Comparison of Principal Ion Fluxes and Their Modifications in the Forest Stands of different Tree Species

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Abstract

Bulk and throughfall deposition under the canopy of the three most common Eastern Baltic region tree species – Scots pine (*Pinus sylvestris* L.), Norway spruce (*Picea abies* (L.) H. Karst.) and silver birch (*Betula pendula* Roth) stands were investigated. The main aim of this study was to assess the effect of tree species on the composition of throughfall fluxes. The highest throughfall enrichment in anions (SO_4^{2-}, NO_3^-, Cl^-), was detected in the case of the largest canopy surface area (Norway spruce), and the smallest in the case of the lowest canopy surface area (silver birch), indicating that the enrichment is mostly linked to the wash-off of dry deposited anions accumulated on the canopy surface. The birch canopy retained higher amounts of inorganic nitrogen compounds (especially ammonium), and lost more base cations than the coniferous canopies. In particular, the highest leaching of K^+ was observed in the birch stand, for which . K^+ fluxes under birch canopies were 1.6 and 2.1 times higher than in the spruce and the pine stand, respectively. The most intense ion exchange with ammonium and hydrogen is considered as the main reason for higher potassium leaching from birch foliage.

Key words: *bulk deposition, dry deposition, leaching, throughfall, tree species, uptake.*

Introduction

The chemical composition of rainwater is strongly altered by the processes within the tree canopies before the water reaches the forest floor as throughfall and may be enriched or depleted in different ions. The precipitation chemistry is modified because of two primary processes: 1) wash-off of dry deposited compounds accumulated on the canopy between the rain events; 2) interaction between the forest canopy and rainfall, i.e. canopy exchange. The canopy exchange process includes leaching of elements from internal plant tissues and uptake of others by foliage, epiphytic flora, twigs and branches. Consequently, the tree canopy may act as either a sink or a source for various ions.

The intensity of rainfall modifications within the tree canopy at the small-scale depends on forest structure (Zirlewagen and von Wilpert 2001), canopy closure (Whelan et al. 1998, Staelens et al. 2006, Žaltauskaitė and Juknys 2007) and tree species composition (Van Ek and Draaijers 1994, Houle et al. 1999, Berger et al. 2008). Several studies have demonstrated a close relationship between Leaf Area Index (LAI) of the artificial foliage and throughfall deposition (Stachurski and Zimka 2000, Kram 2001). Conifers are usually more efficient in capturing dry deposition and cloud droplets than broadleaf trees because they are evergreen, the structure of the foliage of the conifers is finer, more complex and the needle surface area is bigger than that of the leaves (Beckett et al. 2000, Erisman and Draaijers 2003). During the growing season, deciduous tree species tend to lose more cations from the foliage through the leaching process than coniferous tree species, though the coniferous stay green all the year and continue to lose cations during the dormant season.

Tree species may greatly influence the biogeochemistry of the whole forest ecosystem. Field studies have revealed that in the coniferous stands, particularly for spruce, the ion deposition and the soil leaching of acidifying compounds are higher than in the deciduous (Rothe et al. 2002, De Schrijver et al. 2007). Monitoring and assessment of atmospheric deposition is essential not only for estimating deposition impact on forest ecosystems functioning, health and productivity but also for making the necessary decisions regarding the protection of forest ecosystems (de Vries et al. 2000, Juknys et al. 2003, Augustaitis et al. 2010, Braun et al. 2010).

Current data sets of throughfall deposition are dominated by coniferous forests. Much less is known about the impact of deciduous forests on ion deposition and only limited comparisons are made between different tree species in similar site and climatic conditions (De Schrijver et al. 2004). The majority of investigations in the deciduous were performed in beech or in oak stands. A meta-analysis of the data from 37 case studies revealed that approximately 40 % of the studies analysed the differences of throughfall among *Picea abies* and *Fagus sylvatica* stands (De Schrijver et al. 2007). The impact of silver birch on ion deposition was investigated in several cases (Bergkvist and Folkeson 1995, De Schrijver et al. 2000, 2004, Herrmann et al. 2006, Kram 2008, Wuyts et al. 2008). The main aim of this study was to analyse principal ion fluxes and their modifications by the forest canopy of the most common tree species in Eastern Baltic region: Scots pine, Norway spruce and silver birch.

Material and methods

The study was carried out in the urban forest which covers 298.5 ha and is situated approximately 5 km from the centre of the second biggest Lithuanian city – Kaunas (55°422 N, 23°522 E). The study areas were established in three stands of the most common Lithuanian tree species – Scots pine (*Pinus sylvestris* L.), Norway spruce (*Picea abies* (L.) H. Karst.) and silver birch (*Betula pendula* Roth). The coniferous stands were approximately 120 years old, 25 m high and the stand density was 260 trees ha^{-1}. The birch stand was 75 years old, 23 m high and the stand density was 290 trees ha^{-1}. It was assumed that the stands experience equal air pollution load as they are situated in each other's proximity (within a radius of approximately 0.5 km).

