# Ammonium uptake in alpine streams in the High Tatra Mountains (Slovakia)

J. Kopáček[1] & P. Blažka[1,2]
[1] *Hydrobiological Institute, Academy of Sciences, Na sádkách 7, 370 05 České Budějovice, Czech Republic*
[2] *University of South Bohemia, Faculty of Biological Sciences, 370 05 České Budějovice, Czech Republic*

## Abstract

Uptake of $NH_4^+$-N by streambed biota of mountain brooks was studied in the alpine zone of the High Tatra Mountains. Experiments were performed involving *in situ* dosing of ammonium directly to the acidified stream and incubations of ammonium and streambed bryophytes in enclosures within a range of pH from 4.45 to 8.10.

$NH_4^+$-N uptake length decreased with decreasing stream discharge, while comparable values of discharge-normalized uptake lengths were found during two *in situ* experiments.

Maximum uptake rates of $NH_4^+$-N obtained during the incubation of bryophytes (6 to 11 mg m$^{-2}$ h$^{-1}$) were comparable with results of two *in situ* experiments (8 and 12 mg m$^{-2}$ h$^{-1}$). The average $NH_4^+$-N uptake rates observed during incubations lasting 3 to 5 hours (4.3 mg m$^{-2}$ h$^{-1}$) were not related to the pH of stream water. Nitrification of about 50% of the $NH_4^+$-N added was observed in non-acidified streams, but was negligible in acidified streams. Significant photoinhibition of nitrification was observed in non-acidified streams during enclosure experiments.

## Introduction

The chemistry of lakes and streams in small alpine watersheds, with sparse vegetation and a bedrock characterized by low rates of chemical weathering and ion exchange processes, is largely determined by the composition of precipitation (Wright & Gjessing, 1976; Wright & Johannessen, 1980; Catalan *et al.*, 1992). A remarkable exception to other ions is ammonium, which is retained in the watershed, and whose concentrations are considerably lower in lakes than in precipitation. Dillon & Molot (1990) reported 81% to 99% retention of ammonium in stream and lake watersheds in Europe and North America. Similarly, Wathne *et al.* (1989) and Mosello *et al.* (1991) showed that 20% and 50% of inorganic nitrogen from atmospheric deposition reaches the lakes in Norway and in the Alps, respectively.

Concentrations of $NH_4^+$-N in lake water of the High Tatra Mountains follow the same trend, and are usually lower (except during thaw periods) than 30 $\mu$g l$^{-1}$ (Fott *et al.*, 1992; Kopáček & Stuchlík, 1994),

despite high concentrations of ammonium in precipitation. The mean concentration of $NH_4^+$-N was 340 $\mu$g l$^{-1}$ in snow cores (Gazda & Lopašovský, 1983) and 640 $\mu$g l$^{-1}$ in summer precipitation (May to October 1991) (Grodzinska-Jurczak & Krywult, 1992).

The retention of ammonium is related to vegetation uptake, and its oxidation to nitrate, which accelerates the acidification of alpine regions, is assumed to have an important role (Schuurkes & Mosello, 1988; Henriksen & Brakke, 1988; Dillon & Molot, 1990). It is difficult to measure directly the intensity of these processes in the entire watershed, but small mountain streams or lakes, being simpler systems, are better suited for studying transformations of nitrogen and evaluating the role of nitrification in the retention of $NH_4^+$-N (Richey *et al.*, 1985, Rudd *et al.*, 1988, Howard-Williams *et al.*, 1989).

The role of streambed biota in nitrogen transformations during passage downstream has been reported to be considerable in Antarctica (Howard-Williams *et al.*, 1989) and a forested mountain area (Richey *et al.*, 1985). Remarkable changes in $NH_4^+$-N concen-

trations were also observed during our earlier studies in the alpine zone of the High Tatra Mountains. High concentrations of $NH_4^+$-N (usually above 300 $\mu$g l$^{-1}$) in streams originating in melting snow fields decreased drastically, with levels at nearly zero only 100 to 200 m downstream (Sraškrabová & Blažka, 1990). The aim of this study was to quantify this process.

