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Impacts of sulphur and nitrogen deposition in western Canada
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Nitrogen and sulphur deposition and the growth of *Sphagnum fuscum* in bogs of the Athabasca Oil Sands Region, Alberta

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ABSTRACT

One of the consequences of ongoing development of the oil sands reserve in the Athabasca Oil Sands Region (AOSR) near Fort McMurray, Alberta, Canada (56° 39' N, 111° 13' W) is an increase in emissions of nitrogen (N) and sulphur (S), with an attendant increases in regional atmospheric N and S deposition. Regional land cover across northeastern Alberta is a mixture of Boreal Mixedwood, Boreal Highlands, and Subarctic areas. Peatlands occupy between 22 and 66% of these natural regions, and the land cover of bogs varies between 6.7% in the Mixedwood Region to 46% in the Subarctic Region. Ombrotrophic bog ecosystems may be especially sensitive to atmospheric deposition of N and S. Across 10 ombrotrophic bog sites in the AOSR over four years (2005–2008), we found no evidence of elevated deposition of NH_4^+*-N,* NO_3^-*-N, total inorganic nitrogen (TIN;* NH_4^+*-N plus* NO_3^-*-N), or* SO_4^{2-}*-S, with values measured using ion exchange resin collectors averaging 0.61 ± 04, 0.20 ± 0.01, 0.81 ± 0.04, and 1.14 ± 0.06 kg* ha^{-1} y^{-1}*, respectively. Vertical growth and net primary production of* Sphagnum fuscum*, an indicator of elevated deposition, did not differ consistently across sites, averaging 11.8 ± 0.2 mm* y^{-1} *and 234 ± 3.3 g* m^{-2} y^{-1}*, respectively, over the four years. Neither vertical growth nor net primary production of* S. fuscum *was correlated with growing season atmospheric N or S deposition. Our data provide a valuable benchmark of background values for monitoring purposes in anticipation of increasing N and S deposition over a broader geographic region within the AOSR.*

Key words: Sphagnum fuscum*, nitrogen deposition, sulphur deposition, Athabasca Oil Sands Region, peatland, bog, Canada*

1. INTRODUCTION

The boreal forest of western Canada consists of a mosaic of plant communities, including evergreen forests, deciduous forests, treed bogs, open and shrubby fens, emergent marshes, lakes, and streams. Within this mosaic, peatlands form an important component, occupying 166,300 km^2 or about 16% of the provincial area of Alberta (Vitt *et al*. 1996). The oil sands region of northeastern Alberta is a mixture of Boreal Mixedwood, Boreal Highlands, and Subarctic areas (AEP 1994). Peatlands occupy between 22 and 66% of these natural regions, and the land cover of bogs varies between 6.7% in the Mixedwood Region to 46% in the Subarctic Region (Vitt *et al*. 1996).

Continental bogs are ombrogenous peatlands receiving nutrients, minerals, and water only from precipitation (see Wieder & Vitt 2006; Vitt 2008 for reviews). Bogs are acidic owing primarily to dissociation of weak organic acids produced through decomposition processes and from the production of new cation exchange sites on the cell walls of each year's new growth of *Sphagnum* (Hemond 1980). The acidity may contribute to the low species richness and *Sphagnum* dominance of bogs. In continental areas, the dominant species of *Sphagnum* is *S. fuscum*, a species that forms densely packed communities of desiccation-avoiding plants. *Sphagnum fuscum* is rich in polyphenols and as such is resistant to decomposition (Turetsky *et al*. 2008). All of these qualities lead to the ability of this species to form relatively high hummocks that rise from 0.5 to 1 m above the bog water table. Continental bogs in North America typically have open tree canopies of only one species – *Picea mariana*. *S. fuscum* hummocks commonly occur in open areas not overtopped by *P. mariana* branches; these hummocks receive atmospheric deposition, with a chemical composition that has not been altered by dry deposition onto needle surfaces and/or canopy exchange.

The ombrogenous nature of bogs makes them model ecosystems for studying the effects of atmospheric pollution. *Sphagnum fuscum* is the foundational species in these nutrient poor bogs and is an excellent indicator of ecosystem performance (Vitt 2006; Vile *et al*., in press). Bogs generally are N-limited (Walbridge & Navaratnam 2006; Wieder 2006), and this may be especially true in areas like continental western Canada, where atmospheric N deposition is quite low (about 1 kg ha^{-1} y^{-1}; Vitt *et al*. 2003). Interest in the responses of bogs to elevated N deposition grew following studies that implicated high atmospheric N deposition as a causal factor in the decline in *Sphagnum* in bogs of the United Kingdom (Woodin *et al*. 1985; Press *et al*. 1986). A synthesis of the large body of research on N deposition effects in peatlands, and in particular *Sphagnum*, led to the formulation of a conceptual framework that the response of *Sphagnum* to increasing N deposition is triphasic (Lamers *et al*. 2000). At low N deposition (<12 kg ha^{-1} y^{-1}), atmospheric inputs enhance net primary production (NPP) of N-limited *Sphagnum* mosses. As N deposition increases to the point where *Sphagnum* NPP is no longer N-limited, the excess N may be taken up by growing mosses resulting in an increase in tissue N concentrations within the *Sphagnum* canopy (12-18 kg ha^{-1} y^{-1}). As atmospheric N deposition increases beyond the point where the *Sphagnum* canopy is saturated with N (>18 kg ha^{-1} y^{-1}), dissolved inorganic N may pass through the *Sphagnum* canopy into the underlying peat. A possible consequence of elevated atmospheric N deposition is a decrease the C:N ratio of *Sphagnum* mosses and peat, stimulating decomposition and the associated release of CO_2 to the atmosphere (Lamers *et al*. 2000; Berendse *et al*. 2001; Limpens & Berendse 2003; Limpens *et al*. 2006).

