

Water and element budgets in the Forellenbach area of the Bavarian Forest National Park

Vodní a prvková bilance území Forellenbach v Národním parku Bavorský les

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Abstract

The forest ecosystem in the Forellenbach area of the Bavarian Forest National Park has been monitored within the framework of the UN/ECE Integrated Monitoring Programme since 1990. Hydrological and hydrochemical characteristics of the area are quantified by water and element budgets for 1992 to 1995. Element budgets for the ecosystems of beech and spruce stands (B1 and F1 plots, respectively) showed high net losses of $\text{SO}_4\text{-S}$ from soils of $11\text{--}12 \text{ kg ha}^{-1}\text{a}^{-1}$. This reduction in the amount of stored sulphate will retard improvement of the quality of the soil water. Acid input into the soil is buffered by the release of Al ($10 \text{ kg ha}^{-1}\text{a}^{-1}$), which occupies most of the ion exchange sites in mineral soils, and is neutralized by the products of silicate weathering in the regolith. On a catchment scale, net export of acidity in the form of Al complexes is low, while sulphur input and output are balanced. Ninety percent of the total acid load from atmospheric deposition and internal sources is buffered by the release of basic cations ($2.2 \text{ kmol}_c \text{ ha}^{-1}\text{a}^{-1}$). Nitrogen budgets showed a net retention of about $10 \text{ kg ha}^{-1}\text{a}^{-1}$. Net N accumulation in beech ($12 \text{ kg ha}^{-1}\text{a}^{-1}$) and spruce ecosystems ($9.2 \text{ kg ha}^{-1}\text{a}^{-1}$) equals the annual net accumulation of standing biomass. Organic matter in the soil is considered to be the probable nitrogen sink. In contrast to beech plot B1, N losses in spruce plot F1 and the Forellenbach area as a whole accounts for about 40 % of the calculated total N deposition, indicating N saturation of the ecosystem.

Key words: forest ecosystem, element budgets, sulphate release, nitrogen storage

Introduction

Work began in the Forellenbach area in 1990 within the scope of the UN/ECE Integrated Monitoring Programme on Long-Range Transboundary Air Pollution Effects on Ecosystems. The purpose of this international programme is to document the present state of ecosystems and the changes caused by anthropogenic impacts, such as atmospheric contaminants, climate change, and changes in insolation (EDC 1993). These objectives require long-term observation of physico-chemical parameters and of biotic components of ecosystems that point to environmental changes. The Bayerische Landesanstalt für Wald und Forstwirtschaft (Bavarian State Institute of Forestry) was commissioned by the Umweltbundesamt (Federal Environmental Agency) with conducting the scientific programme in the Forellenbach area between 1990 and 1996. Since 1997, the Institut für Bioklimatologie (Bioclimatology Institute) of the University of Göttingen has been responsible for the programme.

The hydrological and hydrochemical characteristics of the Forellenbach area and estimates of water and solute budgets are presented in this paper. These budgets are for the hydrological years 1992 to 1995. The increasing death of spruce stands (NÜBLEIN & FAIBT 1998) due to infestation by the bark beetle (*Ips typographus* L.) since 1996 has caused drastic changes in the vegetation cover that significantly influence input, cycling and output of dissolved substances (BEUDERT, in prep.).

Site description

The Forellenbach experimental area (0.69 km²), located on a hillside in the Bavarian Forest National Park (gauging station: 48°5'38"N, 13°25'26"E), is a representative transect through the main forest types of this part of the Bavarian Forest. This transect is 2.9 km long with elevations between 787 and 1292 m. Mean elevation and inclination are 888 m and 12 %; 69 % of the area has a moderate slope (3–8 %).

The bedrock consists of coarse granite (Älterer Finsterauer Kristallgranit) of Carboniferous age. The lower elevations of the study area (58 %) are covered by sandy-loamy Dystric and Podzolic Cambisols 60–100 cm deep on periglacial deposits. At higher elevations, in the more eroded parts of the study area, these soils are associated with Rankers and Lithosols. Hydro-morphic soils (30 % of the area) are found around springs and on solifluction sediments whose bottom layers are compacted. Mineral soils are acidified, they have a pH_{KCl} of 3.1 in the topsoil layers and pH_{KCl} 4.0 at 45 cm depth and show low percent of base saturation and high degree of Al saturation (< 10 % and 80–95 %, respectively).

In 1990, forest covered 95 % of the Forellenbach area. The stand is dominated by 100-year old *Picea abies* (Norway spruce, 69 %) and about 70-year old *Fagus sylvatica* (European beech) with small amounts of *Acer pseudoplatanus* (sycamore maple). By 1997 the areal extent of the spruce stands had fallen to about 55 % (FAIBT 1998).

High annual precipitation rates (mean: 1319 mm), abundant snow cover, and comparatively low mean annual temperatures (5.6 °C) are characteristic of the climatic conditions (1972–1991, LANG & STRUNZ 1993) recorded at the official weather station in Waldhäuser (945 m elevation), about 3.5 km east of the Forellenbach area. The ambient air concentrations of SO₂ and NO₂ are relatively low. From 1991 to 1997 the annual means varied between 0.9 and 2.6 µg m⁻³ (SO₂) and between 3.7 and 5.2 µg m⁻³ (NO₂). The mean volume-weighted pH was 4.5 in the precipitation and 4.6 and 4.3 in the stand deposition on the B1 beech plot and the F1 spruce plot, respectively. The soil solutions at the lower boundary of the forest ecosystems (defined for the purposes of this programme to be at a depth of 100 cm) have pH values lower than 4.8. The most important ions in the soil water are Al complexes and SO₄²⁻. The runoff water (Forellenbach), however, is dominated by basic cations (e.g., Na⁺ and Ca²⁺) and HCO₃⁻; the median pH is 6.5.

