Trees (2009) 23:531–538
DOI 10.1007/s00468-008-0299-3

ORIGINAL PAPER

The content of total sulphur and sulphur forms in birch (*Betula pendula* Roth) leaves in the air-polluted Krusne hory mountains

Petr Hrdlicka · Emanuel Kula

Received: 28 November 2007 / Revised: 11 November 2008 / Accepted: 24 November 2008 / Published online: 24 December 2008
© Springer-Verlag 2008

Abstract In leaves of birch (*Betula pendula* Roth), changes in the content of total sulphur and its inorganic and organic forms were determined in relation to the decreasing air-pollution load (SO_2) in the air-polluted Krusne hory mountains and the Decin sandstone highlands in 1995, 1998, 2001 and 2004. Results have shown that birch is able to use considerable amounts of sulphur taken through leaves from air-pollution load. Birch responds fast to changes in air-pollution load by fall in the content of total and inorganic forms of sulphur in leaves.

Keywords Birch (*Betula pendula* Roth) · Total sulphur · Inorganic sulphur · Organic sulphur · Air-polluted area (Krusne hory mountains)

Introduction

Large-scale clearcuts, which originated after a dieback of forest stands in the air-polluted Krusne hory mountains and the Decin sandstone highlands, were reforested by stands of substitute tree species making possible to preserve other forest functions. One of the most important tree species in the new stands became silver birch (*Betula pendula* Roth) (Kula 2006). The species is site-undemanding, important from soil-improving aspects, little endangered by game. For reasons of limited knowledge on the species, a programme was worked out of the comprehensive monitoring of the birch. Within the programme, in 1995, in the period of the culmination of air-pollution inputs of the 1990s, the first evaluation was carried out of the content of nutrient and other elements in birch leaves under various site conditions of the eastern Krusne hory mountains and the Decin sandstone highlands (Hrdlicka and Kula 1998). In the following period, effects were systematically monitored of the decrease of air-pollution load on the content of elements in assimilatory organs of birch (Hrdlicka and Kula 2004). The aim of the paper is to assess changes in the content of the total sulphur and its inorganic and organic forms in birch leaves in 1995–2004 in relation to the decrease in sulphur compounds' air-pollution in the Krusne hory basin.

Communicated by H. Rennenberg.

P. Hrdlicka (✉) · E. Kula
Mendel University of Agriculture and Forestry,
Zemedelska 1, 613 00 Brno, Czech Republic
e-mail: hrdlicka@mendelu.cz

Materials and methods

In the north-western part of the Czech Republic, in the area of the eastern Krusne hory mountains ("The Ore Mts") and the Decin sandstone highlands, four altitudinal transects were established: Klasterec (KLA; approximately 50°23′N, 13°02′E), Janov (JAN; approximately 50°32′N, 13°24′E), Litvinov (LIT; approximately 50°38′N, 13°37′E) (500–900 m altitude) and Sneznik (SNE; approximately 50°52′N, 14°03′E) (500–700 m altitude) (Fig. 1 in Hrdlicka and Kula 2004). The transects differ in air-pollution load, which decreases eastwards. In the area under investigation, decrease in SO_2 concentration was noted in the period 1995–2004 (Table 1).

Control branches with fully developed leaves were sampled at the end of the growing season (August 1995, 1998, 2001, 2004) from the upper, released and well-lit part of the crown of permanent sample trees according to standard methodology (UN-ECE 1998). Sampling was carried out in the altitudinal profile of all transects (Hrdlicka and

Table 1 Annual mean atmospheric SO_2 concentrations in particular transects of the Krusne hory mountains

Year	Atmospheric SO_2 concentrations (μg m^{-3} $year^{-1}$)			
	KLA	JAN	LIT[a]	SNE
1995	66.0	65.6	50.0/43.5	44.1
1998	17.1	17.0	28.0/16.8	22.4
2001	7.8	8.3	14.0/8.9	12.4
2004	10.0	8.0	14.0	11.0

Anonymous 1996, 1999, 2002, 2005—Data adopted from stations: KLA–Medenec: 846 m alt.; JAN–Rudolice v Horach: 843 m alt.; LIT–Krupka: 306 m alt./Flaje: 754 m alt.; SNE–Sneznik: 588 m alt

[a] Flaje station measurement finished in 2003

Kula 1998) in 54 stands from 162 trees (1995), in 53 stands from 157 trees (1998), in 52 stands from 156 trees (2001) and in 54 stands from 154 trees (2004). Sampled branches in paper bags were translocated to laboratory conditions where leaves (including petioles) were torn (contamination was eliminated using textile gloves). After natural and gradual drying, leaves were ovendried at 70°C for a period of 24 h. Then, leaves were ground (sieve 0.5 mm), placed in PE bottles under laboratory conditions and analysed. The content of total sulphur (S, μg g^{-1}; LECO analyzer) and its inorganic form (Sa, μg g^{-1}; isotachopheretic analyzer) was determined according to methodology of Hrdlicka (2005). Based on these data, the content of the organic form of sulphur (So = S − Sa) and index Q = So/Sa were calculated. Results are given with a confidence interval ($\alpha = 0.05$). Data were classified according to the year of sampling (Y; values 95, 98, 01, 04), transect (TRAN; KLA, JAN, LIT, SNE) and the stand altitude (ALT; 500, 600, 700, 800 and 900 m).

