FINAL REPORT:

Peatland Monitoring and Synoptic Survey – 2013

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INTRODUCTION AND BACKGROUND

This project has two components: 1) to continue sampling of peatland sites to assess the potential to monitor elevated atmospheric N and S deposition in the Athabasca Oil Sands Region (AOSR), following up on four prior years of monitoring at these sites (cf. Final Report: Development of Lichen Monitoring Tools – 2009-2013; WBEA Agreements No: T102-09, T102-10, T102-11, T105-12), and 2) to undertake a synoptic survey of bog sites with helicopter access only over a period of two days in the summer of 2013 to further evaluate the potential of bogs as monitors of elevated atmospheric N and S deposition in the AOSR.

SYNOPTIC SURVEY

Study Sites and Methods

For the synoptic survey, we established a square 80 x 80 km grid (16 cells, 20 x 20 km each), centered on the midpoint between the Syncrude and Suncor upgrader stacks. In each of the 16 grid cells, Dr. Dale Vitt, Southern Illinois University, identified at least 2 candidate bog sites from satellite imagery. With this information in hand, we deployed two field teams of 4 people each. Each team leader would confirmed a candidate bog site from the air before dropping off the team for sample collection. The pilot then picked up the second team assigned to a separate grid square. Over a two day period (July 6-7, 2013), we successfully visited 20 bog sites, spatially distributed across the grid (Fig. 2).

At each of the 20 sites, we collected 5 replicate porewater samples from the top of the water table. After measuring pH and filtering, samples were frozen and stored for subsequent analysis of NH_4^+-N (alkaline phenate method, Seal AA3 autoanalyzer), NO_3^--N (hydrazine reduction, Seal AA3 autoanalyzer), SO_4^{2-}-S (DIONEX ion chromatograph), and dissolved N concentrations (Shimadzu TC/TN analyzer). In addition, we collected 5 replicate plant tissue samples from *Cladina mitis*, *Evernia mesomorpha, Sphagnum fuscum*, *Sphagnum capillifolium*, *Vaccinium vitis-idaea*, *Oxycoccos microcarpus*, *Ledum groenlandicum*, and *Picea mariana*. Samples were dried at 60 ^{o}C, ground in a Wiley mill, and analyzed for N and S concentrations on a LECO TrueSpec CNS analyzer.

To assess regional patterns in water or plant tissue chemistry, the G3GRID procedure was used in SAS to interpolate concentrations at a scale of 1 km x 1 km across the entire 80 km x 80 km sampling area. Interpolation used the spline option and a smoothing value of 0.05. Using the output from the G3GRID procedure, contour plots were generated in SigmaPlot. We restricted the presentation of the contour plots to the area bounded by the outermost sampling locations. Site S2 was excluded from these analyses, as the site is a fen, rather than a bog.

PEATLAND MONITORING

Study Sites and Methods

For the peatland monitoring component of the work, we continued our efforts at 4 peatland sites (JPH4, McKay, McMurray, and Anzac; Fig. 1). We discontinued monitoring at the Mildred site, dismantling the site at the suggestion of WBEA in advance of anticipated road construction for a new interchange off of Highway 63. These sites and our methodology are fully described in the final report to our previous WBEA-supported work.

SYNOPTIC SURVEY

Based on porewater pH, all sites showed the low pH values typical of bogs except site S2, which with a mean pH of 7.89 (Table 1) was a fen, not a bog. Excluding site S2, mean concentrations of H^+, NH_4^+-N, NO_3^--N, DIN (NH_4^+-N + NO_3^--N), dissolved organic N, and SO_4^{2-}-S were 138 µeq/L (pH of 3.86), 1.45, 0.15, 1.60, 2.31, and 0.36 mg/L, respectively. These values are consistent with those reported from our previously reported values from the JPH4, Mildred, McKay, McMurray, and Anzac bog sites.

Contour plots (Fig. 3) revealed elevated NH_4^+-N and DIN concentrations (DIN being dominated by NH_4^+-N) in bog porewater to the northwest of the oil sands mining area. Across the region, prevailing winds are to the northwest between March and May and to the north-northwest between September and November (*http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/sag7019*) and may transport NH_4^+-N emissions to bogs during these periods. Porewater concentrations of NO_3^--N and DON, however, did not appear to be influenced by proximity to the oil sands mining area. Concentrations of H^+ and SO_4^{2-}-S were substantially elevated near the center of the sampling area, suggesting that S emissions from oil sands mining activities are acidifying bog porewaters. While bogs are naturally acidic, the pH of porewaters has been thought to be reasonably well buffered by biological and chemical processes (Clymo 1964, Hemond 1980, Clymo et al. 1984, Soudzilovskaia et al. 2010). As such, anthropogenic acidification of bog porewaters has received little attention. The effects of evident acidification of bog porewater on vegetation and microbial processes in close proximity to the oil sands mining area warrants further investigation.

In general, when plant growth is N-limited, response to added N initially is increased growth with no increase in tissue N concentration. With further N addition, growth is no longer N-limited and plants may begin to exhibit an increase in N concentration especially in newly formed tissues (Chapin et al. 1986, Iversen et al. 2010). However, when N availability is high, increasing plant tissue N concentrations may have deleterious effects on plant health (cf. Britto and Kronzucker 2002). Peatland plants follow this general pattern of plant responses to added N (Allen, undated).

Of the eight bog species that we examined, four (*Evernia mesomorpha*, *Cladina mitis*, *Ledum groenlandicum*, and *Picea mariana*) showed clear evidence of elevated N concentration in plant tissue with increasing proximity to the oil sands mining area (Fig. 4), with increases between 50 and 100% above background values. Neither *Sphagnum fuscum* nor *Sphagnum capillifolium* exhibited elevated N concentrations near the oil sands mining area. However, we have recently shown that *Sphagnum*-associated biological N_2-fixation by methanotrophic prokaryotes, rather than by cyanobacteria, accounts for the major input of N in the region's bogs (Vile et al. 2014). Down-regulation of N_2-fixation with increasing N deposition is consistent with the absence of a tissue N concentration response in *Sphagnum* tissues. Two other species, *Oxycoccos microcarpus* and *Vaccinium vitis-idaea* are short statured shrubs with very shallow ericoid mycorrhizal roots. It is likely that these species draw their N from near-surface peat, and the N deposition versus N_2-fixation tradeoff in *Sphagnum* may be reflected in the absence of elevated N concentrations in the leaves of these two shrub species.

Peatlands are well known as strong sinks for atmospherically deposited S (e.g. Urban et al. 1989, Moore et al. 2004). The uptake and accumulation of S in bog plants has received little attention, but in general, elevated S availability leads to luxury uptake of sulfate (uptake in excess of plant physiological requirements) leading to higher S concentrations in plant tissues (e.g. Skwierawska et al. 2008, De Kok et al. 2011). Seven of the eight bog plant species (*Vaccinium vitis-idaea* being the exception), exhibited

elevated tissue S concentrations with proximity to the oil sands mining area (Fig. 5, with increases between 25 and 100% above background values. These patterns are consistent with plant luxury uptake of S and with the well-documented S storage capability of peatlands. While it is not known whether elevated S concentrations in bog plant tissues have deleterious effects, the elevated sulfate concentrations in bog waters has the potential to stimulate biological sulfate reduction, altering pathways of carbon mineralization (decomposition) and potentially diminishing methane production and emission to the atmosphere (Vile et al. 2003, Gauci et al. 2004).

PEATLAND MONITORING

Results and Interpretations

The 2013 plant tissue N and S concentration data for the 10 species monitored are shown along with the previously reported data for 2009-2012 (Figs. 6-15). It remains the case that over the 5-year period, plant tissue N concentrations generally increase with proximity to the oil sands mining area for *Cladina mitis, Evernia mesomorpha. Sphagnum fuscum*, and *Oxycoccos microcarpus*, the pattern of increasing N concentrations in plant tissues over time, with the rate of increase becoming greater with increasing proximity to the oil sands mining area, remains evident, especially for *Sphagnum fuscum*, and to a lesser extent for *Evernia mesomorpha* and *Oxycoccos microcarpus*. As we previously reported, rising N concentrations in plant tissues cannot continue indefinitely, and possibly could eventually lead to concentrations that are detrimental to plant health.

Similarly, plant tissue S concentrations generally increase with proximity to the oil sands mining area for *Cladina mitis, Evernia mesomorpha, Picea mariana, Sphagnum fuscum, Sphagnum capillifolium, Oxycoccos microcarpus,* and *Vaccinium vitis-idaea.* However, in contrast to N, S concentrations in plant tissues of several species continue to show a significant decrease over time, which we previously attributed to industry efforts to reduce SO_2 emissions.

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PRESENTATIONS 2013-2014

Wieder, R.K., M.A. Vile, J Quinn, C.M. Albright, K.D. Scott and D.H. Vitt. 2013. Bog plant tissue chemistry and N and S accumulation in peat are influenced by elevated N and S deposition from Alberta oil sands. American Geophysical Union Fall Meeting, San Francisco, California, December 2013.

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Table 1. Water chemical characterization for each site. Values are means (for pH) and means ± standard errors (*n*=5); nw indicates no water collected at site (water table was too far below peat surface), nd indicates not determined because of an insufficient quantity of water available for analysis.

