

Air pollution load of forest stands in Vojířov and the impact on soil and run-off water chemistry

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ABSTRACT: Research plots in Vojířov were established in a spruce stand and in a mixed stand. They are situated south of Jindřichův Hradec, near the border with Austria, on the ridge sloping to the Třeboň basin, exposed to western winds. The soils (Haplic Podzols) have developed on deep overlaps of eolian sands, between boulders of mica granite. Since summer 1991, the chemistry of precipitation water and run-off water from the O-humus horizon has been studied. Bulk deposition has been measured in the open area by the hunter's cottage Dubovice, where the chemistry of water in a local spring has also been studied. During the investigation the deposition of air pollutants in throughfall water was higher in the spruce stand than under beech trees in the mixed stand. In 1996, an increased deposition of pollutants was observed due to long-term winter period and high precipitation. This load of the ecosystem influenced soil water chemistry, mainly the chemistry of water in the spring, expressed by decreased pH, increase in SO_4^{2-} , F^- , Al, Mn, only slowly disappearing in the subsequent years. At the end of the nineties the emissions of H^+ , S/ SO_4^{2-} , F^- , $\text{N}(\text{NO}_3^- + \text{NH}_4^+)$ decreased more significantly under the spruce stand than under beech. On the contrary, pH of precipitation water decreased in the open area. Soil analyses, carried out in 1991 and 1999, confirmed certain improvement of bio-genous supply in the humus horizons and decrease in sorbed basic cations in the surface horizons of mineral soil, and increase in the supply in deeper horizons, but it still remains at a low level.

Keywords: spruce stand; mixed stand; beech; deposition; soil water chemistry; spring water chemistry; soil chemistry; precipitation; throughfall

Research plots in Vojířov were established in 1991 as study objects of the background load of forest ecosystems in wider surroundings of the nuclear power plant in Temelín (JETE). The results of investigations from the early nineties were published in the final report of the partial project *The Impact of JETE on Forest Ecosystems and their Ecological Role*. The project was a part of the main project of the co-ordinating centre T.G.M. Research Institute of Water Management called *The Impact of Temelín Nuclear Power Plant on Hydrosphere and Other Components of the Environment*, coordinated by Dr. Eduard Hanslík.

The aim of research was to determine the level of forest ecosystem load by foreign agents, where, besides typical air pollutants and heavy metals, radio-nuclides were also included. At the same time, the level of soil biological activity, nutrient supply of young stands, transpiration rate, and damage to needles by air pollutants were investigated.

After 1992, the investigation of precipitation water chemistry, both throughfall and bulk soil water chemistry, and chemistry of water in a water source (spring) is ongoing in other projects. It is an object of this report along with evaluation of deposition and soil characteristics.

METHOD

DESCRIPTION OF OBJECTS

Vojířov research plots are situated in the forest complex between the village of Lásenice and the state border with Austria. They are managed by the Forests of the Czech Republic – Jindřichův Hradec forest district. The spruce stand (67 B3) and the mixed stand (67 A5) are at the western border of Českomoravská vrchovina, above the Třeboň basin, near the hunter's cottage Dubovice. More detailed information on the stands is shown in Table 1. The plots are situated about 50 km from JETE, to the south-east, on a moderate slope, at the altitude of 560 m.

Granite is the bed-rock (two-mica and adamelite granite, of small to medium grains, partly porphyritic). The gaps in the slowly weathering mother rock are filled with deep layer of fine eolian sand. Podzolic soils, arenic, rich in humus and iron, have developed at this substrate (Haplic Podzols by FAO classification). The plots, situated at the altitude of 560 m, are at the border of forest zone 3 and 4, forest type 3K6 – acid oak-beech wood with *Deschampsia* sp., moderate slopes with deep layers of sand.

Table 1. Geographical and stand information on sampling sites on Vojířov plots

Plot	Gauss-Krieger		Altitude (m)	Species	Age 1991	Yield class	Forest type
	X	Y					
Open area	349850	543345	530				
Spruce stand	349855	543290	560	spruce	77	2	3K6
Mixed stand	349855	543290	560	spruce 30, beech 35, oak 20, fir 5, pine 5, larch 5	90	4 (beech)	3K6
Spring	349850	543345	530				

The load of forest ecosystems by air pollutants is expressed by the deposition with precipitation. It was moderate to low. It is also documented by SO_2 and F^- concentrations in the air measured at Dubovice since 1997. Daily SO_2 values did not exceed $20 \mu\text{g}/\text{m}^3$, and the monthly ones were below $5 \mu\text{g}/\text{m}^3$. To measure F^- concentrations, 2-week samples were analysed, and the concentrations were rarely above $1 \mu\text{g}/\text{m}^3$.

Measurements of conductivity in one-year-old spruce needles in younger stands situated about 300 m from the research plots, carried out in 1991 by Brejcha (LEDINSKÝ, BREJCHA 1992) provided the values much lower than the limit signaling slight damage ($140\text{--}150 \mu\text{S}/\text{cm}$).

Radio-caesium 134 and 137 activity in the upper soil horizons (Of, Oh, Ah), in spruce needles, mushrooms, lichens and mosses, and in blueberries was comparatively low, and much lower than on the plots Zdíkov-Kůsov (UHLÍŘOVÁ, KONEČNÝ 1994), but higher than on the plots in the surroundings of Temelín. Recently, an indirect investigation of heavy metal deposition by determining their concentration in eatable mushrooms collected in the plot surroundings was carried out by Dr. Uhlířová (UHLÍŘOVÁ et al. 2001; UHLÍŘOVÁ, HEJDOVÁ 1999) in the framework of the project aimed at extraneous matters in the food chain.

The low load of forest ecosystems on the two plots by heavy metals with the exception of Cd, and Hg is confirmed by the results of humus horizon analyses (Tables 6 and 7).

The results of assessment of the species composition of soil micro-organisms showed that the air pollution load at the locality of Vojířov was low only at the beginning of the nineties (HÝSEK, LETTL 1992).

WORK DESCRIPTION

Throughfall precipitation is collected in the stand into troughs, and water running off from the surface humus layer (O) into zero-tension lysimeters. Bulk precipitation is collected in the garden of the hunter's cottage Dubovice into a trough and snow-meter. There is also a spring in the garden where water is taken for analyses. Monthly samples are prepared both of precipitation and spring water and analysed in the Forestry and Game Management Research Institute (FGMRI) laboratory. Water from troughs and zero-tension lysimeters is conducted to containers placed in covered pits.

The analyses of water and soil (samples taken in 1991 and 1999) were carried out in an FGMRI lab according to the methods of an international monitoring programme (ICP Forests, level II).

To measure pH, a glass electrode was used. By 1993 SO_4^{2-} , NO_3^- , NH_4^+ , PO_4^{3-} ions were determined colorimetrically in Technicon Autoanalyser II, the concentrations of Cl^- and F^- with ion selective electrodes. Since 1994, to determine SO_4^{2-} , NO_3^- , Cl^- , F^- , an ion liquid chromatograph Thermoseparation Products has been used, and to determine NH_4^+ a colorimeter SAN Plus Analyser. Since then, total P in water is determined with spectrometer ICP OES LIBERTY 220 by Varian comp., as well as the concentrations of Na, K, Mg, Ca, Zn, Mn, Al, Fe, Cu. These cations were measured with spectrophotometer Varian Techtron in the past. To determine the supply of available cations, extraction with $1\text{N NH}_4\text{Cl}$ was used. To determine total element supply in the humus material, concentrated HCl was used for ash extract (1991), and extract with aqua regia (1999). Total organic carbon (C_{ox}) was determined by Tjurne method, and total nitrogen (Nt) by Kjeldahlization. To determine cations and metals in the extracts, the same equipment was used as for water analyses.

RESULTS

CHEMISTRY OF PRECIPITATION WATER AND DEPOSITION

Bulk precipitation water in the open area was collected into an open trough in the garden of the hunter's cottage Dubovice. Average annual pH values in 1991 to 1998 ranged from 4.85 to 5.15, but a significant decrease could be observed in 1999 and 2000 (Table 2a).

Average annual concentration of SO_4^{2-} decreased gradually from $6.00 \text{ mg}/\text{l}$ (1991) to $2.17 \text{ mg}/\text{l}$ in 1999. Contamination of F^- reached the average values from $0.012 \text{ mg}/\text{l}$ (1994) to $0.076 \text{ mg}/\text{l}$ (1996). During the investigation a decrease in the concentrations of other pollutants such as Al and Zn was also observed (Table 4).