For statistical evaluation, ANOVA procedures were used (StatSoft, Inc. 2005); for the determination of statistically significant differences, the graphic comparison of the confidence intervals was utilized (see Figs. 1, 2). After the data transformation, the estimation of S, Sa and So values for $Q = 1$ was performed by the means of the regression analysis of the model ln $Q = f$(Sa). The alternatives where

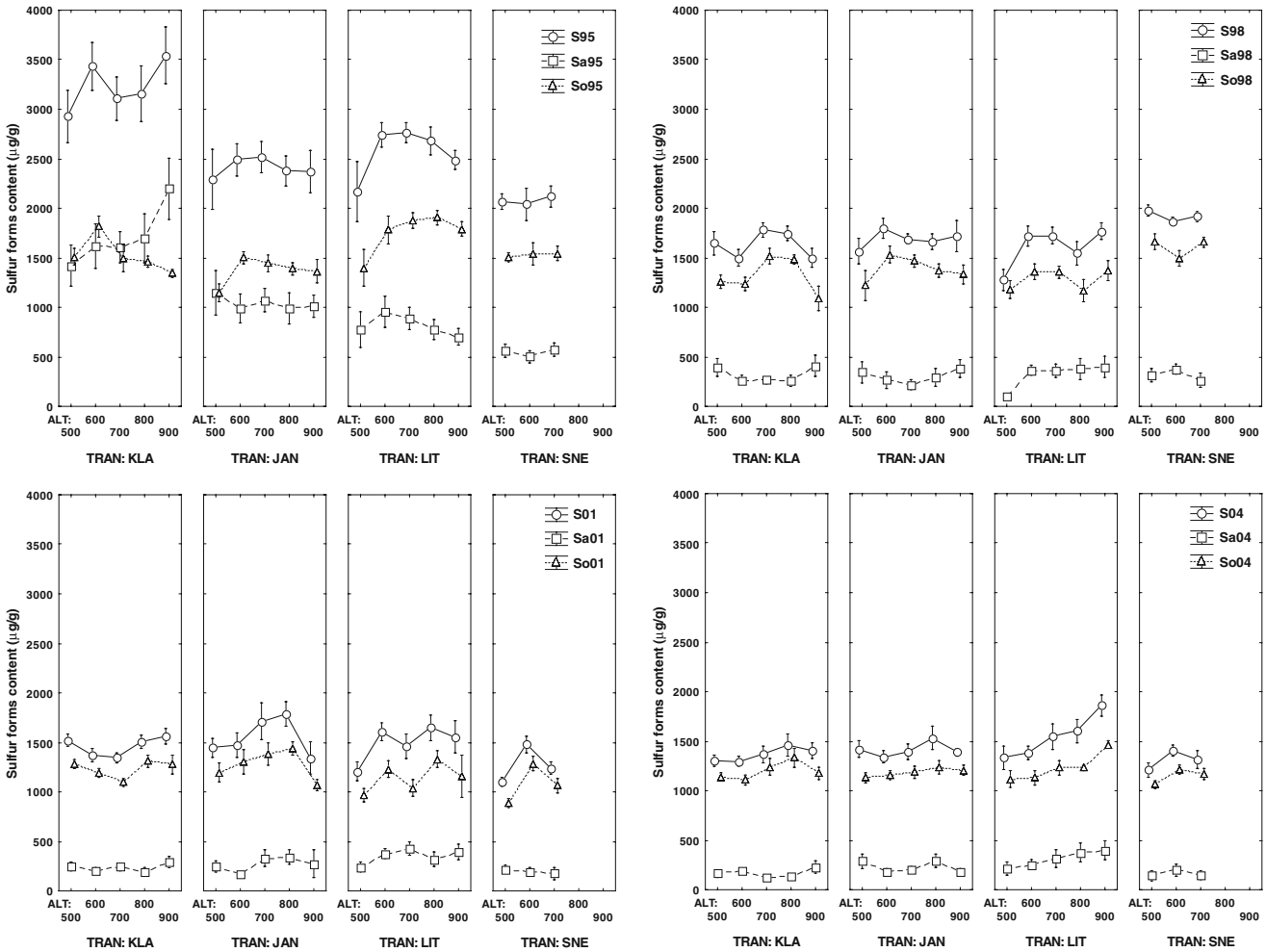

Fig. 1 The content of sulphur forms (μg g^{-1}) in birch leaves in transects (TRA) and altitudes (ALT)—mean ± confidence interval ($\alpha = 0.05$)

