The effect of point application of fertilizers on the soil environment of spread line windrows in the Krušné hory Mts.

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ABSTRACT: The plateau of the Krušné hory Mts. belongs to areas that suffered the greatest damage caused by air-pollution stresses in Europe. A part of cultural practices aimed at the reconstruction of local mountain forests was the inconsiderate use of bulldozer technologies for the preparation of sites for forest stand restoration. In the course of large-scale scarification the top-soil horizons were moved into line windrows, which caused marked degradation of the soil environment. The present revitalization of the soil environment is based on the principle of spreading these man-made windrows. Experimental plots were established in localities affected by scarification; the organomineral material from windrows was superimposed on them and subsequently they were reforested with Norway spruce (*Picea abies* [L.] Karst.). In 2005 the point application of fertilizer tablets of Silvamix type in three treatments and calcic dolomite was performed into the rhizosphere of plants. Before fertilization and after three years of the experiment soil samples were taken from the organomineral zone of the root balls of plants, and the condition of the soil environment on spread windrows and changes in pedochemical properties as a result of applied fertilization were evaluated. Three years after the windrow spreading the content of the majority of soil macrobiogenic elements (N, K, Ca, Mg) is at the level of medium-high to high reserves, and only the low phosphorus reserves pose a certain hazard. The organomineral substrate of spread windrows is a suitable growth environment for the root systems of target tree species. The proportion of humus substances is the most important factor in spread windrows from which the characteristics of the other parameters of soil are derived. Along with the higher proportion of humus substances in Špičák locality significantly higher reserves of major macrobiogenic elements (N, P, K, Ca, Mg) were determined. The applied fertilizers of Silvamix type significantly increased the reserves of soil P, K, Ca, Mg and are a suitable means for the stimulation of spruce plantations in the restored environment of the Krušné hory Mts. Silvamix Forte fertilizer tablets are the most complex fertilizer with the most balanced effects that significantly increases the reserves of soil P, Mg and K. This fertilizer has a high effect on an increase in the reserves of soil phosphorus that may be deficient in conditions of spread windrows. Silvamix R is the most efficient fertilizer to increase potassium reserves. A positive effect of calcic dolomite on an increase in Ca and Mg content was observed while no such effect on the other elements was recorded.

Keywords: fertilization; Krušné hory Mts.; rhizosphere; site preparation

Soil-forming processes directly influence the cycling of matter in the ecosystem. The plant – soil interaction is a specific component of such cycling of matter (Samec et al. 2007). The greatest changes in the nutrition of forest tree species were observed mainly in regions exposed to the heavy deposition

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of air pollutants (Fenn et al. 2006). The Krušné hory Mts. are an area that suffered the greatest damage caused by air pollution stresses in Europe. The air pollution situation in synergism with climatic extremes in the eastern part of this mountain range resulted in the almost absolute disintegration of forest ecosystems (Vacek et al. 2003).

The subsequent total felling of these stands created conditions for the use of heavy-duty machinery for the preparation of forest sites. The soil was scarified with excavators and bulldozers, relatively intact soil horizons not afflicted by air pollutants were denuded and uniform reliefs of windrows were formed (Vavříček et al. 2006). Removal of the forest floor and disturbance of nutrient dynamics were the main cause of soil degradation (Jirgle 1983; Podrázský et al. 2003; Podrázský 2008). The devastation of edatope with machinery led to hazardous losses of humus substances (Kubelka 1992; Vavříček, Šimková 2004). The present spreading of windrows formed during so called bulldozer preparation of sites is the second phase of forest system restoration in the Krušné hory Mts. (Remeš et al. 2005). However, a major part of plots scarified in the past (about two thirds) has been preserved in the form of so called intervening strips with substitute stands without any supply of organic matters from line slash piles, showing the signs of mechanical degradation until now (Vavříček et al. 2006).

Since the beginning of the air pollution disaster different methods of fertilization have been an important measure of prevention and remediation of soil acidification and nutritional degradation. At these degraded sites fertilization is an essential measure for the restoration of a forest system including the fulfilment of its production and environmental functions (Podrázský 2006). The main objective of the present paper is to evaluate the condition of the soil environment in localities afflicted by previous scarification with subsequent superimposition of organic material from line windrows. The evaluation of the influence of Silvamix fertilizer tablets and calcic dolomite on pedochemical parameters of these soils is an integral part of the output.

MATERIAL AND METHODS

Description of the area under study

The Krušné hory massif is formed of undulated plateaus of NW exposure and altitude mostly between 700 and 1,000 m above sea level; the normal fault to basins at the Krušné hory foothills is formed of a steep fault slope oriented to SE (Demek 1965). The bedrock is mostly built of metamorphic rocks (slate, gneiss, mica schist, etc.) and intrusive granitoid bodies. Two localities were selected in the area of the forest district Klášterec nad Ohří: Špičák (185A 2) and Suchdol (403E 2). Selected plots are situated on the plateau of the Krušné hory Mts. at an altitude of 880–890 m a.s.l. where the prevailing soil type is modal Podzol (Vavříček 2003; Šimková, Vavříček 2004a,b). Potential vegetation at these sites corresponds to the association *Calamagrostio-villosae Piceetum* and *Sphagno-Piceetum* (Culek 1996; Neuhäuslová et al. 1998). Site 185A 2 is characterized by northern exposure and forest type group (FTG) 7K (*Fageto-Piceetum acidophilum*). Site 403E 2 is characterized by northern exposure and FTG 6S (*Piceeto-Fagetum mesotrophicum*) (Working Plan 1999–2008, unpublished).

Both localities underwent large-scale scarification during the air pollution disaster. This measure basically led to the destabilization of soil productivity and ecosystems of the Krušné hory plateau (Podrázský et al. 2001). In Špičák locality bulldozers with grubbing blades were used for scarification while in Suchdol locality bulldozers and plain-edge blades were employed that stirred the soil as far as the diagnostic Bs-horizon. The complete spreading of former line windrows was done there for soil revitalization (Vavříček 2003). Before the windrow spreading started, the windrows in Špičák locality contained ca 750–800 $m^3 \cdot ha^{-1}$ of organomineral mass. On plots of Suchdol locality there were huge line windrows of the volume ca 1,150–1,200 $m^3 \cdot ha^{-1}$ (Jirgle 1983).

