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Ecosystem response to 9 years of nitrogen addition at Sogndal, Norway

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Abstract

Since 1983, 7 kg N ha^{-1} $year^{-1}$ as nitric acid has been added to a 1940 m^2 pristine alpine catchment (SOG4) at Sogndal, central Norway, as part of the RAIN project (Reversing Acidification In Norway). During 9 years of treatment SOG4 has retained 90% of the NO_3 inputs, about the same fraction as the adjacent untreated control catchments which received ambient N inputs of 2 kg N ha^{-1} $year^{-1}$. Runoff from SOG4 contains elevated concentrations of nitrate only in conjunction with events of high flow and high concentrations of nitrate in incoming water. The 9 years of N deposition of 9 kg N ha^{-1} $year^{-1}$ has not induced nitrogen saturation. A total of 63 kg N ha^{-1} has been retained over the 9 year period. Retarded decomposition and higher total N concentration indicate that part of this 63 kg N ha^{-1} may be stored in the ectorganic (L+F+H) layer. Measurements of N contents in foliage do not reveal differences that can be ascribed to the N addition.

Keywords: Nitrogen addition; Ecosystem response; NITREX project

1. Introduction

In recent years concern about the effects of acid deposition on terrestrial and freshwater ecosystems has shifted from sulphur to the role of nitrogen. Atmospheric deposition of inorganic nitrogen compounds can lead to disruption of the typically tight cycling of nitrogen within terrestrial ecosystems, and if continued in large doses over sufficient time, can result in increased loss of nitrogen as nitrate to surface waters. This condition is commonly taken as an indication of 'nitrogen saturation' (Aber et al., 1989). Like sulphate, nitrate is a strong acid anion, and in acid soils increased concentrations of nitrate are generally accompanied by acid cations such as H^+ and inorganic Al. The result is acidification of soils and surface waters, with the subsequent adverse effects on organisms.

In 1983 as part of the RAIN project (Reversing Acidification In Norway) a whole-catchment nitrogen addition experiment was begun at Sogndal, Norway. At this pristine alpine site, catchment SOG4 was treated with 50 meq m^{-2} $year^{-1}$ sulphuric and 50 meq m^{-2} $year^{-1}$ nitric acids (Fig. 1). Two adjacent catchments (SOG1 and SOG3) serve as untreated controls. The results after 8 years of acid addition are reported by Wright et al. (1994).

The Sogndal experiment fits within the frame-

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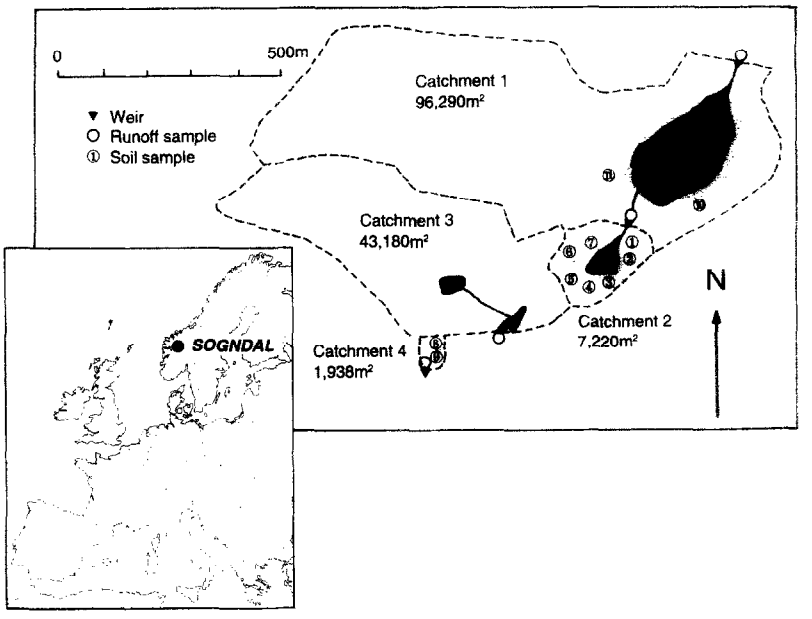

