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A semi-distance-dependent individual tree growth model for coppice forests in Austria

Ein semi-abstandsabhängiges Einzelbaumwachstumsmodell für Niederwälder in Österreich

Gerhard Nachtmann*

Keywords: basal area increment model, height growth model, individual tree model, coppice

Schlagworte: Kreisflächenzuwachsmodell, Höhenmodell, Einzelbaummodell, Niederwald

Summary

Management of coppice forests is becoming more important currently. Therefore a growth simulator was developed for planning. The two core models are presented in this paper. Height growth models for 11 different species and one species-group (other broadleaf species) were developed as well as 5-year basal area increment models for four species and one species-group occurring in Austrian coppice forests. The data were measured on 54 sample plots covering diverse sites, stand ages and treatments. 3,260 trees belonging to 24 different species were used to fit the models. A new coppice-specific competition measure "basal area of larger trees within the stool" *BALi* was introduced, therefore the model is called "semi-distance-dependent". Depending on the biological plausibility either nonlinear or

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robust linear models (tree height) or robustified linear mixed models (basal area increment) were fitted.

Zusammenfassung

Da die Niederwaldbewirtschaftung zur Zeit an Bedeutung gewinnt, wurde als Planungsinstrument ein Wachstumssimulator entwickelt, dessen beiden Hauptmodelle in der Folge beschrieben sind. Für 11 verschiedene Baumarten und eine -gruppe (sonstige Laubhölzer) wurden Höhenmodelle und für vier verschiedene Baumarten und eine -gruppe, wurden Kreisflächenzuwachsmodelle für Niederwälder in Österreich entwickelt. Die Daten wurden auf 54 fixen Probekreisen verschiedener Standorte, Bestandesalter und Behandlungsvarianten erhoben. Die 3.260 Bäume, die zur Modellierung herangezogen wurden, gehören 24 verschiedenen Arten an. Ein neues niederwaldspezifisches Konkurrenzmaß, die "basal area of larger trees" innerhalb desselben Stockes *BALi*, gibt dem Modell das Attribut "semi-abstandsabhängig". Je nach biologischer Plausibilität wurden entweder nichtlineare oder robuste lineare Modelle (Baumhöhe) bzw. robustifizierte lineare gemischte Modelle (Kreisflächenzuwachs) angepasst.

1 Introduction

The Austrian National Forest Inventory (ANFI) defines coppices as vegetatively originated short rotation forests (FBVA, 2001, p. 46). The ANFI uses the term "short rotation", which means to harvest the whole (even aged) stand every 15–30 years. However, the rotation length can be much shorter in other coppice ecosystems around the world.

In eastern Austria and the adjacent regions in Hungary and Slovakia coppice forests are a major part of the landscape. Due to the fact that the interest in firewood was decreasing during the last decades, many of these forests were not utilized any more.

To preserve the high biodiversity in flora and fauna of coppices, it is necessary to manage them actively (Benes et al., 2006; Camprodon and Brotons, 2006; Ellmauer and Traxler, 2000; Luoga et al., 2004; Nagaike et al., 2006; Shibuya et al., 2008). In such forests one can find different adjoining stand development stages (from clearing to closed forest). Hence many light demanding species are able to survive in this habitat. For more details, see also Buckley (1992).

On the other hand, green energy policy points towards enhancing renewable resources, and thus might meet the conservation idea of reviving

coppice forestry in this region. To get an idea about the potential biomass production in coppice forests in Austria, an individual tree growth simulator was developed. Basal area increment models already exist for the main tree species in Austria (e.g. Monserud and Sterba, 1996), but all broadleaf species except beech and oak were modeled together and data from coppice forests were not available. The same problem is in effect enhanced for height models, because of the different growth of shoots belonging to an existing stool. Therefore this paper describes coppice specific height- and basal area increment models. The objective is to calculate the height as well as the diameter for each tree in a plot, after a 5-year growth period.

Munro (1974) classifies forest growth models in

- distance dependent single tree models
- distance independent single tree models
- distance independent stand models

The model presented here is called "semi-distance-dependent" because one does not need to know the exact position (coordinates) of the trees but rather the belonging stool of each sprout. This information is used to calculate the intra-stool-competition.

2 Data

2.1 Study area

The investigated coppice forests are situated in Burgenland (41 sample plots) and Lower Austria (13 sample plots). The climate is temperate, but quite warm and dry with little snow in winter. The plots are located in the growth districts "2 Eastern pannonic semiarid region" and "21 Mountains of the middle Burgenland" after Kilian (1981) (see Fig. 1).

2.2 Measured data

To cover the whole region where coppice forests occur in Austria, 54 sample plots were selected in order to get the whole range of sites, ages and treatments. Depending on stand density, age and Site Index, circular plots of 4, 5, 7 or 10 meter radius were selected in a way that each plot should contain a minimum number of 50 sample trees. Each plot is completely inside the respective stand to avoid edge effects.

