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Effects of sulfuric acid and nitrogen deposition on mineral nutrition of *Picea abies* (L.) Karst.

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Introduction

Since 1980, Mg deficiency in spruce ecosystems of the NE-Bavarian mountains has caused needle yellowing and subsequent dieback of trees growing on soils low in base saturation (Zech and Popp, 1983). At an altitude above 700 m, Mg content of current year needles hardly exceeds 0.03% of dry weight. N needle contents range between 1.3 and 1.6%, which is a sufficient supply. Ca, K and Zn concentrations are low, whereas S concentrations of more than 0.2% of dry weight are extremely high, corresponding to the high SO_2-content of the air in this region (Zech *et al.*, 1983).

The proton input of about 1.5–4.5 kmol·ha·a^{-1} (Kaupenjohann, 1989), measured on experimental sites in the Fichtelgebirge, and low fogwater pH (Trautner, 1989) of 2.2 indicate a high acid stress for forest ecosystems. In fogwater, NH_4 concentrations may also be extremely high (up to 19.5 meq·l^{-1}; Trautner, 1988). Total N deposition of 20–30 kg·ha·a^{-1} exceeds the N demand of trees and high amounts of nitrate are washed out of the soils (Hantschel, 1987).

To study the effects of air pollutants on spruce ecosystems, saplings have been sprayed with artificial acid rain, structured soil samples have been extracted with sulfuric acid, and the effects of high NH_4 inputs on tree nutrition have been measured close to a chicken farm.

Materials and Methods

Sulfuric acid treatment of spruce sapling

Seedlings, 3 yr old, growing in a nutrient solution were sprayed 3 times a day with 62.5 ml of H_2SO_4 (pH 2.4) or deionized water (pH 5.6) during a 10 day period (Kaupenjohann *et al.*, 1988).

Sulfuric acid treatment of naturally structured soil samples

Naturally structured soil samples (100 cm^3) were extracted under saturated conditions using H_2SO_4 concentrations corresponding to calculated (Ulrich, 1983) H^+-buffering of canopies in spruce ecosystems in the Fichtelgebirge (Kaupenjohann and Hantschel, 1987; Kaupenjohann, 1989).

Table I. Total acidity in the nutrient solution, cation leaching from the canopy and K, Ca and Mg needle contents in non-stressed (A) and acidically stressed (B) *P. abies* saplings.

Treatment	*Total acidity (nutrient sol.)*	*Needle leaching*			*Needle conc.*			*Needle Mg content*
		K	*Ca*	*Mg*	*K*	*Ca*	*Mg*	
	(*μeq/tree*)				(*g/kg dw*)			(*μeq/tree*)
A	440	25	–	–	6.8	11.2	1.5	285
B	500	55	20	65	6.1	10.3	0.9	240
B – A	60	30	20	65				–45

Effects of high N-inputs near a chicken farm on nutrient status and vitality of Pinus sylvestris *(L.)*

Vitality, nutrient supply of *P. sylvestris*, chemical constitution of the soil solution and NH_4 concentrations of the air were determined on the experimental site at various distances (50–600 m) and directions from a chicken farm (Kaupenjohann *et al.*, 1989).

Results and Discussion

From saplings treated with sulfuric acid (B) 30 μeq more K had been leached than from control trees sprayed with deionized water (A). No Ca and Mg leaching could be measured in the water treatment (A). Sulfuric acid, however, caused a release of 20 μeq of Ca and 65 μeq of Mg per tree. K and Ca needle contents did not differ between both treatments, however, Mg concentrations in needles of stressed trees decreased significantly by about 45 μeq compared to trees sprayed with water (Table I). In the nutrient solution, we measured an increase of total acidity of about 60 μeq per tree as a result of the acid treatment (Kaupenjohann *et al.*, 1988).

These findings confirm Ulrich's hypothesis (Ulrich, 1983) that cation leaching from a tree's canopy leads to an additional acidification of the rhizosphere resulting from enhanced cation uptake.

The acidification of the root microenvironment affected root nutrient uptake (Schneider *et al.*, 1989): fine root Ca content of acidically treated saplings (B) was significantly lower (26%) compared to those sprayed with deionized water (Table II). The decrease in root Mg was less pronounced due to the high mobility of this element within the plant (Rademacher, 1986). The K contents of fine roots were the same in the two treatments (Table II).