Fig. 1. Map of the four experimental catchments at Sogndal showing locations of soil and water sampling points.

work of the NITREX project (Nitrogen saturation experiments) (Dise and Wright, 1992). The nitric acid addition represents a chronic addition of atmospheric nitrogen, which in the long term might induce nitrogen saturation. Of the seven sites in Europe included in NITREX, Sogndal is the most pristine with the lowest deposition of both nitrogen and sulphur (Wright and Van Breemen, 1995). Measurement of soil chemistry and input–output budgets have been conducted since 1983 as part of the RAIN project. In 1992 we initiated investigations at Sogndal to determine if 9 years of nitrogen addition had resulted in changes within the terrestrial ecosystem. We report here results from the long-term ecosystem response to chronic nitrogen addition at Sogndal.

2. Site description, experimental design and methods

The Sogndal site is located at 900 m elevation and has gneissic bedrock, thin and patchy soils, and alpine vegetation. The soils are classified as Lithic Haplumbrepts, are sandy and siliceous, and average only 30 cm in depth (Table 1). There are no trees; shrub vegetation is dominated by birch (*Betula verrucosa, Betula nana*), juniper (*Juniperus communis*) and willow (*Salix hastata*), with a ground cover of *Calluna vulgaris, Empetrum nigrum, Vaccinium myeartillus, Vaccinium uliginosum, Vaccinium vitis-idaea*

Table 1
Characteristics of soils (classified as Lithic Haplumbrept) at Sogndal (data from Lotse and Otabbong, 1985 and Lotse, 1989)

	Layer	
	0–15 cm	>15 cm
pH (H_2O)	5.1	5.5
Loss on ign. (%)	27.1	17.6
C (%)	13.7	8.4
N (%)	0.61	0.41
S (%)	0.058	0.041
Bulk density (kg l^{-1})	0.51	0.74
CEC (meq per 100 g)	5.52	2.25
Ca saturation (%)	18.3	16.8
Mg saturation (%)	4.9	3.1
Na saturation (%)	2.0	2.0
K saturation (%)	3.0	3.0
Base saturation (%)	28.2	24.9

and various grasses, mosses and lichens. Details on the soils and vegetation are given by Lotse and Otabbong (1985) and Lotse (1989).

Sogndal receives very low levels of sulphur and nitrogen deposition (Table 2). Surface waters have low concentrations of major ions and alkalinity, and are sensitive to acidic deposition.

Catchment SOG4 receives a 1:1 mixture of H_2SO_4 and HNO_3 (50 meq m^{-2} $year^{-1}$ each), and catchments SOG1 and SOG3 serve as untreated controls. Acid is applied as a mist to the snowpack once in April and as five portions of 11 mm of pH 3.2 acid during the snow-free period June–October each year. First acid addition was in April 1984 to the snowpack. A total of 9 years of treatment data are available (November 1983–October 1992).

Weekly samples of bulk precipitation are collected at the Haukås farm (located at 600 m above sea level about 5 km south of the catchments) and sent to the Norwegian Institute for Air Research (NILU) for chemical analysis of pH, Ca, Mg, Na, K, NH_4, NO_3, Cl, and SO_4. Each winter in late March or early April snowpack measurements at the catchments are made to estimate the water-equivalent of the snowpack, and snow cores are taken for chemical analysis. Dry deposition is not measured; for pollutant components sulphate, nitrate ammonium and acid dry deposition is assumed to be negligible in this remote, pristine area. Dry deposition of marine aerosols is estimated by difference from the input–output flux of chloride and the ionic ratios in seawater.

Discharge is gauged continuously by weir and water-level recorder at catchments SOG1 and SOG4. The data are reported as daily mean discharge. The chemical composition of runoff from the four catchments is determined from samples collected daily following acid additions, weekly during the snowfree season, and monthly during the winter. Samples are analysed at the Norwegian Institute for Water Research for pH, conductivity, Ca, Mg, Na, K, NO_3, Cl, SO_4, alkalinity, and reactive and non-labile Al.