Several mechanized technologies were used for windrow spreading, and consequently a differently prepared layer of the organomineral soil was formed at the place of windrows. On its surface there originated a shallow pseudo-topsoil horizon (Ap) 15–25 cm in thickness with different humus content. In Špičák locality the Ap-horizon contains 20–30% of oxidizable carbon (C_{ox} hereinafter) while in Suchdol locality the value of C_{ox} in the Ap-horizon ranges between 12 and 15% (Vavříček et al. 2006).

In each locality working sectors were demarcated on prepared windrows according to the typical technology of windrow preparation. In total 6 working sectors were established in Špičák locality whereas 3 working sectors were established in Suchdol locality. Based on the planting of different forest tree species the working sectors were divided into regular experimental plots of rectangular shape where subsequently the point application of selected direct compound fertilizers was performed to each plant in the spring months of 2005. In each selected working

Table 1. Fertilizer rate applied to one plant (p.n. = pure nutrient)

Type of fertilizer and consumption		N (%)	N p.n. (g)	P_2O_5 (%)	P p.n. (g)	K_2O (%)	K p.n. (g)	CaO (%)	Ca p.n. (g)	MgO (%)	Mg p.n. (g)
Silvamix Forte	total	17.5	8.75	17.5	3.85	10.5	52.5			9	2.7
(5 tablets à 10 g)	water-soluble	7	3.5	7	1.54	8.5	42.5				
Silvamix R	total	10	5	7	1.54	18	90			7.5	2.25
(5 tablets à 10 g)	water-soluble	2.5	1.25	2.7	0.59	15.5	77.5				
Strom-Folixyl stimul	total	11	1.32	0.8	0.22	5.4	0.53	15.1	1.29	8.8	0.64
(8 tablets à 1.5 g)											
Calcic dolomite (80 g)	total							32.3	18.35	18.7	8.98
Nutrient consumption in spruce plant per year			0.23		0.03		0.09		0.09		0.01
Nutrient consumption in beech plant per year			0.5		0.01		0.24		0.52		0.07
Nutrient consumption in maple plant per year			0.95		0.14		0.73		0.57		0.1

sector five research plots were demarcated in total – four plots treated with fertilizers and one control plot. Standard fertilizer tablets Silvamix Forte, Silvamix R and Strom-Folixil and the sprinkling of calcic dolomite were applied to the particular microplots. The fertilizers of the Silvamix type represent classical NPK products, the Strom-Folixil fertilizers are an alternative containing growth stimulators. The point application of fertilizer tablets to the plant stem was used: they were incorporated into a depth of 3–5 cm to prevent the losses of fertilizing constituents due to the influence of biotic and climatic factors. Calcic dolomite was applied in the form of sprinkling to each plant individually. The amounts of products were applied according to the empirical criteria shown in Table 1.

Collection of soil samples and laboratory methods

Field works were always carried out at the end of growing season in September to October. In autumn 2004 soil samples were taken from demarcated microplots before the application of fertilizers. The influence of fertilizers on the soil environment was determined from samples taken in autumn 2007. Soil samples were taken in the form of an organo-mineral mixture from the rhizosphere always in two composite samples from each fertilization treatment and from control plots. In one composite sample the material from the root zone of 3 plants was taken. In Špičák locality 12 composite samples were taken from each fertilization treatment (including the control) while 6 composite samples were collected from each treatment in Suchdol locality. In both localities 90 composite samples in two series (2004, 2007) were taken. Laboratory works performed in an accredited laboratory of the Ekola Bruzovice, s. r. o. company comprised the analyses of active (pH/H_2O) and potential (pH/KCl) soil reaction using a pH-meter with a combined glass electrode (soil/H_2O or 1M KCl = 1:2.5), H^+ concentration on the principle of double pH measurement and available mineral nutrients (Ca, Mg, K) from Mehlich II extract by the method of atomic adsorption spectrophotometry. Phosphorus content was determined spectrophotometrically in the solution of ascorbic acid, H_2SO_4 and Sb^{3+}. Carbon contained in humus acids (hereinafter C-HS) was determined spectrophotometrically according to characteristic absorbances in pyrophosphate. Carbon contained in humic acids (hereinafter C-HA) and carbon contained in fulvic acids (hereinafter C-FA) were detected. Based on these data the C-HA/FA ratio was calculated (Vavříček et al.

Table 2. List of organically bound elements on the basis of C_{org} (%) [C-HA and C-FA (%); C-HA/FA (1)], C_{ox} (%) and N_t (%) [C:N (1)] for the soils of Špičák locality, the situation 4 years after windrow spreading and 3 years after application of fertilizer tablets

FT	C_{ox}	N_t	C:N	C-HS	C-HA	C-FA	C-HA/FA
Silvamix Forte	15.00 ± 3.95	0.67 ± 0.11	22.10 ± 3.34	–	–	–	–
Silvamix R	16.02 ± 2.58	0.67 ± 0.11	23.92 ± 0.97	–	–	–	–
Strom-Folixyl	13.10 ± 1.14	0.52 ± 0.05	25.32 ± 1.84	–	–	–	–
Calcic dolomite	14.73 ± 1.74	0.59 ± 0.12	25.66 ± 3.14	–	–	–	–
Control	17.24 ± 1.92	0.72 ± 0.09	23.99 ± 1.13	4.40 ± 1.04	2.84 ± 0.78	1.56 ± 0.28	1.79 ± 0.23

2006). Oxidizable organic carbon (C_{ox}) was determined by endothermic extraction in a chromium sulphate mixture. The combustion mixture was in excess, the unreacted residue was determined as "dead stop" by Mohr's salt titration. The Kjeldahl method was used to determine total nitrogen (N_t) (Zbíral et al. 1997; Libus et al. 2010).

