



Eleven years of simulated deposition of nitrogen but not sulfur changed species composition and diversity in the herb stratum in a boreal forest in western Canada



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ABSTRACT

Oil sands mining activities in northern Alberta, Canada emit large amounts of nitrogen (N) and sulfur (S) oxides to the atmosphere, increasing N and S deposition. We studied the long-term (2006–2016) effect of elevated concentrations of simulated N and S deposition on soil properties and understory species composition in a mixedwood boreal forest in a two (0 and 30 kg N ha⁻¹ year⁻¹, as ammonium nitrate) × two (0 and 30 kg S ha⁻¹ year⁻¹, as sodium sulfate) factorial experiment. Soil (forest floor and 0–15 cm mineral soil) and understory vegetation samples were collected and the cover of understory vegetation was determined in August 2016. Eleven years of N deposition increased ($p = .045$) total N concentration and decreased ($p < .10$ unless otherwise indicated) carbon to N ratio by 11 and 7%, respectively, in the forest floor. Sulfur deposition decreased ($p = .045$) exchangeable calcium concentration by 36% in the mineral soil. Species evenness (by 7%) and the overall diversity (by 7%) were decreased and community composition was changed ($p = .008$) in the herb stratum by N but not by S deposition, due to species-specific responses to N deposition. However, elevated concentrations of N and S deposition did not change species diversity and composition in the shrub stratum. Decreased foliar phosphorus and potassium concentrations and increased N to phosphorus ratio in some species indicate a potential risk of nutrient imbalance by N deposition. Reducing N emission to minimize its negative effect on boreal forest ecosystems should be a priority in emissions management in the oil sands.

1. Introduction

Increases in fossil fuel combustion emit a large amount NO_x and SO₂ to the atmosphere, and nitrogen (N) and sulfur (S) compounds formed in the atmosphere eventually return to the surrounding areas as N and S deposition, which can cause base cation leaching, nutrient imbalance and soil acidification (Fenn et al., 1998; Lovett et al., 2009), threatening forests surrounding the emission source. The Athabasca oil sands region in northern Alberta, Canada, is the world's largest oil sands reservoir and oil sands mining and upgrading related activities emit approximately 300 and 250–300 Mg day⁻¹ for NO_x and SO₂, respectively, since the mid-2000s (Hazewinkel et al., 2008; The Royal Society of Canada, 2010). The emission rates of NO_x and SO₂ are expected to increase due to the continued oil sands mining operation and expansion (Aherne and Shaw, 2010). Understory composition and soil properties are more sensitive to environmental changes such as N and S deposition than tree species (Gilliam, 2006, 2014a; Jung et al., 2017). Thus determining changes in understory species composition may be an effective

approach for evaluating the sensitivity of forest ecosystems to N and S deposition.

Chronic N deposition can change understory plant species composition by increasing soil N availability and base cation leaching (Fenn et al., 1998; Gilliam, 2006, 2014a; Jung et al., 2017; Lovett et al., 2009). Increases in soil N availability increase the abundance of nitrophilous species (Gilliam, 2014a; Hruška et al., 2012). High concentrations of N deposition increase base cation leaching and aluminum (Al) mobility and toxicity in the soil (Lovett et al., 2009), which in turn can decrease the cover of plant species that require high base cation supply and other species sensitive to acid stress (Lu et al., 2010, 2014). Many studies have evaluated the effect of excess N deposition on understory communities in temperate forest ecosystems with inconsistent results (Gilliam, 2006, 2014b; Hurd et al., 1998; Rainey et al., 1999; Thomas et al., 1999), depending on soil N availability, duration of experimental N addition and amount of N added (Bobbink et al., 2010). Soils in boreal forests in northern Alberta are N limited, and N deposition caused by oil sands mining has increased soil N availability and

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Table 1

Soil properties in the forest floor and the surface mineral soil in a mixedwood boreal forest in the Athabasca oil sands region in northern Alberta, Canada.

