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The Impact of Soil Conditons on the Growth of Douglas-fir in Austria

Der Einfluss des Bodens auf das Wachstum von Douglasie in Österreich

Tamara Eckhart[1,2], Wolfgang Hintsteiner[1,2],
Georg Lair[3], Marcela van Loo[1], Hubert Hasenauer[1]

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Schlagwörter: Douglasie, Klimawandelanpassung, Bestandeskreisflächenzuwachs

Abstract

The Douglas-fir, native to western North America, is a drought-tolerant species and considered as one of the most promising key tree species in Western and Central Europe for forest adaption under changing climate conditions. The wide native distribution range of the Douglas-fir, covering a large latitudinal and elevation range, constitutes genetically differentiated populations. Thus, the selection of suitable proveniences and site conditions are of major importance in guaranteeing a successful cultivation outside its natural distribution range. In this study, we investigate how environmental conditions may influence the growth of Douglas-fir in Austria and Southern Bavaria-fir stands. We develop a basal area increment model based on stand density, tree size and site conditions. Furthermore, the environmental factors climate, topography and soil and their relationship versus site index

1 Institute of Silviculture, University of Natural Resources and Life Sciences, Peter Jordan Straße 82, A-1190 Wien, Austria; e-mail: tamara.eckhart@boku.ac.at
2 alpS-GmbH, Innsbruck
3 Institute of Soil Research, University of Natural Resources and Life Sciences, Peter Jordan Straße 82, A-1190 Wien, Austria

are investigated. Eleven Douglas-fir stands from Austria and Bavaria are randomly selected. The genetic seed sources are from the Western Cascades in Washington and Oregon. The 10 year basal area increment per hectare (BAI10) was modeled with a nonlinear power function explaining 77 % of the existing variation.

Zusammenfassung

Die trockenresistente Douglasie ist eine nordwestamerikanische Baumart und gilt aufgrund der erwarteten Klimaerwärmung als eine der aussichtsreichsten Alternativbaumarten in West- und Mitteleuropa. Das große natürliche Verbreitungsgebiet umfasst unterschiedlichste Standorte und Klimabedingungen, an die sich die Douglasie regional angepasst hat. Aufgrund dieser hohen genetischen Differenzierung ist die Auswahl der geeigneten Herkunft sowie die richtige Standortswahl entscheidend für den Anbauerfolg der Douglasie außerhalb ihres Ursprungsgebietes. In dieser Studie wird der Einfluss des Standortes auf das Wachstum von Douglasienbeständen untersucht. Dazu wird ein Kreisflächenzuwachsmodell auf Bestandesebene mit den Eingangsparametern Bestandesdichte, Baumdimension und Standortsbedingungen entwickelt. Außerdem wird der Einfluss der Umweltfaktoren Klima, Topographie und Boden auf die Oberhöhenbonität untersucht. Die Studie basiert auf elf zufällig ausgewählten Douglasienbeständen in Österreich und Bayern mit bekannter Herkunft. Die untersuchten Douglasienbestände stammen aus dem Gebiet westlich der Kaskaden in Washington und Oregon. Der 10-jährige Kreisflächenzuwachs pro Hektar (BAI10) wurde mit einer nichtlinearen Potenzfunktion modelliert welche 77 % der Gesamtvariation erklärt.

1. Introduction

The range of European forests is mainly determined by climate, whereas climate extreme values limit the distribution of tree species rather than average values. Due to present and future changes of the major limiting factors temperature and precipitation, possible impacts of these changes are of interest. Climate change impacts on European forests vary regionally with diverse effects (Maracchi et al., 2005). While increasing temperature generally leads to higher photosynthesis activity, higher temperatures also trigger drought periods which are assumed to be limiting factors for tree growth in the future (Kapeller et al., 2012). In temperate forests, drought is a major constraint for forest stability and productivity. Due to the predicted increase in the frequency and duration of drought periods under a changing climate, this problem might become even more severe (Peters et al., 2013). Especially the Norway spruce, the most productive coniferous species, is more susceptible to dry periods and may (very likely) not survive under future conditions in some parts of Europe (Kapeller et al., 2012). Hence, adaption strategies have to be developed, and plantations of more tolerant species are highly discussed in Europe. The Douglas-fir (Pseudotsuga menziesii), native to western North America, is a drought-tolerant species and considered as one of the most promising key tree species in Western and Central Europe for forest adaption under changing climate conditions. Moreover, high productivity rates, high wood quality, as well as suitable ecological characteristics like high stability constitute great expectations from Douglas-fir cultivations in Austria and elsewhere (Englisch, 2008, Kleinschmit and Bastien, 1992).