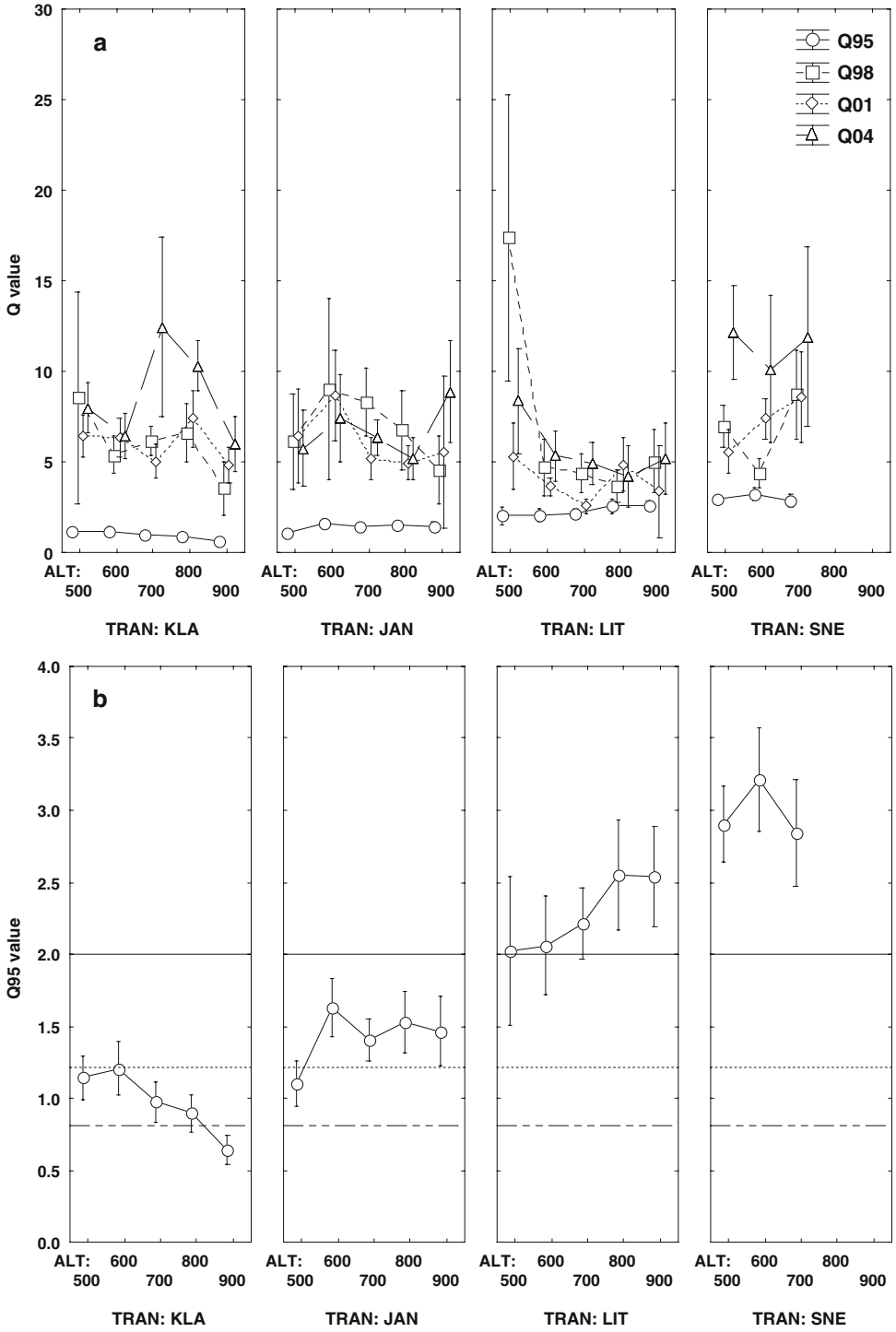

Fig. 2 Values of Q index in birch leaves in transects (TRA) and altitudes (ALT)—mean ± confidence interval ($\alpha = 0.05$): **a** all years, **b** 1995 only (classification values according to Table 3)

$Q > 1$ and $Q \leq 1$ were marked as So-dominant and Sa-dominant, resp. The dominance is dependent on the metabolism of sulphur compounds. In the cases where $Q \approx 1$ or $Q < 1$, the capacity of sulphur compound metabolism is depleted, the organic form is not created and the content of inorganic sulphur compound is enhanced (Gasch et al. 1988, 1990).

Values of the content of total sulphur, the content of inorganic and organic sulphur and Q index were assessed in relation to a hypothesis that changes in air-pollution load (SO_2) become evident in the content of total sulphur or forms of sulphur in birch leaves, whereas the amount of total sulphur or forms of sulphur found in birch leaves provide at least sufficient nutrition of a tree. For this

purpose, criteria of Hrdlicka and Kula (1998) and Fürst (2003) (for content of total sulfur) and criteria of Gasch et al. (1990) and Hrdlicka (2005) (for Q value) were used.

Results

The content of sulphur and its forms (1995)

The content of total sulphur (S) was highest in the Klasterec transect, gradually decreasing towards east (the Janov, Litvinov and Sneznik transects). The content of total sulphur ranked in the stands from sufficient (minor part of values) to optimum/surplus (major part of values), in the Klasterec transect all stands among the CC3 classification class (Table 2). The mean content of total sulphur in stands of various altitude fluctuated or did not change, namely in the Klasterec transect above the level of 3,000 μg g^{-1}, in the Janov and Litvinov transects at the level of 2,500 μg g^{-1}, in the Sneznik transect at the level of 2,000 μg g^{-1} (Fig. 1).