Sphagnum peatlands also appear to be affected by atmospheric deposition of inorganic S compounds (Vile & Novák 2006). The disappearance of *Sphagnum* groundcover from peatlands in the British Pennines was attributed to elevated atmospheric S deposition (Ferguson *et al*. 1978; Ferguson & Lee 1979, 1980). In addition, stimulation of anaerobic dissimilatory sulphate reduction by elevated sulphate deposition may have implications for the functioning of bogs as net sinks for atmospheric carbon (Wieder *et al*. 1990; Vile *et al*. 2003a,b; Gauci *et al*. 2002, 2004, 2006). Alberta bogs receive low atmospheric S deposition, at about 0.5 kg S ha^{-1} y^{-1} (Vile *et al*. 2003a).

One of the consequences of ongoing development of the oil sands reserve in the Athabasca Oil Sands Region (AOSR) near Fort McMurray (56° 39' N, 111° 13' W) is an increase in emissions of nitrogen (N) and sulphur (S), with attendant increases in regional atmospheric N and S deposition (Taylor 1981; EPCM 2002). Between 1980 and 1995, activities in the region released nitrogen oxides (NO_x) to the atmosphere at a rate of 36 to 60 t d^{-1} (CEMA NO_x SO_2 Management Working Group 2005). Estimates for 2010 (and beyond) predict increasing development in the region, with attendant increases in emissions of NO_x up to a potential discharge of approximately 355 tons per day (t d^{-1}). Current emissions of SO_2 are about 300 t d^{-1}, and estimates of future emissions range from 350 to 400 t d^{-1} by 2015 (CEMA NO_x SO_2 Management Working Group 2005 from Golder 2003 data).

Given the sensitivity of *Sphagnum* mosses to elevated atmospheric N and S deposition, bogs in the AOSR provide an opportunity for monitoring and serving as early warning indicators of ecosystem dysfunction. Here we report on four years (2005–2008) of atmospheric N and S deposition data for 10 sites in the AOSR along with the growth response of the foundational bog moss species, *Sphagnum fuscum*, to assess both the potential impact of N and S deposition and any critical ecosystem response.

2. METHODS

2.1. Study sites

Ten bog sites associated with lakes were selected from a set of 50 lakes that form the basis for the Province of Alberta's Regional Aquatics Monitoring Program (RAMP), charged with determining, evaluating, and communicating the state of the aquatic environment and any changes that may result from cumulative resource development within the Regional Municipality of Wood Buffalo, Alberta (www.ramp-alberta.org). Our study sites were located in four geographical areas within the AOSR: the Birch Mountains (BM; Subarctic Natural Region; 3 bogs), northeast of Fort McMurray, (NE; Central Mixedwood Natural Region; 3 bogs), the Stony Mountains, (SM; Boreal Highlands Natural Region; 3 bogs), and west of Fort McMurray (WF; Central Mixedwood Natural Region; 1 bog) (Fig. 1).

All of the sites are ombrotrophic and dominated by a set of species characteristic of Alberta bogs (Belland & Vitt 1995; Vitt *et al*. 1995). The tree layer is composed only of *Picea mariana*; shrubs are *Ledum groenlandicum* and *Vaccinium vitis-idaea*, the field layer consists of *Rubus chamaemorus*, *Smilacina trifolia*, and *Oxycoccus microcarpus*; *Eriophorum vaginatum* is occasionally present. Bryophytes and lichens make up 100% cover of the ground layer. The dominant species of bryophyte is *Sphagnum fuscum*, with *S. magellanicum*, *S. angustifolium*, *Pleurozium schreberi*, and *Aulacomnium palustre* occurring sporadically. *Sphagnum fuscum* often has *Pohlia nutans* and *Leiomylia anomala* occurring epiphytically. *Cladina mitis* and several species of *Cladonia* are also sporadic. Hummocks are well developed, varying from 0.5-1.0 m above the wetter hollows. Bogs in this region of Alberta have pH's in the range of 3.0-4.5 with spring water level at or just below the wettest hollows (Vitt 2000).

Mean annual temperature and total annual precipitation for Fort McMurray are 0.7 °C and 456 mm, respectively. During the 4-year study, monthly temperatures tracked long-term means, with 2005 and 2006 being warmer than average because of a warm 2005-2006 winter and 2008 being cooler than average because of a cool winter and spring (Fig. 2). Annual precipitation was considerably lower than average in 2007, reflecting a dry spring and autumn.

2.2. Sphagnum fuscum *growth*

Growth of *Sphagnum fuscum* was measured using the cranked wire method (Clymo 1970; Vitt 2007). At each site, we placed 20 wires in each of 3 *S. fuscum* hummocks (except at SM8, where we placed 40 wires in each of 3 hummocks).

