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Factors Influencing Site Index of Norway Spruce in Slovenia

Einflussfaktoren auf die Oberhöhenbonität der Gemeinen Fichte in Slowenien

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Key words: site index, environmental factors, *Picea abies*, Slovenia

Schlagwörter: Oberhöhenbonität, Umweltfaktoren, *Picea abies*, Slowenien

Abstract

The effects of stand, topographic, soil and climatic factors on the site index of Norway spruce (Picea abies) in Slovenia were examined. A total of 285 plots in adult even-aged stands dominated by Norway spruce were analysed. Stem analyses were used to determine the mean height at the reference age of 100 years. For each plot, all the available topographic, soil and climatic variables were collected. First, the relationship between site index and elevation was established. In this bivariate analysis about half of the site index variance was explained by elevation. Silicate bedrock exceeds that of carbonate on elevations above 500 m a.s.l. On lower elevations of silicate-dominated sites, site index is almost constant and declines above 700-800 m a.s.l. On the other hand, it decreases practically linearly on car-

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bonate bedrock. Using multivariate regression, 75% of site index variance was explained, exposing soil type, landscape position and elevation as the most influential factors. Productivity is lower on hydromorphic soils, while on cambisols and luvisols productivity increases in comparison with leptosols. Site index decreases with elevation, relative elevation (ratio between elevation of analysed location and the local peak of the mountain massif) and higher inclination. Moreover, site index is higher on silicate bedrock, on sinkhole land and on ridges. Site productivity of spruce is also lower on the steeper slopes exposed to sun, on positions where the sum of autumn sun irradiation is above 420 hours and in the stands with the share of spruce between 70-90%.

Kurzbeschreibung

Die Auswirkungen der Bestände, der topographischen Faktoren, der Boden- und Klimafaktoren auf die Oberhöhenbonität der Gemeiner Fichte (Picea abies) in Slowenien wurden untersucht. Insgesamt wurden 285 Forschungsflächen in den erwachsenen, gleichaltrigen Beständen mit dominierender Gemeiner Fichte analysiert. Auf der Grundlage der Stammanalysen wurde die bei den Bäumen im Referenzalter von 100 Jahren die mittlere Höhe bestimmt. Für jede Fläche wurden alle verfügbaren topographischen, Boden- und klimatischen Faktorenvariablen erhoben. Zunächst wurde das Verhältnis zwischen der Höhenlage und der Oberhöhenbonität festgestellt. In dieser bivariaten Analyse wurde etwa die Hälfte der Oberhöhenbonitätsvarianz mit der Höhenlage erklärt. Das Silikat-Grundgestein überwiegt auf einer Höhenlage von über 500 m. ü. M. gegenüber dem Carbonat-Grundgestein. Bei niedrigeren Höhenlagen mit dominierendem Silikat-Grundgestein bleibt die Oberhöhenbonität nahezu konstant und verringert sich oberhalb von 700 bis 800 m ü. M. Auf der anderen Seite sinkt die Oberhöhenbonität praktisch linear beim Carbonat-Grundgestein. Mit der multivariaten Regression wurden 75 % der Oberhöhenbonitätsvarianz erklärt. Die einflussreichsten Faktoren waren die Bodenart, die Landschaftsposition und die Höhenlage. Die Produktivität der Fichte ist auf hydromorphischen Böden geringer, während die Produktivität auf den Braunerden (Cambisols) und Parabraunerden (Luvisols) im Vergleich zu den Leptosols steigt. Die Oberhöhenbonität sinkt mit der Höhenlage, mit der relative Höhe (Verhältnis zwischen der Höhenlage und dem lokalen Gipfel des Bergmassivs) und mit der höhere Neigung. Darüber hinaus ist die Oberhöhenbonität auf Silikat-Grundgestein, auf karsttrichterischem Land und auf Bergkämmen höher. Die Bestandsproduktivität der Fichte ist ebenso geringer auf sonnenexponierten steileren Hang, in den Lagen, in denen die Summe der Herbstsonneneinstrahlung über 420 Stunden liegt und in den Beständen mit Fichtenanteil zwischen 70-90%.