To test what effects this specific proton input to the rhizosphere has on soil chemistry, cation release from undisturbed soil samples was investigated (Kaupenjohann and Hantschel, 1987) using sulfuric acid of pH's corresponding to the average proton buffering of the canopy of various spruce stands of the Fichtelgebirge. The equivalent fraction of Mg (% Mg of Σ K, Ca, Mg, Al) in the solution of those extracts significantly relates to Mg needle contents (Fig.

Table II. Ca, Mg and K concentrations in living fine roots (μg/g dw) of spruce saplings treated with deionized water (A) and sulfuric acid (B) (Schneider *et al.*, 1989).

Element	*Treatment A*		*Treatment B*	
	$\bar{x}$	*SE*	$\bar{x}$	*SE*
Ca[a]	5102	(249)	3778	(415)
Mg	2271	(144)	2135	(106)
K	6399	(206)	5629	(465)

[a]Significant differences ($P < 0.01$).

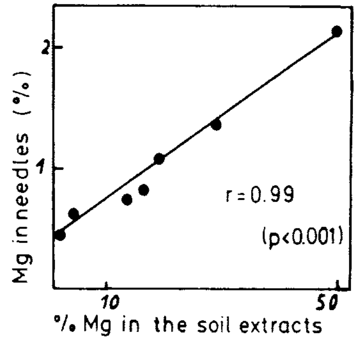

Fig. 1. Mg needle content of recent spruce needles (1985/1986) at various sites in NE-Bavaria as a function of Mg content in sulfuric acid extracts (equivalent fraction of Σ K, Ca, Mg, Al) of naturally structured soil samples (see text; Kaupenjohann, 1989).

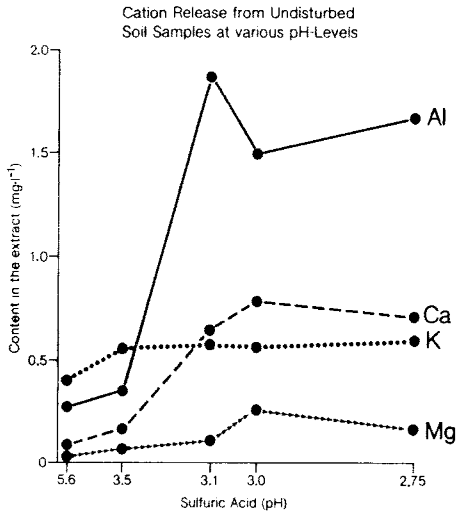

Fig. 2. Cation release from naturally structured soil samples of a declining spruce stand in the Fichtelgebirge at a decreasing pH (H_2SO_4) of the extraction solution (Kaupenjohann and Hantschel, 1987).

1), indicating that Mg availability seems to be mainly a function of acid deposition and Mg supply of the soil (Kaupenjohann, 1989).

It is interesting to note that an increase of the acid load of the same soil (Fig. 2) caused a higher release of both Mg and Ca into the soil solution (Kaupenjohann and Hantschel, 1987). From field studies, we know that the proton input into old stands can exceed that of young ones by a factor of 2–3, because of the higher canopy filtering capacity (Kaupenjohann, 1989). Actual Ca and Mg availability in old spruce stands, therefore, should increase under the same soil conditions (Kaupenjohann, 1989).

Indeed, we measured a significant increase of fine root Mg in an old stand compared to a young stand at the same site (Table III). The Ca content in living fine roots was, however, significantly lower in old than in young spruce. The Ca/Al ratios of roots from old and young trees did not differ significantly (Schneider *et al.*, 1989).

We therefore think that proton release from fine roots may restrict Ca uptake more directly than does Al in the soil solu-

Table III. Contents of Ca and Mg and Ca/Al molar ratio in fine roots of young and old declining spruce (*P. abies* (L.) Karst.) (Schneider *et al.*, 1989).

Stand	n	*H^+-input (kmol)*	*Element ($\mu mol \cdot g^{-1}$)*					
			Ca[a]	*SE*	*Mg*[a]	*SE*	*Ca/Al*[b]	*SE*
Young	5	1.5–2	67.88	58	14.85	34	0.26	44
Old	20	3–4.5	57.21	8	19.99	17	0.27	6

[a] Significant difference; $P < 0.05$.
[b] Not significant.