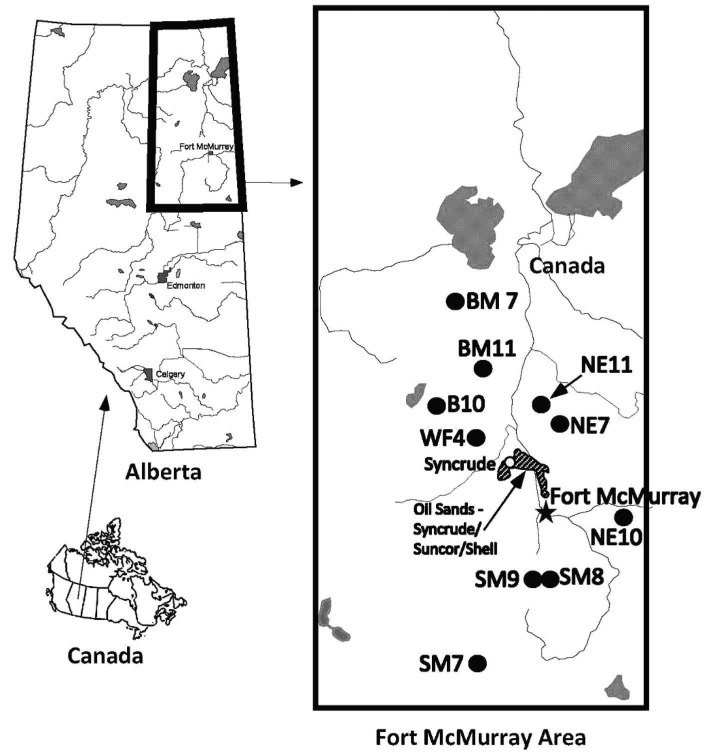

Fig. 1. Location of Fort McMurray, Alberta, Canada and of the 10 bog study sites surrounding Fort McMurray in the Birch Mountains (BM), northeast/east of Fort McMurray (NE), the Stony Mountains (SM), and west of Fort McMurray (WF).

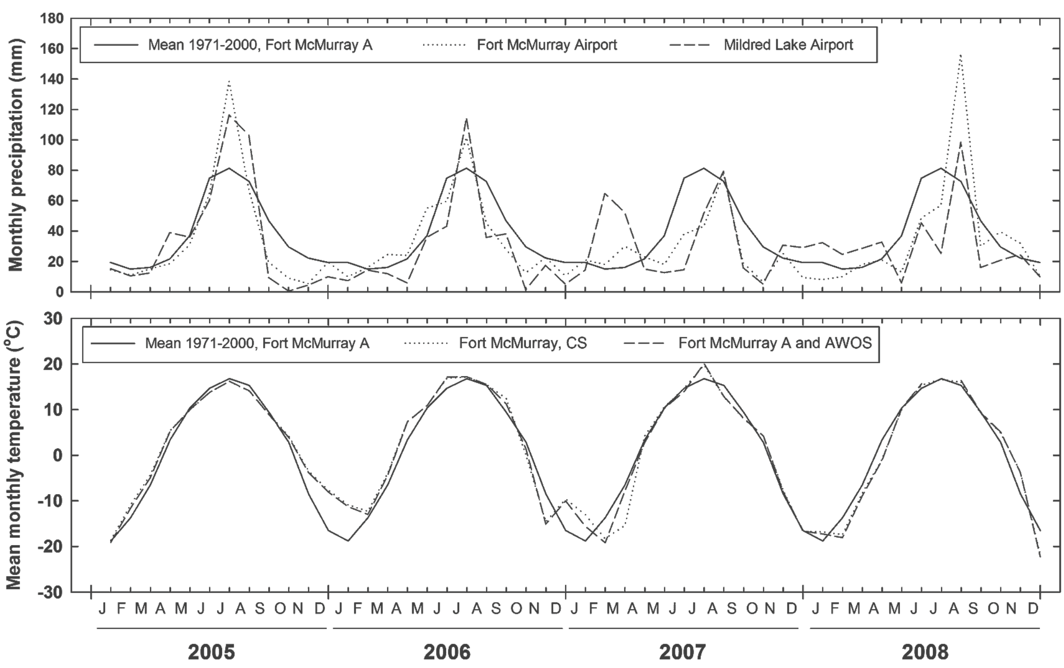

Fig. 2. Monthly precipitation and temperature in the Fort McMurray area. Data are from: Canadian Climate Normals, 1971–2000 (20-year averages from 1971–2000; www.climate.weatheroffice.ec.gc.ca/climate_normals/index_e.html); The Weather Network, Historical Data (precipitation for Mildred Lake and the Fort McMurray airport; www.theweathernetwork.com); and the National Climate Data and Information Archive (precipitation at Fort McMurray A and temperature data from Fort McMurray A, CS, and AWOS stations, www.climate.weatheroffice.ec.gc.ca). For 2005, 2006, 2007, 2008 (averages of the 2 weather stations), and the 20-year average (1971–2000 for Fort McMurray A station), total annual precipitation was 415, 370, 357, 404, and 456 mm, respectively, and mean annual temperature was 2.2, 2.3, 0.3, –0.5, and 0.7 °C respectively.