		Concentration					
Site	pH	H^+ (µeq/L)	NH_4^+-N (mg/L)	NO_3^--N (mg/L)	DIN (mg/L)	DON (mg/L)	SO_4^{2-}-S (mg/L)
S1	3.72	195 ± 17	1.74 ± 0.17	0.14 ± 0.01	1.88 ± 0.18	2.33 ± 0.14	0.27 ± 0.07
S2	7.89	0.12 ± 11	1.56 ± 0.08	0.13 ± 0.01	1.69 ± 0.07	2.68 ± 0.12	0.46 ± 0.10
S3	nw	nw	nw	nw	nw	nw	nw
S4	3.82	156 ± 15	1.60 ± 0.20	0.19 ± 0.04	1.79 ± 0.24	1.99 ± 0.12	0.09 ± 0.02
S5	3.67	213 ± 10	1.35 ± 0.08	0.13 ± 0.07	1.35 ± 0.07	1.74 ± 0.05	0.36 ± 0.04
S6	4.49	122 ± 31	1.53 ± 0.08	0.12 ± 0.00	1.65 ± 0.09	3.09 ± 0.24	0.33 ± 0.10
S7	4.04	103 ± 20	1.45 ± 0.09	0.13 ± 0.01	1.58 ± 0.10	3.35 ± 0.25	0.13 ± 0.07
S8	3.84	145 ± 7	1.50 ± 0.12	0.15 ± 0.02	1.64 ± 0.14	1.95 ± 0.14	0.06 ± 0.01
S9	3.66	145 ± 7	1.50 ± 0.12	0.15 ± 0.02	1.64 ± 0.14	1.95 ± 0.14	0.06 ± 0.01
S10	3.89	218 ± 4	1.33 ± 0.04	0.13 ± 0.01	1.46 ± 0.04	1.94 ± 0.03	0.06 ± 0.01
S11	3.83	151 ± 9	1.52 ± 0.16	0.17 ± 0.03	1.70 ± 0.19	nd	0.14 ± 0.09
S12	nw	nw	nw	nw	nw	nw	nw
S13	3.85	141 ± 10	1.57 ± 0.07	0.12 ± 0.02	1.69 ± 0.08	2.54 ± 0.14	0.08 ± 0.00
S14	3.91	140 ± 27	1.31 ± 0.09	0.20 ± 0.05	1.51 ± 0.13	1.95 ± 0.25	0.16 ± 0.04
S15	4.21	141 ± 44	1.43 ± 0.11	0.14 ± 0.01	1.57 ± 0.11	3.03 ± 0.21	2.69 ± 0.78
S16	3.81	155 ± 10	1.41 ± 0.08	0.15 ± 0.01	1.55 ± 0.09	1.99 ± 0.07	0.03 ± 0.00
S17	3.75	179 ± 6	1.50 ± 0.08	0.14 ± 0.01	1.64 ± 0.08	2.21 ± 0.03	0.11 ± 0.03
S18	3.83	148 ± 6	1.43 ± 0.11	0.30 ± 0.16	1.73 ± 0.18	2.72 ± 0.82	0.14 ± 0.07
S19	3.73	188 ± 12	1.41 ± 0.09	0.13 ± 0.01	1.53 ± 0.10	nd	1.39 ± 0.26
S20	4.04	90 ± 5	1.22 ± 0.08	0.12 ± 0.01	1.34 ± 0.09	nd	0.03 ± 0.01

Table 2. Slopes and associated *p* values of linear regressions of plant tissue N and S concentrations (m/g/yr) as a function of time, over the five years of the study. Statistically significant slopes are highlighted in bold, italic text.

		N		S		C:N		C:S	
Species	Site	mg/g/yr	*p*	mg/g/yr	*p*	yr^{-1}	*p*	yr^{-1}	*p*
Sphagnum fuscum	Mildred	***1.06 ± 0.15***	<0.0001	- 0.043 ± 0.048	0.3703	***-3.13 ± 0.40***	<0.0001	-7.8 ± 4.6	0.0928
	JPH4	***0.87 ± 0.17***	<0.0001	***0.049 ± 0.020***	0.0171	***-2.32± 0.45***	<0.0001	-7.2 ± 4.0	0.0715
	McKay	***0.94 ± 0.11***	<0.0001	***-0.081 ± 0.015***	<0.0001	***-2.53 ± 0.34***	<0.0001	***18.1 ± 3.2***	<0.0001
	McMurray	***0.31 ± 0.10***	0.0019	***-0.091 ± 0.012***	<0.0001	***-0.95 ± 0.36***	0.0088	***28.4 ± 3.9***	<0.0001
	Anzac	***0.38 ± 0.11***	0.0003	***-0.079 ± 0.012***	<0.0001	***-0.78 ± 0.32***	0.0155	***30.1 ± 4.9***	<0.0001
	Utikuma	-0.14 ± 0.39	0.7185	***-0.264 ± 0.042***	<0.0001	0.77 ± 1.40	0.5841	***124.1 ± 21.1***	<0.0001
Sphagnum capillifolium	Mildred	***0.54 ± 0.17***	0.0028	***-0.08 ± 0.04***	0.0409	***-1.49 ± 0.42***	0.0006	***12.4 ± 6.1***	0.0437
	JPH4	-0.16 ± 0.18	0.3711	-0.00 ± 0.03	0.9907	-0.60 ± 0.42	0.1555	-9.8 ± 6.3	0.1256
	McKay	***0.67 ± 0.13***	<0.0001	***-0.04 ± 0.02***	0.0322	***-2.01 ± 0.32***	<0.0001	4.3 ± 4.7	0.3541
	McMurray	0.24 ± 0.12	0.0613	***-0.05 ± 0.01***	0.0004	***-1.30 ± 0.38***	0.0006	***12.3 ± 6.1***	0.0449
	Anzac	***0.47 ± 0.14***	0.0008	***-0.03 ± 0.01***	0.0456	***-1.80 ± 0.35***	<0.0001	4.4 ± 5.2	0.3993
	Utikuma	0.73 ± 0.37	0.0760	***-1.91 ± 0.06***	0.0024	***-3.68 ± 1.40***	0.0097	***69.1 ± 22.1***	0.0033
Cladina mitis	Mildred	***0.29 ± 0.08***	0.0003	***-0.058 ± 0.010***	<0.0001	***-3.13 ± 0.95***	0.0013	***42.7 ± 7.2***	<0.0001
	JPH4	0.16 ± 0.13	0.2349	0.011 ± 0.012	0.3879	-2.05 ± 1.60	0.2009	***18.0 ± 11.1***	0.1067
	McKay	***0.21 ± 0.06***	0.0004	***-0.046 ± 0.007***	<0.0001	***-2.86 ± 1.01***	0.0052	***49.4 ± 7.3***	<0.0001
	McMurray	0.04 ± 0.06	0.5014	***-0.050 ± 0.008***	<0.0001	-0.79 ± 1.09	0.4713	***55.4 ± 10.9***	0.0001
	Anzac	***0.35 ± 0.06***	<0.0001	***-0.303 ± 0.009***	0.0010	***-4.50 ± 1.03***	<0.0001	***50.8 ± 11.5***	<0.0001
	Utikuma	0.46 ± 0.28	0.1116	***-0.130 ± 0.030***	<0.0001	***-12.08 ± 5.36***	0.0323	***227.7 ± 42.1***	<0.0001
Evernia mesomorpha	Mildred	***0.34 ± 0.10***	0.0010	***-0.111 ± 0.013***	<0.0001	***-1.04 ± 0.38***	0.0078	***16.9 ± 2.9***	<0.0001
	JPH4	0.08 ± 0.12	0.4504	0.003 ± 0.022	0.9045	***-1.02 ± 0.53***	0.0561	-3.2 ± 4.9	0.5264
	McKay	0.13 ± 0.07	0.0841	***-0.081 ± 0.015***	<0.0001	-0.82 ± 0.44	0.0640	***20.0 ± 3.7***	<0.0001
	McMurray	-0.05 ± 0.06	0.4261	***-0.095 ± 0.008***	<0.0001	0.32 ± 0.40	0.4233	***33.8 ± 2.9***	<0.0001
	Anzac	***-0.36 ± 0.07***	<0.0001	***-0.106 ± 0.010***	<0.0001	***2.28 ± 0.44***	<0.0001	42.7 ± 4.1	<0.0001
	Utikuma	***-0.60 ± 0.23***	0.0112	***-0.253 ± 0.036***	<0.0001	***6.84 ± 2.66***	0.0133	***131.2 ± 16.7***	<0.0001
Ledum groenlandicum	Mildred	0.43 ± 0.31	0.1716	***-0.059 ± 0.025***	0.0202	-0.49 ± 0.49	0.3235	***29.1 ± 7.3***	0.0001
	JPH4	-0.77 ± 0.52	0.1484	-0.052± 0.033	0.1126	0.59 ± 0.71	0.4052	5.5 ± 9.7	0.5737
	McKay	-0.05 ± 0.30	0.8588	-0.039 ± 0.021	0.0650	-0.20 ± 0.40	0.6278	***12.3 ± 5.7***	0.0483
	McMurray	-0.10 ± 0.35	0.7819	***-0.057 ± 0.024***	0.0178	-0.02 ± 0.48	0.9627	23.4 ± 6.9	0.0010
	Anzac	0.32 ± 0.31	0.3103	-0.046 ± 0.027	0.0338	***-0.84 ± 0.41***	0.0390	***14.2 ± 5.6***	0.0122
	Utikuma	0.71 ± 0.72	0.3288	-0.096 ± 0.054	0.0801	-1.44 ± 1.24	0.2528	20.4 ± 22.1	0.3622