Statistical evaluation

Differences in the values of determined soil characteristics for the particular localities and partial research plots were statistically evaluated by means of linear models using the parametric analysis of variance (ANOVA) or non-parametric Kruskal-Wallis (K-W) and Mann-Whitney *U*-test always at $P < 0.05$. Differences were evaluated not only among the treatments of fertilized microplots but also among untreated microplots on prepared windrows, left windrows and scarified intervening strips. Significance of the result of the analysis of variance was verified by the Fisher-Snedecor *F*-test. If the *F*-test result rejected the null hypothesis (H_0) about the consistency of variances, multiple comparisons were used for the detection of specific statistical differences. Potential correlativeness of acquired data samplings was examined by *t*-tests.

RESULTS AND DISCUSSION

The extreme measure of large-scale soil scarification in the eighties was one of the main factors leading to permanent destabilization of the ecosystem and soil productivity of the Krušné hory plateau. The experimental application of fertilizer tablets in these anthropically influenced conditions helps stimulate the balance of matter of top-soil horizons and the nutrition of successive stands.

Windrow spreading influenced mainly the content of soil nitrogen. Its soil content increased 1.2 to 1.5 times (up to 4 times in an extreme case) (Table 2) compared to scarified plots from untreated intervening strips (Table 3). A marked increase was measured on plots with a higher proportion of C_{ox} in windrows (Špičák locality). Total nitrogen currently reaches the level of very high reserves there (0.6–0.8%). It may indicate not only the potential of above-standard nutrition but also inhibition in hardly degradable intermediate products of humification. On plots with a lower content of C_{ox} the values are high (Tables 3 and 4) and 4 years after

Table 3. List of organically bound elements on the basis of C-substances (%), C_{ox} and N_t (%), one year after windrow spreading

Locality		Horizon	C_{ox}	N_t	C:N	C-HS	C-HA	C-FA	C-HA/FA
Špičák	intervening strips	Ap	10.73 ± 2.88	0.40 ± 0.23	38.13 ± 21.30	2.06 ± 0.00	1.06 ± 0.00	0.98 ± 0.00	1.08 ± 0.00
		Bs	2.64 ± 0.09	0.13 ± 0.01	20.41 ± 1.79	0.77 ± 0.00	0.01 ± 0.00	0.76 ± 0.00	0.01 ± 0.00
	windrows	Ap	13.65 ± 3.69	0.57 ± 0.10	24.41 ± 3.57	4.94 ± 0.60	3.54 ± 0.60	1.40 ± 0.10	2.54 ± 0.49
Suchdol	intervening strips	Ap	6.36 ± 1.86	0.27 ± 0.10	24.02 ± 2.63	1.71 ± 0.47	0.80 ± 0.24	0.90 ± 0.23	0.87 ± 0.04
		Bs	2.54 ± 1.37	0.10 ± 0.04	23.74 ± 3.91	0.65 ± 0.15	0.14 ± 0.07	0.51 ± 0.08	0.26 ± 0.10
	windrows	Ap	7.53 ± 1.39	0.29 ± 0.03	25.65 ± 1.78	2.91 ± 0.80	1.91 ± 0.76	1.01 ± 0.05	1.87 ± 0.67

C-HS – carbon contined in humus acid, C-HA – carbon contained in humic acid, C-FA – carbon contained in fulvic acid

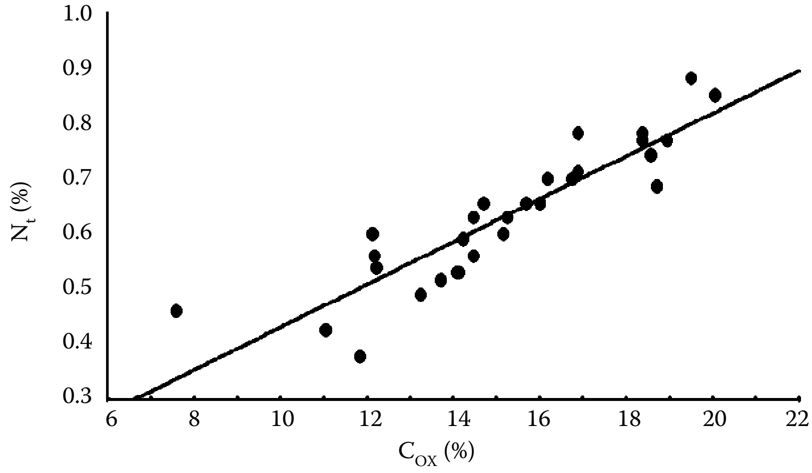

Fig. 1. Linear regression of C_{ox} and N_t in Špičák locality ($y = 0.0447 + 0.0387x$ ($r = 0.89$))

the windrow spreading, without further fertilization measures, from the trophic aspect they belong to the category of soils with a high reserve of total nitrogen (0.35–0.50% N_t).

The quality of organic matter plays an important role in the evaluation of nitrogen availability (Tables 2–4). Organic matter is the basic source of N-compounds (Ugolini, Spaltenstein 1992). Total nitrogen is in a strong correlation with C-substances at $P < 0.01$ (Fig. 1; Tables 5–7). Its negative correlations with the C:N ratio at $P < 0.05$ ($r = –0.78$) were determined in some cases (treatments in Suchdol locality). With increasing values of the C:N ratio nitrogen becomes deficient, indicating the worse quality of organic matters (Brookes et al. 1985). Its correlation with the C-HA/FA ratio was also proved on untreated plots ($r = 0.81$) (Table 11).

The relations between partial parameters are partly changed by the application of selected fertilizer tablets under the influence of soil chemistry and formulation of applied fertilizers (Tables 2 and 4). The correlation of total nitrogen with C_{ox} remains highly significant (Tables 5 and 6). The application of fertilizers decreases the C:N ratio but its negative correlation with N_t was not confirmed in certain cases. The content of total nitrogen in soil is not dependent on the C:N ratio when selected products are applied. On the contrary, a very strong relation was proved between N_t and C-HA ($r = 0.91$) (Table 11). The application of fertilizers increases total nitrogen at a simultaneous significant increase in C-HS. Fertilization influences the qualitative humus trend when at a simultaneous decrease in the C:N ratio the content of a high-molecular fraction of C-HA increases. Within decomposition processes of organic matter the point application of fertilizers has a positive effect on improvement in the quality of properties of organic matters.

