Relations between Site Characteristics and Spruce Stand Productivity

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Abstract

The aim of this study was to estimate the effect of topographic factors and soil properties on the productivity of Norway spruce stands in the Sudety Mountains, Poland. pH, organic C and N contents, hydrolytic and exchangeable acidity, cation contents (Ca^{2+}, Mg^{2+}, K^+, and Na^+), and soil texture were determined. We present soil properties from five parent material types and include separate analyses for the organic and humus-mineral soil horizons. Edaphic factors, together with topography, were significantly related to the Norway spruce site index. Soil properties from the humus-mineral horizon or the organic horizon (with features of topographic position included in the models) accounted for 67 % and 56 % of the site index variability, respectively. Elevation, the Al^{3+}/effective cation exchange capacity ratio, and C and K^+ contents were significant individual predictors of site index. A regression analysis indicated that elevation explains 49 % of the site index variability.

Key words: mountains forest sites; soil properties; site index.

Introduction

Site productivity is a quantitative estimate of the potential to produce plant biomass, and it may be assessed in several ways, usually using either geocentric or phytocentric methods (Skovsgaard and Vanclay 2008). Phytocentric methods are based on site index determination from the height and age of a tree stand. Geocentric productivity indicators are based on site properties, including climate, topography, or soil characteristics (Hägglund and Lundmark 1977). Topographic factors are used in combination with edaphic factors. Soil texture and nutrients levels are commonly used to estimate site index (Pacheco 1991).

Many studies have examined the relationships between site characteristics and productivity (Libiete 2008, Socha 2008, Afif-Khouri et al. 2011, Farrelly et al. 2011, Bösela et al. 2013). Kariūkštis and Juodvalkis (2005), Kuliešis et al. (2010) studied forest site productivity. Early studies presented single-variable relationships between soil or climate variables and site index. Recent studies have generally employed multiple regression techniques that present the ratios of environmental variables to site index (Socha 2012). Previous research examined the relationships between site productivity and topography, climate, and soil properties in lowland and mountainous areas. Sewerniak and Piernik (2012) estimated the impact of soil properties on the site index class of Scots pine on lowland sites, and found that pH_{KCl}, the fine fraction, K^+, and N, and $CaCO_3$ contents, and soil moisture conditions explained site index variability. Starr et al. (2005) estimated impact site, stand and climate factors on above-ground litterfall production. Site productivity in mountainous areas is highly dependent on climatic conditions, and it is affected by soil fertility and geological substrates. According to J. Socha (2008), the Polish West Carpathian Mountains site index is a function of elevation, aspect, slope, the size of the mountain massif, and the soil parent rock. Previous studies used a limited number of soil characteristics and geological substrates to analyze spruce stand productivity (Socha 2008, Bošela et al. 2013). Here, we present soil properties from five parent material types, and include separate analyses of the organic and humus-mineral soil horizons. To our knowledge, information on the relationships between site index and multiple soil properties from multiple geological substrates is very limited.

In Poland, the Sudety Mountains are more geologically variable than the Carpathian Mountains. There are magmatic, sedimentary, and metamorphic rocks of different geological ages. In addition, in the past, this area was subject to a strong anthropogenic impact, and it is dominated by spruce monocultures. Norway spruce (*Picea abies* (L.) Karst.) is the most economically important forest species. In recent years, Europe has had to deal with spruce dieback that was caused by complex biotic and abiotic factors that represent a specific chain-escalating disease process (Małek and Barszcz 2008, Zwoliński 2013).

One of the reasons for the spruce dieback is a change in soil chemistry. Acidification is one of the main processes that can affect soil productivity (Małek 2010). Periodically, extreme conditions or stress factors may appear which could initiate the weakening of stands (water deficit or mass gradations of insects). Now dying spruce cover areas located on both sides of the southern Polish border (Małek et al. 2014). Understanding the relationships between productivity and site factors will help predict risks and possibly prevent spruce dieback.

The aim of this study was to estimate the relationships between topographic factors, soil properties, and the productivity of Norway spruce stands. Our study evaluated which soil properties have the greatest impact on spruce productivity. We hypothesized that (1) edaphic factors, together with topography, explain Norway spruce site index variability in the Sudety Mountains, and that (2) the productivity of spruce stands depends on soil properties associated with the nutrient cycle and acidity.

