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Development of chemical soil properties in the western Ore Mts. (Czech Republic) 10 years after liming

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ABSTRACT: The article focuses on changes in soil chemistry observed on plots limed in 2000 in the western Ore Mts. (Krušné hory) on the basis of chemical analyses done before liming and repeated in 2002, 2005 and 2010. In the deeper mineral soil (down to 30 cm), only the increase in pH and exchangeable magnesium was significant. The increase in exchangeable calcium in upper soil layers was significant in 2002 and 2005 only; ten years after liming the effect was negligible, although the number of Ca deficient samples was lower than in 2000. The exchangeable Mg content increased above the deficiency limit in all samples of upper soil, and an increase was also found in the deeper mineral soil. These changes were reflected in increasing base saturation and lower base cations/aluminium ratio in the organic and organomineral soil layer. Despite these positive shifts, calcium and magnesium deficiency and very low base saturation (< 10%) still prevail in the deeper mineral soil (2–30 cm) and are common even in the upper mineral soil. The increased total nitrogen level observed two and five years after liming indicated enhanced decomposition of the humus layer. On the other hand, N content in the upper organic (FH) horizon as well as in deeper mineral soil did not change significantly.

Keywords: liming; magnesium deficiency; forest nutrition; soil development

The Czech Republic belongs to regions highly affected by air pollution during the second half of the 20th century. The extreme concentrations of sulphur dioxide and acid rain caused vast deforestation in the most affected areas of the western and northern mountains (Krušné hory Mts., Jizerské hory Mts., Orlické hory Mts.). The air pollution decreased rapidly during the 1990s (Hůnová et al. 2004), which resulted in the progressive improvement of young Norway spruce (*Picea abies* [L.] Karst.) stands planted on the areas of previous air pollution felling (Lomský, Šrámek 2004; Lomský et al. 2007). However, the general development of forest health was not so positive. Increased defoliation of forest trees was observed until the beginning of the new millenium, and since then the situation has been stable rather than better (Fabiánek, Hellebrandová 2010). One of the reasons for such a trend was the degradation of forest soils that were exposed to acid atmospheric deposition for a long time and commonly exhibit a low base saturation and deficiency of base cations and phosphorus in mineral soil layers (e.g. Fiala et al. 2005, Šrámek et al. 2010a, b). In the upper part of the western Krušné hory Mts., the situation of Norway spruce stands appeared to be critical in 1999 and 2000. The typical yellowing symptoms caused by magnesium deficiency (Ende, Evers 1997) turned to drying and loss of needles and even to decay and mortality of individual trees, which endangered the stability of forest stands (Lomský, Šrámek 2004). In 2000, the areas with deteriorated forest soils began to be limed according to Czech Republic Government Resolution No. 532/2000. The particular locations for liming were selected based on a set of criteria involving factors such as forest typology, nature protection and water protection status, and also based on the chemical surveys of forest soils and forest nutrition (Šrámek 2005). The chemical surveys are provided not only for the lime ap-

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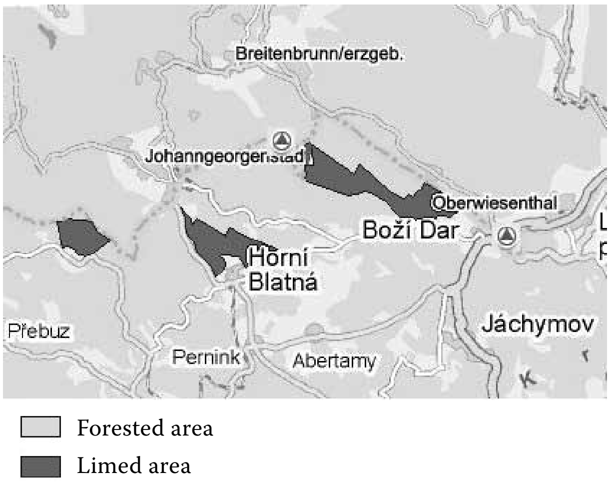

Fig. 1. Limed localities in the western Ore Mts. (2000)

plication planning, but also for the control of the quality of these measures and for the assessment of their medium and long-term effectiveness. For this reason, the sampling and analyses of forest soil and Norway spruce needles are repeated in intervals of two, five and ten years after liming. The results of sampling two or five years after liming were presented for different regions several times (Šrámek et al. 2003, 2006). This article focuses on changes observed on plots that were limed ten years ago in the western Krušné hory Mts., particularly at the Horní Blatná forest administration and in the Boží Dar communal forests.

