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Effects of magnesite fertilization on soil properties and nutrition status of weakened Norway spruce stands in the Śnieżnik Massif of Polish East Sudety Mountains

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Abstract

The aim of this study was to assess the effects of the magnesite fertilization, 6 years after its application. The magnesite fertilizer was applied in amount of 2,000 kg·ha^{-1} in 2006. Fertilization covers the surface of 43 ha. Soil exploration in fertilized and unfertilized areas was carried out in August 2012. Needles and soil samples were collected for basic laboratory analysis. The effect of magnesite fertilization in soil was detected down to the B horizon. The principal excess of exchangeable magnesium (88%) was found in the surface organic horizon, while a substantial excess of total magnesium (57%) was detected in the top mineral horizon. The fertilization with magnesite caused the decreasing: acidity, ratio of calcium to magnesium in the absorption complex, supply of calcium in soil. Additionally, the effectively an increased magnesium supply in soil and in the needles of the investigated spruce stands was noted. Research study confirm the usefulness of ground magnesite in elimination the deficit of magnesium in soils and needles of spruce stands in the Śnieżnik Massif for an extended period of time. Magnesite fertilization at low doses may bring beneficial, quick effects to the health condition and productivity of spruce stands growing on soils well supplied with nitrogen.

Keywords: spruce stands decline; soil properties; magnesite fertilization, nutrition status of spruce

Introduction

Norway spruce is one of the principal species in Poland and neighboring countries, where it provides substantial quantities of valuable wood (Fober 2007, Vacek et al. 2003). The process of spruce monoculture decline has been occurring over large areas in all elevation zones of mountains in Poland (Modrzyński 2003, Małek et al. 2014, Błońska et al. 2015) and other central European countries (Vacek et al. 2013 and 2019). This process has accelerated up to achieving a dramatic rate in the 21st century, especially after 2004 year. Many studies have shown that pronounced yellowing of older foliage in spruce growing on acidic soils is related to a magnesium deficiency (Małek 2010). Magnesium is required for chlorophyll and protein synthesis. A substantial proportion of the total magnesium is involved in the regulation of cellular pH and the cation-anion balance. In most cases, growth is depressed and visual symptoms of magnesium deficiency occur when the proportion of magnesium in the chlorophyll exceeds 20–25% (Marschner 1995). A study on the temporal and spatial development of magnesium deficiency in forest stands in Europe, North America and New Zealand was performed by Landman et al. (1997). The authors emphasized that the yellowing of foliage in spruce was noted on soils poor in base cations, especially magnesium, developed from base-poor parent materials. Magnesium content of parent materials for soil formation varies widely depending on the amount of magnesium containing minerals, such as muscovite, biotite, amphibole and olivine (Katzensteiner and Glatzel 1997). For agricultural soils a content of exchangeable magnesium in excess of 20–30 mg·kg^{-1} seems to be sufficient for crops (Scheffer and Schachtschabel 1989). Magnesium deficiency in Norway spruce (*Picea abies*) below values of 20 mg·kg^{-1} in forest soils of SW Germany was found (Katzensteiner and Glatzel 1997). The research conducted in 2005 by Januszek et al. (in print) allows stating that the dying of spruce stands in the Śnieżnik Massif was associated with the fertility of the forest sites. Strongly weakened spruce stands were found on poor Haplic Podzols, developed from the Śnieżnik gneiss, affected by a severe magnesium deficit. Spruce stands not showing clear symptoms of declining were found mostly on Dystric Cambisols (Protospodic) that developed from mica schist, which were better supplied with magnesium. The concentrations and values of nutrient ratios in soils and needles of the weakened spruce stands in the Śnieżnik Massif in 2005 indicated existed a deficit of magnesium. In order to improve the health condition of strongly weakened spruce stands in the Śnieżnik Massif, a single fertilization with magnesite in the amount of 2,000 kg·ha^{-1} was recommended.

The aim of this study was to assess the effects of the magnesite fertilization 6 years after its application. The following hypotheses were tested: 1) use of magnesite will change the chemical properties of the investigated soils; 2) application of magnesite will improve the nutrient status of tree stands.

Materials and methods

Characteristics of the research area

The study area is located in the Śnieżnik Massif (south of Poland) (Figure 1). The Śnieżnik Massif create a form where the ridges of various lengths and heights are spread from the highest, centrally located point in all directions. The Śnieżnik (1425 m above sea level), rising 100–200 m above the surrounding hills, serves as the central point (Migoń 1996). Essentially, there are two metamorphic rock formations present in the research area: the Stronie formation and the Gierałtów-Śnieżnik formation. The Stronie formation is primarily composed of mica schist and paragneiss. The Gierałtów-Śnieżnik formation is represented by plagioclase and microcline gneiss rocks, known in the literature as the Śnieżnik gneiss (Frąckiewicz and Teisseyre 1977). Strongly weakened spruce stands were found on poor Haplic Podzols. The spruce stands not showing clear symptoms of weakening were found on Dystric Cambisols (Protospodic) which were better supplied with magnesium (Januszek et al. 2020). The total annual precipitation for the Międzygórze station (Figure 2) fluctuated from 1,279 mm in 2001 to 843 mm in 2008. The average annual temperature for the Bolesławów station in the years 2001–2006, 2009, 2010 and 2012 was below 7.5°C and fluctuated from +7.4°C in 2002 to +6.0°C in 2010 (Figure 2). The average monthly temperature in the research area fluctuated from -6.6°C in January of 2010 to 19.5°C in July of 2006. The characteristics were calculated based on average monthly temperatures for the Bolesławów station and monthly precipitation totals for the Międzygórze station for the years 2001–2012, obtained from Poland's Institute of Meteorology and Water Management in Warsaw. The values of the Schmuck's J moisture indicator, modified by Durło (2011), fluctuated from 288 in 2003 to 2,006 in 2010 (Figure 3). The values indicated the conditions were very dry in 2003, dry in the years 2004–2005 and 2008, moderately damp in 2006 and 2011, damp in 2007 and 2009, very damp in the years 2001–2002 and extremely damp in 2010. The Vogel-Daniels habitat dryness index (Durło 2011) indicated the site conditions in the research area were extremely dry in 2006, moderately dry in 2004 and 2005 and exceptionally damp in the years 2009–2012 (Figure 4). Characteristics showed worse moisture conditions and lower air temperatures in 2004–2005 and better moisture conditions and higher temperatures in 2009 and 2011.

