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Developing site index curves under changing site conditions

Erstellung eines Oberhöhenfächers bei variablen Standortsverhältnissen

Georg Erich Kindermann [1]

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Schlüsselbegriffe: *Fichte, Höhenzuwachs, konstante Standortsbedingungen, Picea abies, Klimawandel, Waldwachstumsmodell*

Abstract

The site index is the top height of a stand typical at the age of 100 years and is used to describe the productivity. It can be estimated by using age and top height of the stand in combination with site index curves. Site index curves describe the development of top height over age. Site index curves are typically based on repeated height measurements of stands or stem analysis. Short and long term changes of the environmental site conditions affect tree height growth and the derived growth curves. To develop site index curves for height development under constant site conditions over time, a site-specific site index model was created, which allows eliminating the influence of changes of site conditions on the observed height increments. The site specific index model developed in our study is driven by temperature, precipitation, radiation, altitude, soil and vegetation type, stand density and species composition.

[1] Austrian Research and Training Centre for Forests, Natural Hazards and Landscape, Department of Forest Growth and Silviculture, Seckendorff-Gudent-Weg 8, 1131 Vienna, Austria
Georg Erich Kindermann (georg.kindermann@bfw.gv.at)

This approach allows creating site index curves for height development under constant site conditions, even when the observed height-growth has been affected by changing site conditions. The new approach has been applied to create a site index curve for Norway spruce on basis of observed height increments from the Austrian national forest inventory from 1981 to 2009. The site index curve is given by: h = c0 * log(1 + exp(-8.754 + 4.625e-04 * c0^2.818) * age^3)^0.75, where c0 is describing the yield level. Observed growth deviate around those curves but neither using growth regions nor altitude classes can reduce this deviation. The site index curves can be used as a substitute for those given in yield tables.

Zusammenfassung:

Die Oberhöhenbonität gibt üblicherweise die Bestandesoberhöhe im Alter 100 an und beschreibt die Wuchsleistung. Sie kann aus Alter und Oberhöhe mit Hilfe eines Oberhöhenfächers bestimmt werden. Der Oberhöhenfächer zeigt die Entwicklung der Oberhöhe in Abhängigkeit vom Bestandesalter. Oberhöhenkurven werden traditionell mittels wiederholter Höhenmessungen eines Bestandes oder mit Stammanalysen erstellt. Sowohl kurz-, als auch langfristige Standortsveränderungen beeinflussen das Höhenwachstums und die abzuleitenden Höhenkurven. Um einen Oberhöhenfächer bei konstanten Standortsverhältnissen zu erstellen, wurde ein standortsabhängiges Oberhöhenmodell entwickelt. Dieses ist abhängig von Temperatur, Niederschlag, Strahlung, Seehöhe, Boden- und Vegetationstyp, Bestandesdichte und Baumartenzusammensetzung und erlaubt Einflüsse einer standörtlichen Veränderung zu eliminieren. Dieses Verfahren ermöglicht die Erstellung von Oberhöhenfächern für konstante Standortsbedingungen, selbst wenn die verwendeten Messdaten einer standörtlichen Veränderung ausgesetzt waren. Diese neue Methode wurde eingesetzt, um einen Oberhöhenfächer für die Fichte, auf Basis von Messungen der Höhenveränderung der österreichischen Waldinventur im Zeitraum 1981 bis 2009, zu erstellen. Der Oberhöhengang kann mit h = c0 * log(1 + exp(-8.754 + 4.625e-04 * c0^2.818) * alter^3)^0.75 beschrieben werden, wobei c0 die Bonität beschreibt. Das beobachtete Bestandeswachstum streut um diesen Höhenfächer, jedoch sind weder eine Untergliederung nach Wuchsregionen noch eine Höhenstufengliederung in der Lage diese Abweichungen zu reduzieren. Der hier vorgestellte Oberhöhenfächer kann als Ersatz für jene der Ertragstafel bzw. Hilfstafeln für die Forsteinrichtung verwendet werden.

1. Introduction

Site index curves should show the height development of dominant trees from a forest stand under constant site conditions. In the past this constant site conditions were implied due to the fact that the time span of observations were in the range of up to one century and short to midterm site variations will be automatically leveled out. The possibility of long term trends and their implications on the development and application of site index curves was shown by EIDMANN (1961) and discussed by WECK (1961), HILDEBRANDT (1961), MOOSMAYER (1961), WEIHE (1962), ASSMANN (1962), MITSCHERLICH (1962) and MOOSMAYER (1962). But already BAUR (1877), who was the first to use age and height to describe site productivity, assumed that his site index curves needed to be updated from time to time due to changes. These site changes can be caused by temperature, precipitation, CO_2, emissions, litter raking, forest pasture, soil cultivation, regeneration systems, different provenances, thinning regimes, … This indicates that observed height developments of forest stands most likely do not show the development under constant site conditions, especially those from the last decades, which grow under changing climatic conditions. In addition, even when there are no site changes, it is still possible that the conditions, which affect tree growth, are changing with the size of the tree, e.g. when the roots reach a ground water influenced zone. So it could be distinguished between site index changes due to (1) changes of the site itself and (2) changes in the utilization of the site by the growing tree. Different combinations of these changes affecting the site index can lead to different growth patterns of trees and stands and can be the reason why different yield tables show different growth patterns. In the end the target should be to build site index curves which show the height development of trees whose site conditions are constant. When the site index is changing due to the fact, that the tree is getting larger and will follow these changes in every generation, these permanent site index changes can be given as an additional site characterization but do not need to lead to separate site index systems. The main problem is the detection whether or not site conditions are constant. Therefore a definition of constant site conditions in the context of site index curves is needed. In addition a method needs to be developed which allows the creation of site index curves from observed height increments which eliminates site fluctuations during the observation period. The main target is the creation of site index curves showing the height development under constant site conditions.

