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Spatial and temporal variation of soil solution chemistry and ion fluxes through the soil in a mature Norway Spruce (Picea abies (L.) Karst.) stand

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Abstract. In this study we investigated the spatial and temporal variation in soil solution chemistry and of water and ion fluxes through the soil in a forest ecosystem. Our aim was to evaluate the relevance of these variations for the accuracy of average areal soil solution concentrations and ion fluxes with seepage at 90 cm depth.

Twenty spatially distinct 'subcompartments' of approximately 1 m^2 were established within a mature stand of Norway spruce and ceramic suction lysimeters were installed at depths of 20, 35 and 90 cm. A tensiometer was placed close to each suction lysimeter, and one throughfall sampler was established for each subcompartment.

Soil solution samples were analysed for major ions (H^+, Na^+, K^+, Ca^{2+}, Mg^{2+}, Mn^{2+}, Fe^{3+}, Al^{3+}, Cl^-, NO_3^-, SO_4^{2-}). We calculated water fluxes for each subcompartment separately by a numeric simulation of the soil water flux close to the lysimeters. The ion fluxes at each lysimeter were calculated by multiplying the simulated water fluxes with the ion concentrations on a fortnightly base. Averaging these 20 independent ion fluxes gave the areal average flux and an estimate of its statistical accuracy.

The spatial variation of ion concentrations in the soil solution was high with coefficients of variance ranging from 5% to 128%. Part of the spatial variation was related to stem distance. Temporal variation of the concentrations was less than spatial for most ions. The spatial variation of water and ion fluxes with seepage was also substantial; for example the fluxes of SO_4^{2-}-S calculated for each subcompartment ranged from 21 to 119 kg ha^{-1} yr^{-1}, with an arithmetic average of 47 kg ha^{-1} yr^{-1}. For H_2O, Mg^{2+}, Cl^-, and SO_4^{2-}, the spatial heterogeneity of seepage fluxes was largely explained by the heterogeneity of throughfall fluxes. No such relationship was found for nitrogen.

Despite using 20 replicates, the 95% confidence intervals of the average annual areal fluxes with seepage were found to be 20–30% for most ions.

Key words: forest, ion budgets, seepage output, soil solution, spatial variation, throughfall

Introduction

Numerous papers have been published on soil solution chemistry, ion fluxes with percolation water and on element budgets of terrestrial ecosystems over the last three decades (for overview see Harrison et al. 1989). However, little attention has been given to the problem of spatial variation of soil solution concentrations and water fluxes in the soil and their relevance for the accuracy of element budgets and areal averages of soil solution concentrations on a plot scale.

Only a few investigations have been made on spatial and temporal variation of soil solution chemistry in forest ecosystems. For soil solutions derived from suction cups, Alberts et al. (1977), Heinrichs & Meyer (1982), Raben (1988) and Matzner (1988) observed strong spatial variation at all soil depths. However, the number of samplers in these investigations ranged only between 3 and 10. Grossmann & Kloss (1994) investigated spatial variation in more detail using 20 replicates and reported significant variation depending on the ion considered but with coefficients of variance in the range of 12 to 79%.

Gunderson et al. (1994) and Koch & Matzner (1993) investigated soil solution concentrations as influenced by stem distance in Norway spruce sites. They found ion and depth dependent gradients relative to tree distance. A significant influence of stem distance on water fluxes in the soil was also observed by von Wilpert 1990, von Wilpert & Mies 1991 and Türk 1992.

However, to our knowledge, no investigations have been made about the consequences of these variations for the determination of ion fluxes with seepage. The ion flux with seepage is a function of the ion concentrations in the percolating soil solution and of the water fluxes. In a strict sense, it is not acceptable to average the ion concentrations derived from suction lysimeters over space or time and to calculate with these averages, e.g. annual ion fluxes. But in practice it is common to use bulked samples of soil solution to reduce the costs of the chemical analysis. In addition an average areal water flux is commonly used to multiply with the average concentration yielding an 'average' ion flux with seepage for a specific time (often a month). This procedure might be subject to systematic errors since the spatial patterns of ion concentrations need to be weighted by the local water fluxes.

