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Comparison of deposition fluxes on the open area and in mountain spruce stands of different density

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ABSTRACT: To better understand the chemical transformation of rainfall after the passage through the canopies it is necessary to study throughfall deposition fluxes within forest stands. The comparison of bulk deposition fluxes of Ca, Mg, K, S-SO_4, N-NO_3 and N-NH_4 in mountain spruce stands of different stand density and bulk deposition fluxes on the open area was made at the study site Bílý Kříž (Moravian-Silesian Beskids Mts., Czech Republic) during the period of 1999–2006. A linear relationship between the amount of rainfall on the open area and the amount of throughfall in the spruce stand was found. Throughfall deposition fluxes of selected elements in the dense as well as in the sparse spruce stands were higher when compared with bulk deposition fluxes on the open area. There were mostly statistical significant differences between the bulk deposition fluxes on the open area and those in the studied spruce stands. The throughfall deposition fluxes of Ca, Mg, K and S-SO_4 were influenced by the spruce stand density.

Keywords: throughfall; Norway spruce; Moravian-Silesian Beskids Mts.; Czech Republic

Forest ecosystems are open systems exchanging energy and matters with its environment. The maintenance of a relatively closed matter cycle is necessary for the prosperous development of forest ecosystems. Due to changes caused by anthropogenic activity, the composition of the atmosphere is changing and will continue to change. The changes in the atmosphere are reflected in the functioning and growth of forests. The loss of vitality is related to nutritional imbalances and brings about reduced stand stability and productivity (Rehfuess 1985; Zech et al. 1985; Ulrich 1986; Zöttl, Hüttl 1986).

The atmospheric particles and gaseous compounds are transferred to terrestrial and aquatic ecosystems by dry and wet deposition. It is known that the composition of precipitation is altered considerably after passing through the forest canopy. Internal nutrient cycling includes the nutrients transfer from aboveground biomass to forest soils in the form of litter and also nutrient leaching from the various plant parts or epiphytic organisms to the soil when rainfall passes through the forest canopy as throughfall and stemflow (Parker 1983; Reynolds 1996; Whelan et al. 1998; Barbier et al. 2008; Shachnovich 2008). Nutrient balances depend on the forest type and forest structure (Stogsdill et al. 1989; Yoshida, Ichikuni 1989; Draaijers et al. 1992; Bibnler, Zech 1997; Franklin et al. 2002; Rothe et al. 2002), site characteristics (Fenn, Kiefer 1999; Knulst 2004; Balestrini et al. 2007; De Vries et al. 2007; Fischer et al. 2007) and weather conditions (Bibnler, Zech 1997; Balestrini, Tagliaferri 2001), and may reflect different patterns of behaviour of forest ecosystems.

Air pollution which is the main cause of forest soil acidification was recognized as a serious problem and European countries have made a great effort to evaluate the situation and to prevent further damage

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Table 1. Description of the study site Bílý Kříž (Moravian-Silesian Beskids Mts., Czech Republic)

Geographic coordinates	49 30'N, 18°2'E
Geological subsoil	flysch layer with dominant sandstone
Soil characteristics	typical humo-ferric podzol with mor-moder form of surface humus, medium depth up to shallow, loamy-sand or sandy loam, relatively low nutrient content, depth of 60–80 cm
Climate characteristic	moderately cold, humid, with abundant precipitation; mean annual air temperature 5.5 ± 0.3°C, mean relative air humidity 82 ± 2%, mean annual sum of precipitation 1,121 ± 240 mm

(e.g. "Convention on Long-range Transboundary Air Pollution", "International Cooperative Programme on Integrated Monitoring of Air Pollution Effects on Ecosystems"). In the Czech Republic the forests in the border mountains and the forests at the highlands might be still endangered by the consequence of former soil acidification in spite of the fact that the concentrations of acidifying substances in the air have substantially decreased. In this paper deposition fluxes of selected elements in mountain spruce stands of different stand density and deposition fluxes on the open area are evaluated at the study site Bílý Kříž (Moravian-Silesian Beskids Mts., Czech Republic) for the period of 1999–2006.

METHOD

The study site is located at Bílý Kříž in the Moravian-Silesian Beskids Mts. (Czech Republic). Geographic coordinates, climatic and soil parameters of the site are given in Table 1. Bulk deposition fluxes on the open area and throughfall deposition fluxes of Ca, Mg, K, S-SO_4, N-NO_3 and N-NH_4 in the mountain spruce stands of different stand density were evaluated during the period of 1999–2006.

