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Loss of nutrients due to litter raking compared to the effect of acidic deposition in two spruce stands, Czech Republic

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Abstract We evaluated how litter raking removed basic nutrients from forest soils by simulating this historical silvicultural practice on two spruce stands (*Picea abies*) in the Czech Republic. Experimental litter raking depleted the soil pool of exchangeable base cation nutrients (Ca^{2+}, Mg^{2+} and K^{+}) by up to 31% after the first litter raking in 2003. A second litter raking in the following year further reduced the soil pool by up to 16%, and the third litter raking in 2005 reduced the pool by up to 6% more. These losses of base cations were substantially greater than their annual input into the forest soil (estimated as from total atmospheric deposition and mineral weathering) as well as their annual runoff. The concentration of Mg and Ca in spruce needless decreased considerably within 3 years from the beginning of the experiment. In addition, the observed litter chemistry was used to estimate historical nutrient removal from litter raking by applying them to historical records of litter removal rates. According to these calculations, the annual loss of total Ca, Mg and K from spruce stands would be from 40% to 100% of its present annual input into the soil, and from 50% to 190% of annual runoff. On the basis of previous results estimated by geochemical modeling, we found that the loss of base cations due to litter raking was similar to their leaching due to acid deposition. We conclude that long-term removal of litter as widely practiced throughout the 19th century in Central Europe may have been responsible for a loss of base cations equivalent to that caused by acid deposition during the 20th century.

Keywords Soil acidification · Forest management · Litter raking · Norway spruce · Nutrient loss

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Introduction

Throughout the 19th century, litter from spruce (*Picea abies*), pine (*Pinus sylvestris*), beech (*Fagus sylvatica*) and oak (*Quercus petraea*) was removed in large quantities for various purposes (mainly as bedding for farm animals) in Central Europe: the Czech Republic and Slovakia (Pfeffer 1948), Austria (Glatzel 1990, 1991; Johann 2004), Germany (Ebermayer 1876) and Switzerland (Bürgi 1998; Stuber and Bürgi 2002). In many areas, litter raking continued well into the 20th century, even though its detrimental effects on forest soils and forest productivity had been clearly documented (Ebermayer 1876). In the first half of the 20th century, forest litter was still removed from an area between 2,000 and 5,000 km^2 in the former Czechoslovakia, comprising around 10% of the total forest area (Anger 1929; Pfeffer 1948). This practice did not stop completely until the middle of the 20th century.

The frequency as well as intensity of litter raking was performed quite variably; many forests were raked only once before cutting, while others (mainly municipal forests) were raked annually (Ebermayer 1876; Němec 1933). The raked material contained often not only of fresh litter (O_i horizon of humus), but also a portion of the slightly decomposed humus (O_e horizon of humus). In the first half of the 20th century, the weight of litter removed at three-year intervals from a spruce forest growing on poor soil was roughly 800 g m^{-2} (Pfeffer 1948). Ebermayer (1876) suggested similar amounts for litter raking at several time intervals: from 354 g m^{-2} for annual litter removals to 939 g m^{-2} for removals at six-year intervals and 1,386 g m^{-2} for a stand that had not previously been raked. Because litter raking results is a net loss of nutrients from an ecosystem, it is plausible that repeated historical litter removals had the effect of causing considerable impoverishment of soils.

More recently, inputs of acid anions from atmospheric deposition are known to have had a similar effect on soil nutrients, albeit through different mechanisms (e.g. Schulze 1989; van Breemen et al. 1984; Johnson and Lindberg 1992). Acid deposition causes, among other things, a loss of the acid buffering capacity of affected soils by the leaching of base cations in the soil solution (van Breemen et al. 1984; Johnson et al. 1993). This loss of base cations from an ecosystem can be quantified by monitoring both stream water flux and chemistry at the outflow of the watershed covering this ecosystem (Paces 1985; Hruška et al. 2002).

Although the effects of litter raking practices on soil fertility were studied throughout the 19th and early 20th centuries (Anger 1929; Ebermayer 1876; Kvapil and Němec 1929; Němec 1930, 1933), difference in methods of sampling and analysis make it difficult to quantify nutrient losses in the context of whole-ecosystem nutrient fluxes. Nevertheless, many authors have recently discussed the role of traditional practices (litter raking, pasturing, coppicing and others) in relation to soil acidification and forest decline (Farrell et al. 2000; Glatzel 1990, 1991; Hüttl and Schaaf 1995; Kilian 1998; Jandl 1998; Hunter and Schuck 2002). Although the loss of soil nutrients caused by litter raking were rather hypothetical in these studies, they suggest that the negative impact of long-term litter raking both on soil fertility and forest decline might be underestimated. According to Glatzel (1991), the influence of traditional litter raking on soil acidification in Austrian forests was similar to the effect of acid deposition.

In central Europe, relatively detailed descriptions of the effect of acid deposition on soil and tree conditions are available, including a quantification of nutrient losses from ecosystems caused by nutrient leaching (e.g. Hruška et al. 2002; Oulehle et al. 2007). However, it is difficult to evaluate these findings with respect to historical nutrient losses caused by litter raking given the lack of quantitative estimates of the latter process.

Here, we simulated traditional litter raking in two spruce stands in the Czech Republic and examined the resulting effects on nutrient losses. Furthermore, we compared litter raking and acid deposition for their impact on the loss of exchangeable nutritional base cations (Ca^{2+}, Mg^{2+} and K^+) as well as total Ca, Mg and K. The export of base cations caused by experimental litter raking was related to both the input of base cations to the ecosystem consisting of deposition and weathering, and output of base cations from the ecosystem represented by runoff. The results of litter chemistry were used to estimate historical nutrient removal from litter raking by applying them to litter removal rates given by Ebermayer (1876). In addition, we compared nutrient concentrations in spruce needles at raked and control plots.