Water and element fluxes are monitored on subplots (each 0.24 ha) in the spruce stand F1 (0.5 ha) and the beech stand B1 (0.5 ha), both growing on Dystric Cambisols, tending in some places to Podsollic Cambisols, in the lower parts of the study area (slopes < 5 %). In 1995, the spruce stand (about 110 years old, at 815 m elevation) had a timber volume over bark of 920 m³ ha⁻¹. The periodical volume growth increment of spruce of 7.3% (= 12.6 m³ ha⁻¹a⁻¹) between 1990 and 1995 was consistent with standard yield tables. The beech stand (about 87 years old, at 820 m elevation) showed a periodical volume increment of 18.9% (= 8.4 m³ ha⁻¹a⁻¹) that was much higher than could be expected from yield tables (13.1 to 16.6 %). A group of spruce contributed 120 m³ ha⁻¹ (= 31 %) to the total timber volume over bark of 383 m³ ha⁻¹. For more detailed site data, see BEUDERT et al. (1994, 1997).

Methods

The locations of the field stations and monitored forest stands are shown on the map (Fig. 1). The scientific subprogrammes conducted at each location are also indicated. Field and laboratory methods recommended in the official programme manual (EDC 1993) were used in order to obtain results that are comparable with results obtained in the other countries participating in this programme.

Sampling and measuring inputs

Monthly precipitation data was obtained from the Bayerische Landesanstalt für Wald und Forstwirtschaft and the Bayerisches Landesamt für Wasserwirtschaft (Bavarian Water Management Office). The data from the Forestry Office was obtained using rain gauges that prevent loss of collected precipitation, the data from the Water Management Office was obtained using LÖLF-type collectors. The amount of precipitation in the entire area was calculated using a linear interpolation approach (~100 mm per 100 m in elevation, see BEUDERT & al. 1997 and IBK, in prep.).

Runoff from the Forellenbach catchment was measured in a channel behind a V-notch weir. The water level was measured by detection of the air/water boundary using an electric conductivity instrument. One measurement per minute was made. The stage-discharge relation was confirmed by volumetric and current meter measurements.

The annual water balance of the soils was estimated from (a) the measured precipitation, (b) the canopy interception loss (calculated from precipitation minus throughfall), (c) the daily transpiration calculated according to Penman/Monteith (BAUMGARTNER & LIEBSCHER 1990, HANTSCHER 1987) and (d) the soil water storage determined at the end of each hydrological year. The annual soil-water flux is taken as the difference between the precipitation and evapotranspiration minus the changes in soil water amounts.

Wet and dry deposition was collected in polyethylene bottles with a collector opening of 321 cm². They were installed 125 cm above the ground and emptied weekly. For throughfall measurements in the beech and spruce stands (B1 and F1 plots, respectively), 15 samples per stand were combined to three mixed samples; for the measurements of the deposition in the precipitation collected at open sites, the contents of three collectors were mixed to form one sample. Soil water at 100 cm depth was sampled with four suction cup lysimeters in each stand by applying a continuous underpressure of about 400 hPa. Samples were taken every two weeks and combined to one mixed sample per stand.

Runoff water was sampled automatically (20 mL per 0.5 h). The combined samples for each day were stored at 2 °C for a maximum of one week. The sample of each Monday was analyzed.

Analytical methods

All water samples were treated identically before they were analyzed: The pH was measured with a glass electrode before filtration (0.45 µm); the samples were then stored at about 2 °C until analysis (about four weeks).

The deposition samples were analysed by the Umweltbundesamt (Federal Environmental Agency): pH with a glass electrode; Ca, K, Mg, and Na by atomic absorption spectroscopy; Cl⁻, SO₄²⁻, and NO₃⁻ by ion-exchange chromatography; and NH₄⁺ colorimetrically using a flow injection analyzer.

Runoff and soil water were analyzed by the Bundesamt für Geowissenschaften und Roh-

stoffe (Federal Institute for Geosciences and Natural Resources): pH with a glass electrode; Ca, K, Mg, Na, Al, Mn, and SiO₂ from acidified samples (10 N HNO₃) by ICP-OES using the method in DIN 38406-22; Cl⁻, SO₄²⁻ and NO₃⁻ by ion-exchange chromatography using the method in EN-ISO 10304-1; NH₄⁺ by spectral photometry using the method in DIN 38406-5; alkalinity (HCO₃⁻) by potentiometric titration to pH 4.3; DOC by IR spectroscopy after digestion with persulfuric acid under UV irradiation using the method in DIN 38409.

The average charge of Al complexes in the soil water was calculated according to KOPÁČEK & HEJZLAR (1998) assuming that fluoride (not analyzed) and organic ligands are negligible at DOC concentrations of 1 to 2 mg L⁻¹ (BEUDERT & al. 1997). Organic acid anions in mineral soil waters and runoff were estimated by the model of OLIVER & al. (1983) using a carboxyl content of 10 μmol_c per mg DOC and a mass action quotient calculated from sample pH. The average contribution of the organic anions to the negative charge of soil waters was about 2 % on spruce plot F1 and 10 % on beech plot B1 (IBK, in prep.). DOC in runoff was analyzed infrequently at high discharge, because DOC concentrations at base flow are less than 1 mg L⁻¹. Assuming 4 μmol_c per mg DOC (HAAG 1997) organic anions contribute less than 5 % to the negative charge of runoff water. Additionally, titration of alkalinity includes some organic anions.

Calculation of element fluxes

Element fluxes in the deposition were calculated by multiplying sample concentration (mg L⁻¹) by sample volume per unit area (L m⁻²). Total deposition within each stand was estimated using Ulrich's model (ULRICH 1988), with sodium as a tracer to take particulate deposition and interception of gases into account. Total deposition of basic cations in the Forellenbach area, which showed little variation with elevation, was calculated by extrapolating from the total deposition in the beech and spruce stands. For N, S, and H⁺ the steep gradients of the amount of deposition with respect to elevation in the spruce stands can be described by polynomial functions (BEUDERT & al. 1997). Estimates of the sum of organic anions and HCO₃⁻ fluxes were derived from anion deficits of the calculated total deposition of each stand and of the Forellenbach area.