The collection of bulk and throughfall precipitation was performed on a monthly basis during the growing period from April to November of 2003-2004. Stemflow was not estimated. Bulk deposition was collected with three collectors in a clearing of the forest. In each stand, throughfall collectors were randomly located within a 50 m x 50 m area (7, 6 and 10 collectors in the pine, spruce and birch stand, respectively). The collectors for bulk deposition and throughfall were identical. They consisted of a polyethylene funnel of 17 cm in diameter connected to a 5 l polyethylene bottle. The openings of the collectors were 30 cm above the ground surface. The storage containers were dug into the ground in order to avoid light-induced alterations of the collected water and to keep lower temperature.

Prior to the analysis, the samples of bulk precipitation were combined to provide a composite one and throughfall samples were analyzed each separately. The analysis was performed at the Lithuanian Institute of Physics. The analysis of sulphate (SO_4^{2-}), nitrate (NO_3^-) and chloride (Cl^-) was performed by ion chromatography with conductivity detection (Dionex 2010i). Ammonium (NH_4^+) was determined spectrophotometrically by indophenol blue method. Sodium (Na^+), potassium (K^+) and calcium (Ca^{2+}) were determined by the atomic emission method, pH was measured potentiometrically. The quality of the analytical data was checked by a cation – anion balance. The data quality is assured according to the EMEP manual for sampling and chemical analysis (EMEP 1996).

Deposition fluxes were calculated as the product of volume-weighted mean concentration and precipitation volume for each collection period and sampler. Net throughfall fluxes were calculated by subtracting bulk deposition fluxes from throughfall fluxes. Stand means were calculated for each collection period.

To evaluate the relative contribution of all three processes modifying precipitation – wash-off, leaching and uptake, the following presumptions based on the findings of different investigators (Lovett and Lindberg 1984, Balestrini and Tagliaferri 2001, Rodrigo et al. 2003) were used:

1. If net throughfall is positively related with throughfall water volume, the ionic enrichment is resulted by leaching of ions from plant tissue.
2. If net throughfall is independent of throughfall water volume, the enrichment is linked to wash-off of dry deposited compounds accumulated on the surface of leaves (needles).
3. If net throughfall is negatively related with throughfall water volume, decrease of ions in throughfall is attributed to canopy uptake.

Leaf area index (LAI) was not empirically determined. Based on literary data, it was assumed to approximate 10 m^2 m^{-2} for spruce, 3-5 m^2 m^{-2} for pine and 2-3 m^2 m^{-2} for birch (Kram 1998, Stachurski and Zimka 2000).

ANOVA was used to compare bulk and throughfall deposition and to compare ion deposition under different tree species. The differences were considered statistically significant at $p<0.05$.

Results

The amount of throughfall water was significantly ($p < 0.05$) lower than the amount of bulk precipitation (Fig. 1). The highest (> 50%) interception loss was observed in the spruce stand and the amount of throughfall water under spruce was statistically significantly less than under pine and birch canopies ($p<0.05$). There was no statistically significant difference ($p>0.05$) in throughfall water amount collected under the pine and birch canopies and the interception loss was approximately 30%.

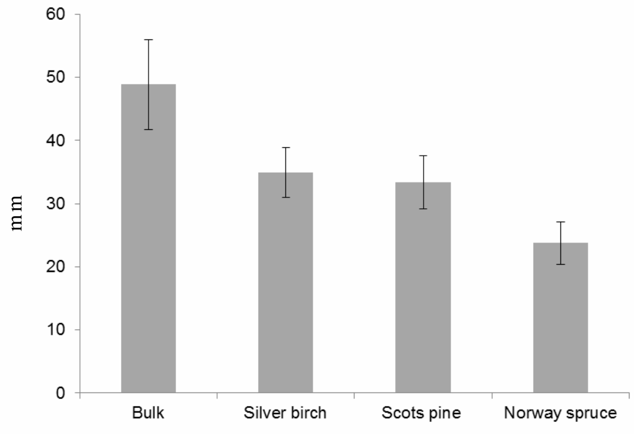

Figure 1. Mean monthly amount of bulk precipitation and throughfall water (mm month^{-1}) (April – November of 2003 – 2004). Bars indicate standard error

Concentrations of principal ions in throughfall within the studied stands were higher than in bulk precipitation with exception of sodium and hydrogen in the birch stand (Table 1). The differences between the concentrations in throughfall and bulk precipitation were statistically significant ($p<0.05$) except for Ca^{2+} in all stands, for NO_3^-, NH_4^+ in the birch stand, H^+ in the pine and spruce stands and Na^+ in the pine and birch stands.