The wide native distribution range of the Douglas-fir (Little, 1971) (Fig. 2), covering a large latitudinal and elevation range, constitutes genetically differentiated populations (Kleinschmit and Bastien, 1992). Accordingly, the selection of suitable proveniences and site conditions are of major importance to guarantee a successful cultivation outside its natural distribution range (Englisch, 2008). The purpose of this work is to understand the growth of the non-native tree species, explained by these three factors: (i) stand competition, (ii) tree size and (iii) site quality. Furthermore, the influence of environmental factors on the site quality is investigated. A common indicator for site quality is the site index, defined as the mean dominant tree height at a given reference age (Kindermann and Hasenauer, 2005).

The objectives of this study are (i) to model basal area increment per hectare by a nonlinear power function, (ii) to investigate the environmental factors affecting Douglas-fir growth, and based on these environmental factors, (ii) to assess soil, topographic and climate factors deriving from the site index.

2. Material and methods

2.1. Study area

In the present study, eleven old Douglas-fir stands were randomly selected in Eastern Austria and Lower Bavaria (Fig. 1) to investigate soil, climatic and topographic factors affecting Douglas-fir growth. The study area represents a variety of climatic environments, with mean annual precipitation ranging from 583 to 1608 mm and an annual temperature gradient between 6.5 and 10.3 °C. The elevation of the study center plots vary from 202 to 786 m above sea level and a slope inclination between 3 and 19 degrees (Table 1). The parent material was determined based on the soil map of Austria (Weber, 1997) and Germany (BGR, 2006) with various granites, gneiss and one limestone bedrock material.

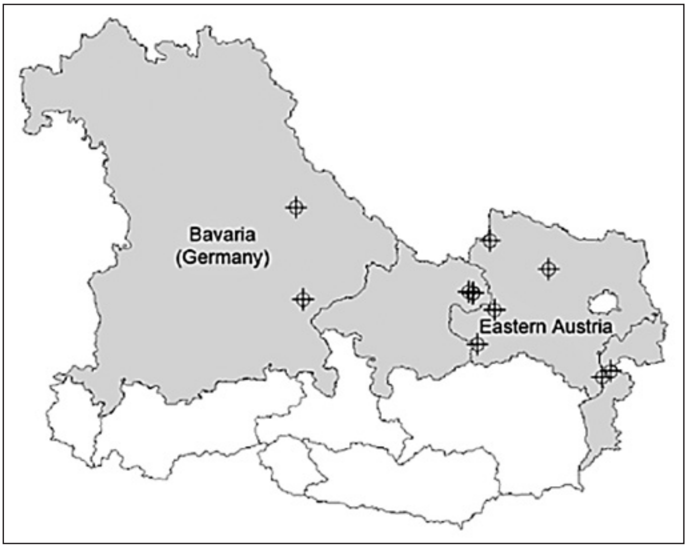

Fig. 1: Location of the study area and plots across Eastern Austria and Bavaria

2.2. Sampling design

All sample plots are located in pure even-aged Douglas-fir stands, with the following constraints:

(i) all stands belong to the coastal variety of the Western Cascades in Washington and Oregon, (ii) stand size ≥ 1 ha, (iii) proportion of Douglas-fir basal area ≥ 80 % and (iiii) a minimum age of 60 years.

The previously unknown origin of the selected Douglas-fir stands, which are recommended for seed harvesting and breeding, was assessed by genetic provenance analyses and could be assigned to the coastal variety of the Western Cascades in Washington and Oregon (Hintsteiner et al., 2014) (Fig. 2).

Fixed area plot

In each forest stand, a fixed area plot with a radius of 20 m (0.02 ha) was randomly selected to represent relatively uniform stand and soil characteristics. Forest stand, soil, and climatic characteristics were assessed on each plot through different variables, which are summarized in table 1.

Fig. 2: Natural origin area of the coastal (dark grey) and inland (light grey) Douglas-fir in North America and assigned provenances of the Western Cascades in Washington and Oregon, (adapted after Little, 1971)

Within a radius of 20 m, the diameter at breast height (DBH), the horizontal distance and the azimuth to the plot center of each tree with a DBH ≥ 10 cm was measured. In order to calculate the stand age and the basal area increment, wood core samples at breast height were taken from five trees closest to the central point of the fixed area plot. Tree height and height to the living crown base were measured with a vertex.