The threshold diameter at breast height (dbh) is 2 cm. Trees with a larger dbh were measured to the nearest millimeter using a diameter tape. The

tree heights and the heights to the crown base were measured using the ultrasonic hypsometer "Vertex" to the nearest decimeter. For fitting the height models, data of 3,260 living trees belonging to 24 different species with undamaged crowns were used. An overview is given in Tables 2 and 1. Every living tree was cored at breast height. The cores were measured to the nearest hundredth of a millimeter in the tree-ring-laboratory using a "Digitalpositiometer" (Johann, 1977) to get the 5-year diameter increment.

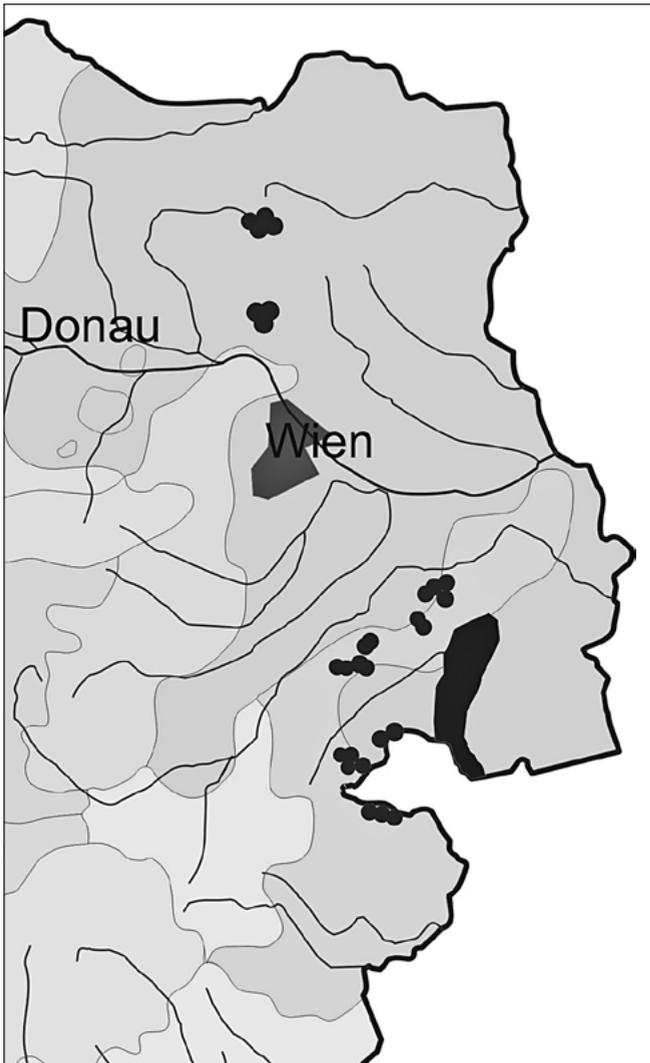


Figure 1: Location of the sample plots.

2.3 Calculated Data

Knowing the 5-year diameter increment, one can derive the dbh five years ago and the 5-year basal area increment. Trees with a dbh < 2 cm five years ago were not used for modeling. The remaining 2,808 trees belonging to 23 different species supplied the data for the basal increment models.

For each tree the "Basal Area of Larger Trees", BAL, (Wykoff, 1990) was computed to quantify the individual tree competition. This is the sum of the basal area per hectare of all trees having a larger dbh than the reference tree. As in coppice forests most of the trees are vegetatively originated (shoots grow out from the stool of the mother tree), a measure of competition within one stool was needed. Therefore, two BAL were computed for each tree. BAL_a considers all trees of the plot (basal area of (all) larger trees [$m^2 \cdot ha^{-1}$]), and the here defined BAL_i just includes the trees within the respective stool (basal area of larger trees within the stool [$m^2 \cdot ha^{-1}$]).

Site productivity was quantified using the "Site Index", SI, i.e. the dominant height [m] of sessile oak at age 30. On particular plots without dominant oaks, the respective dominant heights had to be estimated. Therefore, relationships between dominant heights of other tree species and those of oak were used to get this estimate, which could be used to compute the Site Indices (see Nachtmann, 2011).

As a measure of stand density, Reineke's (1933) "Stand Density Index", SDI, was calculated for each plot (Equation 1), using the quadratic mean diameter D (Equation 2). N is the stem number per hectare and BA is the basal area per hectare.

$$(1) \quad SDI = N \cdot \left(\frac{25}{D [cm]} \right)^{-1.605}$$

$$(2) \quad D [cm] = \sqrt{\frac{BA}{N} [m^2] \cdot \frac{4}{\pi}} \cdot 100$$

For all data the initial state (five years ago) was needed. The diameters could be calculated using the cores (bark increment was neglected), but to get the height-diameter-ratio, h/d , the heights had to be computed applying the height-curves shown in this paper.