Annual output of the elements studied was calculated by multiplying annual water flux estimates by the median element concentrations in soil water, which showed only little temporal variation at that depth.

Element output in the Forellenbach area was estimated by multiplying volume-weighted, monthly mean element concentrations according to EDC (1993) by the sum of the monthly discharge values.

Results

Water balance

From 1992 to 1997, precipitation h_N in the Forellenbach area averaged 1563 ± 230 mm a⁻¹, varying between 1317 mm a⁻¹ in 1996 and 1993 mm a⁻¹ in 1995 (Fig. 2). Runoff h_A averaged 942 ± 169 mm a⁻¹. The ratio of runoff to precipitation, $a = h_A / h_N$, remained nearly constant (0.60 ± 0.02) over this period, indicating undisturbed site conditions. The difference, $h_U = h_N - h_A$, which can be used as an estimate of evapotranspiration in the Forellenbach area, was 621 ± 68 mm a⁻¹. BEUDERT & al. (1997), however, included estimates of changes in the storage values for the soil and groundwater in the water balances for the hydrological years 1992–95. The evapotranspiration values (530–665 mm a⁻¹, mean: 614 mm a⁻¹) resulting from

inclusion of storage values in the water balance varied in the same way as the mean summer temperatures (11.6–12.5 °C), whereas the differences did not.

MORITZ & BITTERSÖHL (in prep.) found similar differences (1989–98: $h_U = 595 \text{ mm a}^{-1}$) for the adjacent Markungsgraben catchment, which is at a higher elevation (890–1355 m) than the Forellenbach area and thus has lower mean air temperatures (ELLING & al. 1987). Both the Forellenbach and Markungsgraben areas are part of the catchment of the Grosse Ohe, for which THUMS (1993) calculated a mean difference of 595 mm a^{-1} for the years 1980 to 1989.

Element budgets for the Forellenbach area

Calculated annual element fluxes in total deposition of cations (Na, K, Ca, Mg), inorganic nitrogen ($\text{NH}_4\text{-N}$, $\text{NO}_3\text{-N}$, ΣN), Cl⁻, $\text{SO}_4\text{-S}$ and H^+ are shown in Table 1 for the Forellenbach area. Nitrogen input (interception of gaseous N compounds by the canopy was not accounted for) averaged $17.2 \text{ kg ha}^{-1}\text{a}^{-1}$, almost equally divided between $\text{NH}_4\text{-N}$ and $\text{NO}_3\text{-N}$. Sulphate-sulphur and proton loads amounted to about $14.5 \text{ kg ha}^{-1}\text{a}^{-1}$ and $0.9 \text{ kg ha}^{-1}\text{a}^{-1}$, respectively, with relatively small variations in this 4-year period. Calculated total deposition in the Forellenbach area is about 15 % higher than in the F1 spruce plot, since 69 % of this area is below 900 m elevation. Therefore, the 2 to 3 times higher deposition loads in high-elevation spruce stands (BITTERSÖHL & al. 1997) are of minor influence. Low input fluxes of Na ($3.8 \text{ kg ha}^{-1}\text{a}^{-1}$), K ($2.6 \text{ kg ha}^{-1}\text{a}^{-1}$), Ca ($5.4 \text{ kg ha}^{-1}\text{a}^{-1}$) and Mg ($0.8 \text{ kg ha}^{-1}\text{a}^{-1}$) indicate the small contribution of particulate deposition in the Forellenbach area, which is far from industrial and agricultural emission sources. Relatively high variability for K and Ca indicates additional sources, especially in 1992 and 1995, and may be related to deposition and partial dissolution of pollen from flowering spruce.

Element input varies little, independent of precipitation, whereas element output, especially of $\text{SO}_4\text{-S}$ and Al, depends highly on stream discharge (Table 1). BEUDERT & al. (1994, 1997), analyzing runoff water chemistry in the Forellenbach area, found highly significant positive correlations between discharge and SO_4^{2-} and Al concentrations at the gauging station. High amounts of precipitation increases the proportion of soil water in the stream discharge, which results in higher concentrations of acidic components (but not NO_3^-) and decreasing concentrations of basic cations. Decreasing acid-neutralizing capacity during high flood events is related more to decreasing concentrations of basic cations than to increasing SO_4^{2-} concentrations. Using these relationships, HAAG (1997) separated the various components of the Forellenbach hydrograph on the basis of its chemical content. He showed that in 1994, which was considered to have average precipitation and runoff conditions, soil water contributed less than 20 % to annual discharge.

Consequently, year to year variations in $\text{SO}_4\text{-S}$ in the total element budget (Table 2) are highly dependent on the amount of runoff, while on average, input nearly equals output ($+0.5 \text{ kg ha}^{-1}\text{a}^{-1}$). There is an average net gain of about 0.8 kmol ha^{-1} in the proton balance, which nearly equals total H^+ deposition. The capacity of geosystems for buffering acids from atmospheric deposition and internal sources becomes evident by high net losses of Ca ($-21.9 \text{ kg ha}^{-1}\text{a}^{-1}$), Na ($-15.9 \text{ kg ha}^{-1}\text{a}^{-1}$) and Mg ($-4.5 \text{ kg ha}^{-1}\text{a}^{-1}$). Silicate weathering in the regolith is the most important mechanism for acid consumption, which is confirmed in this study by the high output rates of SiO_2 ($-88 \text{ kg ha}^{-1}\text{a}^{-1}$).

There is a net retention of $7.4 \text{ kg NH}_4\text{-N ha}^{-1}\text{a}^{-1}$ and of $2.3 \text{ kg NO}_3\text{-N ha}^{-1}\text{a}^{-1}$, which account for 90 % and 27 % of total deposition, respectively.