The content of the inorganic form of sulphur (Sa) decreased from the western to the eastern transect. Higher mean values were determined in stands occurring at 800 and 900 m altitude of the Klasterec transect; in other transects, the Sa content did not differentiate with altitude (Fig. 1). The content of the organic form of sulphur (So) in particular transects was even. It applies (with exceptions) also to mean values in stands of various altitudes (Fig. 1). Values of the content of sulphur in stands of the Klasterec transect exceeding 3,000 μg g^{-1} correspond to comparable values of Sa and So, at higher altitudes even Sa > So. In other transects, Sa < So. Generally, the amount of inorganic form of sulphur between particular stands was in agreement with the content of total sulphur (Fig. 1). Values of Q95 index corresponded to this fact. In stands of the Klasterec transect, values of Q95 decreased with an increasing altitude below a value of 1. Stands belonged to classes of the CQ4 and CQ3 effect of air-pollution (Table 3), which showed evidence of the higher content of Sa95 in leaves. In other transects, Q95 index increased east, effects of air-pollution decreased, classes CQ2 and CQ1 (Table 3, Fig. 2b) as well as the value of Sa95 decreased (Fig. 1).

The regression model ln Q95 = f(ln Sa95) and the estimate of its coefficients were highly significant, showing very high degree of relationship (Table 4). The equivalent value of the coefficient (Gasch et al. 1990) Q = So/Sa = 1 corresponds to the content of an inorganic and organic fraction Sa = So = 1,520 μg g^{-1} and the content of total sulphur 3,040 μg g^{-1}. This value is exceeded by 21% of determinations, all of them from the east Krusne hory mountains area. The one-fifth part of monitored stands is Sa-dominant.

Table 2 Distribution of different classes of sulphur nutrition (%; according to transects and time of sampling)

Transect	Class	1995	1998	2001	2004
KLA	CC1	0	6	19	42
	CC2	0	90	81	58
	CC3	100	4	0	0
JAN	CC1	0	4	19	25
	CC2	15	88	69	75
	CC3	85	8	12	0
LIT	CC1	0	14	31	23
	CC2	10	81	67	72
	CC3	90	5	2	5
SNE	CC1	0	0	63	53
	CC2	40	69	38	47
	CC3	60	31	0	0

CC1: insufficient (S < 1,300 μg g^{-1}); CC2: sufficient (S in range 1,300–2,000 μg g^{-1}); CC3: optimum/surplus (S > 2,000 μg g^{-1}) (see Hrdlicka and Kula 1998; Fürst 2003)

Table 3 Classification of the effect of air-pollution according to Q index (Gasch et al. 1990; Hrdlicka 2005) and distribution of different classes of Q value (%; according to transects only for 1995)

Class	Characteristics of the effect of air-pollution	Q value	KLA95 (%)	JAN95 (%)	LIT95 (%)	SNE95 (%)
CQ1	No effect	>2.00	0	7	74	94
CQ2	Slight effect	2.00–1.21	26	62	17	3
CQ3	Medium effect	1.20–0.81	40	27	9	3
CQ4	Strong effect	0.80–0.51	30	4	0	0
CQ5	Very strong effect	<0.51	4	0	0	0

Table 4 Regression models ln $Q = a - b$(ln Sa) for particular years of sampling (r^2 = index of determination; all transects)

Year	a	b	r^2
1995	7.40	1.01	0.8922
1998	7.48	1.04	0.9378
2001	6.90	0.97	0.8319
2004	6.79	0.95	0.9606

The content of sulphur and its forms (1998, 2001, 2004)

The content of total sulphur was lower in transects of the western Krusne hory mountains as against 1995 being comparable at the level of transects. In the Sneznik transect, it was similar in 1998 as in 1995 and then decreased to the level of transects of the eastern Krusne hory mountains.

The distribution of values to classes gradually shifted to the class of the sufficient and insufficient content (Table 2). The mean content of *S* in stands of the various altitude of transects in the eastern Krusne hory mountains gradually decreased from 1,800 μg g^{-1} in 1998 up to the limit of 1,500 μg g^{-1} in 2004. In the Sneznik transect, the content of *S* in stands of various altitude was at the level of 2,000 μg g^{-1} in 1998; in other years, the content decreased to the level of 1,300 μg g^{-1} (Fig. 1).

The content of inorganic form of sulphur in transects was comparable in particular years gradually slightly decreasing in this period. Mean values gradually decreased from the level of 400 μg g^{-1} to the level of 200 μg g^{-1} (Fig. 1). The content of the organic form of sulphur was balanced in particular transects being slightly higher in the Sneznik transect in 1998 only. Mean values in stands of various altitude fluctuated between 1,000 and 1,400 μg g^{-1} (the Sneznik transect 1998 a level of 1,600 μg g^{-1}) (Fig. 1).

In all the transects, the content of the organic form of sulphur markedly exceeded the content of the inorganic form. At the same time, the content of the So changes similarly as the content of the total sulphur while the content of Sa was stable. The increasing prevalance of So over Sa became evident in the general increase of values of *Q* index (Fig. 2a). The values were, however, considerably variable and predominated class CQ1 (for KLA, JAN all values; for LIT, SNE more than 95% values).