2. Data

The national forest inventory of Austria observes tree heights on permanent sample plots since 1981. If a tree belongs to the dominant trees, if it is a spruce (*Picea abies* (L.) H. Karst.) and if its height was measured at least two times, it was used to create the site index system. A tree is dominant, when adapting the definition of POLLANSCHÜTZ (1973), if it belongs to the group of the highest trees having a total basal area of $12m^2$/ha. As the forest inventory uses angle count sampling with a counting factor of 4, these are the three highest trees in the sample. The inventory was conducted in 1981–1985, 1986–1990, 1992–96, 2000–2002 and 2007–2009. The observations from

1986-1990 are not used as they might have a bias (KINDERMANN 2017). Height increments can be derived from the repeated height measurements. E.g. if a tree was measured three times the height increment between time a - b, a - c and b – c could be used. In total on 6145 inventory points 11995 Spruce trees with 20897 measured height increments have been used.

Site information was taken (soil type, vegetation type) or derived (water holding capacity) from the forest inventory (HAUK AND SCHADAUER 2009).

Soil types were coded as given in table 2 and vegetation types were coded as given in table 3.

Weather information was taken from maps showing daily temperature, precipitation and global radiation on a 1x1 km grid provided by Zentralanstalt für Meteorologie und Geodynamik (HIEBL et al. 2015, HIEBL et al. 2017, HOFSTÄTTER 2016, OLEFS 2015). This weather information has been interpolated from the surrounding grids to the inventory point using a local gradient (KINDERMANN 2010).

Table 1: Final site index table for spruce. The first row gives the stand age and the following rows give the top height for different site indexes. When taking the age of 100 as reference age than the site index ranges from 5m to 45m with 5m steps.

Tabelle 1: Oberhöhentabelle für Fichte. Die erste Zeile gibt das Bestandesalter an. Die folgenden Zeilen zeigen die Oberhöhe für verschiedene Oberhöhenbonitäten. Wenn das Alter 100 als Referenzalter für die Bonität gewählt wird, liegen die Bonitäten im Bereich von 5m bis 45m mit einer Schrittweite von 5m.

Age	5	10	15	20	25	30	35	40	45	50	60	70	80	90	100	110	120	140	160	180	200	250	300	350	400	450	500
Height [m]	0.1	0.4	0.8	1.3	1.7	2.2	2.5	2.9	3.1	3.4	3.8	4.2	4.5	4.8	5.0	5.2	5.4	5.7	6.0	6.3	6.5	6.9	7.3	7.6	7.8	8.1	8.3
	0.2	0.7	1.6	2.6	3.5	4.3	5.1	5.7	6.3	6.8	7.7	8.4	9.0	9.5	10.0	10.4	10.8	11.5	12.0	12.5	12.9	13.8	14.5	15.1	15.7	16.1	16.5
	0.2	1.1	2.4	3.9	5.3	6.5	7.6	8.6	9.5	10.2	11.5	12.6	13.5	14.3	15.0	15.6	16.2	17.2	18.0	18.7	19.4	20.7	21.8	22.7	23.5	24.1	24.7
	0.3	1.5	3.2	5.2	7.1	8.8	10.3	11.5	12.7	13.7	15.4	16.8	18.0	19.1	20.0	20.8	21.6	22.9	24.0	24.9	25.8	27.6	29.0	30.2	31.2	32.1	32.9
	0.4	1.9	4.1	6.6	9.0	11.1	12.9	14.5	15.9	17.2	19.3	21.1	22.6	23.9	25.0	26.0	26.9	28.6	29.9	31.1	32.2	34.4	36.1	37.6	38.9	39.9	40.9
	0.5	2.3	5.1	8.2	11.0	13.6	15.7	17.6	19.3	20.8	23.3	25.3	27.1	28.6	30.0	31.2	32.3	34.2	35.8	37.2	38.5	41.1	43.2	44.9	46.4	47.7	48.8
	0.6	2.9	6.3	9.9	13.2	16.1	18.6	20.8	22.7	24.4	27.3	29.7	31.7	33.5	35.0	36.4	37.6	39.8	41.7	43.3	44.7	47.7	50.1	52.1	53.8	55.3	56.6
	0.8	3.5	7.5	11.7	15.5	18.8	21.7	24.1	26.3	28.1	31.4	34.0	36.3	38.3	40.0	41.5	42.9	45.4	47.5	49.3	50.9	54.2	56.9	59.2	61.1	62.7	64.2
	1.0	4.3	9.0	13.8	18.1	21.7	24.8	27.5	29.9	32.0	35.5	38.4	40.9	43.1	45.0	46.7	48.2	50.9	53.2	55.2	57.0	60.7	63.6	66.1	68.2	70.0	71.7

Table 2: Soil type specific coefficients (cSg) from Loop1 without and Loop2 with removed weather trend.

Tabelle 2: Bodentyp spezifische Koeffizienten (cSg) ohne (Loop1) und mit (Loop2)

Soil	n	Loop1	Loop2
1 Leptosols	43	1.0090	1.0077
2 Dystric Cambisols	545	1.0513	1.0519
3 Eutric Cambisols	620	1.0866	1.0886
4 Spodi-Dystric Cambisol	1837	1.0736	1.0746
5 Climate induced Podzols	224	1.0651	1.0707
6 Substrate induced Podzols	113	1.0594	1.0644
7 Gleyic Podzol	22	1.1168	1.1170
8 Light-textured Cambisols	155	1.0621	1.0627
9 Heavy-textured Cambisols	111	1.0162	1.0154
10 Cambisols and Luvisols derived from calcareous loess	35	0.9751	0.9766
11 Planosols from flysch	158	1.0813	1.0827
12 Planosols derived from loess	22	1.0178	1.0127
13 Temporarily watter logged soils	164	1.0531	1.0541
14 Stagnic Cambisols	111	1.0983	1.1032
15 Ferraloc Cambisols	68	1.0421	1.0413
16 Chernozems	0		
17 Leptosols derived from calcareous material	637	0.8980	0.8944
18 Colluvial soils	539	0.9635	0.9600
19 Chromic Cambisols	519	1.0237	1.0223
20 Gleysols	42	1.0973	1.0875
21 Fuvisols along small rivers	35	1.0499	1.0573
22 Fluvisols	11	1.0540	1.0349
23 Mollic and Umbric Gleysols	71	0.9798	0.9737
24 Terric Histosols	1	0.9746	0.9612
25 Fibric Histosols	6	0.9078	0.9130
26 Anthrosols	4	1.0568	1.0411

Table 3: Vegetation type coefficients (cVt) from Loop1 without and Loop2 with removed weather trend.