Treatment ^a	pH	EC (dS m ⁻¹)	Total C (g kg ⁻¹)	Total N (g kg ⁻¹)	C/N	NH ₄ -N (mg kg ⁻¹)	NO ₃ -N (mg kg ⁻¹)	DOC	DON	Exchangeable cations				
										Ca ²⁺	Mg ²⁺	K ⁺	Al ³⁺	(Ca ²⁺ + K ⁺ + Mg ²⁺)/Al ³⁺
<i>Forest floor</i>														
CK	5.37 (0.26)	2.52 (0.28)	335 (45)	14.9 (1.6)	22.4 (0.6)	10.5 (1.9)	2.0 (0.4)	4103 (910)	333 (70)	55 (2)	92 (4)	2.6 (0.6)	0.08 (0.01)	2053 (316)
+N	5.01 (0.18)	2.66 (0.30)	368 (23)	17.8 (0.8)	20.7 (0.4)	9.0 (1.3)	2.3 (0.9)	4225 (504)	374 (36)	64 (4)	106 (3)	3.0 (0.3)	0.09 (0.02)	2179 (405)
+S	5.01 (0.20)	2.97 (0.14)	355 (28)	15.3 (0.7)	23.2 (0.9)	7.7 (0.9)	2.8 (0.5)	4352 (461)	352 (37)	51 (2)	78 (8)	2.4 (0.2)	0.10 (0.02)	1379 (345)
+NS	5.01 (0.19)	2.84 (0.13)	379 (13)	17.2 (0.5)	22.1 (0.7)	8.1 (0.1)	2.8 (0.4)	3837 (225)	341 (23)	53 (12)	92 (17)	2.1 (0.5)	0.07 (0.01)	2226 (189)
<i>Two-way ANOVA (P value)^b</i>														
N	0.419	0.981	0.355	0.045	0.059	0.667	0.791	0.743	0.759	0.448	0.195	0.908	0.313	0.172
S	0.410	0.213	0.612	0.928	0.121	0.182	0.364	0.908	0.880	0.278	0.217	0.287	0.813	0.363
N × S	0.412	0.581	0.882	0.634	0.671	0.461	0.808	0.597	0.584	0.665	0.975	0.445	0.125	0.305
<i>Surface mineral soil</i>														
CK	4.48 (0.11)	0.34 (0.00)	5.03 (0.49)	0.35 (0.02)	14.4 (1.1)	0.80 (0.06)	ND	72.7 (3.8)	4.2 (0.4)	3.6 (0.5)	6.6 (0.9)	0.18 (0.02)	0.21 (0.05)	57 (15)
+N	4.38 (0.08)	0.34 (0.01)	5.56 (0.54)	0.40 (0.06)	14.0 (0.7)	0.75 (0.11)	ND	75.0 (3.9)	5.2 (0.3)	3.1 (0.9)	6.2 (0.1)	0.16 (0.01)	0.25 (0.03)	39 (5)
+S	4.43 (0.04)	0.56 (0.02)	5.22 (0.37)	0.43 (0.08)	12.7 (1.5)	0.79 (0.07)	ND	72.0 (6.8)	5.7 (0.7)	1.9 (0.1)	5.1 (0.4)	0.19 (0.04)	0.23 (0.09)	45 (19)
+NS	4.52 (0.14)	0.57 (0.07)	5.02 (0.68)	0.36 (0.02)	13.8 (1.0)	0.79 (0.04)	ND	81.3 (0.9)	6.1 (0.7)	2.4 (0.2)	5.0 (1.2)	0.13 (0.01)	0.28 (0.09)	35 (12)
<i>Two-way ANOVA (P value)^b</i>														
N	0.975	0.793	0.758	0.896	0.785	0.892	NA	0.208	0.224	0.951	0.748	0.137	0.532	0.341
S	0.677	< 0.001	0.753	0.698	0.421	0.264	NA	0.525	0.061	0.045	0.119	0.652	0.736	0.562
N × S	0.364	0.811	0.507	0.238	0.487	0.219	NA	0.435	0.617	0.337	0.822	0.403	0.937	0.761

^a CK: control, no nitrogen or sulfur addition; +N: nitrogen addition; +S: sulfur addition; and +NS: combined nitrogen and sulfur addition. ND = not detected, NA = not available.^b Values in bold indicate significance ($p < .1$); Values are means with SE in parentheses ($n = 3$).

acidification (Jung et al., 2013; Laxton et al., 2010), which is expected to change the plant communities.