Species	Site	N		S		C:N		C:S	
		mg/g/yr	p	mg/g/yr	p	yr^{-1}	p	yr^{-1}	p
Picea mariana	Mildred	***0.63 ± 0.23***	0.0071	***-0.058 ± 0.016***	0.0005	-3.60 ± 1.06	0.0010	***19.2 ± 8.5***	0.0255
	JPH4	-0.39 ± 0.40	0.3264	-0.040 ± 0.023	0.0894	2.89 ± 1.64	0.0798	***22.8 ± 9.1***	0.0134
	McKay	-0.01 ± 0.28	0.9700	***-0.081 ± 0.018***	<0.0001	0.53 ± 1.15	0.6443	***51.3 ± 8.1***	<0.0001
	McMurray	0.10 ± 0.29	0.7212	***-0.077± 0.018***	<0.0001	-0.13 ± 1.12	0.9113	***56.8 ± 10.3***	<0.0001
	Anzac	-0.07 ± 0.33	0.8413	***-0.093 ± 0.018***	<0.0001	1.07 ± 1.24	0.3929	***69.9 ± 9.1***	<0.0001
	Utikuma	1.36 ± 1.41	0.3391	***-0.150 ± 0.071***	0.0395	***-1.35 ± 4.93***	0.7863	***169.0 ± 39.6***	0.0001
*Picea mariana**	Mildred	***0.40 ± 0.10***	0.0002	***-0.075 ± 0.018***	<0.0001	***-2.65 ± 0.73***	0.0005	***19.5 ± 9.9***	0.0541
	JPH4	0.24 ± 0.13	0.0629	-0.016 ± 0.012	0.2115	-1.15 ± 1.07	0.2844	14.7 ± 7.4	0.0511
	McKay	-0.02 ± 0.11	0.8686	***-0.089 ± 0.014***	<0.0001	-0.14 ± 0.73	0.8464	***55.9 ± 7.0***	<0.0001
	McMurray	0.04 ± 0.11	0.7351	***-0.097 ± 0.013***	<0.0001	-0.49 ± 0.79	0.5407	***64.6 ± 9.3***	<0.0001
	Anzac	-0.15 ± 0.13	0.2439	***-0.098 ± 0.011***	<0.0001	0.35 ± 0.82	0.6713	***68.8 ± 7.2***	<0.0001
	Utikuma	***-1.40 ± 0.36***	0.0005	***-0.316 ± 0.027***	<0.0001	***10.18 ± 2.67***	0.0006	***259.4 ± 17.3***	<0.0001
Oxycoccos microcarpus	Mildred	***0.46 ± 0.15***	0.0027	***-0.049 ± 0.023***	0.0323	-2.41 ± 1.42	0.0993	***93.4 ± 13.7***	<0.0001
	JPH4	***1.10 ± 0.13***	<0.0001	***-0.066 ± 0.014***	0.0059	***-2.98 ± 0.37***	<0.0001	***29.0 ± 4.5***	<0.0001
	McKay	***1.43 ± 0.10***	<0.0001	***-0.027 ± 0.009***	0.0040	***-4.44 ± 0.33***	<0.0001	***18.5 ± 3.7***	<0.0001
	McMurray	***1.05 ± 0.09***	<0.0001	***-0.033 ± 0.008***	<0.0001	***-3.83 ± 0.36***	<0.0001	***25.9 ± 4.6***	<0.0001
	Anzac	***1.07 ± 0.08***	<0.0001	***-0.034 ± 0.010***	0.0009	***-4.09 ± 0.37***	<0.0001	***23.4 ± 5.1***	<0.0001
	Utikuma	0.44 ± 0.47	0.3607	***-0.183 ± 0.025***	<0.0001	***-6.84 ± 2.66***	0.0133	***131.2 ± 16.7***	<0.0001
Vaccinium vitis-idaea	Mildred	-0.40 ± 0.26	0.1288	***-0.097 ± 0.019***	<0.0001	***1.81 ± 0.84***	0.0346	***17.0 ± 3.6***	<0.0001
	JPH4	0.13 ± 0.18	0.4766	***-0.070 ± 0.022***	0.0019	-1.11 ± 0.59	0.0651	***17.5 ± 5.3***	0.0011
	McKay	0.06 ± 0.14	0.6568	***-0.093 ± 0.014***	<0.0001	-0.68± 0.47	0.1533	***18.1 ± 3.2***	<0.0001
	McMurray	-0.09 ± 0.15	0.5652	***-0.065 ± 0.013***	<0.0001	-0.56 ± 0.53	0.2939	***13.1 ± 3.2***	<0.0001
	Anzac	-0.21 ± 0.11	0.0606	***-0.091 ± 0.012***	<0.0001	0.62 ± 0.43	0.1496	***24.0 ± 3.5***	<0.0001
	Utikuma	***-1.22 ± 0.42***	0.0052	***-0.199 ± 0.047***	0.0001	***5.29 ± 1.53***	0.0010	***60.2 ± 13.8***	<0.0001
Rubus chamaemorus	Mildred	-0.19 ± 0.85	0.8205	***-0.194 ± 0.090***	0.0367	0.18 ± 0.68	0.7951	***16.6 ± 5.5***	0.0041
	JPH4	0.94 ± 0.58	0.1072	-0.012 ± 0.059	0.8450	-0.66 ± 0.43	0.1300	0.7 ± 7.3	0.9263
	McKay	***1.81 ± 0.44***	<0.0001	-0.045 ± 0.030	0.1331	***-1.14 ± 0.33***	0.0008	6.8 ± 5.3	0.1972
	McMurray	***1.35 ± 0.48***	0.0058	0.009 ± 0.030	0.7620	***-1.31 ± 0.50***	0.0105	0.0 ± 0.0	0.9265
	Anzac	***1.69 ± 0.52***	0.0015	-0.042 ± 0.039	0.2843	-0.90 ± 0.31	0.0047	7.6 ± 5.2	0.1504
	Utikuma	***-48.0 ± 7.4***	<0.0001	0.190 ± 0.122	0.1302	***46.3 ± 9.0***	0.0002	***624 ± 101***	<0.0001

Species	Site	N		S		C:N		C:S	
		mg/g/yr	p	mg/g/yr	p	yr^{-1}	p	yr^{-1}	p
Smilacina trifolia	Mildred	1.55 ± 1.01	0.1330	0.015 ± 0.069	0.8226	0.86 ± 0.49	0.0842	4.9 ± 6.9	0.9441
	JPH4	-0.35 ± 2.76	0.9014	***-0.466 ± 0.177***	0.0197	-0.02 ± 1.11	0.9858	***42.5 ± 16.6***	0.0226
	McKay	0.15 ± 0.61	0.8123	***-0.165 ± 0.042***	0.0002	-0.01 ± 0.25	0.9701	***14.4 ± 3.8***	0.0003
	McMurray	***1.25 ± 0.61***	0.0457	0.000 ± 0.039	0.9998	-0.43 ± 0.28	0.1244	**2.47** ± 4.35	0.5721
	Anzac	1.98 ± 1.66	0.2453	-.0002 ± .0003	0.4537	-2.26 ± 1.23	0.0779	17.7 ± 11.2	0.1294
	Utikuma	nd	nd	nd	nd	nd	nd	nd	nd

**Picea mariana* regressions excluding June data for each year, where N and S concentrations in needles exhibited distinct peaks in 2009-2012

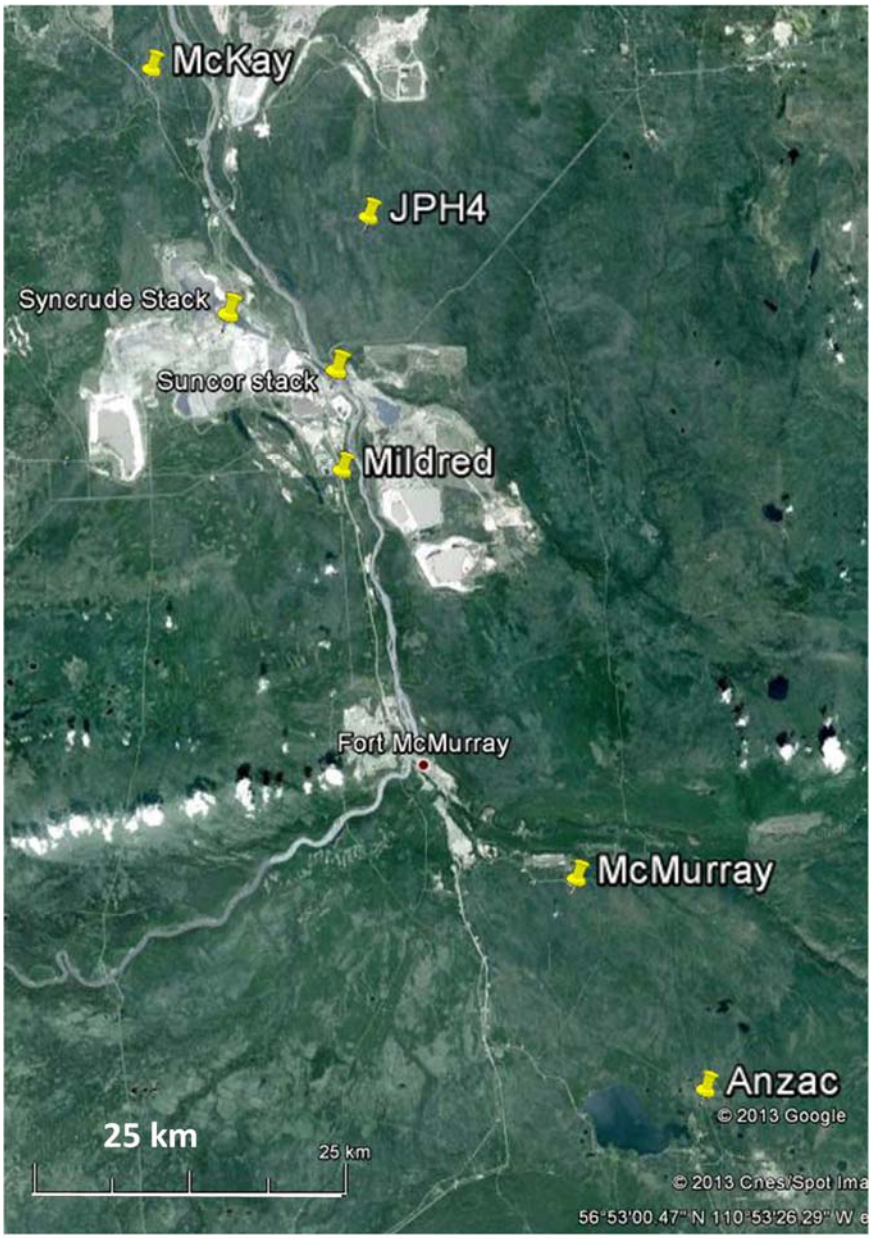

Fig. 1. Location of the four bog study sites within the Athabasca Oil Sands Region. From Google Earth©).