Spruce stand was planted in 1981 using four-years-old seedlings of *Picea abies* (L.) Karst., hence the trees age was 30 years in 2007. The mean slope of the plot with the spruce stand is 13.5°, its exposure is SSE and mean altitude 908 m a.s.l. Dolomitic limestone (31% CaO, 21% MgO) was used for the aerial liming of the spruce stand in 1983, 1985 and 1987 (3 t/ha was applied every year, respectively). The studied spruce stand is divided into two plots with different stand density (FD – dense stand, FS – sparse stand). Leaf area index and stand density of the spruce stand on the studied plots are shown in Table 2.

For throughfall sampling in the spruce stands and atmospheric precipitation sampling on the open area, permanently open polyethylene sampling vessels of an area of 335.33 cm^2 were used (Block, Bartels 1985; Niehus, Bruggemann 1995). The vessels were inserted into the thick-walled plastic pipes in order to shield the samples from solar radiation and to hold the funnels approximately 1 m above the ground. There were 7 collectors randomly

Table 2. Maximum leaf area index and stand density of spruce stands on the studied plots (FD – dense stand, FS – sparse stand) during the studied period 1999–2006

	Leaf area index (m^2/m^2)		Stand density (trees/ha)	
	FD	FS	FD	FS
1999	10.8	8.0	2,600	2,100
2000	11.0	8.2	2,600	2,100
2001	11.5	6.7	2,600	1,880*
2002	11.7	7.7	2,480**	1,820**
2003	12.3	9.1	2,440**	1,820
2004	12.4	9.6	2,050**	1,650*
2005	11.8	10.0	2,040**	1,650
2006	8.5	7.6	1,440**	1,430**

*After thinning, **tree reduction due to the winter disaster

Table 3. List of methods and instruments used for the analysis of rainfall and throughfall waters

Parameter to determine	Method	Instrumentation
K, Mg, Ca	atomic absorption spectrophotometry	AA 30 F4 VARIAN atomic absorption spectrophotometer
NH_4	spectrophotometry at the wave-length of 655 nm after the reaction with hypochlorite and salicylate catalyzed by sodium nitroprusside	UV/VIS spectrophotometer
NO_3, SO_4	high-performance ion exchange liquid chromatography with the gradient elution	DX-600 chromatograph with gradient pump GP50

distributed on each plot. The number of collectors was reduced to 5 during winter. Bulk atmospheric precipitation was sampled with one collector in the nearby open area. Samples were taken once a month in the winter season and in 14-day intervals in the other seasons. Samples were transferred to the laboratory and prepared for the analyses usually the next day after the sampling. In winter it was sometimes necessary to wait one day because the samples were frozen. The methods used for determination of studied elements are listed in Table 3. The average amount of throughfall precipitation for each sampling event was calculated as the arithmetic mean of the amounts captured in the throughfall collectors located on a particular plot. The fluxes of elements (mekv/m^2) in bulk precipitation and in throughfall for each sampling event were calculated as the product of the amount of water (l m^2) and the relevant element concentration (mekv/l). The *t*-test (Microsoft Excel) was used to compare fluxes of elements on the open plot and under crowns, and to analyze differences between throughfall fluxes in the sparse and dense stands. Annual deposition fluxes of elements were calculated as the products of mean annual concentration of individual elements and precipitation totals for the relevant years.

RESULTS AND DISCUSSION

During the studied period of 1999–2006 mean monthly sums of rainfall on the open area were 109 ± 55 mm and 120 ± 60 and 109 ± 58 mm of throughfall in the dense and sparse spruce stand, respectively. Differences in throughfall and rainfall sums were the result of different leaf area index and stand density of the studied stands. Water intercepted by the stand canopy of the sparse stand was vaporized faster than in the dense stand, the accumulation and consequential conflux of water below the canopy was lower and the interception of horizontal precipitation was

