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Stanisław Małek

Effect of the age of spruce stands on the balance of elements in the Potok Dupniański catchment

Abstract: The study analyses the transfer of F^-, Cl^-, NO_3^-, SO_4^{2-}, Na^+, K^+, Ca^{2+}, Mg^{2+}, Fe^{2+}, Mn^{2+} and Zn^{2+} from bulk precipitation to throughfall, soil surface flow, vertical flow and intercover flow of water (gravity lysimeters at 20 cm soil depth) in spruce stands of different age classes (1st, 2nd, 5th, 6th), and the amount of these ions flowing out from the Potok Dupniański catchment in the Silesian Beskid Mts. The results cover the year 2000. The concentration and amount of SO_4^{2-} in throughfall systematically increased and the pH value decreased with the age of the stands and with successive elements of the ecosystem. The NH_4^+ ion was probably absorbed in the canopy, which caused a washout of K^+, Mn^{2+}, F^- and SO_4^{2-} in the vegetation season in older stands. In the winter season, Fe^{2+}, Mn^{2+}, Na^+ and K^+ were washed out from the youngest stands (1st age class), whereas F^-, NO_3^-, SO_4^{2-}, K^+, Ca^{2+}, Mg^{2+}, Mn^{2+} and Fe^{2+} – from older canopies. Decomposition of the organic matter caused a rise in water acidity and an increase in the concentrations of all the analysed ions; their leaching, however, was low (under 1%). Water from intercover flow contributed to an increase in the amount of water and the concentration and amount of ions and to a further decrease in water reaction at a soil depth of 20 cm. All the anions and cations flowed away with water penetrating vertically and horizontally. Considerable amounts of ions, especially SO_4^{2-}, Na^+, K^+, Ca^{2+} and Mg^{2+}, were carried beyond the reach of the main mass of the root system and then out of the catchment, which may adversely affect the development and health of spruce stands.

Additional key words: bulk precipitation, throughfall, surface flow, soil water, stream water

Address: S. Małek, Agricultural University of Kraków, Department of Forest Ecology, al. 29 Listopada 46, 31-425 Kraków, Poland, e-mail: rlmalek@cyf-kr.edu.pl

Introduction

The cycling of elements in spruce stands which are affected by industrial immission has been and still is the subject of numerous studies. Earlier investigations were based on relatively small forest catchments, such as Brenna (Staszewski et al. 1996, 1999; Godzik et al. 1997; Bytnerowicz et al. 1999), and on larger catchments – Czarna and Biała Wisełka (Wróbel 1998). Their goal was to estimate the volume and quality of the deposition of elements and their outflow from the catchment. Those studies, however, did not usually take account of different development stages of the stands nor of their spatial distribution in the catchments. The influence on the quality and volume of throughfall, surface flow or the distribution of water within the reach of the root system were not studied, either.

Several authors analysed changes in the concentrations of various elements during their passage through different components of the forest ecosystem, especially through the canopy and surface soil layers, and investigated the flow of contaminants in the surface soil layer; some of them focused only on one or two components (Leonardi and Fluckinger 1987; Godt et al. 1988; Niklińska et al. 1995; Staszewski et al. 1996, 2001; Kram et al. 1998; Małek and Wężyk 2000a, b, c; Małek 2000, 2002c). One study that considered the effect of various development stages of spruce stands was that of Małek (2002a).

The retention of considerable volumes of contaminants by the canopy and then their removal or washout from the needles by rainfall cause changes in the concentrations of anions and cations reaching the soil surface (Małek and Wężyk 2000c, 2001; Staszewski et al. 2001; Małek 2002a, c). The flow of ions in the surface soil layer is modified by the soil and by intercover flow (Małek 2000, 2002a; Małek and Wężyk 2001; Staszewski et al. 2001).

The present study examines changes in the amount of anions and cations in bulk precipitation, in water passing through the canopy (throughfall), water flowing on the soil surface, and in soil water (vertical and intercover water penetration; lysimeters placed at a soil depth of 20 cm) in spruce stands of different age classes (1st, 2nd, 5th and 6th), and in the waters of a mountainous stream – Potok Dupniański in the Silesian Beskid Mts.