Element budgets of the spruce and beech ecosystems

In contrast to element budgets for the Forellenbach area as a whole, the ecosystem budgets of the F1 spruce plot and the B1 beech plot (Table 3) show an average net release of $\text{SO}_4\text{-S}$ of

about 11.2 and 12.4 kg ha⁻¹a⁻¹, respectively. For Al, which is the dominant cation at mineral soil exchange sites, there is a net loss at the lower boundary of the ecosystems of 9.5 and 10.0 kg ha⁻¹a⁻¹, respectively. Low net release of SO₄-S in 1992 may be an artifact resulting from the installation of the suction cup lysimeters. On the other hand, this year may mark the turning point from net accumulation of SO₄-S to net release in these soils.

Na fluxes are negative (F1: -2.4 kg ha⁻¹a⁻¹, B1: -3 kg ha⁻¹a⁻¹). Of the nutritional basic cations, Ca and K show net retention (+2 and +1.1 kg ha⁻¹a⁻¹) under beech in the B1 plot, and Ca and Mg show net losses of (-1.4 and -2.0 kg ha⁻¹a⁻¹) under spruce in the F1 plot. Mg fluxes in the beech stand and K fluxes in the spruce stand seem to be balanced.

Whereas 95 % of the nitrogen from the precipitation and particulate deposition was retained in the beech ecosystem on plot B1 (12 kg ha⁻¹a⁻¹), only 62 % of atmospheric input of nitrogen was retained in the spruce ecosystem on plot F1 (9.2 kg ha⁻¹a⁻¹). At the lower boundary of the ecosystems, nitrogen losses were due mainly to NO₃-N, while ammonium losses were negligible. In general, the beech ecosystem seem to be more effective than the spruce ecosystem in preventing the leaching of nutrient cations and nitrogen from the pedosphere.

Discussion

Before discussing changes in water quality during passage through ecosystems, aquifer and stream channel, the accuracy of the measured and estimated water fluxes has to be examined. Since Cl⁻ is considered to be an appropriate tracer substance, which interacts only little with soil solids or the biological cycles (MANDERSCHIED & al. 1995), input and output should be balanced at least in the long term. As shown in Fig. 3, Cl⁻ input and output for both the beech and spruce ecosystems, as well as for the Forellenbach area, are nearly balanced and show maximum annual deviations of 39 % from the calculated input. An exact water balance for one or only a few hydrological years cannot be expected. Firstly, throughfall measurements on spruce plot F1 indicate that Cl⁻ is subject to canopy leaching, especially in autumn (BEUDERT & al. 1997). This is confirmed by leaching experiments (MITTERHUBER & al. 1988) and the results of a factor analysis of the chemical content of throughfall in spruce stands in the Black Forest (BRAHMER 1990). Secondly, BEUDERT (in prep.) has shown that during the summer and autumn, transport of solutes through the soil profiles is retarded for several months. Additional problems are the high spatial variability of the element concentrations in soil solution (MANDERSCHIED & MATZNER 1995) and extrapolation of point measurements to unit areas.

The averaged nitrogen budget for the Forellenbach area as a whole (+0.68 kmol_c ha⁻¹a⁻¹) is strongly confirmed by soil nitrogen budgets for the individual stands. Net retention rates of 0.66 and 0.86 kmol_c ha⁻¹a⁻¹ in the spruce and beech stands, respectively, equal the annual net accumulation in the standing biomass within the Forellenbach and Grosse Ohe catchments (0.5–0.7 kmol_c ha⁻¹a⁻¹), estimated by BEUDERT & KENNEL (1995) using the Nutrient Cycling Model (NuCM) of JOHNSON & LINDBERG (1990). MANDERSCHIED & al. (1995) reported similar estimates for spruce ecosystems (0.7 kmol_c ha⁻¹a⁻¹) in the Solling region. But it is unclear whether these quantities were incorporated into the biomass of the trees or of the poorly developed understorey vegetation.

Balancing total deposition and throughfall fluxes of N on a plot scale (BEUDERT & al. 1997), nitrogen losses of about 0.37 kmol_c N ha⁻¹a⁻¹ (F1) and 0.21 kmol_c N ha⁻¹a⁻¹ (B1) become apparent. These losses can be related to the canopy uptake by needles (EILERS & al. 1992: 0.6 kmol_c N ha⁻¹a⁻¹) and leaves (BRUMME & al. 1992: 0.2–0.7 kmol_c N ha⁻¹a⁻¹) or by lichens and algae. Transformation into dissolved organic N compounds could have some relevance as well. Results from a neighboring spruce stand at 1000 m elevation (BITTERSÖHL & al. 1997) suggest

that organic N fluxes in throughfall account for 5 to 10 % ($1\text{--}2 \text{ kg ha}^{-1}\text{a}^{-1}$) of inorganic N fluxes.

N_2O and N_2 fluxes are not measured, therefore denitrification in these ecosystems cannot be quantified. Because the soils on the B1 and F1 plots have very high saturated hydraulic conductivities throughout the soil profiles (BEUDERT & al. 1994), denitrification should be of minor quantitative importance (DENDOOVEN 1996, GUNDERSEN 1991). Similar median nitrate concentrations in the output at the lower boundary of the spruce plot F1 ecosystem, in the groundwater, and the runoff (BEUDERT & al. 1997) indicate little denitrification in the unsaturated regolith and the aquifer.

The most important sink for the retained nitrogen is probably the organic matter in the soil. This can be demonstrated by a constant C/N ratio with humus accumulation (MATZNER 1989) or by a decrease in the C/N ratio. MEIWEES & al. (1999), for example, has reported storage values of $23\text{--}33 \text{ kg N ha}^{-1}\text{a}^{-1}$ for ecosystems in the Solling region over the last 30 years.

The differences in C/N ratios between the beech and spruce ecosystems illustrate the difference in the potential of the two types of stands for storing N. The soil on the F1 spruce plot has C/N ratios in the organic layer and the mineral topsoil of 22–25 and 17–19, respectively. The C/N ratios in the soil on the B1 beech plot are lower in both the organic layer (18–22) and the mineral topsoil (15–16) (BEUDERT & al. 1994). Thus, beech ecosystems seem to be more effective than spruce ecosystems in incorporating atmospheric N into the organic matter of the soil and reducing N losses via leaching.