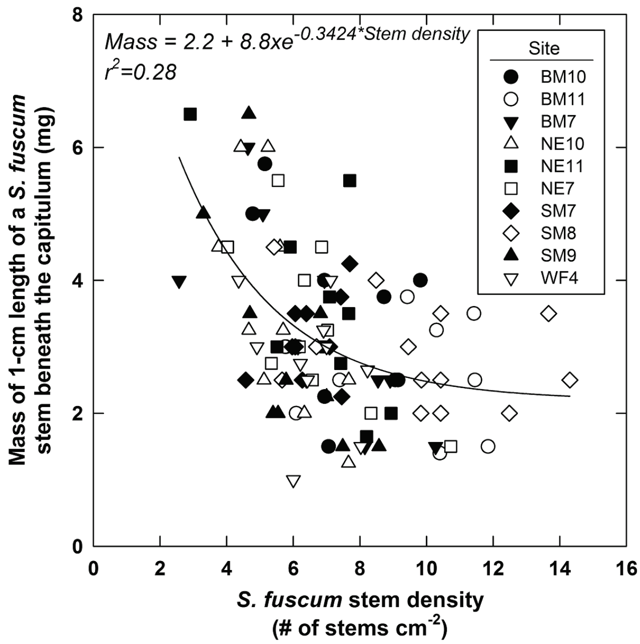

Fig. 3. Relationship between the mass of the 1 cm length of individual *S. fuscum* stems beneath the moss capitulum and *S. fuscum* stem density (number of stems cm^{-2}). Each plotted point represents data from an individual sample from a *S. fuscum* hummock.

Wires were set extending to a uniform height above the peat early in the growing season when *S. fuscum* hummocks were nearly frost-free (24-25 May 2005; 10-11 June 2006; 21 May 2007; 29-30 May 2008 and were re-measured at the end of the growing season (26-27 September 2005; 9-10 October 2006; 4-5 October 2007; 1 October 2008), allowing for quantification of vertical growth.

To convert vertical growth measurements to NPP, at the end of each growing season, an intact core (6.5 cm diam., 5 cm deep) of the *Sphagnum fuscum* canopy was collected from each hummock where cranked wires had been inserted. In each sample, we counted the total number of *Sphagnum* plants. Subsequently, 20 individual *S. fuscum* stems were randomly selected from each sample, the capitula were removed (new vertical growth occurs by extension of the plant stem beneath the capitulum), and the underlying 2 cm of stems were dried at 90 °C for 48 hours and weighed to determine stem mass density. Multiplication of plant densities (number of *S. fuscum* stems cm^{-2}) by stem mass densities (g cm^{-1} of stem) yields bulk density of newly produced biomass (g cm^{-3}), which when multiplied by growth in length (cm y^{-1}) yields NPP (g cm^{-2} y^{-1}). We used site mean bulk density values to calculate NPP from linear growth measurements.

2.3. N and S deposition

We quantified deposition of NH_4^+-N, NO_3^--N and SO_4^{2-}-S using ion exchange resin collectors (Fenn & Poth 2004), increasing the number of collectors per site from 3 to 5 beginning in June 2006 because of loss of samplers from animal damage. We initially used 10 cm diameter funnels, changing to 19 cm diameter funnels in October 2007 to conform with the updated design recommendations of Fenn *et al*. (undated). Snow tube extensions (50 cm tall) were used over the non-growing season. Collectors were placed in open areas, attached to sawed-off black spruce trees, about 1.0 m above the peat surface. In the lab, we submersed resins in 40 mL of 2 M KCl and rinsed with additional 10 mL of 2 M KCl. Extract solutions were analyzed for NH_4^+-N (phenate method), NO_3^--N (hydrazine reduction method), and SO_4^{2-}-S (methylthymol blue method) on a Technicon AutoAnalyzer II for the first 5 collection dates and subsequently on a Lachat QuikChem Automated Flow Injection Ion Analyzer. For each collection period, 3-5 replicate batches of resin that were not placed in the field were extracted as blanks; mean values for blanks were subtracted from values for resins that had been placed in the field.

3. RESULTS

Bulk densities of newly produced *S. fuscum* biomass averaged 0.021 ± 0.001 g cm^{-3}, with the only significant site difference between SM8 (0.027 ± 0.002 g cm^{-3}) and SM9 (0.016 ± 0.002 g cm^{-3}). We found an inverse relationship between the mass of the individual *S. fuscum* stems 1 cm beneath the capitulum and the number of *S. fuscum* stems per cm^2, the two terms that enter into the bulk density calculations (Fig. 3). This inverse relationship reflects considerable variation within and between hummocks and sites in *S. fuscum* stem mass and the number of stems per area, which in combination leads to rather consistent bulk density values.