Table IV. Nutrient contents in current year needles of healthy (A) and declining (B) *P. sylvestris* (L.) (Kaupenjohann *et al.*, 1989).

Stand	*Needle content (mg·g⁻¹ dw)*				
	N	*P*	*K*	*Ca*	*Mg*[a]
A	27	1.6	6.1	3.4	0.92
B	24	1.4	6.7	3.5	0.66

[a] Significant difference; $P < 0.01$.

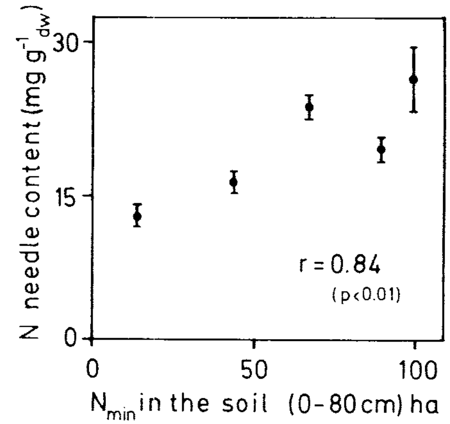

Fig. 3. N needle content as a function of N supply in the soil on experimental plots at various distances from a chicken farm (Kaupenjohann *et al.*, 1989).

tion. Mg uptake does not seem to be restricted by an efflux of protons from roots and average Al concentrations in the soil solution of about 2–8 $mg \cdot l^{-1}$ (Hantschel, 1987).

The results can describe a causal relationship between acid deposition, cation leaching, acidification of the tree's rhizosphere, changes in soil chemistry and plant nutrition. In addition to the proton deposition, N inputs have to be taken into account when investigating influences on nutritional imbalances in forest ecosystems.

We therefore studied the effects of high NH_4 input on *P. sylvestris* (L.) close to a chicken farm (Kaupenjohann *et al.*, 1989). Needle analysis showed high N concentrations (Table IV) in both a healthy stand (A) growing 50 m to the west of a farm and a leeward localized declining stand (150 m to the east). P, K and Ca needle contents also differed between the stands (Table IV). Mg concentrations in needles of damaged trees (B), however, were significantly lower (30%; Table IV) than in healthy trees (A), although soil Mg was even higher in the damaged stand (Table V). The amount of plant-available N in the soil was similar at both plots, which correlates well with the N supply of the trees (Fig. 3) (Kaupenjohann *et al.*, 1989).

Microclimatic observations showed that, in the healthy stand (A), nitrogen was mainly deposited underneath the canopy directly on the soil, whereas at the declining stand (B) N-inputs were impacted on the canopy (Kaupenjohann *et al.*, 1989). It may therefore be assumed that trees are able to metabolize the increased supply of

Table V. pH, N_{min} and elemental content in the soil water extracts of healthy (A) and damaged (B) *P. sylvestris* (L.).

Stand	*pH*	*N_{min} (kg·ha⁻¹)*[a]		*Element (mg·l⁻¹)*[a]			
		NH_4	*NO_3*	*Mg*	*K*	*Ca*	*Al*
A	3.91	36.6	5.2	0.19	13.6	27	17
B	3.99	35.7	3.5	0.29	8.4	27	10

[a] Soil depth: 0–20 cm.

soil N without developing imbalanced nutrient relations within the plant. In contrast, a direct attack of NH_4 on a tree's canopy may decrease nutrient supply due to leaching. Laboratory experiments by Hogrebe and Mengel (in preparation) support this hypothesis. In addition, NH_4/NH_3^- deposition may have toxic effects on the plant tissue (Ewert, 1978).

Conclusion

Acid deposition based on high SO_2^- inputs in the NE-Bavarian Mountains cause an imbalance in the nutrient supply of soils and plants, leading to cation leaching from damaged trees and subsequent acidification of the rhizosphere due to enhanced cation uptake by roots. Mg seems to be especially affected by this process explaining the extensive symptoms of needle yellowing and dieback of spruce stands in this region. Furthermore, proton load, particularly of the canopy, decreases Ca uptake into roots. There is no indication of an imbalancing effect of high N supply on nutrient relations within the plant. Ammonium deposition may, however, cause Mg leaching as sulfuric acid does, and thus induce Mg deficiency.

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