types ($p = 0.026$, Fig. 1f); while both first and second rounds of measurements did not give statistical differences ($p > 0.05$). On the other hand, the non-destructive method did not detect statistical differences in aboveground biomass between industrial and indirectly-affected wetlands in the total sum of rounds ($p = 0.089$, Fig. 1f) or any individual round ($p > 0.05$, all cases).

4. Discussion

Our findings show that *T. latifolia* is a consistent species for wetlands reclamation in industrial ecosystems as its physiological functions were relatively consistent across oil sands wetland types. On the other hand, results also point out that *T. latifolia* plants

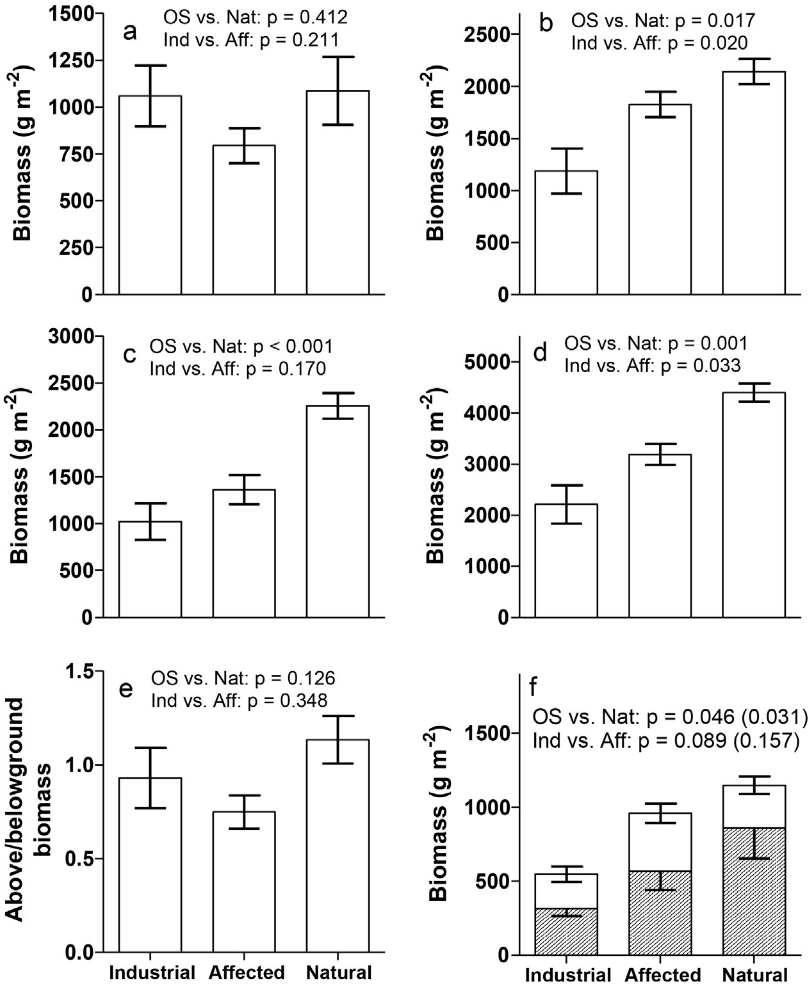

Fig. 1. Destructive (a–e) and non-destructive (f) biomass measurements in *Typha latifolia* stands established in industrial, indirectly-affected wetlands in the oil sands leases and natural off-site wetlands: (a) belowground biomass before growing season, (b) belowground biomass after growing season, (c) aboveground biomass, (d) total biomass, (e) above/belowground biomass, and (f) non-destructive aboveground biomass. Values are mean ± S.E. Results of the a priori orthogonal comparisons between different types of wetlands are shown in the inset. Striped parts of bars in (f) represent second measurement biomass; respective a priori orthogonal contrasts are in brackets in the inset.

in the oil sands wetlands were under a stress level that reduced leaf growth and longevity as well as stand biomass accumulation; indicating suboptimal conditions for the development of some of *T. latifolia*'s most valuable processes and services in the oil sands marshes and ponds.

4.1. Plant performance and stand biomass in oil sands vs. natural wetlands

Oil sands processed waters (OSPW) can drive stomatal closure and reduce transpiration rates (Renault et al., 2000). *T. latifolia* plants established in the oil sands wetlands showed reduced stomatal conductance and transpiration rates suggesting whole plant stress responses in which individuals compensate to balance water loss through transpiration and water uptake through roots and stem flow. Nevertheless, reductions in stomatal conductance did not appear to constitute a rate-limiting effect on carbon assimilation at the leaf level. Chlorophyll *a* fluorescence, however, indicated that photochemical efficiency was appreciably affected as oil sands plants showed less ability than plants from natural wetlands to absorb sunlight energy despite the same abilities to channel that energy into carbon assimilation. All the above mentioned results indicate that regardless of the manifested stress responses, *T. latifolia* photosynthetic activity, the basic physiological function to fuel self-maintenance and growth, was only slightly affected by conditions encountered in the oil sands wetlands.