According to Stoddard's system of nitrogen saturation (STODDARD 1994), the ecosystems of the F1 spruce plot and the Forellenbach area as a whole, in which spruce stands dominate, have to be classified as N saturated (stage 2, BEUDERT & al. 1997). This stage 2 is characterized by little seasonal variation in the nitrate concentration in the soil water, groundwater, and runoff, indicating that biological demand exerts no control over nitrate concentrations in winter and spring.

The criteria for this classification are (i) no month with a NO_3^- concentration in soil water and runoff $\text{L } 3 \mu\text{mol}_e \text{ L}^{-1}$ and (ii) at least three months during the growing season with a NO_3^- concentration $< 50 \mu\text{mol}_e \text{ L}^{-1}$ (TRAAEN & STODDARD 1995). The ecosystem of the B1 beech plot, however, belongs to stage 1 of "initial effects of chronic nitrogen deposition" (ABER & al. 1989), characterized by 1–2 months during the growing season with a NO_3^- concentration in the soil water $\text{L } 3 \mu\text{mol}_e \text{ L}^{-1}$. The differences between the spruce and beech ecosystems with respect to nitrogen retention coincide with differences in growth increments of timber volume over bark between 1990 and 1995 (see chapter Site Description). Beech seems to respond to additional N with increasing tree growth, while spruce did not.

In contrast to inorganic N compounds, there is a high net release of $\text{SO}_4\text{-S}$ in the beech and spruce ecosystems. Adsorption on sesquioxides surfaces and the formation of metastable mineral phases are important mechanisms of sulphate accumulation and acid buffering (REUSS & JOHNSON 1986). Because deposition of $\text{SO}_4\text{-S}$ in this region was about 50 % less in the first half of the nineties than in the eighties (BEUDERT & al. 1997), stored amounts of reversibly bound sulphate are not in equilibrium with the present sulphate and acid input. The reduction of the soil S pool by the release of sulphate, however, generates acidity irrespective of the mechanism (RASMUSSEN & al. 1988).

When acid producing and consuming processes in the soil are compared according to Van Breemen (Table 4) (VAN BREEMEN & al. 1982), the release of SO_4^{2-} contributes about 0.70 and $0.77 \text{ kmol}_e \text{ ha}^{-1} \text{ a}^{-1}$ to the total H^+ -load of 0.85 and $1.47 \text{ kmol}_e \text{ ha}^{-1} \text{ a}^{-1}$ in the spruce and beech stands, respectively. The release of acidic Al complexes is the most important mechanism of acid buffering (0.80 and $0.93 \text{ kmol}_e \text{ ha}^{-1} \text{ a}^{-1}$ in B1 and F1 respectively), the contribution of exchangeable base cations is low.

In contrast to the sulphate and Al budgets for the spruce and beech plots, the sulphate budget of Forellenbach area is nearly balanced and net export of Al is very low ($-0.02 \text{ kmol}_c \text{ ha}^{-1} \text{ a}^{-1}$), indicating efficient sorption mechanisms in the regolith. Elevated concentrations of Al and SO_4^{2-} were found only during high flood events (i.e. snow melt), when a higher proportion of acidic soil water enters the stream via subsurface flow (BEUDERT & al. 1994).

Carbonic acid from root and microbe respiration makes up about 50 % of the total acid load of $2.52 \text{ kmol}_c \text{ ha}^{-1} \text{ a}^{-1}$, while organic anions are of minor importance. Ninety percent of the calculated acid load is consumed by the weathering of minerals. The basic cations released are then unavailable to the vegetation.

Conclusions

High net losses of $\text{SO}_4\text{-S}$ at the lower boundary of both the beech and spruce ecosystems are due to a decrease of reversibly stored amounts. The improvement of soil water quality is retarded. The $\text{SO}_4\text{-S}$ budget for the Forellenbach area as a whole is nearly balanced, but increasingly reflects soil water characteristics with increasing precipitation and discharge.

Acid input is buffered in soils by release of Al and neutralized by bases produced by silicate weathering in the regolith. Storage of nitrogen, probably in soil organic matter, accounts for $9.2 \text{ kg ha}^{-1} \text{ a}^{-1}$ in the spruce and $12 \text{ kg ha}^{-1} \text{ a}^{-1}$ in beech plots. These amounts are 60 % and 90 % of the calculated respective total nitrogen deposition. With spruce being the dominant tree species in the Forellenbach area, net N retention of about $9.8 \text{ kg N ha}^{-1} \text{ a}^{-1}$ in the area as a whole is in good agreement with the values for the beech and spruce stands.

According to the criteria of ABER & al. (1989) and STODDARD (1994) for N saturation, the beech ecosystem on the B1 plot is still able to use and retain N deposition, while N losses of about 40 % of total N deposition indicate N saturation of the spruce ecosystem and the Forellenbach area as a whole.