Tabelle 3: Vegetationstyp spezifische Koeffizienten (cVt) ohne (Loop1) und mit (Loop2)

Veg	n	Loop1	Loop2	Veg	n	Loop1	Loop2
1 Shade tolerant herb types	0			12 Competing grass cover	476	-0.0869	-0.0995
1.1 Asperula-Sanicula	42	-0.0456	-0.0396	12.1 Aira flexuosa	5	-0.0792	-0.0860
1.2 Pulmonaria-Symphytum-Asarum	36	-0.0027	-0.0036	12.2 Calamagrostis villosam	7	-0.1314	-0.1650
1.3 Dent.enneaphyllos-Mercuriali	72	-0.0332	-0.0343	12.3 Calamagrostis arundinacea et c.epigeios	34	0.0251	0.0095
2 Moderately moist herb types	293	-0.0886	-0.0920	12.4 Carex brizoides	18	-0.0340	-0.0288
2.1 Mercurialis	86	-0.0727	-0.0778	12.5 Carex alba	1	-0.3784	-0.3811
2.2 Primula-Hepatica	27	-0.0857	-0.0906	12.6 Calamagrostis varia	3	-0.4522	-0.4649
2.3 Hieracium-Melampyrum	28	-0.1082	-0.1044	12.7 Carex pilosa	1	-0.2366	-0.2427
2.4 Lime light herbs	28	-0.1632	-0.1680	12.8 Other	22	-0.1209	-0.1233
3 Thermophylic herb types	30	-0.1316	-0.1363	13 Depletion types	5	-0.1219	-0.1223
4 Oxalis acetosella types	1151	0.0270	0.0312	14 Subalpine dwarf shrubs	8	-0.1434	-0.1467
4.1 Oxalis typicum	69	0.0163	0.0225	14.1 Rhododendron	8	-0.1628	-0.1670
4.2 Oxalis – Fern	214	0.0822	0.0901	14.2 Vaccinium myrtillus	4	-0.2283	-0.2407
4.3 Oxalis-Cardamine	49	0.0780	0.0834	14.3 Calluna – Juniperus	0		
4.4 Oxalis-Galium rotundifolium	2	0.1014	0.0948	15 Erica types	43	-0.2343	-0.2400
4.5 Oxalis-Homogyne alpina	9	0.0916	0.0886	16 Pasture forest type	82	-0.1256	-0.1373
4.6 Oxalis-Vaccinium myrtillus	183	0.0057	0.0107	16.1 Nardus stricta	5	-0.1490	-0.1594
4.7 Oxalis herb rich	220	0.0349	0.0387	16.2 Larix	5	-0.0400	-0.0321
4.8 Oxalis-Carex brizoides	3	-0.0426	-0.0350	16.3 Salix	5	-0.0052	-0.0168
5 Luxoriant Moss Vaccinium Avenella types	221	-0.0989	-0.1086	16.4 Other	9	-0.1392	-0.1416
6 Sparse Moss Vaccinium Avenella types	1484	-0.0767	-0.0793	17 Pioneer vegetation on extreme sites	0		
6.1 Pteridium aquilinum	65	-0.0927	-0.0970	18 Hydrophytic shrub	78	-0.0081	-0.0064
7 Mose types	59	-0.0820	-0.0940	19 Tall perennial herbs	202	-0.0158	-0.0250
8 Avenella types	64	-0.0517	-0.0467	19.1 Petasites	23	0.0800	0.0901
9 Dry Bluebery types	6	-0.2358	-0.2397	19.2 Adenostyle	15	0.0102	0.0148
10 Calluna types	8	-0.0994	-0.1229	19.3 Felling flora	48	-0.0079	-0.0048
11 Sphagnum Vaccinium Deschampsia types	32	-0.1332	-0.1411	19.4 Impatiens	4	-0.1230	-0.1107
11.1 Sphagnum dominating	2	0.0494	0.0409	19.5 Nitrate flora	41	0.0116	0.0118
				20 Alluvial forest types	4	-0.0527	-0.0305

3. Method

The method can be summarized by:

1. Create site index curves, if needed individual for growth regions, by using the raw observations.

2. Estimate the average site index for each observation point by using the curves form step 1.

3. Create a model, which estimates the site index from step 2 by using site characteristics like temperature and precipitations.

4. Estimate the site index for individual years with the model created in step 3.

5. Create site index curves by eliminating the influence of a possible site index trend by using the estimates form step 4.

At this point the target, creating site index curves which are not influenced by site fluctuations during the observation periods, is reached (loop1). To allow in addition to estimating the site index with site characteristics based on the curves from step 5 we have to go back to step 2 but use here instead of the curves from step 2 those form step 5 and repeat the procedure until step 4 (loop 2).