In Ap-horizons of the studied spread windrows a moderate to marked increase (Tables 8–10) was observed in available phosphorus in both types dif-

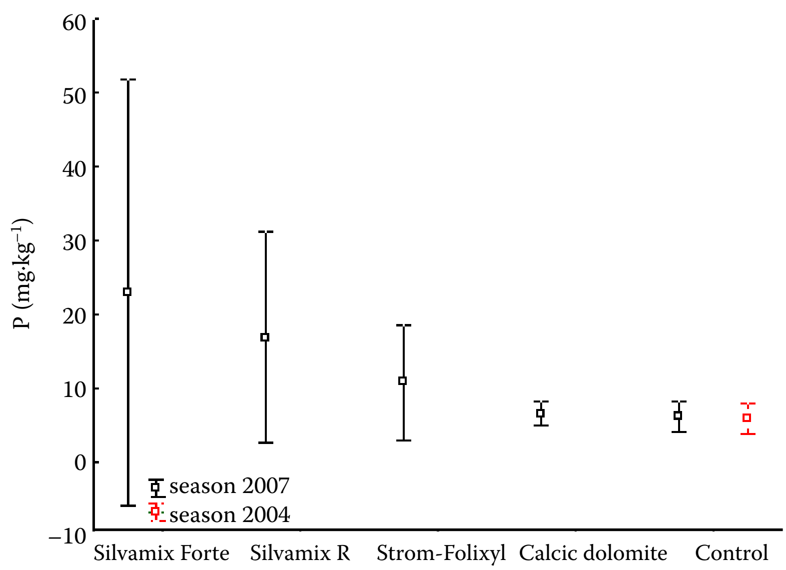

Fig. 2. The effect of point application of fertilizers on available phosphorus content in Špičák locality

Table 4. List of organically bound elements on the basis of C-substances (%) [C-HS, C-HA and C-FA (%); C-HA/FA (1)], C_{ox}(%) and N_t (%) [C:N (1)] for the soils of Suchdol locality, the situation 4 years after windrow spreading and 3 years after application of fertilizer tablets

FT	C_{ox}	N_t	C:N	C-HS	C-HA	C-FA	C-HA/FA
Silvamix Forte	9.17 ± 0.49	0.46 ± 0.05	20.41 ± 3.31	–	–	–	–
Silvamix R	9.84 ± 0.63	0.44 ± 0.03	22.21 ± 0.56	–	–	–	–
Strom-Folixyl	8.59 ± 0.72	0.43 ± 0.08	20.52 ± 2.93	–	–	–	–
Calcic dolomite	8.13 ± 0.93	0.39 ± 0.09	21.32 ± 2.14	–	–	–	–
Control	10.18 ± 3.64	0.43 ± 0.09	23.22 ± 3.17	2.17 ± 0.89	1.17 ± 0.51	0.99 ± 0.39	1.17 ± 0.06

C-HS – carbon contined in humus acid, C-HA – carbon contained in humic acid, C-FA – carbon contained in fulvic acid

fering in scarification technology and in the present content of humus substances. Its values rose up to twice in the profiles with a higher content of humus substances (20–30% C_{ox}). The increase has been substantial especially in the last two years (3–4 years after the windrow preparation). Currently, the values on plots without fertilization are at the level of good reserves in the range of ca 5–10 mg·kg^{-1}. Their range on fertilized plots is wider – 5–25 mg·kg^{-1}.

Phosphorus content is markedly higher on prepared windrows than at sites of intervening strips (0.5–2.5 mg·kg^{-1} P) (Table 8). The increase on plots with a lower proportion of organic matters in the profile was substantially smaller and it is currently at the level of low reserves (on average 3.2–4.2 mg·kg^{-1}) (Tables 9 and 10). The proportion of C-substances is important for phosphorus content and reserve in soil but it does not have a crucial influence on the trophic conditions of the studied edatope. In the four-year period the dynamics of reserves is highly variable while changes in the particular treatments are statistically insignificant. The application of fertilizers 3 years after the windrow spreading did not contribute to the stabilization of P reserves (Tables 9 and 10). The highest, often more than double increase in P in the soil environment over the studied period was determined in fertilizers of Silvamix type (Forte and R) (Fig. 2). Nevertheless, the existence of a strong bond of P with organic matters seems probable. Organic phosphorus, which is released by extracellular enzymes, accounts for a major part of its total content (Hýsek, Šarapatka 1998).

The soil environment at sites with a more friendly method of scarification (20–30% C_{ox}) shows higher values of potassium in spread windrows than in the remaining intervening strips where substitute stands have been left. The augmentation is significant and compared to the original low reserve of 40 to 80 mg·kg^{-1} (Table 8) available potassium attains the medium-high level (70–120 mg·kg^{-1}) (Table 9). In the fourth year after the windrow preparation there was a statistically significant increase from average 63 mg·kg^{-1} potassium to ca 85 mg·kg^{-1}. As this increase was also observed on control plots, it is to assume that the natural relation between decomposition and humification was stimulated significantly in the soil environment. Both values are optimum for the given site conditions and indicate a good reserve

Table 5. The matrix of the coefficients of correlation between selected chemical properties (N = 23) from fertilized microplots on spread windrows in Špičák locality examined in 2007 (the values exceeding the boundary significance $r > 0.43$ at $P < 0.05$ are printed in bold)

	pH/KCl	C	N	C:N	P	Mg	Ca	K
pH/H_2O	**0.95**	–0.33	–0.03	**–0.58**	–0.13	**0.58**	**0.82**	0.06
pH/KCl		–0.29	0.01	**–0.57**	–0.15	**0.54**	**0.81**	0.02
C			**0.87**	0.19	**0.44**	0.34	–0.20	0.37
N				–0.30	0.45	**0.53**	0.06	0.41
C:N					–0.06	–0.41	**–0.51**	–0.11
P						**0.52**	–0.24	0.26
Mg							**0.50**	0.39
Ca								–0.11

Table 6. The matrix of the coefficients of correlation between selected chemical properties (N = 12) from fertilized microplots on spread windrows in Špičák and Suchdol localities examined in 2007 (the values exceeding the boundary significance $r > 0.60$ at $P < 0.05$ are printed in bold)