MATERIAL AND METHODS

In 2000, aerial liming was done on 1,682 ha in the western Krušné hory Mts., 1,577 ha of which belong to the Horní Blatná forest administration and 105 ha to the Boží Dar communal forests (Fig. 1). The altitude of the limed area ranges between 700 and 1,000 m a.s.l. The bedrock mainly consists of granite and phyllite, on which acid podzols and gleyic soils have developed. The prevailing forest type is acidophilous spruce forests with *Calamagrostis* (Chytrý et al. 2001) artificially forested by Norway spruce (*Picea abies* [L.] Karst.), with only minor representation of other tree species such as mountain ash (*Sorbus aucuparia* L.), European beech (*Fagus sylvatica* L.), European larch (*Larix decidua* Mill.), and others. A total dose of 3 tons of dolomitic limestone (MgO > 18%) per hectare was applied in autumn 2000 (September–November).

Soil samples were taken repeatedly in 17 randomly selected forest stands within these locations. Soil samples before liming were taken in May 2000, and control samples were taken in May 2002, 2005 and 2010. Composite samples of humus (FH), upper mineral layer, enriched with humus (A) of usual thickness 1–2 cm, and lower mineral layer down to 30 cm (B) were taken at three spots in each stand. Active pH – pH_{H_2O} and exchangeable pH_{KCl} were recorded in these samples. In 2000–2002, nitrogen content was determined spectrometrically by the Kjeldahl method, the levels of oxidable carbon by iodometric titration after oxidation by the chlorine-sulphur mixture. In 2005 and 2010 the total C and N contents were determined by the CNS element analyzer (Leco). Differences in total nitrogen between these methods are supposed to be negligible. Results of C determination should also be similar with the exception of neutral and basic soils with pH > 6, where the content of total carbon compared to organic carbon is increased by carbonates. The content of exchangeable elements was determined in the extract by ammonium chloride, extractable (pseudo-total) element contents by aqua regia and following spectrophotometric determination by ICP-OES.

Cation exchange capacity (CEC) was calculated from concentrations of particular elements and relative atomic weight:

$$CEC = SBC + SAC + H^+$$

where:

SBC – molar sum of base cations (Ca, K, Mg, Na) content,
SAC – molar sum of acid cations (Al, Fe, Mn) content,
H^+ – molar content of exchangeable H^+.

Base saturation was calculated as the molar ratio of base cation sum and cation exchange capacity:

$$BS = SBC/CEC$$

The molar ratio of base cations and aluminium was calculated in a similar:

$$BC/Al = SBC/Al$$

where:

Al – molar content of aluminium.

The significance of differences in individual parameters before and after liming was tested by Dunn's multiple comparison at the 95% reliability level, using the UNISTAT (US) statistical software package.

Table 1a. Chemical properties of forest soils before, and two, five, and ten years after liming

Soil layer	Sampling year	pH_{H_2O}	pH_{KCl}	C (%)	N (%)	C/N	CEC (mmol·kg^{-1})	BS (%)	BC/Al
FH	2000 (before liming)	3.58^{a}	2.51^{a}	30.9^{a}	1.71^{a}	18.0^{a}	187.3^{a}	–	–
	2002	4.47^{b}	3.42^{b}	32.7^{ab}	1.97^{a}	16.7^{a}	233.4^{b}	–	–
	2005	4.30^{b}	3.27^{b}	36.7^{bc}	1.78^{a}	21.0^{b}	220.0^{ab}	–	–
	2010	4.18^{b}	3.09^{b}	38.0^{c}	1.81^{a}	21.0^{b}	210.6^{ab}	–	–
A	2000 (before liming)	3.63^{a}	2.63^{a}	10.8^{a}	0.57^{a}	19.6^{ab}	120.7^{a}	10.20^{a}	0.13^{a}
	2002	3.91^{b}	3.09^{b}	22.2^{b}	1.32^{b}	17.4^{b}	158.5^{b}	21.20^{b}	0.33^{b}
	2005	3.81^{ab}	2.88^{ab}	18.1^{bc}	0.85^{ab}	21.3^{a}	147.0^{ab}	23.60^{b}	0.38^{b}
	2010	4.01^{b}	3.07^{b}	14.3^{ac}	0.68^{a}	21.1^{a}	142.2^{ab}	19.40^{b}	0.30^{b}
B	2000 (before liming)	3.99^{ab}	2.95^{a}	3.87^{a}	0.20^{a}	19.1^{a}	98.1^{a}	7.14^{a}	0.085^{a}
	2002	4.02^{ab}	3.37^{b}	4.05^{a}	0.23^{a}	17.0^{a}	102.1^{a}	5.83^{a}	0.070^{a}
	2005	3.86^{a}	3.14^{ab}	4.47^{a}	0.23^{a}	18.9^{a}	100.6^{a}	8.92^{a}	0.118^{a}
	2010	4.14^{b}	3.29^{b}	5.10^{a}	0.26^{a}	19.8^{a}	117.9^{a}	7.71^{a}	0.094^{a}