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ECE - Integrated Monitoring Projekt

Forellenbach

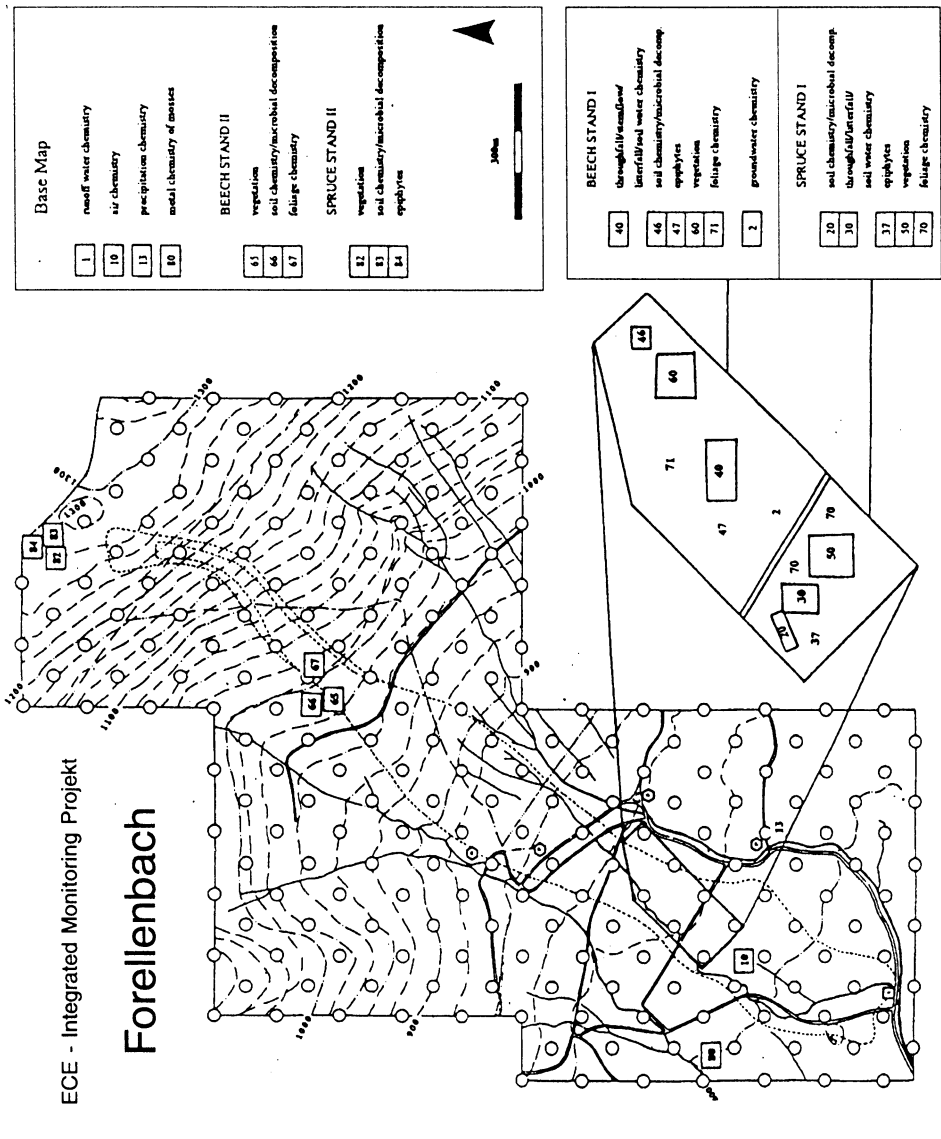


Figure 1. – Base map of the Forellenbach area. The location of field stations and monitored forest stands is shown. The scientific subprogrammes conducted at each location are also indicated.

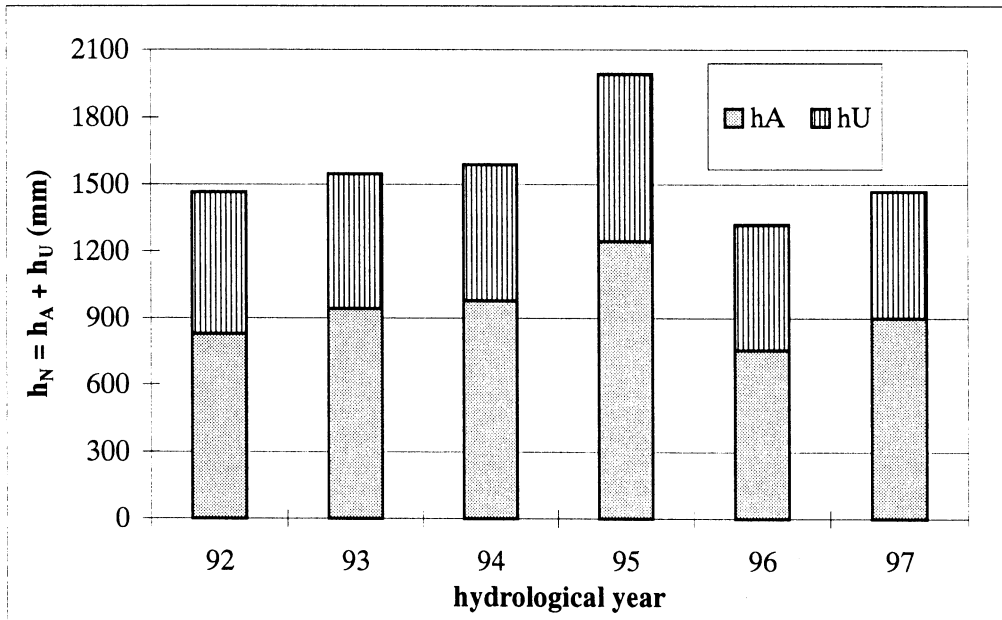


Figure 2. – Components of the annual water balance of the Forellenbach area (mm): precipitation h_N , ru-off h_A and the their difference $h_U = h_N - h_A$.