Material and methods

The study area is not directly exposed to air pollution as it is located at a considerable distance from main industrial centres. The Potok Dupniański catchment of 1.68 km^2 coverage lies in southern Poland in the Silesian Beskid Mts (latitude 49°35', longitude 18°50'). The area of the catchment is overgrown with spruce stands in different development stages, growing on dystric cambisols developed on the Istebna sandstone. The equipment for measuring water volumes in spruce stands (1st, 2nd, 5th and 6th age class) in an open area and at the outflow of the catchment (before a weir on the stream) was installed in 1998. The studies were conducted in the year 2000 using a method described in the ICP-Forest Manual (1998).

During the vegetation season, i.e. from 1 May to 1 November, samples of bulk precipitation directly reaching the catchment were collected from special collectors (5 units) installed in an open area 0.5 m above ground level and connected to a plastic tube with an outlet joining a container and a measuring device installed in a bunker. In winter, from 1 January to 1 May and from 1 November to 31 December, six collectors (plastic, chemically neutral snow bags) were installed at 1.3 m above ground level in the open area at a distance of 120–150 m from the forest wall.

In order to evaluate the volume and quality of throughfall, water was sampled from a sampling system (this time the number of collectors was 15) installed under the canopy, similar to the one installed in the open area during the vegetation season. In winter, six collectors (plastic, chemically neutral snow bags) were installed at 1.3 m above ground level in spruce stands of different age classes.

Water for examining surface flow was collected from a sampling system (connected to a plastic tube with an outlet running into the container and a measuring device placed in a bunker) located under the canopy and covering an isolated fragment of the upper soil layer in the spruce stands mentioned.

Water permeating vertically through the soil was sampled with four gravity lysimeters (L-(20)) isolated from horizontal water penetration, located at a depth of 20 cm, and soil water penetrating horizontally – with four lysimeters (L-20) not isolated from vertical and horizontal penetration, placed in the soil at the same depth in the study stands.

Outflow water was sampled before a weir on the Potok Dupniański. The sampling was performed on the first day of each month. Water was analysed chemically using ion chromatography (Dionex-320) to determine the concentration of F^-, Cl^-, NO_3^-, SO_4^{2-}, PO_4^{3-}, NH_4^+, Na^+, K^+, Ca^{2+}, Mg^{2+}, Fe^{2+}, Mn^{2+} and Zn^{2+}.

Results and discussion

In the study year (2000), 53% of bulk precipitation reached the catchment area during winter, but only the amounts of Na^+ and Mn^{2+} were higher in this part of the year than in the vegetation season. In the winter period, the value of water reaction (pH) was 5.19, and in the growing season 5.14 (see Table 1).

In spruce stands of 1st age class, about 5% more water and higher amounts of Na^+, K^+, Fe^{2+} and Mn^{2+} were observed in throughfall than in bulk precipitation during the wintertime. In the vegetation season, the interception was about 26% but the amounts of K^+ and Mn^{2+} were higher in throughfall than in bulk precipitation, indicating that these ions were washed out or washed from the surface of needles and/or the bark; the other elements were absorbed in the canopy. A considerable proportion of nitrates was absorbed in the canopy, which confirmed the results of Lovett and Schaefer (1992). The concentration of all the anions and cations analysed was higher in surface flow than in throughfall, as was the case with the 1999 studies (Małek 2002a), and their leaching was under 1%. The water reaction was slightly lower in surface flow (4.9) than in throughfall. The intercover flow increased the amount of water (by about 200%) and of all the ions and caused a further decrease in water reaction (down to 4.36 at a depth of 20 cm). Only 2% of the water which reached the upper soil layer got to the depth of 20 cm but large portions of SO_4^{2-}, Na^+, Ca^{2+}, Mg^{2+} and Fe^{2+} were found at this depth, indicating that they were leached from the soil (see Table 1).

In stands of higher age classes, the water amount and pH, interception and concentrations of ions in successive elements of the ecosystem followed roughly the same patterns as in the youngest stands.