Total annual deposition of H^+ ions was about $0.1 \text{ kmol}/\text{ha}$, and since 1999, with the pH decrease, it has increased to $0.32 \text{ kmol}/\text{ha}$ (2000 – see Table 3a). The annual deposition of SO_4^{2-} reached its maximum in 1996 – $48.56 \text{ kg}/\text{ha}$ and minimum in 2000 – $13.94 \text{ kg}/\text{ha}$. F^- deposition was the most oscillating, in 1996 it was $0.724 \text{ kg}/\text{ha}$, and in 1994 it was $0.085 \text{ kg}/\text{ha}$. The highest annual deposition

Table 2a. Average concentrations of elements in precipitation water on the plot Vojířov – open area

Year	pH	H	NH ₄ ⁺	NO ₃ ⁻ (mg/l)	F ⁻	Cl ⁻	SO ₄ ²⁻
II–XI/1992	4.85	0.01473	1.30	4.55	0.055	3.36	5.24
II–XII/1993	4.85	0.01342	0.32	3.39	0.046	3.50	4.48
1994	4.90	0.01312	0.33	3.40	0.012	4.70	4.49
1995	4.90	0.01299	1.20	3.04	0.045	3.71	3.79
1996	4.85	0.01416	0.84	3.22	0.076	3.86	5.13
1997	5.15	0.07440	0.62	2.47	0.039	4.11	3.17
1998	5.00	0.01100	0.66	2.57	0.036	3.32	3.72
1999	4.40	0.04189	0.98	3.20	0.031	5.67	2.17
2000	4.30	0.05392	0.93	3.58	0.021	3.80	2.17

Table 2b. Average concentrations of elements in throughfall water on the plot Vojířov – spruce stand

Year	pH	H	NH ₄ ⁺	NO ₃ ⁻ (mg/l)	F ⁻	Cl ⁻	SO ₄ ²⁻
1992	3.85	0.14369	5.01	9.02	0.162	3.86	24.28
III–XII/1993	4.35	0.03765	1.07	4.38	0.120	1.82	17.82
1994	4.25	0.06727	1.59	6.81	0.072	2.66	20.07
1995	4.50	0.03266	1.52	4.51	0.064	2.08	12.97
1996	4.05	0.09826	2.48	8.34	0.133	3.28	24.92
1997	4.30	0.04814	1.41	7.16	0.091	2.66	14.80
1998	4.15	0.07300	1.56	6.22	0.088	3.90	10.32
1999	4.45	0.03820	2.12	8.40	0.057	3.31	8.78
2000	4.40	0.03715	1.20	5.05	0.079	1.85	6.27

Table 2c. Average concentrations of elements in throughfall water on the plot Vojířov – mixed stand (beech)

Year	pH	H	NH ₄ ⁺	NO ₃ ⁻ (mg/l)	F ⁻	Cl ⁻	SO ₄ ²⁻
IV–XII/1991	5.05	0.00857	2.67	3.40	0.092	1.32	13.36
1992	4.60	0.02459	2.00	4.50	0.110	2.14	10.04
1993	4.95	0.01152	0.66	3.50	0.098	1.43	10.57
1994	4.80	0.01667	0.59	3.57	0.035	1.39	9.50
1995	5.25	0.00557	1.08	2.62	0.062	1.69	7.72
1996	4.70	0.01239	1.16	4.03	0.106	2.47	9.28
1997	5.00	0.01026	1.34	3.02	0.061	2.37	6.31
1998	4.90	0.03500	0.80	4.37	0.049	2.96	4.89
1999	4.80	0.01707	1.36	6.08	0.040	2.88	5.52
2000	4.45	0.03604	2.37	3.62	0.059	1.38	3.80

of N (NO₃⁻ + NH₄⁺) was determined in 1995 and 1996, it amounted to 13.44 and 12.91 kg/ha, respectively. Mainly the increase in NH₄⁺ was responsible for an increase in nitrogen (see Table 3a). Deposition of Al and Zn decreased during the period of investigations.

In 1991 and 1992 the pH value of throughfall precipitation in the spruce stand was lower than 4, in the following period it was above 4 (see Table 2b). Average SO₄²⁻ and F⁻ concentrations decreased during the investigation period, similarly like Al, Mn and Zn. Higher fluctuations in

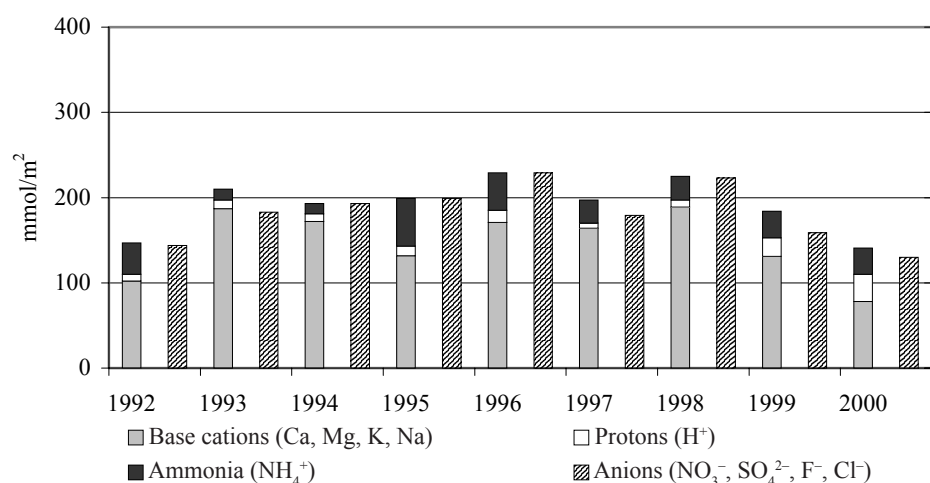


Fig. 1. Molar ratios of cations and anions in precipitation water on the plot Vojířov – open area

particular years could be seen with nitrogen compounds ($\text{NO}_3^- + \text{NH}_4^+$) and phosphorus compounds P (PO_4^{3-}).

Differences in ion concentrations and in the amount of collected throughfall precipitation caused fluctuations of the total annual deposition of H^+ ions between 0.484 kmol/ha (1996) and 0.103 kmol/ha (2000). In the

same years maximum and minimum values of F^- (0.721 kg and 0.216 kg), SO_4^{2-} (134.64 kg and 17.84 kg), $\text{N}/\text{NO}_3^- + \text{NH}_4^+$ (20.40 and 5.70 kg) per ha were recorded (see Table 3b). The total deposition of K, Ca, Mg and Mn with precipitation in the spruce stand was highest in 1996 and lowest in 2000 (Fig. 2).

Table 3a. Total deposition with precipitation water on the plot Vojířov – open area

Year	pH	H	NH_4^+	NO_3^- (kg/ha/year)	F^-	N	SO_4^{2-}
1992	3.06	0.0753	6.64	23.25	0.28	10.41	26.78
1993		0.0966	2.31	24.38	0.33	7.30	32.24
1994	4.07	0.0875	2.23	23.36	0.09	7.01	30.85
1995	3.97	0.1108	10.06	25.42	0.38	13.55	31.69
1996	4.51	0.1378	7.95	30.52	0.72	13.07	48.56
1997	4.27	0.0583	4.92	19.48	0.31	8.22	25.00
1998	4.12	0.0769	5.08	19.77	0.28	8.41	28.66
1999	4.38	0.2243	5.61	18.31	0.18	8.49	16.75
2000	4.27	0.3219	5.67	21.80	0.13	9.33	13.94

Table 3b. Total deposition of elements on the plot Vojířov – spruce stand

Year	pH	H	NH_4^+	NO_3^- (kg/ha/year)	F^-	N	SO_4^{2-}
1992	3.54	0.4345	15.43	27.74	0.50	18.25	74.64
1993		0.1687	4.06	16.64	0.46	6.90	67.62
1994	3.65	0.2227	3.77	25.60	0.27	10.01	75.43
1995	3.84	0.1430	6.65	19.73	0.35	9.12	56.76
1996	3.33	0.4838	13.43	45.07	0.72	17.71	134.64
1997	3.58	0.2631	7.70	39.13	0.50	14.55	80.87
1998	3.55	0.2879	6.61	26.33	0.37	16.51	43.66
1999	4.42	0.1308	7.51	31.68	0.22	12.49	33.11
2000	4.43	0.1034	3.34	14.04	0.22	5.13	17.84

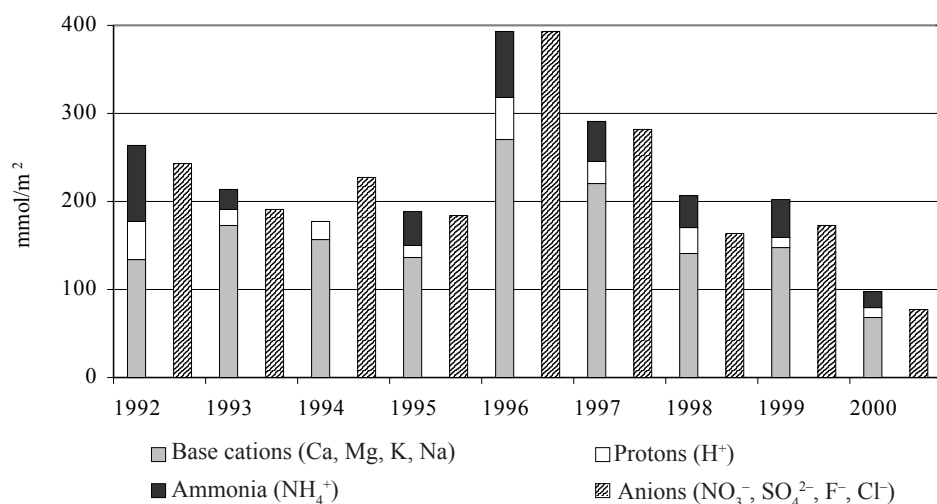


Fig. 2. Molar ratio of cations and anions in precipitation water on the plot Vojřov – spruce stand

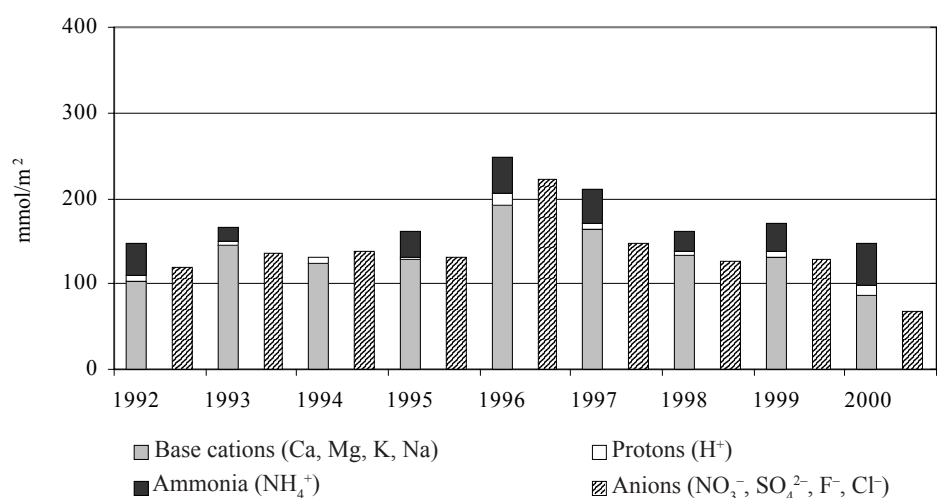


Fig. 3. Molar ratio of cations and anions in precipitation water on the plot Vojřov – mixed stand (beech)