The height growth function h=c0*log(1+exp(c2)*t^c3)^c1 (KINDERMANN 2016) was used to describe the height development, where h is the dominating height at age t and c0 to c3 are regression coefficients to be estimated. KINDERMANN (2015) showed that site index curves could be created either by using (1) age and height, (2) age and height increment and (3) height and height increment. Creating a site index system, that is able to incorporate site changes, KINDERMANN (2017) showed that either (2) age and height increment or (3) height and height increment, could be used, while (1) age and height comes to an infinite number of site index systems when the site is changing. It was also shown that site index curves created by using height and height increment still come to an identical height at an infinite age even under changing site conditions, which is not the case when using age and height increment. So here a site index system was created using height and height increment which means that the function needs to be reformulated to describe height increment as a function of height and site. The height increment dh in the time span dt can be calculated with dh=c0*log(1+exp(c2)*(t+dt)^c3)^c1–h. The growth function can be reformulated for showing the age: t=((exp((h/c0)^(1/c1))-1)/exp(c2))^(1/c3). With this the function can be formulated as

dh=c0*log(1+exp(c2)*((((exp((h/c0)^(1/c1))-1)/exp(c2))^(1/c3))+dt)^c3)^c1–h (equation 1)

which gives the height increment (dh) for a tree with a given height (h) for a specific time span (dt). As this function is only a reformulation of the original growth function the coefficients c0 to c3 can be used in both forms. This allows showing the stand height for a given age and showing the height increment for a given height. As it could be expected that some coefficients of this function are constant and others are varying from site to site due to different site indexes and different growth patterns the coefficients were estimated using mixed models where the inventory plot characterizes the random effect, which enables that selected coefficients can change from site to site.

When the coefficients are estimated, those which are relatively constant and those which are varying between the inventory point, could be selected. If there is more than one changing coefficient a functional relation needs to be defined between them to come to one site index system. It was tested if there are different growth or altitude regions expressed by different relations of the varying coefficients. If this test shows a need to distinguish between regions for each region, an individual site index system will be created.

With this newly developed site index system(s) for each inventory plot the site index (siHIh) could be estimated from the observed height and height increment. This site index could alternatively be estimated by site information such as soil and weather. It was decided to use monthly weather information covering the time range, which is changing between the observations, which was used to estimate the site index with the site index curves. The weather information was not averaged. The individual monthly data has been used. In a first step the plant available water was estimated by using temperature, precipitation and water holding capacity.

```
plant available water = precipitation into the soil + available soil water
precipitation into the soil = precipitation - (interception + runoff)
available soil water = soil water * (soil water / water holding capacity)^cI9
interception = cI7
runoff =  max(0, precipitation - interception - (water holding capacity - soil water))
potential evapotranspiration =  30. * exp(17.62*temperature/(243.12 + temperature))
evapotranspiration =  potential evapotranspiration * cI6
soil water next month = min(water holding capacity , max(0, soil water + precipitation into the soil - evapotranspiration))
```

The potential evapotranspiration is identical with the saturation vapor pressure from the Magnus equation (MAGNUS 1844). Now the contribution of each month to the site index of the year is calculated with:

```
siMonth = cI0*exp(-nn/7990) * days of the month * max(0, cI15 + radiation)^cI16
    * max(0, (cI1 + temperature))^cI2
    * max(0, 1 - potential evapotranspiration /tanh(cI5*plant available
        water)/cI3)^cI4
    * (1. + tanh(cI14 * (tmax- tmin)))
```

Where nn is the altitude, tmax is the highest and tmin is the lowest average monthly temperature of this and the previous 11 months. The site index estimated by the weather (siW) is calculated by summing up the contribution of the 12 individual month:

siW = sum(siMonth)

These steps of site index calculation are done simultaneously which allows the estimation of the coefficients ci0 to ci16 by minimizing the quadratic differences between siW and siHlh.

The influence of soil and vegetation types are added by keeping the coefficients to estimate siW constant. The site index is then estimated with: siWSV =siW * (cSg + cVt) where cSg is a soil type specific and cVt a vegetation type specific coefficient.

According to BÖHMERLE (1903), MÜNCH (1928), SCHMIED (1928) and WIEDEMANN (1951) tree height growth is influenced by stand density. So also the site index is influenced by stand density. When this density effect can be observed in the data, it needs to be included in the site index estimation. First, it needs to be defined how stand density is measured. Here the basal area of the inventory plot is set into relation to a reference basal area. The reference basal area is described with:

gRef = cg0 * (1 - 1/(1+tree height *cg1)) (equation 2)

and the coefficients cg0 and cg1 are estimated by using the upper 95% of the observed plot basal area for a given height range. The stand density sd is calculated with sd = gObserved / gRef. Here the basal area is estimated at height 0m instead of 1.3m. As the trees are measured at 1.3 m the diameter is increased by 1.3cm and if they are smaller than 1.3m their height in meter is used as the diameter in centimeter. The site index, which is also using the stand density, will be calculated with:

siWSVD = siWSV * (cD0 + cD1 * sd) * (1 – sd/cD2) (equation 3)

where the coefficients cD0 to cD2 are estimated by minimizing the quadratic sum of the differences between siWSVD and siHlh.

It is also possible that the site index of a species (in this example spruce) is influenced by other spicies in the same stand. To test this, the site index will be extended with

siWSVDM = siWSVD * 2 / (1 + exp(cMs*share spruce + sum(cMspecies * share species))) (equation 4)

where share is expressed as basal area share of the species.

Now with this site specific site index model the site index can be estimated for each individual year. This makes it possible to examine if there is a trend over time and if there is, how large is its impact on the site index. For each inventory plot and each year the site depending site index was calculated. For the time span, when height increment observations are available on a plot, the average site index of the individual years was built. For each year the relation (siRel) to this average was calculated. For each height increment observed on the individual dominating trees the average siRel for the years, when the increment happened, was calculated (wgt). Now again the same coefficients for equation 1 were estimated with the difference that the coefficient c0 will be divided by the previously calculated wgt what will eliminate site index changes due to weather fluctuations.

4. Results

When trying to find the coefficients for equation 1 it turned out, that solving all 4 coefficients simultaneous by allowing random effects for each, was not possible in one step. So the much simpler equation: h=c0*log(1+exp(c2)*t^c3)^c1 by using the age was parameterized in the first step which allows a distinction between constants and site depending variables. c1 and c3 turned out to be more or less constant for all sites and have a value of c1~0.75 and c3~3. Now by setting those two coefficients constant, the two other coefficients, c0 and c2 could be estimated, both with a random effect, by using equation 1.