Soil sampling and analysis

The study was conducted from August to October 2012. Fertilized plots (FP), number 1–5, were established in divisions 240 and 241 (Figure 1). The plots were fertilized manually with ground magnesite in the amount of 2000 kg·ha^{-1} during the period from July to August of 2006. The magnesite originated from the Braszowice-Grochowa Massif. The magnesite contained: Mg 25.89%; C 11.47%; Fe 0.93%; Ca 0.28%; Mn 359.6 mg·kg^{-1}; Ni 304.1 mg·kg^{-1};

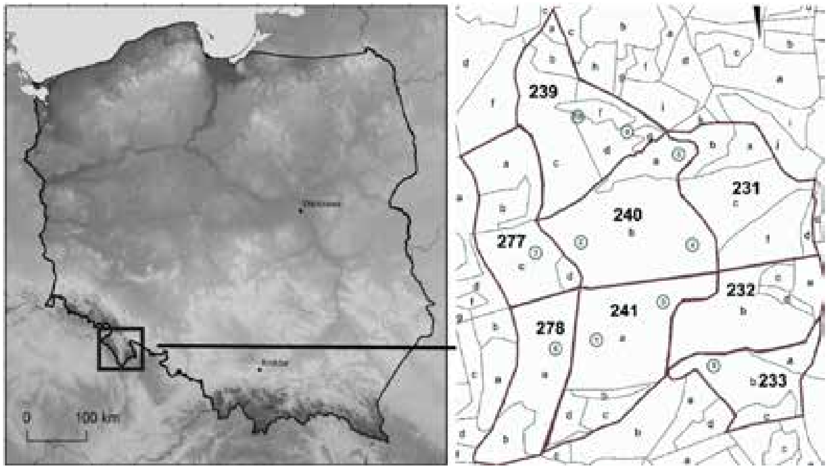

Figure 1. Distribution of study plots in the Śnieżnik Massif (plots 1–5 after fertilization, 6–10 control plots), South Poland

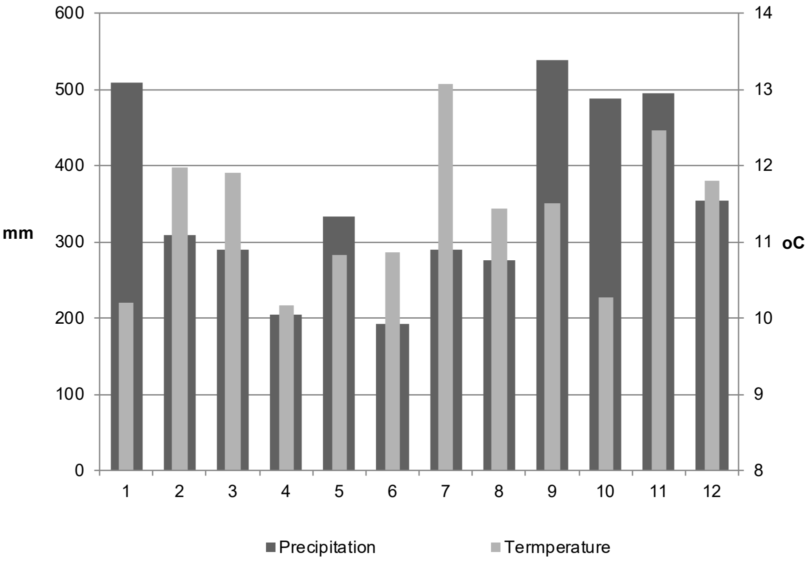

Figure 2. Total rainfall from May to July for Międzygórze station and average monthly temperature for months from May to July for Bolesławów station in years from 2001 (1) to 2012 (12)

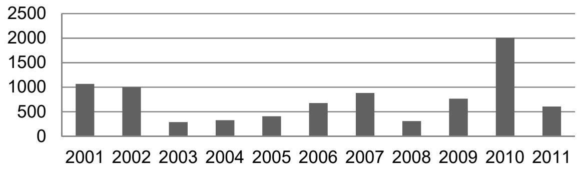

Figure 3. The value of the wetting coefficient of Schmuck, modified by Durło (2011), calculated on the basis of monthly and annual rainfall amounts for the Międzygórze station in 2001–2011

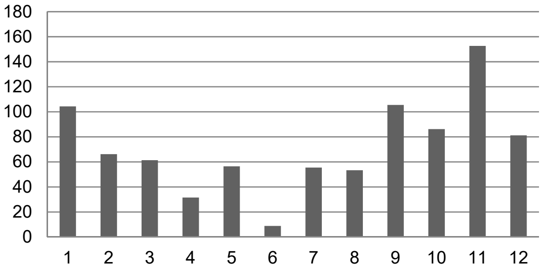

Figure 4. Values of Vogel-Daniels coefficient calculated on the basis of average July temperatures for Bolesławów station and total rainfall in July for Międzygórze station in the years from 2001 to 2012

Table 1. The soil sampling and soil analysis

Soil sampling	Laboratory analysis
From each plot, soil samples from 4 pit with dimensions 20×20 cm and 40 cm depth were collected. The soil samples from three soil horizons were taken: horizon I – organic O without litter; horizon II – first mineral horizon A, AE or E to 25 cm depth; horizon III – second mineral horizon Bfe, Bh, Bhfe from 25 to 40 cm depth. In total, 120 soil samples were collected for laboratory analysis. Using a cylinder with a diameter of 28 cm the organic horizon (O) and mineral horizon up to 25 cm deep was collected from each plot. The air-dry mass of mineral particles (<2 mm) were determined.	pH was analyzed in distilled water and 1 M KCl using the potentiometric method. Exchangeable acidity (H_{H+Al}), aluminium (H_{Al}) and hydrogen (H_H) were determined by the Sokołow method and available phosphorus by Bray-Kurtz method. The hydrolytic acidity was estimated by the Kappen method. The sum of basic cations (BC) was determined after extraction in 1M ammonium acetate by inductively coupled plasma spectrometer ICP OES iCAP 6000 Series Thermo Scientific. The sorption capacity (CEC_e=BC+H_{H+Al}) and base saturation (BS %=BC/CEC_e*100) were calculated. Total nitrogen and carbon content were determined by LECO analyzer with calculation of the C/N ratio. In the soil samples after mineralization the concentration of macro- and selected microelements (B, Ca, Cd, Co, Cr, Cu, Fe, K, Mg, Mn, Mo, Na, Ni, P, Pb, Zn) were determined.

Table 2. The needles sampling and needles analysis

Needles sampling	Laboratory analysis
The needles were collected from one felled average tree on each research plot. Three samples of needles were obtained from each plot: 0.5-year-olds from 1 and 2 whorls (0.5/1+2), 0.5-year-olds from 7 whorls (0.5/7) and 1.5-year olds from 7 whorls (1.5/7).	Samples of needles after separation from the branches were rinsed with distilled water on a nylon sieve and then dried at 40°C. The needles were ground using a stainless-steel mill. Needle samples were tested for moisture by a drying-weight method at 105°C. The concentration of C, N and S was determined using the CNS 2000 Leco elemental analyser. To determine the concentration macro- and micronutrients, ground needles were mineralized in concentrated nitric acid. Their concentration was determined using an atomic spectrometer ICP-OE with inductively coupled plasma. The concentration of marked macro- and micronutrients in needles was converted into absolutely dry mass of needles after determining the water content in weight %. The analysis was based on 4 FPs and 5 CPs. FP number 4 was omitted from the analysis, which was due to a low, and clearly deviating, concentration of Mg in the needles 0.5/1+2, 0.5/7 and 1.5/7 of the investigated tree on the studied plot. The concentration was: 0.05%, 0.04% and 0.02% Mg of DM, respectively, of the concentration of Mg in the needles of trees from the remaining FPs.

Zn 7.0 mg·kg^{-1}; Cr 6.38 mg·kg^{-1}; Pb 0.45 mg·kg^{-1}. Its grain size was 0–2 mm. Unfertilized control plots (CP), number 6–10 were designated in neighboring subdivisions 233b, 239d, 239g, 277c, 278a (Figure 1). Studies were carried out on the circular plots. The size of a research plot depended on the slope of the terrain and the number of trees on the plot and varied from 0.05 to 0.12 ha. Table 1 shows the description of the soil sampling and the methods for the determination of selected soil properties. The soil samples with disturbed structure were air-dried and sieved through a sieve with mesh size ø = 2 mm. Selected properties were determined using methods widely used in soil research (Ostrowska et al. 1991, Procedure 1995). Table 3 shows the location and characteristics of research plots.

