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Combined fertilizers versus dolomitic limestone: A comparative study from a forest habitat with Norway spruce

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Abstract

The research paper with character of case study deals with the influence of amelioration on soil as well as the Norway spruce nutrition and growth, with the focus on dolomitic limestone and combined fertilizer applications. The study was performed in the 7-year-old forest stand (Nízký Jeseník Mountains, Czech Republic, 100% Norway spruce, podzol, mor humus form, slightly undulated slope, 770 m a.s.l.). The soil properties (soil reaction, nutrient status, C/N ratio and cation exchange capacity), the plant nutrition, the plant biomass production and the health status were measured. Neither the expected significant increase in pH due to liming in the root zone nor the increase in calcium and magnesium in the soil was confirmed. In the dolomitic limestone treatment, the highest hydrolytic acidity reaching 260 $mmol_+$/kg, the worst development of assimilatory organs, the growth and health status of individuals were ascertained one year after the usage. The application of combined fertilizers resulted in the highest response in the needle biomass production (0.35 g/100 needles compared to less than 0.30 g/100 needles in the dolomitic limestone treatment), in the potassium and phosphorus nutrition status (suboptimal 4–4.5% of potassium in dolomitic limestone and the control treatment compared to optimal 5.5–7.5% in the combined fertilizers treatments) and simultaneously to the optimization of the health status. Specifically, in forest stands, the effect of dolomitic limestone is rather overestimated and furthermore, chemical amelioration requires the detailed knowledge of the forest site.

Key words: forest soil; acidification; reclamation practice; plant nutrition; nutrient antagonism

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1. Introduction

Soil acidification, defined as the decrease in the neutralization capacity (Merry 2009), is the process by which the base cation content is reduced and the acidic cation content is increased (Singh & Agrawal 2008). The alteration in soil chemistry originates from the contradictory effect of acidifying or alkalizing factors and the soil buffering capacity (Huang et al. 2014). In humid climate, in particular, soil acidification occurs through various natural mechanisms (Hruška & Ciencala 2005; Merry 2009). Numerous authors have attached minimal importance to natural acidification mechanisms in comparison with anthropogenic acidification (Ingerslev 1999; Ingerslev & Hallbäcken 1999), associated with the forest dieback linked to the acid deposition of atmospheric pollutants (Bäck et al. 1995) and inappropriate woody species compositions (Augusto et al. 2002).

Over the past several decades, the elimination of anthropogenic acidification in the Czech Republic has been predominantly based on aerial liming of forest stands (Klimo and Vavříček 1991; Kuneš 2003; Vavříček et al. 2005; Novotný et al. 2008; Kulhavý et al. 2009; Baláš et al. 2010; Šrámek et al. 2012).

However, the outcomes of the liming measures have frequently been inconsistent due to the specificities of forest habitats and forest soils in general (Kreutzer 1995; reviewed for Central-European conditions by Hruška & Ciencala 2005) and many authors have been concerned with the use of combined fertilizers rather than large-scale aerial liming (Lomský et al. 2006; Vacek et al. 2006) for the soil environment and mainly forest stand health and nutrition status improvement. Some of the studies mention a risk joined with forest soil amelioration and only short-term effectiveness in regards to forest production and health status, especially in large scale area applications.

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The application of combined slow-release mineral fertilizers on an individual basis to each transplant has been implemented by several authors (Kuneš et al. 2013; Pecháček et al. 2017). These fertilizers have demonstrated the impact on the optimization of the nutrient and health status of plants and the soil environment. The effect of fertilizers can be accentuated by using growth regulators (Simpson 1986; Seaby & Selby 1990), such as NAA Na^+, SNP Na^+ and IBA K^+.

The scientific treatise reflects on the effect of forest soil amelioration on the soil and the forest stands at the juvenile stage of planted Norway spruce (*Picea abies* [L.] H. Karst), focusing on a comparison of different ameliorative materials including combined fertilizers and dolomitic limestone. The hypothesis was based on the mentioned presumptions that dolomitic limestone is the less effective ameliorative material for soil amelioration, the plant growth as well as the health and nutrition status optimization compared to combined fertilizers. We presumed weak amelioration effect of the dolomitic limestone in contrast to combined fertilizers in the Norway spruce conditions with regards to pH and base saturation improvement nor nutrient status optimization.

2. Materials and methods

The case study study was performed in the 7-year-old forest stand (100% Norway spruce; Nízký Jeseník Mountains, Solná hora Mountain, Czech Republic; GPS coordinates 50.2095833N, 17.4506389E). The effects were tested for the presence of compound fertilizers with a specific composition of macronutrients (Table 1) and growth regulators and dolomitic limestone, compared to the control treatment.

Site Description (Table 2): The soil was covered by 100% with dominance of *Calamagrostis epigejos* (80%), *Avenella flexuosa* (30%), *Senecio Fuchsii* (10%) and bryophytes. The soil taxonomical unit was Entic Skeletic Podzols (Loamic) (IUSS Working Group WRB 2014) with the mor humus form of 6–8 cm thickness; 770 m a.s.l.; slightly undulated slope; N–W exposition (azimuth 285°); slope inclination 21%; annual mean precipitation 800 mm; mean air temperature 6.8 °C; annual mean soil moisture at 8 and 20 cm depth 27.8 % vol. and 27.4% vol., respectively; annual mean soil temperature at 8 and 20 cm depth 6.7 °C and 6.8 °C, respectively.