Only throughfall, not the stem flow, was collected in the mixed stand (beech). Its average pH values were always higher than pH of throughfall precipitation in the spruce stand, in some years even higher than in bulk precipitation. Average pH values exceeded 4, they were even above 5

in 1991 and 1995 (Table 2c). The concentrations of SO_4^{2-} , F^- , and Al decreased between 1991 and 2000. In some years the average concentrations of NH_4^+ and P fluctuated due to increased throughfall concentrations in spring and summer months, which can be explained by the washing

Table 3c. Total deposition of elements on the the plot Vojřov – mixed stand (beech)

Year	pH	H	NH_4^+	NO_3^- (kg/ha/year)	F^-	N	SO_4^{2-}
1992	4.22	0.0851	6.93	15.57	0.38	7.41	34.76
1993		0.0482	2.78	14.65	0.41	5.98	44.25
1994	4.18	0.0714		16.07	0.16	7.82	42.74
1995	4.56	0.0277	5.35	13.00	0.31	8.40	38.27
1996	4.12	0.1372	7.71	27.36	0.71	16.49	61.92
1997	4.26	0.0550	7.20	16.22	0.33	12.72	37.84
1998	3.84	0.0503	3.93	21.48	0.24	14.56	24.03
1999	4.77	0.0676	5.54	24.84	0.16	11.77	22.54
2000	4.44	0.1344	8.83	13.53	0.22	5.15	14.17

down of products and remnants of insect and epiphyte microflora from tree crowns. Also in this mixed stand, deposition of most measured ions was highest in 1996. It was 0.137 kmol H⁺, 61.92 kg SO₄²⁻, 12.03 kg N/NO₃⁻ + NH₄⁺, and 0.705 kg F⁻. In 1993 the lowest annual deposition was determined for H⁺ (0.048 kmol) and N (5.39 kg), in 1994 for F⁻ (0.156 kg), and in 2000 for SO₄²⁻ (14.17 kg) – see Table 3c. Maximum and minimum deposition of Ca and Mg (Fig. 3) was measured in the same years as that of sulphates.

To classify the impact of deposition on the soil environment, besides the data on total annual deposition of air pollutants shown in Tables 3a, b, c, the valence values of the basic cations (Ca²⁺, K⁺, Mg²⁺, Na⁺), protons (H⁺), and ammonia ions (NH₄⁺) in precipitation water are shown in Figs. 1–3. These values are compared with the values of anion sums of strong acids (Cl⁻, F⁻, NO₃⁻, SO₄²⁻) in mmol/m² per year. PO₄³⁻ ions, directly measured until 1994, are not included among anions. Later on, total P was determined, however, according to the data from the early nineties, the deposition of PO₄³⁻ in the spruce stand can be

supposed in mmol/m² per year, and in the mixed stand in high total P deposition, in dozens of mmol/m². In the spruce stand, the difference between cation and anion deposition was higher, in favour of anions, than that in the mixed stand, where it was compensated by higher deposition of H⁺ and NH₄⁺ ions. In precipitation collected under beech trees of the mixed stand since 1997, the sum of basic cations was higher (mol⁺) than the sum of anions of strong acids (mol⁻), without valence values of H⁺ and NH₄⁺ ions.

In bulk precipitation (the garden in Dubovice) the amount of basic cations, protons, and ammonium ions was balanced or slightly higher than the amount of anions.

CHEMISTRY OF SOIL WATER

Throughfall water both in the spruce and mixed stand was enriched with humic matters (C_{ox}) in humus horizon O. The forest floor also affected an increase in H (to pH below 4), Ca, Mg, Fe, Al, P(PO₄³⁻) and NO₃⁻ concentrations, some smaller changes were observed in Na, K, and F⁻. With SO₄²⁻, Cl⁻, Zn and Mn higher concentrations were

Table 4. Average concentrations of elements in water on the plots of Vojřřov in two different periods

Sampling place	Period	pH	H	NH ₄ ⁺	NO ₃ ⁻	F ⁻ (mg/l)	Cl ⁻	SO ₄ ²⁻	PO ₄ ³⁻
Precipitation	1991–1995	4.85	0.0134	0.77	3.46	0.039	3.84	4.41	0.104
– open area	1996–2000	4.65	0.0222	0.79	2.98	0.044	3.80	3.61	0.080
Throughfall	1991–1995	4.20	0.0646	1.99	5.98	0.105	2.54	18.30	0.221
– spruce	1996–2000	4.25	0.0586	1.78	7.22	0.094	3.07	14.33	0.253
Throughfall	1991–1995	4.85	0.0135	1.11	3.46	0.074	1.73	9.35	0.516
– beech	1996–2000	4.75	0.0180	1.34	4.18	0.067	2.45	6.48	0.494
Soil water	1991–1995	3.75	0.1738	1.05	15.41	0.141	3.23	21.74	2.500
– spruce	1996–2000	3.80	0.1594	2.18	12.45	0.102	2.80	12.49	0.818
Soil water	1991–1995	4.45	0.0340	1.00	2.53	0.085	1.50	12.50	1.170
– beech	1996–2000	4.10	0.0840	0.80	2.52	0.069	2.35	5.67	0.455
Spring water	1991–1995	5.30	0.0049	0.63	2.57	0.397	2.37	42.06	
	1996–2000	4.95	0.0110	0.12	2.35	0.496	3.29	53.58	0.069

Sampling place	Period	Na	K	Mg	Ca	Zn (mg/l)	Mn	Fe	Al	Cu
Precipitation	1991–1995	0.45	0.34	0.52	2.96	0.031	0.017	0.010	0.165	
– open area	1996–2000	0.47	0.44	1.42	2.67	0.019	0.019	0.015	0.024	0.003
Throughfall	1991–1995	0.72	4.52	0.94	3.49	0.059	0.462	0.057	0.273	
– spruce	1996–2000	0.69	3.55	0.83	3.79	0.044	0.418	0.081	0.122	0.007
Throughfall	1991–1995	0.52	4.05	0.63	2.26	0.028	0.172	0.021	0.171	
– beech	1996–2000	0.51	3.74	0.42	2.43	0.017	0.169	0.036	0.053	0.006
Soil water	1991–1995	0.70	4.52	1.27	6.70	0.134	1.019	0.245	0.672	
– spruce	1996–2000	0.61	3.72	0.97	4.53	0.045	0.319	0.147	0.351	0.008
Soil water	1991–1995	0.51	4.28	0.92	4.51	0.049	0.576	0.401	0.712	
– beech	1996–2000	0.58	2.48	0.66	3.28	0.024	0.113	0.228	0.377	0.008
Spring water	1991–1995	6.75	1.73	2.09	9.21	0.066	0.087	0.019	0.278	
	1996–2000	6.54	1.78	2.60	11.98	0.073	0.155	0.069	0.457	0.006

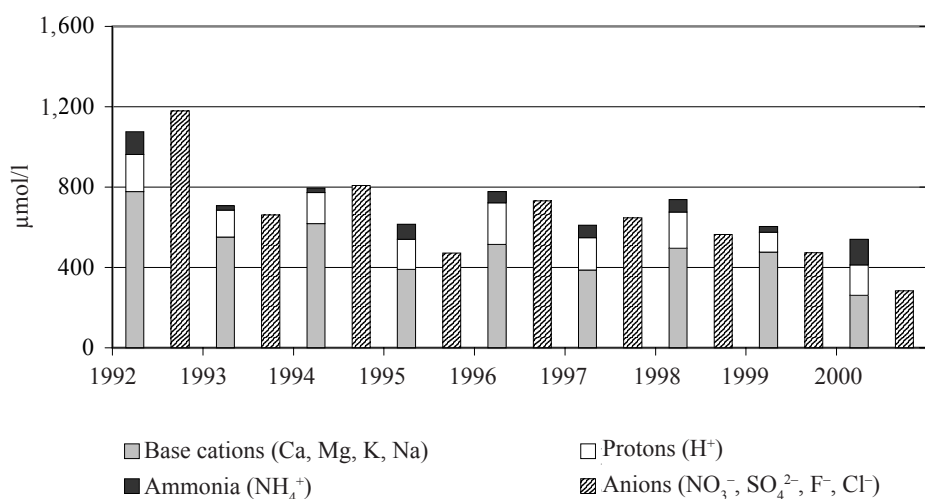


Fig. 4. Molar ratios of cations and anions in soil water below O horizon on the plot Vojířov – spruce

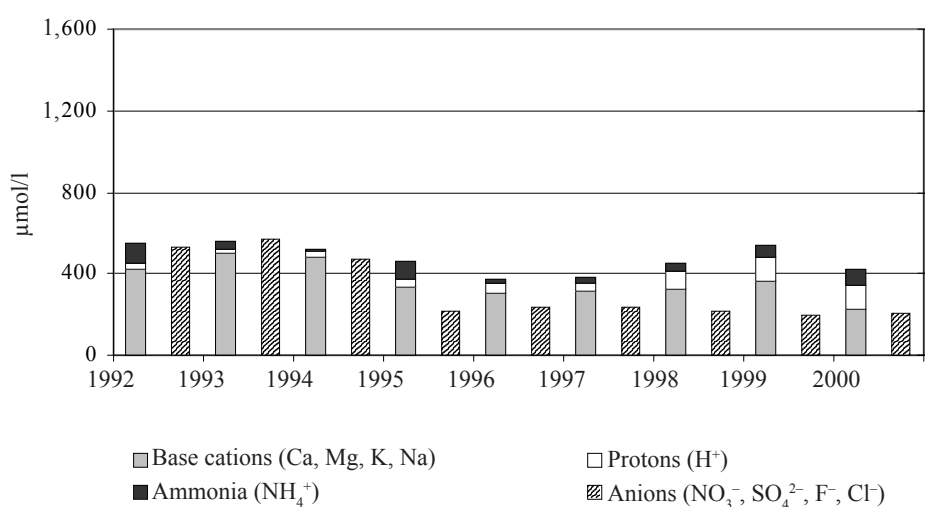


Fig 5. Molar ratios of cations and anions in soil water below O horizon on the plot Vojířov – mixed stand (beech)

recorded until 1995, in subsequent years the average values decreased in comparison with precipitation water. In the second half of the nineties an increase in NH_4^+ was observed (Table 4). In the mixed stand, the O horizon also caused an increase in H^+ ion concentration (average pH was not lower than 4, however), significant increase in Fe and Al (by one order), and less significant increase in Ca, Mg, F^- and Zn. A certain decrease was observed in NH_4^+ , NO_3^- , less in Cl^- . For the other ions, the changes in their concentrations during the investigation did not show a uniform trend. In the second period of investigation (1996–2000), retention of K, Mn, SO_4^{2-} from run-off water was observed in the O horizon.