Table 1. Amount (mm) and reaction (pH) of water and amount (kg · ha^{-1}) of anions and cations in bulk precipitation, catchment outflow, throughfall, surface flow, intercover and vertical flow (L-20) and vertical penetration (L-(20) in vegetation season (from 1 May to 1 November) and in winter (from 1 January to 1 May and from 1 November to 31 December) of 2000 according to age of spruce stands

Item	Water	pH	F^-	Cl^-	NO_3^-	NH_4^+	SO_4^{2-}	PO_4^{3-}	Na	K	Ca	Mg	Fe	Mn	Zn
Bulk precipitation															
Winter (w)	583	5.19	0.020	9.079	10.598	8.213	13.134	0.404	3.395	2.341	11.859	1.318	0.090	0.083	0.159
Vegetation season (v)	510	5.14	0.072	11.496	20.367	9.724	15.388	1.749	3.369	4.859	17.657	2.153	0.615	0.057	0.373
Outflow															
Winter (w)	468	6.40	0.038	6.665	11.159	0.450	87.486	0.010	9.576	6.862	31.567	9.191	0.079	0.054	0.073
Vegetation season (v)	186	6.35	0.044	2.792	3.104	0.630	41.751	0.007	4.904	2.434	15.242	4.379	0.155	0.006	0.015
1st age class															
TFw	615	4.94	0.000	6.596	10.413	6.283	11.804	0.103	3.778	2.420	9.360	1.231	0.098	0.093	0.127
TFv	378	5.23	0.033	2.038	9.390	3.823	11.419	0.075	1.682	5.428	4.967	0.760	0.274	0.079	0.125
SSF	0.225	4.90	0.000	0.008	0.078	0.019	0.035	0.015	0.009	0.018	0.027	0.004	0.000	0.000	0.001
L-(20)	17	4.76	0.008	0.283	0.198	0.185	1.086	0.009	0.194	0.349	0.678	0.120	0.228	0.013	0.025
L-20	49	4.36	0.010	0.411	1.383	0.719	2.087	0.115	0.250	0.861	1.539	0.209	0.490	0.054	0.034
2nd age class															
TFw	623	4.77	0.049	5.979	13.610	4.834	25.090	0.077	3.612	6.446	12.634	1.647	0.125	0.194	0.156
TFv	322	4.78	0.079	3.108	3.925	3.309	15.216	0.032	1.353	9.017	4.493	0.818	0.221	0.196	0.106
SSF	0.065	4.38	0.000	0.005	0.010	0.012	0.017	0.013	0.008	0.010	0.013	0.003	0.000	0.000	0.000
L-(20)	93	4.30	0.062	1.978	7.202	5.569	12.916	0.001	0.397	3.323	2.548	0.366	2.162	0.127	0.106
L-20	167	3.65	0.023	2.330	2.543	3.322	10.837	0.013	0.714	4.483	3.422	0.674	0.293	0.235	0.114
5th age class															
TFw	448	4.32	0.054	6.794	12.368	5.109	31.947	0.152	3.211	9.094	13.824	2.055	0.088	1.452	0.152
TFv	293	4.78	0.089	2.729	6.669	4.585	14.442	0.084	1.105	6.968	5.228	0.925	0.198	0.362	0.134
SSF	1.000	4.36	0.001	0.032	0.136	0.013	0.102	0.010	0.148	0.027	0.051	0.011	0.027	0.001	0.001
L-(20)	58	4.25	0.026	0.858	15.547	1.196	4.101	0.007	0.427	1.101	1.603	0.404	0.054	0.595	0.056
L-20	142	4.14	0.021	2.301	4.650	2.639	8.970	0.246	0.859	2.769	3.383	0.663	0.347	0.962	0.067
6th age class															
TFw	398	4.19	0.131	6.948	17.816	4.934	30.867	0.073	3.296	6.240	14.916	1.979	0.112	0.569	0.203
TFv	267	4.34	0.207	3.157	10.154	5.412	15.533	0.118	1.120	5.717	6.292	1.105	0.265	0.224	0.198
SSF	0.650	4.23	0.001	0.021	0.053	0.015	0.061	0.003	0.067	0.028	0.039	0.007	0.004	0.000	0.001
L-(20)	56	3.80	0.019	0.966	3.365	0.366	5.265	0.000	0.403	0.532	2.105	0.362	0.205	0.170	0.047
L-20	130	3.61	0.050	2.407	8.696	1.286	12.266	0.018	0.971	2.943	4.942	0.811	0.383	0.357	0.098