$^{a-c}$ indicates homogenous group according to results of the Dunn's test; CEC – cation exchange capacity; BS – base saturation; BC/Al – molar ration of base cations to aluminium, FH – organic layer (humus layer), A – upper mineral layer (≈ 0–2 cm), B – lower mineral layer (≈ 2–30 cm)

RESULTS AND DISCUSSION

Chemical properties of forest soils before liming (in 2000) and two, five and ten years after dolomitic lime application are presented in Table 1a–c. Because of aerial application, the upper organic layer and top soil horizon were influenced to the largest extent; the changes were less pronounced and mainly insignificant in the lower soil layers. The soil reaction, however, exhibited significant changes at all depths that were examined. The forest soils were very strongly acidic, with pH_{KCl} ranging between

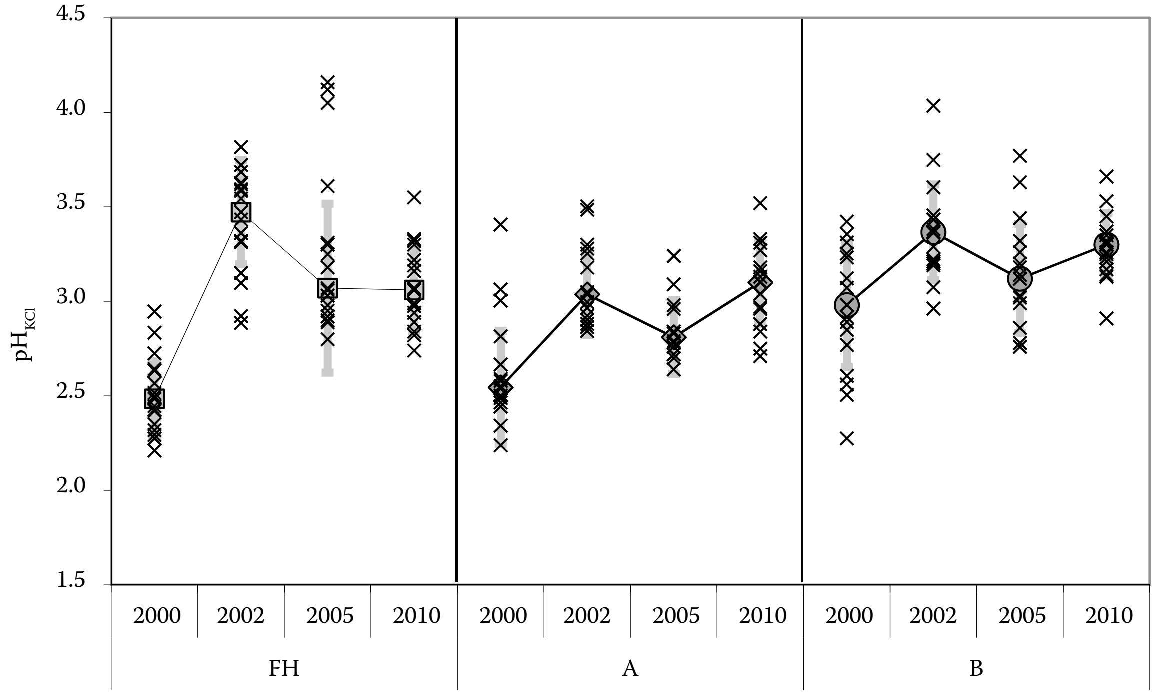

Fig. 2. Development of soil acidity pH_{KCl} at individual limed plots – median and values for individual plots
FH – organic layer (humus layer), A – upper mineral layer (≈ 0–2 cm), B – lower mineral layer (≈ 2–30 cm)

2.2 and 2.9 in the organic layer, and very strongly to strongly acidic (pH_{KCl} 2.2–3.4) in the mineral layers in 2000. Two years after liming, a distinct increase in pH_{KCl} was recorded at all soil depths (Fig. 2) – pH_{H2O} changes in the B layer were not significant. Five and ten year after liming, the change in the humus layer was less pronounced than in 2002, but the increase in pH was still significant. The soil was less acidic in 2010 than in 2005 in both mineral layers, and even though the pH values in 2005 were on average higher than before lime application, only the change in 2010 was significant. An interesting characteristic is the range of pH increase. We find of importance that it was not very rapid – particularly in the organic FH horizon the distinct decrease of acidity may lead to accelerated humus decomposition and leaching of nitrogen and other nutrients (Rosenberg et al. 2003). The effect, however, depends highly on the nitrogen saturation of the ecosystem and on the dose and grain size of the applied limestone, and is often visible only after the canopy removal during reforestation (Bauhus et al. 2004; Bäckman et al. 2004; Schaaf, Hüttl 2006). In our case, most of the sites remained in the category of strongly acidic sites ($pH_{KCl} < 4.0$); only three sites of FH horizons had higher values in 2005 (maximum pH_{KCl} 4.16) and one of the B layer in 2002 (pH_{KCl} 4.04).