The aims of this study were to investigate on a plot scale in high resolution

(1) the spatial and temporal variation of soil solution chemistry,
(2) the spatial and temporal variation of water fluxes through the soil,
(3) the influence of stem distance and throughfall fluxes on (1) and (2) and
(4) to investigate the consequences of the variation for the determination and accuracy of ion fluxes with seepage.

Methods

Site

The investigated Norway spruce (*Picea abies*, (L.) Karst.) stand 'Coulissenhieb' was planted in 1850. The site is about 2.5 ha and located in the

German Fichtelgebirge in the 'Waldstein'-watershed at an altitude of 800 m. The tree density is 322/ha. The slope of the site is less than 5% southwest.

Ground vegetation is represented by grass carpets of *Deschampsia flexuosa* interrupted by patches of *Vaccinium myrtillus*, areas lacking ground vegetation, and patches of *Calamagrostis villosa*. Average precipitation is about 1100 mm and the average annual temperature is 5.2 °C. The soil has developed from weathered granitic bedrock. Different soil types can be found on the plot. They were classified as mosaics of Cambisols and Cambic Podzols (FAO-System, according to Ochreopts and Spodosols, US Soil Taxonomy). The soil texture varies from loamy sand to loam.

The soil is very acid with pH ($CaCl_2$) < 4 and low base saturation (Na^+, Mg^{2+}, Ca^{2+}, K^+) of the NH_4Cl-extract (see Table 1).

Sampling of soil solution

The conceptual approach of this study was to determine the water fluxes through the soil and the ion concentrations in soil solution for 20 spatially distinct 'subcompartments' of the soil having a size of approximately 1 m^2 each. With this design, it was possible to estimate the spatial variation of soil solution concentrations and water fluxes independently and to calculate ion fluxes with percolation water for each of the 20 subcompartments.

Ceramic suction lysimeters (ceramic cups with 5 cm length and 2 cm diameter P80, Staatliche Porzellanmanufaktur Berlin) and tensiometers of the same size were used to collect soil solution and to measure soil water potential. The suction cups were cleaned with 0.1 m HCl, washed in deionized water prior to installation and equilibrated in the field for 8 month after installation in April 1992. The lysimeters were installed vertically by drilling a hole to the desired depth with the diameter of the lysimeter tube. Preferential flow of water at the tubes can be excluded from analysis of the tensiometer data. Tensiometers were installed in the same way using the same tubes.

Each subcompartment was equipped with 3 lysimeters in depths of 20, 35, and 90 cm and 3 tensiometers nearby at each depth. For each subcompartment, a bulk sampler with 326 cm^2 opening was established to measure the throughfall flux at the specific point. In total, 20 suction lysimeters and 20 tensiometers were installed per depth.

Tensiometers were placed approximately 20 cm away from the suction lysimeters. We tested if the tensiometers were influenced by the suction cups, but no such influence was found.

Samples of soil solution were taken at two-week intervals from 25 December 1992 to 28 December 1993 by applying constant suction to the cups (240–320 hPa). Tensiometer readings were done every 60 minutes and registered automatically.

Table 1. Average chemical properties of the soil.

