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SHORT COMMUNICATION

Nitrogen input into *Sphagnum* bogs via horizontal deposition: an estimate for N-polluted high-elevation sites

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Abstract Elevated atmospheric deposition of reactive nitrogen species, mainly nitrate (NO_3^-) and ammonium (NH_4^+), may negatively affect peatland carbon balance and thus contribute to climatic warming. It is difficult to take an accurate inventory of atmospheric N inputs into *Sphagnum*-dominated bogs, due to uncertainties in estimating horizontal deposition. At two mountain-top peat bogs (Czech Republic, Central Europe), we modelled N interception by replacing *S. cuspidatum* capitula with polyethylene (PE) strands of an identical surface area. After a 12-week exposure of the samplers to frequent spring and autumn fogs, we compared the amount of N captured by the PE strands (nitrate, ammonium, and organic N) with vertical N deposition via rainfall. Horizontal deposition added 35–69 % N to rainfall N input. The more polluted site exhibited a significantly higher horizontal N deposition than the less polluted site. We scaled our *S. cuspidatum* data to *S. capillifolium*, a species common in boreal regions in the form of densely packed carpets. Assuming a proportional decrease in N interception with decreasing *Sphagnum* surface, we estimated that horizontal deposition in *S. capillifolium* would add 12–45 % N to rainfall N input. Our data will help to close the N mass balance in peat bogs studies.

Keywords Fog · Deposition · *Sphagnum* · Nitrogen · Mass balance · Wetland

Peatlands store more nitrogen (N) per unit area than any other soil type (Limpens et al. 2003). There are concerns that increasing N inputs will lead to peat degradation, elevated emissions of greenhouse gases, and accelerated warming (Woodwell et al. 1995). Under high N deposition, *Sphagnum* is no longer able to prevent N leaching into deeper peat layers (Lamers et al. 2000). Consequently, roots of invading vascular plants oxygenate deeper peat and augment organic matter decomposition (Bragazza et al. 2013).

Construction of long-term N mass budgets in peat cores is one approach to assessing the response of peatlands to global change (Wu and Blodau 2013). Recently, two studies have observed "excess N accumulation" in vertical peat profiles in high-latitude wetlands, characterized by very low deposition of reactive nitrogen. Vile et al. (2014) reported excess N accumulation in ombrotrophic (rain-fed) bogs, whereas Larmola et al. (2014) arrived at a similar conclusion

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for minerotrophic fens. A comparison was made between the cumulative N deposition in recent decades, and the amount of N accumulated in ^{210}Pb-dated peat cores over the same period of time. Such studies assume that N deposition in remote unpolluted areas has never been greater than today. The authors measure present-day N fluxes via rainfall, and extrapolate the unknown contribution of N by horizontal deposition (fog interception and dry deposition). Most studies assume that horizontal deposition can be as high as vertical (Vile et al. 2014). Total deposition is calculated by doubling the vertical deposition to safely account for the unknown, horizontal portion. Clearly, excess N stored in peat can be better quantified after actual measurements of horizontal N deposition into peat bogs are performed. Nitrogen budget discrepancies can then be more rigorously identified and interpreted.

Our objective was to estimate the maximum contribution of horizontal deposition to total N deposition at two polluted ombrotrophic peat bogs in Central Europe. We hypothesized that in *Sphagnum*-dominated landscapes, N flux via horizontal deposition is smaller than N flux via vertical deposition. We also hypothesized that a more polluted site would exhibit a higher contribution of horizontal deposition to total N input, compared to a less polluted site. Both study sites are located in the Czech Republic (Fig. 1). The peat bogs of Kunstatska kaple (KB; north) and Blatenska slat (BS; south) are situated on mountain plateaux at elevations greater than 1,000 m (Table 1). KB is located close to a large cluster of coal burning power plants (Silesia, Poland), and was historically more polluted with sulfur and nitrogen oxides (SO_x and NO_x), compared to BS. Between 1970 and 1996, the area of KB (north) was affected by massive spruce die-back related to acid rain. In 1999, the area around SB (south) was affected by spruce defoliation caused by a bark beetle infestation. Nitrogen deposition at both sites has been decreasing since the early 1990s (Novak et al. 2014a, b).