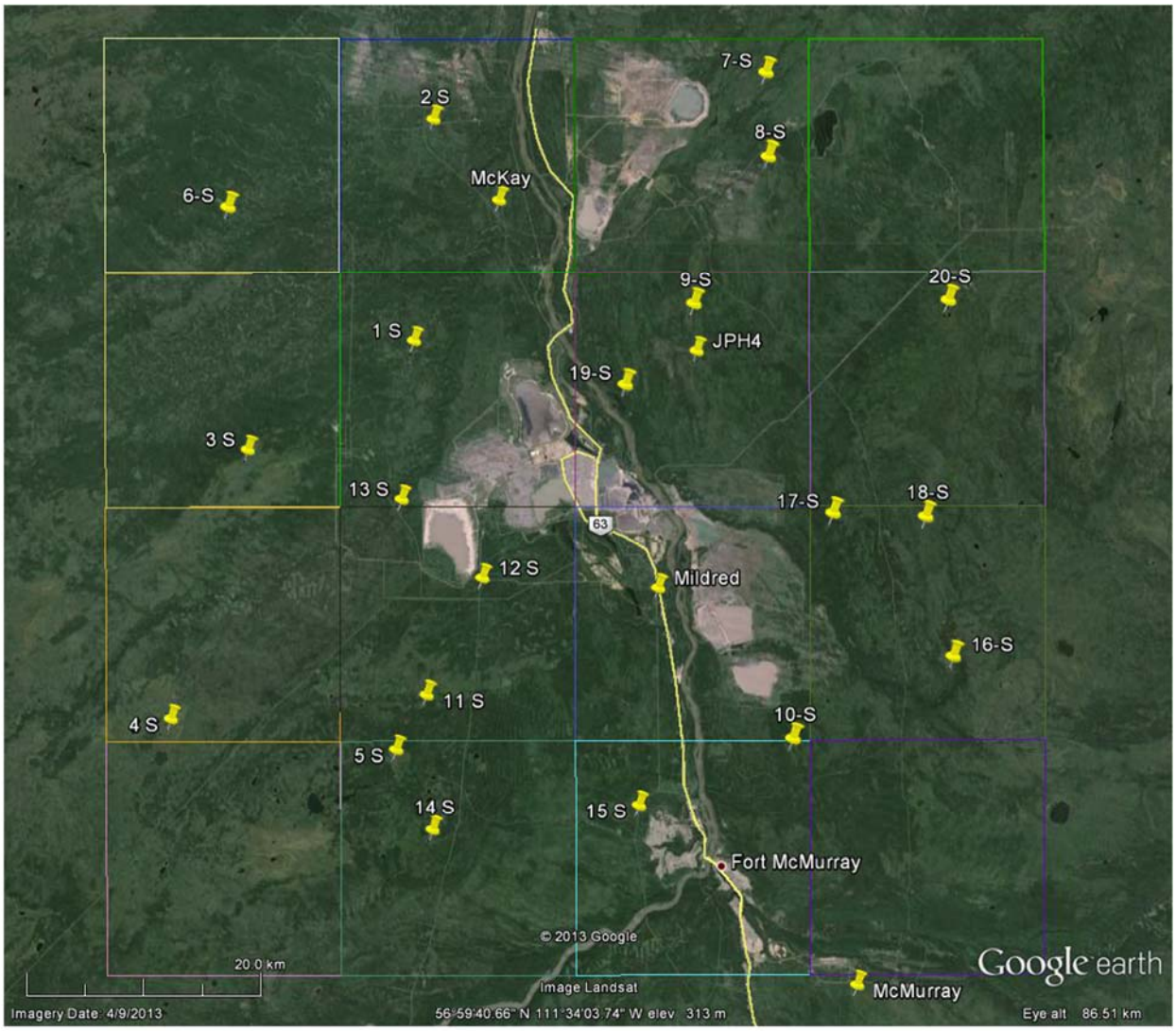

Fig. 2. The 80 km x 80 km grid, divided into 16 20 km x 20 km cells, and the location of the 20 sampling sites.

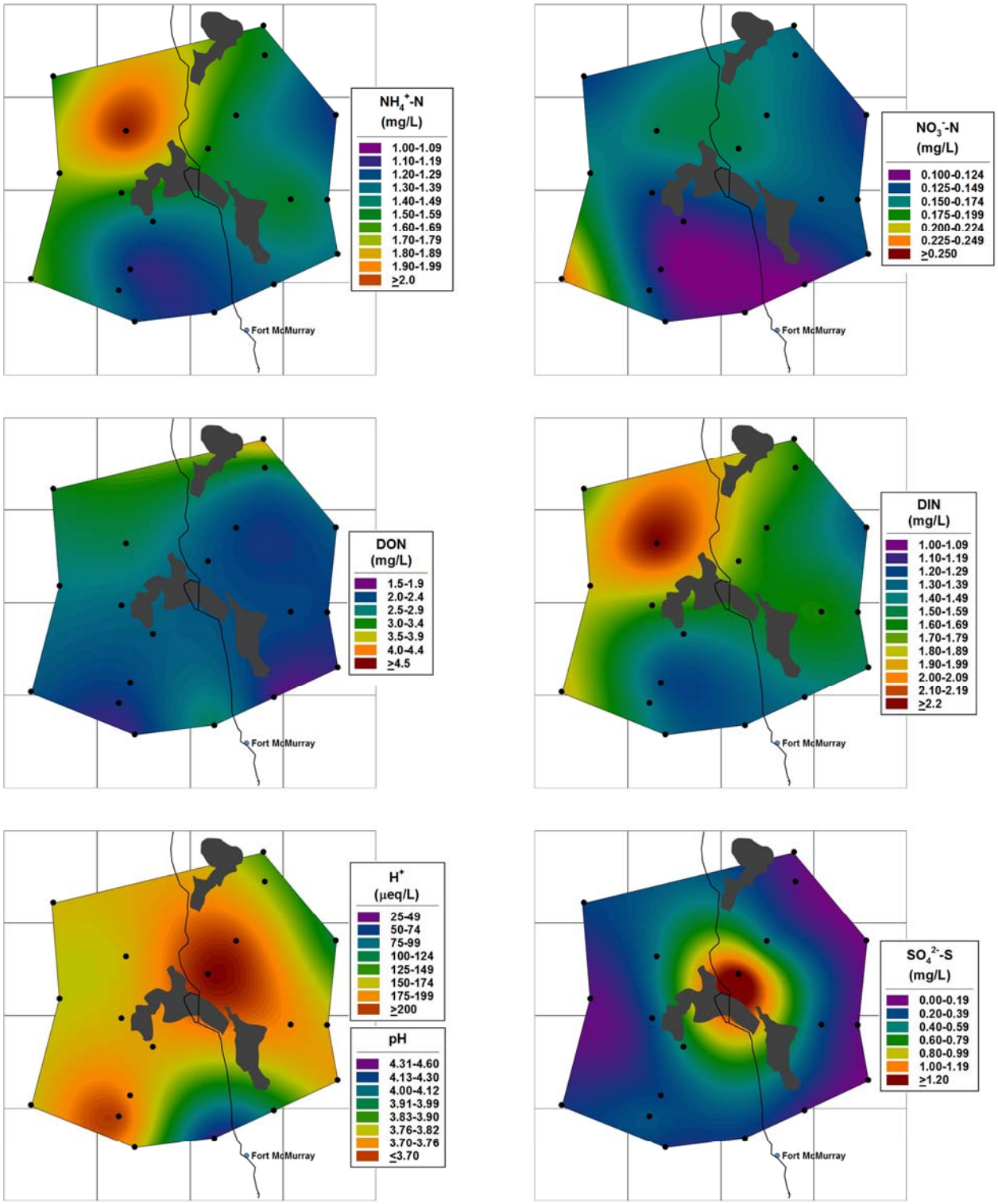

Fig. 3. Contour plots for water chemical parameters for pore water collected at the top of the water table. Dark grey shading indicates land area affected by oil sands surface mining activity.

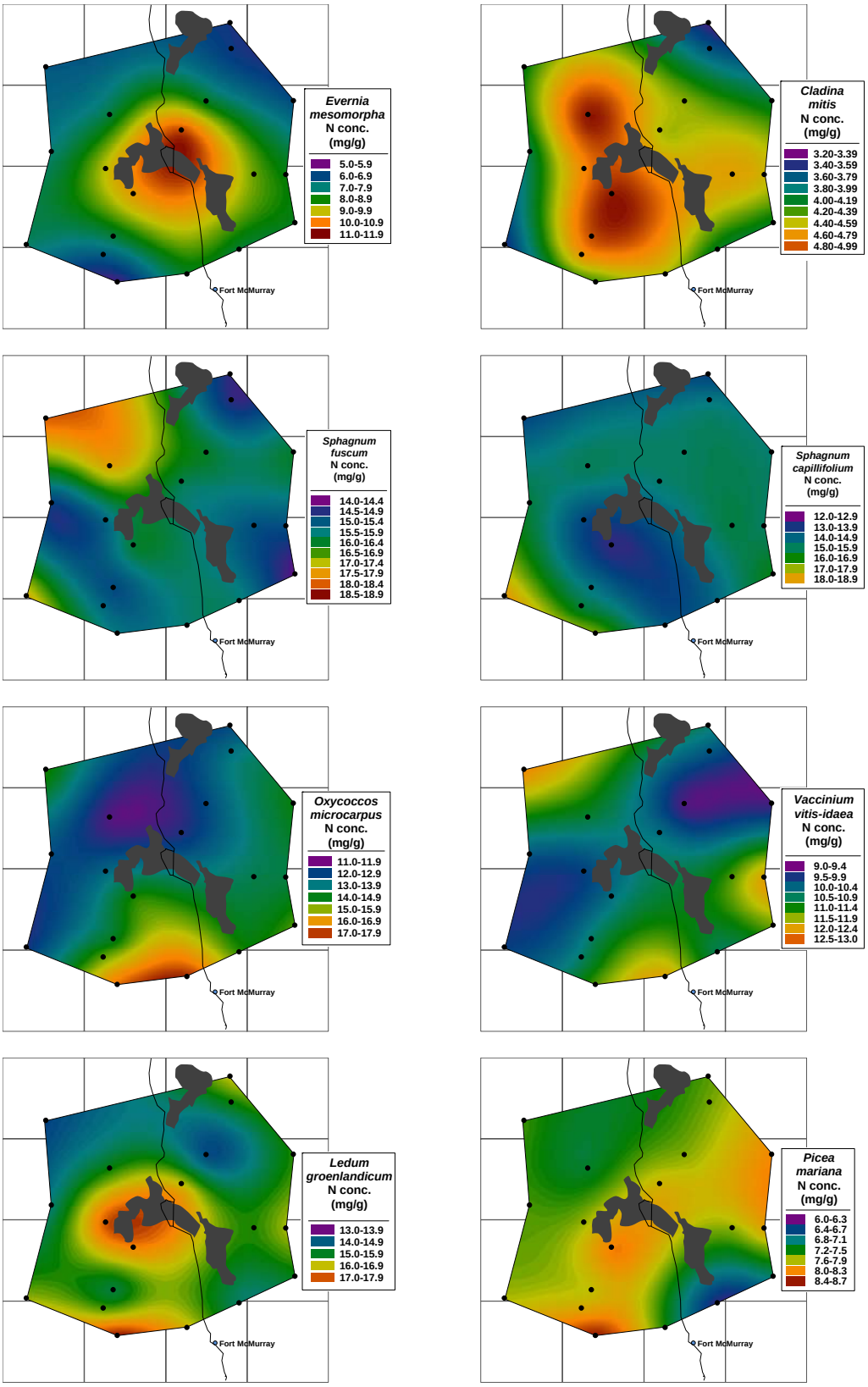

Fig. 4. Contour plots for N concentrations in plant tissues. Dark grey shading Indicates land area affected by oil sands surface mining activity

