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NITROGEN DEPOSITION AND FLUX THROUGH BIRCH STANDS (*BETULA PUBESCENS* EHRH.) IN THE KAMPINOS NATIONAL PARK (CENTRAL POLAND)

ABSTRACT: Nitrogen flow through birch stand canopies was studied in the Kampinos National Park (large forested area with inland dunes and wetlands close to Warsaw) during the growing seasons (April-October) of 2005–2006. The amount of nitrogen deposition including main forms like NO_3, NH_4, organic N and the aerosol-gaseous fraction of deposition were estimated as well as the influence of birch canopies on this process. Because a method of "artificial foliage" allows to measure an aerosol-gaseous fraction of deposition a gradient of rain collectors equipped with artificial foliage of known surfaces were used. The results were compared with amounts of nitrogen measured in the throughfall of three birch forests. All stands (age 20–50 years) were rather similar, but stand II has smaller LAI (Leaf Area Index = 2.5 m^2 m^{-2}) than stands II and III (3.8 and 3.9 m^2 m^{-2}). It was found that nitrogen deposition in the Kampinos National Park is rather high – 1.6 kg ha^{-1} $month^{-1}$. Ammonium-nitrogen made almost half of this value, organic nitrogen – over one third, and nitrate-nitrogen constituted the rest. Aerosol-gaseous input significantly made the deposition increased only in the case of nitrate-nitrogen, but deposition of ammonium- and organic nitrogen were similar and independent of catching leaf area. All fractions of nitrogen were effectively taken up during their passing through birch canopies (57% of nitrogen deposition was retained). Generally two thirds of deposited ammonium-nitrogen, more than half of organic N, and one third of nitrate-nitrogen were taken up by birch canopies. However, uptake efficiency of all N forms was lower for stand with smallest leaf area with no statistically significant retention of organic N.

KEY WORDS: bulk precipitation, leaf area index (LAI), ammonium, nitrate, dissolved organic nitrogen, total dissolved nitrogen, *Betula pubescens*

1. INTRODUCTION

The supply of nitrogen is a key factor regulating biotic structure and function in many ecosystems (Vitousek *et al.* 2002). In boreal forests, dominating in central and northern Europe, nitrogen is considered as the factor limiting forest growth (Tamm 1991).

Atmospheric deposition is one of main sources of the element and it is therefore commonly investigated. However, conventional methods of N deposition measurements are based on the sampling of inorganic N (ammonium, nitrate) in wet or bulk deposition. This approach does not consider gaseous and organic N compounds.

Most N studies in forests have been focused on dissolved inorganic N (DIN: NH_4^+ + NO_3^- + NO_2^-). Due to analytical difficulties only a few studies have reported also dissolved organic N (DON) (Campbell *et al.* 2000, Goodale *et al.* 2000, Hagedorn *et al.* 2001). However, Campbell *et al.* (2000) suggested that DON must be considered in any studies of N budget. A review of studies showed that atmospheric DON deposition should be considered as the main deposited form of nitrogen (Neff *et al.* 2002, Cornell *et al.* 2003).

Similar to DON, aerosol-gaseous input of nitrogen played an important role in the N budget of forest ecosystem. Experiments with artificial leaves show that the atmospheric input of many elements, including N, increases with the increase of leaf surface area. For that reason, the atmospheric input to forest ecosystems can be several times higher than to the bare ground areas or to ecosystems with small leaf area (Lindberg *et al.* 1986, Stachurski and Zimka 2000, Böhlmann *et al.* 2005).

The second important component of nitrogen cycling in forest ecosystems is the process involved in nitrogen flux through forest canopies. Several studies show that inorganic nitrogen is efficiently retained by the tree canopies (Carlisle *et al.* 1966, Stachurski and Zimka 1984, Klopatek *et al.* 2006, Neirynck *et al.* 2007). However, some authors showed that it is the leaching of nitrogen from forest canopies, not the uptake (MacDonald *et al.* 2002, Hansen *et al.* 2007, van der Salm *et al.* 2007). Unfortunately, most of these research concerned only the inorganic nitrogen and/or they did not include aerosol-gaseous part of deposition.

The objectives of this study were to estimate N deposition, including DON and aerosol-gaseous input, as well as direction and rate of their flux through forest canopies on an example of birch stands in the Kampinos National Park.