We attempted to evaluate whether: (1) experimental litter raking substantially affected the budget of base cations in the ecosystems; (2) nutrient concentration in spruce needles reacts to these soil nutrient losses; (3) traditional management such as litter raking could have caused a depletion in base cations comparable with acid deposition during the 20th century.

Materials and methods

Site description

We examined two stands, Lysina (LYS), Slavkov Forest, and Načetín (NAC), Ore Mountains, situated in the western part of the Czech Republic (Fig. 1). Both stands are covered by Norway spruce (*Picea abies*) monocultures (Table 1). The dominant soil type is composed of dystric cambisol with a moder-mor type of humus horizon. The thickness of the litter layer (O_i), fermentation layer (O_e) and humification horizon (O_a) ranged from 1 to 3 cm, 2 to 3 cm and 0.5 to 3 cm, respectively. Before World War II, the regions around both stands had been densely populated and the forests were exploited in many ways. Litter raking for bedding of farm animals was extensive in many areas in western Bohemia (archive of the Forest Management Institute in Karlovy Vary). However, we did not find any documentary evidence which confirmed traditional using of litter raking explicitly at our stands LYS or NAC. We set up an experimental litter raked plot (40 × 20 m), and a control plot (40 × 20 m) 15 m away, at both of these stands.

At both stands, many investigations of biogeochemical fluxes and the impact of acid deposition on soil, soil solution chemistry and streamwater chemistry as well as tree conditions have been performed in the last 15 years (e.g. Hruška and Krám 1994, 2003; Krám et al. 1997; Navrátil et al. 2007 at LYS, Dambrine et al. 1993; Oulehle and Hruška 2005; 2006 at NAC, Hruška et al. 2001 at both sites).

Experimental manipulation

In August 2003 and 2004, litter was removed from each experimental plot (800 m^2) at LYS and NAC,

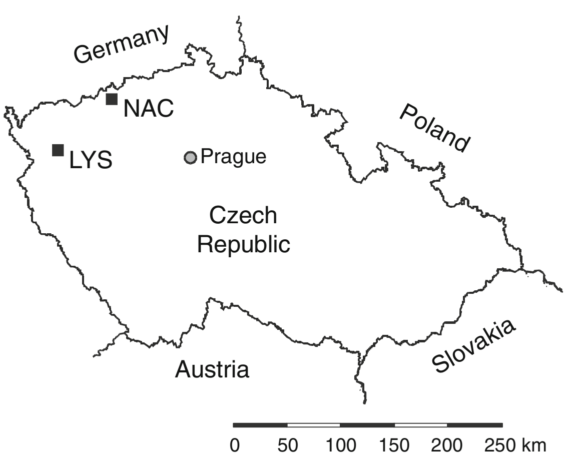

Fig. 1 Location of study sites, Lysina (LYS) and Načetín (NAC)

Table 1 Description of the two study sites

	Lysina (LYS)	Načetín (NAC)
Localization	Slavkov Forest	Ore Mts.
Latitude	50°03′ N	50°35′26″ N
Longitude	12°40′ E	13°15′18″ E
Altitude (m)	880	780
Annual mean temperature (°C)[a]	+5	+6.3
Prec. (mm $year^{-1}$)[a]	900	840
Bedrock	Leucogranite	Paragneiss
Spruce age	47	70

[a] Data of the Czech Hydrometeorological Institute

using manual raking as in the past. In this way, litter (O_i) was removed almost completely, in some places together with part of the fermentation layer (O_e) of humus. The litter layer consisted mainly of spruce needles, but remnants of ground vegetation were also present (e.g. *Calamagrostis villosa*, *Deschampsia flexulosa*, *Vaccinium myrtilus*). Soils and needles were sampled identically at all experimental and control plots.

Soil sampling and analysis

Sampling of soil was performed in July 2003 (before litter raking), July 2004 and 2005 (after litter raking). The quantitative soil samples were based on six soil pits at LYS and NAC (four at each experimental and two at each control plot) in 2003 and 2004. Due to the relatively low spatial variability of soil conditions between soil pits at control and experimental plots in 2003 and 2004, only two soil pits were sampled at the experimental plots in 2005. Soil masses were estimated by excavating 0.5 m^2 pits using methods described by Huntington et al. (1988). In each pit, we collected litter (O_i) and part of the fermentation layer (O_e) of the humus horizon as a single sample (using manual raking) and then the remaining O_e layer plus the humification (O_a) layer of humus as a second sample. We used this separation of the humus horizon in order to evaluate the amount of nutrients removed by litter raking. Thus, litter raking was performed in July at points where soil pits were excavated (at both control and experimental plots), and then in August for the whole remaining area of the experimental plots. Both humus samples were weighed and sieved (mesh size of 5 mm). In each pit, the mineral soil was collected in four depth strata, separated nominally as 0–10, 10–20, 20–40 and 40–70 cm (or to bedrock), and further separated in fractions <2 mm (fine soil), 2–10 mm and skeleton (>10 mm). The average depth of the mineral soil ranged between 50 and 60 cm, only occasionally reaching to 70 cm. A sample of the finest fraction of each soil layer (<5 mm for organic and <2 mm for mineral soil) was taken for chemical analysis.