The soil is characteristic of the dominant podzolization soil-forming process on the shallow soil forming substrate of carboniferous graywacke mixed with clay shale partially metamorphosed to argillaceous schist inclined in angle of 60–75° to the soil surface with stoniness of 80–90% in the soil forming substrate, 50–70% in subsoil and 30–50% near the soil surface, which is very substantial for water regime and water drainage of the habitat in relation to water, as well as nutrient availability.

The rectangular research plot (120 × 150 m) was parcelled out to obtain six identical zones with the dimensions of 20 × 150 m containing 180 to 200 regularly distributed individuals per treatment. The treatment distribution on the plot was performed randomly. 160 g of the ameliorative material was applied individually to the soil surface within the crown projection on the individual basis (cca 80–120 cm in diameter which is cca 0.50 – 1.13 m^2 which would correspond to doses of 1.4–3.2 t of the ameliorant per ha) of each treated spruce in April 2014 and 2015.

The data collection was conducted in October 2015 via (1) mixed soil samples: 5 replicates per treatment (from the root zone under organic horizons; sampling

Table 1. Overview of the treatments and the composition of the tested ameliorative materials.

Treatment symbol	Trade mark / form[1]	Nutrient concentration [%]						Plant growth regulators[3]
		N	P	K	Mg	Ca	S	[%]
C	(Control)	—	—	—	—	—	—	—
SR50_s2	Silvamix®R50+s2	14.5 [1]	3.08	14.94	3.0	—	1.3	0.17
SR_s	Silvamix®R30+s	10.0 [2]	3.08	14.94	4.5	—	4.3	0.35
SR	Silvamix®R30	10.0 [2]	3.08	14.94	4.5	—	4.3	—
SA_s2	AGLUFORM®90+s2	19.0 [2]	3.08	9.13	2.88	—	4.0	0.17
DolLim	Dolomitic limestone	—	—	—	11.22	22.9	—	—

[1] 55% of N as urea-formaldehyde;
[2] 34% of N as urea-formaldehyde;
[3] when 0.17%: NAA Na+ 0.025%; DA-6 0.07%; SNP Na+ 0.05%; IBA K+ 0.025%;
when 0.35%: NAA Na+ 0.15%; DA-6 0.10%; SNP Na+ 0.075%; IBA K+ 0.025%.

Table 2. Properties of the soil profile in FS Solná hora Mountain within the different soil layers.

Soil layer characteristics	Sampling depth [cm]	Nutrient Content pH		Corg	Nt	C/N	P	Mg	Ca	K	CEC [$mmol_+$/kg]	BS
		H_2O	KCl	[%]			[mg/kg]					[%]
Organomineral	12–17	3.93	2.94	8.17	0.40	20	29	306	864	31	379.3	18.2
Eluvial	19–25	4.01	3.21	5.41	0.28	19	30	162	384	25	312.9	10.6
Spodic	34–44	4.21	3.72	5.16	0.27	19	73	75	216	20	271.5	6.4
Soil forming substrate	60–80	4.37	4.10	2.35	0.14	17	71	41	182	9	154.3	8.2
							2390*	21819*	46862*	19540*		

Corg – organic carbon; Nt – total nitrogen; CEC – cation exchange capacity; BS – base saturation; *total element content in substrate horizon using hydrofluoric acid.

depth 8–12 cm; below the crown projection); each replicate was composed of 3 individual samples; (2) mixed samples of needles: 3 replicates per treatment (from the upper third of the crown; from last two shoot year-classes separately as one-year-old and two-year-old needles); each sample was comprised of needles from 10 to 15 individuals; and (3) biometric data: 50 individuals per treatment.

The soil was analysed to assess the soil reaction (pH/H_2O and pH/KCl) in the soil: the eluent ratio of 1:2.5 (w:v); H^+ concentration [$mmol_+$/kg] using dual pH measurement (Adams & Evans 1990); available mineral nutrients (Ca, Mg, K) [mg/kg] from Mehlich II leachate (Mehlich 1978); P content [mg/kg] using spectrophotometry in a solution of ascorbic acid, H_2SO_4 and Sb^{3+}; organic carbon (C_{org}) [%] content spectrophotometrically in a chromosulphuric acid; total nitrogen (N_t) [%] content using the Kjeldahl method in % (Kirk et al. 1950); sulphur content [g/kg] using Regulation (EC) 2003/2003; mobile Al^{3+} content [$mmol_+$/kg] (Sokolov 1939); cation exchange capacity (CEC) [$mmol_+$/kg] using a summation method; base saturation (BS) [%] using the equation BS = (Ca^{2+} + Mg^{2+} + K^+) / CEC; the particular cation content using the equation Cmmol = Cmg / (M/Oxn), where Cmmol is the nutrient concentration in $mmol_+$/kg; Cmg is the nutrient concentration in mg/kg; M is the element molar mass, and Oxn is the nutrient oxidation number; the total element content in the soil substrate using mineralization in hydrofluoric acid. The total nutrient amount in the soil sample was reduced when C_{org} content exceeded 7.25% (12.5% of humus) using the equation $Sn = S_{N\text{-}anal} / \{1/[(100–H_{ox})/H_{ox}]·7\}$, where $S_{N\text{-}anal}$ is the nutrient content in mg/kg; H_{ox} is the humus content (C_{org} · 1.724) and 7 is the empirical value (Vavříček & Kučera 2017). The cation ratio in molar mass was used to obtain the Ca/Al and Bc/Al ratios where the Bc is the sum of base cations.