Table 1: Variables and analytical procedures concerning forest stand, topography, soil and climate

	Variable		Unit	Mean (min-max)	Method
Stand parameters	DBH	Diameter at breast height	cm	62 (41 - 82)	Tree tape
	H	Height	m	40 (23 - 50)	Vertex
	ELEV	Elevation	m a.s.l	538 (202 - 786)	GPS
	SLO	Slope inclination	Degrees	12 (3 - 19)	Inclinometer
	Aspect	Aspect	Degrees	139 (6 - 337)	Wyssen compass
	rel. BAI10	Basal area increment 10yr	%	15 (7-21)	Tree ring analysis
	CCF	Crown competition factor	[-]	145 (40 – 210)	Krajicek et al. (1961), Hasenauer (1997)
	μDBH_1	Mean DBH at the beginning of the growing period	cm	54 (39 – 71)	Equation 6
	SI	Site index 100yr	m	46 (36 - 56)	Mitscherlich and Richards (1919), Kindermann and Hasenauer (2005)
Soil parameters	pH H2O*	Actual pH	[-]	4.5 (4.0 - 5.9)	ÖNORM L 1083
	pH CaCl2*	Potential pH	[-]	4.0 (3.7 - 5.4)	ÖNORM L 1083
	C*	Carbon	%	2.8 (1.4 - 5.4)	ÖNORM L 1080
	N*	Nitrogen	%	0.2 (0.1 - 0.3)	ÖNORM L 1082
	C/N*	C/N ratio	[-]	16.7 (12.6 - 21.0)	ÖNORM L 1082
	AVP*	Available phospor	kg/ha	32 (1 - 139)	Bray and Kurtz 1945
	Ca*	Calcium	kg/ha	4680 (249 - 25589)	ÖNORM L 1086-1
	Mg*	Magnesium	kg/ha	257 (19 - 1058)	ÖNORM L 1086-1
	K*	Potassium	kg/ha	110 (54 - 221)	ÖNORM L 1086-1
	Na*	Natrium	kg/ha	35 (9 - 122)	ÖNORM L 1086-1
	Al*	Aluminum	kg/ha	663 (263 - 1257)	ÖNORM L 1086-1
	Fe*	Iron	kg/ha	17 (0.7 - 52)	ÖNORM L 1086-1
	Mn*	Manganese	kg/ha	120 (18 - 305)	ÖNORM L 1086-1
	H+*	Hydron	mmol/kg	2.4 (0.5 - 4.3)	ÖNORM L 1086-1
	CEC eff.*	Cation-Exchange Capacity	mmol/kg	164 (61 - 654)	ÖNORM L 1086-1
	Bsat*	Base saturation	%	43 (13 - 91)	ÖNORM L 1086-1
	PO43-*	Phosphate	kg/ha	1 (0 - 4)	ÖNORM L 1092
	NO3-*	Nitrate	kg/ha	33 (1 - 77)	ÖNORM L 1092
	NO2-*	Nitrite	kg/ha	1 (0 - 13)	ÖNORM L 1092
	SO42-*	Sulfate	kg/ha	101 (41 - 248)	ÖNORM L 1092
	Clay*	Clay	%	17 (13 - 24)	ÖNORM L 1061
	Silt*	Silt	%	42 (30 - 64)	ÖNORM L 1061
	Sand*	Sand	%	40 (13 - 50)	ÖNORM L 1061
	Skeleton*	Skeleton	%	17 (1 - 34)	ÖNORM L 1061
	PV*	Pore volume	%	67 (55 - 78)	ÖNORM L 1068
Climatic parameters	A-PPT	Mean annual precipitation	mm	886 (583 - 1608)	DAYMET
	S-PPT	Mean summer precipitation [June, July, Aug]	mm	324 (234 - 551)	DAYMET
	W-PPT	Mean winter precipitation [Dec, Jan, Feb]	mm	160 (83 - 340)	DAYMET
	A-TEMP	Mean annual temperature	°C	8.2 (6.5 - 10.3)	DAYMET
	S-TEMP	Mean summer temperature [June, July, Aug]	°C	19.4 (15.4 - 17.1)	DAYMET
	W-TEMP	Mean winter temperature [Dec, Jan, Feb]	°C	-3.2 (-6.3 - 2.1)	DAYMET

*Separately assessed in A and B horizon (0-35 cm)

2.3. Stand parameters

Topography

On each sample plot topographic characteristics were assessed through different variables as listed in table 1. Elevation, slope inclination, aspect and coordinates of each forest stand were taken at the fixed area plot center and measured by a GPS device, inclinometer and Wyssen-compass, respectively.