Materials and Methods

The study was conducted in the Sudety Mountains in Poland. It included the Izerskie, Kaczawskie, Stołowe, and Złote Mountains, and the Ślęża and Śnieżnik Massif (Figure 1). In these research areas, Gleysol, Cambisol, Podzol, Stagnosol, and Regosol soils prevail (WRB 2006). Soils were created on a variety of geological substrates (granite, greenstone, sandstone, gabbro, and crystal rock) (Table 1). The study areas were covered by spruce stands without any symptoms of weakening.

In July 2012, field data were collected from 39 sample plots located in spruce stands aged 60–160 years. The studied stands were located between 440 and 1,180 m a.s.l. Experimental, circular in shape plots of 0.25 ha were established. At each experimental plot, a detailed description of the soil profile was performed, and samples were taken from each genetic horizon to perform a basic analysis of the soil properties to determine the soil subtypes. Samples from the organic horizon (average depth 0–10 cm) and the humus-mineral horizon (average depth 10–25 cm) were taken to determine soil chemical parameters (Table 2). Prior to the analysis, soil samples were air-dried for about 1 week at room temperature, and sieved through a 2-mm sieve.

Figure 1. Location of the research area

The diameter at breast height and tree height of all trees were measured in the experimental plots. Tree age was determined by a Pressler drill. Top height was estimated as the mean height of 100 largest diameter trees per ha. In particular, the number of trees of the sample plot corresponding proportionally to the plot area was used, e.g. 25 largest trees in the 0.25-ha plot. The locations of the sample plots were determined based on topography. The topography was described by elevation, exposition, and slope.

The values of site index for the particular sample plots were determined using the model of the site index system for Norway spruce stands in Poland (Socha 2011) (eqs. 1 and 2):

$$SI = H_1 \frac{8247.84 \cdot \ (T_1^{1,95817} \cdot R + 66568.71)}{T_1^{1,95817} \cdot (8247.84 \cdot R + 66568.71)} \qquad [1]$$

$$R = -15.03036 + H_1 + \sqrt{(-15.03036 + H_1)^2 + \frac{2 \cdot H_1 \cdot 66568.71}{T_1^{1.95817}}} \qquad [2]$$

where

SI is the site index; H is the top height of the stand (mean height of 100 thickest trees per hectare); and T is the stand age.

Statistical data analysis was performed using advanced analytics software package Statistica 10. In order to reduce the number of variables in statistical data set and visualize multivariate data set as a set of coordinates in a high-dimensional data space the PCA method was used. The PCA method was also used in order to interpret factors depending on the kind of data set. The multiple forward stepwise regression method was used to develop models describing the relationship between estimated values of site index to soil characteristics and topography.

Results

The organic horizon of the soils that developed on greenstone had the highest pH (average pH in H_2O of 4.2), the highest exchangeable Ca^{2+}, K^{+}, Mg^{2+}, and Na^{+} contents, the highest C content (average 30.77 %), and a high N content (average 1.53 %) (Table 3). The lowest