2. STUDY AREA

The study was carried out in the Kampinos National Park during the vegetative seasons (April – October) of the years 2005 and 2006. The Kampinos National Park is located in Central Poland on the north-west outskirts of Warsaw. Park's area is close to 385 km^2, 70% of which is covered by forests (mainly pine, but also alder, and birch).

Three forest stands of downy birch (*Betula pubescens* Ehrh.) were selected for the study. All of them are localized in the north part of the Kampinos National Park (52°22'N and 20°31'E).

stand I – 40-50-year old self-sown birch stand on the old wetland (now dry);

stand II – 20-year old self-sown birch stand on wetland with no drainage, on the marsh border;

stand III – 20-year old self-sown birch stand situated only 100 metres south-west from stand II, growing on the same soils, but on an area with old drainage (now partly destroyed).

Bulk precipitation collectors were situated on an open area at the northern part of the Kampinos National Park; 1–4.5 km from the study plots.

3. MATERIAL AND METHODS

To measure aerosol-gaseous input, the method of "artificial foliage" was applied. It consists of modified rain collectors equipped with artificial foliage of a known surface area mounted above the trap (Stachurski and Zimka 2000). The following types of collectors were used: 0 (without artificial surfaces), 2, 6, and 12 m^2 m^{-2} of LAI (leaf area index). Three traps of each variant were placed in open areas. Traps of the variant "0" were also placed under the trees. Four rain collectors were set up in each tree stand.

Stemflow was ignored in this study due to its generally low contribution to the total load of ions (less than 10%) (Eaton *et al.* 1973, Alcock and Morton 1985, Grodzińska and Laskowski 1996).

Once per four weeks, water samples were gathered from rain collectors, and the nylon filters and rain canisters with rain water were exchanged for clean ones. The amount of water in the traps was measured in the field. Samples from every canister were collected and analysed separately.

To avoid solar radiation and the development of algae and microorganisms in collected water, each canister was wrapped with aluminium foil.

Concentrations of total dissolved nitrogen (TDN) in the water samples were determined using the Formacs^{HT} TOC/TN Analyser (SKALAR Analytical, The Netherlands). Concentrations of ammonium-nitrogen (N-NH_4^+) and nitrate-nitrogen (N-NO_3^-) were determined in two analytical cycles with an ion chromatograph Metrohm IC System 690 (Switzerland). Before analyses, the samples were filtered through 0.45 µm Teflon filters.

Organic nitrogen was calculated as the difference between total nitrogen (TDN) and inorganic nitrogen (N-NH_4^+ + N-NO_3^-).

To estimate the real input of the elements to the studied plots, it was necessary to know their leaf area index (LAI). LAI is expressed as the ratio of surface area of leaves per unit of ground area (usually presented in m^2 m^{-2}). In this study, LAI was measured with a method based on measurements of fallen leaves in autumn (method described in detail by Stachurski and Zimka 1975).

The modifying role of birch canopies was evaluated by comparing the pool of nitrogen contained in throughfall with that of the rainfall obtained from rain collectors equipped with artificial intercepting surfaces. For these comparisons, the results were taken from traps of an area most similar to the real leaf area of a given tree stand. For example, the input of N-compounds in throughfall from stand II was compared with the input obtained from traps of a foliage area of 2 m^2 m^{-2}. The throughfall in stands I and III was compared with the input collected in traps with a foliage area of 2 and 6 m^2 m^{-2} (treated separately), whose mean intercepting area (4 m^2 m^{-2}) was closest to the leaf area of those stands.

A student t-test for matched pairs was used to check whether a given compound was retained or not while passing through forest canopies. For each sampling date, the mean nitrogen contents in the water taken under the canopies were compared with the mean contents in the water taken from rain collectors with artificial foliage with the respective surface area. There were 13 such pairs (7 sampling dates in 2005 and 6 in 2006), which made 39 pairs for all examined stands. Since the time intervals between consecutive sampling occasions were not the same (28 days on average), each mean value was divided by the actual number of days and multiplied by 30 to obtain the input in g ha^{-1} $month^{-1}$.

4. RESULTS AND DISCUSSION

The smallest value of LAI was found for birch stand II – leaf area of this stand amounted only to 2.5 m^2 m^{-2}. In the stands I and III, the LAI values were very similar and reached 3.9 and 3.8 m^2 m^{-2}, respectively (Fig. 1).