We measured the uptake rate of $NH_4^+$-N by incubating the streambed biota of different brooks in the alpine zone of the High Tatra Mountains, and compared it to the retention of ammonium in a section of stream during *in situ* enrichment experiments. The role of nitrification in this process was assessed in relation to the pH and to light conditions.

## Description of sites studied

The High Tatra Mountains (HTM; 20° 10' E, 49° 10' N; maximum altitude 2655 m a.s.l.) belong to the Carpathian chain. The bedrock consists mainly of acidic granites with sparse calcareous inclusions in the west and central part of the HTM, while the Belanské Tatry Mts., the eastern part of the HTM, are formed of limestone. The area is loaded by acid deposits, with sulphate and nitrate as dominant anions and an annual weighted mean pH of 4.3 (Cerovský, 1983; Moldan *et al.*, 1987). The acid neutralizing capacity of the stream and lake water in these mountains ranges from 0 to 2800 $\mu$eq l$^{-1}$ and its pH from 4.0 to 8.3 (Stuchlík *et al.*, 1985).

All observations in this study were made above the timberline in the alpine zone, at altitudes of 1600 to 2100 m a.s.l. *In situ* enrichment experiments were conducted in an upper part of the acidified brook, at an altitude of about 2000 m a.s.l. The brook begins between the Huncovský and V. Svišt'ovka peaks, and cascades down a broad gorge toward east-north-east, with a gradient of 40%. The streambed is largely bedrock and gravel, about 50% covered with mixed epiphyte, predominantly bryophytes. During the experiments the stream discharge varied from 1.1 to 2.9 l s$^{-1}$; pH was 4.65 in 1990 and between 4.50 and 4.65 in 1991; temperature varied from 3 °C to 6 °C in 1990 and from 13 °C to 15 °C in 1991. The slopes of the gorge are covered with sparse alpine meadows and bare granitic rocks with patches of lichens. Samples of bryophytes and water, used in enclosure experiments, were also collected in the V. Studená and Žabia Bielovodská valleys (granitic part of the HTM, pH from 4.65 to 6.40)

and in the Tristárská valley (the Belanské Tatry Mts.; pH = 8.10).

## Materials and methods

In this study two different types of experiments were performed: *in situ* enrichment experiments, in which the retention of $NH_4^+$-N by an acidified stream was measured, and enclosure incubations of streambed bryophytes in $NH_4^+$-N enriched water at different pH. All the experiments were conducted in early summer, when the role of vegetation in ammonium uptake and resulting acidification is assumed to be considerable (Schuurkes & Mosello, 1988).

### *In situ enrichment experiments*

The relationship between the concentration of $NH_4^+$-N in stream water and its retention by a section of stream was measured on June 26 and 27, 1990 (Exp. Ia). The time relationship and rate of the $NH_4^+$-N retention was studied on July 14 and 16, 1991 (Exp. Ib).

A stock solution of $NH_4$ Cl and/or $NH_4$ Cl + NaCl (chloride was applied as a conservative tracer) was continuously introduced by a 5 l dropping-bottle into a small waterfall about 3 m upstream from a little pool, the outflow of which we considered as the starting point of the experimental section during the experiments Ia and Ib. The rate of addition of the spike solution was constant (55 ml min$^{-1}$), but its concentration was different in every experiment according to the actual stream discharge and the desired initial concentration of ammonium. The background concentration of Cl$^-$ (0.34 to 0.38 mg l$^{-1}$) was thus increased by about 0.5 to 1.0 mg l$^{-1}$ at the starting point. The end points of the section were in other small pools 71 m (Exp. Ia), and 60 m or 102 m (Exp. Ib) downstream of the starting point. Between the start and end points there was neither a visible inflow nor a snow field, which could be an additional source of $NH_4^+$-N.

Water samples at the start and end points were taken before the experiment and 60 min. after its beginning in Exp. Ia. During Exp. Ib, samples were taken at the starting point at 10- to 15-minute intervals. Samples at the downstream sites were taken at 2- to 5-minute intervals until the concentration of ammonium became stable (plateau was found photometrically by a direct nesslerization method (Golterman & Clymo, 1969) immediately in the field) and then at 5- to 20-minute intervals during the steady-state period.