Table 1. Characteristics of research area

Plot	Mountains region	Elevation, a.s.l.	Exposition	Slope	Geological substrates	Soil type
1	Izerskie Mountains	622	NW	9	GR	Humic Gleysol
2	Izerskie Mountains	756	E	5	GR	Dystric Cambisol
3	Izerskie Mountains	795	E	15	GR	Haplic Podzol
4	Izerskie Mountains	798	S	10	GR	Dystric Cambisol
5	Izerskie Mountains	767	S	15	GR	Albic Cambisol
6	Izerskie Mountains	640	W	5	GR	Albic Cambisol
7	Izerskie Mountains	870	-	2	GR	Haplic Podzol
8	Izerskie Mountains	846	NW	5	GR	Gleysol
9	Izerskie Mountains	803	N	5	GR	Hyperdystric Cambisol
10	Izerskie Mountains	624	NE	12	GR	Haplic Podzol
11	Izerskie Mountains	857	E	7	GR	Histic Stagnosol
12	Izerskie Mountains	1139	E	2	GR	Regosol
13	Izerskie Mountains	1041	N	15	GR	Haplic Podzol
14	Izerskie Mountains	980	SE	6	GR	Haplic Podzol
15	Kaczawskie Mountains	512	SW	25	GS	Hyperdystric Cambisol
16	Kaczawskie Mountains	537	N	25	GS	Epidystric Cambisol
17	Kaczawskie Mountains	650	SW	20	GS	Hyperdystric Cambisol
18	Kaczawskie Mountains	640	SW	15	GS	Hyperdystric Cambisol
19	Kaczawskie Mountains	523	S	25	GS	Hyperdystric Cambisol
20	Kaczawskie Mountains	690	NE	18	GS	Hyperdystric Cambisol
21	Kaczawskie Mountains	440	W	10	SS	Hyperdystric Cambisol
22	Kaczawskie Mountains	620	NWW	31	SS	Haplic Podzol
23	Kaczawskie Mountains	630	NW	14	SS	Haplic Podzol
24	Kaczawskie Mountains	630	W	18	SS	Haplic Podzol
25	Stołowe Mountains	605	N	18	SS	Hyperdystric Cambisol
26	Stołowe Mountains	670	W	15	SS	Stagnosol
27	Stołowe Mountains	673	N	30	SS	Haplic Podzol
28	Stołowe Mountains	775	SW	25	SS	Hyperdystric Cambisol
29	Stołowe Mountains	708	SE	10	SS	Eutric Cambisol
30	Stołowe Mountains	717	N	8	SS	Hyperdystric Cambisol
31	Stołowe Mountains	670	W	30	SS	Haplic Podzol
32	Ślęża Massif	570	SE	25	GB	Hyperdystric Cambisol
33	Kaczawskie Mountains	547	SW	36	GB	Hyperdystric Cambisol
34	Śnieżnik Massif	785	SE	20	CR	Albic Cambisol
35	Śnieżnik Massif	1020	W	15	CR	Albic Cambisol
36	Śnieżnik Massif	1180	NE	7	CR	Stagnosol
37	Złote Mountains	1024	N	18	CR	Albic Cambisol
38	Złote Mountains	1080	N	10	CR	Haplic Podzol
39	Złote Mountains	1040	S	25	CR	Haplic Podzol

Geological substrates: GR – Granite, GS – Greenstone, SS – Sandstone, GB – Gabbro, CR – Crystal rock

Table 2. The sample parameters and methods of analysis

Analyzed parameters	Methods
soil pH	determined potentiometrically, in H_2O and 1M KCl dm^{-3} solutions, with soil-to-solvent proportion of 1:2.5 for mineral soils and 1:5 for organic soils
total C (C_T) and total N (N_T)	CNS 2000 Leco elemental analyzer with the calculation of the C:N ratio (in two horizons)
hydrolytic acidity (total acidity – Hh)	the Kappen method in the extract of 1M of calcium acetate
Exchangeable acidity (Hw), exchangeable aluminium (H_{Al}), exchangeable hydrogen (H_H)	the Sokolov method
calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^+) and sodium (Na^+) (base exchange capacity, S)	in a 1M CH_3COONH_4 extract of pH 7.0 as determined with a Thermo Scientific iCAP 6000 ICP OES Spectrometer, with calculation of effective cation exchange capacity (CEC_E) and total cation exchange capacity (CEC_T)
available phosphorus	Bray & Kurtz method
Particle size	Laser defraction method

pH (average pH in H_2O of 3.6) was noted in the organic horizon of soils that developed on granite and crystal rock. These soils had low exchangeable cation contents (Table 3). The mineral horizon of soils on greenstone and gabbro substrates had the highest dust and clay contents (Table 4). The highest pH was noted in the mineral horizon of soils on greenstone and gabbro substrates (average pH in H_2O of 4.1 and 4.4, respectively). The lowest pH in the mineral horizon was reported for soils on granite (average pH in H_2O of 3.9). The soils on greenstone and gabbro substrates exhibited better organic matter decomposition (average C/N ratios of 20.2 and 17.0, respectively) (Table 4).

The highest average site index of spruce stands was noted in soils that developed on greenstone and gabbro substrates, and the lowest one was reported for soils on granite and crystal rocks (Table 5). The highest variability of the spruce site index was noted for soils on granite substrates, while soils on gabbro had the lowest one (Table 5).

A positive correlation between site index and pH in H_2O in the organic horizon and effective base saturation (V_E), as well as exchangeable cation contents, particularly Ca^{2+} and Mg^{2+}, was observed. Elevation, C and N contents in the organic horizon, the total cation exchange capacity (CEC_T), the effective cation exchange capacity (CEC_E), the Na^+ content, and exchangeable acidity negatively correlated with the spruce site index (Figure 2).