Regression models ln $Q = f$(ln Sa) for particular samplings and estimates of their coefficients were highly significant determination indexes showing the very high degree of relationship (Table 4). The equivalent value of a coefficient Q = So/Sa = 1 corresponds to the content of an inorganic and organic fraction Sa = So, 1,288 μg g^{-1} in 1998 (the content of total sulphur = 2,576 μg g^{-1}), 1,215 μg g^{-1} in 2001 (the content of total sulphur = 2,430 μg g^{-1}) and 1,310 μg g^{-1} in 2004 (the content of total sulphur = 2,620 μg g^{-1}). None of the measured values exceeds the content of total sulphur corresponding to the equivalent value *Q*; the stands are So-dominant.

Discussion

Sulphur is on the one hand an important macroelement inevitable for the growth of trees (Marschner 2002); on the other hand, its compounds (SO_2) rank among important pollutants (Zeleny and Zelena 1996). There are criteria for birch to assess sulphur as a macroelement (Table 2), but there are no criteria from the aspect of air-pollution load. It is possible to proceed data for beech, where negative impacts of air-pollutants (SO_2) are given at the content of total sulphur >2,000 μg g^{-1} (Pfanz et al. 1993). So far published values of the content of total sulphur in birch leaves from stands affected by air-pollution exceed this value; however, visible damage to assimilatory organs does not occur (Nebe 1997; Hrdlicka and Kula 1998, 2004).

Effects of the air-pollution load on the content of sulphur

The content of sulphur (total, organic and inorganic) was monitored in period of 1995–2004 in birch leaves in two air-polluted areas: Krusne hory mountains and Decin sandstone highlands. According to values of air-pollution monitoring by CHMU (Czech Hydrometeorological Institute) stations in the eastern Krusne hory mountains and in the Decin sandstone highlands, decrease in the annual mean atmospheric SO_2 concentration occurred below 20 and 25%, respectively, at the end of this period (2004), in comparison with the level in 1995.

Changes in air-pollution (1995–2004) induced fundamental decrease in the content of the total sulphur throughout the investigated areas (Fig. 2). It showed that in birch leaves the content of total sulphur is dependent on inputs of sulphur compounds (mainly SO_2). Thus, at the air-pollution concentration of $SO_2 > 50$ μg m^{-3} $year^{-1}$, it is possible to expect the content of total sulphur >3,000 μg g^{-1} (cf. Klasterec transect, 1995), but also at a level of 2,500 μg g^{-1} (cf. Janov and Litvinov, 1995). At the level of SO_2 concentration of 30–40 μg m^{-3} $year^{-1}$, the content of total sulphur can reach 2,000 μg g^{-1} (cf. Sneznik, 1995). After exceeding 15 μg m^{-3} $year^{-1}$ SO_2 (or 20–30 μg m^{-3} $year^{-1}$), it is possible to expect the content of total sulphur as 1,500–2,000 μg g^{-1} (cf. the eastern Krusne hory mountains, 1998). At the decline of the amount of SO_2 in air-pollution below 15 μg m^{-3} $year^{-1}$, the content of the total sulphur can range below the level of 1,500 μg g^{-1} (cf. data 2001, 2004). These values correspond well with findings of Nebe (1997) for birch. The total amount of sulphur in birch leaves (at comparable air-pollution load) is slightly lower than that in beech (Pfanz et al. 1993), which confirms increased tolerance of birch to the higher SO_2 air-pollution load as compared with beech (Heilmeier et al. 2000a, b). Existing deviations in relationships between the SO_2 air-pollution concentration and the content of total sulphur in birch leaves demonstrate that air-pollution inputs are not the main influencing factor. Also, a soil analysis did not provide a sufficient argumentation to explain differences in the content of total sulphur in birch leaves depending on SO_2 air-pollution concentrations, because the amount of sulphate in soils of KLA and JAN transects were 10.4 and 15.5 μg g^{-1}, respectively (Hrdlicka 2005). So values of the content of sulphates in soils do not correlate with the content of total sulphur in birch leaves. This is in good

accordance with the current state of knowledge on the regulation of the soil sulphate uptake (Herschbach and Rennenberg 1997; Leustek and Saito 1999).

Air-pollution load reflects in the amount of inorganic (sulphate) form of sulphur in birch leaves. If large amounts of sulphur enter the tree, part of the sulphur becomes excessive being deposited in the form of sulphates in fully developed leaves from where it can be translocated (in case of need) to another part of the tree (Herschbach and Rennenberg 1997). At the high air-pollution concentration of SO_2 (Klasterec, 1995), the content of inorganic form of sulphur was also relatively high (1,400–2,200 μg g^{-1}). At the same time, the content of inorganic and organic form of sulphur in particular altitudes was comparable or higher (Fig. 2). In other transects, the mean content of inorganic form of sulphur was at a lower level in 1995 (Janov 1,000 μg g^{-1}; Litvinov 500–1,000 μg g^{-1}; Sneznik 500 μg g^{-1}). With decreasing values of the content of the inorganic form of sulphur, a difference between the content of inorganic and organic form of sulphur increased. In next years (1998–2004), with decreasing air-pollution concentrations of SO_2 (Table 1), the content of the inorganic form of sulphur also decreased (100–500 μg g^{-1}) (Fig. 2). At the same time, the content of the organic form of sulphur fluctuated (1,000–2,000 μg g^{-1}) and varied similarly as the content of total sulphur.