Horizon	depth	pH	pH	C	N	H	Na	K	Ca	Mg	Mn	Fe	Al
	(cm)	(H_2O)	($CaCl_2$)	(g/100 g)		NH$_4$Cl exchangeable cations (μmol$_c$ g^{-1})							
A	0–8	3.53	2.82	3.62	0.128	28.10	1.53	1.32	4.21	0.91	0.04	6.70	88.92
B_{hs}	8–11	3.54	2.96	5.13	0.214	3.09	1.43	0.82	1.74	0.53	0.13	11.52	152.73
B_{sw}	11–20	3.96	3.77	3.15	0.137	0.57	1.32	0.77	0.67	0.18	0.05	0.32	69.72
B_wC_w	20–40	4.21	4.08	1.26	0.059	0.18	1.37	1.04	0.39	0.09	0.02	0.02	38.65
C_w	40–90	4.27	3.95	0.48	0.030	0.11	1.13	0.86	0.30	0.09	0.01	0.01	25.69

The water samples were analysed for major cations and anions. pH was measured with a glass electrode, major cations (Na^+, K^+, Ca^{2+}, Mg^{2+}, Mn^{2+}, Fe^{3+}, Al^{3+}) were measured by Inductively Coupled Plasma Spectroscopy (ICP-AES). Ammonium was determined colorimetrically with a flow injection analyser and major anions (SO_4^{2-}, NO_3^-, Cl^-) by ion chromatography (IC).

Calculating water fluxes

The water fluxes with throughfall were measured over two-week intervals and related to daily precipitation values according to the distribution measured with an automatic precipitation recorder at the site. Daily soil water fluxes were calculated by a one-dimensional numerical simulation model (SIMULA18, Manderscheid 1991, 1992) for each of the 20 subcompartments separately. The model calculates the fluxes based on the water budget:

$$FN = I + ET_a + A_s + \Delta R$$

where FN is the total precipitation, I the canopy interception, ET_a the actual evapotranspiration, A_s the seepage or capillary rise, and ΔR the storage change in the soil. Surface flow and lateral drainage were neglected. The SIMULA18 model consists of 5 submodels, each describing the major processes of the water budget:

- an infiltration model (throughfall or a snow model; Anderson 1976)
- an evapotranspiration model (Monteith 1990),
- a one dimensional continuity model, based on Darcy's law (Darcy 1856),
- a root uptake model (Feddes et al. 1976; Hornung & Messing 1984) and
- a runoff model.

The following meteorological data are necessary on a daily basis as model input: precipitation, throughfall, air temperature, air humidity, wind speed and global radiation.

The 5 soil horizons found on the site (see Table 1) were represented in the model by different water conductivity ($K(\psi_m)$) and water content ($\Theta(\psi_m)$) functions. The simulated soil matric potentials (ψ_m) were fitted against the measured ones by modifying the $K(\psi_m)$- and $\Theta(\psi_m)$-functions until sufficient agreement was reached. In this way the model was adapted to the local conditions of the 20 subcompartments.

This procedure rests on the following assumptions:

- the water fluxes are one-dimensional and homogeneous within the subcompartments, i.e. there is no preferential flow path.

- the root distribution is the same for all subcompartments. Because of the great disturbances root distribution was not investigated at each subcompartment. Rooting of Norway spruce is generally shallow. During modelling we assumed that 90% of the fine roots are located within the upper 25 cm of the soil.

Results

Spatial variation of ion concentrations in soil solutions

We will focus on the 90 cm depth because of its relevance for calculating output with seepage from the ecosystem. The major conclusions drawn from this data set are also confirmed by the results from the 20 and 35 cm depth. However, the spatial variation of soil solution chemistry and water fluxes in the upper soil layers was larger than at the 90 cm depth.

The spatial variation of the ion concentrations of the soil solution at 90 cm depth was substantial (Table 2) and varied with time. The maximum coefficients of variance (CV) were approximately twice the minimum CVs and exceeded 50% for most ions. No systematic change in CVs with time (e.g. seasonal effects) were detected. Highest variation was observed for Mn^{2+}, Ca^{2+} and NO_3^-.

As an example, the temporal variation of the SO_4^{2-} concentrations at 90 cm depth for each suction lysimeter is given in Fig. 1. The temporal variation of the concentration from a single lysimeter was small, but concentrations ranged from 5 to 16 mg SO_4^{2-}-S l^{-1} when comparing different lysimeters. A similar pattern can be observed for most other ions with the exception of NO_3^- which had a stronger seasonal dynamic with maximum peaks in July.