Stand basal area increment

The basal area increment per hectare over past 10 years in percent was calculated as follows:

$$rel.BAI10 = \frac{rmsBAI10 * N * BUF}{BA} \quad [1]$$

$$BUF = \frac{10000}{A} \quad [2]$$

rel.BAI10 is the 10 year basal area increment in percent, rmsBAI10 is the quadratic mean of the 10 year basal increment of the sample trees, N is the number of Douglas-fir trees, BUF is the blow up factor, BA is the actual basal area per hectare. To get values per hectare, the blow up factor was calculated by dividing 10000 (1 ha) through the area of the plot (A, m²).

Index of stand density

Stand density of forests is commonly assessed with the crown competition factor (CCF) or the stand density index (SDI) (see Hasenauer et al., 2012). For this study, the CCF was applied (Monserud and Sterba, 1995). According to Krajicek et al. (1961), the CCF is the sum of the species-specific potential crown area (PCAi) divided by the plot area (A).

$$CCF = \frac{\sum PCA_i}{A} \quad [3]$$

The potential crown area was calculated with the open grown crown widths (CW, in m) given by Hasenauer et al. (1997), which defines the crown area of a tree at a given diameter at breast height (DBH, in cm) assuming open grown conditions.

$$PCA = \frac{\pi * CW^2}{4} \quad [4]$$

$$\ln(CW) = a + b * \ln(dbh) \quad [5]$$

a and b are species specific coefficients (table 2)

Table 2: Species specific coefficients for the crown width function after Hasenauer (1997).

Tree species	a	b
Norway spruce and other coniferous trees	-0.323	0.6441
Larch	-0.339	0.6823
Black pine	-0.157	0.631
Beech and other broad-leafed trees	0.2662	0.6072

Tree size effect

To describe the mean diameter increment relative to the tree size, the mean diameter at breast height at the beginning of the growing period (µDBH1) was calculated as follows:

$$\mu DBH_1 = \mu DBH_2 - \mu id_{10} \quad [6]$$

μDBH_2 is the arithmetic mean diameter at breast height of the sample trees at the end of growing period and μid_{10} is the mean 10 year diameter increment.

Index of site quality

The site index, as the most common indicator of site quality, is defined as the mean dominant tree height at a given reference age (Kindermann and

Hasenauer, 2005). In this study, SI was defined as the mean height of the 100 tallest trees per hectare (2 tallest trees on 0.02 ha plot) at the base age of 100 years. To calculate the site index at reference age, tree growth functions available for different tree species can be used by applying the dominant height growth function after Mitscherlich/Richard (1919) for the "Douglas-fir northwestern Germany", the SI_{100} was iteratively calculated:

$$OH = a(1 - e^{-b*t})^{c} \quad [7]$$

$$a = a_0 + a_1 * OH_{100} + a_2 * {OH^2}_{100}$$

$$a = a_0 + a_1 * OH_{100} + a_2 * {OH^2}_{100}$$

$$c = c_0 + c_1 * OH_{100} + c_2 * {OH^2}_{100}$$

OH = dominant tree height

OH_{100} = dominant tree height at the age of 100 (directly correlated to SI)

t = stand age at DBH + 10 years

a, b, c = coefficients for „Douglas-fir northwestern Germany" based on the yield table after Bergel (1985) from table 3

Table 3: Coefficients for the dominant tree height function after Mitscherlich/Richard (1919) for "Douglas-fir northwestern Germany (DoNwd)" (Kindermann and Hasenauer, 2005)

	a0	a1	a2	b0	b1	b2	c0	c1	c2
DoNwd	-5.92E+00	1.26E+00	0	9.90E-02	-2.79E-03	2.54E-05	9.43E+00	-3.15E-01	3.03E-03

2.4. Soil parameters

The soil characteristics were assessed through borehole samples and separated into A and B horizon (0-35 cm). In total, 44 borehole samples of four transects distributed across each forest stand were taken in order to overcome the expected heterogeneity of forest soils. The chemical and physical soil properties were analyzed for each transect by standard laboratory methods. Four density core samples per forest stand were taken at the center of each transect to determine the pore volume of A and B horizon. The analytical results were expressed as soil stocks on a mass per unit area basis using bulk density, coarse fragment content, and depth of A and B horizon (0-35 cm). The soil variables listed in table 1 are the weighted mean values of A and B horizon.

2.5. Climatic parameters

The Austrian version of the climate interpolation model DAYMET was applied to calculate daily climatic data (minimum and maximum temperature and precipitation as well as solar radiation) for each study plot from 1960 to 2010 (Thornton et al., 1997, 2000, Hasenauer et al., 2003).