Similarly like in precipitation water, in gravitational soil water collected under the surface humus horizon (O) in the spruce stand the concentrations of most ions were higher than in the mixed stand. These were mainly the concentrations of H^+ , SO_4^{2-} , NO_3^- , F^- , Cl^- , NH_4^+ , Mn, Zn, and $\text{P}(\text{PO}_4^{3-})$. A smaller difference was determined for cations Ca, K, Mg, Na. On the contrary, with Fe and Al, the aver-

age annual concentrations were higher in water collected under the humus horizon below beech trees in the mixed stand. The amount of collected water was higher in the mixed stand than in the spruce stand, the ratio was 3:2.

In Figs. 4 and 5, a more favourable molar ratio of the concentrations of basic cations to strong acid anions (SO_4^{2-} , NO_3^- , F^- , Cl^-) can be seen, and less H^+ ions and NH_4^+ in water running-off from the forest floor in the mixed stand, in comparison with the values determined in water under the spruce stand.

CHEMISTRY OF WATER IN THE WATER SOURCE

In the spring near Dubovice hunter's cottage (about 300 m from the research plots), the concentrations of H^+ ions were by one order lower than those in water run-off to mineral soil from the forest floor in the mixed stand, and by one to two orders lower than in water coming to the mineral soil layer in the spruce stand (plot I). With the

Table 5. Average concentrations of elements in the spring water near Dubovice hunter's cottage

Year	C _{ox}	H	Na	K	Mg	Ca	Zn	Mn	Fe (mg/l)	Al	NH ₄ ⁺	NO ₃ ⁻	F ⁻	Cl ⁻	SO ₄ ²⁻	PO ₄ ³⁻	Cu
IV–XII/1991	3.09	0.0089	5.93	1.70	1.55	6.60	0.056	0.039	0.030	0.186	1.16	2.63	0.36	1.97	34.24	0.407	
II–XI/1992	9.34	0.0038	7.06	1.72	2.05	9.00	0.070	0.106	0.016	0.267	1.13	2.78	0.37	3.27	39.95	0.386	
III–XI/1993	1.10	0.0036	6.89	1.68	2.29	10.66	0.049	0.094	0.005	0.481	0.12	2.82	0.55	2.47	43.05	0.415	
1994	3.76	0.0064	6.77	1.83	2.56	10.90	0.100	0.129	0.008	0.245	0.19	2.25	0.39	2.77	54.66	0.125*	0.004
1995	3.24	0.0021	7.11	1.71	2.02	8.91	0.054	0.067	0.030	0.209	0.58	2.36	0.33	2.27	38.37	0.011	0.009
1996	8.80	0.0228	6.28	1.97	3.27	14.77	0.072	0.243	0.083	1.854	0.14	2.33	0.72	3.95	67.03	0.037	0.009
1997	6.75	0.0165	5.56	1.77	2.86	12.60	0.064	0.209	0.129	1.437	0.17	1.95	0.58	3.08	58.58	0.073	0.008
1998	2.15	0.0050	6.67	1.71	2.45	11.23	0.064	0.112	0.021	0.460	0.17	2.45	0.44	3.80	50.44	0.083	0.005
1999	6.66	0.0065	6.69	1.76	2.59	12.12	0.088	0.138	0.023	0.531	0.08	2.68	0.43	3.85	50.44	0.051	0.005
2000	4.75	0.0041	7.49	1.70	1.85	9.20	0.075	0.074	0.087	0.286	0.04	2.35	0.32	1.77	43.39	0.050	0.003

*since 1994 estimated total P

exception of 1996 and 1997, pH of water in the spring was above 5 (Table 5).

In comparison with water collected under the forest floor, an increase in Na, Mg, Ca, and a decrease in K concentration was evident. The increase in SO₄²⁻ and F⁻ could be observed mainly in recent years (since 1996). Average contents of NO₃⁻ in the spring water were relatively balanced, with the exception of 1997 (1.95 mg/l), they were about 2.25 to 2.82 mg/l. So they were lower than in the soil water under the spruce stand, and similar to those in water running off from the humus horizon in the mixed stand (Table 4).

By 1995 the concentrations of Mn, Fe and Al were also lower than in the soil water. With decreasing deposition of Zn, its concentration in the spring water remained nearly the same or it only slightly increased; that is why the average annual concentrations of this element were higher than the average concentrations in water from the surface humus layer. A decrease in pH (increase in H⁺) of the spring water in 1996 was connected with SO₄²⁻, F⁻, Al, Mn, and Ca increase, this state was still fading away in 1997, and it was most probably a reaction to the increased deposition of pollutants in 1996. The buffer capacity of soil in deep sand layers was low, together with weathering parent material (granite) these materials were not able to neutralise anions of strong acids (NO₃⁻, F⁻, Cl⁻) in the run-off water by basic cations (Ca, K, Mg, Na) (Fig. 6). Probably that is why the acid cations Al, Mn, Fe took part in this process.

SOIL CONDITION

Characteristics of soil chemistry and its development on the plots Vojřov are given in the results of analyses from 1991 and 1999 (Tables 6, 7, and 8).

The soil in the spruce and mixed stand was strongly acid to the subsoil (80+ cm), with pH lower than 4.2. From 30–40 cm to deeper horizons this active pH shows lower values than exchangeable pH, as measured in KCl. The enrichment of fine eolian sand with humic matters is visible to 50 cm (even deeper). Irregular leaching and the presence of humidified remnants of organic material *in situ* influence their non-proportional distribution.

In the forest floor and surface horizons of mineral soil the ratio of C:N was higher than 20. The total element content in the Of horizon with Ca, Mg, K, Na, Mn, and P was higher in the mixed stand than in the spruce stand (Tables 6 and 7). In the mixed stand the typical Oh layer was not formed as in the spruce stand, but the humus material was rich in quartz grains (Oh/Ah). The higher content of humus matters (C_{ox} in the Oh horizon) in this layer in the spruce stand influences the higher total supply of all elements investigated and the sorption capacity CEC, i.e. the supply of available cations. The sorption complex saturation of surface humus layer (BS) is high on both plots. In 1999, it was 82% in Of layer of the spruce stand, and 83% in the beech stand, and in Oh layer it was 76% and 70%, respectively (Table 8).

Table 6. Elements supply in humus layer and in the soil on the plot Vojítov – spruce stand (T – total supply; in 1991 extract with concentrated HCl after combustion mineralization, in 1999 extract with aqua regia, A – supply in the sorption complex – extract with 1M NH₄Cl)

Sampling site	Year	pH H ₂ O	pH KCl	C _{ox} (%)	Al	Ca	Fe	K	Mg	Mn	Na (ppm)	P	As	Cd	Cu	Pb	Zn
Of	1991 T				717	6,610	830	761	391	1,020	63	1,000			11	29	54
	1999 T	4.20	3.62	35.91	1,703	5,930	2,371	757	597	1,382	162	1,184	4.62	0.37	10	47	83
Oh	1999 T			30.02	3,282	3,026	4,235	637	480	362	176	939	7.15	0.26	12	94	52
Oh	1991 A	3.50	2.80	26.46	434	2,006	26	255	146	272	12	36					27
	1999	3.66	3.07	30.02	211	2,634	46.5	240	193	297	27	25					
0–5 cm	1991 A	3.30	2.70	3.27	104	255	9.2	47.8	28.7	17.7	7.7						3.4
	1999	3.63	3.34	1.47	220	55	20.2	12.3	9.9	1.6	8.8	3					
5–10 cm	1991	3.30	3.00	1.26	134	131	6	18.5	16.9	5.8	1.8	19					1.5
	1999	3.72	3.71	1.48	209	28.7	7.5	6.4	7.8	1.9	9.2	113					
10–20 cm	1991	3.40	3.00	0.93	136	31	6.2	10	4.3	1.8	1.6	27					4.4
	1999	3.89	3.71	1.26	208	26.8	6.2	4.6	6.6	0.31	5.2	17					
20–30 cm	1991	3.70	3.70	1.37	314	27	7.2	14.6	3.7	4.9	2.7	548					0.68
	1999	3.94	3.98	1.05	191	32.4	4.5	3.5	6.8	2.7	9.6	258					
30–40 cm	1991	4.10	4.30	0.43	90	11	0.7	13.1	1.7	1.3	2	332					0.97
	1999	4.02	4.37	0.83	115	23.6	0.7	4.7	5.7	1.2	5.3	301					
40–50 cm	1991	4.10	4.30	0.30	82	10	0.5	15.2	1.5	1.4	1.7	340					0.76
	1999	3.96	4.42	0.47	87	22.2	<0.6	10.9	5.7	1.1	4.6	259					
50–60 cm	1991	4.20	4.40	0.29	78	7	0.4	15.5	1.4	0.8	1.9	276					0.92
	1999	3.88	4.43	0.18	77	22.2	<0.6	6.7	5.8	0.7	5.8	218					
60–70 cm	1991	4.20	4.40	0.59	75	7	0.6	16.2	1.2	0.7	1.3	216					0.88
60–80 cm	1999	4.20	4.47	0.06	49.1	19.8	<0.6	5	5.1	0.5	3.4	86					
70–90 cm	1991	4.20	4.40	0.45	77	9	0.1	14	1.4	0.8	1.3	122					1.15
80+	1999	4.05	4.50	0.03	49	26	<0.6	8.4	5.9	1.4	12.6	76					