1 Introduction

Detailed knowledge on site productivity is indispensable for successful management of forest ecosystems. There are several approaches used in the assessment of site productivity (Skovsgaard and Vanclay 2008; Weiskittel et al. 2011). Despite many limitations, site index, i.e. the expected height at a certain reference age, remains the most frequently used measure of site productivity (e.g. Weiskittel et al. 2011).

Determining the site productivity or site index for selected locations, plots or areas is usually only the first step in understanding the forest ecosystem characteristics. In the following steps the established site indices can be interpreted or explained through influential factors (e.g. Nord-Larsen 2002; Pinto et al. 2008; Socha 2008) and used in modelling for very different purposes (e.g. Albert and Schmidt 2010; Sharma et al. 2011).

Traditionally, site productivity is estimated for monospecific stands. For the obvious reasons, dominating tree species are intensively researched. In Central Europe, Norway spruce (Picea abies (L.) Karst.) holds a dominant position, in particular from the economic point of view (e.g. Kenk and Guehne 2001; Jöbstl 2011). Despite many problems related to unstable spruce-dominated stands, e.g. wind-throws, snow breakage, bark beetle outbreaks (e.g. Klopcic et al. 2009), and rot decay (e. g. Kohnle and Kändler 2007), this tree species remains economically attractive as contemporary research studies have confirmed that a significant addition of spruce in broadleaved stands is economically justifiable (e.g. Knoke et al. 2008).

Consequently, there is no doubt that data on the growth and yield potential of spruce stands will be crucial for efficient forest management also in the future.

In Slovenia, the share of Norway spruce in the growing stock is slightly lower than the share of European beech, and reaches about 31% (SFS 2011b). The share of spruce is slowly decreasing on account of broadleaved tree species (ibid.). In general, the species prospers well, except in lowland and submediterranean forests (Kotar and Brus 1999). Several decades ago, it was promoted and planted outside its natural range, whereas in the last decades foresters have been trying to lower the share of spruce on most problematic sites (Diaci 2006). However, it would be reasonable to maintain a sustainable share of spruce in other sites which are more favourable for spruce species (Kotar 2006). Growth characteristics and the potential of Norway spruce stands has only been partially analysed up to now (Kotar 1980; Kotar 2005). The full range of growth conditions has not been investigated previously.

Hence it ensues that a comprehensive and holistic research of site productivity of spruce stands is required. In this respect, the primary objective of this study was to determine the factors or variables which affect the site productivity of Norway spruce in Slovenia. The aim of the research was to cover the maximum range of growth site conditions under which Norway spruce becomes as important element for forest stands in Slovenia. To this aim, the following groups of factors/variables were studied: stand (1), topographic (2), soil (3) and climatic (4). Additionally, special attention was given to the relationship between site productivity and elevation. Site productivity was estimated as site index.

2 Material and Methods

2.1 Study area with site characteristics

The sample contained mature, even-aged stands with the share of spruce in basal area above 70%. Unfortunately, random or regular sampling was not possible (the main limitations included ownership, inaccessibility of forest stands, and harvesting plans). Nevertheless, we tried to carry out a sampling with research plots scattered as regularly as possible across the regions which demonstrate an important share of spruce stands.

A total of 285 plots were set up in 29 different forest associations. The sample covers practically the full range of elevation, rockiness, inclination (Table 1) and aspect conditions in which spruce grows.

Table 1: Basic characteristics of the analysed research plots

Tabelle 1: Allgemeine Eigenschaften der untersuchten Versuchsflächen

Characteristic	Mean	St. deviation	Minimum	Maximum
Elevation (m)	905.6	318.85	250	1710
Inclination (°)	13.0	9.53	0	38
Rockiness (%)	15.8	18.79	0	85
Annual sum of precipitation (mm)	1896.5	442.59	950	3600
Mean annual temperature (°)	6.96	1.776	3.0	9.0
SI_{100} (m)	30.3	6.05	6.9	42.0

2.2 Measurements

The plots of three different dimensions with regard to the height of the dominant trees were set. The number of plots measuring 20m × 20m was 111 (38.9%), the number of plots measuring 25m × 25 m was only 6 (2.1%), and the rest of the plots measured 30m × 30m (168, 59.0%).