Quality	pH/KCl	C_{ox}	N_t	C:N	P	Mg	Ca	K
pH/H_2O	**0.91**	**–0.71**	–0.22	–0.32	0.49	**0.65**	0.53	0.38
pH/KCl		**–0.65**	–0.06	–0.48	0.29	0.43	0.29	0.40
C			**0.65**	–0.04	0.00	–0.18	–0.34	0.01
N				**–0.78**	0.20	0.12	–0.12	0.03
C:N					–0.30	–0.34	–0.17	–0.06
P						**0.96**	0.32	0.37
Mg							0.43	0.40
Ca								–0.02

of potassium. In spite of the increasing values of available potassium in soil the present state of the sorption complex is more or less hazardous. It is in an environmentally dangerous relation to the magnesium content that has been rising due to repeated liming (Podrázský 1993). Particularly some parts of the plot where the values of the Mg:K ratio equalling 10 and more (Table 9) were determined are less suitable for the establishment of nutrient balance in the soil environment.

No such trend and dynamics were confirmed at sites with a lower content of humus substances in windrows (12–15% C_{ox}). The soil-forming substrate is the basic source of potassium in Suchdol locality, which is enhanced by denuded Bs-horizons. During weathering K^+ is released from silicate bonds into the soil environment. In soils with a lower content of humus substances its reserve is optimum also in intervening strips (Table 8). An increase after the windrow spreading is minimum and statistically insignificant with the exception of control plots. It is highly variable at the whole site. The values on control plots are currently at the level of lower to medium beneficial reserves (50–80 $mg \cdot kg^{-1}$).

The values of K are at a very good ratio to the content of magnesium bound in the sorption complex (Table 10). On control untreated and only prepared plots they are optimum at the total content of C_{ox} 12–15%, guaranteeing unproblematic nutrition of both macrobiogenic elements. Fertilizing constituents are an important stimulator of an increase in potassium content in soil and may be utilized mainly at sites with higher sorption capacity and higher content of humus substances. Among the selected fertilizers Silvamix R tablets have the highest proportion of K (18%). The other fertilizers contain a lower

Table 7. The matrix of the coefficients of correlation between selected chemical properties (N = 9) from control microplots on spread windrows in Špičák and Suchdol localities examined in 2007 (the values exceeding the boundary significance $r > 0.66$ at $P < 0.05$ are printed in bold)

Quality	pH/KCl	C_{ox}	N_t	C:N	P	Mg	Ca	K
pH/H_2O	**0.97**	–0.04	0.00	–0.24	0.45	**0.75**	0.65	0.20
pH/KCl		0.02	0.05	–0.15	0.51	**0.78**	0.66	0.21
C_{ox}			**0.97**	0.55	0.62	0.60	0.66	0.60
N_t				0.32	0.61	0.62	0.69	**0.71**
C:N					0.23	0.14	0.15	–0.04
P						**0.82**	**0.83**	0.41
Mg							**0.98**	0.57
Ca								0.65

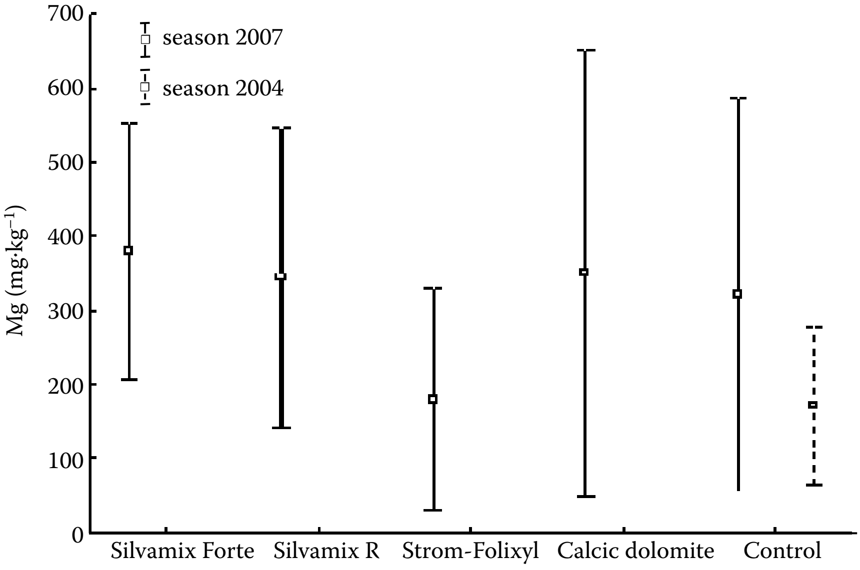

Fig. 3. The effect of point application of fertilizers on available magnesium content in Špičák locality

amount of K and different admixture of other nutrients. Silvamix Forte, containing 9.0% of magnesium, appeared to be the most hazardous fertilizer for the purpose of increasing the magnesium to potassium ratio. The increase in the Mg:K ratio (Tables 9 and 10) is more hazardous in this case than in calcic dolomite. But the Mg:K ratio has not resulted in the hazardous nutrition of any of the above-mentioned elements until now (Ulbrichová, Podrázský 2000; Olsson, Kellner 2002). At sites with a higher content of humus the statistically highest content of potassium was measured in treatments with Silvamix R (Table 9). After its application the values of K in soil are at the level of high limits ca 80 to 140 mg·kg^{-1}. They markedly contribute to optimization and equalization of the Mg:K ratio to the values of the 2:4 ratio (Table 9). Silvamix R eliminates the adverse influence of liming carried out in the past and stabilizes the treated sites toward above-standard nutrition conditions. Similarly, a high increase in potassium content in top-soil horizons was observed on plots with a lower content of C_{ox} (Suchdol) three years after the application of Silvamix R (Table 10). The use of this fertilizer enhances the K values to such an extent that they rise to the category of good to high reserves (80–115 mg·kg^{-1}). A low negative correlation with the increasing mineral proportion was proved only in the relationship between available potassium and mobile aluminium. The relationship of Al to univalent base cations is antagonistic. The risk of a negative effect of Al becomes higher at a decrease in the content of humus substances in forest soil, particularly at sites of the acid ecological series, which is promoted by acid geological and soil-forming substrates (Hruška 2002; Oulehle, Hruška 2005; Fenn et al. 2006).