The streambed area overgrown with biota, which was submerged and/or sprayed during the experiments, and the mean water width was estimated for each 2-metre subsection by each of the authors separately, and then calculated for the whole section, as described by Howard-Williams et al. (1989).

The stream discharges at the start and end points were calculated using the known concentration of $Cl^-$ in the introduced stock solution, its dosing rate, and concentrations of $Cl^-$ in the stream water at the start and end points before and during the experiment (Triska et al., 1989a, b). The difference between downstream and upstream discharges represents subsurface water infiltration into the section.

Volume ($V$) of the section was calculated as:

$$V = \frac{M_{In} - M_{Out}}{C_E - C_B},$$

where $M_{In}$ and $M_{Out}$ are amounts of $Cl^-$ (g) which passed into and out of, respectively, the section during the time period between the beginning of the experiment and reaching the plateau concentration of $Cl^-$. $M_{In}$ was calculated as the sum of mass-balances of $Cl^-$ in subsurface water infiltration and in the stream water at the starting point of the section. $M_{Out}$ was obtained by integrating the relationship of $Cl^-$ flux vs time at the downstream site. $C_E$ is plateau and $C_B$ is background concentration of $Cl^-$ (g m$^{-3}$) at the end point of the section.

Mean water depth and stream velocity were calculated from the discharge, volume, length, and mean width of the stream.

The predicted concentration of $NH_4^+$-N in stream water at the end of the section (assuming no retention of ammonium within the stream) was calculated as described by Richey et al. (1985), using initial concentrations of $NH_4^+$-N and their dilution by infiltrating water.

In all these calculations, we supposed that the background concentration of $Cl^-$ in stream water did not change by infiltration, and we neglected the concentration of $NH_4^+$-N in the infiltrating water (the background concentrations of $NH_4^+$-N varied from 14 to 34 $\mu$g l$^{-1}$ at the upstream site and from 3 to 14 $\mu$g l$^{-1}$ at the downstream sites before the experiments).

*Enclosure experiments*

Uptake of $NH_4^+$-N by streambed bryophytes and its nitrification were determined from changes in ammonium and nitrate concentrations during the incubation of the sample (Exp. II). These experiments were performed in July 1991 and June–July 1992. Samples of bryophytes were carefully taken from the streambed of the brook, so as not to damage their bottom part (rhizoids with retained organic detritus and inorganic sediments). Each sample was divided into 2 parts of approx. equal area (15 to 50 cm$^2$), and each was placed in one of two 500-ml polyethylene bottles, one wrapped in aluminium foil to keep the sample in darkness. Then the sample was covered with 200 to 400 ml of 40 $\mu$m filtered stream water enriched by ammonium. The final concentrations of $NH_4^+$-N ranged from 120 to 515 $\mu$g l$^{-1}$ at the start of incubation, in order to simulate high ammonium loads during snowmelt. Both the light and dark bottles were submerged in the stream. Subsamples of 50 ml of water for chemical analysis were taken immediately after adding the spike and after termination of the experiment, which lasted 3 to 5 hours. Alternatively, the entire experiment was performed at 15 °C in the laboratory on the day after sampling.

Samples were incubated at pH of original stream water. In one of the incubations, when the response of $NH_4^+$-N uptake and nitrification to the drop in pH was studied, samples of bryophytes from nonacidified stream (pH = 6.10) were also incubated in water from the acidified stream (pH = 4.65).

*Chemical analyses and error estimates*

Samples for ammonium, nitrate, nitrite, and chloride determination were filtered immediately after collection through Whatmann GF/C filters (prewashed with original stream water), transported to a field laboratory in polyethylene bottles, and assayed within 5 hours after termination of the experiment.