The number of trees selected for site index calculation followed well-known procedures (Pierrat et al. 1995; Kotar 2005; Charru et al. 2010), in which the analysis includes n trees on n × 100 m^2 measuring plots. On the smallest plots, four thickest spruce trees were used to determine site index; six trees were used on medium-sized plots, and nine appropriate trees were selected on the largest plots. A total of 1,992 thickest (dominant) Norway spruce trees were cut in order to calculate site index. Stem analyses were used to determine the mean height at the reference age of 100 years (hereafter: SI_{100}).

In each plot, all the trees with diameter at breast height (hereafter: dbh) ≥ 10 cm were measured for dbh and the data obtained were used to establish the share of Norway spruce in the stand's basal area (BA).

Furthermore, inclination (in °), rockiness (in % of surface cover), aspect and GPS coordinates were established for each plot. Using GPS coordinates, the following information was extracted from spatial databases: elevation, mean yearly temperature, sum of yearly precipitation, and duration of sun irradiation for four seasons (in hours for spring, summer, autumn and winter) (ARSO 2007; ARSO 2011). Additionally, each plot was classified into the appropriate landscape position (slope, ridge, foothills, plane, bog, frost hollows, or sinkhole land), bedrock type (limestone, dolomite, or silicate), phytosociological unit (associations according to the Braun-Blanquet approach), soil type, and humus form. Phytosociological units were determined using the Slovenia Forest Service base (SFS 2011a). Soil types were classified according to the Slovenian soil map (CPVO 1998) and checked against the described soil types for the established phytosociological unit (due to the fact that phytosociological units were mapped in more detail and this information is therefore more reliable than the soil mapping data). The local soil classification was harmonized with the World Reference Base for Soil Resources (FAO 2006). Humus form was identified by means of a simplified procedure in the field. Only four types of humus were distinguished: mull, moder, mor and histomor (a simplified system on the basis of European Humus Forms Reference Base; Zanella et al. 2011) according to the presence and characteristics of organic horizons.

2.3 Variables

The influence of all available variables (Table 2) on site index was tested to determine the type of bivariate relationships. Some variables were transformed into appropriate dummy variables.

Among stand variables, a dummy variable was used for species mixture to distinguish pure stands from mixed ones. Aspect values evaluated from the azimuth were transformed using the equation proposed by Beers et al. (1966). As regards landscape position, slope served as a reference category. Relative elevation was defined as a ratio between the elevation of the analysed location and the local peak of the mountain massif. Leptosols were taken as a reference category for soil types, and moder type was considered the basis in terms of humus form. Indicating low range in values (up to 5), the duration of sun irradiation by four seasons (originally in sums of hours) was transformed into four dummy variables (Table 2). In order to study the combined effect of precipitation and temperature, we used de Martonne's index of aridity on a yearly basis (which is the ratio between the mean annual values of precipitation and temperature plus 10°C).

In order to avoid multicollinearity, certain variables were omitted from Table 2 and from some other the residuals were obtained. It turned out that age correlates to SI_{100}, because younger stands more often occur on lower elevations, while older stands are more common on higher elevations. Partial correlation between age and SI_{100} (elevation was used as controlling variable) was not significant ($r = -0.015$, $P = 0.801$); therefore, age was omitted from the explanatory model. Furthermore, due to the complete connectedness between hydromorphic soil, histomor and bog a decision was made to include only the first one in the model. As regards temperature, precipitation and de Martonne's index of ariditiy, all these variables are closely dependent on elevation, in particular temperature. Thus the influence of elevation was extracted from precipitation and de Martonne's index and for further analysis the residuals were obtained, whereas temperature was omitted from the model. As the survey of the duration of sun irradiation by seasons gave a practically identical response from autumn and winter, the latter was eliminated.