Surveys of soil chemistry have been conducted each year from 1983 to 1988 and in 1990 (Lotse and Otabbong, 1985; Lotse, 1989). Samples are collected from 11 fixed points (Fig. 1) at three depths and analysed at the Department of Soil

Table 2
Fluxes and volume-weighted concentrations of major chemical components in bulk precipitation and runoff at control catchment SOG1. Values are means for the 9 year period 1983–1992

	Fluxes (meq m^{-2} $year^{-1}$)		Concentrations (μeq l^{-1})	
	In	Out	In	Out
H_2O (mm)	1113	1067	1113	1067
pH			4.9	5.7
H^+	15	2	13	2
Ca	7	18	6	17
Mg	10	12	9	11
Na	46	50	41	47
K	5	3	5	3
Al	0	1	0	1
NH_4	10	1	9	1
NO_3	9	1	8	1
Cl	52	55	47	51
SO_4	23	23	21	21
HCO_3	0	8	0	7
SBC	78	83	70	78
SAA	84	78	76	73
ANC	−6	5	−5	5

SBC, sum base cations (incl. NH_4); SAA, sum strong acid anions; ANC (acid neutralising capacity) = SBC − SSA.

Science, Swedish Agricultural University (SLU), for pH, loss on ignition, C, N, S, exchangeable cations, cation exchange capacity (CEC), and bulk density.

Detection of treatment effects on ecosystem components at Sogndal is complicated by the large variability within the catchments. Four representative and comparable 10–20 m^2 sampling plots were chosen in each catchment. These sampling plots were selected within the dominant plant community of the smallest catchment (SOG4) and in comparable locations in the other

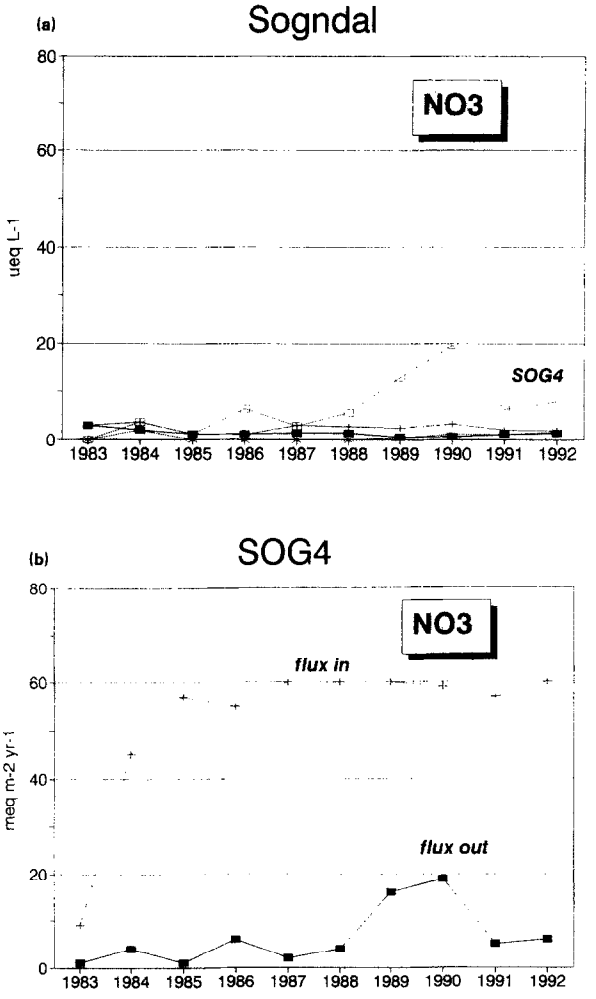

Fig. 2. (a) Volume-weighted average concentrations of nitrate in runoff at Sogndal. (b) Annual input–output flux of nitrate at SOG4. Catchments SOG1 and SOG3 are untreated controls, catchment SOG2 receives H_2SO_4 and catchment SOG4 receives a 1:1 mixture of H_2SO_4 and HNO_3.