Table 3. Location and characteristics of research plots fertilized with magnesite (FP) and control plots (CP)

Plot number	Variant	Forest Division	GPS coordinates		Exposure	Slope	Altitude a.s.l.in m
			Latitude N	Longitude E			
1	FP	241a	50°12'52.6''	16°51'59.6''	E	19	980
2		240b	50°13'02.8''	16°51'55.4''	NE	20	970
3		241a	50°12'54.7''	16°52'11.9''	EES	16	950
4		240b	50°13'03.3''	16°52'11.9''	NE	18	960
5		240a	50°13'12.4''	16°52'14.5''	NE	12	870
6	CP	278a	50°12'54.4''	16°51'54.9''	E	19	1025
7		277c	50°12'59.1''	16°51'48.9''	E	18	1015
8		233b	50°12'46.9''	16°52'23.3	NE	21	865
9		239g	50°13'16.7''	16°52'10.2''	NEE	14	825
10		239d	50°13'16.3''	16°51'59.8''	E	18	895

Needles sampling and analysis

The needles were collected from one felled average tree on each research plot (October 2012). Needle collection methodology, preparation for analysis and analytical methods are listed in Table 2.

Statistical analysis

All calculations (mass and molecular ratios, and nutrient deposits per 1 ha) and graphs were prepared using Microsoft Excel and Statistica 10 software. Distribution of values of the investigated properties of soils and needles from the FP and CP plots were compared using the statistical tests in the Statistica 10 software. The normality of a variable distribution was checked using the Shapiro-Wilk test. The *t*-test for independent trials (with respect to groups) was used for variables having a normal distribution. The Mann-Whitney *U* test and the Kolmogorov-Smirnov test (non-parametric statistics) were used for variables not having a normal distribution.

Results

Properties of soils samples

Comparing FP soils to CP soils, significantly higher average values of pH were found in horizons I, II and III of FP soils. The average pH values were higher by 0.56 ($p < 0.001$), 0.16 ($p < 0.001$) and 0.23 ($p < 0.01$) pH units in H_2O, and by 0.48; 0.21 and 0.23 pH units in KCl ($p < 0.001$), respectively (Table 4). The hydrolytic and exchangeable acidity in the organic horizon of FP soils, in comparison to the organic horizon of CP soils, was found to be lower by 15.1 and 1.43 cmol(+)·kg^{-1} of soil, respectively (Table 4). The values of hydrolytic and exchangeable acidity in the mineral horizon (horizon II) of FP soils, compared to such a horizon in CP soils, were higher by 4.4 and 1.98 cmol(+)·kg^{-1} of soil, respectively (Table 4). A lower concentration of exchangeable hydrogen was found in horizons I and II of FP soils than in the same CP soil horizons. The concentration of exchangeable aluminum in organic horizon of FP soils was slightly lower, which was statistically not significant. In the horizon II the con-

Table 4. Selected physico-chemical and chemical properties of spruce stands soils after magnesite fertilization (FP) and in soils of control (CP)

Properties	Soil horizons	FP		CP		Properties	Soil horizons	FP		CP	
		Mean	*SD*	Mean	*SD*			Mean	*SD*	Mean	*SD*
pH in H_2O	I	3.92^{c}	0.35	3.36	0.13	pH in KCl	I	2.88^{c}	0.35	2.40	0.11
	II	3.74^{c}	0.14	3.58	0.13		II	2.78^{c}	0.21	2.57	0.17
	III	4.10^{b}	0.19	3.87	0.24		III	3.28^{c}	0.26	3.05	0.26
H_h [cmol(+) kg of soil^{-1}]	I	83.8^{a}	22.1	98.9	19.5	H_{H+Al} [cmol(+) kg of soil^{-1}]	I	8.81	3.76	10.24	1.39
	II	24.7^{b}	5.2	20.3	4.9		II	8.59^{b}	1.97	6.61	1.49
	III	22.4	6.6	23.2	10.2		III	7.93	2.17	8.09	2.97
H_H [cmol(+) kg of soil^{-1}]	I	1.56^{c}	0.83	2.35	0.56	H_{Al} [cmol(+) kg of soil^{-1}]	I	7.24	3.57	7.89	1.36
	II	0.23^{a}	0.16	0.33	0.15		II	8.36^{c}	2.05	6.28	1.54
	III	0.10	0.07	0.10	0.08		III	7.82	2.17	7.99	2.99
BC [cmol(+) kg of soil^{-1}]	I	15.80^{c}	17.31	4.08	1.53	CEC_e [cmol(+) kg of soil^{-1}]	I	24.60^{c}	15.72	14.33	1.69
	II	0.77^{c}	0.38	0.31	0.07		II	9.36^{c}	1.98	6.92	1.52
	III	0.36^{c}	0.15	0.24	0.06		III	8.29	2.21	8.32	3.02
BS [%]	I	56.75^{c}	20.68	28.13	8.75	Total C [%]	I	32.44	5.88	35.46	7.43
	II	8.55^{c}	4.64	4.58	1.18		II	6.36^{a}	1.64	5.02	1.47
	III	4.60^{b}	2.08	3.08	1.06		III	4.45	1.81	4.49	1.68
Total N [%]	I	1.497	0.245	1.609	0.302	C:N	I	21.7	1.4	21.9	1.2
	II	0.31	0.09	0.26	0.08		II	20.6	2.3	19.5	2.9
	III	0.20	0.09	0.21	0.09		III	22.2	2.7	20.3	3.8
Ca^{2+} [mg 100 g^{-1}]	I	57.3	27.0	50.8	27.0	Mg^{2+} [mg 100 g^{-1}]	I	103.09^{c}	92.46	7.7	2.2
	II	3.33	2.50	1.39	2.50		II	5.04^{c}	4.13	0.95	0.29
	III	2.70	2.32	1.18	0.37		III	1.46^{c}	0.79	0.69	0.25
K^+ [mg 100 g^{-1}]	I	32.8	8.2	30.4	7.0	Na^+ [mg 100 g^{-1}]	I	2.8	0.7	3.1	0.8
	II	5.76	1.84	4.82	1.48		II	0.95	0.31	0.80	0.25
	III	3.13	0.84	3.32	1.21		III	0.72	0.22	0.80	0.27
Avail. P [mg kg^{-1}]	I	17.4	9.1	16.6	3.4	Ca^{2+}:Al^{3+}	I	1.14	3.02	0.34	0.20
	II	11.2	10.4	11.6	9.5		II	0.023	0.023	0.013	0.009
	III	13.4	15.9	25.0	25.7		III	0.019	0.018	0.009	0.008
(Ca^{2+}+ Mg^{2+}+ K^+):Al^{3+}	I	7.42^{c}	20.32	0.53	0.25	Ca^{2+}:Mg^{2+}	I	0.68^{c}	1.04	3.84	1.21
	II	0.10^{c}	0.06	0.05	0.01		II	0.58^{b}	0.54	0.93	0.40
	III	0.05^{b}	0.02	0.03	0.01		III	1.40	1.43	1.14	0.66
Ca^{2+}:K^+	I	3.49	1.51	3.27	1.44	Ca^{2+}:K^+	III	1.85^{a}	1.70	0.84	0.57
	II	1.41^{a}	1.31	0.64	0.43						
%Ca in CEC_e	I	13.9	7.6	17.4	7.5	%Mg in CEC_e	I	38.4^{c}	23.1	4.4	1.1
	II	1.99	1.80	1.12	0.75		II	4.53^{c}	3.61	1.15	0.28
	III	1.72	1.64	0.87	0.69		III	1.51^{c}	0.77	0.71	0.18
% K in CEC_e	I	3.9^{b}	1.5	5.4	1.1	%Na in CEC_e	I	0.57^{c}	0.19	0.95	0.21
	II	1.59	0.43	1.80	0.40		II	0.45	0.13	0.51	0.16
	III	1.01	0.27	1.05	0.23		III	0.40	0.15	0.45	0.19
% H in CEC_e	I	7.8^{c}	5.32	16.4	3.2	% Al in CEC_e	I	35.5^{c}	18.1	55.5	9.8
	II	2.81^{b}	2.52	5.18	2.65		II	88.6	5.9	90.2	3.4
	III	1.36	0.84	1.48	1.51		III	94.0^{a}	2.5	95.5	2.2