Throughfall was enriched in most of the analysed ions (Fig. 2). The enrichment varied considerably among different stands, suggesting that throughfall deposition strongly depends on tree species compo-

tands, respectively. Similarly, as for sulphate, the ifference between nitrate fluxes to the floor of the

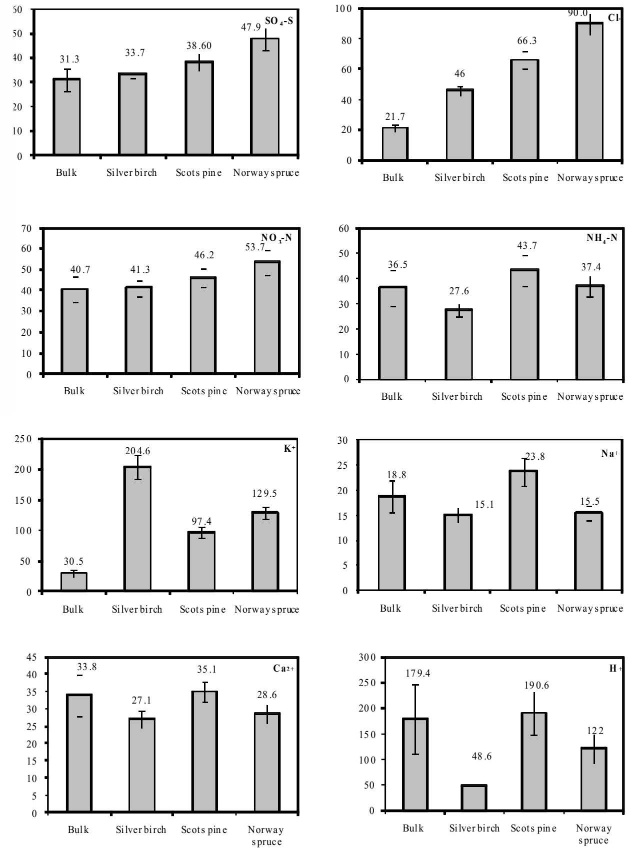

Figure 2. Mean monthly bulk and throughfall deposition fluxes (mg m^{-2} month^{-1}) (April –November of 2003 – 2004). Bars indicate standard error

Table 1. Volume-weighted mean concentrations (mg l^{-1}) of ions in bulk and throughfall deposition (April – November of 2003 – 2004)

	SO_4^{2-}-S	NO_3^--N	Cl^-	$H^{+\,a}$	NH_4^+-N	Na^+	K^+	Ca^+	pH
Bulk	0.64	0.83	0.44	3.67	0.75	0.62	0.38	0.69	5.43
Throughfall									
Silver birch	0.96	1.22	1.34	1.27	0.79	0.43	5.86	0.78	5.90
Scots pine	1.16	1.38	1.99	5.71	1.31	0.71	2.92	1.05	5.24
Norway spruce	2.02	2.26	3.79	4.58	1.57	0.65	5.45	1.20	5.34

^{a} – μeql^{-1}

sition. In the case of sulphate, the greatest enrichment took place in the spruce stand, the lowest was detected in the birch stand. Sulphate deposition in spruce exceeded that in pine by 24% and in birch by 42% ($p < 0.05$). The difference between SO_4^{2-}-S throughfall deposition in the birch and pine stands was rather inconsiderable and amounted to 14% ($p = 0.053$). Throughfall deposition of chloride was significantly higher than bulk deposition. It was 2.1, 3.0 and 4.1 times higher than bulk deposition under the birch, pine and spruce canopies, respectively.

Throughfall fluxes of nitrate in the spruce stand were 16% and 30% higher than in the pine and birch pine and birch stands was rather small (10.6 %). The enrichment of throughfall in NO_3^--N in the birch stand was very negligible and statistically insignificant (1.5 %). Throughfall deposition of ammonium under the different canopies demonstrated a pattern different from that for nitrate. The highest ammonium throughfall deposition was observed in the pine stand and the differences from spruce and birch amounted to 17% and 60%, respectively. Moreover, the NH_4^+-N deposition under the birch canopies was 25% lower than in the open area.

Fluxes of potassium were modified mostly passing through the canopies, though contrary to anions, the greatest enrichment of throughfall in K^+ was detected in the birch stand. K^+ fluxes under birch canopies were up to 2.0 times higher than in the pine stand and 1.6 times higher than in the spruce stands. In contrast, other cations (Na^+, Ca^{2+}, H^+) did not exhibit such a pattern: an increase in fluxes as compared to bulk deposition was detected under pine canopy while a decrease was observed beneath spruce and birch canopies.