Soil moisture was determined gravimetrically by drying at 60°C (samples of litter and humus) and 105°C (mineral soil). Soil pH was determined in distilled water and in 1 M KCl. Exchangeable cations were analyzed in 0.1 M $BaCl_2$-extracts by the AAS method. In removed litter, concentrations of total Ca, Mg and K were also determined by AAS after digestion with H_2SO_4 and HCl. Thus, we identified pools of two different forms of base cations in removed litter: pools of exchangeable base cations (Ca^{2+}, Mg^{2+} and K^+) and pools of total Ca, Mg and K. Furthermore, $BaCl_2$-extracts were titrated by 0.025 M NaOH to pH = 7.8 to measure total exchangeable acidity (TEA). Cation exchange capacity (CEC) was calculated as the sum of exchangeable Ca^{2+}, Mg^{2+}, K^+, Na^+ and exchangeable acidity. Base saturation (BS) was calculated as the fraction of CEC associated with base cations (Ca^{2+}, Mg^{2+}, K^+ and Na^+). Extractable phosphorus ($P_{ex.}$) was determined by digestion with Mehlich III-extract and detected spectrophotometrically according to Mehlich (1984). Total C and N were determined simultaneously using a Carlo-Erba Fisons 1108 analyzer. Element pools were computed using oven dried soil mass and average element concentration.

Sampling and analysis of needles

In order to determine the response of nutrient concentration in needles to the experimental change of soil nutrient concentration, viable needles of 1st and 2nd year classes were collected from the upper part of spruce canopies in October 2003, 2004 and 2005 at both sites. In 2003 and 2004, two mixed samples (needles from five trees each) were taken from experimental plots, and one mixed sample (five trees) from control plots. In 2005, we analyzed needles from each tree separately in order to detect variability among trees. In all samples, concentration of Ca, Mg and K (determined by AAS after digestion with H_2SO_4 and HCl), total N (using the Carlo-Erba Fisons 1108 analyzer) and total P (spectrophotometrically after digestion with HNO_3 and H_2O_2 and addition of $NH_4Mo_2O_5$ and $NH_4V_2O_7$) were evaluated (Zbíral 1994).

Sampling and analysis of precipitation and runoff

In order to compare the loss of base cations to their input and output from the ecosystem, the total deposition and estimated rate of weathering was used as the sum of their input to the ecosystem and runoff flux as the output from the ecosystem. Total deposition was calculated using results of bulk and throughfall precipitation chemistry and fluxes. At LYS and NAC, bulk and throughfall precipitation have been collected monthly since the beginning of the 1990s (for older data see e.g. Dambrine et al. 1993; Krám et al. 1997) using methods described in detail in Hruška et al. (2002) and Oulehle et al. (2006). Both monitoring plots were located in representative parts of the spruce stands at distances of 500 m (LYS) and 100 m (NAC) from the experimental (litter raked) and control plots. The concentrations of Ca^{2+}, Mg^{2+}, K^+, Na^+ and Al^{3+} (using AAS), NH_4^+ (indophenol blue colorimetry), NO_3^-, SO_4^{2-} and Cl^- (ion exchange chromatography) were measured in precipitation samples.

Annual fluxes were determined by multiplying bulk and throughfall concentrations with the water quantity of individual samples. The throughfall flux of base cations is overestimated by canopy leaching, whereas the bulk flux is underestimated by neglecting dry deposition (Lindberg et al. 1986). Therefore, we calculated total deposition of each of the base cations as the sum of its bulk flux and estimated dry deposition. Dry deposition of base cations was calculated according to Bredemeier (1988), assuming negligible internal flux of Na in a spruce stand. The ratio of Na in throughfall to Na in bulk flux was used to estimate dry deposition for Ca, Mg and K.

A single perennial stream drains the watershed at LYS with an area of 0.27 km^2. Runoff was monitored continuously using a V-notch weir and a water level recorder. Stream water was collected weekly and analyzed by methods identical to those used for precipitation samples. Stream water fluxes for individual solutes were computed using annual mean discharge-weighted concentrations and annual water flux. The experimental plot was located outside of the watershed, 150 m from the watershed boundary.

The NAC stand is not a part of a watershed where precise water balance calculations have been performed. Therefore, we calculated runoff from NAC as the seepage flux at the 90 cm depth using monthly data from 7 PRENART® suction lysimeters computed by the one-dimensional soil water model SIMPEL (for details see Oulehle et al. 2007).

In the second half of the 20th century, acid deposition was very high at both LYS and NAC. In the 1990s, desulfurization of coal-fired power plants in Central Europe resulted in a considerable decrease in acid deposition and consequently also the deposition and especially runoff of base cations. Therefore, we present the results of total deposition and runoff of base cations at LYS and NAC for 2 years: 1994 (the end of the period of high acid deposition) and 2004 (the middle year of the experiment).

Inputs of nutrients by weathering

We required data about input of base nutrients by weathering in order to complete an input–output nutrient balance in the experimental plots. We used values optimized by the biogeochemical model MAGIC and published recently for both LYS (Hruška and Krám 2003) and NAC (Oulehle et al. 2007).

Data analysis

The changes in soil and needle nutrient concentrations after litter raking were evaluated using NCSS statistical software (Hintze 2001). Statistical differences between nutrient concentration in needles in 2005 were assessed with one-way ANOVA followed by the Turkey–Kramer multiple test. Spearman's correlation coefficient was used for detecting significance of statistical correlations ($p < 0.05$) between soil and needle nutrient concentrations.

The export of base cations from an ecosystem caused by experimental litter raking was compared with their input (deposition and weathering) and output (runoff). For comparison, we used both pools of base cations determined in the removed litter: the pool of exchangeable base cations (Ca^{2+}, Mg^{2+} and K^{+}) as well as the pool of total Ca, Mg and K. For a specific year, we focused on the pool of exchangeable base cations related to their input and output, due to its importance for both the neutralization of acid deposition and vegetation uptake. When considering the long-term effect of annual litter raking, we focused rather on the pool of total Ca, Mg and K, part of which is stored in dead organic matter. Although at present this portion cannot neutralize strong acids or be taken up by vegetation, it will be potentially available following its mineralization in the future.

In addition, the results of litter chemistry measurements were used to estimate historical nutrient removal from litter raking by applying them to litter removal rates given by Ebermayer (1876).