Lower case letters in upper indices mean significantly different properties between plots at the level of probability: ^{a} $0.05 \geq \alpha > 0.01$; ^{b} $0.01 \geq \alpha > 0.001$ and ^{c} ≤ 0.001.

centration of exchangeable aluminum was significantly higher in soil of FP compared to CP soils (Table 4). The concentration of exchangeable forms of hydrogen and aluminum was at a similar level in horizon III of FP and CP soils (Table 4). Significantly ($p < 0.001$) higher concentrations of exchangeable magnesium were determined in the investigated horizons of FP soils, in comparison to horizons of CP soils, 13.4 times, 5.3 times and 2.1 times as much, respectively (Table 4). Again, comparing FP to CP soils, the concentration of total magnesium was significantly higher ($p < 0.05$) in horizons I and II: 4.1 times, 1.5 times as much, respectively; it was also higher in horizon III: 1.1 times as much, yet it was statistically not significant (Table 5). The concentrations of exchangeable and total calcium were higher in FP soils than in CP soils (Table 4 and 7). The amount of exchangeable Ca was 21.06 kg more (15.1% higher, Table 6) and the amount of total Ca was 36.38 kg more (9.6% higher) per 1 ha in soil horizons I and II together (Table 7). The concentration of total Ca in horizon III of FP soils was over twice as much. After 6 years from the application of the magnesite fertilizer, significant changes in the concentration of potassium and sodium, either in exchangeable or total forms, were not found (Table 4–7). The values of the (Ca+Mg+K):Al ratio for all horizons of FP soils were higher than in such horizons of CP soils. The ratio values in FP soil horizons were: 7.42; 0.10 and 0.05, respectively, and in CP soil horizons they were: 0.53, 0.05 and 0.03, respectively. The values of the Ca:Al ratio were also higher in horizons I, II and III of FP soils than in such horizons of CP soils, although the differences were statistically not significant (Table 4). The share of magnesium in the absorbing complex in horizons I–III significantly increased by: 34%, 3.38% and 0.8%, respectively (Table 4), as a result of fertilizer use. The share of exchangeable hydrogen in horizons I and II decreased by: 6.5% and 2.4%, respectively, which was also statistically significant. The share of exchangeable aluminum in organic horizon decreased by 20.0% (statistically not significant), and in horizons II and III the share of aluminum remained at a similar level (Table 4). Six years

Table 5. The total concentration of Al, macro- and some trace elements in soils of spruce stands (in mg·kg^{-1} of soil) after magnesite fertilization (FP) and in soils of control (CP)

Element	Horizons	FP		CP	
		Mean	*SD*	Mean	*SD*
Al	I	8988.40	883.34	7959.80	1532.99
	II	21921.0	2650.8	18210.0	2098.9
	III	24112.0^{a}	3265.8	19623.0	2498.3
K	I	2146.86	326.77	1902.56	393.34
	II	5576.00	573.11	5246.00	910.05
	III	5677.40	373.73	5107.80	679.18
Ca	I	937.52	286.33	872.56	333.36
	II	265.31	174.49	165.76	95.42
	III	327.80^{a}	157.48	132.38	113.88
Na	I	156.67	20.16	167.16	15.50
	II	263.78	29.35	266.98	35.11
	III	248.06	15.67	237.56	16.10
Mn	I	124.3	71.8	84.7	12.1
	II	138.1	27.6	101.0	28.4
	III	236.5	219.3	133.4	33.5
Zn	I	21.6	5.0	26.8	5.0
	II	25.9^{a}	6.5	16.0	4.2
	III	33.2^{a}	12.6	19.5	4.2
B	I	6.72	1.76	6.10	0.88
	II	11.30	1.64	11.99	2.15
	III	8.78	1.65	8.91	1.42
Ni	I	19.70^{a}	8.01	9.96	1.92
	II	2.75	0.9	2.61	0.65
	III	3.52	0.9	3.75	1.93
Pb	I	106.82	10.70	120.00	12.03
	II	53.67^{a}	11.23	36.07*	8.22
P	I	875.08	83.74	850.42	48.42
	II	630.89	120.93	402.18	120,93
	III	795.83	474.03	666.88	408.52
Mg	I	2089.45^{a}	876.72	507.32	65.10
	II	1173.13^{a}	137.02	777.72	48.81
	III	1211.30	165.57	1075.46	289.86
Fe	I	5732.40	1095.74	5475.80	2006.70
	II	10807.2^{a}	1383.7	6988.0	1956.8
	III	14283.0	2727.7	12901.8	6284.2
Cu	I	9.91	2.11	13.06	3.78
	II	4.94	2.39	2.78	1.16
	III	4.43	1.88	2.33	2.54
Co	I	1.30	0.27	1.07	0.22
	II	1.14	0.35	0.76	0.15
	III	1.27	0.34	0.95	0.31
Mo	I	0.94^{a}	0.04	1.43	0.45
	II	0.75	0.04	0.92	0.32
	III	0.79^{a}	0.10	1.17	0.37
Cr	I	15.85^{a}	6.33	6.77	1.84
	II	8.32	2.78	6.81	1.57
	III	8.81	2.86	9.02	3.98
Cd	I	0.20^{a}	0.04	0.28	0.06
	II	0.16	0.05	0.09	0.05
	III	0.28	0.06	0.19	0.15
Pb	III	52.4	8.9	47.0	19.8

Lower case letters in upper indices mean significantly different properties between plots at the level of probability: ^{a} $0.05 \geq \alpha > 0.01$; ^{b} $0.01 \geq \alpha > 0.001$ and ^{c} ≤ 0.001.