3 Models

3.1 Tree height models

The basic height curve by Petterson (1955) (cit Pretzsch, 2001) is shown in Equation 3:

$$(3) \quad h [m] = \frac{1}{\left(a + \frac{b}{dbh [cm]}\right)^c} + 1.3$$

The tree height h is similar to Pollanschütz (1973) a function of dbh and a constant c . a and b were modified using additional variables: age, SDI, SI, seedling (yes/no).

Depending on the biological plausibility either nonlinear regression models (see section 4.1) were fitted to Equation 3 or robust linear regression models (see section 4.3) to the linearized version (Equation 4).

$$(4) \quad \frac{1}{\sqrt[c]{h - 1.3}} = a + \frac{b}{dbh}$$

To accommodate for the transformation bias, a correction factor λ is used (Marklund, 1987). h_{obs_i} are the observed values and h_{pred_i} are the predicted tree heights:

$$(5) \quad \lambda = \frac{\sum_{i=1}^n (h_{obs_i} - 1.3)}{\sum_{i=1}^n (h_{pred_i} - 1.3)}$$

The constant 1.3 should added only after applying λ to ensure that the theoretical height of a tree with a dbh of zero equals to 1.3 m:

$$(6) \quad \hat{h} = \left(\frac{1}{\left(a + \frac{b}{dbh}\right)^c} \right) \cdot \lambda + 1.3$$

3.2 Basal area increment models

Cole and Stage (1972, p. 2) tried radial increment as well as basal area increment and a logarithmic transformation of both as dependent variable for modeling the diameter growth. Applying "indices of fit" (Furnival, 1961) they found that the logarithm of basal area increment is the most appropriate one. Their statement is based on a large dataset from management planning inventories and forest survey locations.

Therefore, a mixture of the equations by Hegershoff (1936)(cit Peschel, 1938) and Wykoff (1990) was used for modeling the 5-year basal area increment BAI_5 . Equation 7 shows the logarithmic fundamental model:

$$(7) \quad \ln(BAI_5) = a + b \cdot \ln(x) - c \cdot y^d$$

Depending on the biological plausibility, y stands either for stand age (t) or dbh , while x is always the dbh . The intercept a characterizes the absolute size of BAI_5 . The coefficient b describes the initial growth, where higher values of b lead to a higher BAI_5 and a shift of the culmination to higher diameters. The coefficient c is a measure for the inhibited growth in the saturation period and therefore negatively signed. The larger is the absolute value of c , the earlier is the culmination of BAI_5 and the smaller is its size. The exponent d shows the leverage of y . The value of d is not estimated using statistical methods but determined on an empirical basis and can be either 1 or 3.

Equation 7 is the basic model for fitting linear regressions described in section 4.5. Similar to Wykoff (1990), further parameters were included in the model:

$$(8) \quad \ln(BAI_5) = f(t, dbh, SI, SDI, BALa, BALi, h/d, S)$$

h/d is the height-diameter-ratio $\left(\frac{\text{tree height [m]}}{\text{dbh [m]}}\right)$ and S is a logical value being 1 if the respective tree originated generatively (seedling) and zero otherwise. For description of variables, see also section 5.

To get rid of the transformation bias, a correction factor λ similar to Equation 5 was used.

4 Methods

4.1 Nonlinear regression

All statistical analyses were carried out using the open source software R (R Development Core Team, 2010). To fit nonlinear regression models, the R-function `nls()` was used. Starting estimates are required to initiate the iterative parameter estimation. The “`nl2sol`” algorithm from the Port library (<http://www.netlib.org/port/>) was advantageous, because it excuses “wrong” starting estimates. The latter are deciding if the result is just a local optimum or a global one.

4.2 Multicollinearity

Wykoff (1990) used ridge regression to avoid multicollinearity (see also Faraway, 2004). To fit such models, `lm.ridge()` of R-package MASS (Venables and Ripley, 2002) was applied. The estimated coefficients are biased but a reduction in the variance may be obtained at the price of an increased bias (Faraway, 2004, p. 145). In this case GCV (generalized crossvalidation) was used to select (using `select()`) a tuning parameter. The minimum GCV value was reached when this tuning parameter was zero. Therefore, ridge regression was not used in further consequence.

4.3 Robust linear regression

Robust linear regression was carried using the function `ltsReg()` provided by R-package `robustbase` (Rousseeuw et al., 2008; Rousseeuw and Van Driessen, 2006). The idea of least trimmed squares (LTS) regression is to regard just a subset h out of n observations, having the smallest sum of squared residuals.

Using LTS-regression prevents from the negative impact of possible outliers, which could not be found using the least squares (LS) estimator. Positive leverage points stay in the h -subset and make the regression hyperplane more stable, while negative ones are excluded.