No significant nitrogen changes in the organic FH horizon were observed. On the other hand, there was a significant increase in nitrogen content in the upper mineral layer A two years after liming; the average value was nearly twice higher, reaching 1.32% N. These values indicate the release of nitrogen from organic substances, which can be mainly observed in the border zone between the organic layer and mineral soil. In the deeper layer (B), the change in nitrogen was not significant, although the absolute values were increasing slowly. In 2005 and 2010, the N content in the A layer was lower again, with no significant difference compared to the situation before liming. The C/N ratio in the FH horizon showed an insignificant decrease two years after liming, then it increased significantly in 2005 and 2010. This corresponds to the development of carbon concentration, which increased significantly in 2005 and 2010. It is not possible to say whether these changes were caused by liming or by other factors. The decomposition processes of organic matter depend on many variables, including meteorological conditions, lignin/hemicellulose ratio, or the supply of other nutrients important for microbial activity such as phosphorus (Berg, Laskowski 2006), and are more pronounced in clearcuts and open areas (Kuneš 2003; Podrázský 2006). The C/N ratio before liming was quite low (≈ 20), indicating a risk of increased nitrogen leaching from the humus layer. The stable level of nitrogen concentration in the B layer, however, does not document a shift of nitrogen to the lower mineral soil. This is consistent with the results of Vortelová et al. (2007), who did not find a significant increase

Table 1b. Chemical properties of forest soils before, and two, five, and ten years after liming – exchangeable nutrients (mg·kg^{-1})

Soil layer	Sampling year	Ca	Mg	K	Fe	Mn	Al
FH	2000 (before liming)	879^{a}	128.5^{a}	291.4^{a}	208.7^{a}	43.3^{a}	949^{a}
	2002	2,208^{b}	634.0^{b}	388.6^{b}	83.1^{b}	55.7^{a}	359^{b}
	2005	1,896^{b}	635.9^{b}	298.8^{a}	152.8^{ab}	93.5^{a}	386^{b}
	2010	1,369^{ab}	395.1^{b}	351.9^{ab}	203.6^{a}	52.6^{a}	612^{ab}
A	2000 (before liming)	118.4^{a}	36.6^{a}	103.7^{a}	224.8^{a}	10.1^{a}	838^{a}
	2002	281.5^{b}	157.0^{b}	214.6^{b}	134.9^{a}	9.6^{a}	1,055^{a}
	2005	306.4^{b}	186.6^{b}	116.2^{a}	189.8^{a}	5.0^{a}	906^{a}
	2010	198.0^{ab}	160.5^{b}	118.9^{a}	225.6^{a}	8.2^{a}	917^{a}
B	2000 (before liming)	65.1^{a}	18.5^{a}	47.6^{a}	119.2^{a}	12.6^{a}	748^{a}
	2002	53.9^{a}	22.0^{ab}	49.0^{a}	107.2^{a}	14.7^{a}	802^{a}
	2005	72.1^{a}	37.6^{bc}	34.5^{a}	98.2^{a}	26.7^{a}	765^{a}
	2010	43.2^{a}	47.0^{c}	46.4^{a}	106.6^{a}	18.1^{a}	925^{a}

$^{a–c}$ indicates homogenous group according to results of the Dunn's test. FH – organic layer (humus layer), A – upper mineral layer (≈ 0–2 cm), B – lower mineral layer (≈ 2–30 cm)