OSPW can affect plant morphology by reducing plant growth (Renault et al., 1999, 2000); effects that were noticeable on *Carex aquatilis* plants established on OSPW affected wetlands (Mollard et al., 2012). *T. latifolia* leaves of plants growing in oil sands wetlands were significantly smaller than leaves of natural wetlands plants. Leaves of plants subjected to salinity suffer a strong and protracted growth inhibition well before ions accumulate to toxic levels (Munns and Tester, 2008). However, plant symptoms indicated that toxic damages may also occur in oil sands wetlands: oil sands plants had fewer green leaves per shoot than plants from natural wetlands. OSPW changes plant ion concentrations to levels at which mineral imbalances can occur (Renault et al., 2004). Accordingly, plants established in the oil sands wetlands had higher Na concentrations and lower concentration of K, Ca, and lower K/Na and Ca/Na ratios than plants established in natural wetlands. Suitable leaf levels of macronutrients as K and Ca are essential for the preservation of basic cell functions such as maintenance of cellular metabolism and membrane selectivity (Tester and Davenport, 2003). While plants utilize different halotolerance mechanisms to deal with the risks imposed by ion toxicity (e.g.: ion exclusion, ion compartmentalization in vacuoles), all mechanisms imply a usage of metabolic energy (Tester and Davenport, 2003; Hauser and Horie, 2010) and, consequently, an increase in plant maintenance costs. It appears that the combination (additive or multiplicative relationships are not discernible) of specific Na toxicity, loss of ion homeostasis, toxicity through other unmeasured potentially toxic constituents (NA, PAH, metals), and/or channelization of metabolic energy into halotolerance mechanisms represent an energetic tradeoff that impaired morphological performance and produced the stress symptoms observed in oil sands plants.

When related to oil sands freshwater, OSPW is not only higher in potentially toxic constituents but also enriched in macronutrients (e.g.: nitrogen due to ammonia), micronutrients (e.g.: boron), and beneficial elements (e.g.: sodium). This nutritional enrichment may explain the better performance of some wetland plants grown in OSPW when compared to control freshwater treatments (Bendell-Young et al., 2000; Pouliot et al., 2012). Elevated ammonia levels in oil sands effluent have been proposed to subsidize *T. latifolia* performance by improving its carbon assimilation rates (Bendell-Young et al., 2000) and opening the possibility of using *Typha* growth as a means to mitigate nutrient enrichment in hypereutrophic waters, an option that has been tested in other systems and wetland species (Chua et al., 2012; Zhao et al., 2012). Whereas *T. latifolia* photosynthesis and growth are susceptible to nutrient limitations in natural wetlands (Sullivan et al., 2010), ammonia detoxifies rapidly in oil sands marshes and ponds (Harris, 2007). Thus, the beneficial effects of N supplementation in the field are expected to be a transitory effect, unlikely to be consistently observed across different wetland conditions and exposures. In our study, water-dissolved N contents were not statistically different among wetlands types. Moreover, leaves from plants in natural wetlands had higher total Kjeldahl N than plants in the oil sands marshes. These results suggest that the beneficial effects of ammonia pollution or other nutrients in plants performance, if they exist in the field, may be confined to areas of process-affected water inputs in well-exposed wetlands.

The maintenance of a high leaf area index is the most significant factor determining productivity of *T. latifolia* stands (Longstreth, 1989). The observed leaf growth restrictions in oil sands wetlands during 2010 are in line with results found in 2011, which indicate a lower aboveground and total biomass in oil sands wetlands compared to the natural wetlands. Likewise, at the moment of peak biomass, *T. latifolia* stands established in natural wetlands had a higher belowground biomass than stands in oil sands wetlands; however belowground biomass sampled before the growing season suggests that differences may be blurred during the harsh winter conditions in the region. It is expected to find higher above to belowground biomass ratios in *T. latifolia* stands established in nutrient rich wetlands (Lieffers, 1983). However, plants established in the different wetlands did not demonstrate a contrasting carbon partitioning as above to belowground ratios were similar among sites. Taken together, the above-mentioned results indicate that while year to year *T. latifolia* stand perpetuation might not be compromised in the oil sand wetlands, significant shortage in carbon inputs are expected in the emergent area of those industrial wetland ecosystems.