Fig. S1 in the Electronic Annex gives monthly data on the water table depth at three previously studied ombrotrophic bogs in the Czech Republic. The average water table depth across these sites during the growing season was 12 cm below the top of *Sphagnum* capitula. At KB and BS, the water table depth at the time of sampling was 7 cm below bog surface. At each of our study sites, we collected five typical *Sphagnum cuspidatum* plants. For planimetry, we considered 7-cm long *S. cuspidatum* plants. The number of leaves was counted under a binocular microscope (Nikon SMZ 800 N). The surface area of leaves and stems was approximated by triangles and cylinders. The surface area of individual leaves was measured using the NIS ELEMENTS AR 3.2 software on a Nikon Eclipse 600 polarizing microscope. Fig. S2 (Electronic Annex) gives an example of the planimetric procedure, along with a generalized mathematical formula for the calculation of *Sphagnum* surface. The surface of an average *Sphagnum* plant was multiplied by 175, the average number of *Sphagnum* plants per research plot (a 10-cm diameter circle; an average for three replicate plots). The calculated *S. cuspidatum* surface area per a 78.5-cm^2 research plot was 5,660 cm^2. The same

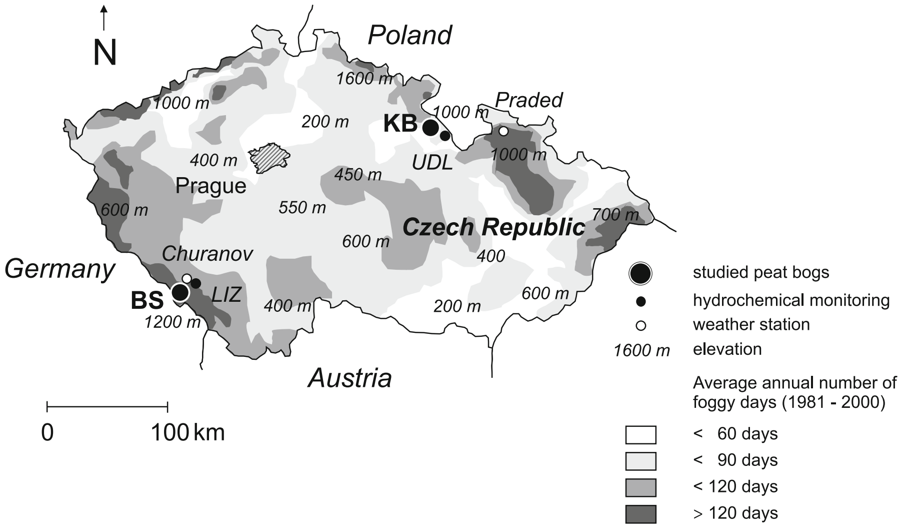

Fig. 1 Location of the study sites. High-elevation areas characterized by frequent fogs are marked with *dark grey colour*. Lowlands (*while* and *light gray*) are associated with fewer foggy days per year. Data by Czech Hydrometeorological Institute, Prague

Table 1 Study site characteristics

Site	Location	Elevation (m)	Mean annual temperature (°C)	Annual precipitation (mm)
Kunstatska kaple bog (KB)	50°14′N 16°27′E	1,040	4.5	1,320
Blatenska slat (BS)	48°58′N 13°27′E	1,260	3.5	1,150

surface area was modelled by 7 cm-high "bristles", formed by polyethylene (PE) strands. Loose vertical strands were prepared from mesh (0.3 by 0.3 mm openings) by removing horizontal strands. The surface area of the removed horizontal strands was disregarded in surface area calculations. At the bottom of the loose vertical strands, an intact stripe of the mesh was preserved for easier handling. 150-cm long, 8 cm-wide strips were wrinkled and folded at the bottom, using a nylon thread (Fig. S3, Electronic Annex). In all, a 13.5-meter long strip of the mesh was used in one fog collector, separated into nine bristles. The nine bristles completely filled a cylindrical PE funnel, 10-cm in diameter (Fig. S4, Electronic Annex). The funnel was attached to a 2-L PE bottle for solute collection. The top of the fog collector was situated at a similar level as the surrounding *Sphagnum* capitula. For the measurement of horizontal deposition, three replicate collectors were used at each site. Vertical deposition was simultaneously measured by a cylindrical PE funnel, 10-cm in diameter, at each site.