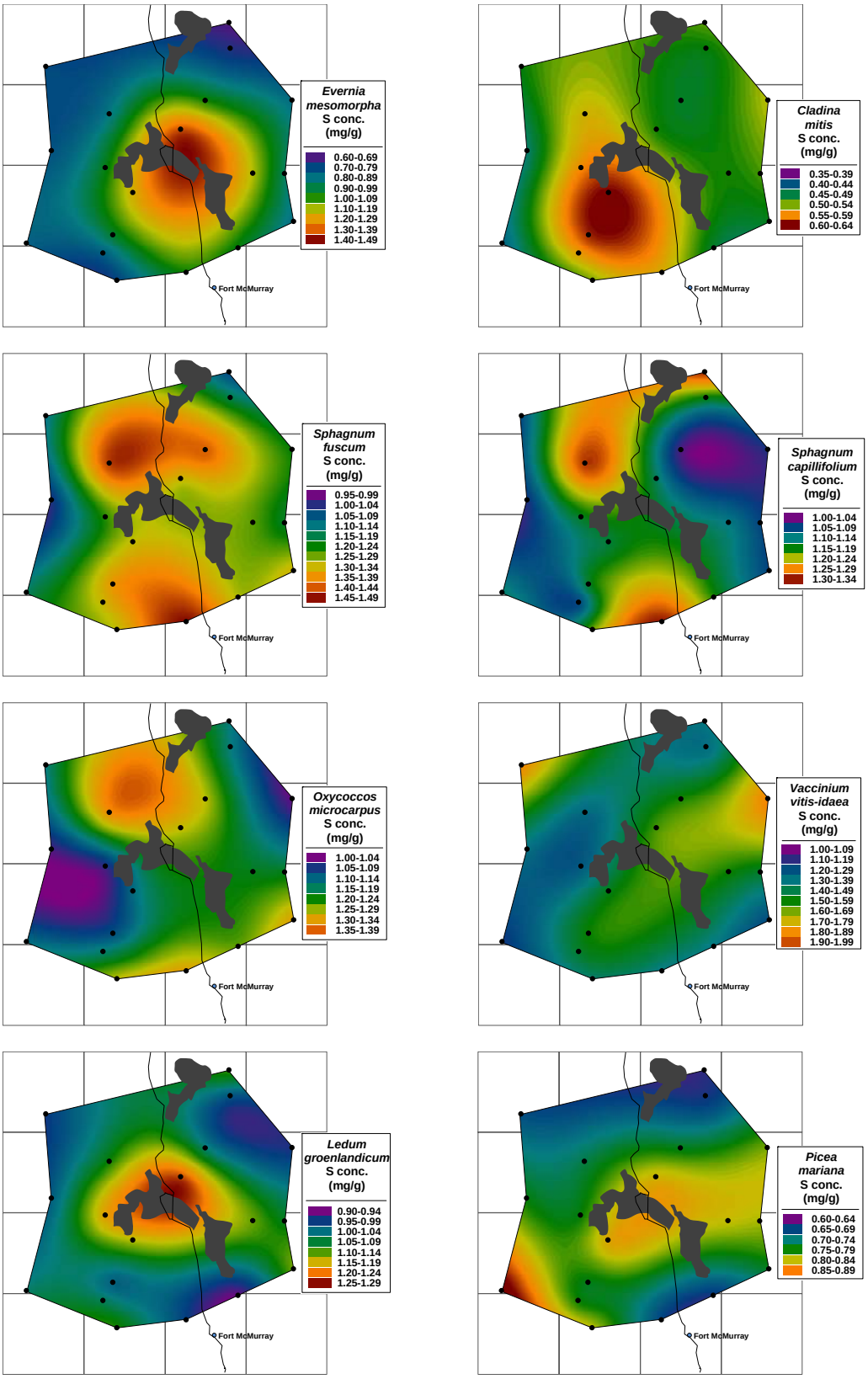

Fig. 5. Contour plots for S concentrations in plant tissues. Dark grey shading Indicates land area affected by oil sands surface mining activity

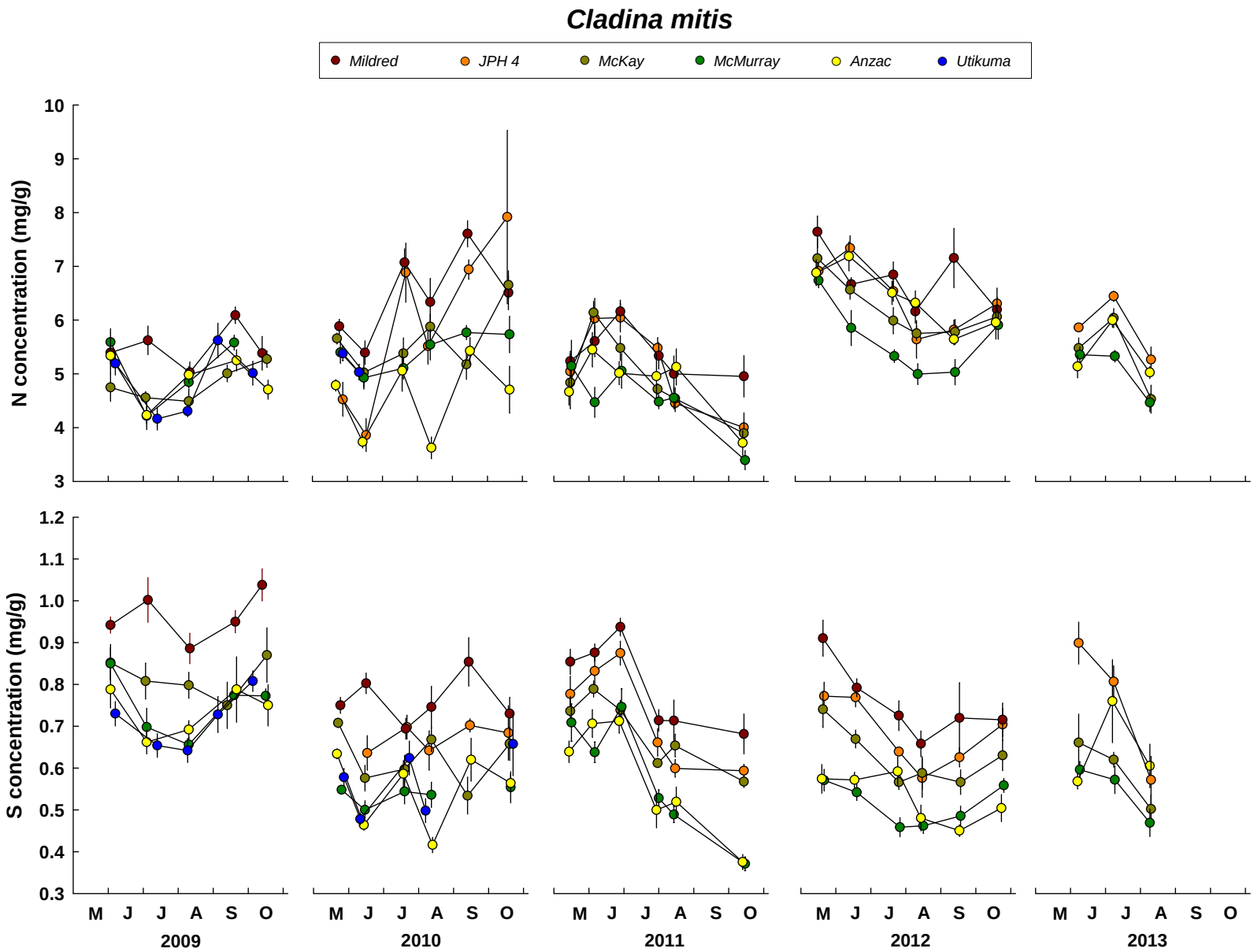

Fig. 6. Seasonal variation in N and S concentrations *Cladina mitis* for all sites over five years. Values are means ± standard errors; $n \leq 5$.

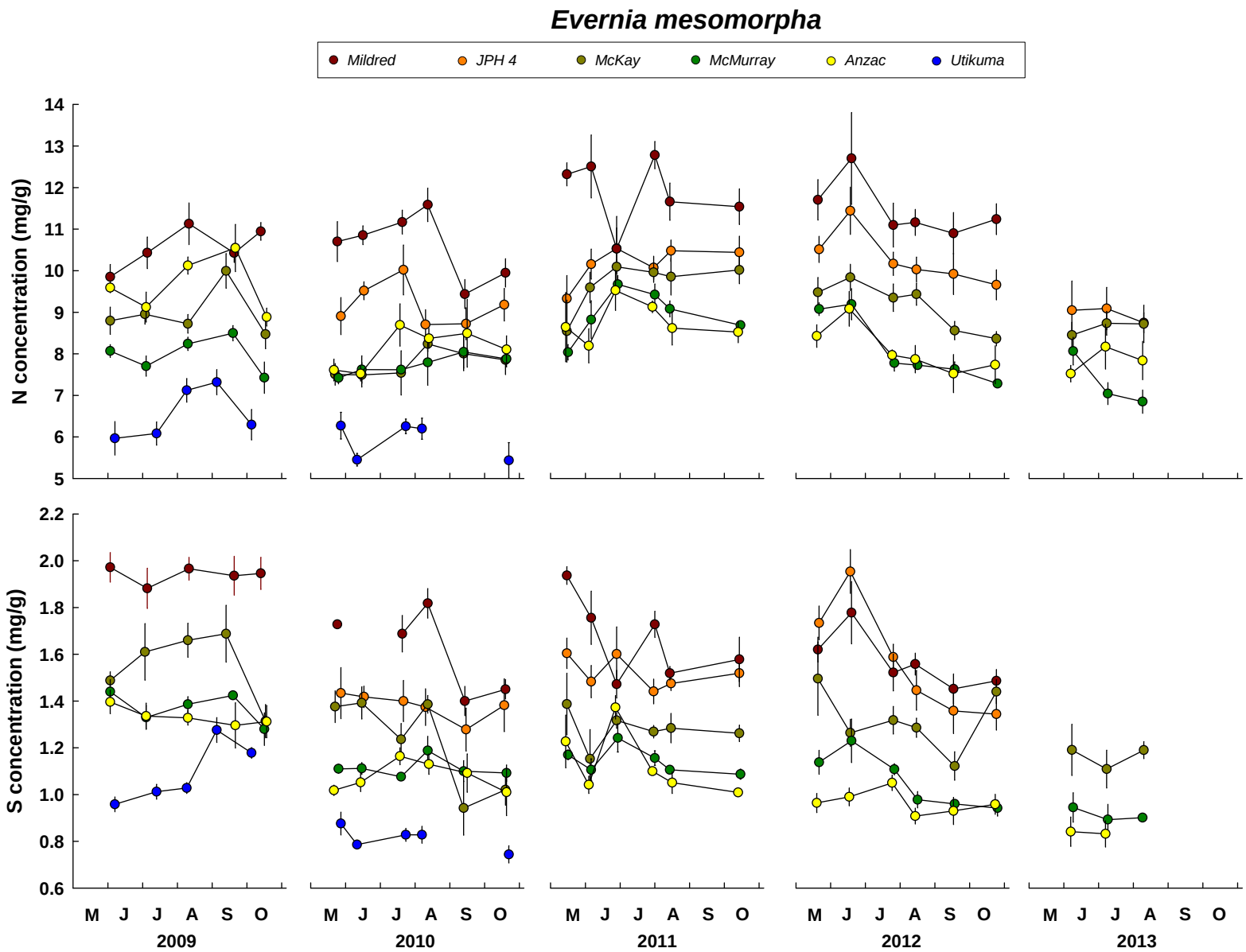

Fig. 7. Seasonal variation in N and S concentrations in *Evernia mesomorpha* for all sites over five years. Values are means ± standard errors; $n \leq 5$.