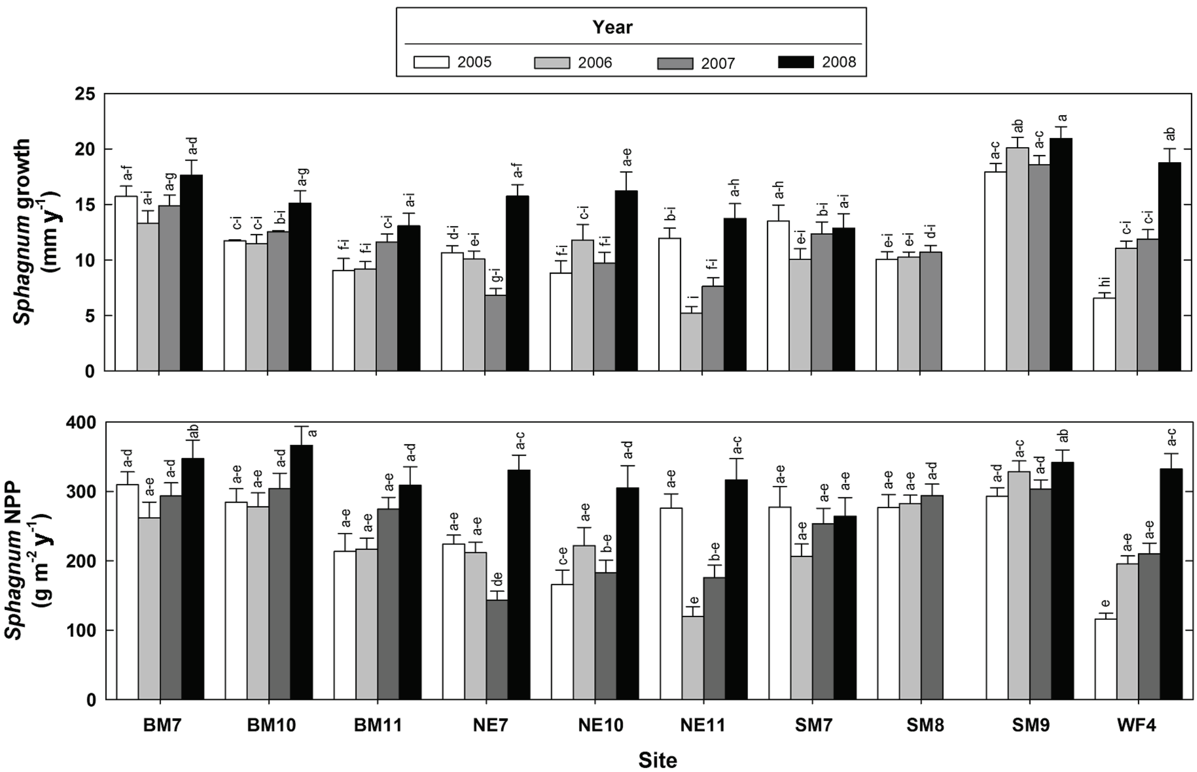

Fig. 4. *Sphagnum fuscum* vertical growth (top panel) and NPP (bottom panel). Values are means ± standard errors (n = 53–60 except at SM8 where n = 121). Data were analyzed using a repeated measures ANOVA (repeated measurements on each cranked wire); *a posteriori* comparisons to characterize the site x year interaction were conducted using Tukey's Honestly Significant Difference test. Means with the same letter above the error bars do not differ significantly. No data for site SM8 in 2008.

Both linear growth of *Sphagnum* and *Sphagnum* NPP exhibited a significant site by year interaction (p <0.0001), indicating no consistent differences between sites or between years (Fig. 4). Overall, linear growth averaged 11.8 ± 0.2 mm y^{-1} and NPP averaged 234 ± 3.3 g m^{-2} y^{-1} (means ± standard errors, n = 2448).

Mean daily deposition of NH_4^+-N, TIN (NH_4^+-N plus NO_3^--N), and SO_4^{2-}-S was significantly greater during the growing season than during the rest of the year; this pattern was not consistent across all sites for NO_3^--N deposition (Fig. 5). Although there were some differences between sites in mean daily deposition of NH_4^+-N and TIN that were consistent across all sampling periods, no pattern is evident between the four regions (BM, NE, SM, WF). Mean daily SO_4^{2-}-S and NO_3^--N deposition did not differ between sites. Overall mean weighted (by the number of days in each collection period) deposition of NH_4^+-N, NO_3^--N, TIN, and SO_4^{2-}-S was 166 ± 10, 54 ± 2, 221 ± 11, and 311 ± 16 µg m^{-2} d^{-1}, respectively, equivalent to annual deposition values of 0.61 ± 0.04, 0.20 ± 0.01, 0.81 ± 0.04, and 1.14 ± 0.06 kg ha^{-1}, respectively.

Mining of oil sands in the Fort McMurray area began at the site in 1973, with the first barrel of oil shipped five years later. Using the Syncrude mine site facilities as a reference location, we found no significant relationships between distance from Syncrude (Tab. 1) and deposition of N and S at our 10 sites. The weighted average wind direction at Fort McMurray is southerly and the prevailing wind directions are east to east-southeasterly (from Walmsley & Bagg 1978). We found no significant correlations between vectors of distance from Syncrude multiplied by the deviation of our site bearings (Tab. 1) from the average or prevailing wind direction bearing (in absolute value) with N and S deposition at our 10 sites.

Neither *S. fuscum* linear growth nor *S. fuscum* NPP were significantly correlated with growing season deposition of NH_4^+-N, NO_3^--N, TIN, or SO_4^{2-}-S (Fig. 6). We used stepwise regression to evaluate the effects of monthly (May-September) temperature and precipitation, growing season mean temperature, and growing season total precipitation on *S. fuscum* linear growth or NPP. Both linear growth and NPP were positively related to only August precipitation (p = 0.0006 and p = 0.0383, respectively, but August precipitation explained only 0.5% and 0.2% of the variation in linear growth and NPP, respectively. In 2005, 2006, 2007, and 2008 August precipitation was 85, 41, 78, and 128 mm (mean August precipitation from 1971-2000 was 72.7 mm), respectively. Averaged across all sites (means ± standard errors; n = 612), linear growth was 11.5 ± 0.3, 11.2 ± 0.3, 11.7 ± 0.3, and 12.9 ± 0.4 cm, respectively, and NPP was 248 ± 7, 239 ± 6, 250 ± 6, and 259 ± 9 g m^{-2} y^{-1} respectively.