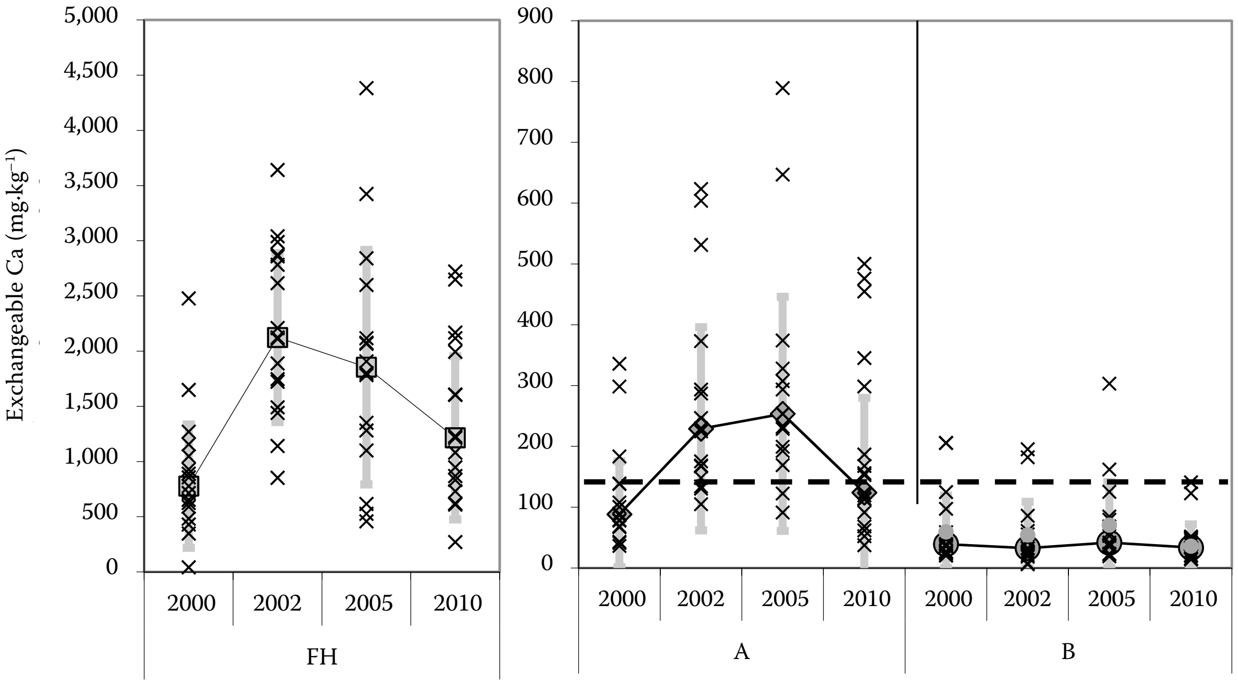

Fig. 3. Development of exchangeable calcium content – median and values for individual plots
Black dashed line – the calcium deficiency limit (140 mg.kg^{-1}), FH – organic layer (humus layer), A – upper mineral layer (≈ 0–2 cm), B – lower mineral layer (≈ 2–30 cm)

in nitrogen leaching on limed plots in the eastern Krušné hory Mts. The nitrogen saturation of forest soils must be assessed by more complex criteria than only by the C/N ratio (Aber 1992; Dise et al. 1998, 2009). The current C/N ratio of the FH layer in limed forest stands corresponds to the median value for forest soils in the Czech Republic (21.9), as was found in the international BIOSOIL project (Šrámek et al. 2010b). On the other hand, there is still a possibility that the change observed in the carbon content and thus in C/N was caused by a change in the methods. As it was already stated, total carbon could be increased compared to organic carbon by carbonate occurrence in calcareous soils with pH > 6. The pH was not higher than 4.5 in our case, but some carbonates were certainly obtained in limestone grains deposited in the upper organic and mineral layers and thus they influenced our results. This is just a hypothesis but there is no possibility to make a clear statement about the C/N ratio development in limed forest soils before it is tested.

Calcium and magnesium represent two main nutrients contained in dolomitic limestone; their increase on the studied plots is obvious (Kreutzer 1995). Extractable ("pseudo-total") content of Ca and Mg increased significantly only in the organic FH horizon (Table 1c); the highest values were recorded in 2002, then a subsequent decrease is documented. No significant change was detected in mineral soil. The dynamics of calcium and magnesium exchangeable forms on a temporal scale and within different soil depths can be of interest. The exchangeable Ca content in the humus layer (Fig. 3) was more than doubled (mean value 251%; median 271% of 2000 content) two years after the treatment and a very high increase was also documented in 2005 (mean value 216%; median 240% of 2000 content). Ten years after liming, the increase in Ca was less pronounced when both the median and mean values were by 160% higher than in 2000. The 2010 exchangeable calcium mean did not differ significantly either from the results recorded before the lime application or from the results in 2002 and 2005. A similar trend with lower absolute values could also be observed in the upper mineral layer A. There was a clear and significant increase in Ca two and five years after liming (238% and 259% increases of the mean value), followed by a slighter (168%) and insignificant increase in 2010. The relative availability of nutrients is particularly important in the A layer, where is a high density of Norway spruce sorption roots. The deficiency limit for exchangeable calcium is often defined as 140 mg Ca·kg^{-1} (Materna 2002). According to these criteria, more than 80% of samples taken in 2000 were deficient in calcium. Two years after liming, the