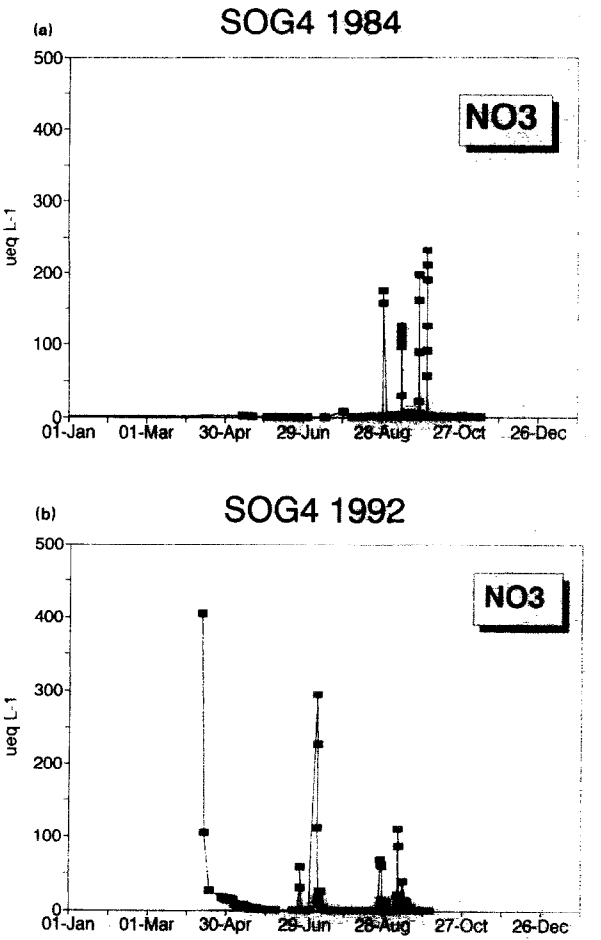

Fig. 3. Nitrate concentrations in runoff from catchment SOG4 at Sogndal during (a) the first year of treatment 1984 and (b) the ninth year of treatment 1992. The concentrations in runoff from the untreated control catchments SOG1 and SOG3 (not shown) were less than 6 $\mu eq\ l^{-1}$ in all samples.

catchments. This plant community consisted in decreasing order of abundance of: *Calluna vulparis* as bushes about 50 cm high and as young shoots; *Betula verrucosa* as bushes with a maximum height of about 2 m; *Empetrum nigrum*; *Vaccinium myeartillus*; *Betula nana*; *Salix hastata*. Grasses included *Molinia caerulea*, *Deschampsia flexuosa*, and *Nardus stricta*. In addition various mosses and lichens were present. The four plots in each catchment consisted of two with a northern and two with a southern exposure.

Current-year leaves were sampled from five

Table 3
Nitrate-nitrogen budgets (in meq m^{-2}; values in parentheses are kg N ha^{-1}) at Sogndal summed over the 9 year period 1983–1992

	In			Out	% out
	Precipitation	Added	Total		
SOG1	88	0	88	11	12
	(12)	(0)	(12)	(2)	
SOG2	88	0	88	20	23
	(12)	(0)	(12)	(3)	
SOG4	88	426	514	63	12
	(12)	(60)	(72)	(9)	

Table 4
Total nitrogen concentration (%) in current year (1992) leaves. Samples were taken randomly from four sampling plots within the catchments. Numbers are mean values with the standard deviation in parentheses

Species	SOG1 (control)	SOG4 (H_2SO_4/HNO_3)
Betula verrucosa	2.40 (0.47)	2.56 (0.09)
Calluna vulgaris	1.60 (0.31)	1.63 (0.18)
Empetrum nigrum	1.77 (0.15)	1.60 (0.16)
Vaccinium myrtillus	1.76 (0.23)	1.88 (0.18)
Salix hastata	2.49 (0.34)	2.40 (0.26)

Table 5
Total nitrogen concentrations (%) in dead leaves

Species	SOG1 (control)	SOG4 (H_2SO_4/HNO_3)
Betula verrucosa	0.88	1.02
Calluna vulgaris	1.44	1.29
Vaccinium myrtillus	1.12	0.88
Betula nana	0.54	0.85

dominant plant species for analysis of nitrogen concentrations in foliage. The plant species were *C. vulgaris*, *B. verrucosa*, *E. nigrum*, *V. myeartillus*, and *S. hastata*. Dead shoots of *C. vulgaris* and dead coloured leaves of *B. verrucosa*, *B. nana* and *V. myeartillus* were sampled by shaking and by picking the plants. They were bulked to one composite sample for each species for each catchment. The dead *C. vulgaris* shoots and the *B. verrucosa* leaves were used as initial material for the litterbag experiment. After drying the leaves at 70°C and grinding, the total nitrogen concentration in the litter from each individual litterbag was determined by means of a salicylic acid–thiosulphate modification of the regular Kjehldahl procedure (Bremner and Mulvaney, 1982).