3. Statistical analysis

3.1. Stand basal area increment model

Stand basal area increment per hectare is determined by the three factors: (i) stand competition, (ii) tree size and (iii) site index parameters (Wykoff, 1990). Thus, a nonlinear power function including these three factors was defined:

$$rel.BAI_{10} = a * x_{SD}^{b} * x_{TSE}^{c} * x_{SI}\ d \qquad [8]$$

rel. BAI is the 10 year relative basal area increment per hectare of the Douglas-fir stands, x_{SD}, x_{TSE}, x_{SI} are variables corresponding to the three factors stand density, mean tree size and site index, and a, b, c, d represent model coefficients. The coefficients b and d describe the curvature of the power function. The parameterization of the nonlinear model function rel. BAI_{10} was carried out with the statistical program PASW 18. In order to test for multicollinearity, the variation inflation factor (VIF) after Snee (1973, 1977) was calculated for each explanatory variable.

$$VIF = \frac{1}{1-R^2} \qquad [9]$$

A large VIF (e.g. > 5) would indicate a strong correlation between certain predictor variables which can produce misleading results due to inadequate independent information (Hasenauer, 1997).

3.2. Site index versus site variables

Linear regression plots of Site Index (SI) versus site variables did not indicate any non-linear relation. Thus the following multiple linear equation was used to study the variation of site index in relation to site variables:

$$SI = a + bx_t + cx_s + dx_c + \varepsilon \qquad [10]$$

SI is the site index, x_t, x_s, x_c are variables corresponding to topographic, soil and climatic factors, a, b, c, d represent model coefficients and ε is the additive error term. For statistical calculations, the program R was applied.

The analysis of the data followed four steps:

I. The selection of environmental factors that are significantly related to the variation in the SI and ecologically sound
II. The entering of significant variables sequentially according to their coefficient of determination R^2, starting with the most significant variable
III. Testing for multicollinearity according to a variation inflation factor (VIF) < 5 for each predictor variable after Snee (1973, 1977)
IV. The selection of the best model to explain and predict the SI of environmental variables according to the adjusted coefficient of determination R_{adj}^2

4. Results

4.1. Prediction model for stand basal area increment

A basal area increment model at stand level was developed for the 11 Douglas-fir sites. The following nonlinear model was determined to predict the relative 10 year basal area increment projection per hectare for the Douglas-fir (rel.BAI_{10}):

$$rel.BAI_{10} = a * CCF^b * \mu DBH_1^c * SI * d \qquad [11]$$

CCF is the crown competition factor, μDBH_1 corresponds to the mean diameter at breast height at the beginning of the growing period and SI is the site index.

Due to the rather small sample size of only eleven Doulgas-fir stands, a resampling of the data was necessary to increase the accuracy of the model, defined by the standard error. The bootstrapping method was applied, as recommended by Adèr et al. (2008), to resample the original data set to a random sample size of 100 and to calculate the bootstrapped standard error. The resulting model explains 77 % of the variation in the 10 year basal area increment per hectare. All parameters entered the model significant at a 5 % probability level and multicolinearity was controlled to be a required variation inflation factor (VIF) < 5.

Table 4: Regression coefficients related to equation 11, the bootstrapped standard error of the nonlinear model and the coefficient of determination (R^2) as a measure of the goodness of fit.

	Coefficients	Estimates	Standard error*
Constant	a	8.587	13.284
CCF	b	-0.761	0.184
μDBH_1	c	-1.568	0.388
SI	d	8.591	13.281
R^2	0.77		
*Bootstrapped standard error based on a sample size of 100			

The predictor variables CCF and μDBH_1 correlate negatively and the SI positively, versus the predicted 10 year stand basal area increment per hectare.

Sensitivity analysis

The theoretical effects of the independent variables CCF, μDBH_1 and SI versus the stand basal area increment was tested by modeling the rel. BAI_{10} variation and carrying one variable within its measured range (minimum – maximum value) while the other independent drivers were kept constant at the corresponding mean values. Figure 3 provides the results for the competition factor CCF, which indicates the strongest effect, followed by the tree size factor μDBH_1 and the site index SI.