Ammonium was determined by the rubazoic acid method (Procházková, 1964), as modified by Kopáček & Procházková (1993), nitrate by reduction to nitrite using alkaline hydrazine (Procházková, 1959), nitrite following Bendschneider & Robinson (1952), and chloride according to Zall et al. (1956). Alkalinity was determined by Gran titration (Mackereth et al. 1978); pH was measured in the field with a pH meter (Radiometer PHM 29b) after standardization of glass electrodes (Radiometer) with 10$^{-4}$ M HClO$_4$. The samples of bryophytes (Exp. II) were dried at 105 °C, and organic and inorganic matter were determined at 550 °C as, respectively the loss of weight on ignition (LI) and total residue (TR).

*Table 1.* Experimental conditions and load calculations for Exp. Ib.

| | Units | Date of experiment (1991) | |
| --- | --- | --- | --- |
| | | July 14 | July 16 |
| *Background concentration:* | | | |
| Upstream site: | | | |
| $NH_4^+$-N | $10^{-3}$g m$^{-3}$ | 15 | 14 |
| $Cl^-$ | g m$^{-3}$ | 0.38 | 0.38 |
| *Downstream site:* | | | |
| $NH_4^+$-N | $10^{-3}$ g m$^{-3}$ | 5 | 8 |
| $Cl^-$ | g m$^{-3}$ | 0.38 | 0.38 |
| *Initial concentration:* | | | |
| $NH_4^+$-N | $10^{-3}$ g m$^{-3}$ | 302 | 296 |
| $Cl^-$ | g m$^{-3}$ | 1.11 | 1.07 |
| *Plateau downstream concentration:* | | | |
| $NH_4^+$-N | $10^{-3}$ g m$^{-3}$ | 54 | 172 |
| $Cl^-$ | g m$^{-3}$ | 0.84 | 0.905 |
| *Experimental section:* | | | |
| Length | m | 102 | 60 |
| Mean water depth | $10^{-2}$m | 3.1 | 2.4 |
| Mean water width | m | 0.71 | 1.20 |
| Volume | m$^3$ | 2.24 | 1.77 |
| Overgrown and sprayed area | m$^2$ | 70 | 72 |
| Discharge (starting point) | $10^{-3}$m$^3$ s$^{-1}$ | 1.1 | 2.2 |
| Discharge (end point) | $10^{-3}$ m$^3$ s$^{-1}$ | 1.74 | 2.89 |
| Stream velocity | m s$^{-1}$ | 0.050 | 0.076 |
| Residence time | min | 34 | 13 |
| *Mass-balance:* | | | |
| Input of $NH_4^+$-N[1] | g | 4.38 | 6.83 |
| Output of $NH_4^+$-N DI[2] + AI[3] | g | 1.21 | 5.20 |
| Net retention of of $NH_4^+$-N[4] | g | 3.17 | 1.63 |

[1] Sum of background plus added amount of $NH_4^+$-N at the starting point.

[2] Output of $NH_4^+$-N from the experimental section during infusion of stock solution.

[3] Output of $NH_4^+$-N from the experimental section after infusion of stock solution was finished.

[4] Difference between the input and total output of $NH_4^+$-N.

Results of the enclosure experiments are calculated as N uptake per unit area of bryophytes periphyton (mg m$^{-2}$ h$^{-1}$) to be easier comparable to the results of *in situ* enrichment experiments. Conversion to approximate values of the $N$ uptake per unit mass of organic matter (in mg of N per g$_{LI}$ of bryophytes) can be made by dividing mg m$^{-2}$ by 820, since the mean value of LI was 820± 260 g (± SD; n = 11) per 1 m$^2$ of bryophytes periphyton.