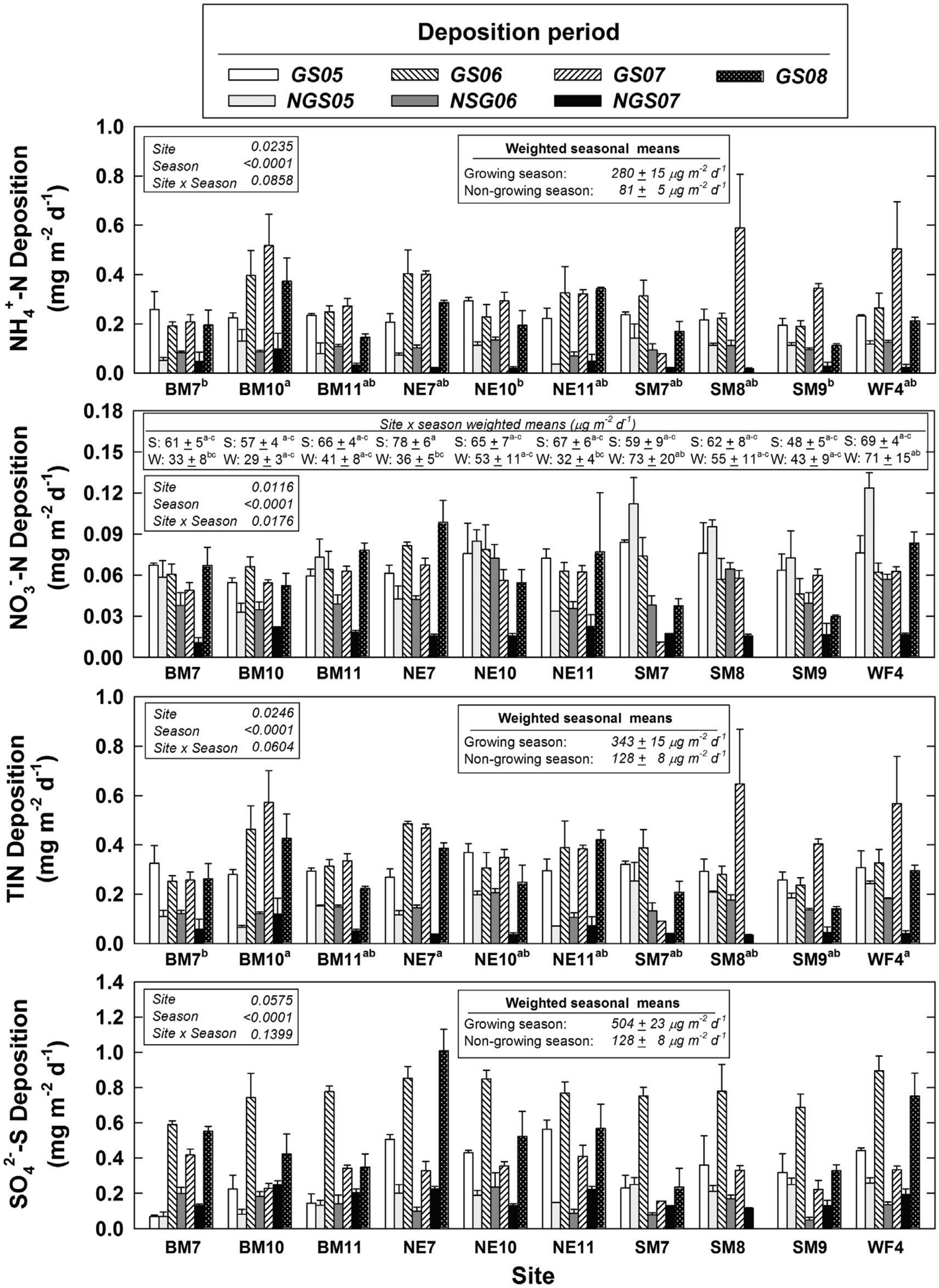

Fig. 5. Deposition of NH_4^+-N, NO_3^--N TIN (NH_4^+-N plus NO_3^--N) and SO_4^{2-}-S from ion exchange resin collectors. Values are means ± standard errors (n = 1–5). Data were analyzed using weighted (by number of days that each batch of resins was in the field) ANOVA, with collections dates categorized into growing season (GS; exactly corresponding to the duration of NPP measurements in Fig. 4) and non-growing season (NGS); *a posteriori* comparisons to assess the site x season interaction for NO_3^--N were conducted using Tukey's Honestly Significant Difference test, while *a posteriori* comparisons of site means for NH_4^+-N and TIN were conducted using a least significant difference approach with a comparisonwise α = 0.05 (Tukey's HSD failed to reveal any site differences). For these *a posteriori* tests, mean values with the same letter superscript do not differ significantly. When a significant season effect with no interaction was obtained, seasonal means are shown. No data were obtained for site SM8 for the growing season of 2008.