Performing a multiple regression analysis allowed us to formulate an equation explaining the site index using selected topographic parameters and the properties of soils in the organic horizon. The results of the multiple regression analysis showed that the site index of spruce stands was significantly affected by elevation and C and K^+ contents in the organic horizon. The model describing the site index of spruce stands expressed as a function of the above variables explained over 56% of the variance ($R^2_{adj} = 0.56$, equation 3).

$$SI = 54.3 - (0.02 \times Elevation) - (5.2 \times \log[C]) + (1.89 \times \log[K^+]) \quad [3]$$

Figure 3 presents the projection of topographic factors and properties of soil in the humus-mineral horizon on the factor-plane 1×2. Strong relationships between spruce site index and exchangeable cation contents and base saturation in the humus-mineral horizon were noted. Additionally, the clay content correlated with spruce site index. The spruce site index deteriorated with increasing sand content in the humus-mineral horizon, increasing C/N ratio, and

Table 3. Chemical soil properties in the organic humus horizon (Ofh) used to develop the discriminant rule to estimate the site index in *Picea abies* on the different geological substrates

Variable	GR	GS	SS	GB	CR
C	28.00±11.18	30.77±5.78	25.61±9.97	30.26±1.68	31.20±11.76
N	1.31±0.54	1.53±0.24	1.24±0.43	1.35±0.17	1.59±0.53
C/N	21.6±1.9	20.1±1.9	20.4±2.1	22.5±1.6	19.3±1.3
S	2.49±1.72	12.97±9.76	4.13±2.14	10.47±1.95	5.46±3.28
CEC_T	82.1±33.0	82.5±12.2	67.3±33.6	77.2±10.2	95.4±55.2
V	3.4±2.8	16.1±12.8	7.5±5.4	13.5±0.7	9.0±10.5
pH H_2O	3.6±0.3	4.2±0.5	3.7±0.2	4.0±0.3	3.6±0.3
pH KCl	3.0±0.2	3.4±0.5	2.9±0.2	3.2±0.2	2.7±0.3
Ca	19.8±16.2	190.2±152.4	55.8±40.1	174.3±28.2	71.6±54.6
K	28.3±23.5	47.9±32.5	23.9±7.7	23.0±0.6	30.2±10.9
Mg	7.5±4.4	25.9±17.4	7.9±3.0	13.4±6.5	12.5±5.7
Na	3.7±1.7	2.9±0.9	2.0±0.7	2.1±0.5	1.9±0.7
Ca/CEC_T	0.014±0.013	0.118±0.100	0.052±0.051	0.112±0.003	0.060±0.074
K/CEC_T	0.009±0.008	0.015±0.011	0.010±0.005	0.008±0.001	0.013±0.015
Mg/CEC_T	0.008±0.006	0.026±0.019	0.011±0.004	0.014±0.005	0.016±0.016
Hw	22.3±4.5	12.6±7.3	15.2±3.7	10.5±0.9	19.6±9.2
CEC_E	24.8±4.5	25.5±4.1	19.3±4.5	21.0±2.9	25.0±9.6
Al	19.5±4.9	9.5±6.9	12.7±2.9	8.6±0.6	17.5±9.0
Al/CEC_E	0.788±0.145	0.395±0.283	0.664±0.088	0.409±0.029	0.681±0.176
P	36.9±16.8	65.8±24.6	23.3±11.1	35.2±25.2	22.7±15.5

Geological substrates: GR- Granite, GS – Greenstone, SS – Sandstone, GB – Gabbro, CR – Crystal rock; C – total organic carbon (%), N – total nitrogen (%), C/N – C/N ratio, S – sum of exchangeable base cations ($cmol(+)\cdot kg^{-1}$), CEC_T – total cation exchangeable capacity ($cmol(+)\cdot kg^{-1}$), V – saturation of base cations (%), Ca, K, Mg, Na – exchangeable Ca, K, Mg, Na ($mg\cdot 100g^{-1}$), Hw – exchangeable acidity (by the Sokolov method) ($cmol(+)\cdot kg^{-1}$), CEC_E – effective cation exchangeable capacity ($cmol(+)\cdot kg^{-1}$), Al – exchangeable aluminium ($mg\cdot 100g^{-1}$), P – available phosphorus (by the Bray & Kurtz II method) ($mg\cdot kg^{-1}$)

Table 4. Chemical and physical soil properties in the mineral-humus horizon (A-AE) used to develop the discriminant rule to estimate the site index in *Picea abies* on the different geological substrates