Error for uptake length (Exp. Ib) was calculated according to Hart *et al.* (1992) and is given in Table 2. The sprayed and overgrown area of the streambed was estimated with about ± 20% error (based on differences between the authors' individual estimates for each subsection). Consequently, error for N uptake by streambed biota in the *in situ* enrichment experiments is also about ± 20%. Errors associated with the data on uptake rates and net retention values (Exp. II) were

*Table 2.* Some basic uptake parameters of the stream (Exp. Ib), calculated according to Stream Solute Workshop (1990) and Hart *et al.* (1992) using data from Table 1.

| | Units | Date of experiment (1991) | |
| --- | --- | --- | --- |
| | | July 14 | July 16 |
| Uptake of $NH_4^+$-N per area, $U^{(1)}$ | mg m$^{-2}$ h$^{-1}$ | 12.0 | 8.0 |
| Estimated error in $U$ | % | 20 | 20 |
| Uptake rate coefficient, $k_c^{(2)}$ | $10^{-4}$ s$^{-1}$ | 6.1 | 4.0 |
| Mass transfer coefficient, $v_f^{(3)}$ | $10^{-5}$ m s$^{-1}$ | 1.9 | 1.0 |
| Uptake length, $S_w^{(4)}$ | m | 82 | 190 |
| Estimated error in $S_w$ | % | 5 | 10 |
| Normalized uptake length, $S_w(n)^{(5)}$ | $10^3$ m$^{-2}$s | 75 | 86 |

(1) $U$ is calculated as net retention of $NH_4^+$-N per overgrown and sprayed area of the section.

(2) $k_c = \frac{u}{x} \cdot ln\frac{C_u}{C_x}$, where $u$ is stream velocity (m s$^{-1}$), $x$ is length of the section, and $C$ is background corrected concentration of $NH_4^+$-N, and the subscripts are: 0, initial; x, observed plateau after dilution correction.

(3) $v_f = h\,k_c$, where $h$ is water depth (m).

(4) $S_w = u/k_c$, where $u$ is stream velocity (m s$^{-1}$).

(5) $S_w(n) = S_w/Q$, where $Q$ is stream discharge (m$^3$ s$^{-1}$).

estimated from the differences in the results of duplicate incubations; relative errors of the averages varied from ± 4% to ± 13% with the mean value of ± 9%.

## Results and discussion

### In situ enrichment experiments

*1. Exp. Ia:* The five initial stream $NH_4^+$-N concentrations (the first two background, the others background with added nitrogen) at the starting point during Exp. Ia were 20, 34, 57, 145, and 465 μg l$^{-1}$. The predicted concentrations of $NH_4^+$-N at the downstream site (based on the assumption that $NH_4^+$-N behaves conservatively) were 13, 25, 38, 96, and 337 μg l$^{-1}$, and those observed were 3, 14, 26, 59, and 114 μg l$^{-1}$.

The data obtained show that actual concentrations of $NH_4^+$-N at the downstream site were significantly lower than predicted. Retention of $NH_4^+$-N by the stream section appeared to be constant (10 to 12 μg l$^{-1}$) at low, initial concentrations (20 to 57 μg l$^{-1}$), but it increased at higher concentrations.

The data do not allow a differentiation between two possible mechanisms of the increased retention of $NH_4^+$-N at its higher initial concentrations (>100 μg l$^{-1}$): an increased ammonium uptake by bryophytes or an increased physical/chemical adsorption of ammonium (Stream Solute Workshop, 1990).

*2. Exp. Ib:* Experimental conditions and load calculations for Exp. Ib are shown in Table 1. Input of $NH_4^+$-N was calculated as the sum of background and added amounts of $NH_4^+$-N at the starting point of the experimental stream section. Total output of $NH_4^+$-N from the section was obtained by integrating the area under the observed concentration of $NH_4^+$-N at the end point *vs.* time curve, and multiplying by the respective stream discharge. The calculation was performed for the time period from the beginning of the experiment until the time when the concentration of $NH_4^+$-N at the end point attained its background value again, once the infusion was stopped (see Fig. 1). The retention of $NH_4^+$-N by the experimental section (the net difference between the input and the output) was 3.17 g on July 14 and 1.63 g on July 16.