Biomass was analysed to assess the contents of macrobioelements [N in %; P, K, Ca, Mg, S in g/kg] (Strížová 2014). The nutrient ratio was used in one-year-old and two-year-old needles separately to obtain the Ca/Mg, K/Mg, Ca/N and Mg/N ratios. Biometry was assessed for annual height increment [cm], weight of 100 needles dried at 105 °C [g] and health status (1 – the best to 5 – the worst).

Data processing was performed with R software, version 3.6.2 (2019-12-12) and RStudio, version 1.2.5033. As graphical tools, we used the boxplot graphs (the boxes show medians and quantiles 0.25 and 0.75) and plotting with 95% confidence intervals in case of parametric multiple comparison, using ´plotmeans´ function from package ´gplots´ version 3.0.1.2. We applied the parametric and nonparametric analyses of variance (ANOVA, Kruskal-Wallis test, respectively), the parametric and nonparametric post-hoc analyses (Tukey HSD and nonparametric multiple comparison – nonparametric relative contrast effect with "Tukey" type of contrast, respectively). The normality was tested using Shapiro-Wilk test with $\alpha = 0.05$. The Principal component analysis (PCA) was performed with the ´vegan´ package version 2.4-3 after data standardization.

The abbreviations used in the graphical figures are as follows: Soil_C_N – C/N ratio; Soil_pH_H_2O and Soil_pH_KCl – active and exchangeable soil reaction, respectively; Soil_Ca, Mg, K, P, S, Nt, H – element content in soil; Soil_BS – base saturation; Soil_CEC – cation exchange capacity; Nutr_P, Mg, Ca, K, N, S, CaMg, KMg – nutrient content in needles and the nutrient ratio; HundrNeedl – weight of 100 needles; GrowAnn – annual height increment; Health – health status. The individual treatment variants in the experiment are labelled according to Table 1.

3. Results

The high variability of the soil properties resulted in the use of the nonparametric tests, which revealed the differences among all the parameters.

The soil reaction was strongly acidic for all the treatments, with the lowest acidity observed in C (Fig. 1; see also Table 3). The soil exchangeable reaction was the lowest for the DolLim, which also had the most variable values.

Based on Table 3, merely the control treatment (C) was typical of the statistically different (higher) values of

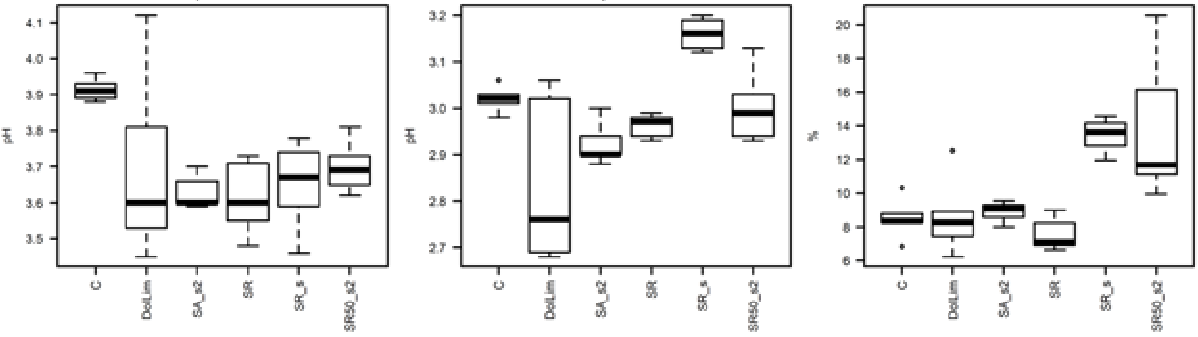

Fig. 1. Physical-chemical soil parameters in the individual treatments in the organo-mineral soil horizon (for the abbreviations, explanations see Materials and Methods Section and Table 1).

the active soil reaction while the exchangeable reaction was more diverse (the lowest in DolLim and the highest in SR_s). However, the values of pH/H_2O in the control treatment correspond with the natural situation in the soil (cf. with Table 2) while in other treatments the soil reaction was lower and close to the natural situation in the treatments SA_s2 and SR in case of pH/KCl.