The number of samples required to match the real average can be calculated if the desired statistical precision is fixed. The computations follow the equation (Sachs 1984):

$$n_{\bar{x}} = \left(\frac{Z_\alpha}{\bar{x} - \mu}\right)^2 \cdot \sigma^2$$

where $n_{\bar{x}}$ = minimal number of samples, Z_α = z-value, here 1.96 for $\alpha = 0.05$, $(x - \mu)$ = demanded precision and σ = standard deviation of population. σ has to be estimated, in this case conservatively with $\sigma = s$, where s is the standard deviation of the sample. The precision $(\bar{x} - \mu)$ was fixed to ± 10% of the corresponding fortnight average, which can be seen as a moderate requirement. The computation requires normal distribution of the underlying data. This was tested with the W-Statistic Test (Shapiro et al. 1965; Anonymous 1990)

Table 2. Annual average ion concentrations of the soil solution at 90 cm depth, minimal (CV_{min}) and maximal (CV_{max}) fortnightly coefficients of variance and the required minimal (n_{min}) and maximal (n_{max}) number of samples (statistical security: 95%, demanded precision of the average: ± 10%).

	Soil Solution at 90 cm				
	$\bar{x}$	CV_{min}	CV_{max}	n_{min}	n_{max}
	mg l^{-1}	%			
H^+	0.09	5.1	127.4	1	528
Na^+	2.7	21.0	63.6	17	155
K^+	1.5	31.5	82.9	38	264
Ca^{2+}	3.4	43.5	62.5	73	150
Mg^{2+}	0.9	18.9	54.7	14	123
Mn^{2+}	0.4	45.8	128.3	81	633
Al^{3+}	6.2	20.7	74.1	17	211
Cl^-	3.3	5.2	42.1	1	68
NO_3^--N	5.6	44.5	75.8	76	221
SO_4^{2-}-S	9.3	15.3	46.8	9	84

for each ion, each compartment and each sampling date. The zero-hypothesis, that the values are normally distributions, could not be rejected at the 99% significance level.

The number of samples required to fulfill the chosen level of precision differs with the ions. Ever under conditions of low variation more than 20 replicates are needed for most ions (see Table 2). Under conditions of high spatial variation it is almost impossible to fulfill this level of precision at our site. Reducing the required accuracy of the average to ± 20% would reduce the number of samples by a fourth.

The spatial variabilities of soil solution chemistry can be partly explained by distance to the nearest tree.

Although significant relationships between the soil solution concentration and stem distance can be found for most ions (with increasing concentration approaching the stem), a substantial degree of explanation (54%) was only observed for SO_4^{2-}. The water flux with seepage did not explain the spatial variation of the concentrations since concentrations and water amount were not correlated (Table 3).