Exchangeable magnesium and its most important fraction for revitalized plots are bound to the organomineral sorption complex (Fenn et al. 2006). In general, its proportion in the total amount of ex-

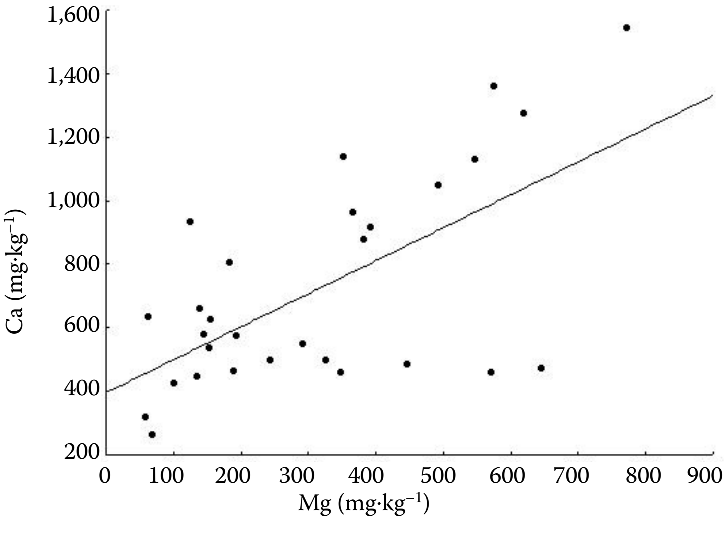

Fig. 4. Linear regression of Ca and Mg in Špičák locality
($y = 395.524 + 1.037x$ ($r = 0.63$))

Table 8. The values of active (pH/H_2O) and exchangeable (pH/KCl) soil acidity, analyses of macrobiogenic elements according to Mehlich II (mg·kg^{-1}) method one year after windrow spreading. Intervening strips – in the past scarified plots without the supply of humus substances, windrows – scarified plots enriched with organic matters from spread windrows

Locality		Horizon	pH/H_2O	pH/KCl	P	Mg	Ca	K	Mg/K	Ca/Mg
Špičák	intervening strips	Ap	5.14 ± 1.16	4.22 ± 1.38	1.50 ± 1.08	190.00 ± 49.40	2,381.33 ± 2,485.16	67.00 ± 31.59	3.89 ± 2.57	10.22 ± 8.90
		Bs	4.76 ± 0.26	3.91 ± 0.30	2.50 ± 1.47	39.67 ± 8.18	201.00 ± 40.77	21.67 ± 5.73	1.86 ± 0.11	5.13 ± 0.72
	windrows	Ap	3.92 ± 0.23	3.20 ± 0.17	5.80 ± 1.50	171.20 ± 76.88	643.50 ± 177.26	66.60 ± 5.84	2.49 ± 0.92	4.09 ± 0.84
Suchdol	intervening strips	Ap	4.67 ± 0.61	3.71 ± 0.59	1.33 ± 0.62	146.33 ± 116.92	377.00 ± 292.00	83.67 ± 35.65	1.50 ± 0.60	2.59 ± 0.34
		Bs	4.54 ± 0.17	3.97 ± 0.29	12.67 ± 14.10	35.33 ± 6.85	102.67 ± 5.79	34.33 ± 2.49	1.03 ± 0.20	2.98 ± 0.40
	windrows	Ap	4.09 ± 0.00	3.54 ± 0.03	6.25 ± 0.25	44.00 ± 12.00	214.00 ± 43.00	64.50 ± 3.00	0.69 ± 0.22	4.97 ± 0.38

Table 9. The values of active (pH/H_2O) and exchangeable (pH/KCl) soil acidity, analyses of macrobiogenic elements according to Mehlich II method (mg·kg^{-1}) for the soils of Špičák locality, the situation 4 years after windrow spreading and 3 years after application of fertilizer tablets (FT – fertilization treatment)

FT	pH/H_2O	pH/KCl	P	Mg	Ca	K	Mg/K	Ca/Mg
Silvamix Forte	4.08 ± 0.35	3.15 ± 0.33	23.00 ± 25.00	379.00 ± 150.77	771.67 ± 348.02	79.00 ± 10.91	5.12 ± 2.60	2.30 ± 1.07
Silvamix R	4.08 ± 0.07	3.10 ± 0.05	16.83 ± 12.37	344.67 ± 176.09	584.50 ± 210.72	120.17 ± 43.93	2.85 ± 1.17	2.09 ± 1.00
Strom-Folixyl	4.09 ± 0.18	3.15 ± 0.19	10.83 ± 6.74	178.83 ± 130.68	624.33 ± 201.96	70.17 ± 11.41	2.49 ± 1.71	5.20 ± 2.92
Calcic dolomite	4.16 ± 0.41	3.20 ± 0.33	6.60 ± 1.20	350.80 ± 218.32	797.80 ± 387.93	77.20 ± 9.06	4.35 ± 2.59	2.71 ± 0.72
Control	4.09 ± 0.28	3.22 ± 0.33	6.17 ± 1.86	320.83 ± 231.10	839.17 ± 367.82	86.00 ± 12.07	3.62 ± 2.57	3.23 ± 1.00

Table 10. The values of active (pH/H_2O) and exchangeable (pH/KCl) soil acidity, analyses of macrobiogenic elements for the soils of Suchdol locality according to Mehlich II method (mg·kg^{-1}), the situation 4 years after windrow spreading and 3 years after application of fertilizer tablets (FT – fertilization treatment)