In July as well as in September 1992 the ectorganic layer (L+F+H) underneath bushes of *C. vulgaris* and of *B. verrucosa* was sampled. The sampling locations were selected such that the organic layer consisted dominantly of litter of only one of the two species. Material from about five locations within each catchment were bulked to one composite sample. The organic material was air-dried and gently mixed by hand. The amount of adsorbed nitrogen was determined by means of extraction of the litter with 1 M KCl (w/v 1:30) in duplicate. The extracts were filtered and analysed colorimetrically for NH_4 and NO_3. The dissolved organic nitrogen (DON) concentration was determined after digestion of the sample with K_2SO_4/H_2SO_4 and subsequent analysis of the NH_4 concentration. The organic matter content was determined by loss-on-ignition at 500°C for 16 h. The total nitrogen concentration was determined by the modified Kjeldahl procedure and the sulphur concentration by inductively-coupled plasma atomic emission spectrometry alter digestion of the organic matter in concentrated HNO_3 (Novozamsky et al., 1986).

Net nitrogen mineralisation and nitrification were determined in all litter types by an incubation procedure. Before the start of the incubation, the air-dried litter was wetted to moisture

Table 6
Organic matter content, loss of ignition (LOI), total nitrogen and sulphur concentrations and concentrations of absorbed nitrogen in the ectorganic layer. The concentrations are corrected for mineral soil contamination

		SOG1 (control)	SOG4 ($H_2SO_4+HNO_3$)
Betula verrucosa			
July	LOI (%)	96.8	83.9
	N (mg g^{-1})	19.8	24.5
	S (mg g^{-1})	1.64	2.04
	N/NH_4 (mg kg^{-1})	13	14
	N/NO_3 (mg kg^{-1})	0.1	0.1
	N/DON (mg kg^{-1})	14	9
September	LOI (%)	96.2	75.7
	N (mg g^{-1})	21.4	24.2
	S (mg g^{-1})	1.77	2.02
	N/NH_4 (mg kg^{-1})	6	5
	N/NO_3 (mg kg^{-1})	0.2	0.2
	N/DON (mg kg^{-1})	13	12
Calluna vulgaris			
July	LOI (%)	88.3	88.5
	N (mg g^{-1})	16.0	17.1
	S (mg g^{-1})	1.74	1.82
	N/NH_4 (mg kg^{-1})	3	7
	N/NO_3 (mg kg^{-1})	0.1	0.1
	N/DON (mg kg^{-1})	8	14
September	LOI (%)	93.1	89.7
	N (mg g^{-1})	16.4	15.3
	S (mg g^{-1})	1.73	1.74
	N/NH_4 (mg kg^{-1})	7	8
	N/NO_3 (mg kg^{-1})	0.1	0.2
	N/DON (mg kg^{-1})	8	8

Table 7
Nitrogen transformation (mg N kg^{-1} per 4 week period) and respiration (mg C kg^{-1} h^{-1}) rates in the ectorganic layer. All rates are corrected for mineral soil contamination

		SOG1 (control)	SOG4 ($H_2SO_4+HNO_3$)
Betula verrucosa			
July	Net mineralisation	64	79
	Nitrification	0.7	0.0
	Respiration	26	13
September	Net mineralisation	22	29
	Nitrification	−1.4	−1.0
	Respiration	36	36
Calluna vulgaris			
July	Net mineralisation	6	ND
	Nitrification	−0.4	−1.2
	Respiration	29	17
September	Net mineralisation	2	2
	Nitrification	−1.4	−1.4
	Respiration	30	28

content of 200% of oven dry weight and stored at 20°C for 1 week. After this pre-incubation, petri dishes of 9 cm diameter were filled with representative subsamples of the organic material. The initial ammonium and nitrate concentrations in all litter types were determined in three non-incubated and three incubated (17 days, 20°C) samples. Ammonium and nitrate were determined after a 1 M KCl extraction (w:v 1:30). Net nitrogen mineralisation and nitrification rates, respectively, were defined as the difference between the mean initial and incubated concentrations of total inorganic nitrogen and nitrate.