Base saturation was the lowest in SR but statistically equal with C, DolLim and SA_s2 while the BS of the treatments SR_s and SR50_s2 was even above 10%. In all the treatments the BS was markedly lower than in the natural soil.

Using fertilizers, the nutrient content in the soil (Fig. 2, Table 4) was optimized or even supraoptimized in case of K and partially also for P while the Mg and Ca contents were suboptimal neither in the natural soil, typical of medium or high values nor in mineral (eluvial) horizon. The nitrogen content was the highest in DolLim (not significantly) and the lowest in SR – in all the treatments in high levels, which can be related to the elevated organic carbon content in the whole soil profile (Table 2), bonding nitrogen, as well as other nutrients via cation exchange. The C/N ratio was in the optimal values which could even seem to be untypical of the forest soil with Norway spruce. ANOVA revealed significantly higher C/N ratio in the treatments with DolLim and SR50_s2 which are still in the optimal values. Such high nitrogen content is probably due to high stoniness and organic matter infiltration to the depth, being characteristic of leptic soils. Acid cations, both H^+ as well as Al^{3+}, are highly concentrated with the significant differences in all the treatments with the highest values surprisingly in Dol-

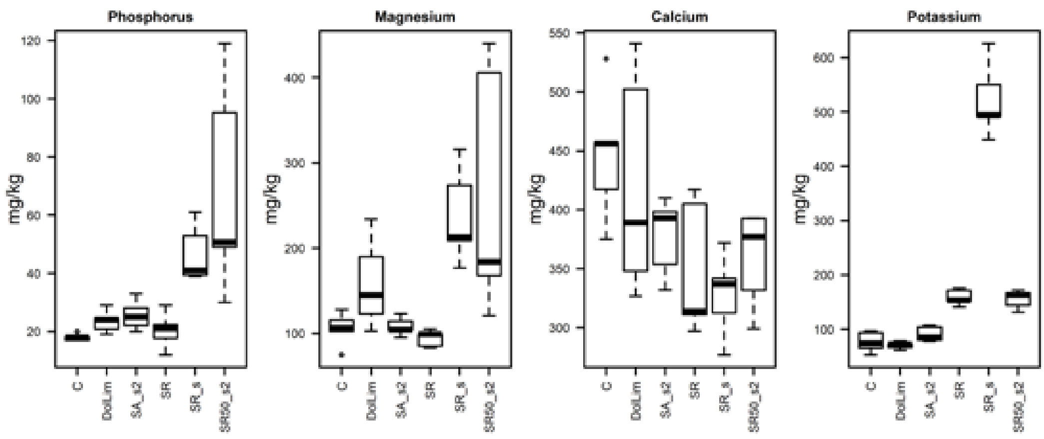

Fig. 2. Exchangeable nutrients content (Mehlich II) in the soil in the individual treatments in the organo-mineral soil horizon (for the abbreviations, explanations see Materials and Methods Section and Table 1).

Table 3. Mean values and results of statistical testing of the physical-chemical soil parameters in the individual treatments in the organo-mineral soil horizon.

Parameter	Units	C	DolLim	SA_s2	SR	SR_s	SR50_s2	Test Type	p–value
		mean							
pH/H_2O	—	3.91^a	3.70^b	3.63^b	3.61^b	3.65^b	3.70^b	aov	*
pH/KCl	—	3.02^{ab}	2.84^b	2.92^{ab}	2.96^{ab}	3.16^a	3.00^{ab}	aov	***
CEC	$mmol_+/kg$	387.2^a	417.1^a	337.9^b	386.2^a	366.8^b	314.7^b	aov	***
Bc	$mmol_+/kg$	33.0^b	36.0^b	30.0^b	29.4^b	49.4^a	43.4^b	K-W	*
BS	%	8.5^b	8.7^b	8.9^b	7.6^b	13.4^a	13.9^a	K-W	**

Superscripts following the mean values denote mutual statistical differences at α=0.05 on the basis of the post-hoc multiple comparison (test type: "aov" – parametrical ANOVA; "K–W" – Kruskal-Wallis test; p–values: " *** " < 0.001; " ** " 0.001–0.01; " * " 0.01–0.05; " . " 0.05–0.1). For the abbreviations, explanations see Materials and Methods Section and Table 1.

Table 4. Mean values and results of statistical testing of the nutrient content, the C/N ratio, the acid cations content and the Ca/Al and Bc/Al ratios in the individual treatments in the organo-mineral soil horizon.