Variable	GR	GS	SS	GB	CR
Sand	52.3±12.8	36.7±7.5	61.1±21.4	36.6±3.6	64.0±12.7
Dust	39.5±11.0	54.0±8.2	30.4±16.5	55.0±1.4	30.0±10.7
Clay	8.2±3.0	9.3±2.1	8.5±6.8	8.5±2.1	6.0±3.1
C	4.63±2.49	4.11±2.38	1.33±0.46	2.45±1.95	5.01±2.92
N	0.19±0.11	0.21±0.13	0.07±0.03	0.13±0.10	0.20±0.13
C/N	24.5±3.4	20.2±4.4	23.0±9.6	17.8±1.9	28.9±7.3
S	0.36±0.20	0.70±0.45	0.43±0.58	0.58±0.34	0.38±0.16
CEC_T	21.5±8.2	19.6±9.2	10.6±5.3	11.5±7.4	23.8±14.6
V	1.7±0.9	4.6±3.9	5.3±8.5	5.2±0.4	2.0±1.1
pH H_2O	3.9±0.2	4.1±0.2	3.9±0.2	4.4±0.2	4.0±0.3
pH KCl	3.2±0.2	3.2±0.1	3.1±0.2	3.6±0.0	3.4±0.4
Ca	2.5±2.5	7.5±5.8	5.4±9.1	8.1±6.4	2.8±1.6
K	3.9±1.8	2.7±2.4	2.6±1.8	2.7±1.6	4.3±2.0
Mg	1.1±0.7	2.6±1.4	0.9±1.1	1.0±0.6	1.2±0.6
Na	1.0±0.4	1.0±0.3	0.4±0.3	0.7±0.2	0.7±0.2
Ca/CEC_T	0.006±0.007	0.021±0.011	0.035±0.072	0.033±0.006	0.007±0.003
K/CEC_T	0.005±0.001	0.004±0.003	0.008±0.007	0.009±0.009	0.006±0.006
Mg/CEC_T	0.004±0.002	0.018±0.023	0.008±0.008	0.007±0.000	0.005±0.003
Hw	12.1±4.3	14.0±2.2	7.4±5.2	9.3±1.5	9.5±3.9
CEC_E	12.5±4.4	14.7±2.2	7.8±5.6	9.8±1.9	9.9±4.0
Al	11.4±4.1	13.5±2.1	7.1±5.2	8.9±1.3	9.3±3.8
Al/CEC_E	0.914±0.031	0.921±0.046	0.877±0.083	0.908±0.042	0.939±0.010
P	11.3±9.9	5.2±2.7	1.4±0.5	3.5±0.5	4.8±4.1

Geological substrates: GR – Granite, GS – Greenstone, SS – Sandstone, GB – Gabbro, CR – Crystal rock; Sand, dust, clay (%), C – total organic carbon (%), N – total nitrogen (%), C/N – C/N ratio, S – sum of exchangeable base cations ($cmol(+) \cdot kg^{-1}$), CEC_T – total cation exchangeable capacity ($cmol(+) \cdot kg^{-1}$), V – saturation of base cations (%), Ca, K, Mg, Na – exchangeable Ca, K, Mg, Na ($mg \cdot 100g^{-1}$), Hw – exchangeable acidity (by the Sokolov method) ($cmol(+) \cdot kg^{-1}$), CEC_E – effective cation exchangeable capacity ($cmol(+) \cdot kg^{-1}$), Al – exchangeable aluminium ($mg \cdot 100g^{-1}$), P – available phosphorus (by the Bray & Kurtz II method) ($mg \cdot kg^{-1}$)

Table 5. Site index (SI) of spruce and elevation on the different geological substrates

Parameters	GR	GS	SS	GB	CR
Site index (SI)					
Average	26.1	32.1	31.2	32.1	26.1
Maximum	32.6	35.9	36.2	32.5	32.4
Minimum	8.1	26.9	23.6	31.8	18.5
SD	6.2	3.4	4.2	0.5	5.0
Altitude					
Average	824	592	649	559	1022
Maximum	1139	690	775	570	1180
Minimum	622	512	440	547	785

Geological substrates: GR – Granite, GS – Greenstone, SS – Sandstone, GB – Gabbro, CR – Crystal rock

increasing soil acidity, expressed as the ratio of exchangeable hydrogen to CEC_E (H/CEC_E) (Figure 3).