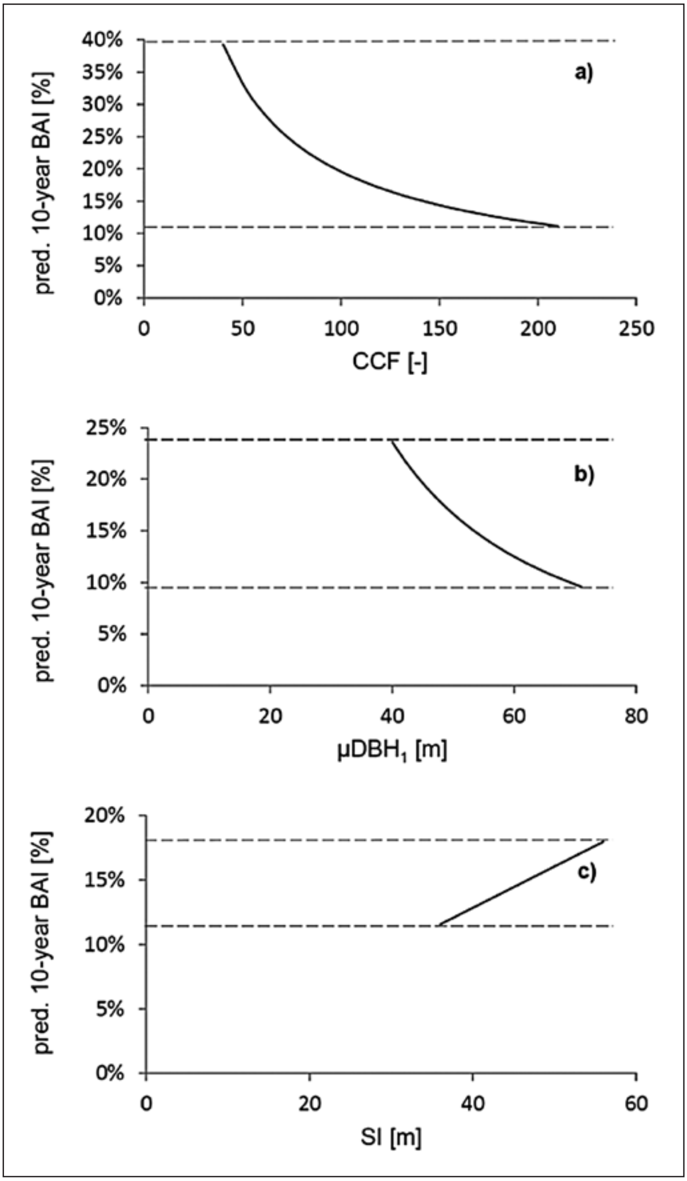

Fig. 3: Sensitivity analysis of the main influencing parameters CCF, μDBH_1 and SI
(a) CCF within the range of min – max and the mean values of SI and μDBH_1, (b) DBH_1 within the range of min – max and the mean values of CCF and SI (c) SI within the range of min – max and the mean values of CCF and μDBH_1

4.2. Site index versus site variables

The site index, defined as the dominant stand height attained at a particular age, may be considered as a surrogate of the environmental and/or site conditions for a forest stand. Thus, we next relate the site index to a number of soil parameters available for our forest sites to identify and explore the key drivers in the site index variation. Figure 4 provides the results including the correlation coefficients.

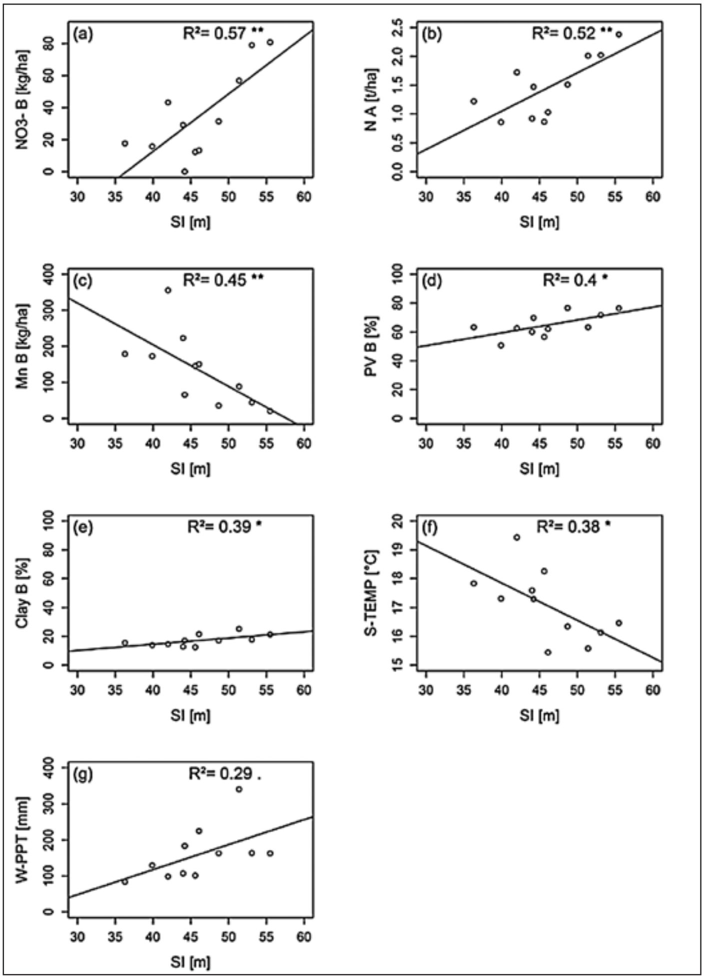

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Fig. 4: Environmental factors (a-g) significantly related to the variation in Douglas-fir site index