Parameter	Units	C	DolLim	SA_s2	SR	SR_s	SR50_s2	Test Type	p–value
		mean							
P	mg/kg	18.0^b	23.5^b	25.6^b	20.4^b	46.7^a	68.8^a	K–W	***
Mg		105.5^b	158.9^a	108.2^b	94.3^b	237.7^a	263.7^a	K–W	**
Ca		446.7^a	421.4^b	377.4^b	348.8^b	328.1^b	358.7^b	aov	*
K		76.6^b	70.0^b	90.8^b	158.8^{ab}	522.2^a	155.5^{ab}	K–W	***
N	%	0.34^a	0.41^a	0.31^a	0.27^b	0.34^a	0.32^a	K–W	.
C/N	—	18.7^b	23.1^a	20.3^b	20.2^b	15.3^b	23.3^a	aov	***
H^+	$mmol_+/kg$	199.0^{ab}	226.9^a	206.8^a	187.5^b	189.2^b	184.5^b	K–W	*
Al^{3+}		155.2^a	154.4^a	101.0^b	169.5^a	128.2^{ab}	86.6^b	K–W	***
Ca/Al	—	0.14^b	0.14^b	0.19^a	0.10^b	0.13^b	0.21^a	aov	***
Bc/Al	—	0.21^b	0.23^b	0.30^a	0.17^b	0.39^a	0.52^a	K–W	***

Superscripts following mean values denote mutual statistical differences at α=0.05 on the basis of post-hoc multiple comparison (test type: "aov" – parametrical ANOVA; "K–W" – Kruskal-Wallis test; p–values: " *** " < 0.001; " ** " 0.001–0.01; " * " 0.01–0.05; " . " 0.05–0.1). For the abbreviations, explanations see Materials and Methods Section and Table 1.

Lim, and rather equal in all the variants with the lowest in SR50_s2, respectively.

The response of the trees within the treatments was marked more in the plant nutrition than in biometrics. The annual growth was evaluated as almost being equal (Table 5), nevertheless, the highest in SR_s and SR50_s2 treatments and the lowest in DolLim followed by the control. Needle biomass was diversified in one-year-old needles with the most massive biomass in SR_s and the least massive in DolLim. The DolLim treatment was also distinctive to the worst health status (decolouration, multicoloured needles, etc.).

Compared to the soil nutrient content, the plant nutrition was specific for rather normal data distribution (Table 6) and the significant differences among the treatments. In two-year-old needles the lowest and the highest content of P was in DolLim and SR50_s2, respectively.

Among the macrobioelements which were mostly contained in the optimal concentrations (mainly Mg, Ca), S and K occurred in the low limit values. The sulphur content was markedly lower (on the lower optimum limit) in one-year-old needles in C and DolLim treatments while potassium was deeply below the optimal values in both needle years in the treatments. The nitrogen content was the lowest in C and DolLim in both years of needles – in two-year-needles even below the optimum limit in DolLim. The nutrient ratio is rather in the optimal values except for DolLim in Ca/Mg due to the extremely low Ca content and except for C and DolLim in K/Mg due to the extremely low K content. The proportions of Ca/N and Mg/N were found as optimal, however significantly differentiated according to the treatment.

4. Discussion

Chemical amelioration, namely liming, substantially affects organic horizons especially on humus-rich sites (Nilsson et al. 2001; Hruška & Ciencala 2005). The alterations are performed mainly in soil organic layers in the sense of intensive mineralization and related biological/biochemical processes. In our study, we reached the lower pH values in all the treatments compared to the control one. The phenomenon of the distinct soil chemistry is not necessarily grounded in the treatments. However, we applied either alkaline or physiologically acidic ameliorative materials which can lead to the decrease of pH below surface organic layers for different reasons (Huettl & Zoettl 1993). As we sampled the soil in the rooting zone typical of the wide range of natural reasons for soil acidification, such as root exudates and nutrient uptake or also stimulation of plant metabolism using phytostimulants, which lead to lower pH/H_2O values.

The mean values of the soil exchange reaction properties showed the least favourable state in the DolLim, even with the respect to base saturation which was the highest in SR_s and SR50_s2 treatments. The nutrient contents in the soil (Fig. 2 and Table 4), as well as in needles (Fig. 3) indicated the antagonism of bivalent cations with potassium, which was significantly suppressed. Despite the assumptions stated in the literature (Formánek & Vránová 2003), the concentration of acidic protons and, notably, aluminium (Al^{3+}) was not reduced; this finding was accompanied by very strong hydrolytic acidity.

Our results demonstrated that there was an increased concentration of protons bound to the soil sorption complex (see also Fig. 1 and Table 4), which occupied over 90% CEC. After displacement from the soil sorption complex, these protons moved downwards into the root zone of the soil profile, increasing the risk of elevated aluminium mobility (see also Matzner 1992).

With regard to excessive soil chemistry alterations caused by chemical amelioration, the issues related to potassium are fundamental, yet little is known about them (Sardans & Peñuelas 2015). The presence of potassium in the soil can particularly be ensured by a targeted supply of fertilizers (cf. Fig. 2), and, in contrast, a high susceptibility to leaching by antagonistic bases can cause an imbalance in the soil trophic state in the root zone. This finding was also confirmed in the DolLim treatment, which had a significant excess of Ca^{2+} and Mg^{2+} and in SA_s2 due to the excessive dosage of a monova-

Table 5. Mean values and results of statistical testing of shoot biomass and the health status of the individuals in the individual treatments.