Results

Soil conditions

The average mass of litter removal in 2003 from NAC was 3,735 g m^{-2}, and from LYS 3,570 g m^{-2}, which is 39% and 33% of humus dry weight, respectively. On average, the proportion of removed material was between 0.5% and 1% of the total dry weight of the total soil mass in both stands (Table 2). As expected, the amount of removed litter was substantially lower in 2004 (second year of litter raking): 20% of humus dry weight at NAC and 11% at LYS. Similarly, raked litter represented 9% of humus dry weight at NAC and 15% at LYS in 2005 (third year of litter raking).

In 2003, the litter removed by raking was acidic at both stands, with pH (H_2O) ranging mostly between 3.8 and 4.5, which is similar to pH in deeper horizons of mineral soil (>20 cm). Base saturation (BS) in raked litter reached 70% and 80% in 2003 at LYS and NAC, respectively, but less than 10% in almost all mineral soil samples. Exchangeable Ca^{2+} represented roughly 80% of the total Ca content in removed litter, exchangeable Mg^{2+} between 50% and 60%, and exchangeable K^{+} between 60% and 80%.

In 2003, the litter removed by raking contained 4,215 mg m^{-2} of exchangeable Ca^{2+} at LYS and 5,323 mg m^{-2} of exchangeable Ca^{2+} at NAC, representing 24% and 30%, respectively, of their soil pools. The proportion of removed Ca^{2+} decreased to 14% in 2004 and to approximately 5% in 2005 at both stands. The amount of removed Mg^{2+} and K^{+}

Table 2 Mean conditions and amount of nutrients in removed litter and its mean proportion in the total soil nutrient pools (in italics) in the study plots (C-control, R-raked) in 2003, 2004 and 2005

Site	LYS					NAC				
Year	2003		2004		2005	2003		2004		2005
Plot	C	R	C	R	R	C	R	C	R	R
pH (H_2O)	3.84	4.09	3.88	3.81	3.74	4.43	4.21	4.45	3.53	3.52
pH (KCl)	2.71	2.87	2.84	3.03	2.77	2.96	3.00	3.41	2.80	2.78
BS (%)	51.2	62.6	66.0	68.0	62.9	69.7	71.3	83.7	52.5	45.3
Ca^{2+} (mg m^{-2})	3585	4215	4434	1995	1332	4889	5323	7051	2814	841
(%)	*24.0*	*24.1*	*31.2*	*14.1*	*5.8*	*32.9*	*30.7*	*33.2*	*14.0*	*4.9*
Mg^{2+} (mg m^{-2})	330	330	488	151	124	860	750	1047	383	93
(%)	*13.5*	*16.1*	*22.1*	*6.7*	*2.9*	*22.3*	*16.1*	*22.6*	*7.2*	*1.7*
K^+ (mg m^{-2})	1629	1928	2110	684	502	2004	2118	2696	646	201
(%)	*20.7*	*20.0*	*23.2*	*5.8*	*5.3*	*22.0*	*24.4*	*29.3*	*7.2*	*2.3*
Na^+ (mg m^{-2})	77	75	84	18	29	79	56	102	45	14
(%)	*3.6*	*3.8*	*6.5*	*1.3*	*1.1*	*4.4*	*3.3*	*3.9*	*2.1*	*0.2*
Al^{3+} (mg m^{-2})	636	374	336	160	168	562	239	276	690	330
(%)	*0.4*	*0.2*	*0.3*	*0.1*	*0.1*	*0.5*	*0.2*	*0.3*	*0.6*	*0.2*
TEA (mmol$_c$ m^{-2})	245	176	165	57	56	182	152	103	158	67
(%)	*1.2*	*1.1*	*1.0*	*0.3*	*0.3*	*1.3*	*1.1*	*0.7*	*1.0*	*0.3*
CEC (mmol$_c$ m^{-2})	497	466	483	188	146	550	536	615	348	122
(%)	*2.4*	*2.6*	*2.6*	*1.0*	*0.7*	*3.5*	*3.4*	*3.7*	*2.1*	*0.6*
C (g m^{-2})	1527	1236	1211	469	351	1551	1407	1610	773	222
(%)	*13.6*	*12.2*	*14.0*	*4.9*	*4.2*	*11.5*	*10.6*	*11.2*	*5.8*	*2.0*
N (g m^{-2})	55	45	44	17	15	63	55	65	28	12
(%)	*11.8*	*11.3*	*11.6*	*4.1*	*3.1*	*11.6*	*9.7*	*11.0*	*5.0*	*1.7*
$P_{ex.}$ (mg m^{-2})	236	301	314	103	71	207	250	261	63	14
(%)	*0.3*	*0.5*	*0.5*	*0.2*	*0.1*	*6.3*	*7.4*	*11.2*	*2.9*	*0.5*
Soil mass (g m^{-2})	3557	3570	2926	1136	2850	4231	3735	4403	2008	1850
(%)	*0.5*	*0.5*	*0.4*	*0.2*	*0.3*	*0.6*	*0.6*	*0.6*	*0.3*	*0.2*
Fine soil mass (g m^{-2})	3279	3062	2745	1090	2717	3647	3186	3654	1908	1642
(%)	*0.7*	*0.8*	*0.7*	*0.3*	*0.5*	*1.0*	*1.0*	*1.0*	*0.5*	*0.2*

At the control plots, litter was removed only from the area of the soil pits

were absolutely and relatively lower in comparison with Ca^{2+} (Table 2). The proportion of Mg^{2+} in removed litter decreased from 16% of its soil pool in 2003 to near 2% in 2005 at both stands. Similarly, the proportion of removed K^+ decreased from 20% and 24% of its soil pools at LYS and NAC in 2003, respectively, to 5% and 2% in 2005, respectively.