Additionally, the multiple regression analysis allowed us to formulate an equation explaining the site index using selected topographical parameters and properties of soils in the humus-mineral horizon. The results of the analysis showed that the site index of spruce stands was significantly affected by elevation, the log of the Al^{3+}/CEC_E ratio, and the K^+ content in the humus-mineral horizon. The model describing the site index of spruce stands expressed as a function of the above variables explained over 67 % of the variance (R^2_{adj} = 0.67, equation 4).

$$SI = 47.6 - (0.024 \times Elevation) - (28.29 \times \log[Al^{3+}/CEC_E]) + (1.78 \times \log[K]) \quad [4]$$

Growth of spruce stands and their site index depends on the characteristics of the geological substrate. Less favourable conditions for spruce growth were found for soils that developed on granite and crystal rock. Higher spruce stand site indices were found for soils that developed on sandstone, and the best ones were found for soils that developed on greenstone and gabbro. Regoliths in the order of granite rock – crystal rock – sandstone – greenstone – gabbro are characterized by increasing clay content, sorption capacity, basic exchangeable cation contents, and decreasing sand content and acidity. The role of such geological substrates in creating soil is associated with the height of the mountain range. The highest elevations of the Sudety Mountains developed from granite and poorer metamorphic rocks – crystal rock. Forest stands in regions with these rocks have the greatest range of site index values. Greenstone and gabbro developed on the lowest ridges, and stands on these rocks have the highest site indices as a result of synergies between soil and climatic factors. Figure 5 presents the relationship between spruce site index and elevation.

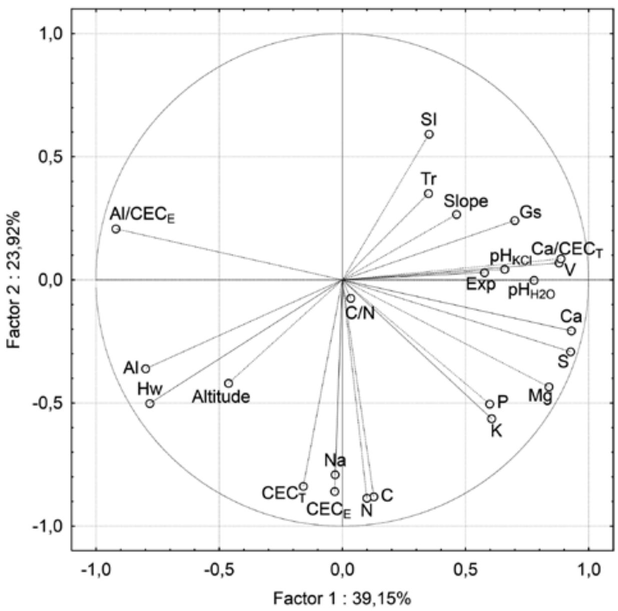

Figure 2. Projection of variables on the factor-plane 1×2 (site index and properties of the Ofh horizon)

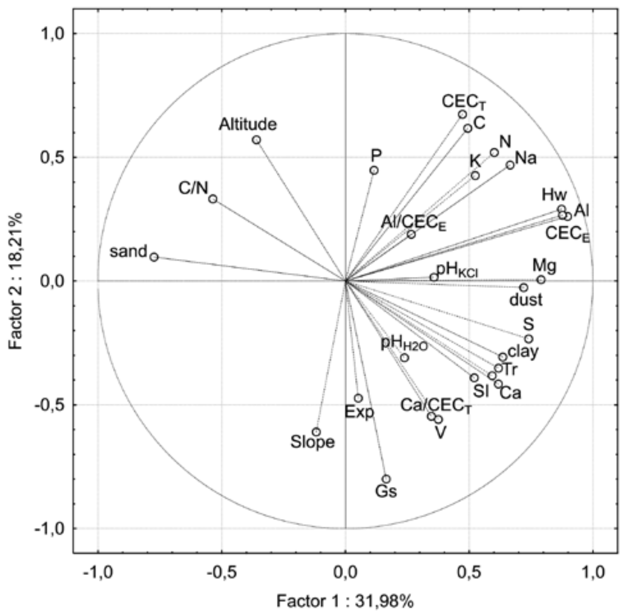

Figure 3. Projection of variables on the factor-plane 1×2 (site index and properties of the humus-mineral horizon)