In order to get more insight into temporal variability of fluxes to the forest floor, seasonal variability of bulk and throughfall deposition fluxes was examined (Fig. 3). The higher enrichment of throughfall in sulphur was detected at the end of spring and at the end of autumn. Seasonal variability of throughfall fluxes of sulphur in June-November was almost identical in the studied stands, though in spring and especially in May, the clear differences may be observed and deposition of sulphur under spruce canopy was considerably higher than that under pine and birch canopy..

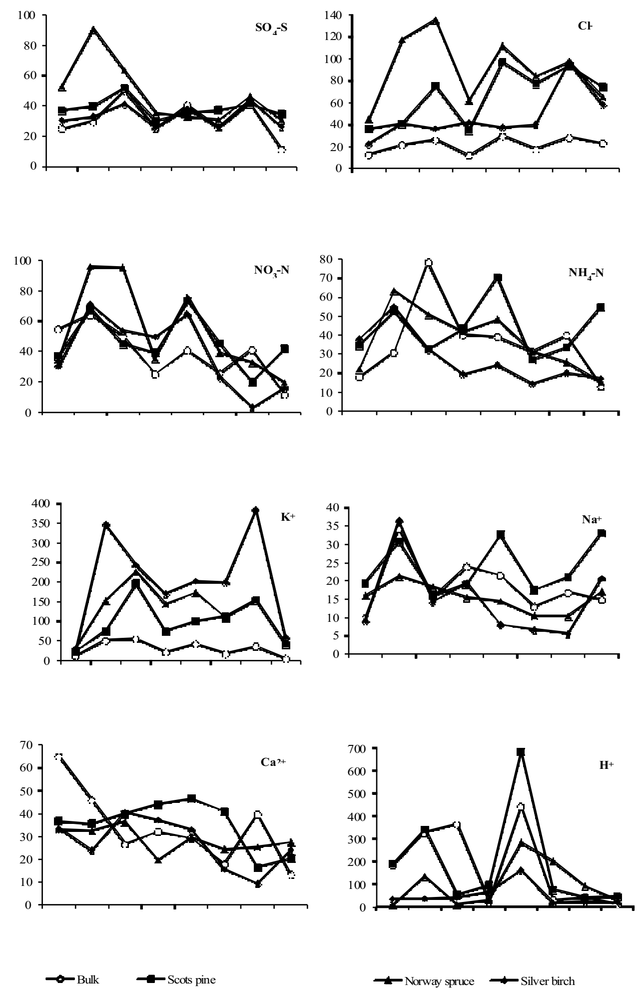

Figure 3. Seasonal trends of bulk and throughfall deposition fluxes (mg m^{-2} $month^{-1}$) (April – November of 2003 – 2004)

Monthly nitrogen throughfall deposition exhibited strong seasonal patterns in all three stands, though there were some differences between ammonium and nitrates. Throughfall enrichment in nitrates was observed within all stands during the whole growing season with exception of April and October when retention of nitrates was observed especially in the birch stand. The highest enrichment in nitrates was detected under spruce canopy in the very end of spring and the beginning of summer (May and June). Deposition of nitrates under the spruce canopy were registered to be almost two times higher than under pine and birch canopies during this period (Fig. 3)

The throughfall fluxes of ammonium in the birch stand were lower than in open area, indicating a net uptake of ammonium during the June-October period. The retention of ammonium by all canopies was recorded in the beginning of summer and in October, whereas the process of wash-off of dry deposition dominated in spring and in November.

The temporal variability of througfall fluxes of base cations and H^+ was rather high with the higher fluxes in the growing season and lower ones in the dormant season (April, November). The throughfall fluxes of potassium clearly showed the highest values in birch stand ($p < 0.05$) in comparison with coniferous. Significantly higher throughfall enrichment in potassium ($p < 0.05$) under the birch canopy was in May and October. The coniferous in the growing season also showed higher values of K^+ throughfall relative to the dormant season ($p < 0.05$), though the magnitude of the enrichment was not so considerable as in the birch stand.

One of the most important and complicated questions when investigating the modifications of precipitation in tree canopy is how to distinguish the input of different processes. In order to evaluate the relative contribution of the main processes modifying precipitation, the relationship between throughfall water volume and net throughfall fluxes of investigated ions was examined (Table 2). The relationship between net throughfall of anions (SO_4^{2-}, NO_3^-, Cl^-) and volume of throughfall water was very weak and statistically insignificant, except for sulphate in the birch stand and chloride in the spruce stand (Table 2). Enrichment of throughfall under canopy is mostly linked to wash-off of dry deposited compounds accumulated on the canopy surface in the case of these compounds.