Table 2: Independent variables tested as influential variables on SI_{100}

Tabelle 2: Unabhängige Variablen als einflussreiche Variablen auf SI_{100} getestet

Level	Variable	Variable type/ Dependency form	Dummy variables coding	
			Name	Transformation
Stand	Mixture	0/1	mixed stand	1 = stands with Norway spruce share in BA between 70-90%; 0 = stands with share above 90%
	Age	continuous/linear	-	-
Topography	Elevation	continuous/parabolic	-	-
	Inclination	continuous/parabolic	-	-
	Rockiness	continuous/linear	-	-
	Aspect	continuous/linear	-	-
	Landscape position	0/1	sinkhole land	1 = sinkhole land; 0 = other
			frost hollow	1 = frost hollow; 0 = other
			bog	1 = bog; 0 = other
			ridge	1 = ridge; 0 = other
			foothills &plain	1 = foothills, plain; 0 = other
	Relative elevation	continuous/linear	-	-
Soil	Bedrock type	0/1	carbonate bedrock	1 = limestone, dolomite; 0 = silicate
	Soil type	0/1	hydromorphic	1 = ombric histosol, planosol; 0 = other
			cambisol	1 = cambisol; 0 = other
			luvisol	1 = luvisol, podzol; 0 = other
	Humus form	0/1	mull	1 = mull; 0 = other
			mor	1 = mor; 0 = other
			histomor	1 = histomor; 0 = other
Climate	Precipitation (annual sum)	continuous/linear	-	-
	Temperature (mean annual)	continuous/linear	-	-
	Duration of sun irradiation	0/1	spring	1 = duration > 470 h; 0 = other
			summer	1 = duration > 700 h; 0 = other
			autumn	1 = duration > 420 h; 0 = other
			winter	1 = duration > 320 h; 0 = other
	De Martonne's index of aridity	continuous/parabolic	-	-

2.4 Statistical analyses

First, a number of functions (linear and nonlinear) were tested to describe the relationship between site index and elevation for carbonate and silicate bedrock types separately. Adjusted R^2 was used was a criterion.

We started the regression procedures with the complete set of variables with removing at each separate simulation run independent variables which were not significant, in order to develop a model for explaining site index using stand, topographic, soil and climate variables or descriptors.

Since the relationship between site index and the independent variable is often parabolic (e.g. Seynave et al. 2005), a quadratic term was added to the models for certain continuous variables when so indicated by the bivariate analysis and data survey. All categorical variables were transformed into dummy variables (Table 2). In addition to the main effects of independent variables, many interactions were also tested: inclination×aspect (according to Alissow et al. 1956), rockiness×inclination, elevation×inclination, and rockiness×elevation. None of these proved to be useful.

In order to avoid multicollinearity, only variables with a tolerance factor higher than 0.2 were included in the model. Details are explained in chapter 2.3.

In the statistical procedures the influence of outliers was eliminated. The cases where the studentized residuals were 2.0 or greater were classed as outliers.

All analyses were carried out using PASW SPSS Statistics 18. The level of significance is 5%.

3 Results

3. 1 The dependence of site index on elevation

Elevation is one of the strongest and very obvious factors influencing growth and production; therefore it deserves special analysis. On the basis of experiences and analysis of covariance (site indices differed significantly between bedrock types, $F = 7.488$, $P = 0.007$; elevation was used as a covariate), the relationship between site index and elevation is analysed by bedrock types (Figure 1). The first step included all sites. All regression parameters are listed in Appendix 1. For the carbonate bedrock type, a higher share of variance was explained. Lower site indices on silicate on higher altitudes could be assigned to plots on bogs. On carbonate bedrock, site productivity decreases with elevation more slowly and all the time, whereas on silicate bedrocks the maximum is achieved on about 600 m a.s.l.