4.4 Mixed models

To fit mixed models, the function `lmer()` of R-package `lme4` (Bates and Maechler, 2009) was used as described in Bates (2005) and Faraway (2006). The plot number is the unknown random effect, which has to be estimated, leading to the fact that the F-statistic does not follow an F-distribution any

more (Faraway, 2009). Furthermore, the degrees of freedom have to be approximated.

Therefore, in the most recent version of lme4 no p-values are shown. Bates (2006) himself as well as Faraway (2009) recommend to use Markov Chain Monte Carlo (MCMC) methods for inference instead. As suggested by Bates (2006) and Faraway (2009), `mcmc` of R-package lme4 (Bates and Maechler, 2009) was used to get 50,000 samples as a basis for the calculation of the Highest Posterior Density (HPD) intervals (`HPDinterval()`) for the fixed effects. The respective variable is part of the model if its HPD interval does not overlap zero at a predefined probability (in this case 95%).

4.5 Robustified mixed models

In order to robustify the basal area increment models, modeling was done in two steps:

1. The LTS-estimator was used to find outliers, which were excluded in further consequence.
2. Based on the remaining data, mixed models were estimated using the plot as random effect.

The reason for robustification is that data could be faulty despite screening. One "bad" outlier is enough to tilt the LS-regression hyperplane. The reduced efficiency of the LTS-estimator is the price for the robustness but if just a few observations are left out, it makes almost no difference. The basal area increment model for other broadleaf species was parametrized without the sole elm as a consequence of robustification, but it is recommended that the basal area increment of this species nevertheless be calculated using this model.

4.6 Evaluation

The data were not split up into a training- and a validation-data-set – all data were used for modeling. To evaluate the models, they were implemented in an individual tree growth simulator (Nachtmann, 2011). The height- as well as the diameter development over time showed a plausible behavior, in accordance with the expectations. Therefore, the models are ready to predict future basal area increments.

5 Results

5.1 Tree height models

The height curve by Petterson (1955) (cit Pretzsch, 2001) fits best setting the constant $c = 3$. The coefficients a and b from Equation 3 were extended in the following way:

$$(9) \quad a = a_0 + a_{hado} \cdot hado + a_1 \cdot SI + a_2 \cdot SDI + \frac{a_3 + a_4 \cdot S}{t} + \frac{a_5}{\sqrt[3]{SI}}$$

$$(10) \quad b = b_0 + b_{hado} \cdot hado + b_1 \cdot SI + b_2 \cdot SDI + \frac{b_3 + b_4 \cdot S}{t}$$

where

hado . . . dummy variable; 1 for hawthorn or dogwood and 0 otherwise

SI Site Index (dominant height [m] of sessile oak at age 30)

SDI Stand Density Index

t age [years]

S logical value; 1 for seedling and 0 for coppice

Distinct models could be developed for oak (turkey oak [*Quercus cerris* L.] and sessile oak [*Quercus petraea* Liebl.]), European hornbeam (*Carpinus betulus* L.), linden (*Tilia* spp.), European beech (*Fagus sylvatica* L.), field maple (*Acer campestre* L.), Norway maple (*Acer platanoides* L.), sycamore maple (*Acer pseudoplatanus* L.), ash (flowering ash [*Fraxinus ornus* L.] and European ash [*Fraxinus excelsior* L.]), European white birch (*Betula pendula* Roth), black locust (*Robinia pseudoacacia* L.) and hazel (*Corylus avellana* L.). Other broadleaf species were modeled together. The respective species names and tree numbers are summarized in Table 1.

Table 1: Number of trees per species total and after LTS-regression used for "other broadleaf species" height models.

Tabelle 1: Anzahl der Bäume je Species gesamt und nach der LTS-Regression, für das Höhenmodell "Sonstige Laubhölzer".

Species	Scientific Name	n_{LTS}	n_{total}
Bird cherry	<i>Prunus avium</i> L.	10	10
Elm	<i>Ulmus</i> spp.	1	1
Common whitebeam	<i>Sorbus aria</i> Crantz	3	4
Wild service tree	<i>Sorbus torminalis</i> Crantz	21	23
Goat willow	<i>Salix caprea</i> L.	6	6
Poplar	<i>Populus</i> spp.	11	11
Hawthorn	<i>Crataegus</i> spp.	5	7
Dogwood	<i>Cornus</i> spp.	14	17
Northern red oak	<i>Quercus rubra</i> L.	4	4
Wild pear	<i>Pyrus pyraeaster</i> Burgsd.	4	5
European chestnut	<i>Castanea sativa</i> Mill.	0	1
Tree of heaven	<i>Ailanthus altissima</i> Swingle	2	2

How many trees by species were used for modeling and the values of the respective correction factor λ (see Equation 5) can be found in Table 2. The latter was calculated separately for the species groups (i) other broadleaf species and (ii) hawthorn and dogwood. The height model for other broadleaves consists of (i) and (ii). If nonlinear models were fitted (asterisked in Table 2) " n_{LTS} " = n_{total} and $\lambda = 1$ because no transformation was needed in this case.