Concentrations of $NH_4^+$-N and Cl$^-$ at the end point increased rapidly during the passage of the pulse, then reached a plateau and became constant. After some time, concentrations of $NH_4^+$-N began to increase again, contrary to the tendency in concentrations of chloride (see Fig. 1). This phenomenon, observed in
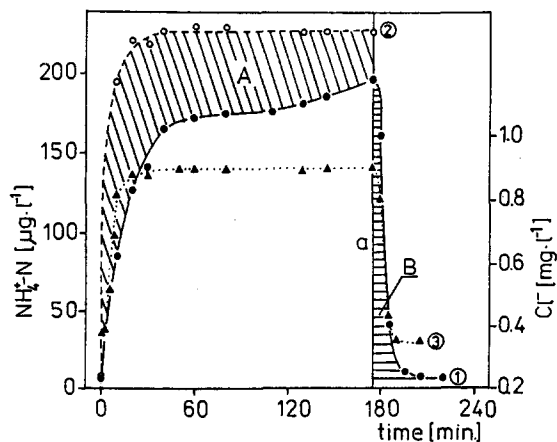
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*Fig. 1.* Ammonium and chloride concentrations *vs* time for the Exp. Ib at the end point of the experimental section (July 16, 1991): (1) observed concentrations of $NH_4^+$-N; (2) predicted concentrations of $NH_4^+$-N; (3) observed concentrations of $Cl^-$; (a) 175 min (the end of the infusion of $NH_4^+$-N); (A) area represents retention of $NH_4^+$-N during infusion; (B) area represents output of $NH_4^+$-N after infusion was finished.

all of the experiments, suggests a gradual saturation of the section by $NH_4^+$-N. Concentrations of $NO_3^-$-N were nearly equal at either sampling site before and during the experiments, and varied from 1310 to 1340 $\mu g$ $l^{-1}$ and from 1210 to 1250$\mu g$ $l^{-1}$ on July 14 and July 16, respectively. Nevertheless, they did not follow any apparent trend. Concentrations of $NO_2^-$-N at both the sampling sites were less than 2$\mu g$ $l^{-1}$ either before or during experiments. Downstream alkalinity and pH increased slightly both before and during experiments. This increase was related to the length of the section in the same way as the increases in concentrations of Ca, Mg, and Mn, which suggests the release of alkalinity from the bedrock. At the applied concentrations of $NH_4^+$-N, the release of alkalinity was higher than the production of strong acid generated by the consume of ammonium.

The main basic uptake parameters of the stream were calculated according to Stream Solute Workshop (1990) and Hart *et al.* (1992) (Table 2). The uptake rates of $NH_4^+$-N, related to the overgrown and sprayed area of the experimental section, were 12 and 8 mg m$^{-2}$ h$^{-1}$; the higher value obtained during lower stream discharge. Uptake rate coefficients (a measure of the uptake on a volumetric basis), calculated from initial and observed plateau (for dilution by infiltrating water corrected) concentrations of $NH_4^+$-N, were 6.1 $10^{-4}$ s$^{-1}$ on July 14 and 4.0 $10^{-4}$ s$^{-1}$ on July 16. Their inverses, representing the aver-

age turnover time of ammonium in the water column (Stream Solute Workshop, 1990), are 27 min. and/or 42 min. at the higher stream discharge. Mass transfer coefficients (a measure of the vertical velocity at which ammonium migrates through the bottom/water interface) were 1.9 $10^{-5}$ m s$^{-1}$ and 1.0 $10^{-5}$ m s$^{-1}$ on July 14 and 16, respectively. Considerably higher value of uptake length was obtained at increased stream discharge (the initial concentrations of $NH_4^+$-N were the same during Exp. Ib), which confirmed strong relation between the uptake length and discharge reported by Howard-Williams *et al.* (1989) and Stream Solute Workshop (1990). More comparable are the results of discharge-normalized uptake lengths (75 000 m$^{-2}$ s and 86 000 m$^{-2}$ s), calculated for the observed stream discharges (Hart *et al.*, 1992).