Changes in the content of the inorganic and organic form of sulphur corresponded to changes in the value of coefficient Q. The results implicate that it is possible to suppose that the value of coefficient Q of birch stands not affected by air-pollution will range from 5 to 10. The conclusion cannot be compared with literature data, because there is no evaluation for broadleaved species. Values for birch are slightly higher than that for spruce and pine (needles of the first year-class, $Q = 5$–5.3; Manninen and Huttunen 2000). Thus, in birch leaves, for the same amount of total sulphur, the proportion of the organic form of sulphur as compared with the inorganic form will be higher. In the year 1995, about one-fifth of the stands were Sa-dominant (the value $Q \leq 1$). In trees of these stands, the input of inorganic sulphur compounds (especially SO_2) was excessive; the trees were unable to assimilate all sulphur compounds. Unused sulphate was stored in vacuoles (Gasch et al. 1988, 1990; Herschbach and Rennenberg 1997, 2001; De Kok et al. 2002). In further years on trees monitoring, the stands were So-dominant ($Q > 1$); the content of sulphate in leaves was decreased and input sulphur compounds were used in maximum.

Total content of sulphur in birch leaves

The content of total sulphur in birch leaves and the proportion of organic and inorganic form depend upon the actual conditions of a site (availability of macro- and micro-elements and air-pollution load). Connection of both the sources creates conditions to supply plant tissues by substances necessary for the growth of trees. Air-pollution concentration of substances must not reach acute toxicity resulting in the physical damage to tissues. The content of sulphur in birch leaves depends upon the uptake of sulphur compounds by roots (in the form of sulphates) and leaves (in the form of small amounts of SO_2) under conditions of otherwise undisturbed nutrition of birch by other substances. However the uptake of sulphates from the soil is actively inhibited by the organic sulphur compounds, especially by glutathione and cysteine (Herschbach and Rennenberg 1997, 2001), the input of SO_2 via the leaves' stomata is influenced depending on how much the stomata are opened (Slovik et al. 1992). In the case of enhanced SO_2 leave impact, the organic sulphur compounds are synthesised (De Kok et al. 2002; Slovik et al. 1992) and that leads to the repression of the sulphate uptake via roots. If the amount is excessive (over the plant need), the sulphate is created and stored in vacuoles, and it does not take part in the reduction processes any further (Herschbach and Rennenberg 1997, 2001; De Kok et al. 2002).

The amount of sulphur in leaves depends also on the course of the vegetation period. Our monitoring in the year 2000 in the transect Litvinov proved that the total sulphur content was increased consecutively from May to July from the starting level of 1,500 μg g^{-1} to the level 2,000 μg g^{-1} and after that decreased again to the level 1,500 μg g^{-1}. Similar trends of changes were observed also both for the organic sulphur content (from the level 1,300 μg g^{-1} to the level 1,500 μg g^{-1} and back to the original level) and for the inorganic sulphur content (from the level 250 to 500 μg g^{-1} and back again) (Hrdlicka and Kula 2001). The starting level of the sulphur content is influenced also by the sulphate content in xylem sap at the beginning of the vegetation period. The sulphate content in birch xylem sap varied in the range 0.5–39.5 mg l^{-1} (Hrdlicka and Kula 2003). For example, in comparison with the beech (up to 60 mg l^{-1}, Rennenberg et al. 1994), the content is clearly lower.

In 1995, the content of total sulphur in birch leaves in the eastern Krusne hory mountains was relatively high (maximum level being in the Klasterec transect >4,000 μg g^{-1}). Mean values of transects in the eastern Krusne hory mountains (Klasterec 3,229 ± 117 μg g^{-1}, Janov 2,413 ± 87 μg g^{-1}, Litvinov 2,212 ± 214 μg g^{-1}) markedly exceed the current used lower limit of the optimum content (2,000 μg g^{-1}) (Table 2). Thus, supply by sulphur was optimal from the aspect of needs of the species. Because at the total content of sulphur mentioned above birch leaves were not damaged and even symptoms of damage to trees or limitation of their growth were not observed, it is possible to specify the upper limit of

optimum to minimally 3,400 μg g^{-1} (cf. Nebe 1997). On the basis of pot experiments with birch seedlings, Heilmeier et al. (2000a) mention that when the content of total sulphur slightly exceeds a level of 2,500 μg g^{-1}, the growth of the seedlings is not disturbed.

In next years, the content of total sulphur responds to the fall of air-pollution inputs of SO_2 receding to a level of 1,300 μg g^{-1} (lower limit of the sufficient content). Also, other authors (Nebe et al. 1996; Nebe 1997) mention similar values for forest stands at low air-pollution load without describing the decreased dynamics of growth or symptoms of health damage to trees.