Our field experiment was carried out between April 19 and November 15, 2013. Fog and rain collectors were exposed to atmospheric deposition for 84 days at KB and 92 days at BS. One precipitation sampling was performed in spring, and two precipitation samplings were performed in autumn. No sampling took place between July and September because of lower fog occurrence. For the July–September period, fog collectors were removed from the research plots. At the end of each sampling, the PE samplers were thoroughly rinsed by DDW, the sample volume and the concentrations of NO_3^-, NH_4^+ and total organic nitrogen (TON), were measured. Nitrogen fluxes were calculated for a 12-week period. Horizontal N deposition was calculated by subtracting vertical deposition from total deposition onto fog collectors. Statistical analysis was performed using the PASW (Version 18) software by SPSS.

The more polluted site KB exhibited 3.4 times higher horizontal N deposition than the less polluted site BS (Fig. 2; *S. cuspidatum*). Relative to vertical N deposition, horizontal N deposition added 69 % N at KB and 35 % N at BS (Fig. 2). KB exhibited a higher contribution of horizontal deposition to total N input, compared to BS. Ammonium–N input was greater than nitrate–N input at both sites (Fig. 2). This indicates that agricultural N sources were more important at both sites than industrial N sources. Organic N represented the smallest N input, averaging 14 % of total N at both sites.

Our sampling design focussed on fog-rich, snow-free seasons (spring and autumn, *cf.* Fig. S5, Electronic Annex). Therefore, our estimated percentage of horizontally deposited N, relative to rainfall N, represents an upper limit. In the following paragraphs, we discuss some of the caveats intrinsic to our approach, and attempt to scale our temperate-zone *S. cuspidatum* results to boreal regions. Compared to our Central European study sites, peat bogs in the boreal zone are usually characterized by lower elevation, lower precipitation totals, fewer foggy days per year, less pollution, and more densely packed *Sphagnum* carpets.

Large segments of the boreal regions are located on the Canadian and Siberian Shield at elevations of 300–400 m, i.e., 600–700 m lower than our study sites. As seen in Fig. 1, fog frequency in Central Europe decreases with a decreasing elevation. In the Central part of the Czech Republic (elevation of 350 m), less than 60 foggy days per year were recorded by the Czech Hydrometeorological Institute (Fig. 1). This is about five times less than in the mountainous regions near our study sites (up to 300 foggy days; Fig. S5, Electronic Annex). Rainfall totals at our upland study sites and the lowland center of the country differ by a factor of 2.5 (ca. 1235 mm vs. 500 mm per year). For the KB–BS nitrogen pollution