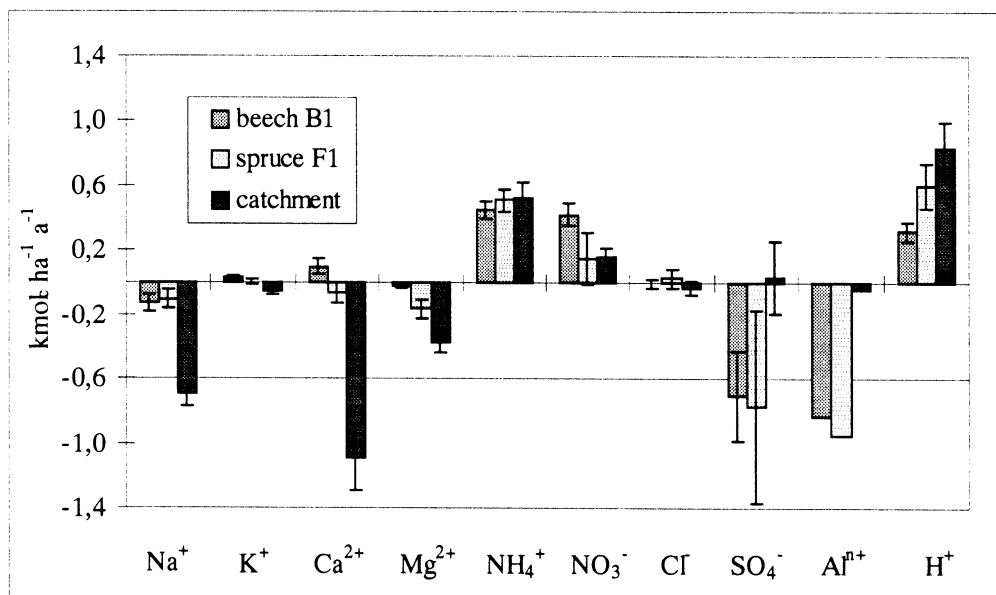


Figure 3. – Mean element balances and standard deviations for the B1 (beech) and F1 (spruce) ecosystems and the Forellenbach area as a whole (1992–95).

Table 1. – Annual water and element fluxes in the total deposition (TD) on spruce plot F1, beech plot B1 and the total Forellenbach area (TFA) and in seepage output (at 100 cm depth) and runoff output (O):(s: standard deviation).

N	Na		K		Ca		Mg		NH ₄ -N		Cl		NO ₃ -N		SO ₄ -S		H		MnAl		SiO ₂		HCO ₃ ⁻					
	TD	O	TD	O	TD	O	TD	O	TD	O	TD	O	TD	O	TD	O	TD	O	TD	O	TD	O	TD	O	TD	O		
F1																												
mm																												
92	493	3.1	3.8	2.8	1.7	6.1	5.9	0.9	2.1	8.7	0.2	9.3	5.7	8.2	6.6	14.5	14.7	0.9	0.1	0.9	0.1	0.9	6.6	22.8				
93	658	4.0	6.5	1.9	2.4	4.2	7.0	0.7	2.2	6.8	0.3	7.3	8.6	7.0	7.8	11.1	23.5	0.7	0.1	1.8	11.3	34.7						
94	1024	629	3.3	5.8	2.1	2.0	4.9	6.0	0.7	3.0	7.3	0.2	7.2	5.5	3.8	12.6	26.1	0.7	0.3	1.4	9.8	28.0						
95	1328	981	4.1	8.0	3.0	2.9	5.5	7.3	0.8	3.6	6.8	0.4	8.1	8.0	3.7	12.5	36.0	0.6	0.5	1.9	13.4	41.8						
Ø92-95	1080	690	3.6	6.0	2.4	2.3	5.2	6.6	0.8	2.7	7.4	0.3	8.0	7.0	7.6	5.5	12.7	25.1	0.7	0.2	1.5	10.3	31.8					
± s	167	207	0.5	1.8	0.5	0.8	0.7	0.1	0.7	0.9	0.1	1.0	1.6	0.6	2.1	1.4	8.8	0.1	0.2	0.4	2.8	8.2						
B1																												
92	1365	708	2.5	4.3	2.3	1.1	5.1	2.3	0.7	7.2	0.3	5.4	5.0	6.8	1.6	9.8	15.6	0.6	0.2	0.3	7.7	31.8						
93	1444	904	3.3	7.5	1.6	1.4	3.5	3.0	0.6	1.1	5.7	0.4	4.8	6.3	5.9	0.9	8.4	19.5	0.5	0.2	0.3	9.6	46.9					
94	1454	862	3.3	5.4	2.0	0.7	4.9	2.2	0.7	7.2	0.3	5.1	4.1	7.0	0.2	8.8	19.8	0.5	0.2	0.2	8.8	38.8						
95	1829	1247	3.8	7.5	2.7	1.2	5.1	3.0	0.7	1.0	6.3	0.5	6.0	6.2	7.4	0.6	10.2	27.0	0.5	0.2	0.3	12.7	51.1					
Ø92-95	1523	930	3.2	6.2	2.1	1.1	4.6	2.6	0.7	0.9	6.6	0.4	5.3	5.4	6.7	0.8	9.3	20.5	0.5	0.2	0.3	9.7	42.1					
± s	208	227	0.5	1.6	0.5	0.3	0.7	0.4	0.1	0.2	0.7	0.1	0.5	1.0	0.6	0.6	0.9	4.8	0.0	0.0	0.1	2.1	8.6					
TFA																												
92	1465	830	3.1	16.8	2.9	4.3	6.2	23.6	0.9	4.4	9.5	0.4	8.7	7.7	8.9	6.2	16.0	11.3	1.1	0.0	0.1	1.6	70.4	1.5				
93	1547	942	4.0	20.0	1.9	4.5	4.3	30.8	0.7	5.0	7.5	0.8	7.0	8.8	7.7	6.7	12.6	12.7	0.7	0.1	0.1	1.4	80.8	1.4				
94	1588	978	3.6	19.4	2.3	4.8	5.3	25.0	0.8	5.4	9.1	1.5	7.2	7.9	8.8	5.4	14.9	13.6	0.8	0.0	0.1	1.5	86.3	1.6				
95	1993	1245	4.3	22.2	3.2	5.7	5.9	29.8	0.8	6.4	7.9	1.8	8.1	10.8	9.3	7.1	14.5	18.4	0.8	0.0	0.1	2.5	114.9	1.7				
Ø92-95	1648	999	3.8	19.6	2.6	4.8	5.4	27.3	0.8	5.3	8.5	1.1	7.7	8.8	8.7	6.4	14.5	14.0	0.9	0.0	0.1	1.7	88.1	1.5				
± s	235	176	0.5	2.2	0.6	0.6	0.9	3.5	0.1	0.8	1.0	0.6	0.8	1.4	0.7	0.7	1.4	3.1	0.2	0.0	0.0	0.5	19.1	0.1				

Table 2. – Annual input-output budgets of the Forellenbach area (- net loss, + net gain, s: standard deviation).