The respiration rate of all litter types was determined with the wetted litter as the daily headspace accumulation of CO_2 from litter samples in 135 ml air-tight jars during a 2 day incubation.

A litterbag study was started in SOG1 and SOG4 in the growing season of 1992 in order to study the decomposition of leaf litter of *C. vulgaris* as a function of treatment. The experiment was designed to provide information on the indirect effect of the treatment via substrate quality, as well as the direct treatment effect on decomposition by placing litterbags from each of the two catchments SOG1 and SOG4 in both catchments. After air drying, the 0.6 mm mesh, 7 cm × 8 cm bags were filled with an amount of air-dried litter corresponding to about 4 g litter dried at 70°C. The bags were placed underneath bushes of *Calluna* within the four sampling plots in the two catchments. Sampling of the litterbags occurred randomly per plot after 2 and 12 months. After sampling, the litter was dried at 70°C to constant weight. The weight losses were tested with a three-way ANOVA, with incubation time and the indirect and direct treatment effects as factors.

Emission of N_2O from the soil was measured 30–31 July 1993 in SOG2, SOG3 and SOG4 by the closed-chamber method (Hutchinson and Mosier, 1981). A PVC chamber (width 17.5 cm,

depth 11.5 cm, height 7.6 cm) was inserted less than 1 cm into the soil. The N_2O concentrations were measured with a Brüel & Kjær Multi-gas Monitor based on the photo-acoustic infra-red detection method. The concentrations were measured at 4 min intervals over a 24 min period. The N_2O fluxes were calculated as a function of the concentration change within the chamber over the period. Sixteen measurements were carried out in each of the three catchments.

3. Results

3.1. Runoff chemistry

Chronic additions of nitric acid at catchment SOG4 have resulted in significantly higher concentrations of nitrate in runoff (Fig. 2). Nitrate concentrations during snowmelt each spring are much higher in runoff at SOG4 than at the untreated control catchments. During the summer the general pattern is one with sharp peaks during and immediately after each acid addition followed by rapid decline back to very low levels (Fig. 3). These patterns are present each of the 9 years of treatment, although during the last several years of treatment the decline following nitrate additions proceeded more slowly, and runoff between additions contained elevated concentrations of nitrate. The appearance of elevated nitrate concentrations was especially pronounced during the autumn.

Acid addition at SOG4 has caused other major changes in runoff chemistry (Wright et al., 1988, 1994). Sulphate concentrations increased, base cations increased and acid neutralising capacity (ANC) decreased. pH levels declined and concentrations of inorganic aluminum species increased. All these changes are characteristic of the general path of acidification of freshwaters.

Input–output budgets indicate that catchment SOG4 retains nearly 90% of added nitrogen (Table 3). Thus, for the 9 year period 1983–1992