4.2. Plant performance and stand biomass in industrial and indirectly-affected wetlands

Water analyses of wetlands studied in 2010 indicated that chemical conditions were milder in the indirectly-affected wetlands than in the industrial wetlands as salinity, pH, and chloride concentrations were significantly lower in the former. Furthermore, leaf chemistry analyses showed that Na, K/Na and Ca/Na ratios of indirectly affected wetlands resembled natural conditions more closely than leaves of plants established in the industrial sites. In spite of the differences in plant ion concentrations and macronutrient balances, the hypothesized differences in *T. latifolia* individual plant performance between oil sands wetland types were supported by neither physiological nor morphological results. Apparently in line with 2010 results, both the destructive and the non-destructive methods of biomass determination carried out in 2011 failed to show differences between industrial and indirectly-affected wetlands in terms of aboveground biomass. However, at the end of the growing season, both total and belowground biomasses were significantly different between industrial and indirectly affected sites, showing that there are important differences between indirectly-affected and industrial wetlands in terms of potential productivity of *T. latifolia* stands.

5. Conclusions

This paper reveals that the relatively stable physiologic functions of *T. latifolia* plants across different wetland types makes possible the achievement of some basic reclamation objectives such as the maintenance of thriving plant stands to provide waterfowl and wildlife habitat as well as a steady source of organic carbon to fuel aquatic food webs. *T. latifolia* can produce litter mats of stems and rhizomes in less than a decade, thereby playing a stabilization role and contributing organic material to problematic wetland substrates. The present contribution shows a higher *T. latifolia* stand productivity in wetlands created on natural substrates and freshwater than on OSPM. A reduced *T. latifolia* stand biomass accumulation in industrial wetlands represents a potential area of concern as it means a limitation for the production of organic sediments and peat, critical ecological processes that are already constrained in the mined landscape. These results suggest that if more robust emergent stands are desired, freshwater amendments or the use of milder sources of water than OSPW may be needed to foster ecological contributions of emergent plant stands in industrial wetlands.

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Appendix 1.

Characteristics and coordinates of the industrial, indirectly-affected (IA), and natural wetlands (off-site) studied in the oil sands region.

Name	Type	Sediment	Water	Study	Latitude (N)	Longitude (W)
4m-CT	Industrial	CT/peat	OSPW	M, Ch, Ph, B	56°59′31″	111°32′05″
MFT-S	Industrial	MFT	OSPW	M, Ch, Ph	56°59′31″	111°32′05″
Test Pond 5	Industrial	CT	OSPW	M, Ch, Ph	57°05′03″	111°41′39″
Test Pond 8	Industrial	CT	OSPW	M, Ch, Ph, B	57°05′01″	111°41′33″
Test Pond 9	Industrial	Mineral	OSPW	B	57°05′03″	111°41′31″
Test Pond 10	Industrial	MFT	OSPW	M, Ch, Ph, B	57°05′01″	111°41′29″
Mike's Pond	Industrial	MFT/clay	OSPW	M, Ch, Ph	57°06′39″	111°40′50″
1m-CT	Industrial	CT/peat	OSPW	B	56°59′23″	111°31′51″
V-Notch	Industrial	Mineral	OSPW	B	56°59′17″	111°31′58″
Natural S	IA	Mineral/peat	Freshwater	M, Ch, Ph, B	56°58′50″	111°30′37″
Duck	IA	Mineral/org.	Freshwater	M, Ch, Ph, B	56°59′15″	111°32′21″
Species	IA	Mineral	Freshwater	M, Ch, Ph, B	56°59′37″	111°32′08″
Test Pond 1	IA	Mineral	Freshwater	M, Ch, Ph	57°05′06″	111°41′35″
Fireweed	IA	Mineral/org.	Freshwater	M, Ch, Ph	57°04′57″	111°41′36″
N Beaver	IA	Mineral/org.	Freshwater	M, Ch, Ph	57°06′44″	111°41′24″
Crane Lake	IA	Mineral	Freshwater	B	56°59′33″	111°32′55″
High S	IA	Mineral	Freshwater	B	56°59′49″	111°33′09″
N-20	Natural	Mineral/peat	Freshwater	M, Ch, Ph, B	56°44′41″	111°29′55″
Dam	Natural	Mineral/peat	Freshwater	M, Ch, Ph	56°56′36″	111°38′49″
Beaver lodge	Natural	Mineral/peat	Freshwater	M, Ch, Ph, B	56°30′53″	111°16′15″
Mosquito	Natural	Mineral/peat	Freshwater	M, Ch, Ph, B	56°36′53″	111°20′03″
HHS	Natural	Mineral/peat	Freshwater	M, Ch, Ph	56°45′43″	111°35′60″
N-1	Natural	Mineral/peat	Freshwater	M, Ch, Ph	56°44′46″	111°29′50″
Broken wing	Natural	Mineral/peat	Freshwater	M, Ch, Ph, B	56°58′14″	111°41′22″
No name	Natural	Mineral/peat	Freshwater	B	56°45′46″	111°36′56″
Jumping dog	Natural	Mineral/peat	Freshwater	B	56°56′19″	111°39′41″

CT: consolidated tailings; MFT: mature fine tailings; OSPW: oil sands processed water; Org: organic. Study: M (plant morphology), Ch (leaf chemistry), Ph (physiology), B (plant biomass).

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