In contrast to humus, the pool of exchangeable base cations increased from 2003 to 2005 in all mineral soil horizons at LYS and in deeper horizons of mineral soil also at NAC. The concentration of exchangeable cations increased between these years as well, although in some horizons only moderately (Fig. 2).

Unlike base cations, the proportion of exchangeable Al^{3+} removed with litter was extremely low in both stands (<1% of its soil pool) (Table 2). The relative proportion of extractable phosphorus ($P_{ex.}$) removed with litter from LYS was similarly low, although the amount of removed $P_{ex.}$ was generally higher than at NAC (Table 2).

In 2003, a relatively large quantity of N was removed from both LYS (average of 45 g m^{-2}) and NAC (55 g m^{-2}), representing about 10% of the N

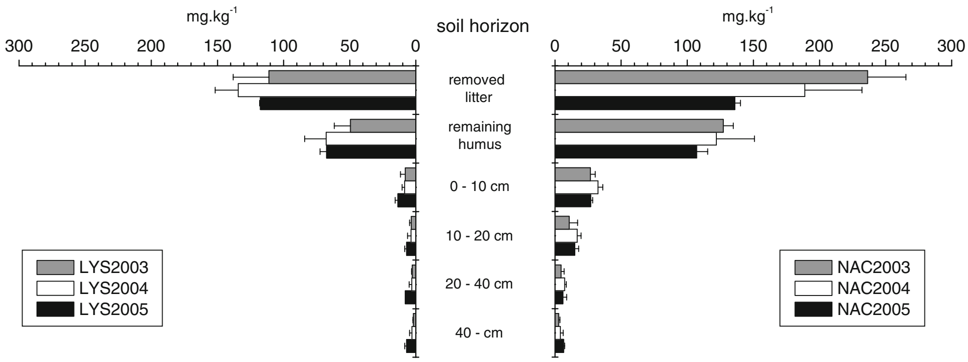

Fig. 2 Mean and standard deviation of soil concentration of Mg^{2+} at experimental plots at (a) LYS, (b) NAC in 2003, 2004 and 2005

soil pool at both stands. The amount of removed N decreased to about 4% and 5% of the soil pools at LYS and NAC, respectively, in 2004, and further to 3% and 2% in 2005, respectively. The average loss of N after 3 years of litter raking was surprisingly high: 77 g m^{-2} for LYS and 95 g m^{-2} for NAC.

Needle chemistry and its relationship to soil

A relatively strong response of Mg (and partially also Ca) concentration in needles to litter raking was found at both sites. In 2005, the Mg concentration in current year needles differed significantly between the experimental and control plots at both LYS and NAC ($p < 0.05$; Fig. 3). Similarly, the Ca concentration was lower at raked plots, but only significantly in second year needles at LYS ($p < 0.05$) (at NAC $p = 0.0503$). On the other hand, concentrations of K, N and P in needles did not change during the 3 years of our experiment.

The concentrations of Mg and Ca in needles were related to the Mg^{2+} and Ca^{2+} pools in the humus horizons, respectively ($p < 0.05$). Concentrations of all other nutrients in needles did not correlate significantly with their pools in the humus horizon. Additionally, we did not find any significant correlation between nutrient concentration in needles and their total soil pools.

Precipitation and runoff chemistry

Due to desulfurization of coal-fired power plants in Central Europe during the 1990s, the throughfall flux of S in 2004 represented less than 30% and 40% of its flux in 1994 at LYS and NAC, respectively. Consequently, we observed a significant decrease in the leaching of base cations by runoff from both LYS and NAC, while this trend was not found in their deposition with the exception of Ca^{2+} (Table 3). The history of acid deposition at LYS is described in detail by Hruška et al. (2002), and at NAC by Oulehle et al. (2006, 2007).

Budget of base cations

Fluxes of nutrient base cations at LYS and NAC are shown in Table 3. The amount of Ca^{2+} removed with litter from the first raking was nearly five times greater than the present (2004) annual input of Ca^{2+} to the ecosystem by deposition and weathering at LYS, and even more than eightfold at NAC (Table 3). Similarly, with repeated removal of litter the following year, the amount of Ca^{2+} lost was still much higher, particularly at NAC, than the annual deposition and weathering (Table 3). These differences are even more marked when comparing the annual Ca^{2+} input with the total Ca removed with litter.

The amount of annual runoff of Ca^{2+} from the LYS watershed in 2004 equaled 17% of the Ca^{2+} removed by litter raking in 2003, 37% in 2004 and 55% in 2005 (Table 3). When compared with Ca runoff during the end of the period of high atmospheric deposition (1994), values were higher, i.e. 41% of Ca^{2+} removed by litter raking in 2003, 86% in 2004 and 130% in 2005.

As in the case of Ca^{2+}, the losses of Mg^{2+} and K^{+} caused by litter raking in the first year of the experiment greatly exceeded both their input to the ecosystem by deposition and weathering and output by runoff, but these differences decreased in the next 2 years of the experiment (Tables 2 and 3).