Net throughfall of ammonium was negatively correlated with the volume of throughfall water, indicating uptake of this compound, though in the coniferous stands, the relationship was statistically insignificant. The strongest and statistically significant positive correlation of K^+ net throughfall with volume of

Table 2. Spearman's rank correlation coefficients between net throughfall fluxes of investigated ions and the amount of throughfall water

	SO_4-S	NO_3-N	Cl^-	NH_4-N	Na^+	K^+	Ca^{2+}	H^+
Silver birch	-0.65*	0.27	0.31	-0.63*	-0.47	0.43*	0.28	0.30
Scots pine	-0.16	0.24	0.38	-0.30	-0.20	0.44*	0.29	0.36
Norway spruce	-0.11	0.38	0.50*	-0.05	-0.22	0.83*	-0.22	-0.23

* – $p < 0.05$

throughfall water was characteristic of all investigated stands, indicating leaching of this element. No significant relationship was found between net throughfall of most cations (Ca^{2+}, Na^+ and H^+) and the volume of throughfall water.

For ions whose enrichment was mainly attributed to wash-off of dry deposited material, in order to verify whether any canopy exchange processes occurred during rainfall passage through the canopy, the relationship between bulk and throughfall deposition of these elements was investigated. For SO_4^{2-}-S a clear and statistically significant correlation was found between bulk and throughfall deposition in all investigated stands (pine – R^2=0.60, spruce–R^2=0.36, birch – R^2=0.64; $p<0.05$) indicating that there was no interaction with internal tissues of plants. A close relationship was also determined for Cl^- ions (R^2=0.22-0.59, $p<0.05$). For nitrate, the relationship between bulk deposition and throughfall was not significant ($p>0.05$), indicating that dry deposition was not the only process modifying the concentration of nitrate in the deposition flux passing through the forest canopies.

To obtain more insight into differences between nitrogen (nitrate and ammonium) canopy interaction mechanisms, the net throughfall of nitrate and ammonium were plotted against their bulk deposition (Fig. 4).

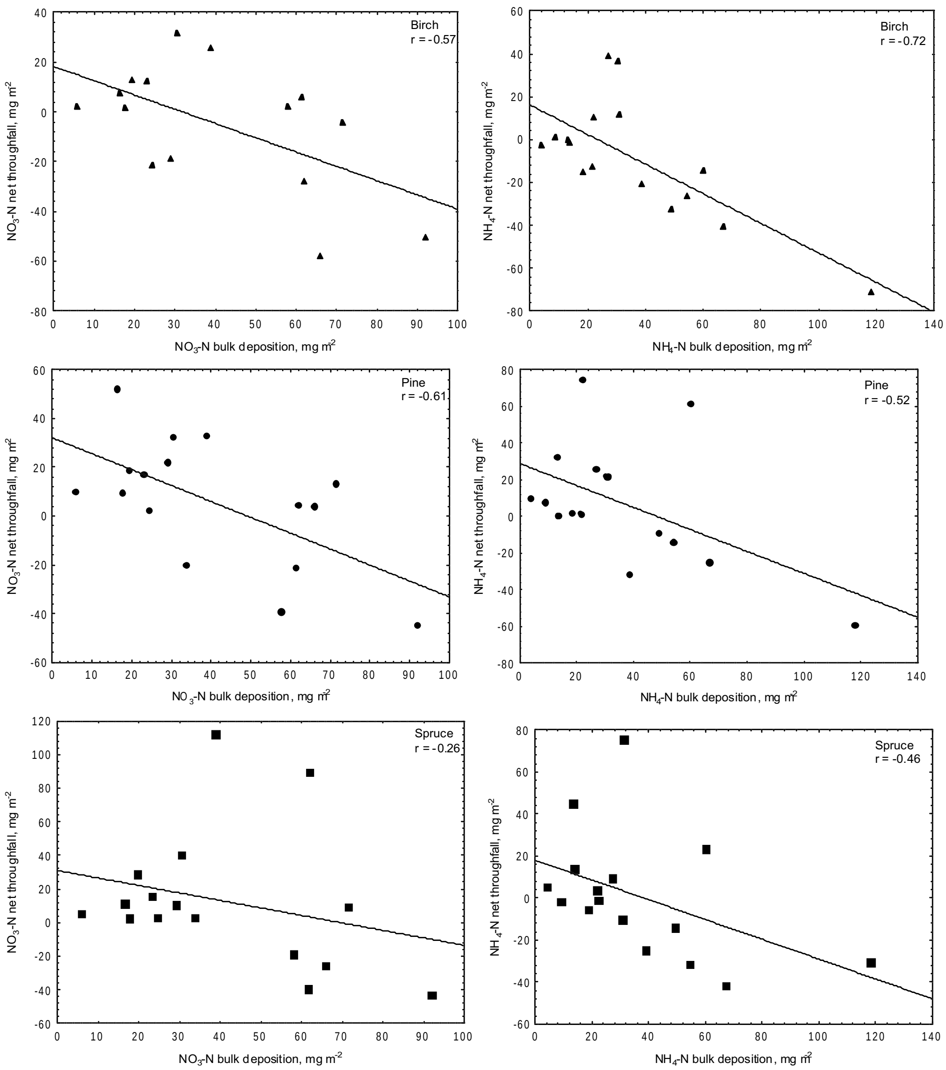

Figure 4. Relationship between bulk and net throughfall deposition of NO_3^--N and NH_4^+-N (mg m^{-2} $month^{-1}$) in different stands