Table 6. Dry mass (DM) and chemical properties of soils after magnesite fertilization (FP) and soils of control (CP)

Properties	Horizons	FP		CP	
		Mean	*SD*	Mean	*SD*
DM [kg ha^{-1}]	I	229215	95913	264897	130676
	II	1018903	188350	1030809	214011
	I+II	1248118	262357	1295706	113904
H_{H+Al} [kmol(+) ha^{-1}]	I	20.19	8.45	27.00	13.56
	II	93.63	18.37	69.55	23.36
	I+II	113.82	21.64	96.55	14.88
H_{H} [kmol(+) ha^{-1}]	I	3.33	0.93	6.01	2.81
	II	2.03	1.08	3.49	1.11
	I+II	5.36^{a}	1.48	9.50	2.04
CEC_{e} [kmol(+) ha^{-1}]	I	57.98	31.78	37.10	17.39
	II	100.63	18.79	72.78	24.46
	I+II	158.61^{a}	42.06	109.88	12.93
Total N [kg ha^{-1}]	I	3501	1641	4145	1892
	II	3148	456	2714	931
	I+II	6649	1787	6858	1688
Ca^{2+} [kg ha^{-1}]	I	130.3	61.3	124.83	58.21
	II	29.88	17.91	14.29	4.27
	I+II	160.18	72.26	139.12	57.58
K^{+} [kg ha^{-1}]	I	75.79	33.79	75.99	30.72
	II	58.06	2.05	51.31	21.38
	I+II	133.85	33.48	127.30	20.75
H_{h} [kmol(+) ha^{-1}]	I	216.8	58.0	253.4	116.6
	II	262.6	54.8	212.4	68.7
	I+II	479.4	108.5	465.6	85.7
H_{Al} [kmol(+) ha^{-1}]	I	16.86	7.65	21.00	10.80
	II	91.62	18.87	66.06	22.23
	I+II	108.48	21.86	87.06	15.08
BC [kmol(+) ha^{-1}]	I	37.79	26.50	10.09	4.22
	II	6.99	0.71	3.23	1.15
	I+II	44.78^{a}	13.03	13.32	3.17
Total C [Mg ha^{-1}]	I	75.62	34.86	90.62	39.97
	II	65.91	6.90	52.63	18.94
	I+II	141.53	35.59	143.24	32.72
Avail. P [kg ha^{-1}]	I	3.79	1.80	4.36	2.19
	II	11.29	9.05	13.06	10.07
	I+II	15.08	10.45	17.41	8.70
Mg^{2+} [kg ha^{-1}]	I	264.51^{b}	199.74	19.01	7.17
	II	43.27^{a}	8.31	10.11	3.86
	I+II	307.78^{a}	202.13	29.12	4.07
Na^{+} [kg ha^{-1}]	I	6.52	3.32	7.98	3.25
	II	9.94	2.61	8.59	4.03
	I+II	16.46	5.71	16.57	3.07

Lower case letters in upper indices mean significantly different properties between plots at the level of probability: ^{a} $0.05 \geq \alpha > 0.01$; ^{b} $0.01 \geq \alpha > 0.001$ and ^{c} ≤ 0.001.

Table 7. Total content of Al, macro- and selected microelements in the organic horizon (I) and mineral horizon (II) up to 15 cm depth (kg·ha^{-1}) and in the horizons I and II together of the soils after fertilization with magnesite (FP) and soils of control (CP)

Properties	Horizons	FP Mean	FP *SD*	CP Mean	CP *SD*
Al	I	2035.9	843.3	2198.7	1319.1
	II	23044.1	3569.7	18853.2	4690.0
	I+II	25080.0	4359.5	21051.9	3656.5
K	I	403,38	116.87	513.01	271.14
	II	5637.83	722.65	5411.92	1411.52
	I+II	6041.21	776.87	5924.93	1253.23
Ca	I	214.26	104.45	213.90	102.23
	II	199.88	98.23	163.86	78.70
	I+II	414.14	172.06	377.76	149.38
Na	I	35.06	13.62	43.65	21.42
	II	269.77	28.48	273.10	53.28
	I+II	304.83	37.72	316.75	39.51
B	I	1.44	0.48	1.65	0.87
	II	11.82	2.33	12.72	4.87
	I+II	13.26	2.55	14.38	4.22
Zn	I	4.81	2.10	6.68	2.69
	II	26.70	8.26	17.00	7.35
	I+II	31.51	11.69	23.69	5.84
Ni	I	4.97	3.99	2.48	1.03
	II	2.42	0.55	2.70	0.90
	I+II	7.39	4.50	5.18	0.87
P	I	201.69	87.78	224.48	114.08
	II	644.81	133.90	429.45	204.25
	I+II	846.50	194.30	653.93	165.31
Mg	I	416.97^{a}	260.79	139.89	84.50
	II	1156.34^{a}	113.14	794.22^{a}	119.56
	I+II	1573.31^{a}	428.17	934.11^{a}	53.65
Fe	I	1313.7	628.1	1602.4	1328.5
	II	10932.4	1291.2	7328.0	3002.6
	I+II	12246.1	1820.1	8930.4	2947.1
Mn	I	26.55	14.64	22.70	13.26
	II	132.64	36.03	103.27	31.80
	I+II	159.19	45.34	125.97	28.46
Cu	I	2.36	1.45	3.18	1.48
	II	5.67	2.90	2.93	1.65
	I+II	8.03	4.79	6.11	1.81
Cr	I	3.84	2.75	1.71	0.95
	II	8.41	2.87	6.98	2.23
	I+II	12.25	5.17	8.69	1.65
Pb	I	24.40	10.23	31.34	15.88
	II	52.51	4.30	38.25	15.73
	I+II	76.91	10.96	69.59	13.06

Lower case letters in upper indices mean significantly different properties between plots at the level of probability: ^{a} $0.05 \geq \alpha > 0.01$; ^{b} $0.01 \geq \alpha > 0.001$ and ^{c} ≤ 0.001.

after the magnesite application no statistically significant changes in the share of exchangeable potassium in the absorbing complex were found; no clear trends for changes were present as well (Table 4). The concentration of total carbon in the organic horizon of FP soils, in comparison to such horizon of CP soils, was slightly lower (by 3.1%), which was statistically not significant. The concentration of C in horizon II was significantly higher (by 1.4%), and in horizon III no differences were found (Table 4). The concentration of total nitrogen in the investigated soils, fertilized soils and control soils, behaved similarly to total carbon (Table 4).

After magnesite fertilization, the concentrations of total nickel and chromium were higher in the organic horizon of FP soils than in the same horizon of CP soils (Table 5). The amounts of Ni and Cr determined in horizons I and II together, expressed per 1 ha, were greater by 2.21 and 3.56 kg, respectively (Table 7). The concentration of total molybdenum and cadmium was found to be significantly lower in the organic horizons of FP soils than in the organic horizons of CP soils (Table 5). A higher concentration of total iron was found in horizon II of FP soils than in horizon II of CP soils. The concentration of zinc was higher in both horizon II and III of FP soils compared to the same horizons of CP soils. Significant differences in the total concentration of copper, cobalt, manganese and boron were not found in the investigated soil horizons of FP and CP soils (Table 5).