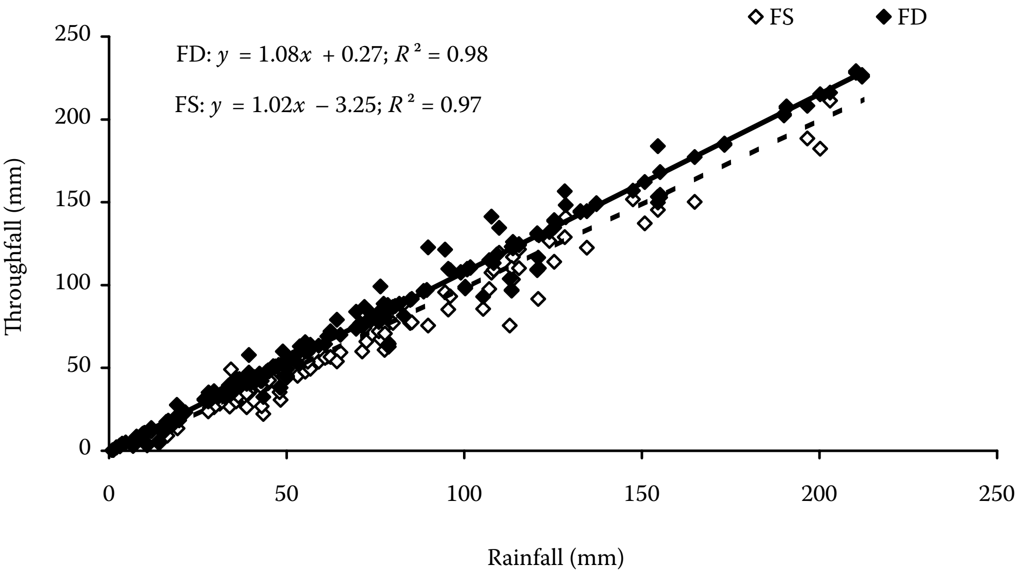

Fig. 1. The relationship between the amount of rainfall on the open area and throughfall in the studied spruce stands (FD – dense stand – solid line, FS – sparse stand – dotted line) during the period of 1999–2006

Table 4. Mean annual deposition fluxes of selected elements in the bulk precipitation on the open area in some localities in Europe (values in kg/ha)

Element	Deposition fluxes	Locality
Ca^{2+}	6.7 ± 1.6	Bílý Kříž (Czech Republic)[1]
	2.1	Austria[2]
	12.4	Czech Republic[3]
Mg^{2+}	1.2 ± 0.5	Bílý Kříž (Czech Republic)[1]
	0.3	Austria[2]
	2.4	Czech Republic[3]
K^{+}	4.1 ± 1.2	Bílý Kříž (Czech Republic)[1]
	3.2	Austria[2]
	3.3	Czech Republic[3]
S-SO$_4^{2-}$	10.0 ± 1.5	Bílý Kříž (Czech Republic)[1]
	4.2–5.7	Czech Republic[4]
	5.7–8.0	Czech Republic[5]
	3.3–4.2	Czech Republic[6]
N-NO$_3^{-}$	5.4 ± 0.7	Bílý Kříž (Czech Republic)[1]
	3.2–6.3	Czech Republic[4]
	4.5–6.3	Czech Republic[5]
	1.8–3.2	Czech Republic[6]
N-NH$_4^{+}$	6.9 ± 1.0	Bílý Kříž (Czech Republic)[1]
	5.1–7.5	Czech Republic[4]
	5.1–7.5	Czech Republic[5]
	3.3–5.1	Czech Republic[6]

[1] Bílý Kříž locality (Moravian-Silesian Beskids Mts.), 908 m a.s.l., 1999–2006

[2] Kreinbach locality (Lower Austria), 480 m a.s.l., 2002–2003 (Berger et al. 2008)

[3] Jablunkov locality (Moravian-Silesian Beskids Mts.), 550 to 700 m a.s.l., 2004–2006 (Novotný et al. 2008)

[4] Area of the Krušné hory Mts., 700–1,200 m a.s.l., 2003–2005 (Lorenz et al. 2008)

[5] Area of the Moravian-Silesian Beskids Mts., 700–1,300 m a.s.l., 2003–2005 (Lorenz et al. 2008)

[6] Area of Southern Bohemia, 2003–2005 (Lorenz et al. 2008)

lower as well. Mainly the interception of horizontal precipitation is important in mountain forest stands. Thus the lower amount of water penetrated onto the forest floor in the sparse stand. From the statistical point of view the differences between the throughfall amounts and rainfall on the open area amounts were not significant on the level of significance α = 0.05. The individual studied years differed both in the precipitation amounts and in the annual distribution of precipitation. A linear relationship between the amount of rainfall on the open area and the amount of throughfall in the spruce stand was found (Fig. 1). In the dense spruce stand the amount of throughfall was higher in comparison with the open area whereas in the sparse spruce stand the amount of throughfall was the same in comparison with the open area.

Water collected under the forest canopy normally contains substantially larger amounts of ions than rainfall collected in the open area (Yoshida, Ichikuni 1989; Bibnler, Zech 1997; Whelan et al. 1998; Fenn, Kiefer 1999; Gordon et al. 2000; Balestrini, Tagliafferi 2001; Moffat et al. 2002; Bélanger et al. 2004; Chiwa et al. 2004; Drápelová, Kulhavý 2008). Bulk deposition fluxes of selected elements in both the dense and the sparse spruce stand were higher when compared with bulk deposition fluxes on the open area (Tables 4 and 5). Throughfall deposition fluxes were lower in the sparse spruce stand when compared with the dense spruce stand.