The amount of sulphur corresponding to organic and inorganic form is related to the content of total sulphur. Thus, we can expect that when the amount of total sulphur is >3,000 μg g^{-1} (cf. Klasterec transect, 1995), the content of inorganic form is >1,500 μg g^{-1} and Sa > So. At the content of total sulphur level of 2,500 μg g^{-1} (cf. Janov and Litvinov, 1995), the content of the inorganic form of sulphur ranged at a level of 1,000 μg g^{-1} and lower while the content of the organic form of sulphur reached 1,500 μg g^{-1} and more. At the content of total sulphur level of 2,000 μg g^{-1} (cf. Sneznik, 1995), the level of inorganic form was 500 μg g^{-1} and the level of organic form was 1,500 μg g^{-1}. At the total sulphur content of 1,600–1,800 μg g^{-1}, the content of inorganic form was 400 μg g^{-1}. At the total sulphur content level of 1,400–1,600 μg g^{-1}, the content of inorganic form was 200–400 μg g^{-1}. The total sulphur content of 1,200–1,400 μg g^{-1} is related to the content of inorganic form 200 μg g^{-1} (Fig. 2). Determined contents of the inorganic form of sulphur are consistent with data for pine needles (Turner et al. 1977) in spite of different tree species. It is possible to note that the content of S–SO_4^{2-} in birch leaves of >400 μg g^{-1} is in accordance with the content of total sulphur CC3, of 200–400 μg g^{-1} is in accodance with CC2 and of <200 μg g^{-1} with CC1 (Table 2). This sulphate is stored in the vacuole and is more or less unavailable for reduction to organic sulphur compounds (Herschbach and Rennenberg 1997, 2001; De Kok et al. 2002).

Conclusion

Decrease in the air-pollution load (expressed as the annual mean amount of SO_2) became evident through the fall of the content of sulphur in birch leaves corresponding to the change in air-pollution. At the high air-pollution load (65 μg m^{-3} $year^{-1}$), the amount of total sulphur was in the class of the optimum/surplus content (CC3), equivalent content of total sulphur for $Q = 1$ was 3,040 μg g^{-1}. At the high content of total sulphur (>4,000 μg g^{-1}), So ≤ Sa; the content of the inorganic form of sulphur was at a level of 1,500 μg g^{-1} or exceeded it. At the lower content of total sulphur (2,000–2,500 μg g^{-1}), the content of the inorganic form was at a level of 500–1,000 μg g^{-1} and So > Sa. After decreasing the air-pollution load to a level of 10–20 μg m^{-3} $year^{-1}$, the amount of total sulphur decreased to the class of the sufficient or even insufficient content; the equivalent content of total sulphur for $Q = 1$ was at a level of 2,500 μg g^{-1}. It applied always that So > Sa; the content of the inorganic form of sulphur was at a level of 500 μg g^{-1} gradually decreasing to 100 μg g^{-1}. The content of the organic form of sulphur was variable, in case of So > Sa, changing according to the content of total sulphur. Results have shown that birch is able to use considerable amounts of sulphur received through leaves from air-pollution load. Birch responds fast to changes in air-pollution load through the decline in the content of total and inorganic form of sulphur in leaves.

Acknowledgments The project was financed from the funds of NAZV 1G46002 and VZ MSM 6215648902. It was sponsored by the following companies and organizations: Netex Co., Děčín; Alusuisse Co., Děčín; Municipal Office, Děčín; Setuza Co., Ústí nad Labem; ČEZ Co., Prague; Cement Works Co., Čížkovice; North-Bohemian Mines Co., Chomutov; Dieter Bussmann Co., Ústí nad Labem.

References

Anonymous (1996) Air pollution, chemical composition of precipitation and meteorological data (in Czech). General annual tabular report for 1995. Czech Hydrometeorological Institute, Prague, 247 pp

Anonymous (1999) Air pollution and atmospheric deposition in data (in Czech), Czech Republic, 1998. General annual report. Czech Hydrometeorological Institute, Prague, 295 pp

Anonymous (2002) Air pollution in the area of the Czech Republic in 2001 (in Czech). Czech Hydrometeorological Institute, Prague, 162 pp

Anonymous (2005) Air pollution in the area of the Czech Republic in 2004 (in Czech). Czech Hydrometeorological Institute, Prague, 185 pp

De Kok LJ, Castro A, Durenkamp M, Stuiver CE, Westerman S, Yang L, Stulen I (2002) Sulphur in plant physiology. In: Proceedings no. 500. International Fertiliser Society, York, 29 pp

Gasch G, Grünhage L, Jäger HJ, Wentzel KF (1988) Das Verhältnis der Schwefelfraktionen in Fichtennadeln als Indikator für Immissionsbelastungen durch Schwefeldioxid. Angew Bot 62:73–84

Gasch G, Wentzel KF, Jäger HJ, Grünhage L (1990) Die Schwefelbelastung der Fichtenbestände in den Räumen Wiesbaden—Taunus und Hessischer Spessart in den Jahren 1977, 1980 und 1983. Schriftenreihe Hessischer Landesanstalt für Umwelt, Heft Nr. 102

Fürst A (2003) Classification values for European foliar datas. http://bfw.ac.at/600/1128.html (load 11 November 2006)