Concentration of macronutrients and trace elements in the needles

The average concentrations of: C, K, Ca, Mg, Na and Fe were found to be higher, and the average concentrations of: N, P, S, Mn, Zn, Cu and B, were found to be lower in the needles 0.5/1+2 of FP spruce trees, in comparison to such needles obtained from CP spruce trees. However, the differences were not statistically significant (Table 8). In the needles 0.5/7 of FP spruce trees, in comparison to such CP needles, the concentration of magnesium was found to be significantly higher ($p = 0.019$), nearly 2 times as high: 0.127% and 0.068% Mg DM, respectively. The concentrations of the remaining investigated macroelements and trace elements in the needles 0.5/7, collected from FP and CP spruce trees, were similar and statistically not significantly different. Sodium concentration in FP needles was 36% less than in CP needles, but statistically the distributions were not significantly different (Table 8). It was found that in the needles 1.5/7 of FP spruce trees, in comparison

Table 8. The concentrations of macro- and some micronutrients in 0.5-year-old needles from 1 and 2 whorl (0.5/1+2) and 0.5 yearly from 7 whorl (0.5/7) and 1.5 yearly from 7 whorl (1.5/7)

Mean – mean value and *SD* – standard deviation; N – number of replications; lowercase letters in upper indices represent the differentiated average values between FP and CP and biger case letters between 0,5- and 1,5-annual old needless respectively of the same plots at the levels: 0.05 ≥ a, A > 0.01; 0.01 ≥ b, B < 0.001 and c, C ≤ 0.001.

Variant	Value	N	C	N	P	K	Ca	Mg	S	Na	Mn	Zn	Cu	Fe	B
			% dry mass							mg kg^{-1} dry mass					
							Needles 0.5/1+2								
FP	Mean	4	51.91	1.488	0.159	0.450	0.321	0.140	0.149	36.1	273.9	23.4	3.28	59.1	22.4
	SD		0.25	0.153	0.020	0.151	0.095	0.035	0.024	4.5	132.6	9.8	1.47	22.9	3.9
CP	Mean	5	51.54	1.588	0.189	0.426	0.315	0.110	0.159	35.2	384.9	26.7	6.51	41.8	26.3
	SD		0.22	0.192	0.045	0.151	0.087	0.031	0.016	5.3	82.1	11.0	3.60	26.4	8.3
							Needles 0.5/7								
FP	Mean	4	51.55	1.598^{A}	0.185^{A}	0.549	0.274	0.127^{a}	0.161	35.5	186.3	19.9	7.54	56.9	20.2
	SD		0.45	0.044	0.012	0.093	0.114	0.030	0.017	3.8	80.7	8.1	3.66	32.0	3.4
CP	Mean	5	51.54	1.664	0.188	0.554	0.244	0.068	0.160	55.7	205.4	20.2	6.80	41.5	20.2
	SD		0.34	0.238	0.031	0.173	0.099	0.024	0.016	34.2	81.6	9.9	2.18	16.3	3.0
							Needles 1.5/7								
FP	Mean	4	51.75	1.385	0.143	0.494	0.402	0.086^{a}	0.156	48.5	265.7	14.7	3.31	74.7	23.5
	SD		0.49	0.063	0.014	0.093	0.178	0.039	0.008	7.9	36.9	8.9	2.16	24.8	4.0
CP	Mean	5	51.86	1.461	0.161	0.475	0.379	0.038	0.159	46.9	274.4	12.7	5.04	70.7	24.9
	SD		0.54	0.213	0.047	0.109	0.083	0.012	0.015	7.8	37.4	5.3	1.69	37.0	4.3
							All needles together (N = 15)								
FP	Mean	12	51.74	1.491	0.162	0.498	0.333	0.117^{b}	0.156	40.1	242.0	19.4	4.71	63.5	22.0
	SD		0.40	0.128	0.023	0.113	0.133	0.040	0.017	8.1	93.0	8.9	3.14	25.7	3.7
CP	Mean	15	51.65	1.571	0.179	0.485	0.313	0.072	0.160	45.9	288.2	19.9	6.12	51.3	23.8
	SD		0.39	0.217	0.041	0.146	0.101	0.038	0.014	20.9	100.4	10.3	2.55	29.4	5.9

to such needles collected from CP spruce trees, similarly as in the needles 0.5/7, the concentration of magnesium was more than 2 times as high ($p = 0.02$) and the concentration of sodium was lower by 23% ($p = 0.066$). It was found that in all the FP needles taken together for analysis, compared to all the CP needles, the concentration of magnesium was significantly higher, on average 1.6 times as high ($p = 0.0058$). Simultaneously, the concentrations of other elements were lower, which was statistically not significant (Table 8).

Discussion

Assessment of soils condition after magnesite fertilization

Six years after fertilization with magnesite, a significantly higher concentration of exchangeable aluminum was found in the 1st mineral horizon (horizon II) of FP soils than in CP soils. Magnesite fertilization of the surface Oie horizon of the studied soils, under strongly acidic conditions, resulted in increasing of Mg concentration in the soil solution. Mg^{2+} cations displaced Al^{3+} from the exchange sites into the solution, and leached to the AE mineral horizon. At AE horizon Al displaced base cation from the exchange sites of this horizon. It was most likely the effect of fertilization with magnesite and the action of exchange reactions (McBride 1994), which may have delayed the effects of fertilization with magnesite. Significantly more exchangeable and total magnesium was found in the fertilized soils than in the control soils. That would imply that a small amount of magnesium was taken up by plants in the area, and also that a small amount of magnesium was drained with rainwater within a period of 6 years. The likely mechanism for binding Mg here was adsorption and possible diffusion of Mg to the precipitated solid of the amorphous polymer of aluminum hydroxide, which is created when acidic soils are limed (Augustin et al. 1997). The FP and the CP soil profiles contained relatively large quantities of total forms of C and N, but the quantities were not significantly different. However, a clear tendency can be observed that the soluble forms of C and N, present in soils fertilized with magnesite, were likely to move from the organic horizon down to the first mineral horizon. The decreased carbon content in the surface soil in this present study is an agreement with the result of early research (Chan and Heenan 1999, Ernani et al. 2004, Aye et al. 2016). The total amount of nickel and 60% of total chromium found in soil I horizon confirm a closer affinity of nickel versus chromium to organic matter and a greater mobility of chromium versus nickel (Kabata-Pendias 2011). The concentrations of investigated heavy metals in FP and in CP soils were lower than in the soils of the Karkonosze Mountains (Drozd et al. 1995). The concentrations indicate the heavy metal content was the one that exists naturally (Kabata-Pendias 2011).

Evaluation of the nutrition status of stands after magnesite fertilization

According to Zöttl (1990), sufficient concentrations of: N, P, K, Ca, Mg, Mn, Zn, Cu and B were found in the needles 0.5/1+2, collected from FP as well as CP trees. According to Mellert and Göttlein (2012), in the needles 0.5/7 of FP and CP stands the concentrations of nitrogen and phosphorus were found to be at the middle level of the normal range, the concentration of potassium was at the lower end of the normal range and calcium was in the hidden deficit part of the range. The concentration of magnesium in the needles 0.5/7 of FP spruce trees was in the upper part of the normal range and in the needles of CP trees the concentration represented a hidden deficit. According to Cape et al. (1990) the average concentration of sulfur in the needles 0.5/7 of FP and CP variants was at an optimal level. It was found that in the needles 1.5/7 of CP and FP variants the concentrations of nitrogen and potassium were at deficit levels while calcium was at the optimal levels, magnesium at a deficit level for growth in the CP variant and at middle levels for FP stands. According to Brække and Salih (2002) the concentration of nitrogen and potassium in the needles 0.5/7 of FP and CP spruce stands and the magnesium concentration in CP needles were at their pre-optimum levels, while the concentration of magnesium in the needles of FP stands and the remaining investigated elements in the needles of both groups of tree stands were at their optimal levels. Nutrition status is better reflected by ratios of nutrients contained in needles than by concentrations directly, because for optimal nutrition all fundamental nutrients are taken up in appropriate proportions with respect to nitrogen (Cape et al. 1990, Bræke and Salih 2002, Mellert and Göttlein 2012). Furthermore, ratio not only reflect nutrient balance, but they are also less affected by growth dilution, concentrations of nonstructural carbohydrates and aging processes (Flückiger and Braun 2003). The average values of the ratios of N:P, N:K in the needles 0.5/7 of both FPs and CPs, and the N:Mg ratio in such FP needles (Table 9), indicated an uninterrupted balance between these essential elements (Mellert and Göttlein 2012). Also, the average concentrations of phosphorus and potassium with respect to nitrogen, in the needles of both FP and CP stands, may be regarded to be almost optimal (10% and 33%) as interpreted by Bræke and Salih (2002). According to Mellert and Göttlein (2012) the average values of the N:Ca ratios exceeded the upper critical value in the needles of both FPs and CPs. The average concentrations of Ca with respect to the concentration of N in FP and CP needles exceeded the threshold value of 4% (Bræke and Salih 2002). According to Cape et al. (1990), the values of the N:Ca ratio in the needles 1.5/7 of FP and CP did not indicate risk of dying off for these stands. In the needles 0.5/7 FP the share of Mg with respect to N exceeded the optimal 4% threshold (Bræke and Salih 2002). The values of the ratio