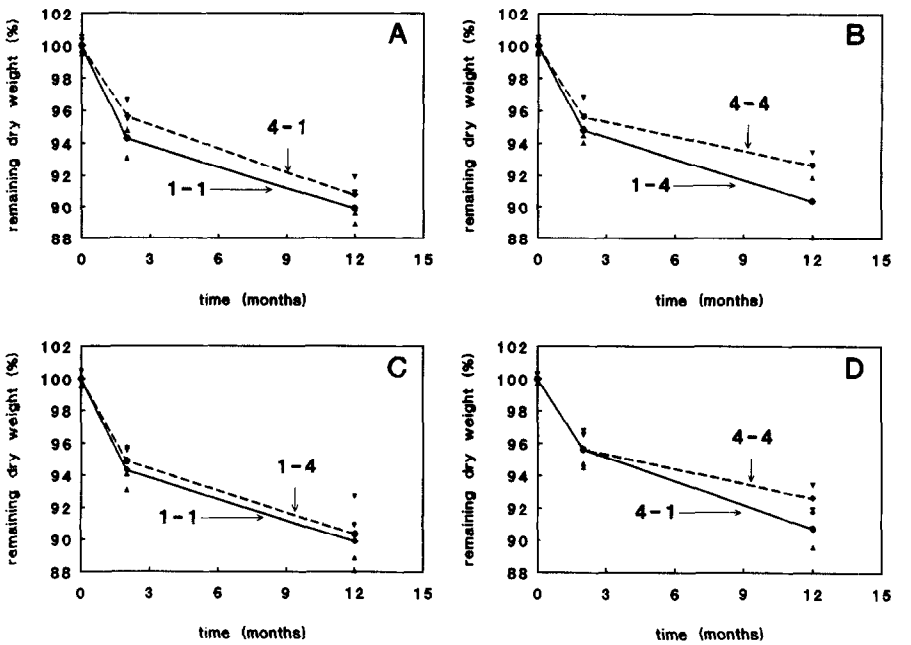

Fig. 4. Percent dry weight remaining as a function of time in decomposing leaves of *Calluna vulgaris*. (A) and (B) show the indirect effect of the H_2SO_4/HNO_3 treatment via substrate quality, tested by the comparison of litter from different origins in the same location; (C) and (D) illustrate the direct effect of the treatment on the decomposition process, tested by comparing litter from the same origin in different locations. The combination of the two numbers (1, SOG1 (control); 4, SOG4 (H_2SO_4/HNO_3)) indicates the origin (the first number) and the location (the second number) of the litter. The closed triangular symbols signify the mean plus (▾) and minus (▴) the standard deviation.

of 88 NO_3 meq m^{-2} in precipitation and 426 meq m^{-2} added, only 63 meq m^{-2} left the catchment in runoff. This catchment ecosystem is still very efficient at retaining nitrogen.

3.2. Nitrogen in living and dead foliage

A large variation in nitrogen concentration in current year leaves was found between the replicates (Table 4). No statistical differences ($P \leq 0.05$) could be detected between the catchments. In the dead leaves of the two *Betula* species, a higher total nitrogen concentration was found in SOG4, whereas in dead foliage of *C. vulgaris* and *E. nigrum* the nitrogen concentration in SOG4 was found to be lower than in the control (Table 5).

3.3. Ectorganic horizon

The ectorganic layer of SOG4 underneath *Betula* and *Calluna* has higher total N and S concentrations than the control catchment. For *Betula* this difference is about 0.4% (2.4% vs. 2.0% N of pure organic matter), and for *Calluna* 0.05% (1.70% vs. 1.65%). The S concentrations in the ectorganic layer underneath *Betula* are higher in SOG4 than in the control catchment (Table 6). For *Calluna* the S concentrations of both catchments are about equal. In both catchments the ectorganic layer contained nearly no nitrate and low ammonium and DON concentrations (Table 6).

No clear differences in net nitrogen mineralisation in the ectorganic layer of SOG4 and the control catchment could be detected (Table 7). Much higher rates were found in *Betula*-dominated organic matter compared with *Calluna*. Net mineralisation rates underneath *Betula* decreased after the litterfall of new leaves in September, possibly due to increased gross nitrogen immobilisation into this fresh litter.

3.4. Decomposition

There was a relatively high weight loss during the first 1–2 months of decomposition (Fig. 4). Despite the long winter snow cover, a significant weight loss was measured in both litter types. The first year results indicate a trend of lower decomposition rate in litter from SOG4 and litter placed in SOG4 compared with the control catchment SOG1 (Fig. 4). The indirect treatment effect via litter quality had a significant ($P<0.05$) influence on the weight loss rate (Figs. 4(A) and 4(B)). The location of the litter (SOG1 or SOG4) was significant ($P<0.05$) only for location SOG1 (Fig. 4(A)).

3.5. Trace gas emissions

In only a few instances was there a significant change in N_2O concentration underneath the chamber. Fluxes ranged from -2.0 to 3.5 mg N_2O m^{-2} day^{-1}. Assuming an active period of 120 days per year the corresponding annual fluxes are -1.5 to 2.7 kg N_2O-N ha^{-1} $year^{-1}$. No differences between the treatments were found.