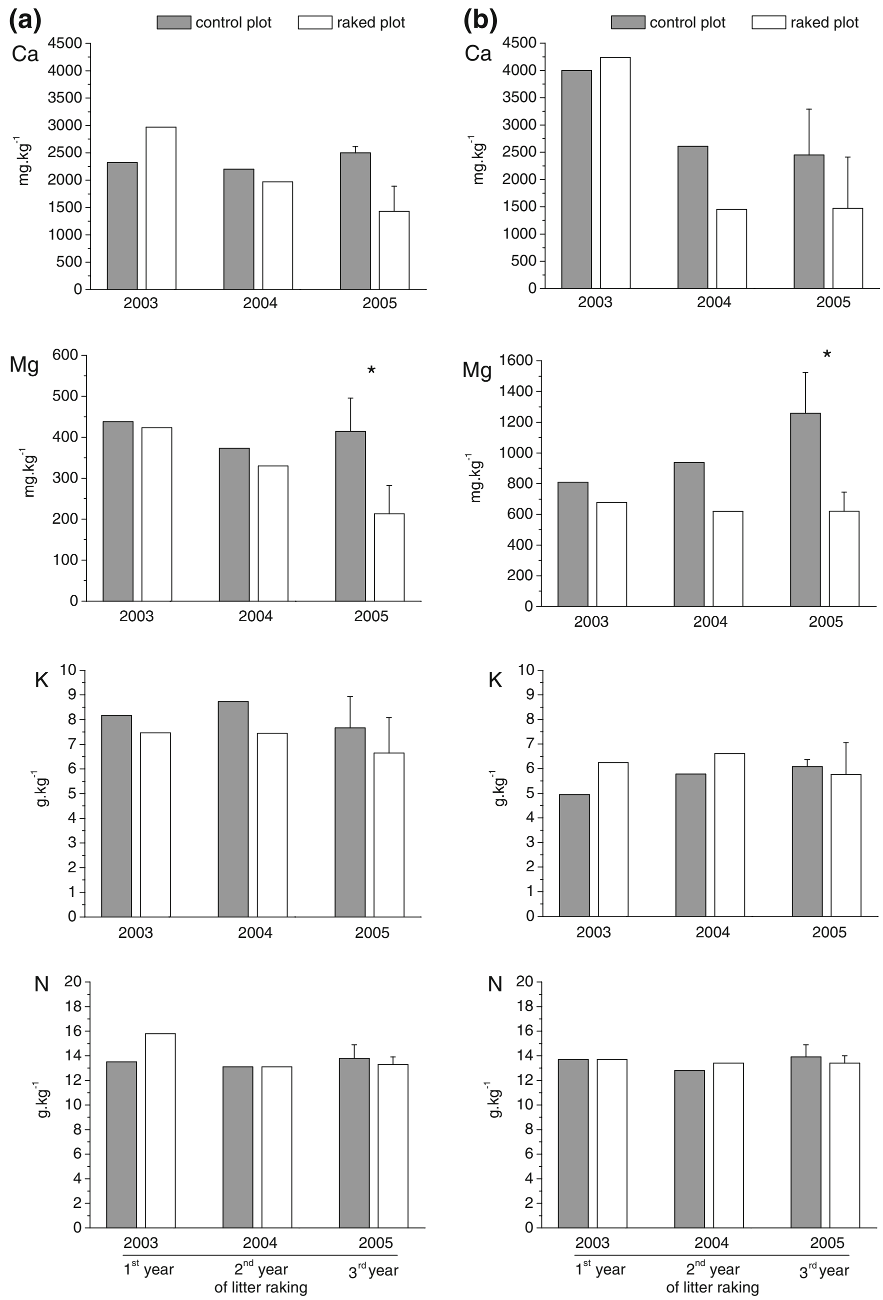

Fig. 3 Mean and standard deviation of nutrient concentration in 1st year spruce needles in the study plots at (**a**) LYS and at (**b**) NAC. Columns with * differed significantly at $p < 0.05$

Nutrient losses due to traditional litter raking

In the first year of litter raking, we found an almost three times higher average amount of removed litter (3,570 g m^{-2} at LYS and 3,735 g m^{-2} at NAC) in comparison with historic records (Ebermayer 1876). The amount of raked litter remained considerably higher even in the third year of the experiment (1,105 g m^{-2} at LYS and 770 g m^{-2} at NAC).

Hypothetically, if the litter amount removed from LYS and NAC in 2004 equaled the amount given by Ebermayer (1876) for an annually raked spruce forest, the average loss of Ca^{2+}, Mg^{2+} and K^{+} should be 574, 44 and 214 mg m^{-2} at LYS, respectively, and 419, 57 and 103 mg m^{-2} at NAC, respectively. By this calculation, annual loss of Ca^{2+} by litter raking would be two-thirds of the present Ca input to the ecosystem (deposition and weathering rate) at

Table 3 Import of exchangeable base cations by deposition and weathering (data from 1994 Hruška and Krám 2003 at LYS, Oulehle et al. 2007 at NAC) and export by litter raking (total form in parentheses) and runoff in the years 1994 and 2004

	Import			Export			
	Total deposition ($mg\ m^{-2}\ year^{-1}$)		Weathering ($mg\ m^{-2}\ year^{-1}$)	Litter raking ($mg\ m^{-2}\ year^{-1}$)		Runoff ($mg\ m^{-2}\ year^{-1}$)	
	1994	2004		1th treatment	2nd treatment	1994	2004
LYS							
Ca	557	267	581	4215 (*5243*)	1995 (*2124*)	1725	736
Mg	98	73	122	330 (*779*)	151 (*278*)	309	176
K	152	183	156	1928 (*3164*)	684 (*979*)	688	211
NAC							
Ca	593	397	251	5323 (*6727*)	2814 (*3774*)	1529	296
Mg	126	119	225	750 (*1397*)	383 (*1137*)	592	203
K	176	301	117	2118 (*2590*)	646 (*1159*)	412	111

both stands (Fig. 4). Simultaneously, it would represent 78% and 142% of the Ca output via runoff from LYS and NAC, respectively. The Mg^{2+} lost in this way would reach around one-quarter of both its present input to the ecosystem and output by runoff. The proportion of annual loss of K^+ would be 63% and 25% of its present input at LYS and NAC, respectively, while it would approximately equal the present output from both localities (Fig. 4). The amount of annually removed Ca^{2+} would represent between 2% and 4% of its present soil pool, while in the case of Mg^{2+} and K^+ it would be slightly lower (1–2.5%).