Atmospheric N deposition in the temperate zones of highly industrialized regions of the world (North America, Europe, eastern Asia) has dramatically increased during the previous decades due to the emission of

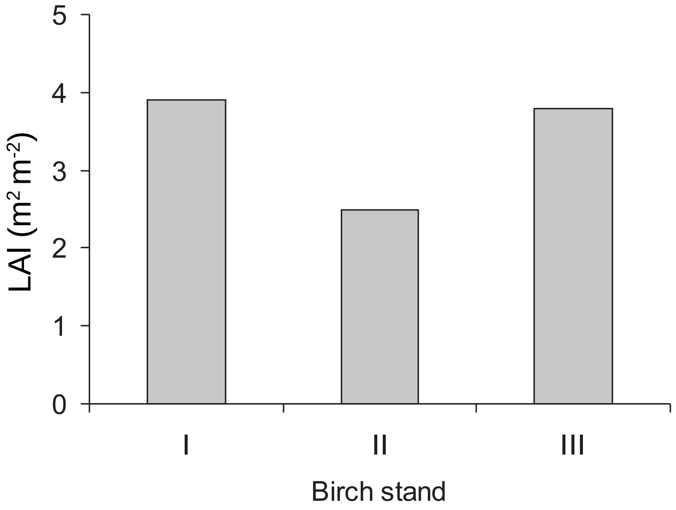

Fig. 1. Average LAI (leaf area index) of investigated birch stands in 2005.

Table 1. Atmospheric input of nitrogen forms (g ha^{-1} month^{-1}) to the study sites in the Kampinos Natonal Park for growing seasons 2005–2006 (mean values n = 6).
P – significance of difference between seasons 2005 and 2006; ns – *P*> 0.05.

Form of N	Mean	% N	2005	±SD	% N	2006	SD	% N	*P*
N-NH4	741.0	46	808.4	±276.9	42	673.5	±12.6	53	ns
N-NO3	254.8	16	213.9	±12.3	11	295.6	±37.2	23	<0.05
organic N	607.2	38	909.5	±457.0	47	304.8	±47.5	24	ns
total N	1 602.9		1 931.8	±742.8		1 274.0	±44.1		ns

Table 2. Coefficients of linear regression for the relationship between LAI values and loads (g ha^{-1} month^{-1}) of nitrogen forms to rain collectors. Calculations made for the growing seasons (April-October) 2005–2006; n = 24; ns – not significant statistically (*P*> 0.05)

Form of N	Intercept (a)	Slope (b)	±SD	R	*P*
N-NH4	717.5	7.9	4.7	0.16	ns
N-NO3	253.2	12.7	3.0	0.78	<0.0001
organic N	608.9	14.1	4.7	0.18	ns
total N	1 582.7	34.5	4.6	0.28	ns

Table 3. Comparison between atmospheric load of nitrogen forms and their fluxes in throughfall through the birch canopy in g ha–1 month–1. Mean values for growing season (April-October).
A – atmospheric deposition; T – throughfall; CR – canopy retention (CR = A – T); SD – standard deviation of mean; *P* – significance of the differences between A and T values according to the Student t-test. No further calculations were made when the differences between A and T values were not significant. Calculations were based on the data collected in 2005 and 2006. The atmospheric deposition of nitrogen to birch canopy was taken from the rain collectors fitted with artificial leaves of LAI = 2 m^2 m^{-2} (for stand II) and LAI = 2 and 6 m^2 m^{-2} (for stands I and III).

A). All three birch stands. n = 39.

	Atmospheric deposition		Throughfall		Canopy retention		
Form of N	A	±SD	T	±SD	*P*	CR	% CR/A
N-NH4	650.9	539.4	211.0	216.0	<0.0001	439.9	68
N-NO3	260.6	124.5	177.5	147.1	<0.0001	83.1	32
organic N	598.0	554.0	260.2	190.5	<0.0001	337.9	57
total N	1 513.7	1 121.2	648.7	415.9	<0.0001	865.0	57

B). Stands I, II, and III – separated calculations (n = 13).