Tab. 1. Site locations and distance and bearing from Syncrude mine site facilities, 40 km north of Fort McMurray (57° 01' N; 111° 38' W).

Site Name	Latitude (N)	Longitude (W)	Distance from Syncrude Mine Site Facilities (km)	Bearing from Syncrude Mine Site Facilities
BM7	58° 03.545'	112° 16.486'	112.1	341°43'
BM10	57° 19.032'	112° 23.840'	56.9	305°58'
BM11	57° 41.514'	111° 54.455'	76.9	347°39'
NE7	57° 8.810'	110° 51.809'	48.7	72°42'
NE10	56° 37.600'	110° 11.800'	97.6	116°23'
NE11	57° 17.500'	111° 14.000'	39.0	39°16'
SM7	55° 40.870'	111° 49.610'	149.0	184°35'
SM8	56° 12.600'	111° 12.000'	93.5	163°32'
SM9	56° 12.600'	111° 15.110'	92.7	165°25'
WF4	57° 8.887'	111° 59.029'	25.7	304°35'

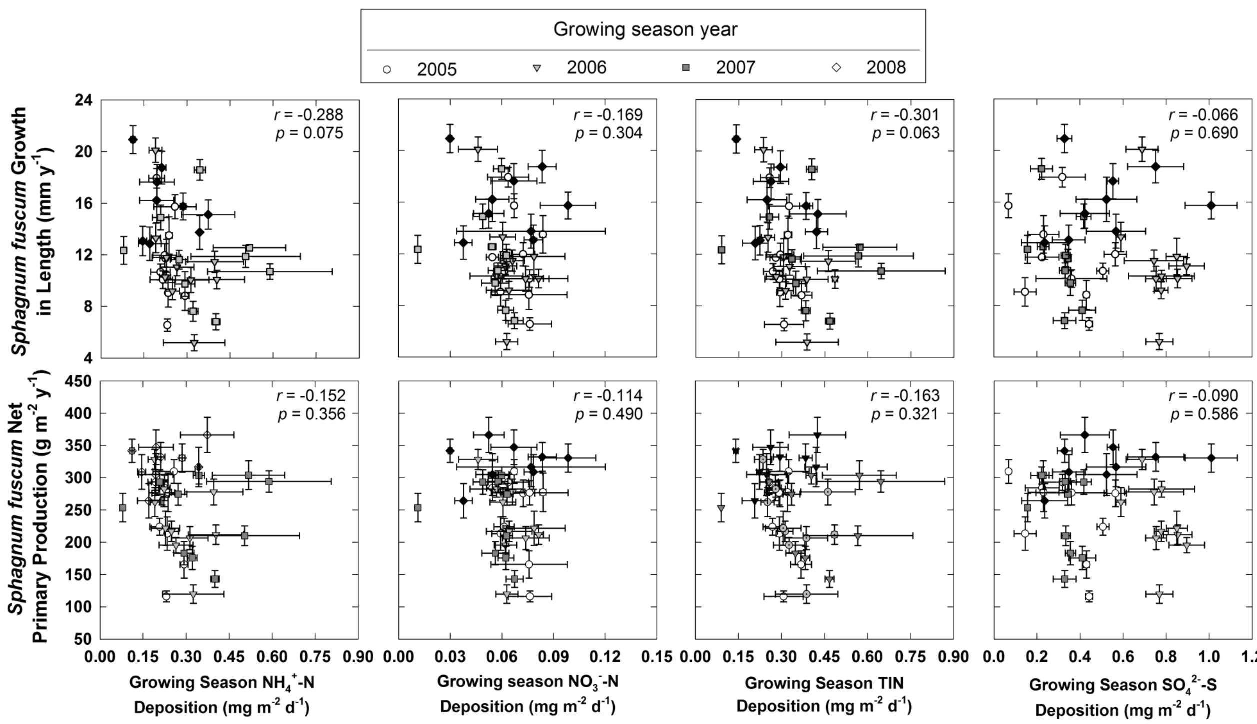

Fig. 6. Correlations between *S. fuscum* vertical growth or NPP with growing season NH_4^+-N, NO_3^--N, TIN (NH_4^+-N plus NO_3^--N), and SO_4^{2-}-S deposition. Values are means ± standard errors. Pearson correlation coefficients (r) were corrected for attenuation due to errors in both growth and deposition variables (van Belle *et al*. 2004) using the ratios of the pooled standard deviations to the overall mean for each variable.

4. DISCUSSION

Emissions of NO_x and SO_2 from development of the oil sands resource on the AOSR ultimately return to regional ecosystems via atmospheric deposition. As summarized by Schindler *et al*. (2006), background N deposition in the AOSR was less than 2 kg ha^{-1} y^{-1} prior to oil sands development, but as development proceeds, N deposition may increase to as high as 66 kg ha^{-1} y^{-1} in areas near to the oil sands activity (Allen 2004), and may exceed 20 kg ha^{-1} y^{-1} over thousands of square kilometres (Anonymous 2000, cited in Schindler *et al*. 2006). At the same time, SO_x emissions from the oil sands sector in Alberta are predicted to increase from about 90,000 t y^{-1} to over 160,000 t y^{-1} in 2015 (Alberta Environment 2008), so an attendant increase in S deposition across the AOSR is expected, as well. As Schindler *et al*. (2006) note, predictions of present and future deposition have been derived from modelling efforts and have not been verified by direct measurements.