FT	pH/H_2O	pH/KCl	P	Mg	Ca	K	Mg/K	Ca/Mg
Silvamix Forte	4.25 ± 0.24	3.32 ± 0.21	31.67 ± 32.97	225.33 ± 230.72	255.33 ± 83.52	73.00 ± 21.18	2.50 ± 2.06	2.56 ± 1.67
Silvamix R	4.16 ± 0.10	3.29 ± 0.08	11.67 ± 4.50	84.00 ± 24.66	266.00 ± 53.84	98.33 ± 17.99	0.84 ± 0.14	3.66 ± 1.67
Strom-Folixyl	4.19 ± 0.14	3.29 ± 0.14	4.33 ± 0.47	65.33 ± 13.52	315.67 ± 25.32	72.00 ± 7.07	0.91 ± 0.21	5.01 ± 0.92
Calcic dolomite	4.38 ± 0.11	3.49 ± 0.09	5.33 ± 1.25	108.67± 15.97	315.33 ± 52.32	75.00 ± 13.59	1.53 ± 0.45	2.90 ± 0.17
Control	4.07 ± 0.17	3.21 ± 0.14	3.67 ± 0.47	57.00 ± 3.74	262.67 ± 25.72	65.33 ± 13.47	0.92 ± 0.21	4.61 ± 0.35

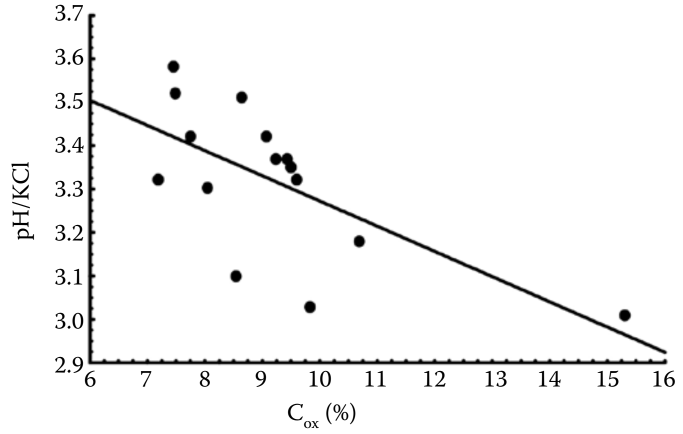

Fig. 5. Linear regression of C_{ox} and pH/KCl in Suchdol locality ($y = 3.853 - 0.058x$ ($r = -0.66$))

changeable cations of agricultural soil is about 10–30% (Vlček et al. 2007). In forest soils, which are acid as a result of natural acidification, its proportion in the cation exchange capacity (CEC) is lower. On plots with a higher content of HS, i.e. with higher acidity, its values are at the level of 2–7% of CEC. At sites with lower sorption capacity and higher proportion of mineral fraction its values amount to 2% of CEC.

The available fraction of magnesium increased after the windrow preparation. The increase was highly significant and its values are currently in the range of ca 100–450 mg·kg^{-1} on untreated control plots (Table 9). These values are high, showing an almost excessive level for the given site conditions without the effect of fertilization. Magnesium concentrations above 500–600 mg·kg^{-1} may cause nutrition antagonism, especially in relation to univalent cations. Its luxury nutrition in biomass was recorded particularly after the point application of calcic dolomite (Podrázský 1993; Remeš et al. 2005).

The measured values of Mg at sites with a lower content of HS in the soil profile are at an acceptable level of the medium reserve 55–120 mg·kg^{-1} (Table 10). A significant increase in these values was also observed there. Four-year dynamics is similar to that at sites with a higher proportion of organic matters in the profile. The present reserve of available magnesium in soil is the same as in mineral intervening strips. However, the balance reserve is much higher. It was approximately 300 kg·ha^{-1} before the windrow preparation while currently it is about 700 kg·ha^{-1} on the spread windrows (Vavříček et al. 2006).

All used fertilizers continue to influence magnesium content in soil three years after their application (Fig. 3; Table 9). Currently, the highest increase in Mg was proved mainly after the application of Silvamix Forte. The influence of Silvamix R and calcic dolomite on its increase in soil is also significant. The situation and dynamics are similar at sites with a lower content of HS, especially after the application

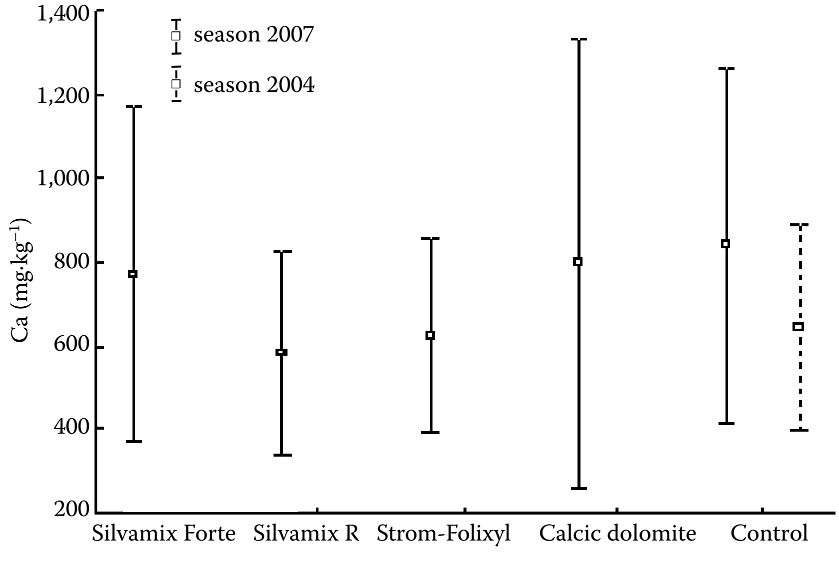

Fig. 6. The effect of point application of fertilizers on available calcium content – Špičák locality

Table 11. The values of the coefficients of correlation between soil reaction, selected mineral nutrients and extracted humus compounds (N = 9) from control microplots on spread windrows in Špičák and Suchdol localities examined in 2007 (the values exceeding the boundary significance $r > 0.66$ at $P < 0.05$ are printed in bold)

Quality	C-HS	C-HA	C-FA	C-HA/FA
pH/H_2O	0.14	0.21	–0.02	0.30
pH/KCl	0.23	0.28	0.09	0.30
C_{ox}	**0.94**	**0.91**	**0.96**	**0.80**
N_t	**0.92**	**0.91**	**0.92**	**0.81**
C:N	0.43	0.38	0.54	0.25
P	**0.82**	**0.86**	**0.67**	**0.90**
Mg	**0.73**	**0.77**	0.60	**0.78**
Ca	**0.76**	**0.79**	0.62	**0.85**
K	0.55	0.55	0.54	0.54
C-HS	–	**0.99**	**0.97**	**0.89**
C-HA	**0.99**	–	0.93	0.93
C-FA	**0.97**	**0.93**	–	0.76
C-HA/FA	**0.89**	**0.93**	**0.76**	–

C-HS – carbon contined in humus acid, C-HA – carbon contained in humic acid, C-FA – carbon contained in fulvic acid

of very finely ground calcic dolomite. At the present time it is also higher on control plots than in the initial phase before the above-mentioned technology was used and than in intervening strips.