TFw – throughfall in winter, TFv – throughfall in vegetation season, SSF – surface flow

In winter, the amounts of some ions were higher in throughfall than in bulk precipitation. These were: F^-, NO_3^-, SO_4^2, Na^+, K^+, Ca^{2+}, Mg^{2+}, Fe^{2+} and Mn^{2+} in stands of 2nd age class, F^-, NO_3^-, SO_4^2, K^+, Ca^{2+}, Mg^{2+} and Mn^{2+} in stands of 5th and 6th age classes, and Zn^{2+} in stands of 6th age class.

Only in stands of 2nd age class was in winter 5% more water in throughfall than in bulk precipitation, same as in 1st-age-class stands. The interception in the vegetation season was the following: 37% – 2nd age class, 23% – 5th age class, 38 – 6th age class. Despite that fact, the throughfall water contained greater amounts of F^-, K^+ and Mn^{2+} in stands of all three age classes, indicating that these ions were washed out or washed from the surface of needles and/or the bark. The other ions studied were absorbed in the canopy. A substantial absorption of nitrates, especially in the growing season, observed in this study, confirms the results of Lovett and Schaefer (1992). In stands of 2 age class, up to 80% of nitrogen was absorbed in tree crowns, which is similar to the value established by Zimka and Stachurski (1996).

After passing through the canopy, water decreased its pH value: in winter – from 5.19 (in bulk precipitation) to 4.77 (stands of 2nd age class), 4.32 (5th age class) and 4.19 (6th age class); in the vegetation season – from 5.14 (in bulk precipitation) to 4.78 (2nd and 5th age class) and 4.34 (6th age class).

Compared to throughfall, the surface flow water had higher concentration of all the anions and cations analysed, as in 1999 (Małek 2002a), and a slightly lower reaction (4.38 – stands of 2nd age class, 4.36 – 5th age class, 4.23 – 6th age class). The leaching of all the ions was under 1%.

The intercover flow increased the amount of water by around 100, 150 and 120%, respectively, in stands of 2nd, 5th and 6th age classes and the amounts of all the ions, except F^-, NO_3^- and SO_4^{2+} in 2nd age class, and F^- and NO_3^- in 5th age class. The water reaction lowered further to 3.65 (2nd age class), 4.14 (5th age class) and 3.61 (6th age class). About 9% (2nd age class) or 8% (5th and 6th age class) of the water that reached the soil surface penetrated vertically to a depth of 20 cm. At that depth, large amounts of NO_3^-, SO_4^{2}, NH_4^+, Na^+, K^+, Ca^{2+}, Mg^{2+}, Fe^{2+}, Zn^{2+} and Mn^{2+} were found, indicating that these ions were leached from the soil.

In a spruce stand in the Ojców National Park, an increase in the concentrations of all alkaline cations was recorded (Staszewski et al. 2001), whereas in the present studies only the concentration of K^+ increased in successive elements of the ecosystem (bulk precipitation, throughfall, soil water at 20 cm – vertical penetration; lizymeter L-(20)), with the exception of water in stands of 2nd and 6th age classes, in 2000 as well as in 1999 (Małek 2002a) (Table).

The concentration of NO_3^- was higher than that of NH_4^+ in all the elements of the ecosystem, with the exception of soil water at 20 cm, which confirmed the results obtained by Staszewski et al. (2001) for the Ojców National Park, except for 2nd-age-class stands.