Table 1c. Chemical properties of forest soils before, and two, five, and ten years after liming – extractable (pseudo-total) nutrients

Soil layer	Sampling year	Ca tot (mg.kg^{-1})	Mg tot (mg.kg^{-1})	K tot (mg.kg^{-1})	Fe tot (mg.kg^{-1})	Mn tot (mg.kg^{-1})	Al tot (mg.kg^{-1})
FH	2000 (before liming)	462^{a}	279.1^{a}	464.2^{ab}	9,436^{ab}	113.4^{a}	6,789^{a}
	2002	6,110^{b}	3,013^{b}	572.1^{a}	6,943^{a}	136.6^{a}	4,812^{ab}
	2005	3,330^{bc}	1,619^{b}	293.4^{ab}	8,707^{ab}	477.2^{a}	6,772^{ab}
	2010	1,666^{ac}	640^{b}	485.0^{b}	10,209^{b}	129.8^{a}	8,409^{b}
A	2000 (before liming)	344.3^{a}	1,245^{a}	1,280^{ab}	20,419^{a}	189.5^{a}	13,003^{a}
	2002	454.9^{a}	870^{a}	994^{a}	11,967^{a}	71.9^{b}	10,884^{a}
	2005	477.3^{a}	1,029^{a}	1,029^{a}	13,352^{a}	81.5^{ab}	11,310^{a}
	2010	451.7^{a}	1,419^{a}	1,532^{b}	17,679^{a}	155.3^{ab}	14,407^{a}
B	2000 (before liming)	302.0^{a}	2,068^{a}	1,667^{a}	32,548^{a}	562.6^{a}	16,742^{a}
	2002	315.5^{a}	2,252^{a}	1,853^{a}	29,994^{a}	351.3^{a}	17,562^{a}
	2005	261.0^{a}	1,540^{a}	1,507^{a}	19,386^{a}	323.1^{a}	14,592^{a}
	2010	355.6^{a}	2,296^{a}	2,145^{a}	31,422^{a}	501.7^{a}	19,307^{a}

$^{a-c}$ indicates homogenous group according to results of the Dunn's test, FH – organic layer (humus layer), A – upper mineral layer (≈ 0–2 cm), B – lower mineral layer (≈ 2–30 cm)

share of samples exhibiting a deficiency decreased to less than 20%, and in 2005 to even less than 15%. Ten years after liming, the calcium deficiency was still found in only 53% of samples, compared to 81% in 2000. In the deeper mineral soil layer (B), no significant change in exchangeable calcium was recorded, and the vast majority of samples were calcium deficient in all four surveys.

The development of exchangeable magnesium in the organic humus layer FH is similar to that of Ca