Coefficients for Equation 3 combined with 9 and 10 are shown in Table 3. Zero was not included in any of the respective 95% confidence intervals.

Table 2: Number of trees total (n_{total}) and after LTS-regression (n_{LTS}) per height model (if used, asterisked for nonlinear models) and bias correction factor λ (equals 1 for nonlinear models).

*Tabelle 2: Anzahl aller Bäume (n_{total}) und jener, die bei nach der LTSRegression übrigblieben (n_{LTS}) für jedes Höhenmodell (falls robust gerechnet; bei nichtlinearer Schätzung mit * versehen) sowie der Korrekturfaktor λ (bei nichtlinearen Modellen 1).*

Species	n_{LTS}	n_{total}	λ
Oak	443	490	1.0077
Hornbeam	1 467	1 580	1.0133
Linden	163	192	0.9998
Beech	164*	164	1*
Field maple	41	46	1.0209
Norway maple	59*	59	1*
Sycamore maple	82*	82	1*
Ash	368*	368	1*
Birch	64	68	1.0061
Black locust	43	49	0.9805
Hazel	63	68	1.0156
Other broadleaf species	81	91	1.0292
Hawthorn, dogwood			0.9659
*nonlinear model			

Table 3: Coefficients for the height models (Equation 3 combined with 9 and 10).

Tabelle 3: Koeffizienten für die Höhenmodelle (Gleichung 3 in Kombination mit 9 und 10).

a_0	a_{hado}	a_1	a_2	a_3	a_4	a_5	b_0	b_{hado}	b_1	b_2	b_3	b_4
Oak	0.358	-0.00465	4.33e-05	2.82	-0.695		1.80		-0.0457	-0.000847	-0.0377	0.0349
Hornbeam	0.385	-0.00330		1.95	2.41		0.996		-0.0309	-6.39e-05		-0.164
Linden	0.424	-0.00798		2.21					0.0559			
Beech				2.40		0.728	0.745					
Field maple	0.371						0.922					
Norway maple	0.318			2.94			0.262					
Sycamore maple	-0.430			3.06		1.86	0.335					
Ash	-0.0575			3.11		0.842	0.458					
Birch	0.368						0.706					
Black locust	0.286						1.76					
Hazel	0.431						3.25		-0.118	-0.000801		
Other broadleaves	0.341	0.261					1.23	-1.13				

5.2 Basal area increment models

The full model shown in Equation 11 has a very general form. As a first step, coefficients for Equation 7 were estimated. Where the basic growth curve showed a feasible behavior, additional parameters could be added.

(11)

$$\begin{aligned} \ln(BAI_5) = & b_0 + b_{0_{libi}} \cdot libi + b_{0_{sc}} \cdot sc + b_1 \cdot \ln(dbh) + b_{1_{libi}} \cdot libi \cdot \ln(dbh) \\ & + b_{1_{sc}} \cdot sc \cdot \ln(dbh) + b_2 \cdot \ln(SI) + b_3 \cdot \ln(SDI) + b_4 \cdot \ln(h/d) \\ & + c_1 \cdot dbh^3 + c_2 \cdot t + c_3 \cdot t^3 + c_4 \cdot BALa \\ & + c_5 \cdot \frac{BALa}{\ln(dbh + 1) + 1} + c_6 \cdot \frac{BALi}{\ln(dbh + 1) + 1} \\ & + c_7 \cdot h/d + c_8 \cdot SI + c_{8_{libi}} \cdot libi \cdot SI + c_9 \cdot S \end{aligned}$$

where

BAI5 . . . basal area increment in a 5-year period [cm^2]

libi dummy variable; 1 for linden and birch and 0 otherwise

sc dummy variable; 1 for scrubs and 0 otherwise

dbh diameter at breast height [cm]

SI Site Index (dominant height [m] of sessile oak at age 30)

SDI Stand Density Index

h/d height-diameter-ratio ($\frac{tree\ height[m]}{dbh[m]}$)

t age [years]

BALa . . . basal area of (all) larger trees [$m^2 \cdot ha^{-1}$]

BALi . . . basal area of larger trees within the stool [$m^2 \cdot ha^{-1}$]

S logical value; 1 for seedling and 0 for coppice

For oak (turkey oak [*Quercus cerris* L.] and sessile oak [*Quercus petraea* Liebl.]), European hornbeam (*Carpinus betulus* L.), European beech (*Fagus sylvatica* L.) and ash (flowering ash [*Fraxinus ornus* L.] and European ash [*Fraxinus excelsior* L.]) it was possible to fit separate models. The remaining species were modeled together because of the low number of trees. The different growth behavior of linden and birch (*libi*) on the one hand, and scrubs (*sc*) on the other hand, is described using dummy variables. Scrubs are hazel, hawthorn and dogwood. Table 4 shows species names and tree numbers of the trees subsumed as "other broadleaf species".