Its invariable and significant correlation with calcium (Fig. 4; Tables 5–7) demonstrates that it comes from the aerial application of surface liming. C-substances participate in Mg^{2+} content rather in a negative bond that was not however proved statistically. Exchangeable magnesium bound in the sorption complex is mostly easily available to tree species and along with calcium it influences the exchange reaction of soil significantly. On the contrary, the exchange reaction of soil is in a significant negative correlation with the content of C-substances of soil humus (Fig. 5; Table 6). Its intensity is higher at sites with lower humus content in soil. The optimum Ca:Mg ratio of 4–5:1 in sorption bonds is sporadically to largely disturbed three years after the application of fertilizers in favour of magnesium (Tables 9 and 10). This ratio is mostly maintained on untreated control plots.

Calcium in fertilized treatments in Špičák locality is in a significant negative correlation with H^+ and in a positive correlation with the value of the exchange reaction of soil (Table 5). This relationship was not confirmed in Suchdol locality. The used fertilizers also have a significant influence on an increase in available calcium, and they currently increase the otherwise high values in control plots (Fig. 6). Different effects of various mineral fertilizers on an increase in Ca content in soil were not proved statistically. The average relatively highest reserve (650–950 mg·kg^{-1}) in Špičák locality was observed in Silvamix Forte and calcic dolomite (Table 9). Calcium content is high at sites with a higher content of humus substances and is probably influenced mainly by the aerial application of surface liming. The content of this nutrient is lower at sites with lower CEC (Table 10) and oscillates between ca 210 and 360 mg·kg^{-1}. Its contents can be classified to the categories of medium low to medium reserves. No correlations with the other parameters were proved. If the absence of C-substances was pronounced, no correlation between Ca content and the value of soil reaction was demonstrated (Table 6). The pH values are significantly higher at a lower calcium reserve compared to sites with higher humus content.

Humus sorption is significant and the application of mineral water-soluble fertilizers is efficient. Silvamix R was found to be the most efficient fertilizer. The ratio of true humus fractions to C_{ox} is high and their content is sufficient for the soil environment of forests (Hyvönen et al. 2000). The proportion of humus fractions C-HS in C_{ox} is comparable with the values of humification horizons H of intact profiles on control plots without fertilization.

The abilities of clay minerals to fix potassium diminish with the increased content of humus substances. The soil contents of potassium, phosphorus and calcium were increased significantly by fertilization. Their balance highly depends on organic matter dynamics. Humus fractions form coatings on mineral colloids and restrict the entry of K^+ and NH_4^+ ions (Priha, Smolander 1999). Potassium is present in soil in three basic forms that underlie its availability to vegetation. Exchangeable and water-soluble K is easily available to plants. Unexchangeable K is defined by 3 fractions (K bound in the crystal lattice of silicates, fixed into clay minerals and organic K) that are hardly available to plants (Purdon et al. 2004).

It is to suppose that the aerial application of surface liming may be one of the causes of imbalances in the availability of the studied bases. It mainly affected natural processes of humus formation in forest soils and disturbed natural bonds of mineral elements to organic residues (Podrázský 1992). Liming in synergy with mechanical scarification of top-soil horizons in the Krušné hory Mts. caused serious degradation of the edatope; nevertheless, the sequence of revitalization measures supported by the point application of fertilizers to forest plantations contributes to stabilization of the cycling of matter.

CONCLUSION

In the course of large-scale scarification the top-soil horizons were moved into line windrows in the Krušné hory Mts., which caused marked degradation of the soil environment. The present revitalization of the soil environment is based on the principle of spreading these man-made windrows. Experimental plots were established in localities affected by scarification; the organomineral material from windrows was superimposed on them and they were subsequently reforested with Norway spruce (*Picea abies* [L.] Karst.). In 2005 the point application of fertilizer tablets of Silvamix type in three treatments and calcic dolomite was performed into the rhizosphere of plants. On each plot of the spread windrow there were 4 treatments with fertilizers and 1 control plot. Before fertilization and after three years of the experiment soil samples were taken from the organomineral zone of the root balls of plants, and the condition of the soil environment on spread windrows and changes in pedochemical properties as a result of applied fertilization were evaluated.

Three years after the windrow spreading the content of the majority of soil macrobiogenic elements (N, K, Ca, Mg) is at the level of medium-high to high reserves, and only the low phosphorus reserves pose a certain hazard for the established plantation of Norway spruce (*Picea abies* [L.] Karst.). The organomineral substrate of spread windrows is a suitable growth environment for the root systems of target forest tree species. The proportion of humus substances is the most important factor in spread windrows from which the characteristics of the other parameters of soil are derived. Along with the higher proportion of humus substances in Špičák locality significantly higher reserves of major macrobiogenic elements (N, P, K, Ca, Mg) were determined.

The applied fertilizers of Silvamix type significantly increased the reserves of soil P, K, Ca, Mg and are a suitable means for the stimulation of spruce plantations in the restored environment of the Krušné hory Mts. The formulation of fertilizers declared by the manufacturer is evenly reflected in higher soil reserves of nutrients on fertilized plots compared to control plots. Silvamix Forte fertilizer tablets are the most complex fertilizer with the most balanced effects that significantly increases the reserves of soil phosphorus, magnesium and potassium. This fertilizer should be used to increase the reserve of soil phosphorus that may be deficient in conditions of spread windrows. Silvamix R is the most efficient fertilizer to increase potassium reserves. A positive effect of calcic dolomite on an increase in Ca and Mg content was observed while no such effect of this fertilizer on the other elements was recorded.

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