Table 7. Element supply in the humus layer and in the soil on the plot Vojřov – mixed stand (T – total supply; in 1991 extract with concentrated HCl after combustion mineralization, in 1999 extract with aqua regia, A – supply in the sorption complex – extract with 1M NH₄Cl)

Sampling site	Year	pH H ₂ O	pH KCl	C _{ox} (%)	Al	Ca	Fe	K	Mg	Mn	Na (ppm)	P	As	Cd	Cu	Pb	Zn
Of	1991 T			38.43	991	9,380	780	858	413	1,844	45	1,200			33	20	50
	1999 T	5.00	4.57	36.25	761	9,260	1,352	1,348	799	3,965	237	1,597	<2.5	0.45	10.9	23	70
Oh	1991 T			31.8	2,261	4,270	2,540	687	334	843	72	1,100			46	55	51
Oh/Ah	1999 T	3.54	3.02	12.36	1,608	949	1,706	490	202	136	135	444	<2.5	<0.2	4.1	35	17
Of	1999 A			36.25	1.2	5,579	0.68	991	530	1,345	40.8	151					
Oh/AhOh	1999 A			12.36	76	647	17.2	185	62.8	84.3	23.1	22					
0–5 cm	1991 A	3.40	2.80	3.03	115	221	9.8	90.9	19.6	18.8	4.3	12					3.7
	1999	3.79	3.27	1.62	38.2	114	5.2	42.6	14.8	12.3	8.9	3					
5–10 cm	1991	3.50	3.00	0.99	134	51	7	32	5.4	4.4	1.9	13					1.1
	1999	3.78	3.43	0.33	66.7	26.4	2.7	10.5	6.2	0.25	8.5	3					
10–20 cm	1991	3.60	3.30	0.55	129	22	4.2	12.9	2.7	1.5	1.6	18					0.46
	1999	3.74	3.46	0.29	77.3	22.5	3.3	8.8	5.9	<0.1	7.8	9					
20–35 cm	1991	4.10	3.90	1.25	330	24	11.7	18.9	3.8	2.6	3	600					1.3
20–30 cm	1999	3.81	3.63	0.24	79.5	18.1	2.5	4.5	5.1	<0.1	7.8	17					
35–45 cm	1991	4.10	4.10	1.1	196	16	4.4	14.7	2.3	0.8	2.8	568					1.3
30–40 cm	1999	3.83	3.86	0.76	199	25.1	7.7	8	6.7	0.42	7.3	233					
45–55 cm	1991	4.20	4.20	1.51	138	34	3.4	10.5	2.5	0.5	2.6	608					0.87
40–50 cm	1999	3.96	4.15	1.38	224	22	1.9	11.2	6.3	0.88	9.2	617					
55 +	1991	4.00	4.20		137	16	5.1	10	1.6	0.4	2.6	520					1.1
50–60 cm	1999	3.85	3.99	0.97	246	40.1	3.2	15.8	7.5	1.2	10.7	719					
60–80 cm	1999	3.97	3.91	0.42	153	34.3	<0.6	11.6	6.5	2	13.2	466					
80 +	1999	4.22	4.39	0.23	74.1	30.1	<0.6	6.8	6	0.4	14.5	222					

Table 8. Sorption conditions in the soil on the plots Vojřřov (H – protons, AC – acid cations, BC – base cations, CEC – sorption capacity in mmol/kg, BS – base saturation of the sorption complex in %)

Depth	Year 1991					Year 1999				
	H	AC	BC	CEC	BS	H	AC	BC	CEC	BS
Spruce stand										
Of						3.76	54.01	256.78	314.55	81.63
Oh	7.93	64.56	119.15	199.64	62.20	6.68	42.17	154.60	203.45	75.99
0–5 cm	4.99	13.03	16.63	34.65	47.99	1.11	25.61	4.49	31.21	14.39
5–10 cm	2.50	15.54	12.71	30.75	41.33	0.50	23.78	2.63	26.91	9.77
10–20 cm	2.50	15.56	3.23	21.29	15.17	0.50	23.65	2.21	26.36	8.38
20–30 cm	0.50	35.58	2.14	38.22	5.60	0.25	21.59	2.69	24.53	10.97
30–40 cm	0.13	10.12	1.12	11.37	9.85	0.22	12.89	2.00	15.00	13.33
40–50 cm	0.13	9.23	1.08	10.44	10.34	0.20	9.72	2.18	12.00	18.17
50–60 cm	0.10	8.74	0.95	9.79	9.70	0.20	8.68	2.05	10.83	18.93
60–80 cm	0.10	8.41	0.92	9.43	9.76	0.19	5.51	1.69	7.29	23.18
80+ cm	0.09	6.75	0.91	8.56	10.63	0.08	5.53	2.57	8.18	31.42
Mixed stand of spruce beech and oak										
Of						0.36	73.70	359.04	433.10	82.90
Oh (Ah)						7.18	13.95	47.68	68.81	69.29
0–5 cm	3.96	14.35	15.16	33.47	45.29	2.02	5.20	8.40	15.62	53.77
5–10 cm	2.50	15.53	3.88	21.91	17.71	0.98	7.71	2.47	11.16	22.13
10–20 cm	1.25	37.42	1.71	40.38	4.23	0.89	8.79	2.47	12.15	20.33
20–30 cm	0.32	37.48	2.12	39.92	5.31	0.56	8.65	1.77	10.98	16.12
30–40 cm	0.20	22.08	1.49	23.77	6.27	0.35	22.68	2.32	25.35	9.15
40–50 cm	0.16	15.56	2.29	18.01	12.72	0.30	25.07	2.31	27.68	8.35
50–60 cm	0.16	15.53	1.31	17.00	7.72	0.25	27.63	3.49	31.37	11.13
60–80 cm						0.32	17.18	3.11	20.61	15.09
80+ cm						0.10	8.37	2.80	11.27	24.84

Humus matters represent carriers of sorption complex (CEC) in the soil profile. In the mineral soil samples taken at 10 cm sequences to 90 cm, this value was from 7.29 to 31.21 mmol/kg in the spruce stand, and between 10.98 and 31.37 mmol/kg in the mixed stand. The level of sorption complex saturation (BS) ranged from 8.38 to 31.42 under the spruce stand, and from 8.35 to 53.77% under the mixed stand.

When comparing the results of soil analyses from 1991 and 1999, we have to respect high spatial variability in the distribution of humic matters in the soil profile and the presence of big granite boulders. It is obvious, however, that in the surface humus layer of the spruce stand the total content of Mg, Mn, and Na increased (Table 6). In the Oh layer there was also a visible increase in available Ca, Mg, and Na. In the surface horizons of mineral soil the supply of available Ca and Mg decreased, it increased in deeper parts of the horizon. The content of sorbed K and Mn decreased in the whole mineral soil profile, on the contrary the content of Na increased.

In the mixed stand, higher total supply of K, Mg, Na, Mn, and P was observed in the humus layer Oh in 1999 (Ta-

ble 7). The lower content of humus matters in Oh/Ah layers, in comparison with the Oh layer investigated in 1991, is most probably a cause of the total lower content of Ca, K, Mg, Al, Fe, Mn, P, Cu, and Zn. Lower supply of C_{ox} was also determined in the whole mineral soil profile in 1999. Similarly like under the spruce stand, the supply of available Ca and Mg in the surface mineral horizons also decreased here, on the contrary it increased in deeper horizons. The supply of available K decreased in the whole profile, Na supply increased on the other hand. The supply of available P also decreased in the rhizosphere.

Changes in cation supply (BC) in the soil sorption complex under spruce caused a decrease in the saturation level (BS) in the surface horizons of mineral soil, and its increase in deeper horizons (Table 8). In the soil under the mixed stand, a moderate increase in the saturation level of sorption complex was observed in 1991 to 1999.

During the investigated period, active and exchangeable pH in the soil under spruce increased to a depth of 30 cm, in deeper layers pH/H₂O decreased. In the mixed stand, the pH/H₂O and pH/KCl values also increased in upper horizons to 30 cm, and decreased in deeper horizons.

DISCUSSION AND SUMMARY

Air pollution load of the investigated forest stands in Vojířov is lower in comparison with the load of forest ecosystems in Central and Eastern Bohemia (Table 9). In 1992–2000, the total annual deposition of H^+ , S/SO_4^{2-} , $N/(NO_3^- + NH_4^+)$, and F^- in the spruce stand was lower than in the spruce stand of the plot Želivka (in the watershed of water dam basin), and significantly lower than in the spruce stand in Šerlich in the Orlické Mts. On the contrary, lower deposition of the elements mentioned (ions) was observed in the spruce stand of Zdikov (lower part of the watershed “U Lizu”). To evaluate the deposition of air pollution elements with the throughfall precipitation in the beech stand (Table 9), the fact that in Želivka the investigation is carried out only in the stand of age class II, and on the other plots there are beech stands of age class V and older, is to be taken in account.

In 2000, in the proximity of the investigated plots the plot of an intensive monitoring of forest ecosystems – level II was established. Another plot of this level is situated about 30 km in south-east – Dobersberg (08), Austria.