According to Fig. 4, nitrogen in the form of nitrate (NO_3^-) in horizon B indicates the highest positive correlation and accounts for 57 % of the variation in SI. Manganese stock in horizon B (Mn B) is negatively correlated (R^2 0.45) to the SI. Pore volume PV and clay content in horizon B show positive correlations to the SI and account for 40 % and 39% of the variation, respectively. Mean summer temperature indicates a negative correlation to SI (R^2 0.38) and winter precipitation shows a weak positive correlation (R^2 0.29). In a next step, those variables with the greatest influence were sequentially combined into a multiple regression equation.

Best model output

Multiple linear regression method was used to calibrate a model for predicting the site index as it may depend on quantitative environmental drivers.

$$SI = a + bNO_3^- \mathrm{B} + cMn\,B \quad [12]$$

The linear model includes the two soil variables NO_3^- B and Mn B, which are statistically highly significant at the 95 percent level, and explains 73 % percent of the variation in the site index (table 5). Multicolinarity was controlled by a requested inflation factor (VIF) of ≤ 5. The remaining standard error of the model estimate is 2.98 m.

Table 5: Estimates, standard error and p-values for the multiple regression model (equ. 12)

	Estimates	Standard error	p-value	VIF
Constant	45.501767	2.269763	< 0.001	
NO3- B	0.127458	0.036029	< 0.01	1.10
Mn B	-0.02842	0.009963	< 0.05	1.10
Radj²	0.73			

Sensitivity analysis

Again, the theoretical behavior of the predictor variables NO_3^- B and Mn B versus the resulting SI (Site index) was tested by modeling the SI development for different levels by varying one parameter within the measured range (minimum to maximum value), while keeping the other parameters constant at its mean value (see Fig. 5). The effect of NO3- B and Mn B on the SI development ranges between 42 – 52 m and 40 – 49 m, respectively. According to Fig. 5, the predictor variables NO3- B and Mn B have a similar effect on the development of the site index.

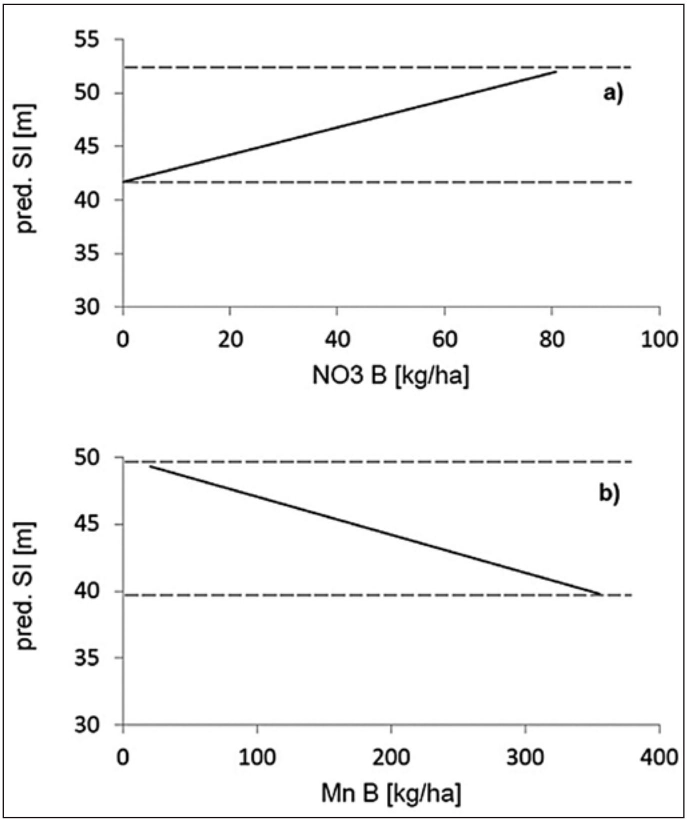

Fig. 5: Sensitivity analysis of the main influencing parameters NO3- B and Mn B (a) NO3- B within the range of min – max and the mean value of Mn B and (b) Mn B within the range of min – max and the mean value of NO_3^- B

5. Discussion

The stand level of the Douglas-fir model predicts the relative 10 year basal area increment per hectare as a nonlinear power function with the predictor variables crown competition factor, mean diameter at breast height at the beginning of the growing period and site index (equ. 11). The basal area increment relative to tree size is greatest in low density stands with a high site quality. Theoretically, the accurate relationship between increment and tree size would have a positively skewed unimodal form as increment increases to a maximum in early life and then gradually decreases (Wykoff, 1990).