Heilmeier H, Baronius K, Kuhn AJ, Nebe W (2000a) Biomass and nutrient relationships of *Betula pendula*, *Fagus sylvatica*, *Picea abies* and *Abies alba* with varying nitrogen and sulphur additions in a pot experiment (in German). Forst Cbl 119:161–176. doi: 10.1007/BF02769135

Heilmeier H, Baronius K, Kuhn AJ, Opfermann M, Nebe W (2000b) Influence of simulated sulphur and nitrogen depositions on

biomass and nutrient relationships of mountain ash, European beech and Norway spruce in a pot experiment with two soil substrates from the Ore Mountains (in German). J Plant Nutr Soil Sci 163:57–63 doi:10.1002/(SICI)1522-2624(200002)163:1<57::AID-JPLN57>3.0.CO;2-8

Herschbach C, Rennenberg H (1997) Sulfur nutrition of conifers and deciduous trees. In: Rennenberg H, Eschrich W, Ziegler H (eds) Trees—contributions to modern tree physiology. Backhuys, Leiden, pp 293–311

Herschbach C, Rennenberg H (2001) Sulfur nutrition deciduous trees. Naturwissenschaften 88:25–36. doi:10.1007/s001140000200

Hrdlicka P (2005) The content of total sulphur and forms of sulphur in assimilatory organs of forest tree species *Betula pendula* Roth and *Picea abies* [L.] Karst (in Czech). Habilitation thesis, Mendel University of Agriculture and Forestry, Brno, 85 pp

Hrdlicka P, Kula E (1998) Element content in leaves of birch (*Betula verrucosa* Ehrh.) in an air polluted area. Trees (Berl) 13(2):68–73

Hrdlicka P, Kula E (2001) Element content in leaves of birch in the Litvinov transect during the growing season. In: Slodičák M, Novák J (eds) Results of forestry research in air-polluted area of the Ore Mts. Proceedings from the workshop of the Grant Project Phare, Teplice 1.3.2001, VÚLHM 2001, pp 63–68

Hrdlicka P, Kula E (2003) Xylem sap of birch as a factor to determination of element uptake from soil environment. In: Slodičák M, Novák J (eds.) Results of forestry research in the Ore Mts. in 2000. Proceedings from the national workshop, Teplice 27.3.2003, VULHM 2003, pp 43–52

Hrdlicka P, Kula E (2004) Changes in the chemical content of birch (*Betula pendula* Roth) leaves in the air polluted Krusne hory mountains. Trees (Berl) 18:237–244. doi:10.1007/s00468-003-0301-z

Kula E (2006) Factors affecting the stability of birch stands in the eastern Krušné hory Mts. In: Slodičák M, Novák J (eds) Reviewed proceedings from the national scientific workshop, Teplice 20.04.06, VÚLHM VS Opočno 2006, pp 111–144

Leustek T, Saito K (1999) Sulfate transport and assimilation in plants. Plant Physiol 120:637–643. doi:10.1104/pp.120.3.637

Manninen S, Huttunen S (2000) Response of needle sulphur and nitrogen concentration of Scots pine versus Norway spruce to SO_2 and NO_2. Environ Pollut 107:421–436

Marschner H (2002) Mineral nutrition of higher plants, 2nd edn. Academic Press, London, 890 pp

Nebe W (1997) Tree species selection in the ridge and hight-altitude positions of the Erzgebirge Mountains (in German). Forst Holz 52:336–338

Nebe W, Opfermann M, Weiske A (1996) Forest reconstruction in the Erzgebirge (in German). Forst Holz 51:345–348

Pfanz H, Lomský B, Hynek V, Vollrath B, Oppmann B, Materna J (1993) Nutrient content and photosynthesis in beech (*Fagus sylvatica* L.) leaves taken from stands growing at sites with different levels of SO_2 load (in Czech). Lesnictví For 39:222–230

Rennenberg H, Schupp R, Glavac V, Jochheim H (1994) Xylem sap composition of beech (*Fagus sylvatica* L.) trees: seasonal changes in the axial distribution of sulphur compounds. Tree Physiol 14:541–548

Slovik S, Kaiser WM, Körner C, Kindermann G, Heber U (1992) Quantifizierung der physiologischen Kausalkette von SO_2—Immissionsschäden (I–Ableitung von SO_2–Immissionsgrenzwerten für akute Schäden an Fichte) (in German). Allgemeine Forst Z 15:800–805

StatSoft, Inc. (2005) STATISTICA Cz, version 7.1. http://www.StatSoft.cz

Turner J, Lambert MJ, Gessel SP (1977) Use of foliage sulphate concentrations to predict response to urea application by Douglas-fir. Can J For Res 7:476–480. doi:10.1139/x77-061

UN-ECE (1998) Manual on methods and criteria for harmonized sampling, assessment, monitoring and analysis of the effects of air pollution on forests, Hamburg, Germany; [current version: http://www.icp-forests.org/reports.htm (load 11 November 2006)]

Zeleny F, Zelena E (1996) Sulphur and its need for plant nutrition (in Czech), Review, Rostlinna vyroba 5, UZPI, Praha, 42 pp