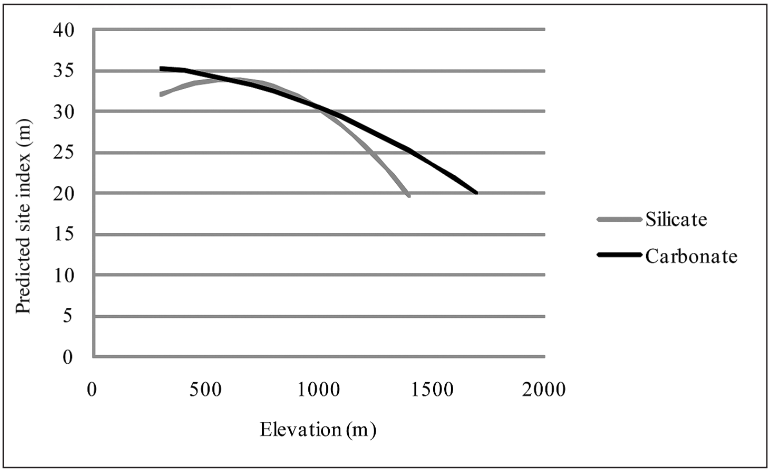

Figure 1: The dependence of site index on elevation by bedrock types – all plots

Abb. 1: Die Abhängigkeit der Oberhöhenbonität von der Höhenlage nach Grundgesteinsarten – alle Versuchsflächen

In order to eliminate the effects of landscape position (e.g. bog, frost hollow) and make the analysis clearer, only slope positions were included in the next step. Silicate bedrock exceeds that of carbonate on elevations above 500 m a.s.l. (Figure 2). On lower elevations of silicate-dominated sites, site index is almost constant and declines above 700-800 m a.s.l. On the other hand, site index decreases practically linearly on carbonate bedrock. The relationship between site index and elevation limited to slope positions is strong, in particular on carbonate bedrock (Appendix 1).

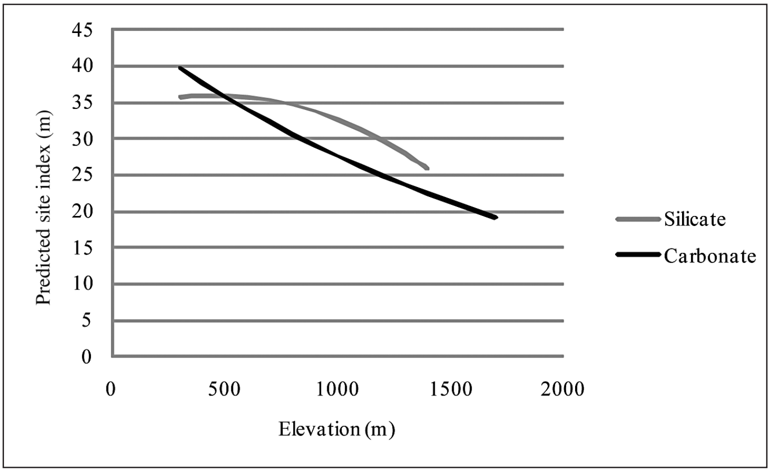

Figure 2: The dependence of site index on elevation by bedrock types – only slope positions

Abb. 2: Die Abhängigkeit der Oberhöhenbonität von der Höhenlage nach Grundgesteinsarten – nur Hangpositionen

3. 2 Variables influencing site index

As much as 75% of site index variance was explained using the explanatory multivariate model (R^2 = 0.75; R^2_{adj} = 0.74). Among all tested variables, 12 turned out to be significant (Table 3), with soil type, landscape position and elevation as the most influential. On hydromorphic soils productivity is lower, while on cambisols and luvisols it increases in comparison with leptosols. With elevation, relative elevation and higher inclination site index decreases. Moreover, SI_{100} is higher on silicate bedrock, on sinkhole land and on ridges. The latter is a bit surprising, but it could be explained by the fact that analysed ridges are mostly on higher elevations, where aridity is no more a strong limiting factor. Besides, many ridges are of local character (local ridges on slopes). Site productivity of spruce is also lower on the steeper slopes exposed to sun, on positions where the sum of autumn sun irradiation is above 420 hours and in the stands with the share of spruce between 70-90%.