Parameter	Units	C	DolLim	SA_s2	SR	SR_s	SR50_s2	Test Type	p-value
				mean					
Annual growth	cm	54.3	48.0	57.9	55.9	62.2	62.1	K–W	.
Health	—	2.0[a]	2.7[b]	1.9[a]	1.6[a]	1.8[a]	1.7[a]	K–W	***
100 needles (1st yr)	g	0.30[b]	0.28[b]	0.32[b]	0.31[b]	0.36[a]	0.31[b]	aov	**
100 needles (2nd yr)	g	0.39	0.41	0.38	0.38	0.42	0.37	aov	> 0.1

Superscripts following the mean values denote mutual statistical differences at α=0.05 on the basis of the post-hoc multiple comparison (test type: “aov” – parametrical ANOVA; “K–W” – Kruskal-Wallis test; p–values: “ *** ” < 0.001; “ ** ” 0.001–0.01; “ * ” 0.01–0.05; “ . ” 0.05–0.1). For the abbreviations, explanations see Materials and Methods Section and Table 1.

Table 6. Results of the variance analysis of the nutrient content and the ratio in assimilatory organs separately for one-year-old and two-year-old needles of the individuals in the individual treatments at α = 0.05.

Needle Age	Parameter	P	Mg	Ca	K	N	S	Ca/Mg	K/Mg	Ca/N	Mg/N
1st yr	Test Type	aov	aov	aov	K–W	aov	aov	aov	K–W	aov	aov
	p–value	***	***	***	***	***	***	***	***	***	***
2nd yr	Test Type	aov	aov	aov	aov	aov	aov	aov	K–W	aov	aov
	p–value	***	***	*	***	**	*	***	***	**	***

(test type: “aov” – parametrical ANOVA; “K–W” – Kruskal-Wallis test; p–values: “ *** ” < 0.001; “ ** ” 0.001–0.01; “ * ” 0.01–0.05; “ . ” 0.05–0.1). For the abbreviations, explanations see Materials and Methods Section and Table 1.