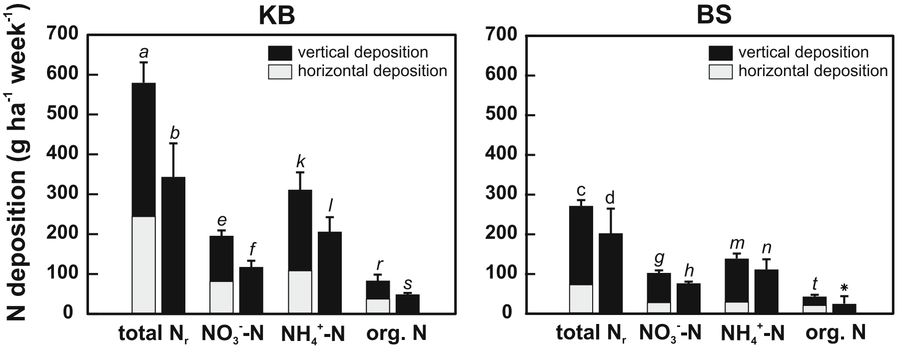

Fig. 2 A comparison of horizontal (*grey*) and vertical (*black*) N deposition in *Sphagnum* bogs (mean ± SE). The sum of horizontal and vertical deposition was measured by PE collectors with a high surface area, identical to that of locally growing *Sphagnum*. Vertical deposition was measured by rain collectors installed in an unforested area. Total $N_r = NO_3^-$-N + NH_4^+-N + organic N. For the statistical evaluation, a mixed model with covariant structure was used, corresponding to repeated measures (PASW 18 software by SPSS). KB and BS differed significantly in the sum of vertical and horizontal N deposition ($p = 0.001$). Deposition of NO_3^--N, NH_4^+-N and organic N also differed significantly ($p = 0.150$). *Different letters mark* significantly different values ($p < 0.05$). Only two replicate measurements were available for organic N at BS (*)

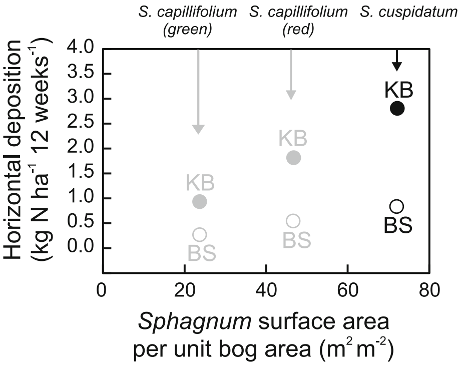

Fig. 3 Extrapolation of horizontal deposition from Central European peat bogs to *Sphagnum* species prevailing in boreal regions. Scaling from *S. cuspidatum* to *S. capillifolium* along a *Sphagnum* surface area gradient. See text for details

range, a proportional scaling down the fog-frequency gradient gives 14–28 % horizontal N deposition, relative to vertical N deposition. We note that in other parts of the world, low-elevation sites may be associated with a very high fog frequency, depending on local climatic conditions and the amount of condensation nuclei (dust particles) present in the atmosphere.

In unpolluted boreal regions, Vile et al. (2014) reported a vertical deposition of 1 kg N ha^{-1} $year^{-1}$. In Fig. 2, a less N-polluted site had a lower horizontal N deposition, relative to vertical N deposition, than a more N-polluted site (35 vs. 69 %). Accordingly, the unpolluted sites studied by Vile et al. (2014) may be characterized by a total N_r deposition of 1.35 kg ha^{-1} $year^{-1}$, or less. For a more rigorous extrapolation of our data (Fig. 2) to the pristine sites studied by Vile et al. (2014), horizontal deposition should be measured at more than just two sites along the N-pollution gradient.

We note that our estimates of *S. cuspidatum* surfaces may be too high for typical boreal *Sphagnum* species, such as *S. fuscum* and *S. capillifolium*. We were not able to identify *S. fuscum* at our relatively warm sites. We scaled our data to two forms of *S. capillifolium,* a red short form, typical of thick carpets (Fig. S6), and a green tall, “fluffy” form. Planimetry was carried out on both *S. capillifolium* forms, as described above ($n = 3$). The surface of the red dense-carpet form of *S. capillifolium* was measured only to the depth of 1.5 cm from the top of the capitula (*cf.,* Fig. S6, Electronic Annex), whereas the surface of the green *S. capillifolium* form was measured to the depth of 7 cm, similar to *S. cuspidatum.* It was unlikely that fog droplets (mean diameter of 10 µm; Pruppacher and Klett 1997) could freely penetrate deeper than 1.5 cm below the tops of the capitula of the red *S. capillifolium* form. The calculated *Sphagnum* surface area per 78.5-cm^2 research plot was 3,666 cm^2 for the red *S. capillifolium*, and 1,867 cm^2 for the green *S. capillifolium*. In Fig. 3, we scaled horizontal N deposition in *S. cuspidatum* to lower surface areas of *S. capillifolium.* Because plastic collector surfaces eliminated inner cycling of deposited N within aboveground *Sphagnum* biomass, we suggest that the amount of horizontally captured N may be directly