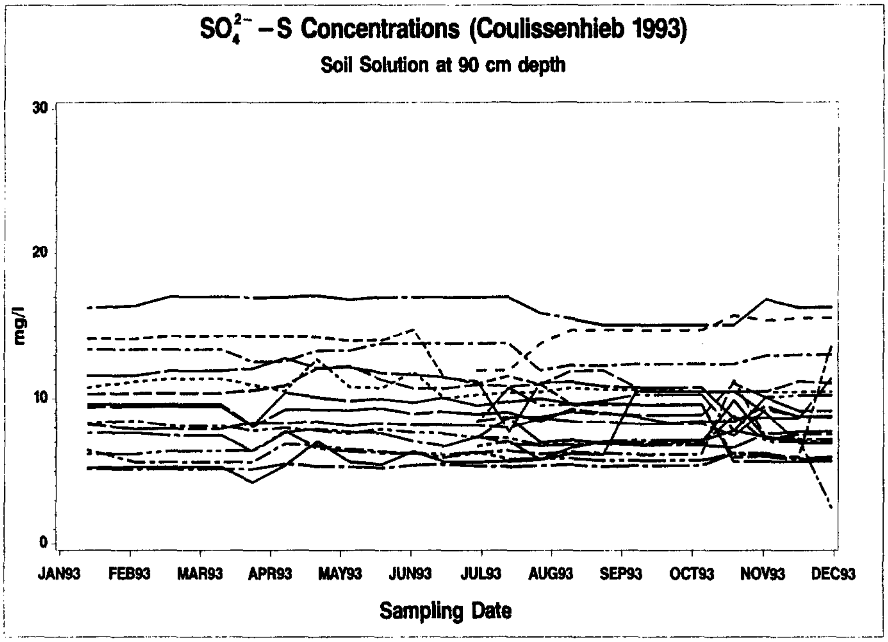

Fig. 1. Temporal development of the SO_4^{2-} -S concentrations in soil solution for each of the 20 suction cups (90 cm depth) during the sampling period.

Table 3. Correlations of soil solution concentrations at 90 cm depth to stem distance and to the flux of water with seepage.

	Soil Solution Concentrations at 90 cm vs.			
	Stem Distance		Water Fluxes	
	r^2	significance	r^2	significance
H^+	0.00	n.s.	0.17	s.
Na^+	0.22	s.	0.00	n.s.
Ca^{2+}	0.08	s.	0.00	n.s.
K^+	0.01	n.s.	0.00	n.s.
Mg^{2+}	0.18	s.	0.01	n.s.
Mn^{2+}	0.11	s.	0.01	n.s.
Al^{3+}	0.06	s.	0.00	n.s.
Cl^-	0.27	s.	0.00	n.s.
NO_3^--N	0.00	n.s.	0.01	n.s.
SO_4^{2-}-S	0.54	s.	0.01	n.s.

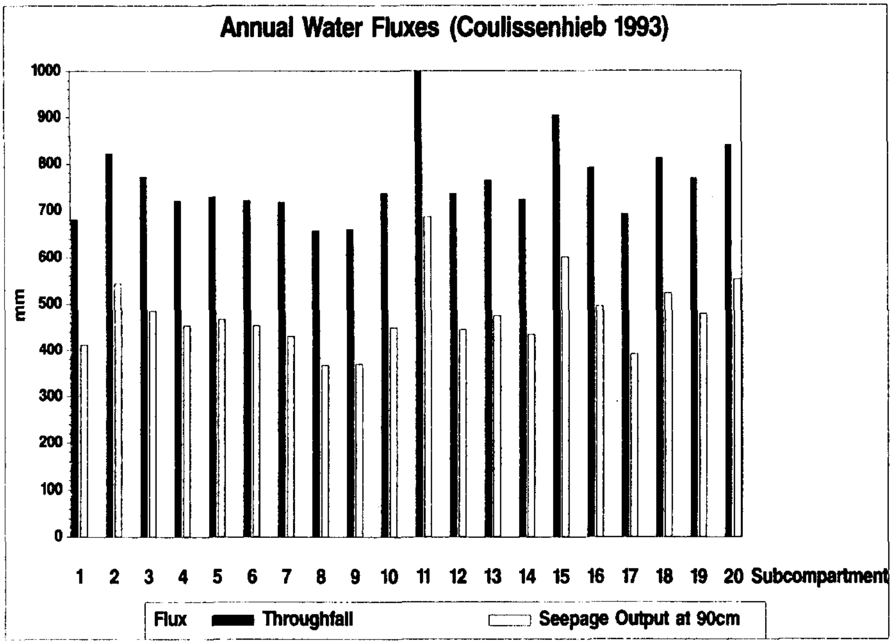

Fig. 2. Spatial variation of the water fluxes with throughfall and seepage output in 90 cm.