Table 9. The average values of mass ratios and the equivalent ratio Ca:Mg in the needles of the spruce stands after fertilization with magnesite (FP) and control (CP)

Variant	Value	N	C:N	K:Ca	K:Mg	S:Ca	S:Mg	S:K	Ca:B	Ca:Mn	Ca:Mg	Mg:B	Mg:Mn	N:Ca	N:Mg	N:P	N:K	N:S
0.5 years old needles from 1 and 2 whorl																		
FP	Mean	4	35.2	1,46	3.68	0.51	1.15	0.35	149.5	14.4	1.49	63.2	5.66^{a}	5.02	11.37	9.45	3.52	10.06
	SD		3.8	0.46	2.53	0.19	0.44	0.09	58.0	8.6	0.65	16.9	1.60	1.75	3.90	1.10	0.91	0.66
CP	Mean	5	32.9	1.44	4.35	0.53	1.53	0.43	131.3	8.2	1.78	46.5	2.84	5.24	32.9	8.65	4.28	9.95
	SD		4.7	0.71	2.34	0.11	0.38	0.21	55.5	1.1	0.37	20.5	0.42	1.04	32.3	1.38	2.15	0.73
0.5 years old Needles from 7 whorl																		
FP	Mean	4	32.3^{A}	2.28	4.50	0.68	1.32^{a}	0.30	140.3	16.6	1.28^{a}	64.2	7.75^{a}	6.75	13.1^{a}	8.66	2.97	9.97
	SD		1.1	0.92	1.14	0.29	0.31	0,06	67.7	7.8	0.32	17.7	3.24	3.01	2.9	0.47	0.45	0.80
CP	Mean	5	31.6	2.85	9.48	0.77	2.59	0.43	124.7	12.0	2.15^{A}	34.9	3.44^{A}	7.95^{A}	26.9	8.86	3.31	10.38
	SD		5.6	2.11	5.57	0.38	0.90	0.21	58.3	1.2	0.25	15.3	0.69	4.11	9.6	0.49	1.43	0.89
1.5 years old Needles from 7 whorl																		
FP	Mean	4	37.4	1.39	6.44^{a}	0.46	2.10^{a}	0.33	173.1	14.7	2.86^{a}	37.2^{a}	3.14^{a}	4.13	18.8^{a}	9.75	2.88	8.88
	SD		1.6	0.53	2.11	0.22	0.85	0.07	78.2	4.8	0.60	17.8	1.08	2.09	8.1	1.24	0.56	0.52
CP	Mean	5	36.2	1.33	14.12	0.44	4.59	0.34	158.3	13.8	6.19	16.1	1.41	4.04	42.2	9.39	3.20	9.19
	SD		5.7	0.55	8.19	0.12	1.95	0.06	51.6	2.9	0.93	6.0	0.50	1.21	18.4	1.39	0.89	1.13
All Needles together																		
FP	Mean	12	35.0	1.71	4.87^{a}	0.55	1.52^{b}	0.33	154.3	15.2	1.88	54.9^{a}	5.52^{b}	5.30	14.4^{b}	9.28	3.12	9.64
	SD		3.1	0.74	2.19	0.23	0.68	0.07	63.6	6.6	0.88	20.5	2.78	2.41	5.9	1.02	0.67	0.83
CP	Mean	15	33.1	2.34	11.03	0.66	3.26	0.40	135.9	12.6	3.49	28.6	2.76	6.65	32.0	8.97	3.60	9.84
	SD		5.7	1.79	6.48	0.33	1.58	0.16	54.5	2.0	2.05	15.1	1.15	3.70	14.3	1.13	1.54	1.00

SD – standard deviation; N – number of replications; lowercase letters in upper indices represent the differentiated average values between plots, and binger case letters between 0,5- and 1,5-annual old needless respectively at the levels: 0.05 ≥ a, A > 0.01; 0.01 ≥ b, B < 0.001 and c, C ≤ 0.001.

of N:Mg in the needles 0.5/7 CP (26.9) indicated an unbalanced relationship between nitrogen and magnesium, exceeding the established uppermost value of this ratio equal 21.0 for Norway spruce in Central Europe proposed by Mellert and Göttlein (2012); whereas the concentration of Mg with respect to N indicated an optimal share of Mg (4.1%) according to the data established for spruce in the Nordic countries (Bræke and Salih 2002).

The average value of the ratio of N:Mg in the needles 1.5/7 of the CP variant, which equaled 42.2, indicated a heightened risk of dying off for these stands (Cape et al. 1990). The average values of the mass ratio of K:Mg (significant distributions in the needles 1.5/7: 6.44 and 14.12, respectively) do not indicate a heightened risk of dying off for these stands (Cape et al. 1990). The average values of the S:Mg ratio in the needles 1.5/7 CP, being at the level of 4.59, exceeded the threshold value (>3) due to deficit magnesium concentrations, and indicated a heightened risk of dying off for these stands (Cape et al. 1990). The FP and CP stands were also different in terms of the equivalence ratio of Ca:Mg, having significantly different distributions in the needles 0.5/7 and 1.5/7: 1.28 and 2.15, and, 2.86 and 6.19, respectively, which would indicate an emergence of an unbalanced relationship between Ca and Mg in CP needles. Larger values of the mass ratio of Mg:Mn were recorded in the needles of FP spruce trees than in the needles of CP spruce trees, with statistically significant differences in the needles 0.5/1+2, 0.5/7, 1.5/7 and all the needles together. Also, larger values of the ratio of Mg:B were recorded in FP needles than in CP needles, with statistically significant differences in the needles 1.5/7 and all the needles together. An analysis of the ratios of nutrients in needles allowed stating that what separates the investigated variants of the experiment (fertilized and not fertilized) best is the value of the mass ratio of Mg:Mn. In order to evaluate the risk of the emergence of damage symptoms in spruce stands in Western Europe, Cape et al. (1990) designed a risk index (RI) based on the amount of Ca (<0.3%) and Mg (<0.05%) contained in older needles, and on the value of mass ratios of S:Ca (>0.4), S:Mg (>3), N:Ca (>5), N:Mg (>30), K:Ca (>2) and K:Mg>15. Therefore, the risk index, or an indicator of the risk of spruce stand dieback would be enhanced by two additional criteria: in the needles 1.5/7, the equivalence ratio of Ca:Mg with a threshold value >3 and the mass ratio of Mg:Mn with a threshold value <2, while the Ca concentration would be skipped due to an excessively wide sub-range of Ca concentration considered as the optimum interval specified for coniferous species in the literature (Brække and Salih 2002, Cape et al. 1990, Mellert and Göttlein 2012). Table 10 showed calculated values of this index based on the average values of concentration of Mg and the abovementioned ratios of essential elements in the needles 1.5/7. Based on the evaluation so performed it may be concluded that the risk of the emergence of spruce stand damage in the areas fertilized with magnesite decreased by 55%.