Our ion exchange resins, placed in the open away from the influence of the black spruce canopy, quantified bulk deposition of inorganic ionic forms of N and S directly onto *S. fuscum* hummocks. Our N deposition values (Fig. 5) are consistent with previously reported model estimates of low background N deposition (cf. Vitt *et al*. 2003). One exception is that Vitt *et al*. (2003) reported modelled N deposition for the Steepbank area, west northwest of Fort McMurray (bearing 305°), of 4.04 kg N ha^{-1} y^{-1}; the Steepbank site is about the same distance from the Syncrude mine site facilities as our WF4 site, but is east-southeast of Syncrude (bearing of 123°). Jeffries *et al*. (2003) synthesized measured NO_3^--N deposition values for western Canada, reporting values of <2 kg NO_3^- ha^{-1} y^{-1} (<0.45 kg NO_3^--N ha^{-1} y^{-1}) for most of the area west of Manitoba. McDonald *et al*. (1996) reported wet S deposition in Fort McMurray as 1.8 kg ha^{-1} y^{-1} (measured) and 1.2-1.3 kg ha^{-1} y^{-1} (modelled), and modelled dry deposition of <1 to 5 kg ha^{-1} y^{-1} across the AOSR region. We found no significant correlations between N or S deposition and distance from the heart of the oil sands mining area (the Syncrude mine site facilities) and/or prevailing wind direction. Our low values for N and S deposition suggest that elevated deposition from mining activity is restricted to areas closer to and/or immediately downwind of the active mine sites.

Published *Sphagnum* NPP values range from 9-1450 g m^{-2} y^{-1} and average 259 g m^{-2} y^{-1} (Gunnarsson *et al*. 2005). Our overall value for *Sphagnum fuscum* NPP of 234 ± 3.3 g m^{-2} y^{-1} (Fig. 4) is comparable to other measurements in northern Alberta (ranging from 64 ± 79 to 245 ± 147 g m^{-2} y^{-1}; summarized in Vitt *et al*. 2003), with the exception of a value of 600 ± 462 g m^{-2} y^{-1} for the Steepbank site, which also has a modelled elevated N deposition. Neither *Sphagnum fuscum* vertical growth nor NPP was correlated with deposition of N or S (Fig. 6). Lamers *et al*. (2000) suggested that at low atmospheric N deposition, *Sphagnum* NPP is N-limited and therefore increasing N deposition should result in increasing NPP without an increase in plant tissue N concentrations. Overall, our N and S deposition values are quite low and typical of unpolluted areas. Across our 10 sites, the ranges of both annual N deposition (weighted averages across all resin collection dates of 0.64 ± 0.07 kg ha^{-1} y^{-1} at BM11 to 0.93 ± 0.15 kg ha^{-1} y^{-1} at WF4) and growing season N deposition (weighted averages across all resin collection dates of 0.26 ± 0.03 mg m^{-2} y^{-1} at SM9 to 0.43 ± 0.05 mg m^{-2} y^{-1} at BM10) were narrow. Similarly narrow across-site ranges were obtained for both annual S deposition (0.92 ± 0.15 kg ha^{-1} y^{-1} at SM9 to 1.48 ± 0.26 kg ha^{-1} y^{-1} at NE7) and growing season S deposition (1.41 ± 0.02 mg m^{-2} y^{-1} at SM9 to 2.47 ± 0.03 mg m^{-2} y^{-1} at NE11). If *S. fuscum* NPP is affected by either N or S deposition, a wider gradient of deposition values may be needed to reveal responses.

The Canadian Prairie Provinces are susceptible to periodic drought, which can extend north of the agricultural areas to Fort McMurray (Khandekar 2004). Our study was conducted during years that were warmer and drier than the long-term averages (for 2005, 2006, 2007, 2008, total annual precipitation was 91, 81, 78, and 89% of normal, respectively, and mean annual temperature was 2.9, 3.0, 1.0 and 0.2 °C higher than normal; Fig. 2). It is possible *S. fuscum* growth does respond to variation in N and/or S deposition, but that such responses are manifested only in years with normal or cooler, wetter climatic conditions.

Finally, ^{210}Pb dating of peat from bogs in Alberta (Burke-Scoll 2008) and across eastern Canada (Moore *et al*. 2004) has indicated that accumulation of N in peat is several-fold higher than can be accounted for by precipitation inputs, implying an unidentified source or sources of N to peat. Possible sources of N include dry deposition, deposition of organic N compounds, pollen, or biological N_2-fixation, but any relationships between these additional N inputs and *S. fuscum* growth remain unresolved.

5. CONCLUSION

Across our 10 study sites, we found no evidence for elevated N or S deposition, no consistent site differences in N or S deposition, no consistent site differences in *Sphagnum fuscum* growth, and no relationships between either N or S deposition and *S. fuscum* growth. We show a significant, but weak, relationship indicating that *S. fuscum* linear growth and NPP is positively related to August precipitation. Our data provide a valuable benchmark of background values for monitoring purposes in anticipation of increasing N and S deposition over a broader geographic region within the AOSR.

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