A comparison of bulk deposition fluxes of selected elements on the open area and throughfall deposition fluxes in the dense and sparse spruce stands was done for the period of 1999–2006. Statistically significant differences (α = 0.05; *t*-test) were found for calcium, magnesium, potassium and sulphate ions (Table 6). Deposition fluxes of selected elements were dependent on the stand density (Table 7). Statistically significant differences (α = 0.05; *t*-test) were found in the throughfall deposition fluxes of Ca, Mg, K and S-SO$_4$ between the dense and sparse spruce stand. Throughfall deposition fluxes are influenced by the processes in the canopy layer. In the denser stand we can expect a higher contribution of dry deposition and a higher contribution of elements that are leached out from the crowns. Some elements are taken up by the canopy, which lowers their throughfall deposition (Bibnler, Zech 1997; De Vries et al. 2007; Balestrini et al. 2007; Fischer et al. 2007; Berger et al. 2008; Drápelová et al. 2008).

CONCLUSION

Throughfall deposition fluxes of Ca, Mg, K, S-SO$_4$, N-NO$_3$ and N-NH$_4$ in the mountain spruce stands of different stand density and bulk deposition fluxes on the open area were measured at the study site Bílý

Table 5. Mean annual throughfall deposition fluxes of selected elements in the spruce stands in some localities in Europe (values in kg/ha)

Element	Deposition fluxes	Locality
Ca^{2+}	15.7 ± 3.4	Bílý Kříž (Czech Republic) – FD stand[1]
	11.6 ± 5.1	Bílý Kříž (Czech Republic) – FS stand[1]
	7.0	Italy[2]
	9.5	Estonia[3]
	9.5	Austria[4]
	18.3	Czech Republic[5]
Mg^{2+}	4.2 ± 1.1	Bílý Kříž (Czech Republic) – FD stand[1]
	3.0 ± 1.6	Bílý Kříž (Czech Republic) – FS stand[1]
	2.0	Italy[2]
	2.0	Estonia[3]
	2.2	Austria[4]
	2.6–4.0	Austria[6]
K^+	19.2 ± 6.0	Bílý Kříž (Czech Republic) – FD stand[1]
	12.7 ± 3.4	Bílý Kříž (Czech Republic) – FS stand[1]
	19.0	Italy[2]
	2.9	Estonia[3]
	13.0	Austria[4]
	6.6–9.6	Austria[6]
	20.7	Czech Republic[5]
$S\text{-}SO_4^{2-}$	22.5 ± 4.1	Bílý Kříž (Czech Republic) – FD stand[1]
	16.4 ± 3.4	Bílý Kříž (Czech Republic) – FS stand[1]
	3.0–5.0	Italy[2]
	4.1	Estonia[3]
	3.1–7.9	Austria[6]
$N\text{-}NO_3^-$	8.9 ± 0.9	Bílý Kříž (Czech Republic) – FD stand[1]
	7.4 ± 1.5	Bílý Kříž (Czech Republic) – FS stand[1]
	3.0	Italy[2]
	2.1	Estonia[3]
	2.3–4.3	Austria[6]
$N\text{-}NH_4^+$	7.7 ± 1.4	Bílý Kříž (Czech Republic) – FD stand[1]
	6.6 ± 1.4	Bílý Kříž (Czech Republic) – FS stand[1]
	3.5	Italy[2]
	2.5	Estonia[3]
	1.6–4.2	Austria[6]

[1] Bílý Kříž locality (Moravian-Silesian Beskids Mts.), 908 m a.s.l., 1999–2006 (FD stand – dense stand, FS – sparse stand)

[2] Localities Renon and Lavazé Pass (Southern Alps), 1,750 and 1,780 m a.s.l., 1993–1996 (Marchetti et al. 2002)

[3] Saarejärve locality, 1995–2002 (Pajuste et al. 2006)

[4] Kreinbach locality (Lower Austria), 480 m a.s.l., 2002–2003 (Berger et al. 2008)

[5] Jablunkov locality (Moravian-Silesian Beskids Mts.), 550–700 m a.s.l., 2004–2006 (Novotný et al. 2008)

[6] Eiseneck locality (Northern Alps), 1,300 m a.s.l., 1996–1998 (Katzensteiner 2003)