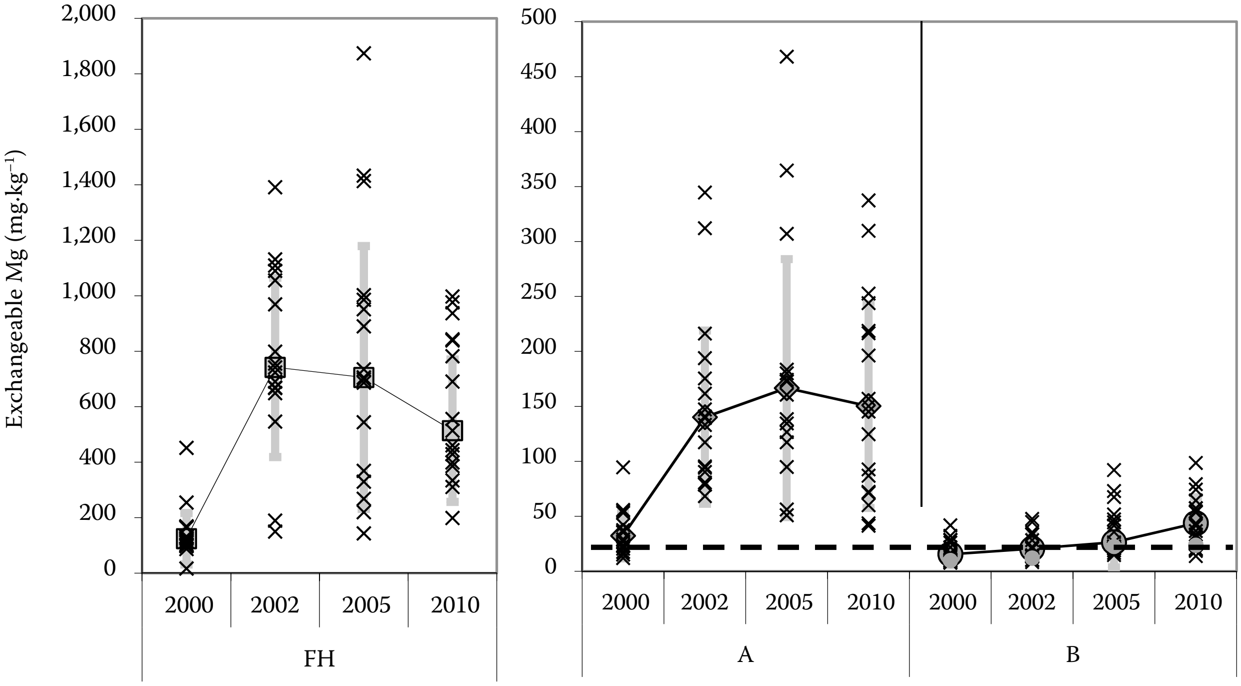

Fig. 4. Development of exchangeable magnesium content – median and values for individual plots
Black dashed line – the magnesium deficiency limit (20 mg·kg^{-1}), FH – organic layer (humus layer), A – upper mineral layer (≈ 0–2 cm), B – lower mineral layer (≈ 2–30 cm)

(Fig. 4). The highest increase in this nutrient was recorded two and five years after liming (495% increase of mean values, more than 560% increase of median values compared to the year 2000); in 2010, the total increase was less pronounced (307% in the mean, 414% in the median), but still highly significant. The magnesium change in mineral soil layers is more favourable than the calcium change. In the A layer, a significant increase in the entire ten-year period after liming can be observed with very similar median values, as well as the range of analyzed values in 2002, 2005 and 2010. Nearly 20% of the samples taken from the A layer exhibited magnesium deficiency (< 20 mg Mg·kg^{-1}) before liming. On the other hand, no Mg deficiency was found during the surveys in 2002, 2005 and 2010. The positive response was also observed in the deeper B layer, where the exchangeable magnesium increased gradually. Its content in 2005 was significantly higher than in 2000; the values from the last survey (2010) differed significantly from both 2000 and 2002. While 65% of samples exhibited magnesium deficiency before the treatment, the share of deficient samples after liming decreased to 47% in 2002 and to 18% in both 2005 and 2010.

Potassium is another main base cation and an important nutrient that is not contained in dolomitic lime. The change in potassium content is of special interest because its uptake by roots can be blocked by excessive calcium concentration (SCHULZE et al. 2005). Its extractable contents did not differ significantly in the surveys before and after liming. In the mineral soil, the pseudo-total K content was much higher than that of Ca, which indicated a possibility of recharging this element to the soil sorption complex by weathering. Exchangeable forms of potassium showed a significant increase in 2002, in both the FH and A layers (Fig. 5). This effect could be linked to the increased pH of humus and thus improved K availability in the sorption complex. Although the potassium contents in 2005 and 2010 did not differ significantly from the period before liming, they were slightly higher, which means that the K supply for trees was not reduced. Even after liming, the relative disposable content of potassium was better than that of calcium; K deficiency (< 30 mg K·kg^{-1}) was not observed in the mineral A layer. In the deeper mineral layer B, the number of potassium deficiency samples was steady at 12% in 2000, 2002 and 2010.

The increase of exchangeable Ca, Mg and partly K led to significantly increased base saturation in the upper mineral soil; no significant change was observed (Table 1a) in the lower mineral layer B. In the A layer, the base saturation was at the limit of sufficiency (20%) even after liming, and it remained critical in the deeper mineral soil (< 10%) (MEIWES et al. 1986).