Forest site condition in the Śnieżnik Massif

An analysis of atmospheric precipitation at the Bolesławów station suggests that moisture conditions in the research areas were worse before the application of fertilizer. The combination of drying soil and low pH has

Table 10. The modified risk index of threat to spruce stands (RI) (Cape et al. 1990) of fertilized plots (FP) and control plots (CP)

Variants	Criteria									RI [%]
	Mg <0,05	S:Ca >0,4	S:Mg >3	N:Ca >5	N:Mg >30	K:Ca >2	K:Mg >15	Mg:Mn <2	Ca:Mg >3	
FP	-	+	-	-	-	-	-	-	-	11.1
CP	+	+	+	-	+	-	-	+	+	66.7

a negative effect on the rate of *P. abies* root growth (Oren and Schulze 1989). Upon soil rewetting, root growth recovers much more slowly at low pH, a factor which may strengthen the effect of soil drying on element uptake (Oren and Schulze 1989). High concentrations of nitrogen determined in needles of the tree stands researched, of both CPs and the FPs, may be an effect of a higher rate of mineralization of organic matter in the years 2009–2012 which occurred due to higher temperatures and precipitations. The higher concentrations of nitrogen may also provide evidence of the adaptation characteristics of Norway spruce regarding varying rate of uptake of nutrients under the conditions of disturbed balance between nutrients in an ecosystem. An increased deposition of nitrogen in a large part of Europe substantially increases nitrogen availability for plants and today N is in excess in many European ecosystems. Nitrogen deposition in many parts of Europe considerably exceeds calculated critical loads (Gundersen 1991, Rosén et al. 1992). Increased demands for nutrients, created as a result of an excessive nitrogen supply, may as well lead to nutrient deficiencies in trees. Deficiencies related to nitrogen deposition have been shown for magnesium (Evers and Hüttl 1990, Katzensteiner et al. 1992, Landman et al. 1997), potassium (Thelin et al. 1998) and phosphorus (Jonard et al. 2015, Veresoglou et al. 2014).

In the case of a low supply of Mg, the antagonistic uptake of Al may easily cause a deficiency of Mg, while a high supply of Mg rarely causes an inhibition of growth. Therefore, the stabilization of the root system by fertilization with Mg is often necessary in order to increase the tree stand vitality that was lost due to magnesium insufficiency in acidic forest soils (Raspe 1997). It was determined that increases in the diameter at breast height as well as in the volume of tree stands were becoming larger during the period after the application of magnesite fertilizer on strongly weakened spruce stands in the Śnieżnik Massif (Szydłowska and Socha 2014). The effect of fertilization increased with time and in each subsequent year after fertilization, tree increments on the fertilized areas as compared to the increments on the control plots were increasing. An increase in the diameter at breast height in the last 2 years was larger by an impressive 38% than in the period of 2 years prior to fertilization (Szydłowska and Socha 2014). The accelerated increase in diameter at breast height and of the volume of the researched spruce stands in the Śnieżnik Massif as a result of fertilization with magnesite may be an effect not only of enrichment of the researched soils in magnesium but also an effect of a probable increase in pH and an increased mineralization of organic compounds of nitrogen. According to Persson et al. (1990) liming increased the CO_2 evolution rate in needle litter, mor humus and mineral soil. Research performed by Silva et al. (2001a and 2001b) allows stating that magnesium was 100 times more effective than calcium in reducing aluminum toxicity for roots, suggesting a biochemical effect rather than an ion power that is related to calcium. Katzensteiner et al. (1995) concluded based on a number of field experiments in the Bohemian Massif that any Mg application to Mg-deficient forests improves Mg content of needles and that fertilization of forests on acidified soils is particularly efficient when the supply of nutrients is combined with pH stabilization. As a result of fertilization of the researched soils with magnesite, the concentration of calcium as well as its share in the absorbing complex in the top horizons of the fertilized soils decreased, while the concentration of Ca in needles increased and was not differentiated between the needles of trees of fertilized and control plots. This would not indicate an antagonism between Ca and Mg regarding an uptake by roots, but would confirm a passive way of uptake of calcium by Norway spruce trees (Sicard et al. 2006). Among the basic cations (K, Ca and Mg), Mg has the longest average circulation time in coniferous forests of the temperate climate zone, which is estimated to be 12.9 years (Cole and Rapp 1981). The rate of uptake of Mg is not only controlled by its concentration in the soil solution, but also depends on the concentration of the remaining ions. As soil pH deceases, the chemical activity of the aqueous solution of Al^{n+} inhibits the uptake of Mg^{2+} even more as an effect of cation antagonism (Feger 1997). This was confirmed by numerous field research studies that a direct toxic influence of Al in most habitats is not very likely (Feger 1997).

The decision on the kind of fertilizers to be applied in order to revitalize soils under tree stands should be preceded by a detailed examination of site conditions and nutrient status of tree stands. Should it be necessary to revitalize soils under spruce stands, attention should be paid to relationships between essential and trace elements, especially the relationship between calcium and magnesium in the soil as well as in the needles, due to small calcium requirements of coniferous species and passive uptake of calcium by plants. Based on a large set of forest production experiments, it has been concluded that forest fertilization is a simple and cost-effective silvicultural practice to increase forest yields (Saarsalami and Mälkönen 2001, Strengborn and Nordin 2008).

Conclusions

Research studies confirm the usefulness of ground magnesite in elimination the deficit of magnesium in soils and needles of spruce stands in the Śnieżnik Massif for an extended period of time and for increasing the productivity of spruce stands. After 6 years from the time of fertilization of the soil with magnesite fertilizer, by distributing an amount of 2,000 kg per 1 ha, the effect of fertilization that was detected reached down to the B horizon, inclusively (the 2nd mineral horizon down to the depth of 40 cm). The principal surplus of exchangeable magnesium (88%) was found in the surface organic horizon, while a substantial surplus of total magnesium (57%) was detected in the top mineral horizon. This would indicate that the releasing of magnesium ions occurred primarily in the organic horizon, and that the solubility of magnesite was weak, and that granules of magnesite were flushed down into the mineral horizon. Magnesite fertilization at low doses may bring beneficial, quick effects to the health condition and productivity of spruce stands growing on soils well supplied with nitrogen, where the ratio of C:N is below 30. The decision on the kind of fertilizer to be applied in order to revitalize soils under tree stands should be preceded by a detailed examination of forest site conditions and nutrient status of tree stands. Should it be necessary to revitalize soils under spruce stands – special attention should be paid to the ratio between calcium and magnesium in the soil as well as in the needles, due to the low calcium requirements of coniferous species and passive uptake of calcium by plants.

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