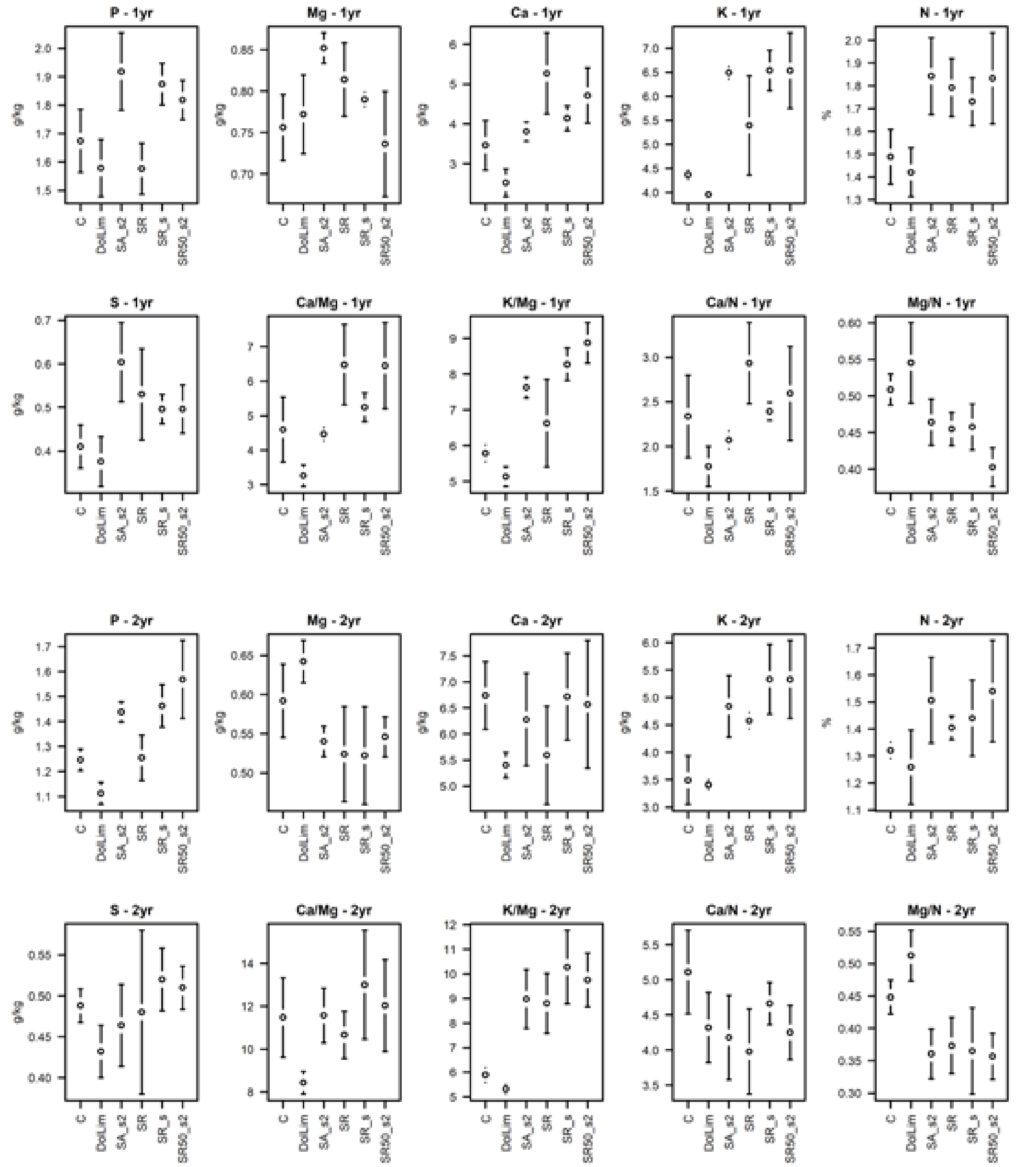

Fig. 3. Content of the nutrients in one-year-old needles (a) and two-year-old needles (b) in the individual treatments, expressed as the post-hoc multiple comparisons with the mean values and 95% confidence intervals. (for the abbreviations, explanations see Materials and Methods Section and Table 1).

lent ammonium ion (NH_4^+) with comparable lyotropic properties.

The Ca/Al and Bc/Al ratios contribute to the optimum level of soil chemistry in addition to absolute concentrations. These ones are at very low levels (far below 1, even below 0.2) in most cases, which has already been considered a significant environmental risk (Cronan & Grigal 1995; Vanguelova et al. 2007).

Nevertheless, the growth and nutritional responses of the stand are differentiated, although this ratio had not been significantly differentiated by any measure. On the contrary, the biomass production and the health status are the most favourable at treatments with combined fertilizers supplemented with the growth regulators. However, it should be noted that a considerable number of the literature (including that one listed here) operates with the Ca/Al and Bc/Al ratios in the soil solution, not the soil sorption complex. Nonetheless, according to the ratio law (Schofield 1947 in White 2006), it is also possible to take this ratio into account as a guideline for the assessment of soil chemistry.

The higher nitrogen content in values up to the supraoptimal concentration (Table 4) for DolLim can result in its accelerated mineralization and loss from the root zone not only of nitrogen, but also to equivalent loss of Mg, Ca and K (Huettl & Zoettl 1993). In soil chemistry with the C/N ratio lower than 30 and ammonia nitrogen form dominance, mineralization and nitrification lead to the increase in H^+ concentration and acidification of lower soil parts and heavy metals mobilization. Hence the amelioration on one side can be interlinked to the risk of nitrogen leaching (Huettl & Zoettl 1993; Vesterdal & Raulund-Rasmussen 2002), on the other side, it can precede nitrogen immobilization via biological fixation when the C/N ratio higher than cca 30–35 (Kai et al. 1969; White 2006).

The growth responses were not significantly different in the annual growth (Table 5) but showed the lowest effect in the DolLim treatment, which corresponded with the lowest vitality. The lowest biomass production in one-year-old needles was in DolLim treatment and the highest in SR_s treatment; in two-year-old needles the needles biomass production was not under the direct influence of the treatments as the needles developed before the experiment commencement.

The effect of treatments on the assimilation organ development was documented in the factorial plane (Fig. 4); in one-year-old needles, the vector of the HundNeedl categorical variable evinced a slight negative relation in DolLim, while in two-year-old needles, the same vector manifested no relation with the treatment.

The element content in biomass and nutritional balance were highlighted in Table 6 and Fig. 3, with a detailed representation of the graphical display of the PCA (Fig. 4). The cumulative proportion of explained variability with the first two principal components was 53.02% and 53.76% for dataset with one-year-old and two-year-old needles, respectively. In one-year-old assimilation organs (Fig. 4a), the Mg nutrient concentration was relatively unresponsive to Ca, and its intake was bound to the Silvamix compound fertilizers. In the C and DolLim treatments, potassium was at the lower optimum limit, especially in the two-year-old needles. In the two-year-old needles (Fig. 4b), the K/Mg nutrient ratio was completely antagonistic; Mg was forwarded at the expense of K, and Mg was distributed to a younger needle year-class (da Silva et al. 2011) while presenting a deficiency due to a suboptimal intake during the dry period throughout the vegetation. In connection with the initial natural (soil) conditions, the question is the legitimacy of forest ecosystem subsidy with magnesium, which was in the optimum values in the soil within the particular area and yet did not enter into nutrition due to the limited income in relation to its hydration requirements (Gransee & Führs 2013) that manifest during the short-term drought in the growing season. Thus, Mg is still within the optimum range in one-year needles while it is below the limit of deficiency in two-year needles. Furthermore, when using combined fertilizers, the K/Mg ratio was more optimized than C and DolLim.

Based on herein results and other works, fertilization and amelioration of forest ecosystems still seem to be questionable measures and many research studies provide contradictory interpretations, depending on forest management, as well (Podrázský 1994; Nilsson et al. 2001; Sjöberg et al. 2004; Remeš et al. 2005; Vacek et al. 2006; Vavříček et al. 2010; Šrámek et al. 2012). Compared to agrosystems, where liming is an essential part of the soil environment care (Goulding 2016), the overhead humus forms that are typical of forest soils (Klinka et al. 1990) represent a significant buffering factor (James & Riha 1986), as well as an important nutrient reservoir. From this perspective, it seems to be auspicious to repeat the investigation in the longer time horizon.