	Fixed effect		Random effect	
	Estimate	Std. Error	Variance	Std. Dev
c0	10.0494980	0.0004154	4.4330	2.1055
c2	-9.0584709	0.0004006	0.4719	0.6869

Between c0 and c2 was a relationship which could be described with c2 = cc0+cc1*c0^cc2 (Figure 1) where cc0 = -9.513 ± 0.015(Std. Error), cc1 = 0.00077 ± 0.00016 and cc2 = 2.793 ± 0.078.

The map of the residuals of the regression between c0 and c2 suggested that there is neither regional nor elevational clustering (Figures 2 and 3).

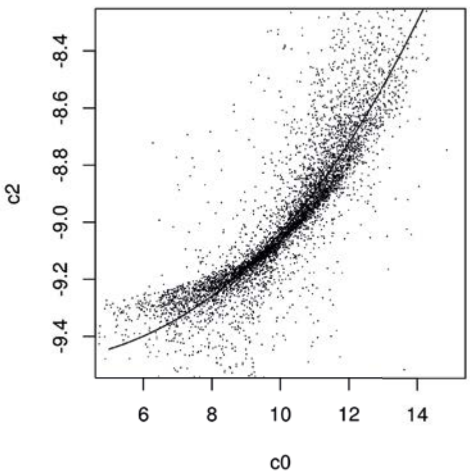

Figure 1: Relation between the growth curve describing coefficients c0 and c2. Points ... Observations, Line ... Trend curve used to get c2 out of c0

Abbildung 1: Zusammenhang zwischen den Oberhöhenverlauf beschreibenden Koeffizienten c0 und c2. Punkte ... Beobachtungen, Linie ... Trendkurve zur Ableitung von c2 aus c0

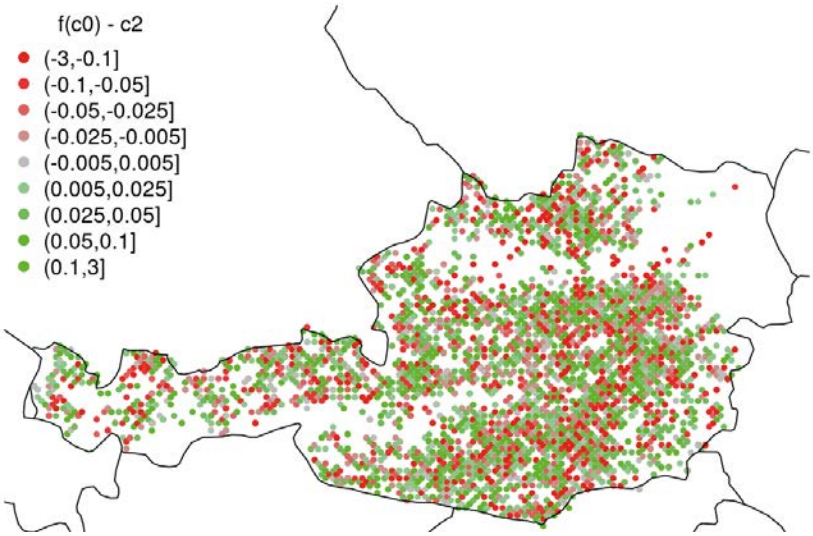

Figure 2: Map of the residuals between c2 estimated by using c0 [f(c0)] and c2, which defines the growth shape, to see if a regional zoning of different growth pattern is needed.

Abbildung 2: Karte der Residuen zwischen c2 und mit c0 [f(c0)] geschätztem c2, welcher den Wachstumsverlauf beschreibt, um den Bedarf einer regionalen Gliederung zu zeigen.

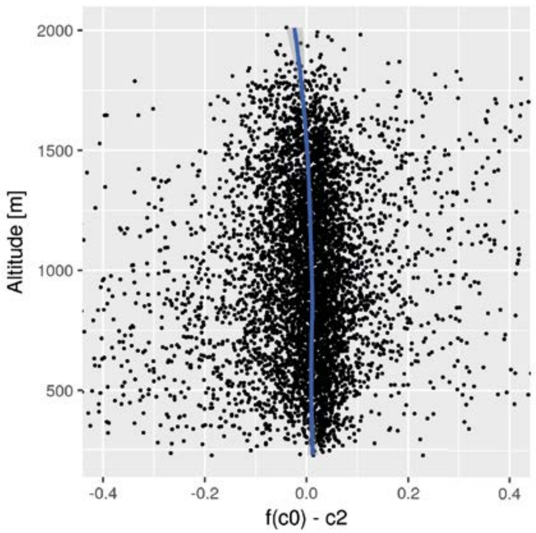

Figure 3: Residuals along an Altitude gradient between c2 estimated by using c0 [f(c0)] and c2 to see if a horizontal zoning is needed.

Abbildung 3: Residuen zwischen c2 und mit c0 [f(c0)] geschätztem c2 um den Bedarf einer Höhenzonierung zu zeigen.

Now with this a site index system can be created with

h = c0*log(1 + exp(c00+c01*c0^c02)*age^c3)^c1

which is used to get the site index from the observed height and height increment for each individual inventory plot. When the coefficient c0 is known in this system, also the site index is known. So this coefficient c0 will be described with site factors starting with monthly temperature, precipitation and radiation. Also here it turned out, that some of the estimated coefficients are statistically not significant for a significance level of 5% and even not for 10%. The coefficients of the weather sensitive model are:

cl0 = 7.070e-06 ± 1.125e-04 (Std. Error), cl1 = 8.338e+00 ± 2.240e+01, cl2 = 2.472e+00 ± 4.480e+00, cl3 = 1.573e+02 ± 5.051e+01, cl4 = 1.790e+00 ± 2.446e+00, cl5 = 2.948e-02 ± 6.304e-03, cl6 = 8.123e-01 ± 1.920e-01, cl9 = -8.265e-01 ± 2.074e+00, cl14 = 5.162e-02 ± 4.285e-02, cl15 = -6.499e+00 ± 1.229e+01, cl16 = 5.109e-01 ± 6.208e-01

Figure 7 (grey color) shows the estimated site index for different temperature and precipitation combinations. A temperature optimum exists which is increasing by an increasing precipitation amount.