4. Discussion

Although the increased nitrogen inputs caused increased nitrogen output, the catchment SOG4 still retains about 90% of inputs, approximately the same fraction as the untreated controls SOG1 and SOG3 (Table 3). Most of the nitrate in runoff comes in events during which both the flux of water through the catchment and the concentration of nitrate in the input water are high. Nitrate losses are pronounced during the first phases of snowmelt when the meltwater contains very high concentrations of nitrate, and immediately during or following experimental acid additions during the snow-free season (Fig. 3).

There is little evidence that the 9 years of nitrogen addition at 7 kg N ha^{-1} $year^{-1}$ have induced nitrogen saturation, the condition under which the "availability of ammonium and nitrate is in excess of total combined plant and microbial nutritional demand" as manifest by "an increased leaching of NO_3 or NH_4 below the rooting zone" (Aber et al., 1989). The ecosystem retains over 90% of the added nitrogen. The increased loss apparently is because the mecha-

nisms for nitrate retention within the catchment have insufficient time or capacity to immobilise all the incoming nitrate during events of high flow and high concentration.

Nitrogen deposition at Sogndal (ambient plus added) falls below the 10 kg N ha^{-1} $year^{-1}$ 'threshold' at which nitrogen saturation begins to be manifest in forest ecosystems throughout Europe (Grennfelt and Hultberg, 1986; Dise and Wright, 1995). Many of these sites have received N deposition of 7–10 kg N ha^{-1} $year^{-1}$ for decades and still retain nearly all incoming inorganic N. The dose at Sogndal of 9 kg N ha^{-1} $year^{-1}$ (ambient plus added) is apparently too little for too few years to induce nitrogen saturation; perhaps many decades of inputs at this rate would be required to 'saturate' the ecosystem.

The question remains whether the 63 kg N ha^{-1} added to SOG4 over the 9 year period has resulted in changes within the ecosystem. Clearly it is unlikely that this 63 kg N ha^{-1} can be found within the ecosystem inasmuch as the soils contain about 100 times as much nitrogen (5000–8000 kg N ha^{-1}; Wright et al., 1994).

We thus focused our investigations on potentially sensitive components of the ecosystem. The organic layer is one such sensitive indicator of ecosystem response to changes in atmospheric inputs. Atmospheric inputs reach the organic layer relatively unaltered in quantity and quality. For most elements the organic layer comprises a relatively small pool within the ecosystem which makes it easier to find changes in the pool size or distribution as a result of changed fluxes. Finally, element dynamics in the organic layer are dominated by microbial activity, and the microbial community is known for its ability to adapt relatively quickly to a changed abiotic environment.

The results indicate a possible response in the organic layer. Higher total nitrogen concentrations were found in the organic layer of SOG4. In addition, the litterbag experiment showed a significantly retarded decomposition indirectly as a result of inferior litter quality in SOG4 and a trend of retarded decomposition directly as a result of the H_2SO_4/HNO_3 treatment. A direct negative effect of N addition is often found in recalcitrant substrates and is explained by a possible disturbance of the microbial succession, the blockage of enzyme synthesis or the formation of toxic compounds (Fog, 1988). The combination of retarded decay rate and higher total nitrogen concentrations as a result of nitrogen addition might imply an increased nitrogen storage in the organic layer in SOG4.

The vegetation is also a sensitive ecosystem component. If plant production is nitrogen limited, more biomass might result from increased nitrogen availability. Owing to the highly variable vegetation cover and plant species composition, accurate measurements of plant production between the catchments are difficult to obtain. Furthermore, nitrogen concentrations in current year plant tissue also showed a very high variability.

To our knowledge the experiment at Sogndal is the only such chronic addition of nitrogen to a natural alpine site. Such terrain is widespread in upland regions of Europe such as the Alps, central Scandinavia and Scotland and Wales in the UK. The sensitivity of these ecosystems to chronic nitrogen addition, and the threshold for 'nitrogen saturation' are insufficiently known. More research is needed on the long-term effects of nitrogen deposition to such ecosystems.

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