Soil buffering is a significant factor affecting the liming efficiency, especially treatments targeting elevated

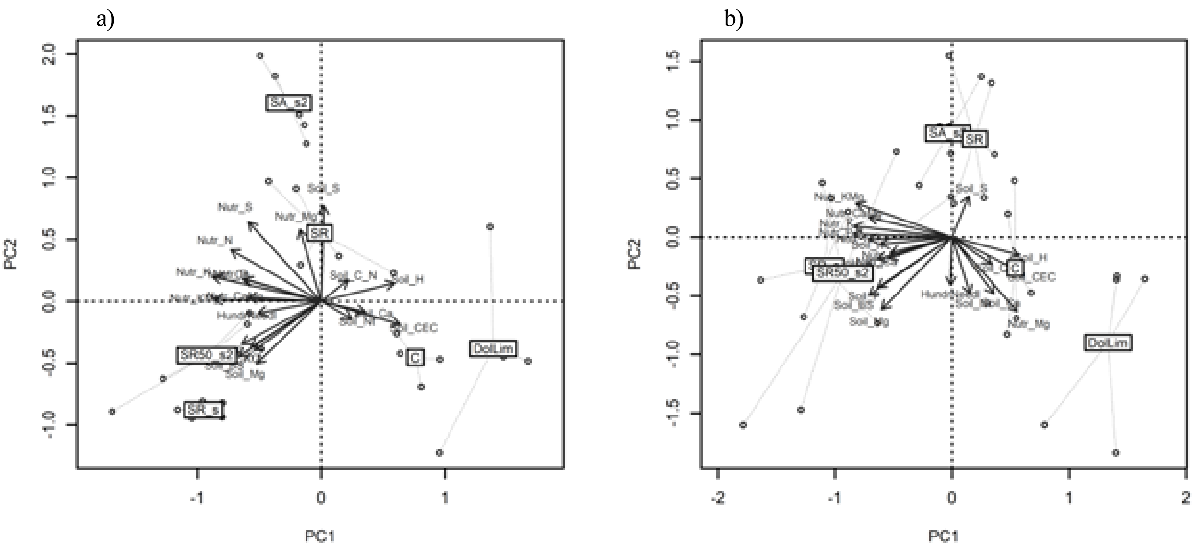

Fig. 4. PCA ordination graph illustrating the relation between categorical variables and the individual treatments (a): concerning the nutritional status of one-year-old needles; (b) concerning the nutritional status of two-year-old needles (for the abbreviations, explanations see Materials and Methods Section and Table 1).

mountainous locations with a naturally acidic soil reaction (pH/KCl even < 3.0) in the podzol soil zone. In organo-mineral and mineral horizons, the buffering capacity extends to the exchange zone and even down to the aluminium zone (Matzner 1992). Liming of these habitats results in conflicts related to the paradoxical application of the carbonate buffering zone in the naturally occurring buffer zone of iron and aluminium. Based on the frequently contradictory standpoints, the positive effect of liming (especially the air largescale) is not unquestionable. Hence, beside the routine soil parameters (pH, exchangeable nutrient content, base saturation), the nutritional status of the stand, the forest floor vegetation and site conditions should be individually examined.

5. Conclusion

The combined fertilizers use in the forest ecosystems was more effective for soil chemistry, the plant growth, as well as the nutrition status compared to the dolomitic limestone. Liming negatively affected the nutrient status of the soil and plants in comparison with the effects of compound fertilizers and caused disproportionate nutrient levels on soil colloids and nutritional imbalances.

Liming can significantly impact ion exchange processes in the soil sorption complex, the soil chemical status and, consequently, biological activities, mineralization processes, humus conditions, the plant nutrition and health statuses.

Soil chemistry, nutrition status and biometrical parameters of the Norway spruce individuals were positively affected using combined fertilizers. In addition to liming, there are alternative amelioration methods, e.g. the application of compound fertilizers containing a wide range of macrobioelements using nanotechnologies, such as growth regulators, for improving tree vitality, metabolism, nutrient uptake and root system development.

Individual application of ameliorative materials is optimal method for stands with juvenile development stage.

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List of Abbreviations

aov	– ANOVA
Bc	– base cations
C	– control
CEC	– cation exchange capacity
DolLim	– dolomitic limestone
GrowAnn	– annual height increment
Health	– health status
HundrNeedl	– weight of 100 needles
K–W	– Kruskal-Wallis test
Nutr_P, Mg, Ca, K, N, S, CaMg, KMg	– nutrient content in needles and the nutrient ratio
SA_s2	– AGLUFORM®90+s2
Soil_BS	– base saturation
Soil_C_N	– C/N ratio
Soil_Ca, Mg, K, P, S, Nt, H	– element content in soil
Soil_CEC	– cation exchange capacity
Soil_pH_H_2O and Soil_pH_KCl	– active and exchangeable soil reaction, respectively
SR	– Silvamix®R30
SR_s	– Silvamix®R30+s
SR50_s2	– Silvamix®R50+s2