To this weather sensitive model soil type and vegetation type is added. The estimated coefficients and number of observations for the soil group are given in table 2 and for the vegetation types in table 3 in column Loop1.

The reference basal area was estimated with eq. 2 using the following coefficients: cg0 = 1.233e+02 ± 5.249 (Std. Error), cg1= 14.892e-02 ± 4.425e-03

The coefficients for the stand density dependency using eq. 3 are: cD0 = 0.918273 ± 0.009895 (Std. Error), cD1 = 0.476625 ± 0.051825, cD2 = 3.755223 ± 0.344995. Figure 4 shows the relation of coefficient c0, which describes the site index, estimated using either the height increment or site data, along the stand density gradient. This relation has much noise but still an optimum can be located. Higher and lower stand densities show a lower site index.

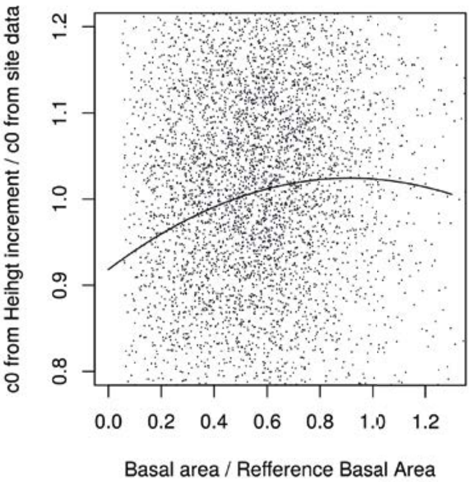

Figure 4: Relation of coefficient c0, which describes the site index, and stand density.

Abbildung 4: Abhängigkeit des, die Oberhöhenbonität bestimmenden Koeffizienten c0 vom Bestockungsgrad.

In the last step the effect of the proportion of the species other than spruce on the site index was described by using equation 4 with the coefficients for: spruce = 0.049470 ± 0.006616, beech = -0.151397 ± 0.029308, Scots pine = -0.311359 ± 0.034348, larch = -0.044700 ± 0.034404, fir = -0.086116 ± 0.042344, birch = -0.083982 ± 0.072397, black alder = 0.014035 ± 0.111476 and ash = -0.010595 ± 0.075105.

The model at the current stage has a correlation of r = 0.60. The standard deviation of c0 estimated either with the observed height growth or with the site information is ± 2.90 which is equivalent to ± 6.90 m of the site index expressed as the height of the dominating trees at age 100.

Now with the site specific model it is possible to reduce the influence of weather fluctuations on the site index curves. The estimated coefficients are then:

	Fixed effect		Random effect	
	Estimate	Std. Error	Variance	Std. Dev
c0	9.30242	0.06507	3.9324	1.9830
c2	-8.51914	0.04989	0.2532	0.5032

Also the relation between c0 and c2 has changed as shown in figure 5 and is now estimated with the coefficients: cc0 = -8.754e ± 6.079e-03, cc1 = 4.625e-04 ± 7.766e-05, cc2 = 2.818e ± 6.372e-02

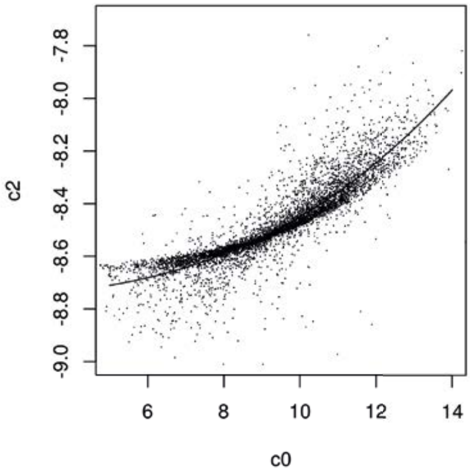

Figure 5: Relation of c0 and c2 as shown in figure 1 but when weather influence is eliminated

Abbildung 5: Zusammenhang zwischen c0 und c2 wie in Abbildung 1

Figure 6 shows the site index system with and without weather correction, and table 1 gives the corresponding height at a given age for a specific site index for the weather corrected site index system.

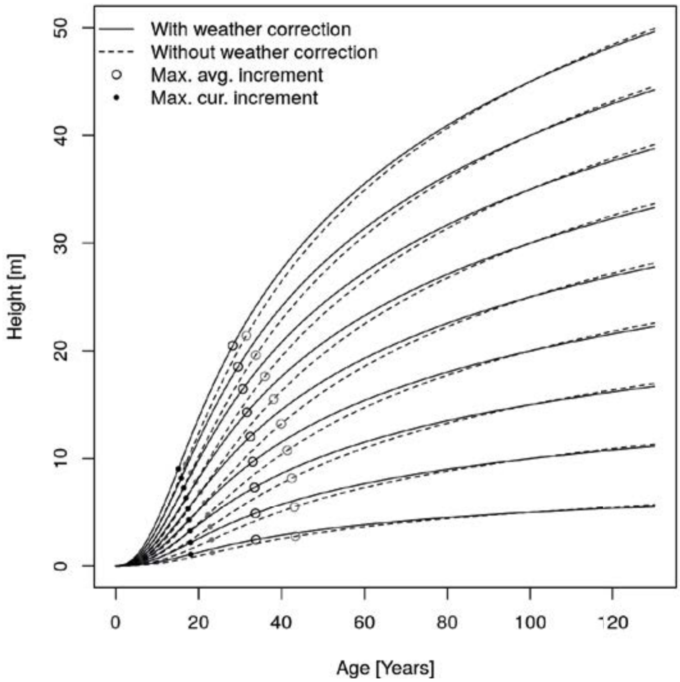

Figure 6: The site index system for spruce.