Table 6. Statistical analysis (*t*-test) between the deposition fluxes of selected elements (mekv/m^2) on the open area and in the dense (FD) and in the sparse (FS) spruce stand during the period of 1999–2006 (X – statistically significant differences at the level of $\alpha = 0.05$)

		Ca^{2+}	Mg^{2+}	K$^+$	N-NH$_4^+$	S-SO$_4^{2-}$	N-NO$_3^-$
1999	FD	X	X	X	–	X	X
	FS	–	–	–	–	–	X
2000	FD	X	X	X	–	X	–
	FS	X	X	X	–	X	–
2001	FD	X	X	X	–	X	X
	FS	X	X	X	–	X	–
2002	FD	X	X	X	–	X	X
	FS	X	X	X	–	X	–
2003	FD	X	X	X	–	X	X
	FS	X	X	X	–	X	–
2004	FD	X	X	X	–	X	–
	FS	–	–	X	–	–	–
2005	FD	X	X	X	X	X	X
	FS	X	X	X	–	X	–
2006	FD	X	X	X	X	X	X
	FS	X	X	X	–	X	X
1999–2006	FD	X	X	X	–	X	X
	FS	X	X	X	–	X	X

Kříž in the Moravian-Silesian Beskids Mts. (Czech Republic) during the period of 1999–2006.

A linear relationship between the amount of rainfall on the open area and the amount of throughfall in the studied dense and sparse spruce stands was found. Water collected under the forest canopy contained larger amounts of ions than rainfall collected in the open area. Statistically significant differences ($\alpha = 0.05$) were found between the throughfall deposition fluxes of Ca, Mg, K and S-SO$_4$ in the spruce stands and bulk deposition fluxes on the open area. Throughfall deposition fluxes of Ca, Mg, K and

Table 7. Statistical analysis (*t*-test) between the deposition fluxes of selected elements (mekv/m^2) in the dense and in the sparse spruce stand during the period of 1999–2006 (X – statistically significant differences at the level of $\alpha = 0.05$)

	Ca^{2+}	Mg^{2+}	K$^+$	N-NH$_4^+$	S-SO$_4^{2-}$	N-NO$_3^-$
1999	X	X	X	–	X	X
2000	X	X	X	–	X	–
2001	X	X	X	–	X	–
2002	X	X	X	–	X	X
2003	X	–	X	–	X	–
2004	–	–	–	–	–	–
2005	–	–	–	–	–	–
2006	–	–	–	–	–	–
1999–2006	X	X	X	–	X	X

$S\text{-}SO_4$ were dependent on the stand density. Mean annual bulk deposition fluxes of Ca, Mg, K, $S\text{-}SO_4$, $N\text{-}NO_3$ and $N\text{-}NH_4$ on the open area calculated for the period of 1999–2006 were 6.7, 1.2, 4.1, 10.0, 5.4 and 6.9 kg/ha, respectively. Mean annual throughfall deposition fluxes of Ca, Mg, K, $S\text{-}SO_4$, $N\text{-}NO_3$ and $N\text{-}NH_4$ in the dense and sparse spruce stand were 15.7 and 11.6, 4.2 and 3.0, 19.2 and 12.7, 22.5 and 16.4, 8.9 and 7.4, 7.7 and 6.6 kg/ha, respectively.

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Srovnání depozičních toků na volné ploše a v horských smrkových porostech s různou hustotou

ABSTRAKT: Studium depozičních toků v lesních porostech je důležité pro pochopení chemických změn, ke kterým dochází při průchodu srážek korunovou vrstvou porostů. V letech 1999–2006 byly sledovány depoziční toky Ca, Mg, K, S-SO_4, N-NO_3 a N-NH_4 v horském smrkovém porostu na dvou plochách s různou hustotou a na volné ploše na experimentálním ekologickém pracovišti Bílý Kříž (Moravskoslezské Beskydy). Byla zjištěna lineární závislost mezi množstvím srážek dopadajících na volnou plochu a množstvím podkorunových srážek na obou studovaných plochách. Podkorunové depoziční toky vybraných prvků byly ve sledovaném období vyšší ve smrkových porostech než depoziční toky na volné ploše. Pro většinu vybraných prvků byly zjištěny statisticky významné rozdíly mezi depozičními toky na volné ploše a ve studovaných smrkových porostech. Depoziční toky Ca, Mg, K a S-SO_4 byly ve smrkovém porostu ovlivněny jeho hustotou.

Klíčová slova: podkorunové srážky; smrk ztepilý; Moravskoslezské Beskydy; Česká republika

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