We summarize that annual litter raking entails an output of Ca^{2+} and K^+ from these spruce ecosystems similar to their present output by runoff. The influence of annual litter raking seems to be less pronounced in the case of Mg^{2+}. If we compare annual losses of total Ca, Mg and K by litter raking with their input and output in 2004, the effect of litter raking will further increase (Fig. 4).

Discussion

Changes in the soil nutrient pools

As expected, the litter raking experiment caused dramatic changes in the soil pool of nutrients from 2003 to 2005. Our results partly corresponded with the estimation of nutrient losses caused by litter raking compiled by Glatzel (1991) from the older data of other authors. In that study, the estimated losses of Ca, Mg,

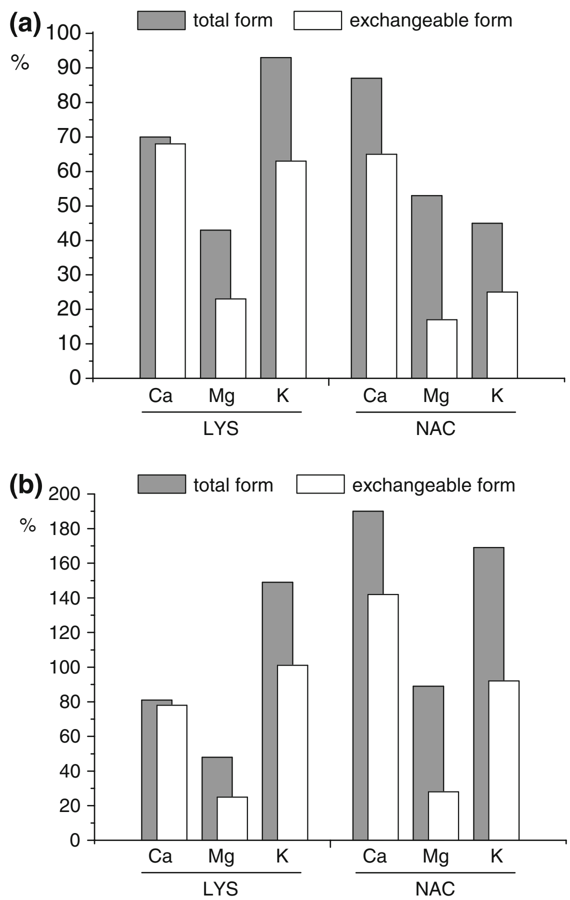

Fig. 4 The proportion of export of total Ca, Mg and K and exchangeable Ca^{2+}, Mg^{2+} and K^+ by annual litter raking at LYS and NAC recalculated according to data from Ebermayer (1876) in relation to their (**a**) annual input by atmospheric deposition and mineral weathering in 2004 and (**b**) output by runoff in 2004

K, P and N due to litter raking ranged from 1,500 to 4,000, 300 to 1,000, 1,200 to 2,500, 200 to 400 and 2,000 to 5,000 mg m^{-2} $year^{-1}$, respectively. The loss of nutrients due to litter raking in the first year of our experiment ranged around the upper limit of the range predicted by Glatzel (1991) with the exception of N, for which the loss was 10 times higher than estimated. The amount of litter removed in our experiment was probably substantially higher than in the past as indicated by comparison of our data with historical records (Ebermayer 1876; Pfeffer 1948). On the other hand, the concentration of base cations in the litter at our stands may have been diminished by the long-term effect of acid deposition (Jonsson et al. 2003; Olsson et al. 1996). Furthermore, the results from the third year of our experiment ranged around the lower boundary of the interval calculated by Glatzel (1991), again with the exception of N, for which the loss exceeded the upper limit of Glatzel's interval by more than a factor of two. This excess may be explained by N deficiency in forest soils exposed to long-term litter raking in the past on the one hand and by the recent accumulation of N deposition in the humus layer on the other.

Amount of removed litter

In the past, litter was usually raked at intervals of between 1 and 7 years (Ebermayer 1876; Kvapil and Němec 1929; Němec 1933). Our three-year experiment documents that frequent removal of litter resulted in reduced quantities of both litter and nutrients lost per removal. However, our average amount of removed litter was almost three times higher in the first year of litter raking in comparison with historical records, and remained considerably higher even in the third year of the experiment (Ebermayer 1876). At first, this difference may have been caused by a higher intensity of litter raking. We raked litter thoroughly to simulate the long-term effect of litter raking in a short time scale. On the other hand, we removed only that material which could have been used for bedding for farm animals, similar to what would have occurred in the past. This consisted mostly of non-decomposed needles and other organic material, with only a small portion of partially decomposed material (around 20%). In addition, not all litter was removed completely, and some remained on the experimental plots because it easily passed through the gaps of the rake. Therefore, another reason for the high amount of removed material compared to historical records is likely. One explanation may be a considerably slower mineralization of litter and accumulation on these nutrient-poor soils suffering from strong acid deposition in the 2nd half of the 20th century, as suggested by Mulder et al. (2001) and Oulehle et al. (2006). A long-term accumulation of dead organic matter at our stands may explain the apparently unrealistic amount of raked material in comparison with historic data (Ebermayer 1876). Many other indicators show that an increase in soil biological activity started a few years ago at NAC as a consequence of the reduction in sulfur deposition. For example, the weight of humus decreased from 17,600 g m^{-2} in 1994 to 15,200 g m^{-2} in 1997 and then to 12,600 g m^{-2} in 2003 (Oulehle et al. 2006). An increase in Mg concentration in spruce needles at the control plot at NAC during the experiment could also be explained by an improvement in soil availability of Mg^{2+} followed by enhanced mineralization after the decline of acidic deposition (Fig. 3). Moreover, Mg concentration in needles was rather stable in the years before our experiment, being very similar in 2003 (the beginning of the experiment) and 1994 (Oulehle et al. 2006).