According to SMIDT (2001) and NEUMANN et al. (2001), the results of investigations from 1996 to 1998 show that the bulk deposition of H-ions in the open area was lower in Vojířov (0.091 and 0.17 kmol/ha per year) and throughfall in the spruce stand was slightly higher (0.34 and 0.32 kmol/ha per year) in the respective years. In the open area near Dubovice hunter's cottage, the deposition of other ions was higher, with the exception of K and NH_4^+ . The deposition of Na (3.7 kg/ha per year)

and N/NH_4^+ (7.2 and 7.1 kg/ha per year) under the spruce stand in Vojířov and Dobersberg was similar. The deposition of K, Ca, Mg, Cl^- , NO_3^- , SO_4^{2-} and $N/(NO_3^- + NH_4^+)$ was higher in Vojířov. It is necessary to stress, however, that in 1996–1998 the bulk precipitation in Vojířov was 835 mm and throughfall was 503 mm per year, and in Dobersberg the respective values were 609 and 431 mm. The plots of Vojířov are situated on the western border of the massif above the Třeboň basin exposed to northern winds. An extremely long winter period from November 1995 to April 1996 and high total precipitation amount influenced the highest annual deposition of air-pollutants in the whole period investigated. Mainly the spruce crowns by deposition interception (aerosols, gases and solid matters) significantly increased the amount of air pollutants in throughfall precipitation. A significant increase in air-pollution was also observed under the beech trees in the mixed stand and in the open area.

A deviation in the deposition of air-pollutants was reflected by an increase in H^+ , Ca, NO_3^- , F^- , SO_4^{2-} ion concentration in water run-off from the surface humus horizon O in the spruce stand. In the mixed stand, changes in water under the humus horizon were not significant (Fig. 5). A significant decrease in pH and an increase in H-ions by one order in the annual average value, in comparison with the previous period, was observed in the spring water. The change of pH was followed by an increase in Al, Mn, F^- , SO_4^{2-} ion concentration. This state was ongoing also in 1997. A sharp increase in Al, F^- , SO_4^{2-} was probably caused by the decomposition of unstable compounds of aluminium oxides with sulphates

Table 9. Deposition of air pollutants in spruce and beech stands on the plots FGMRI since 1990 – maximum and minimum values (kg/ha/year)

Plot	Element	Spruce – throughfall				Beech – throughfall				Including stemflow			
		min	year	max	year	min	year	max	year	min	year	max	year
Vojířov 1992–2000	H	0.103	2000	0.484	1996	0.028	1995	0.137	1996				
	S	5.960	2000	44.980	1996	4.400	2000	20.680	1996				
	N	5.700	2000	20.400	1996	5.390	1993	12.030	1996				
	F	0.216	1999	0.721	1996	0.156	1993	0.705	1995				
Šerlich 1990–1997	H	0.432	1997	1.680	1991	0.055	1997	0.460	1990				
	S	45.400	1997	74.300	1990	18.800	1996	33.000	1990				
	N	25.200	1994	47.000	1990	8.700	1996	22.700	1991				
	F	1.020	1994	1.880	1996	0.470	1994	1.300	1990				
Zdikov 1990–2000	H	0.047	1998	0.490	1991	0.012	1999	0.116	1991	0.022	1999	0.152	1991
	S	5.390	2000	22.020	1996	3.020	2000	10.760	1995	3.590	1999	15.040	1995
	N	5.640	2000	16.130	1991	2.980	1999	12.200	1990	4.270	1999	14.910	1990
	F	0.120	2000	0.582	1996	0.080	2000	0.401	1995	0.110	2000	0.496	1995
Želivka 1990–2000	H	0.091	2000	0.715	1991	0.029	1997	0.118	1996				
	S	14.260	2000	64.640	1991	4.630	2000	23.920	1996				
	N	17.190	1996	40.690	1991	4.080	1990	11.250	1999				
	F	0.289	2000	1.560	1990	0.130	2000	0.740	1997				

Table 10. Average annual flux of elements with precipitation soil water and spring water in 1995–2000 (kg/ha/year)

Element	Deposition with precipitation			Run-off from the O horizon		Loss with spring water
	Open plot	Spruce stand	Mixed stand	Spruce stand	Mixed stand	
C _{ox}	31.80	70.34	48.98	117.97	167.16	
H ⁺	0.1213	0.2353	0.0787	0.3434	0.2404	0.019
S/SO ₄ ²⁻	7.79	20.42	11.07	9.72	7.01	34.32
Cl ⁻	28.54	12.59	11.51	5.43	6.86	6.24
F ⁻	0.332	0.396	0.328	0.102	0.069	0.936
N/NO ₃ ⁻	4.96	6.45	4.27	5.26	1.49	1.03
N/NH ₄ ⁺	5.11	5.88	5.01	2.62	1.17	0.304
Na	3.60	3.08	2.55	1.39	1.89	13.27
K	3.28	18.17	19.34	4.07	8.53	3.54
Mg	3.12	3.48	2.80	2.00	2.18	5.02
Ca	19.23	15.45	11.26	9.88	11.23	22.94
Al	0.183	0.506	0.261	0.887	1.434	1.590
Fe	0.109	0.323	0.167	0.380	0.891	0.124
Mn	0.130	1.710	0.768	0.806	0.374	0.281
Cu	0.026	0.030	0.029	0.015	0.024	0.013
Zn	0.180	0.180	0.082	0.103	0.088	0.140
P	0.592	0.917	2.096	1.270	1.510	0.101
Amount of water (mm/year)	754	434	496**	208	334	200*

Note: * annual run-off 200 mm according to the Atlas ČSSR (1966)

**without stemflow (10–20% of precipitation on the open plot)

and fluorides in the soil profile or in the soil substrate, and their leaching caused by a higher supply of lower pH water (ALEWELL, MATZNER 1993; KHANNA, ULRICH 1985; HERRNSTADT 1995; MANDERSCHIED et al. 1995; MATZNER, ULRICH 1990).

Table 10 shows a highly negative balance of these three ions in the soil and weathered rock mantel, based on the data on deposition of the investigated matters and on calculated loss with run-off water in the Dubovice spring in 1995 to 2000.

The negative balance of SO₄²⁻ in forest soils was described mainly by German authors (KREUTZER et al. 1986; MANDERSCHIED et al. 1995; ROTHE 1997) on the plots of a significant lowering of very high sulphur deposition at the end of the eighties. In the nineties, within the research plots of FGMRI, a variable increase in SO₄²⁻ in water collected in B-horizons could be observed (LOCHMAN 1996, 1997, 2000a,b).

Under the conditions existing on the research plots and most probably in the whole catchment of the spring investigated, the sufficient sorption of released Al from decomposed alumo-sulphates did not occur. Average concentration of Al in the spring was 1.85 mg/l in 1996, it was also highest in the subsequent years in comparison with the conditions in other catchments investigated by FGMRI (LOCHMAN 1996, 1997, 2000a,b, and LOCHMAN et al. 2000, 2002).

Na is another element strongly influenced by leaching from the soil and substrate. With Mg and Ca lower negative balance can be observed. The input of protons (H⁺ ions) into the soil is the cause of leaching of these elements (basic cations, Al, Mn – see Table 10). This soil load is higher in the spruce stand. The above-mentioned decomposition of complex compounds SO₄²⁻ with Al oxides is an important source of protons and soil acidification (KHANNA, ULRICH 1985; ROTHE 1997; VAN BREEMEN et al. 1983) in deeper mineral soil horizons. Since 1995, the concentrations of SO₄²⁻ in gravitational water run-off from the surface humus horizon O were only little different from the concentrations in throughfall precipitation. If the volume of water run-off to mineral soil is lower than that of precipitation, no increase in SO₄²⁻ flow into the mineral profile can be supposed in comparison with its deposition and possible further leaching with run-off water to the water source.

Proton balance in the soil sub-system is also influenced by the production of nitrogen compounds, their consumption, changes and losses. When NH₄⁺ ions are formed from organic compounds, H⁺ is consumed when the ammonium ions are changed into NO₃⁻, 2 H⁺ ions are released. Contrary to NH₄⁺ uptake by vegetation H⁺ is released, and in NO₃⁻ uptake 2 H⁺ ions are consumed (KHANNA, ULRICH 1985).

In Table 11 deposition of NH₄⁺ and NO₃⁻ with precipitation and flows with soil water are presented, and their

Table 11. Proton (H^+) flux through forest ecosystems and influence of nitrogen compounds on the proton uptake and release in the humus layer and in mineral soil in the period 1995–2000 (kmol/ha/year)

H^+ flux	Spruce stand	Mixed stand
Precipitation on the open area	0.1213	0.1213
Throughfall	0.2353	0.0787
Run-off from O	0.3410	0.1618
Run-off from the catchment	0.0190	0.0190
Balance H^+ ions in the O horizon		
a) uptake H ions with NO_3^- uptake in O horizon	0.1754	0.4070
b) release H ions with NH_4^+ consumption in O horizon	0.2319	0.2765
Difference	–0.0565	0.1305
Balance H^+ ions in mineral soil		
a) uptake H ions with NO_3^- uptake in mineral soil	0.6192	0.0674
b) release H ions with NH_4^+ consumption in O horizon	–0.1647	–0.0579
Difference	0.4545	0.0095

losses in the spring water (in kmol/ha per year). The presented balance shows an even deposition of the two forms of nitrogen with throughfall precipitation under spruce and beech. In the spruce stand in the forest floor horizon the consumption of NH_4^+ ions is much higher than that of NO_3^- , so the production of H^+ ions is higher (0.0565 kmol/ha per year). In the surface humus under beech there is a higher consumption of nitrates (NO_3^-) that influences proton uptake from the soil environment (0.1305 kmol/ha per year – see Table 11).