Table 4: Number of trees per species total and after LTS-Regression used for "other broadleaf species" basal area increment models.

Tabelle 4: Anzahl der Bäume je Species gesamt und nach der LTS-Regression, für das Kreisflächenzuwachsmodell „Sonstige Laubbölzer“.

Species	Scientific Name	n_{LTS}	n_{total}
Linden	<i>Tilia</i> spp.	188	195
Field maple	<i>Acer campestre</i> L.	36	38
Norway maple	<i>Acer platanoides</i> L.	33	34
Sycamore maple	<i>Acer pseudoplatanus</i> L.	22	22
Bird cherry	<i>Prunus avium</i> L.	10	10
Elm	<i>Ulmus</i> spp.	0	1
European white birch	<i>Betula pendula</i> Roth	64	64
Common whitebeam	<i>Sorbus aria</i> Crantz	5	5
Wild service tree	<i>Sorbus torminalis</i> Crantz	17	20
Goat willow	<i>Salix caprea</i> L.	5	5
Poplar	<i>Populus</i> spp.	11	11
Black locust	<i>Robinia pseudoacacia</i> L.	49	51
Hazel	<i>Corylus avellana</i> L.	48	49
Hawthorn	<i>Crataegus</i> spp.	5	5
Dogwood	<i>Cornus</i> spp.	13	13
Northern red oak	<i>Quercus rubra</i> L.	6	6
Wild pear	<i>Pyrus pyrastrer</i> Burgsd.	4	5
European chestnut	<i>Castanea sativa</i> Mill.	1	1
Tree of heaven	<i>Ailanthus altissima</i> Swingle	2	2

Numbers of plots and trees as well as bias correction factors λ are shown in Table 5. For other broadleaves λ was computed separately for the species groups (i) linden and birch, (ii) other broadleaf species and (iii) scrubs.

Table 5: Number of plots per basal area increment model (n_{plots}), number of trees total (n_{total}) and after LTS-regression (n_{LTS}) and bias correction factor λ . n_{plots} says the number of plots n_{LTS} are located in.

Tabelle 5: Anzahl der Plots für jedes Kreisflächenzuwachsmodell (n_{plots}), in welchen sich n_{LTS} befinden, Anzahl aller Bäume (n_{total}) und jener, die bei nach der LTS-Regression übrigblieben (n_{LTS}) sowie der Korrekturfaktor λ .

Species	n_{plots}	n_{LTS}	n_{total}	λ
Oak	35	449	473	1.1096
Hornbeam	47	1 348	1 380	1.2122
Beech	13	170	179	1.1311
Ash	13	225	239	0.9208
Linden, birch				1.1988
Other broadleaf species	42	519	537	1.1194
Scrubs				1.0352

Table 6: Coefficients for the basal area increment model (Equation 11).

Tabelle 6: Koeffizienten für das Kreisflächenzuwachsmmodell (Gleichung 11)

	Oak	Hornbeam	Beech	Ash	Other broadleaf species
b_0	-1.24	-0.882	6.43	-6.59	4.67
b_{0libi}					1.63
b_{0sc}					2.04
b_1	1.09	0.926	0.63	1.7	1.25
b_{1libi}					0.0953
b_{1sc}					-1.09
b_2		-2.94e-05		-0.0377	
b_3					-1.78e-06
b_4	-0.018		-2.92e-05		
c_1		-0.0378	-0.239		
c_2	-0.743			2.75	
c_3					-0.409
c_4	-0.262	0.795			
c_5	0.158		0.775		
c_6	0.625				
c_7		-0.00167			
c_8					-1.2
c_{8libi}					-0.0838
c_9			-0.93		

Table 6 shows the results of the robustified mixed models. Zero was not included in any of the respective 95% Highest Posterior Density intervals for the fixed effects estimated using 50,000 MCMC samples for each model.

6 Discussion

Because of the fact that coppice forests are even-aged, the stand age can be used as one of the explanatory variables for the height growth (see Equation 3 combined with 9 and 10) and it is not necessary to use substitutes. In this case tree-heights were measured just once at the end of the period and therefore the height models are "static" (see Schmidt, 2008). The height increments were not measured directly, but calculated using data at the beginning of the period. Therefore implausible increments are not possible, because all heights are on the same height-curve. An example for hazel is shown in Figure 2.