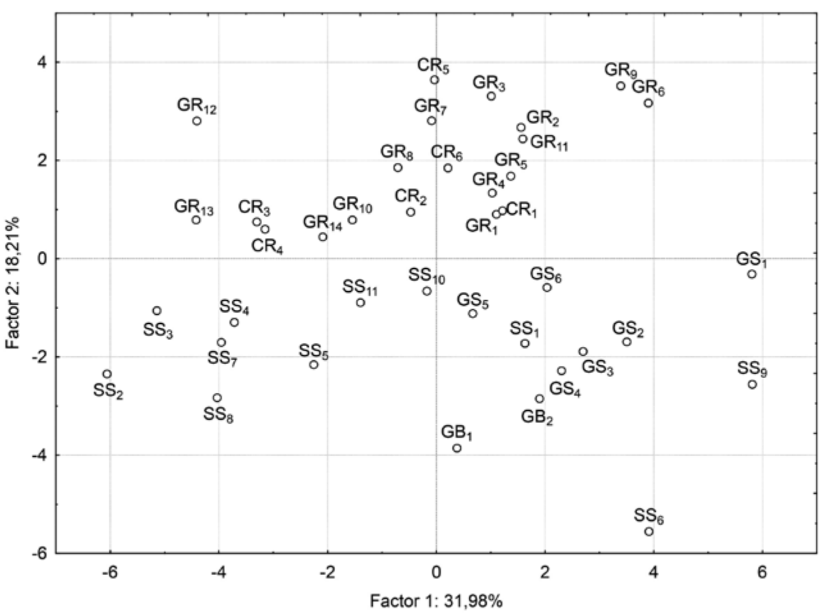

Figure 4. Factorial plan of variables on the factor-plane 1×2 (geological substrates)

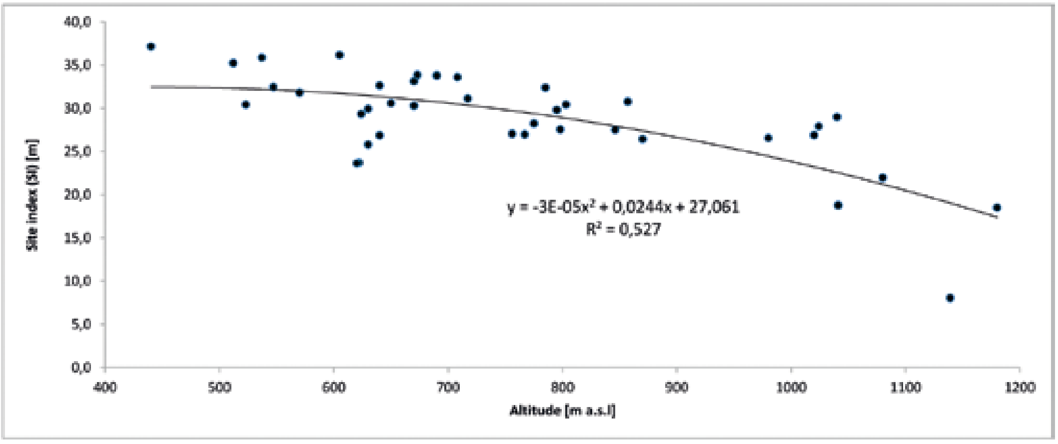

Figure 5. Relationship between site index of spruce stands and elevation

Discussion and conclusions

Many researchers have formulated growth models of mountain spruce stands and searched for site characteristics that determine spruce growth. M. Bošela et al. (2013), who conducted similar studies in the Western Carpathians, concluded that the most important factors influencing the site index of spruce stands are climatic factors, particularly the length of growing season, and selected soil characteristics. The authors analyzed only soil pH and the C/N ratio in the first surface horizon to a 10-cm depth, with no division into the organic and humus-mineral horizons. According to the authors, ecological factors explained most (76 %) of the site index variation. J. Socha (2008), in a study conducted in the Western Beskid Mountains, explained 79 % of the site index variability using site factors such as geological substrate, elevation, and position relative to the height of the mountain range. In our study, the soil properties of the humus-mineral or organic horizons, together with features of position, accounted for 67 % and 56 %, respectively, of the site index variability. Obtaining a more accurate estimation of site index using the properties of the humus-mineral horizon rather than those of the organic horizon is not surprising. The organic horizon is less processed and it contains more labile C fractions that are more diverse. Its physical and chemical properties are less stable, and are subject to strong fluctuations (depending on thermal conditions, the structure of the stand, the understory vegetation, and micro-relief conditions) (O'Donnell et al. 2009). The humus-mineral horizon is better for assessing the quality of soils and sites than the organic horizon. The humus-mineral horizon contains weathered, earthy parts that are associated with much processing, and it has a more stable organic matter fraction (Rumpel and Kögel-Knabner 2011). Additionally, the bio-physico-chemical properties of the humus-mineral horizon are less variable. Mismatches between the tree species composition and site conditions lead to changes in soil properties (Maciaszek et al. 2000, Maciaszek et al. 2009). Drawing conclusions on the basis of the properties of surface horizons, where the distorting effect of spruce monocultures is focused, requires extreme caution.