Table 3: The dependence of site index on stand, topographic, soil and climate characteristics

Tabelle 3: Die Abhängigkeit der Oberhöhenbonität von dem Bestand, den topographischen Faktoren, den Boden- und Klima-Eigenschaften

Independent variable	Parameter (β)	Standard error (β)	*P*-value (error probability)	Partial correlation coefficient
Constant	42.196	1.958	0.000	-
Hydromorphic soil type	-15.129	1.293	0.000	-0.587
Elevation	-0.006	0.001	0.000	-0.298
Carbonate bedrock	-2.646	0.675	0.000	-0.236
Sinkhole land	2.999	0.520	0.000	0.337
Ridge	2.607	0.956	0.007	0.167
Luvisol	2.613	0.709	0.000	0.223
Cambisol	1.412	0.583	0.016	0.149
Relative elevation	-7.308	1.819	0.000	-0.242
Inclination	0.156	0.074	0.036	0.130
Inclination^2	-0.005	0.002	0.012	-0.156
inclination×aspect	-7.141	2.672	0.008	-0.164
Mixture	-1.008	0.468	0.032	-0.132
Autumn irradiation sum	-1.702	0.483	0.028	-0.136

The analysis of a relationship between the measured (observed) site indices and predicted site indices shows that the relationship is linear in character (Figure 3). The residuals have normal distribution (Figure 4).

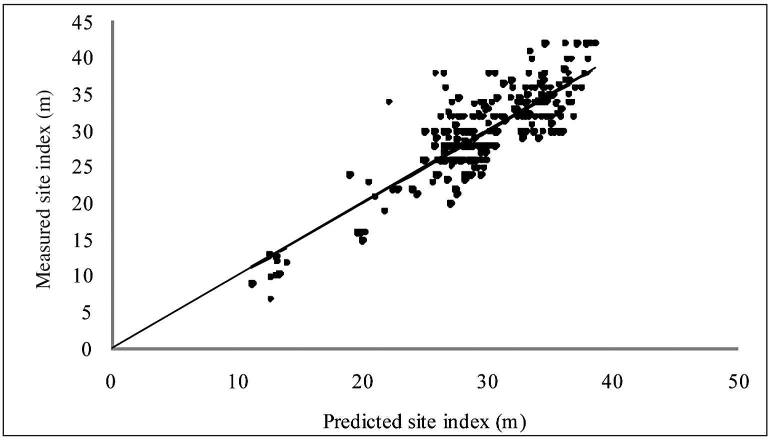

Figure 3: Relationship between measured and predicted values of site index

Abb. 3: Das Verhältnis zwischen den gemessenen und den vorhergesagten Werten der Oberhöhenbonität

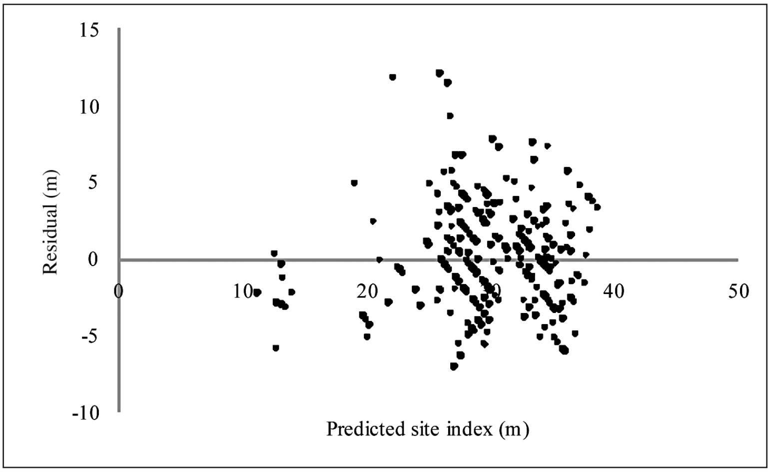

Figure 4: Relationship between residuals of the site index model and the predicted site index values

Abb. 4: Das Verhältnis zwischen den Residuen des Oberhöhenbonitätsmodells und den vorgesehenen Werten der Oberhöhenbonität

The least productive phytosociological units were peatland spruce forests (*Sphagno-Piceetum*) and subalpine spruce forests on carbonate bedrock (*Adenostylo glabrae-Piceetum*), while silver fir forests with ferns on fresh, deep soils (*Galio rotundifolii-Abietetum*) and submontane beech sites were the most productive.