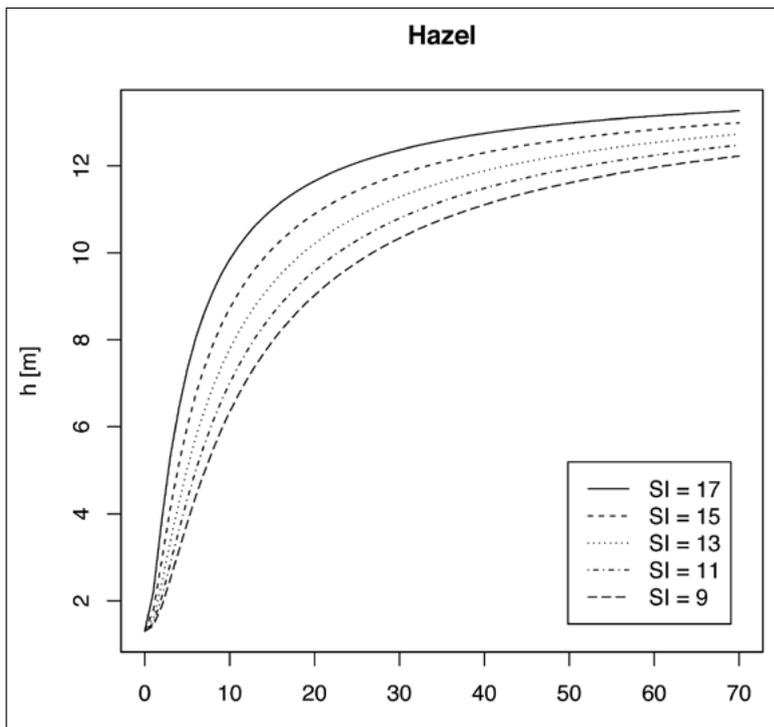


Figure 2: Height course (h) of a hazel on a plot with SDI = 800 for different Site Indices (SI) plotted against the diameter at breast height (dbh).

"Dynamic" height increment models by Knieling (1994), Schieler (1997) and Gschwantner (2004) were developed for data completion. They should not

be used for simulation, because diameter increment is one of the explanatory variables. Another possibility to ensure a logical height growth course is to use models with a maximum dominant height reduced by competition measures. Such models are implemented in the individual tree growth simulators MOSES (Hasenauer, 1994) and SILVA (Pretzsch, 2001).

The basal area increment models (Equation 7) covered in this paper show as well as the height models (Equation 4) a logical behavior. The initial growth is described distinct from the growth later in life, where the increment asymptotically decreases to zero (see Figure 3). This conforms with Hugerhoff (1936) (cit Peschel, 1938) and Wykoff (1990). The intercept de-/increases the BAI_5 . It was retained in the model even if it was not significantly different from zero (oak, hornbeam).

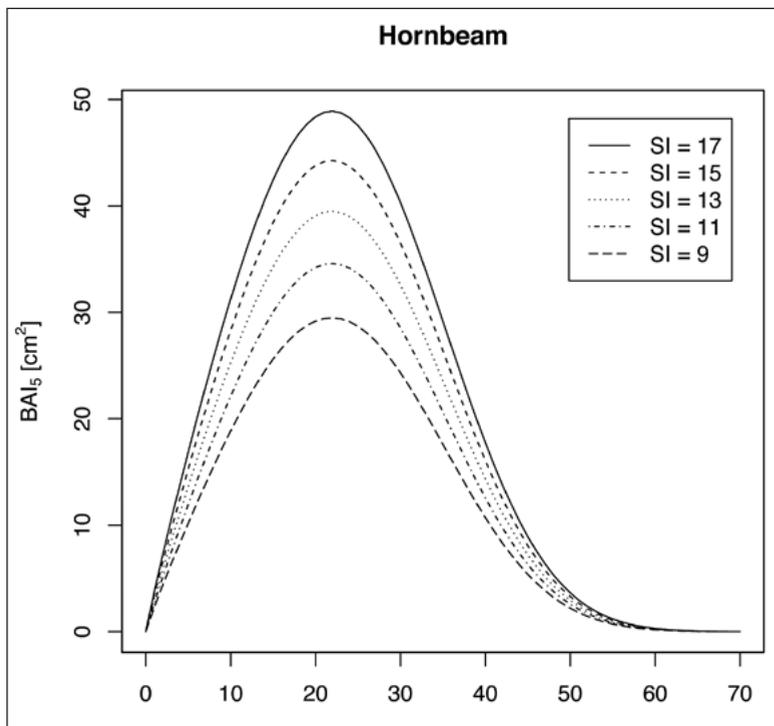


Figure 3: 5-year basal area increment (BAI_5) of a competition free (basal area of larger trees = 0) hornbeam for different Site Indices (SI) plotted against the diameter at breast height (dbh).

Variables on the logarithmic scale express the initial growth. Beside $\ln(dbh)$ there is an additional variable $\ln(SI)$ in case of hornbeam and ash, which means that they grow faster on better sites. The coefficient for $\ln(h/d)$ is positively signed for oak and negatively signed for beech, which might be due to light preferences: Young oaks have to grow up faster because they are light demanding. Other broadleaf species show inhibited youth growth in denser stands ($\ln(SDI)$). Linden and birch as well as scrubs grow more slowly than the other species modeled together, which is expressed by the species-specific negative contribution to the coefficient of $\ln(dbh)$.