Elevation was one of the site parameters that were used to explain the site index of spruce stands in the Sudety Mountains. The regression analysis indicates that this parameter explains 49 % of the site index variability. In mountainous areas, elevation is directly related to thermal conditions and the length of growing season, and, in the Sudety Mountains, the geological substrate. According to Socha J. (2008) and Gömöryova E. and Gömöry D. (1995), topographic factors, especially elevation, can be used to explain the variability of the site index of mountain spruce stands. The properties of the surface horizon of soil in these studies explain approximately 10–20 % of the site index variation of spruce stands, depending on whether the organic horizon or the humus-mineral horizon was considered.

Among the properties of the surface soil horizons, the regression analysis identified two features in the humus-mineral horizon that affect the growth of spruce stands. The first feature, the Al^{3+}/CEC_E ratio, can be treated as an indicator of acidity, and it is correlated with the potential toxicity of Al^{3+} in the soil (Gruba 2004a). Spruce soil tests indicate that a high concentration of Al^{3+} in the soil contributes to the inhibition of root growth and the inhibition of P and Ca^{2+} uptake and, consequently, leads to disorders in metabolic processes and growth inhibition (Gruba 2004b). The exchangeable K^+ content was the second property of the humus horizon that was shown by the multiple regression analysis to affect the site index of spruce stands. According to the literature, spruce dieback is caused by a long-term disease process, which may have been initiated by rainfall deficits (Lexer et al. 2000). We assume that a K^+ deficiency in the soil (K^+ is responsible for proper hydration and cell turgor) (Walker et al. 1996) leads to disorders in the growth of spruce stands and the subsequent growth inhibition. Gömöryova and Gömöry (1995) proved in their study that there is a significant relation between the K^+ content in the soil and the height of spruce stands. The total organic C content in the organic horizon and the exchangeable K^+ content in both horizons were the properties that best explain the variability of the spruce site index. The K^+ level is associated with metabolic processes and proper cell hydration. Additionally, the deterioration of climatic conditions for the growth of spruce is closely associated with a higher accumulation of weakly decomposing organic matter on the surface of the mineral soil (Drewnik 2006).

The area of the Sudety Mountains covered by the analysis in this study has unique characteristics. A large part of the Sudety Mountains, especially the Izerskie and Karkonosze Mountains, were affected by an ecological disaster: a massive dieback of forest stands as a result of the strong impact of industrial emissions in the 1970s (Landmann and Bonneau 1995, Sienkiewicz et al. 2005). The tested spruce stands survived, but for a long time the area has remained under the influence of acid rain and toxic emissions. Our results indicate that the acidity of the forest soil, as well as the nutrient cycle, affects the spruce site index. These soil properties may enhance the negative effects of stress factors, leading consequently to deterioration of spruce productivity and, in extreme cases, to the disintegration of stands. Strongly acidified soils with a K^+ deficit will show a higher susceptibility to stress factors. To reduce the negative impact of stress factors, one should ensure the correct cycling of nutrients and prevent soil acidification. These soil properties can be improved by breeding spruce with an admixture of deciduous species. These actions may be more effective at lower positions on a rich geological substrate (sandstone, gabbro, or greenstone).

Topographic factors do not fully account for the variability of the site index of spruce stands in the Sudety Mountains. The regression analysis indicates that elevation explains 49% of the site index variability, while 20 % of the site index variation of spruce stands depends on soil properties. Using the properties of the humus-mineral horizon rather than those of the organic horizon resulted in a more accurate estimation of the site index. Properties associated with the movement of nutrients, in particular K^+, had the largest effects on the site index of spruce stands. A K^+ deficiency in the mountain soils can lead to the growth inhibition of spruce stands. Additionally, the concentration of Al^{3+} in the sorption complex has an inhibitory effect on site productivity. Furthermore, the $Al^{3+}CEC_E$ ratio can be treated as an indicator of acidity.

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