A close negative relationship between bulk deposition and net throughfall of both oxidized and reduced ions of nitrogen was detected in the birch and pine stands, suggesting that uptake of these ions increases along with increasing fluxes of nitrate and ammonium in bulk precipitation. In the spruce stand, the correlation between bulk and net throughfall fluxes of nitrate was not significant ($p>0.05$), while for ammonium, the negative relationship was stronger and significant. High leaf area may lead to higher load of dry deposition and it may mask the canopy uptake. In all stands the net throughfall of nitrate correlated less to bulk deposition than ammonium did and the data were more scattered. This suggests that ions of ammonium are more available for uptake than nitrate ions, though the wash-off of dry deposited ammonium was the prevailing process during the interaction with pine and spruce canopy (Fig. 3-4, Table 2).

A statistically significant positive correlation of K^+ net throughfall with volume of throughfall water was characteristic of all investigated sites (Table 2) confirming that leaching of K^+ prevails during the interaction of rainfall with tree canopy. To explain the differences in K^+ leaching extent among the analyzed species, a correlation analysis was conducted to detect the canopy leaching dependency on net throughfall of ammonium, hydrogen and throughfall of single anions and the sum of anions (sulphate + nitrate + chloride) (Table 3).

Discussion

Evaporation from leaf surface and canopy uptake cause interception losses and reduced throughfall water amount as compared to bulk precipitation. Usually higher interception losses are reported for coniferous stands (Van Ek and Draaijers 1994, Houle et al. 1999, De Schrijver et al. 2004). According to our study the average interception losses in the spruce stand were 50 % and approximately 30 % in the pine and birch stands. Evidently, interception loss might be more dependent on leaf area than on tree species or their being coniferous or deciduous.

It was observed that sulphate and chloride throughfall deposition increased along with the increase of tree leaf area (Fig. 2). A higher leaf (needle) surface area represents a higher surface for dry material deposition and a longer contact between water and foliage. Generally, forest canopies are considered as inert surfaces for sulphur and chloride and the enrichment of throughfall in these ions is mostly linked to the wash-off of dry deposited material. The correlation between net throughfall of SO_4^{2-}-S and volume of throughfall water was very weak and statistically insignificant (Table 2) in coniferous stands, indicating that enrichment of throughfall in sulphate could be attributed to dry deposition. It was also proved by the same seasonal variability of bulk and throughfall fluxes in studied stands (Fig. 3). Higher LAI of pine and

Table 3. Spearman's rank correlation coefficients between net throughfall of potassium (K^+) and net throughfall of H^+, NH_4^+-N, throughfall of single anions (SO_4^{2-}-S, NO_3^- -N, Cl^-) and the sum of anions (SO_4^{2-}-S + NO_3^- -N + Cl^-)

	H^+	NH_4^+-N	SO_4^{2-}-S	NO_3^--N	Cl^-	Anions (SO_4^{2-}-S + NO_3^--N + Cl^-)
Silver birch	-0.33*	-0.27*	0.39*	0.09	0.56*	0.39*
Scots pine	0.10	-0.20*	0.42*	0.18	0.74*	0.57*
Norway spruce	0.12	0.09	0.64*	0.62*	0.78*	0.76*

* – $p < 0.05$

Net throughfall of K^+ significantly positively correlated with the total amount of anions in throughfall under all studied canopies. The strongest relationship between anions input and K^+ leaching was detected for spruce, the medium – for pine and in the case of birch, the relationship was relatively weak. Calculated negative relationships between net throughfall of K^+ and net throughfall of H^+ and NH_4^+-N were relatively weak but statistically significant under the birch canopy, although in the coniferous stands (except for NH_4^+-N in pine) there were no significant relationships as no canopy uptake of ammonium and hydrogen was observed.

especially of spruce resulted in higher amount of dry deposited sulphur compounds compared to birch. A higher sulphur load under coniferous canopies in comparison with deciduous stands was observed during the studies in various forest ecosystems (Van Ek and Draaijers, 1994, Bini and Bresolin 1998, Houle et al. 1999). Moreover, in spruce stands sulphur fluxes are usually higher than in pine ones (Raben et al. 2000, Pajuste et al. 2006). For the birch stand, a significant negative relationship between the volume of throughfall water and net throughfall of sulphate indicates that sulphate might be retained by the birch canopy. However, the positive net throughfall shows that dry sulphur deposition compensates the negligible uptake. It is generally accepted that sulphates in throughfall are derived only from atmospheric deposition, i.e. rainfall deposition, dry deposition of gaseous SO_2 and particulate SO_4^{2-}. Experiments with sulphur isotopes showed that foliar leaching of sulphur has a minor contribution to the enrichment of throughfall in SO_4^{2-}, and that it could be ignored (Garten et al. 1988, Cape et al. 1992, Veltkamp and Wyers 1997).