Abbildung 6: Der fertige Oberhöhenfächer für Fichte.

For each inventory plot the site index is estimated by using this site index system and this can again be described by site information as done before. The coefficients for this are:

cl0 = 2.088e-05 ± 3.123e-04 (Std. Error), cl1 = 8.024e+00 ± 2.140e+01, cl2 = 2.361e+00 ± 4.156e+00, cl3 = 1.536e+02 ± 4.409e+01, cl4 = 1.617e+00 ± 2.104e+00, cl5 = 2.886e-02 ± 6.056e-03, cl6 = 8.184e-01 ± 1.887e-01, cl9 = 7.808e-01 ± 2.038e+00, cl14 = 5.475e-02 ± 4.286e-02, cl15 = -4.132e+00 ± 8.598e+00, cl16 = 3.850e-01 ± 6.359e-01

Figure 6 shows, that the weather corrected site index system estimates are practical identical until a monthly precipitation of 40 mm and estimate slightly lower site indexes for higher precipitations.

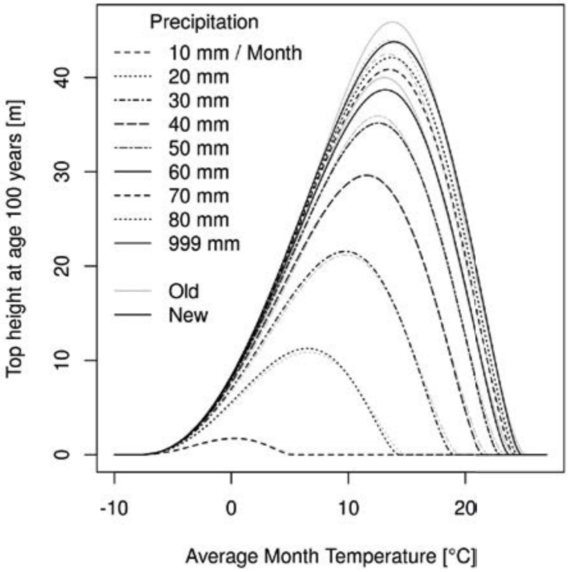

Figure 7: Site index described by temperature and precipitation; Radiation = 200W, Altitude = 400m. Old ... Site index from not weather corrected site index system, New ... Site index from weather corrected site index system

Abbildung 7: Oberhöhenbonität in Abhängigkeit von Temperatur und Niederschlag bei einer Strahlung von 200W und 400m Seehöhe. Old ... Oberhöhenbonität vom unkorrigierten Oberhöhenfächer, New ... Oberhöhenbonität vom Wettertrend bereinigtem Oberhöhenfächer

The estimated coefficients and number of observations for the soil group are given in table 2 and for the vegetation types in table 3 in column Loop2.

The coefficients for the stand density dependency using eq. 3 are: cD0 = 0.91314 ± 0.01022 (Std. Error), cD1 = 0.50090 ± 0.05201, cD2 = 3.62371 ± 0.31311.

In the last step the share of other species on the site index will be described by using eq. 4 with the coefficients for: spruce = 0.045768 ± 0.006843, beech = -0.139201 ± 0.030313, Scots pine = -0.313676 ± 0.035533, larch = -0.035989 ± 0.035576, fir = -0.063066 ± 0.043799, birch = -0.112714 ± 0.074916, black alder = 0.002965

± 0.115315 and ash = 0.018277 ± 0.077687.

The final model has a correlation of r = 0.60. The standard deviation of c0 estimated either with the observed height growth or with the site information is ± 2.82 which is equivalent to ± 6.68 m of the site index expressed as the height of the dominating trees at age 100.

5. Discussion:

Creating site index systems or estimating the site index by using site characteristics is not novel (e.g. NEBE 1968, MOOSMAYER et al. 1996). The new way is where these two methods were combined to allow creating a site index system, which describes the height development under constant site conditions even when the observed data does not show constant site conditions. The site index system was created iteratively. In the step (1) the system was estimated by using observed height and height increment. But the shape of this system is influenced by a changing site. Anyway it could be used to (2) estimate the approximate site index of single stands or inventory plots which could be used to (3) parameterize a site depending model. This site depending model is now used to (4) update the site index system by eliminating the weather trend. Now again the site index could be estimated with this updated site index system which is again used to update the site-specific model. Now this circle could be continued but at this point the changes might be marginal and so this iteration process was stopped here.

The reference basal area could alternatively be described with the CD-Rule (gRef = cg0 * tree height^cg1) but its shape gives especially for younger stands untypical high basal areas which are not the case with the here used function. In the methods a reference basal area was defined which could be extended by estimating it depending on the yield level, but it was not done as observing the yield level is not easy and the effect by including this will not be large.

Some of the estimated coefficients are statistically not significant. The estimates were still used, as the total function behavior looked plausible and it could be expected that the input variables have much noise, which will make it hard to come to a statistically significant solution.

With the described method only weather fluctuations are eliminated. It is still possible, that there are other factors influencing the site. If their effect can be observed, their influence can be eliminated in the same way as done in this study concerning weather.

The coefficients for soil type and vegetation type are estimated independent of each other but it could be expected that there exists an interaction between both. So the coefficients could be estimated on a matrix, where for each individual combination a specific coefficient was given. But with this the number of observations for every single combination will be small and the model can only be used on sites where a coefficient was estimated for a specific combination.

As site conditions are changing from year to year also the site index is fluctuating between years. Until now it was assumed that this annual fluctuation has no effect on the shape of the site index curve. To see if a site fluctuation could have an effect on the curve shape the height development of a stand whose site is changing form year to year between 25 m and 35 m was drawn. Here two extremes can be distinguished. Either the physiological age (a) of the tree is used or the age is estimated using its height in combination with its site index (b). In case (a) the height at age 100 is 30.0 m and in case (b) 30.5 m. This height difference is small but it still would not be a problem even if the difference would have been larger as this would only mean that a symmetric fluctuation between SI25 and SI35 is not leading to an SI30. A difference in the shape would be a problem. In this example the maximum difference of the shape until the age of 140 years was in case (a) 12 cm at the age of 18 years and in case (b) 29 cm at the age of 33 years. So even short term site index fluctuations without trend could influence the shape of a growth curve but in this case in a range which might not be of practical relevance.