More ammonium and nitrate ions come to the mineral soil with run-off water in the spruce stand in comparison with the beech stand. Their major part is consumed in the soil profile because a small amount of NO_3^- (1.034 kg N/ha per year) and an even lower amount of NH_4^+ (0.304 kg N/ha per year) is transported with the run-off water. The balance of proton consumption and production in the mineral soil of the two stands cannot be determined more precisely as the soil water was not studied. For basic orientation the

values of NH_4^+ and NO_3^- losses as calculated for the spring within the basin (Table 10), however, do not respect different losses (run-off) of these ions from the soil on the two plots (different amounts of water and concentration of N compounds).

Lower deposition of nitrogen compounds into beech stand, in comparison with N deposition under spruce, and mainly lower nitrate leaching from the soil profile under beech was reported by KREUTZER et al. 1986; MATZNER and MEIWES 1994; ROTHE et al. 1998; ULRICH et al. 1981. Similar conditions were found by LOCHMAN (2000b) under spruce and oak on the FGMRI plots in Sulice.

Higher leaching of nitrogen from the forest floor under spruce can also be supported by transfer of the biomass of beech leaves from the adjacent mixed stand, which influences the composition of deposition and forest floor material to a distance of several dozen meters. It was confirmed by ROTHE (1997), who mentioned a possibility

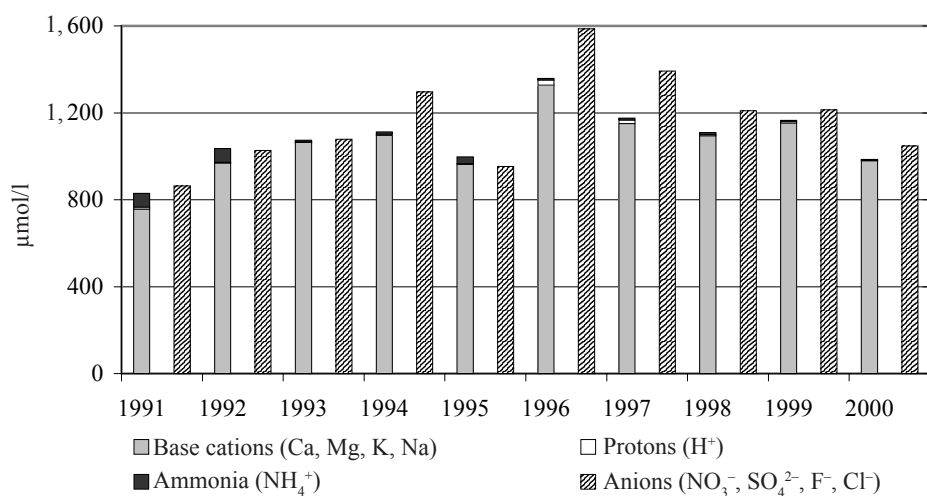


Fig. 6. Molar ratios of cations and anions in spring water near the hunter's cottage Dubovice

of the transfer of about 30% of nutrients on the basis of investigations in Höglwald.

The humus material and products of leaf decomposition that form complexes with Al and Fe, and also higher water deposition, take part in the leaching of the two elements from the forest floor horizon into the mineral soil.

The soil on the research plots Vojířov is acid, with higher nutrient supply in the humus horizons where, besides comparatively high sorption capacity, there is also a favourable level of the sorption complex saturation with cations. The supply of available nutrients in the mineral soil fluctuates in relation with the content of humus material and sorption complex saturation. It is around 10% in the surface horizons under spruce. These conditions correspond with the acidification level and saturation of the soil sorption complex under spruce stands growing on acid substrates such as granite and other acid rocks in the Czech Republic, and also in the border region with Austria neighbouring with Jindřichův Hradec region. JANDL et al. (1999), and NEUMANN et al. (2001) described the soils under spruce stands on the monitoring plots in this region. The soils were formed on acid bedrocks as strongly acid, of low sorption capacity in the mineral profile, and low level of the sorption complex saturation in the horizons A 6.1 to 12%, and in deeper horizons lower than 10%. According to the typology by Institute for Forest Management, they can be characterised as crypto-podzolic and pseudo-gleyic.

In 1990 to 1992, the nutrition of young spruce stands in the proximity of the plots in Vojířov was evaluated positively in spite of the fact that the nutrition supply in mineral soil was low (PASUTHOVÁ, LEDINSKÝ 1994). The results of needle analyses showed a good level of mineral nutrition with K, Ca, Mg, Mn, P, only in some spruce samples of the first needle year-class the content of N was lower than 1.35% (below the good nutrition level). In this connection it is to note that in the studied spruce stand in Vojířov the C:N ratio in the soil to 30 cm was above 20 in 1999. In the soil under beech trees this ratio was more favourable.

Complex evaluation of the impact of beech and spruce, and their mixture on the water chemistry of soil and on development of soil characteristics on Höglwald plots was presented by ROTHE (1997). It is given mainly by deposition of air pollutants, biomass decrease and different volume of roots in the soil. Maximum of fine roots (0–2 mm) taking nutrients from the soil solution in the spruce stand is on the surface of mineral soil (0–10 cm), in the beech stand it is at 10–30 cm (WITTKOPF 1995).

On the plots Vojířov, with less favourable forms of humus, a significant portion of fine roots is in Oh and Ah horizons, with both spruce and beech. It is obvious, however, that under the beech stand, in the layer to 10 cm, pH/H₂O was higher, and in the layer deeper than 10 cm it was lower than under the spruce stand. The values of pH/KCl under beech were also higher in the humus horizons, and lower in mineral soil, mainly deeper than 30 cm. The supply of available Ca and Mg under beech was also

higher than under spruce on the soil surface (0–5 cm), and lower at the depth of 5–30 cm. In 1991 to 1999, in the soil under beech, a smaller decrease or even increase in Ca, Mg, K cations available in the rhizosphere was observed than that under spruce.

The more significant positive effect of beech on the soil is influenced by many factors (REHFUESS 1990), it decreases in purer sites (soils). That is why a higher proportion of broadleaves in the stand is necessary to reach the same effect on oligotrophic soils. In pure sandy soils with low supply of available nutrients in the sorption complex and low cation supply of minerals, it is necessary to reach a proportional and fluent release of nutrients during mineralization of the deposition to ensure sufficient nutrition of the tree species.

CONCLUSION

The results presented in this article have confirmed that the air pollution load of forest ecosystems on the research plots in Vojířov is lower than in the Central and Western part of Bohemia, but still higher than in the forest ecosystems in the Šumava foothills (Zdíkov).

The difference between spruce and broadleaved (beech) stand in the deposition of S/SO₄²⁻, F⁻, Al, Zn, N(NO₃⁻ + NH₄⁺) and H decreased during the ten-year observations, due to higher deposition in the spruce stand. The consumption of precipitation protons (H⁺) in the beech crowns causes cation leaching, mainly K, from the leaves. The lowering of both cation and anion concentration in bulk precipitation is connected with pH decrease.

High total precipitation amount and long winter in 1995/1996 contributed to an increased deposition of pollutants (H⁺, SO₄²⁻, F⁻, N-compounds, and metals). It also influenced higher leaching of these ions from the humus horizon to mineral soil. Low buffering capacity of sandy soil and weathered bedrock caused a significant pH decrease and an increase in SO₄²⁻, F⁻, Al, Mn content in the spring water, fading away in the subsequent years.

The element balance shows that SO₄²⁻, F⁻, Na, and less Mg, and Ca ions were released from the soil and weathered bedrock into run-off water in 1995–2000. Deposition of nitrogen compounds (NO₃⁻ + NH₄⁺) was lower under the beech stand and their release in the humus horizon was also higher than in the spruce stand. If the deposition was about 11 kg of (NO₃⁻ + NH₄⁺) per ha/year and the losses with the run-off spring water were 1.3 kg of N, the calculated consumption of this element in forest ecosystems within the basin was about 10 kg per ha/year.

The supply of biogenous elements in the soil is associated mainly with their relation to humic matters in the forest floor and mineral soil. Soil analyses carried out at the beginning and at the end of the nineties (1991–1999) showed a slight increase in the supply of cations in the forest floor horizon, decrease in their supply in the sorption complex in the upper horizons of mineral soil layer (with the exception of Na), and their increase in the lower part of rhizosphere where the supply remains very low. At the

same time, the movement of available P to deeper horizons was observed. The differences in the nutrient supply and soil acidity under spruce and beech are not significant.

Under the conditions of lowered regional pollution within the region, the impact of local emission sources is of higher importance.

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Imisní zatížení lesních porostů na Vojířově a jeho vliv na chemismus odtékající vody a půdy

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ABSTRAKT: Výzkumné plochy Vojířov v porostu smrku a ve smíšeném porostu leží jižně od Jindřichova Hradce poblíž hranice s Rakouskem, na hřebenu sousedním s Třeboňskou pánví a jsou exponovány západnímu proudění vzduchu. Jejich půdy – humusové podzoly – se vyvinuly na eolickém písku mezi balvany žuly. Na plochách je od léta 1991 sledován chemismus srážkové vody a vody odtékající z humusového horizontu O. Spad látek je zjišťován na volné ploše (u myslivny Dubovice), kde je také sledován chemismus vody pramene. Během pozorování byla zjišťována vyšší depozice imisních látek s podkorunovými srážkami v porostu smrku než pod bukem ve smíšeném porostu. V průběhu let se projevil nárůst spadu imisních látek v roce 1996 během dlouhotrvajícího zimního počasí a vysokého úhrnu srážek. Toto zatížení lesního ekosystému ovlivnilo chemismus půdní vody a zejména vody v prameni poklesem jejího pH, zvýšením koncentrací SO_4^{2-} , F^- , Al, Mn, které doznávalo ještě v dalších letech. Koncem devadesátých let se snížil spad H^+ , $\text{S}/\text{SO}_4^{2-}$, F^- , $\text{N}(\text{NO}_3^- + \text{NH}_4^+)$ zřetelněji ve smrku než pod bukem. Na volné ploše naopak pH srážkové vody pokleslo. Analýzy půdy v letech 1991 a 1999 ukázaly určité zlepšení zásoby biogenů v humusových horizontech a snížení zásoby sorbovaných bazických kationtů v povrchových horizontech minerálních půdy a zvýšení zásoby v horizontech hlubších, kde přesto zůstává na velmi nízké úrovni.