As our sampling design was restricted to forest stands with a minimum age of 60 years, no modification of the power function was necessary. The sensitivity analysis (Figure 3) indicated a substantial effect of the competition parameter CCF on the basal area increment. Note that in our data we had covered a wide range of CCF values (40-120) (see Table 1). For the tree size parameters, the sampling design restricted a broader range in our data due to the fact that we only recorded stands older than 60 years. This is also evident for the site conditions which would have required a broader range in the sampled forest stands.

The genetic material of our Douglas-fir stands comes from the coastal variety of the Western Cascades in Washington and Oregon (Hintsteiner et al., 2014). Furthermore we selected only pure even aged Douglas-fir forests by ensuring a relative Douglas-fir proportion in a total stand basal area of ≥ 80%. This suggests that any difference in the growth rates of our Douglas-fir stands are only driven by stand density as well as soil and/or site conditions. As shown in Table 4, crown competition factor CCF, a measure for stand density, mean diameter at breast height and the site index entered the model significantly.

A correlational study determining the key driver for the site index (see Figure 4 a-g) revealed that the large number of environmental parameters (Table 1) can be reduced to only seven where the two soil parameters NO_3^- B and Mn B explain about 73 % of the site index variation (see Table 5). While nitrogen is the most limiting macronutrient in forests all over the world (Littke Hanft, 2012), manganese as a micronutrient intervenes in photosynthesis (Millaleo et al., 2010). Previous studies that examined the correlations between nitrogen fertilization and growth response in the Pacific Northwest illustrated positive responses of Douglas-fir growth (e.g. Gardner, 1990; Miller et al., 1986). Moreover, nutrient deficiencies in Douglas-fir stands were consistently demonstrated only for nitrogen (Weetman et al., 1992), which is consistent with our results.

Compared to the positive effect of nitrogen, manganese was negatively correlated to the site index (Fig. 4c). Manganese is an essential micronutrient for plants but may turn toxic in excessive concentrations. The amount of available manganese is influenced by soil pH, excess of water, poor drainage or applications of organic material (Millaleo et al., 2010). According to our study, the negative impact of manganese could be an indication of waterlogged soil conditions, as Mn B is positively correlated to the pore volume in horizon B ($R^2 = 0.40^*$). No correlation between Mn B and soil pH B was found. The sensitivity analysis (Figure 5) showed an equal effect of both soil parameters on the Douglas-fir site index.

Pore volume PV, indicating the air- and water holding capacity of soils, and clay content, alluding the water- and nutrient holding capacity of soils, in horizon B showed positive correlations to the SI (Fig. 4 d-e). The positive effect of the soil parameter clay content in B horizon is in agreement with the results of the soil-site study after Steinbrenner (1979) on sedimentary and volcanic soils in western Oregon. Other studies also revealed negative correlations of clay content and site index (e.g. Corona et al., 1998). Soil nutrients and soil texture were varied highly within all assigned bedrock materials (gneiss, granite, limestone). Accordingly, the use of soil parent material differentiated site indices would not be meaningful.

Correlations between climatic parameters and the SI are evident, with a negative correlation of mean annual summer temperature (Fig. 4f) and a positive correlation of mean winter precipitation (Fig. 4g) versus the SI. Under a changing climate with projected increases of mean summer temperatures and mean winter precipitation in Austria (Loibl et al., 2011), the climate sensitivity of the Douglas-fir is of particular interest to enable a successful incorporation in adaptive forest management considerations.

No significant correlations were found between the SI and the remaining environmental parameters (see Table 1), possibly due to the limited range of the selected Douglas-fir sites. To enlarge the gradient of the environmental parameters, Douglas-fir stands developed under extreme conditions should be sampled. This includes Douglas-fir sites under dry conditions as well as calcareous sites. Current recommendations for Douglas-fir cultivation in Austria and Germany are basically restricted to non-calcareous soils (e.g. Englisch, 2008), which could not be confirmed in our study.

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