Chronic S deposition can decrease plant growth resulting in early leaf senescence, leaf chlorosis and cation deficiency symptoms (Schulze, 1989) and causing a “divergence problem” (Lloyd and Bunn, 2007). Sulfur deposition increases cation leaching, soil acidification and Al toxicity in soils by affecting plant growth and diversity (Lovett et al., 2009). Soils in boreal forests in northern Alberta have low sulfate (SO₄²⁻) sorption capacity (Jung et al., 2011; Whitfield et al., 2010) and would be sensitive to S deposition. Since boreal forest ecosystems are typically low in S availability (Liang and Chang, 2004), S deposition may alleviate S limitation in the boreal forest and improve the growth of species that require more S. A study conducted in a boreal forest in northern Alberta found that seven years of simulated S (or combined N and S) deposition decreased species diversity and cover in the shrub stratum without significant effects on the herb stratum (Jung et al., 2017). Since the Jung et al. (2017) study is the only one conducted in boreal forests in western Canada, further research to determine responses of soils and understory species to the longer term of S deposition is required.

We examined the responses of soil chemistry and understory plant diversity to 11 years (2006–2016) of elevated concentrations of simulated N and S deposition in a boreal forest in northern Alberta, Canada. We hypothesized that (1) chronic N and S deposition would decrease cation concentrations and increase N and S availabilities in the soil, and (2) chronic N and S deposition would cause nutrient imbalances in understory foliage and could change the overall understory species composition and decrease species diversity by changing the cover of specific species in a boreal forest in northern Alberta, Canada.

2. Materials and methods

2.1. Study site and experimental design

Research plots were located in a boreal mixedwood forest (56.1°N 110.9°W), approximately 100 km southeast of Fort McMurray, Alberta, Canada (Jung and Chang, 2012). The mean annual temperature and precipitation were 1.0 °C and 418 mm, respectively, from 1981 to 2010 (Environment Canada, 2014). The dominant tree species were approximately 65-year-old trembling aspen (*Populus tremuloides*) and 30- to 60-year-old white spruce (*Picea glauca*), at 71 and 22% in density, respectively (Jung and Chang, 2012). Soils are Gray Luvisols based on the Canadian system of soil classification (Soil Classification Working Group, 1998) or Cryalf in Soil Taxonomy (Soil Survey Staff, 2014).

Most of the surface mining and upgrading activities in the region were located approximately 30 km north of Fort McMurray, and approximately 130 km away of research plots from active oil sands mining area; therefore, the site for this study was likely unaffected by deposition of acidic material originating from the oil sands. To determine N and S deposition rates, four collectors consisted of a 1 L bottle and a funnel (10 cm radius) with a screen (1 × 1 mm opening size) were installed in open areas near experimental plots between September 2014 and August 2016. The collectors were replaced every two months during the growing seasons and stayed over the winters. Samples were filtered with a 0.22 μm syringe filter and concentrations of ammonium (NH₄⁺) and nitrate (NO₃⁻) were determined using a wet chemistry analyzer (SmartChem 200, Discrete, MA, USA) and SO₄²⁻ using an ion chromatography (Dionex DX 600, Sunnyvale, CA, USA). The mean total inorganic N bulk deposition rates were 1.0 kg N ha⁻¹ yr⁻¹, with 0.7 and 0.3 kg N ha⁻¹ yr⁻¹ for NH₄⁺ and NO₃⁻, respectively, and bulk deposition rate of S was 0.5 kg S ha⁻¹ yr⁻¹. Dry deposition rate of NH₃ was not monitored however, according to the measurement by passive

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