Klíčová slova: smrkový porost; smíšený porost; buk; spad; chemismus půdní vody; chemismus pramenité vody; půdní chemismus; srážky; podkorunové srážky

Výzkumné plochy Vojířov leží na Jindřichohradecku, mezi obcí Lásenice a státní hranicí s Rakouskem, nedaleko myslivny Dubovice. Plochy leží na hřebenu, který na západní straně klesá do Třeboňské pánve, a jsou vystaveny proudění vzduchu od západu a severozápadu. Jejich půdy patří mezi humusové podzoly (Humic Podzols), které se vyvinuly na hlubokých překryvech eolického písku mezi balvany drobně zrnité dvojslídne žuly.

Od roku 1991 je zde prováděn výzkum vlivu dospělého porostu smrku a buku ve starším smíšeném porostu na depozici látek s podkorunovými srážkami a na chemismus vody odtékající z pokryvného humusu. U myslivny Dubovice na volné ploše je také sledován chemismus srážek (bulk), spad látek a je odebírána voda z pramene. Srážková voda je zachycována v korytech a gravitační půdní voda pod pokryvným humusem lyzimetry. Voda je sumarizována a odebírána pro laboratorní rozborů v měsíčních intervalech. Odběry vzorků půdy ze sond pro analýzy pod porosty proběhly v letech 1991 a 1999. Rozborovou činnost u vod a půd provádějí zkušební laboratoře Výzkumného ústavu lesního hospodářství a myslivosti v Jilovišti-Strnadech podle metodik mezinárodního monitoringu stavu lesů ICP Forests.

Z výsledků šetření uvedených v příspěvku vyplývá, že lesní ekosystémy na výzkumných plochách jsou zatěžovány rozdílnou depozicí imisních látek s patrným vývojem v průběhu let pozorování. Srážková voda na volné ploše (bulk precipitation) u myslivny Dubovice měla v letech 1991 až 1998 průměrné roční pH mezi 4,85 až 5,15, v roce 1999 a 2000 se zde však projevil pokles hodnot. Celkový roční spad H iontů se zde pohyboval okolo 0,1 kmol/ha a od roku 1999 se v souladu s poklesem pH zvýšil až na 0,32 kmol/ha (2000). Roční spad SO_4^{2-} dosáhl maxima v roce 1996 – 48,6 kg na ha a minima v roce 2000 – 13,2 kg na ha. Největší kolísání vykazoval spad F^- , který v roce 1996 činil 0,724 kg na ha a v roce 1994 0,085 kg na ha. Nejvyšší roční spad N ($\text{NO}_3^- + \text{NH}_4^+$) byl stanoven v letech 1995 a 1996, a to 13,4 a 12,9 kg na ha. Na růstu depozice dusíku se především podílelo zvýšení u NH_4^+ .

V podkorunových srážkách v porostu smrku v letech 1991 a 1992 nedosahovala průměrná hodnota pH 4,0, v dalším období překračovala 4,0. Celková roční depozice H^+ iontů kolísala mezi 0,484 kmol/ha (1996) a 0,103 kmol/ha (2000). Ve stejných letech byla zjištěna maxima a minima depozice F^- (0,721 kg a 0,216 kg),

SO_4^{2-} (134,7 kg a 17,8 kg) a $\text{N} (\text{NO}_3^- + \text{NH}_4^+)$ (20,40 kg a 5,70 kg), přepočtená na ha.

Ve smíšeném porostu pod bukem je zachycována pouze okapová voda, bez stoku vody po kmenech. Její průměrné pH bylo vždy vyšší než v okapové vodě pod smrkem a v některých letech i vyšší než ve srážkách z volné plochy. Průměrné hodnoty překračovaly 4 a v letech 1991 a 1995 byly větší než 5. Také v tomto smíšeném porostu byl u většiny sledovaných iontů zjištěn největší spád v roce 1996. Ten dosahoval 0,137 kmol H^+ , 61,9 kg SO_4^{2-} , 12,0 kg $\text{N} (\text{NO}_3^- + \text{NH}_4^+)$ a 0,705 kg F^- . Nejnižší roční spád na ha byl stanoven v roce 1993 u H^+ (0,048 kmol), u N (5,4 kg), u F^- v roce 1994 (0,156 kg) a u SO_4^{2-} v roce 2000 (14,2 kg).

Tak jako ve srážkové vodě byly i v gravitační půdní vodě zachycované pod horizontem pokryvného humusu (O) v porostu smrku vyšší koncentrace většiny sledovaných iontů než ve smíšeném porostu. Jedná se především o H^+ , SO_4^{2-} , NO_3^- , F^- , Cl^- , NH_4^+ , Mn a P . Menší rozdíl byl stanoven u kationtů Ca , K , Mg a Na . Naopak u Fe , Mn , Zn , ale i u Al byly zjišťovány vyšší průměrné roční koncentrace ve vodě jímání pod humusovým horizontem O ve smíšeném porostu pod bukem. Množství zachycené vody bylo vyšší pod bukem než pod smrkem, a to v poměru 3 : 2.

Ve vodě pramene je v porovnání s vodou zachycovanou pod pokryvným humusem patrné zvyšování pH, nárůst koncentrací Na , Mg , Ca a snížení koncentrací u K . Zvýšení u SO_4^{2-} a F^- se projevilo především od roku 1996. Průměrné obsahy NO_3^- byly poměrně vyrovnané a v ročních průměrech nepřekročily 2,82 mg/l. Snížení pH vody pramene v roce 1996 pod hodnotu 5 doprovázel nárůst SO_4^{2-} , F^- , Al , Mn a Ca a tento vzestup dozníval ještě v roce 1997.

Půdy v porostu smrku i ve smíšeném porostu jsou silně kyselé až do spodiny (80+ cm), s $\text{pH}/\text{H}_2\text{O} \leq 4,2$. Sorpční kapacita (CEC) a stupeň nasycení bázemi (BS) minerální půdy obou ploch se zásadně neliší a vzhledem k zrnitostním poměrům je nízký až velmi nízký.

Při porovnání výsledků rozborů půdy z let 1991 a 1999 byl v pokryvném humusu půdy pod smrkem zjištěn nárůst přístupného Ca , Mg a Na , v povrchových minerálních horizontech jejich pokles a v hlubší části profilu také zvýšení. V půdě smíšeného porostu se projevíly obdobné tendence vývoje zásoby Mg a Ca jako ve smrku. Zásoba přístupného K v obou půdách poklesla.

Z výsledků uvedených v příspěvku vyplývá, že lesní ekosystémy na výzkumných plochách byly a jsou méně zatěžovány imisními spady než porosty ve střední a severovýchodní části Čech (Želivka, Šerlich), ale ve větší míře než lesní ekosystémy v předhůří Šumavy (Zdíkov). Rozdíly ve spadu imisních látek ($\text{S}/\text{SO}_4^{2-}$, F^- , $\text{N} (\text{NO}_3^- + \text{NH}_4^+)$, H^+ , Al , Zn) s podkorunovými srážkami v porostu smrku a ve smíšeném porostu (v buku) se během desetiletého pozorování snížily díky většímu poklesu spadu v porostu smrku. Spotřeba protonů (H^+) ze srážek vyvolává v korunách buku vymývání kationtů z listů, především K . Snížení koncentrací kationtů i aniontů ve srážkách zachycovaných na volné ploše (bulk), zjištěné v poslední době, je spojeno s poklesem jejich pH.

Vysoké srážkové úhrny a dlouhotrvající zimní počasí v letech 1995 a 1996 způsobily zvýšení spadu imisních látek (H^+ , SO_4^{2-} , F^- , sloučenin N a kovů). To ovlivnilo i větší vymývání těchto iontů z humusového horizontu O do minerální půdy. Nízké pufrací kapacity písčitých půd a zvětralinového pláště zapříčinily zřetelný pokles pH a nárůst SO_4^{2-} , F^- , Al , Mn ve vodě pramene, který se projevoval ještě v následujících letech.

Z bilance prvků vyplývá, že v letech 1995 až 2000 byly z půdy, eolitického písku a zvětralinového pláště uvolňovány ionty SO_4^{2-} , F^- , Na a méně Mg a Ca do odtékající vody. Z měření depozice celkového minerálního $\text{N}/\text{NO}_3^- + \text{NH}_4^+$ na všech třech místech je možné uvažovat jeho průměrný spád v povodí asi 11 kg na ha za rok, což při roční ztrátě 1,3 kg $\text{N} (\text{NO}_3^- + \text{NH}_4^+)$ s odtékající vodou v prameni naznačuje spotřebu tohoto prvku v lesních ekosystémech povodí okolo 10 kg na ha za rok.

Zásoba biogenů v půdě je především spojena s jejich vazbou na humusové látky v pokryvném humusu i v minerální půdě. Rozbory půdy provedené na počátku a na konci devadesátých let (1991 a 1999) ukázaly mírné zvýšení zásoby kationtů v pokryvném humusu, snížení jejich zásoby v sorpčním komplexu ve svrchních horizontech minerální půdy (s výjimkou Na) a nárůst ve spodní části rizosféry, kde však zůstává jejich zásoba velmi nízká.

Současně byl zjištěn i posun přístupného P do hlubších horizontů. Rozdíly v zásobě živin a v půdní kyselosti pod smrkem a pod bukem ve smíšeném porostu nejsou podstatné.

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