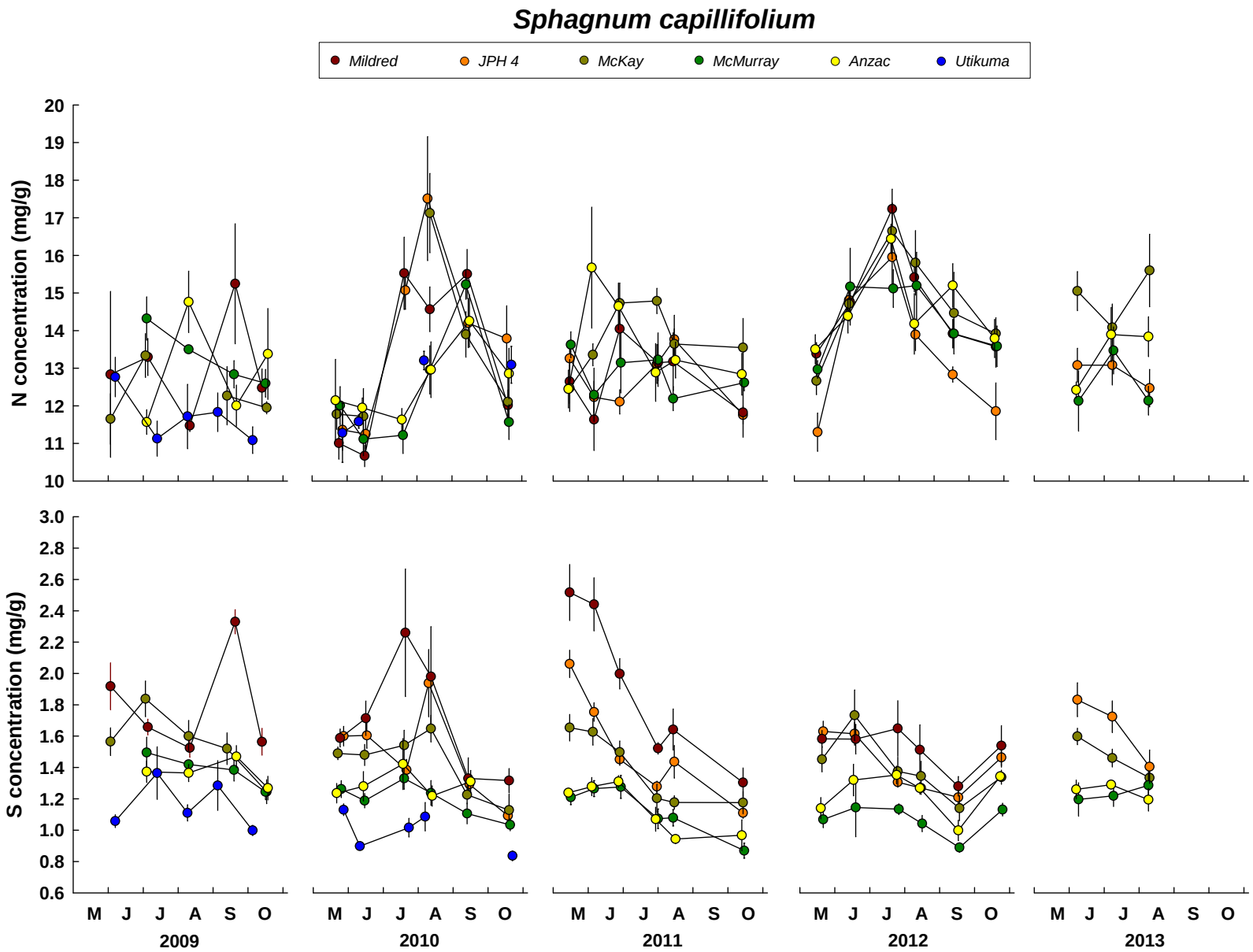

Fig. 8. Seasonal variation in N and S concentrations *Sphagnum capillifolium* for all sites over five years. Values are means ± standard errors; $n \leq 5$.

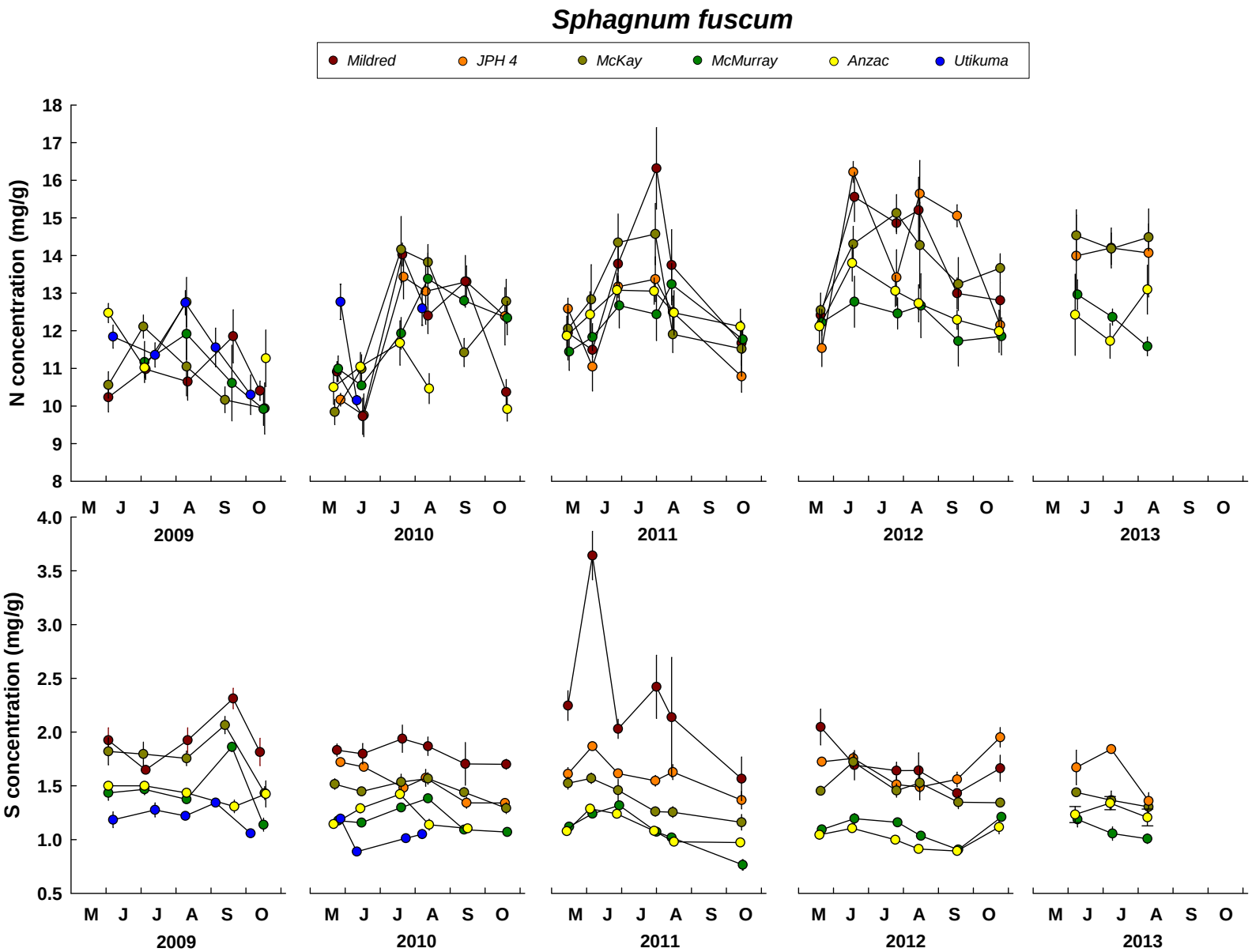

Fig. 9. Seasonal variation in N and S concentrations in *Sphagnum fuscum* for all sites over five years. Values are means ± standard errors; $n \leq 5$.

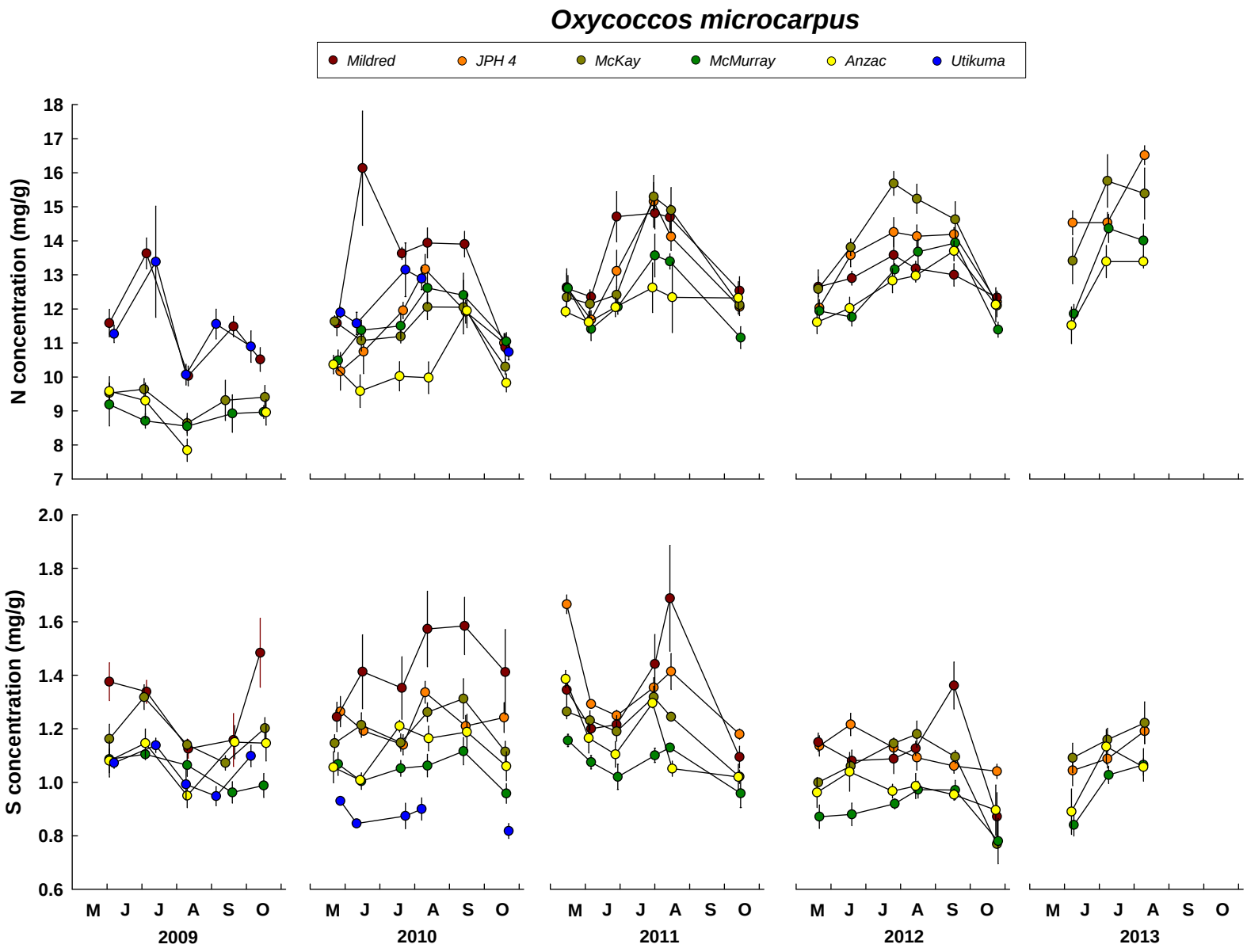

Fig. 10. Seasonal variation in N and S concentrations in *Oxycoccos microcarpus* for all sites over five years. Values are means ± standard errors; $n \leq 5$.