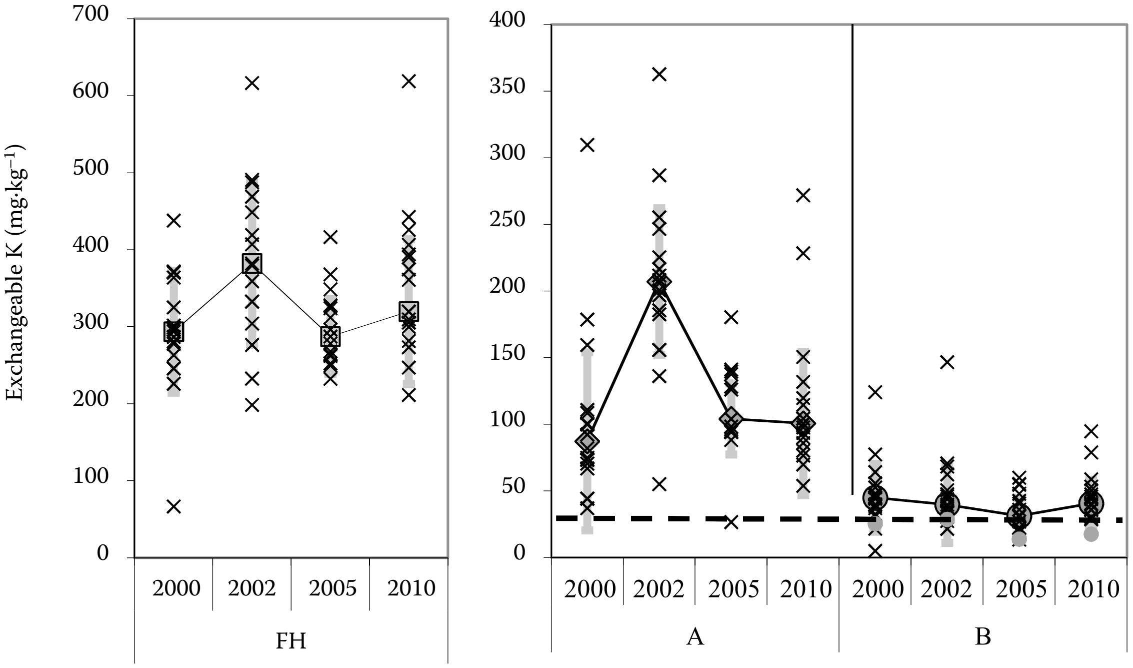

Fig. 5. Development of exchangeable potassium content – median and values for individual plots
Black dashed line – the potassium deficiency limit (30 mg·kg^{-1}), FH – organic layer (humus layer), A – upper mineral layer (≈ 0–2 cm), B – lower mineral layer (≈ 2–30 cm)

Two important micronutrients – iron and manganese – were not apparently influenced by liming. The only significant change compared to the period before the treatment was a decrease of extractable (pseudo-total) manganese in the upper mineral layer A. However, it did not apply to aluminium. The exchangeable aluminium content in the organic layer decreased significantly two and five years after the treatment. Its 2010 values were also generally lower than in 2000 (Table 1b), which is consistent with the findings of for example Bořůvka et al. (2005) or Álvarez et al. (2009). No change was detected in the mineral soil. Exchangeable aluminium in forest soils is of particular importance, because its toxic forms (mainly Al^{3+}) can damage fine roots and contribute to decreased forest vitality (Bakker 1999). Not only the absolute Al content but also its ratio to base cations in the sorption complex (BC/Al) is essential. The molar BC/Al ratio for mineral soil is presented in Table 1a. BC/Al increased significantly in the upper mineral soil, while no significant change was detected in the deeper mineral soil. Although the BC/Al ratio is used mainly for evaluating the soil solution properties (Van Scholl et al. 2004), our results suggest a decreased risk of toxic aluminium stress in the A layer after liming.

CONCLUSIONS

The effect of liming is visible mainly in the humus layer and in the upper mineral layer A, which is consistent with many other studies (Kreutzer 1995; Meiwes et al. 2002; Lundström et al. 2003; Schaaf, Hüttl 2006). In the deeper mineral soil (down to 30 cm) only the increase of pH and exchangeable magnesium was found significant. The increase of exchangeable calcium in upper soil was significant in 2002 and 2005 only; ten years after liming the effect was negligible, although the number of Ca deficient samples was 30% lower than in 2000. The development of exchangeable magnesium content was more favourable with no content under the deficiency limit after liming in the A layer and there was an upward trend in deeper mineral soil (B). These changes were reflected in increasing base saturation and lowered base cations/aluminium ratio in the A layer. No negative effects connected with the K and Ca antagonism in the sorption complex were recorded. Despite these positive shifts, calcium and magnesium deficiency and very low base saturation (< 10%) still prevail in the deeper mineral soil (2–30 cm) and are common (25–50% of samples) even in the A layer. This suggests a possibility of repeated liming in such localities in the interval of 5 to 10 years after the first treatment.

The increased total nitrogen content observed in the A layer two and five years after liming indicated enhanced decomposition of the humus layer. On the other hand, the N content in the upper organic (FH) horizon did not change significantly, and the increase in total carbon could not probably be the result of the treatment. Changes in the humus layer cannot be evaluated without additional data sources.

For a comprehensive evaluation of the influence of liming on forest stands, additional information is also needed, mainly the nutrition of trees estimated on the basis of foliar analyses (Huber et al. 2006). Such data is also available for the studied region but it is scarce compared to soil chemistry data. A sufficient statistical evaluation will thus be possible after samples have been taken in 2011 and 2012.

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