Water and ion fluxes

The spatial variation of water fluxes with throughfall and seepage at 90 cm depth is given in Fig. 2. Throughfall water fluxes ranged from 657 to 999 mm yr^{-1} with an annual arithmetic average of 763 mm yr^{-1} (total precipitation 1036 mm yr^{-1}). The spatial variation of water fluxes in the soil was ranging from 366 to 686 mm yr^{-1} when calculated for each subcompartment with an arithmetic average of 476 mm.

In order to evaluate the reason of the spatial variation of seepage fluxes we calculated correlations of throughfall and seepage fluxes for the 20 subcompartments (Table 4).

The spatial variations of the water, SO_4^{2-}, Cl^-, and Mg^{2+}-fluxes with seepage were highly correlated with the spatial patterns of throughfall. On an annual (but not shorter) time scale, water and ion fluxes through the soil strongly depended on the input with throughfall. Thus, other factors influencing spatial patterns of water and ion fluxes through the soil, such as root uptake, soil properties and mineralization were of minor importance. For NO_3^- and H^+, however, seepage fluxes were not correlated to throughfall.

Table 4. Correlations between ion fluxes with throughfall and seepage for the 20 subcompartments ($N_t = NH_4^+ + NO_3^-$).

	Throughfall vs. Seepage Output at 90 cm	
	r^2	significance
H_2O	0.98	s.
H^+	0.18	n.s.
Na^+	0.42	s.
Ca^{2+}	0.34	s.
K^+	0.09	n.s.
Mg^{2+}	0.61	s.
Mn^{2+}	0.17	n.s.
Al^{3+}	0.25	s.
Cl^-	0.71	s.
N_t	0.06	n.s.
SO_4^{2-}-S	0.89	s.

Generally element fluxes with seepage at the 20 subcompartments were highly correlated with water fluxes through the soil (not shown).

As outlined in the methods section, we calculated the annual ion fluxes with seepage through each subcompartment by multiplying the fortnightly water flux with the fortnightly ion concentration for each of the 20 subcompartments. The resulting spatial variation of the annual ion fluxes with seepage can be seen from the SO_4^{2-}-S-fluxes, which are given as an example in Fig. 3.

Throughfall fluxes of SO_4^{2-}-S varied between 18 to 60 kg ha^{-1} yr^{-1} (arithmetic average 31 kg ha^{-1} a^{-1}), but the spatial variation of SO_4^{2-}-S fluxes through the soil was even greater and ranged from 21 to 119 kg SO_4^{2-}-S ha^{-1} yr^{-1}, with an arithmetic areal average of 47 kg ha^{-1} yr^{-1}.

The spatial variation of the fluxes for other ions was similar to SO_4^{2-}-S (data not shown).

Calculating the ion fluxes for the 20 subcompartments independently results in an estimate of the accuracy of the areal average flux for the entire experimental site.

The spatial variation of throughfall fluxes was generally less than that for fluxes which is indicated by the 95% confidence intervals (Table 5). The 95%