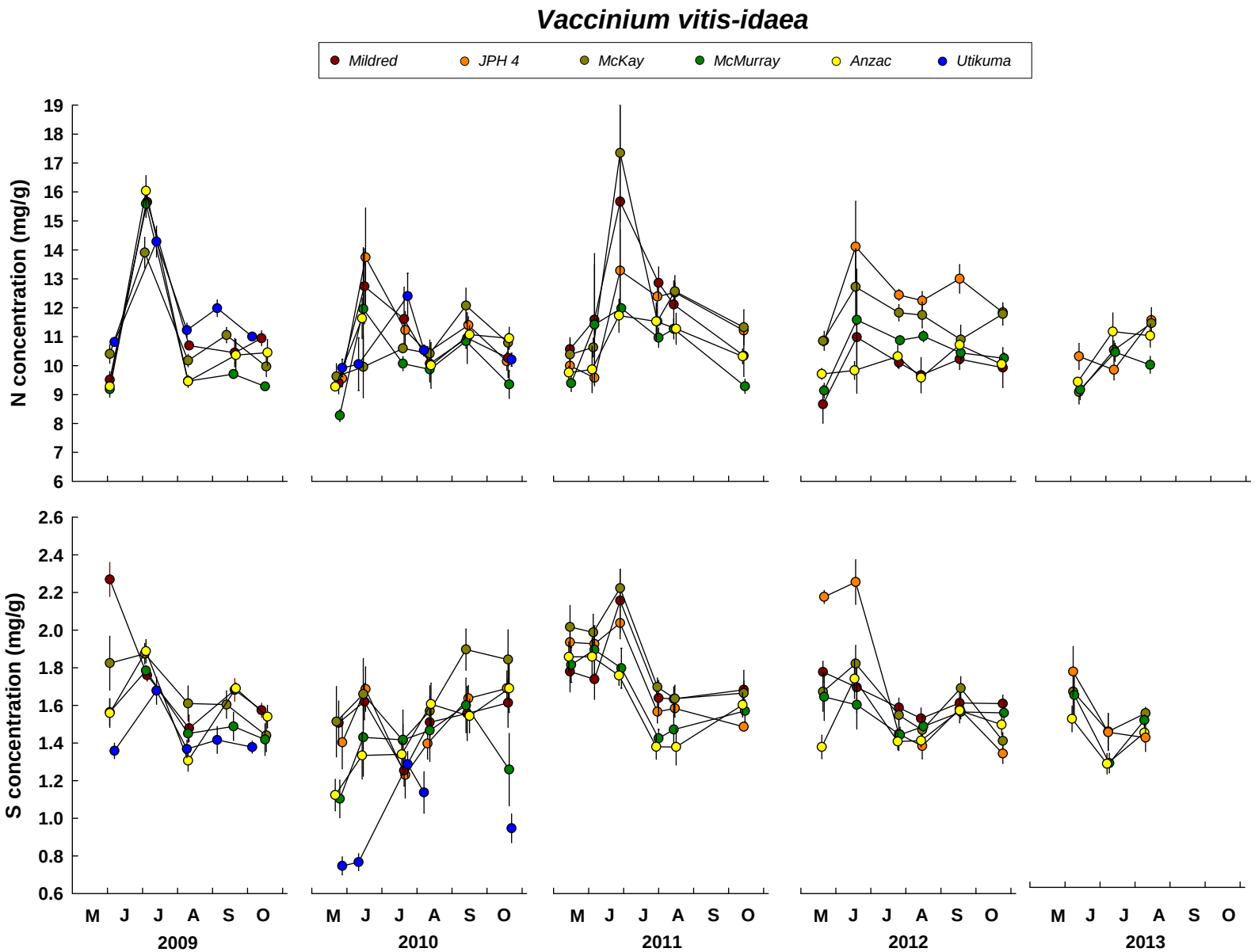

Fig. 11. Seasonal variation in N and S concentrations in *Vaccinium vitis-idaea* for all sites over five years. Values are means ± standard errors; $n \leq 5$.

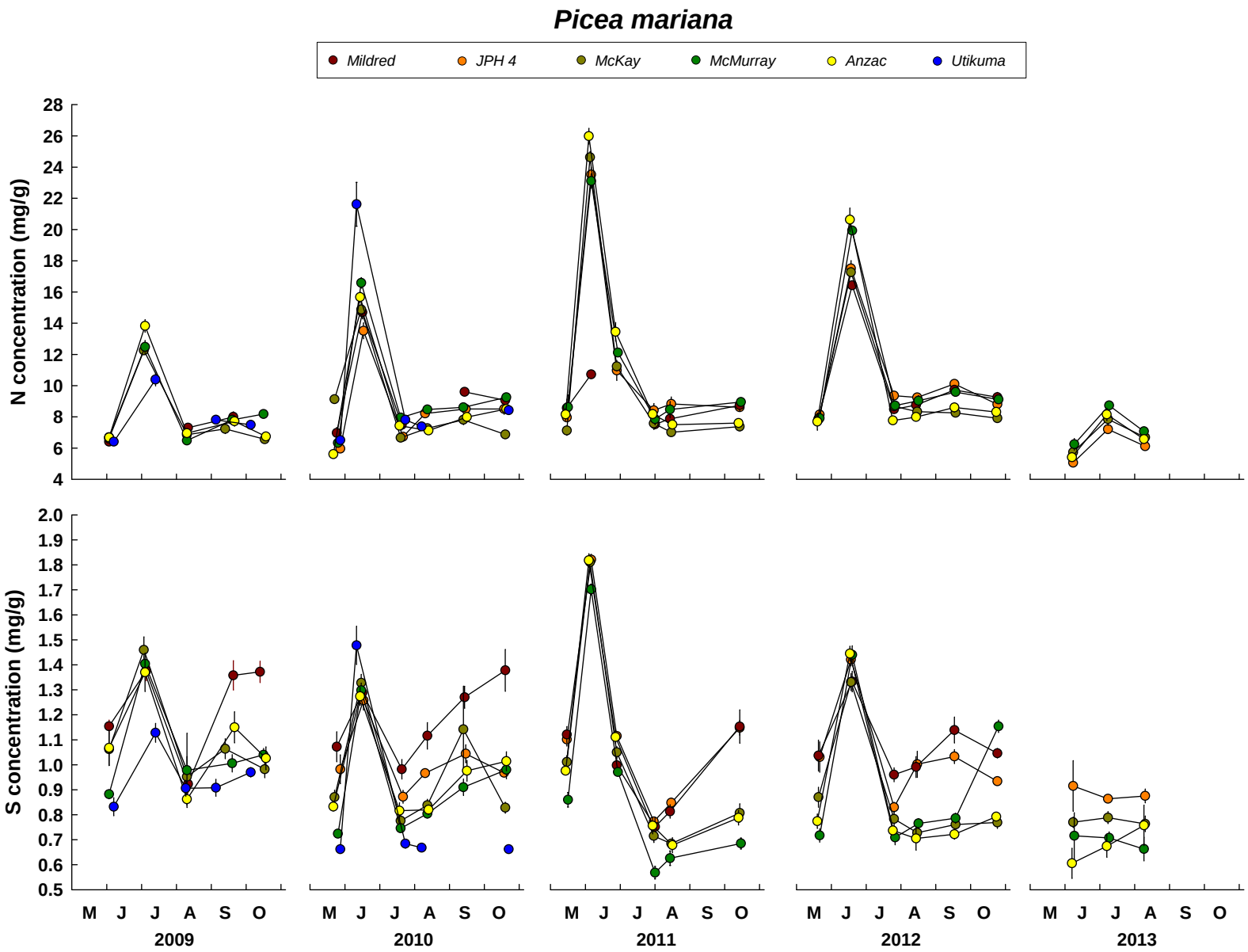

Fig. 12. Seasonal variation in N and S concentrations in *Picea mariana* for all sites over fiver years. Values are means ± standard errors; $n \leq 5$.