The enrichment of throughfall in chloride in pine and birch stands is linked to dry deposition as well. The significant positive relationship between the net throughfall of Cl^- and throughfall water amount in the spruce stand suggests possible canopy leaching. Generally, the increase of Cl^- in throughfall is attributed to wash-off of dry deposition and the canopy leaching computed for Cl^- is regarded as deposition of gaseous HCl (Draaijers et al. 1994). However, several studies suggested the possible canopy leaching of Cl^- from senescent tree leaves (Houle et al. 1999, Staelens et al. 2007).

Our results lead to a presumption that in the case of conservative elements, such as S, Cl, throughfall enrichment is mostly dependent on physical (deposition area on canopy surface) rather than physiological properties of trees; and throughfall fluxes within the different forest types to a large extent may be explained by the leaf area index of the dominant tree species.

According to our investigations, modifications of oxidised and reduced forms of nitrogen passing through the canopy differ essentially. The pattern of nitrate modifications is similar to that of conservative elements (S and Cl) and an increase in fluxes of this compound along with an increase in leaf area can be noted. A presumption can be made that in the case of nitrate, wash-off is a prevailing process of rainfall modifications. A weak and insignificant correlation between the throughfall water amount and net throughfall of nitrate in studied stands confirms this presumption (Table 2). The analysis of the relationship between bulk and net throughfall of nitrate revealed that canopy uptake could also have occurred (Fig. 4), but this might have been obscured by relatively high dry deposition, especially in the spruce stand with high LAI. The same suggestion was made by De Schrijver et al. (2007), after review of 38 case studies in monitoring and evaluation of atmospheric deposition. As the retention of nitrates was observed at the moments of leaf sprounting (April) or leaf senescence (October) (Fig. 3), it may be linked to nitrates uptake by the twigs and stems (Brumme et al. 1992, Eilers et al. 1992).

Fluxes of NH_4^+-N under birch canopy were significantly lower than that in the open area (Fig. 2-3), suggesting the prevailing of uptake process in rainfall modification by trees canopies, which was confirmed by the significant negative relationship between throughfall water amount and net throughfall (Table 2). In contrast, in coniferous stands, slight enrichment of throughfall in ammonium ions was detected. The closest negative relationship between bulk deposition and net throughfall of ammonium was characteristic namely of the birch stand (Fig. 4), suggesting that the uptake of NH_4^+-N increases along with increasing fluxes of ammonium in bulk deposition. In coniferous stands, the negative correlation between bulk and net throughfall fluxes of ammonium was weaker. It was weakest in the spruce stand, suggesting that high LAI may lead to high load of dry deposition and may mask the canopy uptake. The wash-off of dry deposited ammonium was the prevailing process during the interaction with spruce canopy (Fig. 4, Table 2).

It was observed that the tree canopies assimilated NH_4^+-N ions to a greater extent than NO_3^--N ions and key differences were detected for the birch canopy (Figs. 3-4, Table 2). This phenomenon was recorded for deciduous and coniferous species in several experiments and field studies (Garten and Hanson 1990, Brumme et al. 1992, Wilson and Tiley 1998, Cape et al. 2001). It can be explained by the canopy ability to absorb ammonium from two different sources, from gaseous-aerosol and from rain-water input, whereas nitrate is absorbed mainly from gaseous-aerosol input and uptake from rain-water if negligible (Lindberg et al. 1987; Stachurski and Zimka 2002). Moreover, a negative charge of a cuticle surface is more favourable to absorb cations and repel anions (Riederer 1989). Due to a thinner cuticle and a higher wettability of leaves, deciduous trees absorb nitrogen more effectively than conifers (Bini and Bresolin 1998, De Schrijver et al. 2004), though a higher retention capacity is characteristic of coniferous stands (Brumme et al. 1992, Eilers et al. 1992). A conclusion could be drawn that the interaction of nitrogen with tree foliage is very complicated and the intensity of nitrogen deposition cannot be attributed simply to the amount of precipitation or LAI. Due to various deposition and canopy processes and their temporal variability, the data of nitrogen deposition monitoring must be treated with special care.