*Enclosure experiments*

*1. Ammonium uptake*: The mean value of $NH_4^+$-N uptake rate obtained in all 3- to 5-hour experiments (in field and laboratory) was 4.3± 1.1 mg m$^{-2}$ h$^{-1}$ (mean± standard deviation (SD), $n = 20$) and 6.0± 3.0 $\mu g$ $g_{LI}^{-1}$ h$^{-1}$ (mean± SD, $n = 11$) related to the sample area of bryophytes and to the organic matter, respectively. Uptake of $NH_4^+$-N was negligible in blanks without samples of bryophytes. The maximum velocities of $NH_4^+$-N uptake (6 to 11 mg m$^{-2}$ h$^{-1}$) occurred between the 1st and 3rd hours of enclosure experiments and agree well with the *in situ* results obtained in Exp. Ib.

No significant relationship was observed between $NH_4^+$-N uptake rates and the pH of the stream water in the range from 4.45 to 8.1. No significant differences in ammonium uptake were obtained in light or in dark bottles. The concentration of $NO_2^-$-N and the pH did not significantly change during these experiments.

Alkalinity, however, increased within a wide range, from 0.8 to 7.0 $\mu eq$ m$^{-2}$ h$^{-1}$ and/or 0.1 to 1.9 $\mu eq$ $g_{TR}^{-1}$ h$^{-1}$, according to the area of the sample and/or its inorganic matter. The production of alkalinity from inorganic sediments retained in the bottom part of bryophytes exceeded acid production from the ammonium conversion in these experiments. The alkalinity produced by weathering processes in the HTM is thus nowadays a sufficient buffer to acid production by biochemical conversion of ammonium in its common concentrations in precipitation.

The area of bryophytes used in enclosure experiments was at least 15 cm$^2$, so as to reduce the release of $NH_4^+$-N from damaged samples, which was observed

*Table 3*. Average $NH_4^+$-N uptake rate and $NO_3^-$-N release obtained during 3- to 5-hour enclosure experiments. (Light bottles, and temperature of between 7 to 11 °C in field and 15 °C in laboratory experiments).

| pH | Alkalinity[1] ($\mu$eq l$^{-1}$) | $NH_4^+$-N Initial conc: ($\mu$g l$^{-1}$) | Loading (mg m$^{-2}$) | Uptake[2] (mg m$^{-2}$h$^{-1}$) | $NO_3^-$-N Initial conc. ($\mu$g l$^{-1}$) | Release[2] (mg m$^{-2}$h$^{-1}$) | % of $NH_4^+$-N uptake |
|---|---|---|---|---|---|---|---|
| 4.45[3] | −35 | 195 | 180 | 5.8 | 670 | 0.0 | 0 |
|  |  | 515 | 105 | 2.6 | 685 | 0.0 | 0 |
| 4.65 | −30 | 320 | 32 | 3.5 | 440 | 0.0 | 0 |
|  | −15 | 415 | 54 | 5.6 | 440 | 0.5 | 9 |
| 6.30 | 27 | 120 | 55 | 4.9 | 455 | 2.3 | 47 |
|  |  | 315 | 51 | 2.3 | 455 | 1.2 | 52 |
| 6.40 | 18 | 210 | 34 | 4.5 | 655 | 1.8 | 40 |
|  |  | 410 | 34 | 4.9 | 640 | 2.3 | 47 |
| 8.10 | 880 | 275 | 33 | 5.2 | 420 | −4.2[4] | — |

[1] Gran titration.

[2] Estimated error in $NH_4^+$-N uptake and $NO_3^-$-N release is ±9%.

[3] These two experiments were done in laboratory.

[4] Uptake occurred instead of production.

*Table 4*. Average $NH_4^+$-N uptake rate and $NO_3^-$-N release obtained during 5-hour incubation of bryophytes, taken from 2 different sites of a non-acidified stream, in their original water (pH = 6.1) and in water taken from an acidified stream (pH = 4.65). Samples (area of 25 cm$^2$) were incubated at 15 °C in light bottles (laboratory).