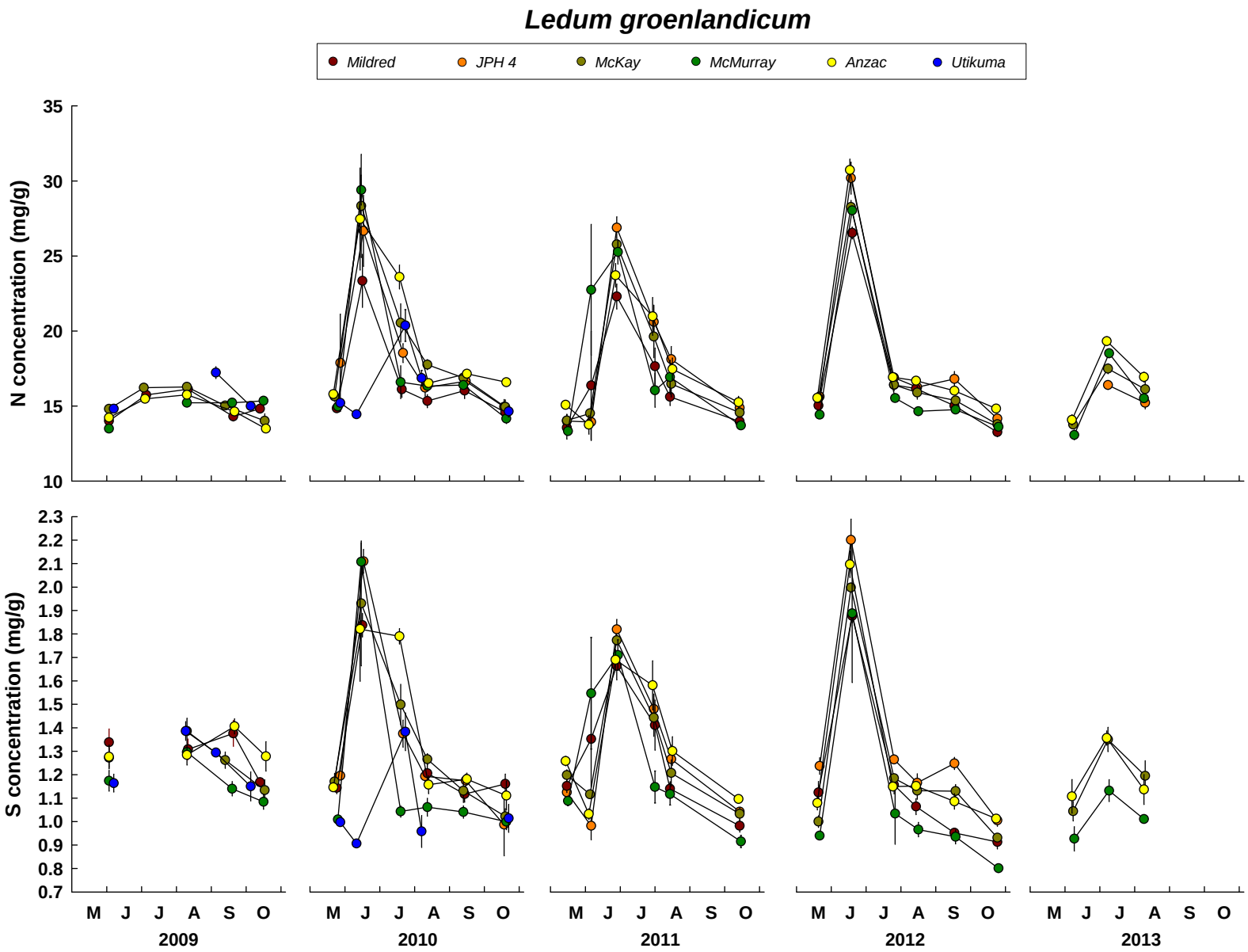

Fig. 13. Seasonal variation in N and S concentrations in *Ledum groenlandicum* for all sites over five years. Values are means ± standard errors; $n \leq 5$.

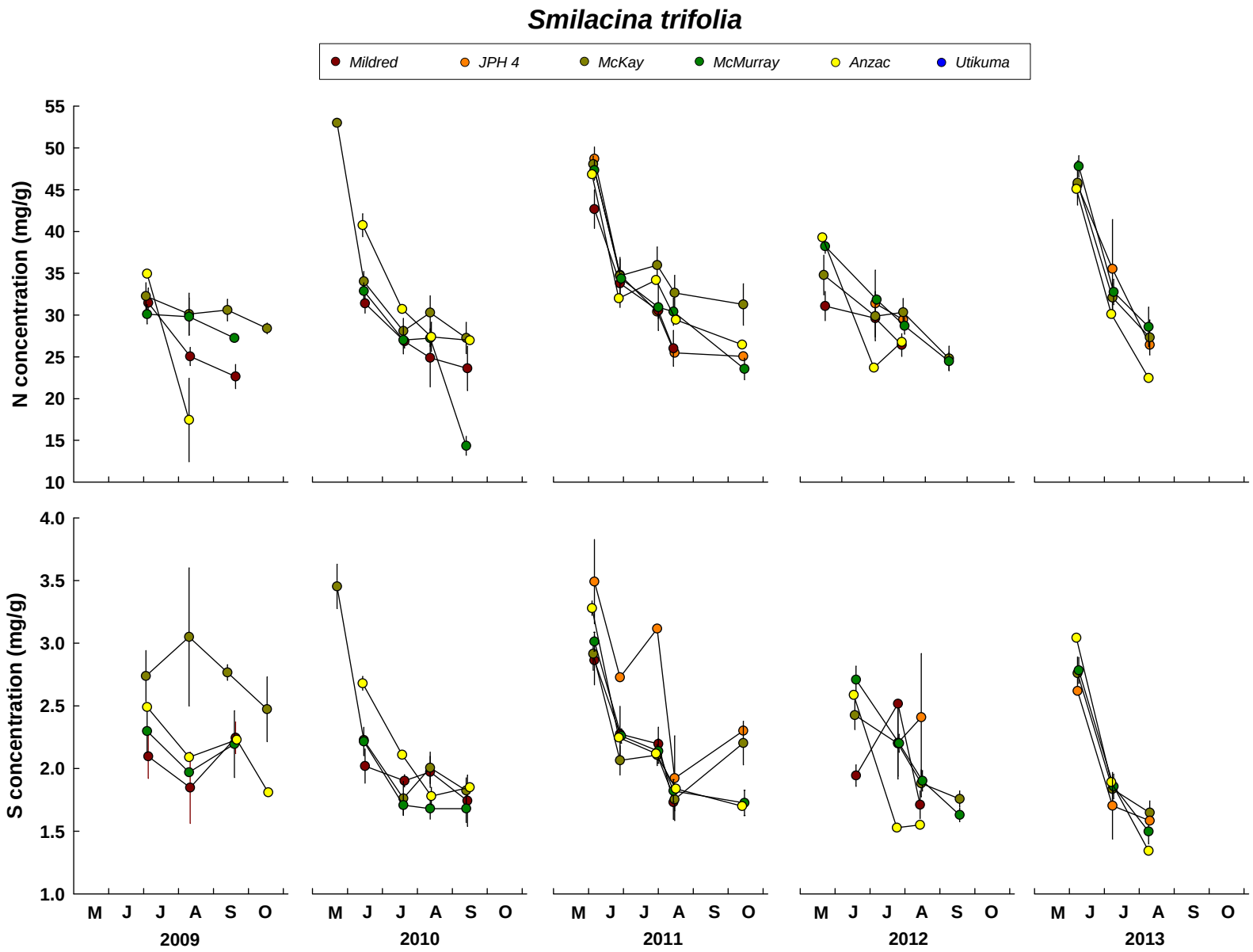

Fig. 14. Seasonal variation in N and S concentrations in *Smilacina trifolia* for all sites over five years. Values aremeans ± standard errors; $n \leq 5$.

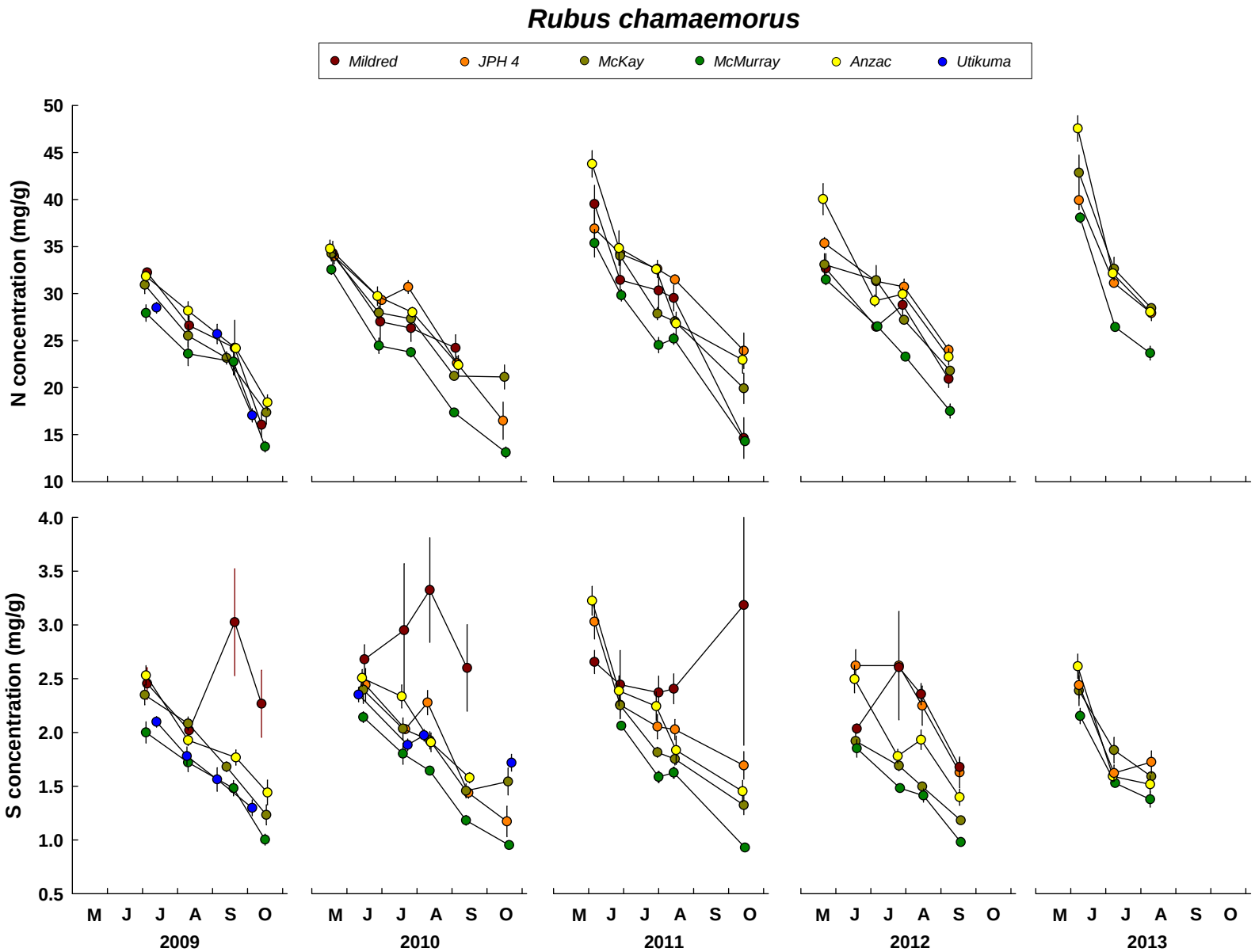

Fig. 15. Seasonal variation in N and S concentrations in *Rubus chamaemorus* for all sites over five years. Values are means ± standard errors; $n \leq 5$.