The greatest enrichment of throughfall in K^+ was detected in the birch stand where input with throughfall was almost 7 times higher than in bulk deposition. The highest canopy leaching of K^+ from the birch canopy could be explained as a consequence of physiological differences between the deciduous and the coniferous species. The deciduous trees are more susceptible to canopy leaching because of a thinner cuticle. Moreover, the major pools of K^+ are held in apoplast and K^+ is not so tightly bound in structural tissues on enzyme complexes as other cations. Van Ek and Draaijers (1994), Houle et al. (1999), De Schrijver et al. (2004) and Herrmann et al. (2006) also found that deciduous canopies lost significantly more K^+ than coniferous ones. Particularly high throughfall enrichment in K^+ in birch stand was recorded during the leaf emergence (May) and senescence (October) (Fig. 3). Higher leaching capacities of K^+ during leaf emergence and senescence by comparison with the fully leafed period have also been reported by several authors for different deciduous tree species (André et al. 2008, Draaijers et al. 1992, Houle et al. 1999, Van Ek, Draaijers 1994).

Leaching of K^+ depends on deposition of anions (SO_4^{2-} + NO_3^- + Cl^-) with throughfall (Juknys et al. 2007). In the birch stand, the fluxes of anions were 20 % and 37 % lower than in the pine and spruce stands, respectively. The regression analysis showed that in the birch stand, the relationship between input of anions and net throughfall of K^+ was the weakest (Table 3). So, the highest leaching of K^+ from the birch canopy cannot be attributed to the different load of anions and it may be presumed that the higher leaching rate from the deciduous canopy could be explained by the exchange reactions with other cations – H^+ and NH_4^+. The negative relationships ($p<0.05$) between net throughfall of K^+ and net throughfall of H^+ and NH_4^+ support this presumption (Table 3). A rather weak, yet statistically significant relationship between K^+ leaching and retention of H^+ and NH_4^+ intensity was reported by Langusch et al. (2003). Conclusion can be drawn that higher leaching of K^+ from birch canopies could be attributed to more intense ion exchange with H^+ and NH_4^+. Physiological characteristics, i.e. a thinner cuticle and higher nutrients concentrations in birch leaves compared to pine or spruce needles could be considered as an additional reason for more intensive leaching of K^+ from birch canopy (Johansson 1995).

Summing-up the behaviour of the investigated ions, it was revealed that the deciduous trees exhibit more intense canopy exchange processes than the coniferous. In the birch stand higher retention of nitrogen and hydrogen leading to more intense canopy leaching of potassium was observed in comparison with the pine and spruce stands.

Conclusions

Essential differences between ion fluxes and their modifications in the stands of different species were detected. The highest throughfall enrichment in anions (SO_4^{2-}, NO_3^-, Cl^-) especially in the end of spring very beginning of summer (May and June), was found in the case of the largest canopy surface area (Norway spruce), and the smallest – in the case of the lowest canopy surface area (silver birch), indicating that the enrichment is mostly linked to wash-off of dry deposited anions accumulated on the canopy surface.

When the net throughfall intensity is determined by canopy exchange rates (K^+) or by both processes – wash-off of dry deposition and canopy exchange (N) – one of the main factors determining the tree species impact on net throughfall is physiological tree characteristics. The most intense canopy exchange processes were detected in the birch stand. Birch canopy absorbed higher amounts of nitrogen compounds (especially ammonium), and lost much more potassium cations than the coniferous trees. The most intense ion exchange with ammonium and hydrogen is considered as the main reason for higher potassium leaching from birch foliage.

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СРАВНЕНИЕ АТМОСФЕРНЫХ ВЫПАДЕНИЙ ОСНОВНЫХ ИОНОВ И ИХ МОДИФИКАЦИЙ В ДРЕВОСТОЯХ РАЗЛИЧНЫХ ДРЕВЕСНЫХ ПОРОД

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Резюме

Исследования атмосферных выпадениях были проведены в открытой местности и под пологом наиболее распространённых в Восточном Балтийском регионе древесных пород – сосны (*Pinus sylvestris* L.), ели (*Picea abies* (L.) H. Karst.) и берёзы (*Betula Pendula* Roth). Основной целью данного исследования было сравнение количество и химического состава атмосферных выпадений под пологом различных древесных пород. Наиболее существенное обогащение анионами (SO_4^{2-}, NO_3^-, Cl^-) было установлено под пологом ели, который отличается наибольшей поверхностью листьев (хвои) и наоборот – наименьшее обогащение характерно выпадениям под пологом берёзы, который отличается наименьшей поверхностью листьев. В пологе берёзы установлено наибольшая абсорбция неорганических соединений азота, особенно ионов аммония, и большее по сравнению с хвойными вымывания катионов. Вымывание K^+ из полога берёзы было 1.8 раза более интенсивно чем из полога ели и 2.6 раза интенсивнее чем из полога сосны. Более интенсивный обмен между ионами водорода и аммония трактируется как основная причина более интенсивного вымывания ионов калия из листвы берёзы.

Ключевые слова: атмосферные выпадения, сухие выпадения, вымывание, выпадения под кроной деревьев, древесные породы, абсорбция.