	Atmospheric deposition			Throughfall				Canopy retention		
Form of N	LAI	A	±SD	Stand	LAI	T	±SD	*P*	CR	% CR/A
N-NH$_4$	4	658.7	512.8	I	3.9	227.5	264.9	<0.01	431.1	65
	2	635.5	628.5	II	2.5	268.1	224.7	<0.05	367.4	58
	4	658.7	512.8	III	3.8	137.4	131.8	<0.01	521.3	79
N-NO$_3$	4	270.7	131.5	I	3.9	179.1	182.8	<0.01	91.5	34
	2	240.5	111.7	II	2.5	198.8	129.1	<0.05	41.6	17
	4	270.7	131.5	III	3.8	154.5	131.9	<0.001	116.2	43
organic N	4	620.9	530.0	I	3.9	254.0	204.4	<0.01	366.8	59
	2	552.4	637.6	II	2.5	279.5	209.0	ns	–	–
	4	620.9	530.0	III	3.8	247.0	169.6	<0.01	373.9	60
total N	4	1 553.2	1 073.0	I	3.9	660.7	496.0	<0.01	892.5	58
	2	1 434.5	1 291.7	II	2.5	746.5	436.8	<0.05	688.0	48
	4	1 553.2	1 073.0	III	3.8	538.8	295.5	<0.01	1 014.4	65

NOx from combustion processes and NH_3 gas from agricultural activities (Vitousek 1994, Galloway *et al.* 1995, Holland *et al.* 1999). The total nitrogen atmospheric input found in this study site was relatively high – 1.6 kg month^{-1} ha^{-1} (Table 1). Assuming that the level of N deposition for the growing season can be extrapolated on the whole year – the value of yearly load equal to 20 kg N ha^{-1} year^{-1} is obtained. This value suggests an increase of nitrogen deposition in region of the Kampinos National Park. Investigations made by Zimka (1989) nearly 20 years ago reported the value equal to 10.4 kg ha^{-1} year^{-1}; it is by 50% smaller than the recent nitrogen deposition in that region. Nevertheless value of around 20 kg ha^{-1} year^{-1} of nitrogen deposition is similar to the ones reported from other parts of Poland (Zimka 1989, Szarek-Łukaszewska 1999). The level of deposition equal to 23 ± 7 kg N ha^{-1} year^{-1} is considered to be the critical load averaged over all vegetation and soil types (Van Dobben *et al.* 2006).

In first year (2005) of study the amounts of atmospheric deposition of ammonium-nitrogen and organic N were high and variable, which caused that the differences between the first and second year of study were not statistically significant. The only exception was nitrate-nitrogen, which deposition was greater in the second, 2006, year of study (Table 1).

Ammonium-nitrogen constituted almost half of total nitrogen deposition in the study area, organic nitrogen made over one third, and nitrate-nitrogen made the rest (Table 1). Such proportions between nitrogen forms are similar to those reported from other regions of Europe and the world. In eastern Finland, the mean annual bulk deposition of total N was 3.83 kg^{-1} ha^{-1}, 33% of which was NH_4^+, 26% – NO_3^-, and 41% – organic N (Piirainen *et al.* 1998). Also, studies by Ham and Tamiya (2006) conducted in central Japan showed that 48% of the total dissolved nitrogen was made by ammonium, 32% – by organic N, and 20% – by nitrate. Such proportions between nitrogen forms were similar in spite of almost 10 times greater annual atmospheric deposition of N, which in Japan reached over 30 kg (Ham and Tamiya 2006). Generally, reports of the share of organic nitrogen in total N deposition varied from 11 to 56%, being at average 23% (± 8%) in different regions in Europe (Cornell *et al.* 2003). These results clearly shows that organic nitrogen is an important part of nitrogen deposition, and should be included in the N cycle studies.

Earlier studies showed that the aerosol-gaseous input of nitrate-nitrogen as well as of ammonium-nitrogen are considerable (Stachurski and Zimka 2000, Kram 2001, 2005). But only in the case of nitrate-nitrogen a strong increase of deposited amounts was found along with the increasing artificial leaf surfaces fitted on rain collectors (Fig. 2). It caused 10% greater nitrate-nitrogen deposition in the stands with greater LAI (in this investigation stands I and III) than in the stand with smaller LAI (stand II). It also caused 20% greater deposition than in the areas with very low or without vegetation. In spite of such increase of nitrate deposition with increasing leaf area the aerosol-gaseous part of deposition of the total atmospheric deposition of nitrogen was statistically insignificant. It was because the deposition of ammonium-nitrogen as well as of organic nitrogen did not increase with increasing leaf area (Table 2).