4 Discussion

In the present study about 75% of site index variability was explained using multivariate regression. In the research in the West Carpathian a very similar share (79%) was explained (Socha 2008). The best model for the site index in the eastern part of France explained 64% (Seynave et al. 2005). In Austria site index prediction models achieved R^2 between 0.38 and 0.66 (Schadauer 1999). By far the highest share of variance was explained by the model of Shrivastava, i. e. 97.4% (Shrivastava 1976). In this model the height at the age of 80 years was used as dependent variable. The majority of variance was explained with soil variables (C/N ratio, soil volume, K, Ca, Mg, available P, O_h thickness,...), elevation and precipitation during vegetation period (Shrivastava 1976).

Our study identified elevation as one of the main explanatory factors, which is in accordance with practically all analyses of the Norway spruce site index

(Seynave et al. 2005; Socha 2008). Above the elevation of about 700-800 a.s.l., site index starts to decrease, while it stays relatively stable below this elevation. This shows that the lowest elevations are not more suitable for Norway spruce than the positions at medium elevations. The reason could be the inversion of temperatures and the frequency of fogs in lowlands. Another explanation was proposed by Socha (2008), who stated that lower temperatures are compensated by an increase in precipitation, while above the elevation of 700-800 m, growth is probably limited by thermal conditions and worse soils.

Previous studies ascertained the importance of soil conditions for Norway spruce productivity (Shrivastava 1976; Seynave et al. 2005; Socha 2008; Vallet and Pérot 2011), which is consistent with our research. Carbonate bedrock is less productive, in particular with higher rockiness, as is also indicated by the results of French studies (Seynave et al. 2005). Cambisols and luvisols were found to be more productive soil types than leptosols, the finding corresponding with the established positive effect of soil depth on productivity in Germany and France (Shrivastava 1976, Seynave et al. 2005).

The established negative impact of (higher) inclination on site index is in agreement with other studies (Shrivastava 1976; Schadauer 1999; Socha 2008) and is easily understandable.

Further, Socha (2008) confirmed the positive influence of the mountain massif on site index. We established that site index is lower if the analysed location is closer to the (local) peak. Both findings are in accordance with the mass-elevation or mountain-mass effect, described by the studies of mountain timberlines (e.g. Holtmeier 2009). This effect was first mentioned by Kasthofer (1822, cit. Holtmeier 2009) and it means that larger mountain massifs serve as a heating surface which absorbs solar radiation and transforms it to long-wave energy (Holtmeier 2009). If the location is closer to the local peak, it experiences a "ridge" effect. It means that the water and nutrient supply is worse than lower on the slope, while the wind effect is usually stronger. Our research pointed out that ridges are more productive in comparison with other landscape positions. Although contradictory, this result could be explained by the fact that the analysed ridges were mostly on higher elevations, where aridity is not a strong limiting factor, while light conditions are better. Besides that, many of the analysed ridges were of local character (local ridges on slopes). Besides ridges, sinkhole land showed a positive effect on productivity. This is much easier to explain. On concave terrain the moisture and nutrient conditions are better. Seynave et al. (2005) also confirmed topographic concavity as a positive factor on site index of Norway spruce.

Many research studies established the negative effect of C/N ratio on site index (Shrivastava 1976, Seynave et al. 2005). As regards the impact of soil characteristics on productivity, hydromorphic soil types also turned out to be less suitable in comparison with other soils. In the group of hydromorphic soils, ombric histosols were prevailing with extremely unfavorable properties as very acid, nutrient poor soils with very low base saturation. This explains the strength of influence of that variable on site index.