At NAC, the average annual amount of litterfall was 372 g m^{-2} $year^{-1}$ in 1994–2004 (Cudlín unpublished; some results in Oulehle et al. 2006), which corresponded well to the spruce litterfall in the second half of the 19th century measured by Ebermayer (1876): 396 and 338 g m^{-2} $year^{-1}$ for spruce stands from 30 to 60 and from 60 to 90-years old, respectively. The spruce needles represented three quarters of litterfall mass measured at NAC from 1994 to 2004, and the average annual amount of Ca, Mg and K in fallen needles represented 900, 100 and 435 mg m^{-2} $year^{-1}$, respectively. These values are comparable to amounts of Ca and Mg in litter removed in the third year of our experiment.

Loss of base cations by litter raking versus acid deposition

Long-term leaching of base cations via runoff was computed using the geochemical model MAGIC (Cosby et al. 2001) at LYS (Hruška et al. 2002) and

NAC (Oulehle et al. 2007). The leaching of base cations in 1850 can be considered as unaffected by acid deposition. Therefore, we can estimate the leaching of base cations caused by acid deposition, if the loss in 1850 is subtracted from each following year. Furthermore, we can compare this loss caused by acid deposition with the loss caused by hypothetical annual litter raking using our data (for total Ca, Mg and K) which was determined using the amount of annually raked litter in the past (Sect. 'Nutrient losses due to traditional litter raking'). This comparison (Fig. 5) shows that litter raking would have represented a several times higher loss of base cations (especially Ca and K) than acid deposition until 1950, if it had been performed annually. Since 1950, acid deposition increased considerably throughout Central Europe (Kopáček and Veselý 2005). Nevertheless, the total Ca which could have been removed by annual litter raking from 1950 to 2000 still represents 48% and 96% of its leaching caused by acid deposition at LYS and NAC, respectively (Fig. 5). Similarly, litter raking reached 41% and 61% of total Mg lost caused by acid deposition at LYS and NAC. This is even more pronounced in the case of total K, for which the loss would be almost twice the acid deposition runoff (Fig. 5). These results indicate that the loss of base cations caused by long-term litter raking may be comparable to that caused by acid deposition during the 20th century.

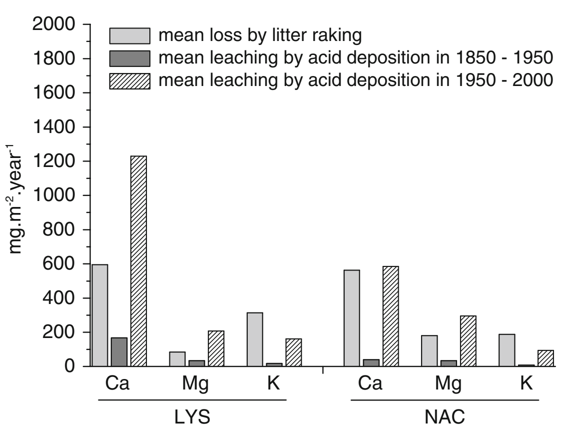

Fig. 5 The loss of base cations caused by hypothetical litter raking at LYS and NAC (data of total Ca, Mg and K recalculated according to average amount of litter given by Ebermayer (1876)) with that caused by acid deposition at these stands estimated by geochemical modeling (Hruška et al. 2002; Oulehle et al. 2007)

Forest management in the past

Accepting the fact that removal of litter was responsible for a considerable loss of nutrients, we should determine the proportion of forest area which was traditionally raked. However, this issue is difficult and may even be impossible to solve due to lack of historical records. In the first half of the 20th century, a relatively small proportion of the forest in the former Czechoslovakia was regularly raked (less than 20% of the total forest area) (Anger 1929; Pfeffer 1948). Although this area was probably larger throughout the 19th century, we cannot exactly quantify by how much. In addition, other commonly used practices such as extraction of tree stumps, cutting branches (pollarding), grazing, etc. were also responsible for losses of nutrients, but they were even less well documented (Glatzel 1991; Rackham 1998). In the 18th and 19th century, almost all European forests suffered from some of these practices (Hüttl and Schaaf 1995; Peterken 1996). As early as in the 18th century, poor soils or their degradation caused by massive deforestation were considered to limit the successful growth of new forests (Nožička 1957).

Considering these facts, it is extremely difficult to estimate nutrient changes in forest soil caused by human management during the past several centuries. However, we have shown that long-term litter raking, as a one important example of this management, may affect soil base cations similarly to elevated acid deposition. This should be considered in contemporary assessments of forest soils and forest tree conditions.

Conclusions

The loss of basic nutrients caused by litter raking in each year of a three-year manipulation experiment greatly exceeded their annual input into the soil (from total deposition and weathering). In addition, it was several times higher than the output of nutrients in the stream or seepage water. However, the amount of litter removed from our experimental sites was 2–3 times higher in comparison with historical records. When results are converted to the amount of litter removed in the past, loss of total Ca, Mg and K from spruce stands would be from 40% to 100% of present annual input into the soil and from 50% to 190% of annual runoff.

The losses of Mg and Ca from the soil were reflected in their needle concentrations. Acid deposition apparently influenced the concentration of base cations in humus as well as the amount of humus itself.

The leaching of base cations from soil caused by acid deposition in the second half of the 20th century was recently estimated at both study stands using the MAGIC model (Hruška et al. 2002; Oulehle et al. 2007). This leaching flux was similar to hypothetical loss of base cations by litter raking if it had been performed annually at our stands. Therefore, removal of litter could have strongly influenced the nutrient and acidification status of spruce forests in the past. The long-term removal of litter and other historical forms of forest management may have been responsible for a loss of basic nutrients equivalent to that caused by acid deposition.

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