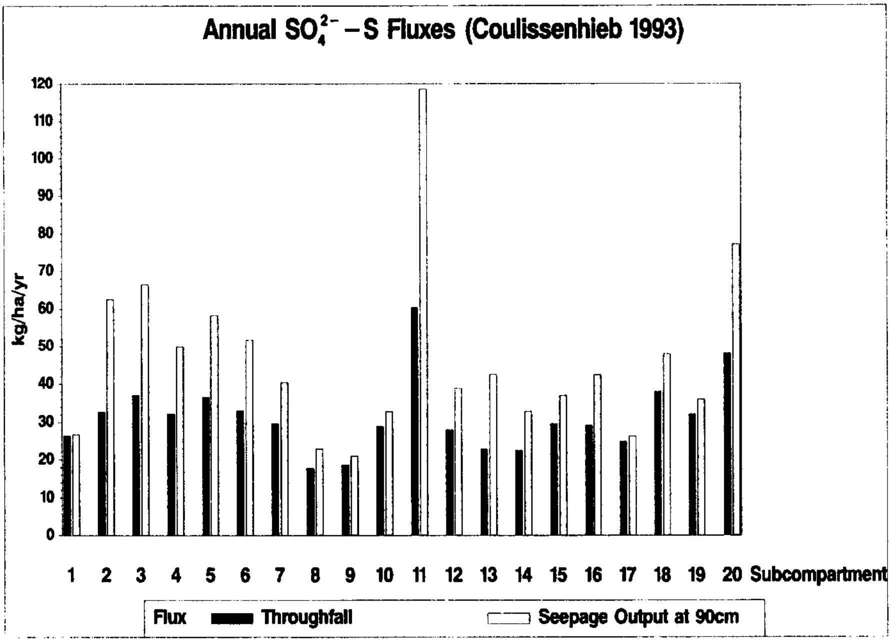

Fig. 3. Spatial variation of the SO_4^{2-}-S fluxes with throughfall and seepage output in 90 cm.

confidence intervals of the average annual fluxes differ according to the ion from 9% (Na^+) to 26% (NO_3^-) for throughfall and from 15% (Cl^-) to 42% (Mn^{2+}) for seepage output.

Discussion

Our aim was (1) to evaluate the spatial variation of soil solution chemistry and ion fluxes through the soil and (2) to estimate the statistical errors and attainable levels of precision for areal averages.

Studies on the spatial and temporal variations in throughfall volume and chemistry have been reported by Kimmins (1973), Parker (1983), Freiesleben et al. (1986) and Petersen (1992). Petersen (1992) found that diameter-corrected stem distance explains 50–85% of the variation of the chemical concentrations and of the throughfall volume. This result was obtained from 3 plots with 30 year old Sitka spruce. In our investigations the explanation level of stem distance is < 20% for throughfall and soil solution concentrations for most ions. This might be explained by the relatively low stem density and the height of the canopies in our 140 year old site.

Table 5. Arithmetic areal average ion fluxes in 1993 with throughfall and seepage and their 95% Confidence Intervals (95% CI).

	Fluxes with			
	Throughfall		Seepage Output at 90 cm	
	$\bar{x}$	95% CI	$\bar{x}$	95% CI
	$\frac{kg}{ha \cdot yr}$		$\frac{kg}{ha \cdot yr}$	
H^+	1.17	± 0.19	0.58	± 0.11
Na^+	6.06	± 0.57	6.10	± 2.15
K^+	23.09	± 3.51	6.48	± 1.70
Ca^{2+}	12.23	± 1.56	15.96	± 3.36
Mg^{2+}	1.48	± 0.24	3.89	± 0.65
Mn^{2+}	0.46	± 0.08	1.62	± 0.68
Al^{3+}	1.09	± 0.22	30.55	± 5.40
NH_4^+-N	8.44	± 0.80	n.d.	
Cl^-	12.14	± 1.26	14.82	± 2.40
NO_3^--N	13.69	± 3.94	24.39	± 5.94
SO_4^{2-}-S	31.41	± 4.30	46.58	± 9.89

The approach of calculating average water and ion fluxes from the fluxes of 20 independent subcompartments is unique and thus no direct comparison of the estimated statistical error with published data is possible.

Our findings about the spatial variation of soil solution concentrations under mature stands of Norway spruce are generally in agreement with the variation reported by Gunderson et al. (1994) and Grossmann & Kloss (1994). However, the variation at our site was slightly greater which is probably caused by the smaller stem density of our site as compared with others. Furthermore the soil conditions at our site can be considered as very heterogeneous on a plot scale, due to the mosaic of soil types.