The only directly influencing climatic variable was autumn irradiation sum. The negative effect of that variable could be explained with its correlation to elevation.

Slovenia is relatively rich in precipitation, and this tendency is even more expressed in regions with spruce. In submediterranean and subpannonian part of Slovenia, where the deficit of precipitation is more pronounced, the share of Norway spruce is irrelevant. In these two regions and in plains the stands with higher shares of Norway spruce are hard to retain. In the future spruce will probably disappear from these locations, and its share will continue to decrease in the hilly and submontane vegetation belt.

Site productivity could be different for the same species depending on whether the site is linked to a pure or mixed stand. For mixed European beech-Norway spruce stands Pretzsch and Schütze (2009) found a 21% production advantage for Norway spruce and even 37% for beech. On the other hand, Vallet and Pérot (2011) showed that for Norway spruce-silver fir mixtures, only silver fir benefits from the mixture at the stand scale; there is no effect on Norway spruce. Interestingly, Pinto et al. (2007) found that radial growth of silver fir was low in the presence of Norway spruce, whereas the height growth of silver fir increased in the presence of the fast growing *Picea abies* (Pinto et al. 2008). However, it is probably impossible to entirely divorce the association between species diversity and productivity from other biotic and environmental factors (Vilà et al. 2005). Our data showed negative influence of admixed tree species in Norway spruce site index, but the share of admixed tree species was limited to 30% within the research area. Furthermore, the study did not distinguish between different tree species.

There are two geographical zones relevant for spruce in Slovenia: the Alps and the dinaric zone. It would surely be interesting to analyse each zone separately, but our sample is not large enough for a division. The risk of overfitting would be too high. Most of other studies analysed site index curves separately by regions (Keller 1978; Schadauer 1999; Seynave et al. 2005), but differences between regions were not always detected (Sharma et al. 2011).

Another important issue regarding site productivity is the long-term effects of logging residue removal (e.g. Wall and Hytönen 2011). Recent studies showed that site productivity of Norway spruce stands was only temporarily reduced due to the whole-tree harvest (Nord-Larsen 2002; Egnell 2011), or the effects were inconclusive due to the confounding effect of site factors (Wall and Hytönen 2011). Despite that, further research activities are needed to get conclusive results, particularly in the temperate zone.

In the last two decades many studies in Central Europe established accelerated growth of forests (Spiecker et al. 1996). As regards Norway spruce, its growth has increased as well (e.g. Pretzsch 1996; Schadauer 1996; Wenk and Vogel 1996). Our research showed that the relationship between age and site index is not significant if the influence of elevation is eliminated (younger stands were situated on lower elevations in average and *vice versa*). Concerning the causes of growth trends in Europe, the role of increased nitrogen availability for the past changes was exposed (Kahle et al. 2008), whereas for the future climate change and especially CO_2 fertilization will be of increasing importance (ibid.). Recent research studies showed that Norway spruce is quite vulnerable to climate change, in particular at low-elevation sites (Lexer et al. 2002; Albert and Schmidt 2010).

In the future the studies on the productivity of mixed and uneven-aged stands should be carried out. In such forests the existing yield tables will become increasingly unreliable (Hasenauer 2006). As a potential alternative, tree growth models have been developed (ibid.).

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Appendix

Appendix 1: Regression parameters

Figure	Bedrock type	Curve form	R^2_{adj}	*P*
1	Silicate	$SI_{100} = 26.0426 + 0.026 \times Elevation - 0.00002 \times Elevation^2$	0.212	0.0001
	Carbonate	$SI_{100} = 35.538 + 0.0005 \times Elevation - 0.00001 \times Elevation^2$	0.435	0.0000
2	Silicate	$SI_{100} = 33.254 + 0.011 \times Elevation - 0.00001 \times Elevation^2$	0.463	0.0000
	Carbonate	$SI_{100} = 46.418 \times (0.999^{Elevation})$	0.577	0.0000