Further variables reflect the inhibited growth. The main factor is either dbh^3 or t ; t^3 was used only for other broadleaf species because t would have been too weak as "growth brake". The coefficient of BAL_a for hornbeam is negatively signed, which means that higher competition retards the growth. For oak it is positively signed but there are additional terms with negatively signed coefficients of competition regarding the interaction with tree size (i.e. dbh).

The respective term introduced by Wykoff (1990) $\frac{BAL}{\ln(dbh+1)}$ was modified in the following way: $\frac{BAL}{\ln(dbh+1)+1}$. If $dbh = 0$ and further on $\ln(dbh + 1) = 0$, a division by zero would arise. To preserve it, for mathematical correctness only, 1 is added in the denominator. This case could not occur in practice because of the threshold diameter of 2 cm.

The above mentioned interaction term of BAL_a with dbh is present in the model for beech and oak. The latter one also includes one such term for BAL_i , which is a measure for the competition within the stool. The reason why it is only present in the oak model could be that oaks are light demanding. However, one can interpret the better growth of beech if they originated from seedlings caused by lower "within stool" competition: BAL_i has to be zero in this case.

The higher the h/d-value is the smaller the basal area increment of hornbeam is. Those trees probably were suppressed in younger stages, therefore they could not develop very well. Consequently they grow worse than dominant trees later in life. Higher Site Indices increase the growth of other broadleaf species. This amount is much lower for linden and birch. However, they show, as well as scrubs, bigger intercepts than the remaining other broadleaves.

Although a similar individual tree growth simulator called PROGNAUS (Ledermann, 2006) is available, coppice species are mainly covered within species group models. The new developed models are based on a coppice specific

dataset to get an idea of the growth there. Regarding the aggregated structure of coppice forests (see Sterba and Zingg, 2006), the competition measure was improved resulting in *BAL*.

7 Conclusion

Using 3,260 sample trees belonging to 24 different species located on 54 sample plots, twelve tree height models and five basal area increment models were developed. Within a framework of an individual tree growth simulator (Nachtmann, 2011), it is possible to estimate the 5-year basal area increment depending on any thinnings and different rotation lengths. One just has to know the plot radius, the associated stool of a shoot, the species, the dbh, the tree height, the stand age, the Site Index and whether the respective shoot is a seedling or not. In the appendix a simple calculation is carried out to show how the models work.

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Appendix: Calculation example

We use consider a 38-year-old linden with a dbh of 11 cm in a stand with an SDI of 600 and an SI of 12. Applying the coefficients for linden from Table 3 and λ from Table 2 to Equation 6 combined with 9 and 10, we get the respective tree height:

(1)

$$\begin{aligned}\hat{h} &= \left(\frac{1}{\left(0.424 - 0.00798 \cdot SI + \frac{2.21}{t} + \frac{0.0559 \cdot SI}{dbh}\right)^3} \right) \cdot \lambda + 1.3 = \\ &= \left(\frac{1}{\left(0.424 - 0.00798 \cdot 12 + \frac{2.21}{38} + \frac{0.0559 \cdot 12}{11}\right)^3} \right) \cdot 0.9998 + 1.3 = \\ &= 12.5 \text{ m}\end{aligned}$$

To calculate the dbh after 5 years Equation 11 is applied with the respective coefficients (from Table 6). The dummy variable *libi* is 1 because it is a linden.

(2)

$$\begin{aligned}\ln(BAI_5) &= 4.67 + 2.04 \cdot 1 + 1.63 \cdot \ln(dbh) - 0.409 \cdot 1 \cdot \ln(dbh) \\ &\quad - 1.09 \cdot \ln(SDI) - 1.78 \cdot 10^{-06} \cdot t^3 \\ &\quad + 0.0953 \cdot SI - 0.0838 \cdot 1 \cdot SI\end{aligned}$$

To get the basal area increment, we can write:

$$(3) \quad BAI_5 = \left(\exp(6.71 + 1.221 \cdot \ln(dbh) - 1.09 \cdot \ln(SDI) - 1.78 \cdot 10^{-06} \cdot t^3 + 0.0115 \cdot SI) \right) \cdot \lambda$$

which is for our example linden tree

$$(4) \quad BAI_5 = \left(\exp(6.71 + 1.221 \cdot \ln(11) - 1.09 \cdot \ln(600) - 1.78 \cdot 10^{-06} \cdot 38^3 + 0.0115 \cdot 12) \right) \cdot 1.1988$$

Now we can calculate the dbh at the age 43:

$$\begin{aligned}(5) \quad dbh_{43} &= \sqrt{\left(\frac{dbh_{38}^2 \cdot \pi}{4} + BAI_5\right) \cdot \frac{4}{\pi}} = \\ &= \sqrt{(95.0 \text{ cm}^2 + 17.9 \text{ cm}^2) \cdot \frac{4}{\pi}} = \\ &= 12.0 \text{ cm}\end{aligned}$$

After 5 years our linden has reached a dbh of 12 cm.

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