Site index curves are used, since Baur (1877) to estimate the yield level of a site. The first yield tables for Austria from Feistmantel (1854) and also their revisions from Rokitansky (1876) and Weiss (1909) did not have any information on tree height. In the third edition of the tables from Weiss (1909) has added a height table. The last revision of the yield tables from Feistmantel (1854) has been done by Jelem (1948) and shows site index curves. Those tables do not distinguish between growth regions or altitude classes although the area they are used was much larger than the current area of Austria. The tables presented by Guttenberg (1896, 1915), Schiffel (1904), Ribel Pelleter (1929), Hudeczek (1936, 1938) or Krenn (1945) are based on a site index system and are typically dedicated to a specific region in Austria. Some of those tables are revised and published by Bundesministerium für Land und Forstwirtschaft (1952), Frauendorfer (1954), Griess (1966) and Marschall (1975). Those revisions distinguish now either between altitude classes or growth regions but did not describe how they come to these groupings. The tables for Tirol (Amt der Tiroler Landesregierung Abt. Forstplanung 2004) are developed for Tirol and distinguish between Soil types. Currently the tables from Marschall and those for Tirol are in use. Those form Marschall are based on the tables form Guttenberg (1896, 1915) and are named "Weitra" and "Hochgebirge", from Ribel and Pelleter (1929) named "Bruck" and from Assman and Franz (1963) named "Bayern". Marschall splits Austria into 4 growth regions where the 4 different yield tables have to be used. In this work neither regions nore altitude classes have show different growth patterns. This does not mean that all forests show the same height development given in the site index curves. There are different patterns but they can neither be clustered by regions nor by altitude. As it can not be distinguished if this different patterns are caused by differences in height development e.g. due to different proveniences, uncertainties in height measurement or to changes in site here only one curve system is presented and all deviations from this system are explained as changes in site.

Figure 8 compares the new developed site index curves with those of the yield tables currently in use by using the equations from Kindermann and Hasenauer (2005). By looking at the site index curves which reaches a height of 30m at the age of 100 years (the 3'rd from above and below) it can be seen that for young stands Weitra is similar to the new curve and all other show a slower development. This can come from competition by older trees or grasses and shrubs at the juvenile stage, browsing or damages when planting the trees. It is also possible that observations at this are age missing and the shape comes from extrapolations. The height development of older stands is similar to those shown by Bayern and Hochgebirge. Bruck and Weitra show lower and Tirol higher increments than the new curves. For yields above 30m at 100 years the older forests show a lower increment for the tables Bayern, Bruck, Hochgebirge and Weitra and a higher increment for the tables form Tirol. A reason for this can be, that for the tables in Marschall observations of old forests with high yields are underrepresented or missing and lead to flatter curves. The tables of tirol are based on newer observations where an increasing yield can be expected what causes stretched shapes.

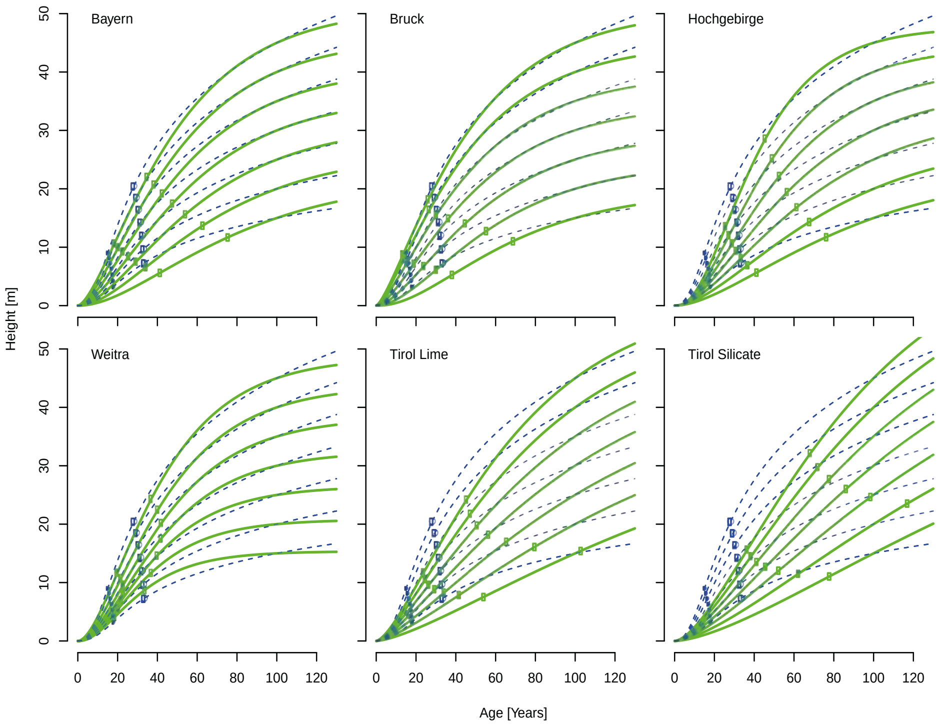

Figure 8: Comparison of site index curves from yield tables, green ... curves of the yield tables, blue ... new curves

Abbildung 8: Vergleich mit den Oberhöhenfächern der Ertragstafeln, grün … Ertragstafel-Kurven, blau … neue Kurven

Conclusions

*) Site index curves, which show height development under constant site conditions, can be created, even when the observed height-growth has been affected by changing site conditions.

*) There are different growth patterns but neither growth regions nor altitude classifications can be used to distinguish between them.

*) The new site index curves can be used as a substitute for those of the yield tables form Marschall (1975) or Tirol.

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