Table 2 Atmospheric deposition of reactive nitrogen

Year	UDL near KB (north)		LIZ near BS (south)	
	Open-area deposition (kg N ha^{-1} $year^{-1}$) ± SE	Open-area deposition	Open-area deposition (kg N ha^{-1} $year^{-1}$) ± SE	Spruce throughfall deposition
1994	25.9	58.0	5.0	6.8
1995	30.7	55.8	12.7	8.7
1996	39.6	51.3	16.9	10.3
1997	26.1	50.3	7.5	8.0
1998	53.5	70.0	6.8	7.3
1999	54.6	67.9	7.0	11.1
2000	16.5	81.7	10.2	17.6
2001	24.1	66.6	7.2	9.8
2002	34.6	48.0	6.8	11.1
2003	14.1	76.2	7.6	17.7
2004	15.3	53.1	7.0	10.5
2005	11.1	55.2	6.8	8.0
2006	16.2	41.5	7.2	8.2
2007	17.0	44.5	6.9	7.9
2008	14.6	54.2	4.5	6.0
2009	27.8	71.8	4.6	7.1
2010	20.3	26.5	6.9	5.8
2011	11.6	30.8	6.3	6.6
2012	11.4	28.2	8.1	7.8
2013	17.3	29.6	6.6	7.0
Mean	$24.1^{a} \pm 2.8$	$53.1^{b} \pm 3.6$	$7.6^{c} \pm 0.6$	$9.2^{d} \pm 0.7$

Data from the Hydrochemical Monitoring Network GEOMON. Nine collectors installed in a 10 by 10 m grid were used to sample spruce canopy throughfall, two collectors 10–30 m apart were used to sample open-area precipitation. Annual N fluxes were calculated from monthly observations of nitrate and ammonium deposition

Statistically different means *($p < 0.05$)* are marked with different letters (a, b, c, d; Wilcoxon paired test). For the location of UDL and LIZ see Fig. 1

SE standard error

proportional to *Sphagnum* surface area, i.e., land surface roughness. Horizontal N deposition in Fig. 3 (grey circles, *y*-axis) was then recalculated relative to the vertical N deposition. Horizontal N deposition may contribute between 12 % (minimum; green *S. capillifolium* at BS) and 45 % (maximum; red *S. capillifolium* at KB) to vertical N deposition. Generally, our scaling trials resulted in a horizontal N deposition not exceeding 45 % of the vertical N input.

Table 2 gives data on atmospheric N deposition in two spruce-forested catchments, situated in the vicinity of KB and BS, respectively (Fig. 1). Nitrogen input fluxes in the catchments have been measured monthly for a period of 20 years (1994–2013). In a spruce-*Sphagnum* analogy, open-area deposition exactly corresponds to vertical deposition, while forest canopy throughfall only vaguely corresponds to total deposition (PE fog collectors). Similar to our fog collectors, canopy throughfall includes fog interception and dry deposition, in addition to rainfall. In contrast to our fog collectors, canopy throughfall contains N newly leached from the foliage, while a portion of atmospherically deposited N is immobilized in the aboveground biomass (Gebauer et al. 1994). In the more polluted north, canopy throughfall added 120 % N relative to vertical N deposition (Table 2).

In the medium-polluted south, canopy throughfall added 21 % N relative to vertical N deposition, i.e., 10 times less. Spruce canopy throughfall exhibited a larger between-site variability in captured N, compared to PE collectors in peatlands (ten-fold vs. two-fold, *cf.,* Table 2; Fig. 2). We propose that forest canopy throughfall is not a suitable proxy for estimating horizontal N deposition into open *Sphagnum*-dominated peatlands in the Czech Republic. The amount of N immobilized in, and leached from, forest canopy may not be at a steady state. The N sink/source balance in aboveground forest biomass depends on a number of site-specific parameters, such as tree species, age and health status, N pollution level, and chemical speciation of incoming N. In peat-bog N mass balances, plastic constructs, which eliminate cycling of atmospherically derived N in aboveground biomass (*cf.,* Clymo 1963), may be a more promising proxy for estimating horizontal wet and dry deposition than actual *Sphagnum* throughfall collectors.