In the winter period, higher concentrations of NH_4^+, PO_4^{3-}, Mn^{2+} and Zn^{2+} and a lower water reaction were noted for bulk precipitation reaching the catchment than for water flowing out of the catchment. During the vegetation season, higher concentrations of F^-, Cl^-, NO_3^-, NH_4^+, PO_4^{3-}, Fe^{2+}, Mn^{2+} and Zn^{2+} and a lower water reaction were recorded for bulk precipitation, which was consistent with the 1999 results (Małek 2002a). The outflow of water and all the ions, except NH_4^+, from the catchment was much higher in the winter time (water – 73% of the total outflow). The difference between the bulk precipitation and the outflow indicates that Cl^-, SO_4^{2-}, Na^+, K^+, Ca^{2+} and Mg^{2+} were carried out of the catchment area during the whole year (F^-, NO_3^-, SO_4^{2-}, Na^+, K^+, Mg^{2+} and Zn^{2+} in winter, and SO_4^{2-}, Na^+, Ca^{2+} and Mg^{2+} in the vegetation season).

Tree crowns, and especially needle surfaces, are places where dust pollutants, particularly heavy metals such as Zn and Cd (Kabata-Pendias and Pendias 1993) and Pb and Cu (Kram et al. 1998), are deposited mechanically. These pollutants are removed from canopies by atmospheric precipitation. The effectiveness of their removal differs according to the ion (Poborski and Staszewski 1996). It also depends on other factors, namely the presence of NH_4^+ ions and foliofags, the concentration of elements in the foliage, and on ion exchange reactions. Such reactions make it possible for the plants to take up elements directly from rainwater, which causes the removal of Na^+, K^+ and Zn^{2+} from the plants, thus intensifying the transfer of those ions to the soil (Stachurski 1987). In the case of spruce stands growing in the Potok Dupniański catchment, increased concentrations of K^+ and Mn^{2+} in throughfall were recorded in all the development stages, as in 1999 (Małek 2002a), except for Fe^{2+}. Magnesium and calcium are probably absorbed directly from rainfall, thus compensating for the considerable washout of these elements beyond the reach of the root system.

An analysis of the balance of elements reaching the catchment and flowing out of it with the waters of the Potok Dupniański demonstrated that the ions washed out in the year 2000 were Cl^-, SO_4^{2-}, K^+, Ca^{2+}, Na^+ and Mg^{2+}. The remaining ions analysed were retained in the catchment, as was the case witch the year 1999 (Małek and Wężyk 2000a, b; Małek 2002a). Especially worrying phenomena are the washout of magnesium, which is indispensable for the proper development of plants (and whose deficit was observed in the same spruce stands studied earlier (Małek 2002b)), and the accumulation of heavy metals. The relatively low reaction of surface soil layers (3.8–4.3) and throughfall water may contribute to the release of heavy metals in the sorption complex of soil, which can adversely affect the development and health of spruce stands. In addition, the increased concentrations of heavy metals in the outflow water in the period of intensive snow thawing lower its quality and are an indirect indicator of difficult conditions for the development of the young generation of plants.

Conclusions

1. The concentration and amount of SO_4^{2-} in throughfall systematically increased and the reaction of water decreased with the age of spruce stands and with successive elements of the ecosystem.
2. The NH_4^+ ion was probably absorbed in the canopy, causing the washout of K^+, Mn^{2+} and F^-, SO_4^{2-} in older stands in the vegetation season. In the winter season, Fe^{2+}, Mn^{2+}, Na^+ and K^+ were washed out from the canopy in the youngest stands, whereas F^-, NO_3^- SO_4^{2-}, K^+, Ca^{2+}, Mg^{2+}, Mn^{2+} and Fe^{2+} – in older stands.
3. Decomposition of the organic matter increased the concentrations of all the ions analysed and rose water acidity, but only a small portion of ions was carried away by surface flow (under 1%).

4. Water from intercover flow increased the amount of water and the concentration and amount of all the analysed ions and further decreased water reaction.
5. All the analysed ions were removed from the soil by water penetrating vertically and horizontally. Considerable amounts of ions, especially SO_4^{2-} Na^+, K^+, Ca^{2+} and Mg^{2+}, were washed out of the main root mass and the catchment, which may have a negative effect on the development and health of spruce stands.

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