	Na	K	Ca	Mg	NH ₄ -N	Cl	NO ₃ -N	SO ₄ -S	Al	SiO ₂	H ⁺
kg ha ⁻¹										kmol ha ⁻¹	
1992	-13.7	-1.4	-17.4	-3.6	+9.1	+1.0	+2.7	+4.7		-70	+1.1
1993	-16.0	-2.5	-26.5	-4.2	+6.7	-1.8	+1.0	-0.1		-81	+0.7
1994	-15.8	-2.6	-19.7	-4.7	+7.6	-0.7	+3.4	+1.3		-86	+0.8
1995	-17.9	-2.5	-23.9	-5.6	+6.1	-2.7	+2.1	-3.9		-115	+0.8
∅ 92-95	-15.9	-2.3	-21.9	-4.5	+7.4	-1.1	+2.3	+0.5	-1.5*	-88	+0.8
± s	1.7	0.6	4.1	0.9	1.3	1.6	1.0	3.5		19	0.2

*Estimate of unmeasured Al input from GIETL (1990); SiO₂ input considered zero.

Table 3. - Annual input-output budgets for F1 (spruce) and B1 (beech) ecosystems (- net loss, + net gain, s: standard deviation).

	Na	K	Ca	Mg	NH ₄ -N	Cl	NO ₃ -N	SO ₄ -S	Al	SiO ₂	H ⁺
kg ha ⁻¹										kmol ha ⁻¹	
1992	-13.7	-1.4	-17.4	-3.6	+9.1	+1.0	+2.7	+4.7		-70	+1.1
1992	-1.8	+1.2	+2.7	0.0	+6.9	+0.3	+5.1	-5.9			+0.4
1993	-4.2	+0.2	+0.5	-0.5	+5.4	-1.6	+4.9	-11.2			+0.3
1994	-2.1	+1.2	+2.6	+0.0	+6.9	+1.0	+6.8	-11.0			+0.3
1995	-3.7	+1.6	+2.1	-0.3	+5.8	-0.2	+6.7	-16.8			+0.3
∅ 92-95	-3.0	+1.1	+2.0	-0.2	+6.2	-0.1	+5.9	-11.2	-9.5*	-42	+0.3
± s	1.2	0.6	1.0	0.2	0.8	1.1	1.0	4.5			0.1
F1											
1992	-0.7	+1.1	+0.2	-1.2	+8.5	+3.6	+1.6	-0.1			+0.8
1993	-2.5	-0.5	-2.9	-1.5	+6.5	-1.3	-0.9	-12.3			+0.6
1994	-2.5	0.0	-1.1	-2.3	+7.0	+1.7	+3.3	-13.5			+0.6
1995	-3.9	+0.1	-1.7	-2.9	+6.4	+0.1	+4.3	-23.5			+0.5
∅ 92-95	-2.4	+0.2	-1.4	-2.0	+7.1	+1.0	+2.1	-12.4	-10.0*	-32	+0.6
± s	1.3	0.7	1.3	0.7	1.0	2.1	2.3	9.6			0.1

* Estimate of unmeasured Al input from GIETL (1990)

Table. 4. – Calculation of acid producing and acid consuming processes ($\text{kmol}_e \text{ ha}^{-1} \text{ a}^{-1}$) in the ecosystems of B1 and F1 plots and in the Forellenbach area as a whole (1992 - 95) according to Van Breemen & al. (1982).

	B1			F1			Forellenbach area		
	in	out	net	in	out	net	in	out	net
$+ \text{H}^+_{\text{in}} - \text{H}^+_{\text{out}}$	0.49	0.17	0.32	0.74	0.14	0.60	0.86	0.03	0.83
$- \text{SO}^{2-}_{4\text{in}} + \text{SO}^{2-}_{4\text{out}}$	0.58	1.28	0.70	0.79	1.56	0.77	0.90	0.87	-0.03
$+ \text{NH}^+_{4\text{in}} - \text{NH}^+_{4\text{out}}$	0.47	0.03	0.45	0.53	0.02	0.51	0.61	0.08	0.53
$- \text{NO}^-_{1\text{in}} + \text{NO}^-_{1\text{out}}$	0.48	0.06	-0.42	0.54	0.39	-0.15	0.62	0.45	-0.17
$- * \text{A}^-_{\text{in}} +$	0.25	-0.17	0.35		-0.29	0.29		1.36	
DOC _{out}		0.06			0.05			0.11	
$\text{HCO}^-_{1\text{out}}$		0.02			0.01			1.54	
\sum acid load			0.83			1.47			2.52
$- \text{BC}_{\text{in}} + \text{BC}_{\text{out}}$	0.48	0.50	0.02	0.54	0.87	0.33	0.57	2.78	2.21
$- \text{Mn}^{2+}_{\text{in}} + \text{Mn}^{2+}_{\text{out}}$	0.001*	0.01	0.01	0.001*	0.05	0.05	0.001*	0.03	0.02
$- \text{Al}^{n+}_{\text{in}} + \text{Al}^{n+}_{\text{out}}$	0.02	0.83	0.80	0.02	0.95	0.93	0.02	0.04	0.02
\sum acid consumption			0.83			1.31			2.24

$\text{BC} = \sum \text{Na}^+, \text{K}^+, \text{Ca}^{2+}, \text{Mg}^{2+}$. Average charge of Al^{n+} complexes: $n = 2$ in deposition (GIETL 1990), $n = 2.3, 2.5$ and 1 in B1, F1 and runoff, respectively. *A: $\sum (\text{HCO}_3^-)$ and/or DOC) estimated from anion deficit of total deposition.