We note that our plastic constructs do not precisely mimic the forms of *Sphagnum* plants. In future studies, the effect of *Sphagnum* forms may be tested by a set of fog collectors with an identical surface area but contrasting surface geometry. It also remains to be seen whether interception of alkaline fog droplets is more efficient on an acidic *Sphagnum* surface than on a neutral surface of a PE construct. If so, this mechanism may affect the cumulative N deposition only at the begining of a foggy period. Over time, pH of the solutes on *Sphagnum* surface is likely to increase, converging to the pH of the atmospheric deposition.

We conclude that in reconstructions of long-term N deposition into open *Sphagnum* bogs, horizontal deposition should be considered as a significant additional N input. However, even in high-N deposition areas, this unmeasured horizontal N input is likely smaller than the measured vertical N input via rainfall. Preliminary scaling of Central European *S. cuspidatum* data to conditions typical of the boreal regions confirmed this conclusion. For biogeochemical modelling in *Sphagnum*-dominated landscapes, a factor of 1.7, or less, can be used to convert vertical to total N deposition. Our data support the conclusions by Vile et al. (2014) who argued that horizontal N deposition was too low to explain excess N storage in peat and invoked high N_2 fixation rates in pristine wetlands.

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References

Bohdalkova L, Curik J, Kubena AA et al (2013) Dynamics of methane fluxes from two peat bogs in the Ore Mountains, Czech Republic. Plant Soil Environ 59:14–21

Bragazza L, Parisod J, Buttler A et al (2013) Biogeochemical plant-soil microbe feedbacks in response to climate warming in peatlands. Nat Clim Change 3:273–277

Clymo RS (1963) Ion exchange in *Sphagnum* and its relation to bog ecology. Ann Bot (Lond) 27(106):309–324

Gebauer G, Giesemann A, Schulze ED, Jager HJ (1994) Isotope ratios and concentrations of sulfur and nitrogen in needles and soils of *Picea-abies* stands as influenced by atmospheric deposition of sulfur and nitrogen compounds. Plant Soil 164:267–281

Lamers LPM, Bobbink R, Roelofs JGM (2000) Natural nitrogen filter fails in polluted raised bogs. Glob Change Biol 6:583–586

Larmola T, Leppanen SM, Tuitila E-S et al (2014) Methanotrophy induces nitrogen fixation during peatland development. Proc Natl Acad Sci USA 111:734–739

Limpens J, Berendse F, Klees H (2003) N deposition affects N availability in interstitial water, growth of *Sphagnum* and invasion of vascular plants in bog vegetation. New Phytol 157:339–347

Novak M, Stepanova M, Jackova I et al (2014a) Isotopic evidence for nitrogen mobility in peat bogs. Geochim Cosmochim Acta 133:351–361

Novak M, Gebauer G, Thoma M et al (2014b) Denitrification at two nitrogen-polluted, ombrotrophic *Sphagnum* bogs in Central Europe: Insights from porewater N_2O-isotope profiles. Soil Biol Biochem (in press). DOI 10.1016/j.soilbiol.2014.10.021

Pruppacher HR, Klett JD (1997) Microphysics of clouds and precipitation. Atmospheric and Oceanographic Sciences Library, vol 18. Kluwer Academic Publishers, Dordrecht, p 954

Vile MA, Wieder RK, Zivkovic T et al (2014) N_2-fixation by methanotrops sustains carbon and nitrogen accumulaton in pristine peatlands. Biogeochemistry (in press). DOI: 10.1007/s10533-014-0019-6

Woodwell GM et al (1995) Will the warming feed the warming? In: Woodwell GM, Mackenzie FT (eds) Biotic feedbacks in the global climatic system. Oxford University Press, New York, pp 393–411

Wu Y, Blodau C (2013) PEATBOG: a biogeochemical model for analyzing coupled carbon and nitrogen dynamics in northern peatlands. Geosci Model Dev 6:1173–1207