A comparison of amounts of nitrogen forms in throughfall through the birch canopies with its depositions to the traps equipped with artificial foliage (of area similar to real LAI of investigated stands) showed that more than half of deposed nitrogen was retained in birch canopies (Table 3A). Moreover, it was found that all nitrogen forms (nitrate, ammonium, and organic N) were retained. The greatest retention was found for ammonium-nitrogen; it reached a level of two thirds of its atmospheric deposition. The retention of organic nitrogen was also very high – half of deposition being retained. The smallest retention was found for nitrate-nitrogen, with only one third deposition retained (Table 3A).

The pool of nitrogen retained in the canopies reached the average value of 0.9 kg ha^{-1} month^{-1}. During the entire vegetation season, it was more than 5 kg of nitrogen per ha, which is a significant amount when related to the N cycling in the forest ecosystem.

Retention level of atmospheric nitrogen was the smallest one in the case of birch

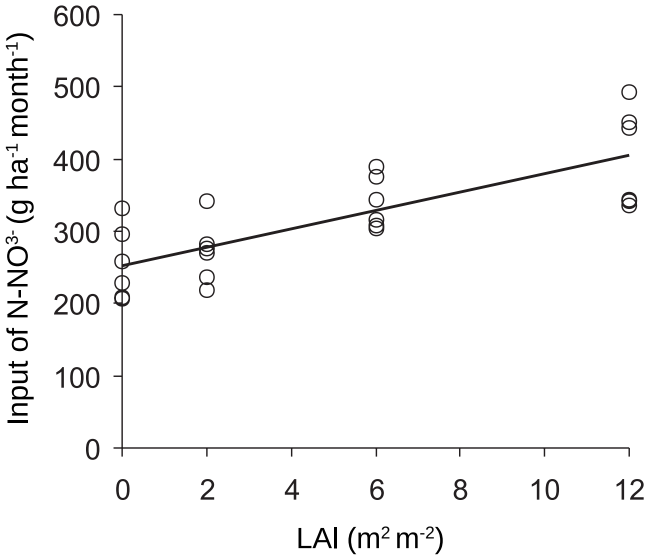

Fig. 2. Relationship between the artificial leaf area (LAI) and the input of nitrate-nitrogen to rain collectors in the Kampinos National Park (monthly average for two growing seasons – 2005 and 2006).
$y = 12.7\,x + 253.2$; r = 0.78; $P < 0.0001$; n = 24.

stand II (Table 3). In this stand, all nitrogen forms were retained in lower proportion than in both other stands, and in the case of organic nitrogen, such retention was not statistically significant (Table 3B). Stand II has the smallest leaf area index (Fig. 1). In that way stand II took the smallest pool of nitrogen from the atmosphere, and at the same time, its throughfall was found to constitute the greatest pool of nitrogen. That fact could support the hypothesis that leaf area is more important for canopy nitrogen retention than for capturing the aerosol-gaseous forms from the atmosphere.

Tomaszewski *et al.* (2003) has reported the exceptionally high values of canopy nitrogen uptake – as much as 90% of the deposition of NH_4 and 70–80% of NO_3 were retained. Such a high canopy nitrogen uptake may contribute to 10–15% of the foliar N requirement for canopy growth (Tomaszewski *et al.* 2003). Klopatek *et al.* (2006) showed that all tree species are extremely efficient in reducing the input of inorganic N to the forest floor. Morris *et al.* (2003) reported a 73% reduction of ammonium-nitrogen and a 47% reduction of nitrate-nitrogen in a black spruce forest in northwestern USA. Piirainen *et al.* (1998), who investigated mature spruce forests in Finland, found that 64% of NH_4 and 38% of NO_3 in bulk precipitation was retained by the tree canopy. Such results are almost the same as presented in this work, with the exception of organic N. In case of spruce in Finnish forests, organic N was released from the tree canopy (Piirainen *et al.* 1998), as opposed to present work, where DON was retained. Organic nitrogen is likely simultaneously retained and released in canopies, and in different studies the final result of these two processes is presented, in which the first process is usually more intensive than the second.

Although most authors showed the uptake of nitrogen in forest canopies, many authors as well described the leaching of inorganic nitrogen in this site. Most of these results were reported from regions with very high nitrogen deposition, and it is suggested that it happens only in cases of saturated ecosystems. It is suggested that nitrogen leaching is strongly dependent on the amount of nitrogen deposed in throughfall (i.e. N input) and it increases the C/N ratio in the soil (Macdonald *et al.* 2002). Dise and Wright (1995) showed that a combination of two factors (N-input and soil pH) explained 87% of the variability of nitrogen output from forest ecosystems.

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