|  | Unit | Sample 1 | | Sample 2 | |
|---|---|---|---|---|---|
| pH of water |  | 6.10 | 4.65 | 6.10 | 4.65 |
| *Initial concentration:* |  |  |  |  |  |
| $NH_4^+$-N | $\mu$g l$^{-1}$ | 310 | 320 | 310 | 320 |
| $NO_3^-$-N | $\mu$g l$^{-1}$ | 645 | 440 | 645 | 440 |
| *Final concentration:* |  |  |  |  |  |
| $NH_4^+$-N | $\mu$g l$^{-1}$ | 94 | 41 | 145 | 140 |
| $NO_3^-$-N | $\mu$g l$^{-1}$ | 680 | 515 | 705 | 525 |
| *Uptake*[1]: |  |  |  |  |  |
| $NH_4^+$-N | mg m$^{-2}$ h$^{-1}$ | 4.1 | 5.3 | 3.0 | 3.4 |
| *Production*[1]: |  |  |  |  |  |
| $NO_3^-$-N | mg m$^{-2}$ h$^{-1}$ | 1.4 | 1.4 | 1.1 | 1.6 |
| *Nitrification* of $NH_4^+$-N | % | 34 | 26 | 37 | 47 |

[1] Estimated error in $NH_4^+$-N uptake and $NO_3^-$-N production is ±9%.

[2] *Scapania undulata*

[3] *Bryum weigelii*

at the beginning of the enclosure experiments. This release was dependent on the area of the bryophytes as samples with smaller area show comparatively more damage than the larger ones. The release of ammonium from damaged samples probably arose from its desorption from the bottom part of the bryophytes, since streambed sediments are a significant pool of adsorbed ammonium (Rithey et al., 1985).

2. *Nitrification*: Nitrification of the added ammonium strongly depended on the pH of the stream from which the bryophytes were taken from (Table 3). Nitrification was significant in streams with pH of 6.3 and 6.4. It reached levels of about 50% of the retained $NH_4^+$-N in light bottles, and increased about 1.4 times in dark bottles. In acidified streams (pH<5), no significant production of nitrate was detected. In the alkaline stream (pH>8), where the original concentration of ammonium was zero, nitrate was utilized as the principal nitrogenous substrate, together with added ammonium. The $NO_3^-$-N uptake rate was considerably higher in light bottle (4.2 mg m$^{-2}$ h$^{-1}$) than in dark bottle (1.9 mg m$^{-2}$ h$^{-1}$).

Nearly the same values for the $NH_4^+$-N uptake rate and the related percentage of nitrification were observed during the 5-hour incubation of two samples of bryophytes from the nonacidified stream (pH = 6.1), in both their original water and in water from the acidified stream (pH = 4.65) (Table 4). The data obtained suggest that short-term drops in streamwater pH, which usually happen during rain or snowmelt periods, do not influence the ability of streambed biota to oxidize ammonium. Probably, as described by Rudd et al. (1988) in lakes, a longer time of decrease in pH under 5.4 is needed to disrupt nitrification.

The higher intensity of nitrification observed in the dark bottles confirms the significance of the photoinhibition of nitrification in shallow, transparent waters (Vrba,1990).

## Conclusions

The retention of $NH_4^+$-N by the stream was related to its initial concentration.

The mean value of the rate of $NH_4^+$-N uptake by streambed biota, primarily bryophytes, in 3- to 5-hour enclosure incubations was 4.3 mg m$^{-2}$ h$^{-1}$, and was not related to the pH of stream water. The maximum velocities of $NH_4^+$-N uptake (6 to 11 mg m$^{-2}$ h$^{-1}$) were obtained between the 1st and 3rd hour of incubation,

and agreed well with results obtained in 3-hour stream enrichment experiments (8 and 12 mg m$^{-2}$ h$^{-1}$).

Nitrification of the added $NH_4^+$-N was related to stream water pH; it was significant (about 50%) at pH of 6.3 and 6.4, and negligible in acidified streams (pH<5). Significant photoinhibition of nitrification was observed; the share of nitrification in ammonium uptake was about 1.4 times higher in dark than in light bottles.

A short-term decrease in stream water pH did not influence the ability of bryophytes taken from the bottom of a non-acidified stream to oxidize added ammonium.

Acid production, from biological conversion of the ammonium loads to which the High Tatra Mountains are exposed, did not exceed the production of alkalinity from weathering processes, in both the stream and the enclosure experiments.

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