The estimates of statistical errors indicate that a 95% confidence interval of the annual fluxes with throughfall and seepage of less than 15–30% seems unattainable under our site conditions with affordable expenditure. Thus the element budget for the whole site, calculated from total deposition and seepage water output, cannot be more accurate. In addition, the systematic and random error of estimating total deposition will have to be taken into account when evaluating the uncertainty of the ecosystem budget. This is not the subject of this study, however for most ions the errors of determining total deposition will be in the same range as those for seepage fluxes. This can be concluded for our site from the 95% confidence intervals of the throughfall fluxes. Thus, the element budget of the ecosystem will not be interpretable if there are only small differences between rather big fluxes (e.g.: total deposition vs. seepage). The difference between those fluxes will be interpreted as a process in the ecosystem. As an example the Ca^{2+}-flux with throughfall was 12.2 and with seepage 16.0 kg ha^{-1} a^{-1}. The 95% confidence intervals of each flux show that no conclusion on a sink or source function of the ecosystem is possible.

The potential errors of budgets especially need attention if long term budgets over several years are established (Matzner 1989). Systematic errors during the establishment of single fluxes will then add up over the years.

The reason for the spatial variation of seepage fluxes for most ions is the variation of throughfall and thus of ion and water input to the soil which is indicated by the correlation of the ion water fluxes with seepage and throughfall. This implies only little interaction of the ions in throughfall e.g., SO_4^{2-} and Mg^{2+}, with soil solids. No relation between throughfall and seepage fluxes was found in case of NO_3^-. Thus, the reason for the spatial variation of the NO_3^- fluxes with seepage must be spatial patterns of nitrification, immobilization and nitrate uptake by plants.

Correlations of the spatial patterns of throughfall ion fluxes to seepage fluxes on a plot scale have not been reported in the literature to our knowledge. For water fluxes, Goodrich et al. (1993) also pointed to the relevance of spatially stratified throughfall sampling for modelling seepage fluxes. Blanck et al. (1993) reported a reduction in the spatial variation of soil solution chemistry following the installation of a roof system underneath the canopy of a spruce stand and after artificial and spatially homogeneous irrigation of the soil with a constant throughfall concentration. Their results confirm our conclusion that throughfall chemistry is relevant for soil solution chemistry and seepage fluxes.

The spatial variation of throughfall fluxes within a forest stand is of special importance in small scale field experiments in biogeochemistry, like litter bag studies, soil columns, fertilizer, and tracer studies. In all of these cases, the location of the experiment will determine the actual ion input to the soil. The measurement of the actual input at the specific location is thus necessary if elemental budgets are established (like with soil columns) or if experimental findings are related to throughfall fluxes.

Our approach of evaluating spatial patterns of percolation water fluxes also has shortcomings: We assume an homogeneous water and ion flux through the stratified subcompartments. This might not be the case, because the suction cups were 30 cm away from the tensiometers and heterogeneity of soil solution chemistry within a few centimeters can be very high (Göttlein et al.

1995). Furthermore, the calculated water flux through the subcompartment was simulated by a mathematical model and might also be subject to systematic and random errors resulting, e.g., from the parameter fitting during computation and from errors connected to the model input variables. Thus, we cannot give an 'ultimate', 'real' ion flux with percolation water for the investigation stand. However, our estimate is a closer approximation to reality than previously used methods because it allows a calculation of statistical errors for an areal average seepage flux and avoids systematic errors inherent in multiplying average concentrations with average percolation water fluxes. The 'traditional' calculation of seepage fluxes by averaging concentrations and water fluxes revealed deviations of 0.6% (H^+) to 16% (Mn^{2+}) for the different ions and was thus relatively close to our new calculation. This is attributed 1) to the large number of replicates we used in this study. Using a smaller number which is very common, might have enlarged the difference. 2) to our site conditions, characterized by a low temporal variation of the soil solution concentrations, and 3) to the seepage flux of about 480 mm at our site which is relatively high and thus homogeneous as compared to sites with less seepage.

Conclusions

We conclude that

- the spatial variation of soil solution concentrations and seepage fluxes is largely depended on the spatial pattern of throughfall concentrations and fluxes
- the spatial variation of fluxes needs careful consideration in order to estimate the accuracy of fluxes and budgets
- a spatially stratified analysis of fluxes is an important tool to resolve the biogeochemical processes on a stand scale.

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