A growth simulator for oak in Southern Sweden

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Introduction

Compared to other broadleaved species in Sweden the timber market for Oak (*Quercus robur, Q. petraea*) has been consistently good over time, with high prices for high quality timber of big dimensions. In older times a major use of oak timber was for ship building, and in the early 19th century the Swedish crown planned to establish extensive oak plantations in order to supply the naval fleet industry. However, the plans materialized only at one place, the island of Visingsö in lake Vättern, where in the 1830s 400 ha were planted. (Schotte, 1923; Kardell, 1997). Currently high-quality timber is used in the furniture and the flooring industry, while small dimensions and poor quality is mainly used for energy and for domestic uses, fencing etc.

Grading of high-quality have varied over time, including restrictions on log-dimensions, annual ring width patterns, maximum annual ring widths and on the occurrence of knots. (Attocchi, 1985). Today the requirements are not as sharp as they have been. However, there is a general understanding that the goal for oak silviculture is to produce large trees (dbh > 50 cm) with a clean bole up to at least 6 m height.

To achieve a high timber quality a long and consistent management is considered necessary, starting from an initially dense often planted stand and thinned on a number of occasions (>10) resulting in a final stand with app. 50 – 70 trees per ha (Carbonnier, 1975; Attocchi, 1985). To promote high quality manual pruning of branches and epicormics is recommended. Furthermore, establishment of an understory is advised to reduce the problem with formation of epicormics. On fertile sites in Sweden the outlined programme is expected to last for about 120 years (Carbonnier, 1975). There is a major difference between the Scandinavian and the European continental programme for traditional oak management. On the Continent stands are kept denser, thus requiring longer rotations in order to reach desired dimensions (Attocchi, 1985). The willingness to invest in an understory is also higher on the Continent.

Other silviculture models for oak management exist. In several countries in Europe the paradigm of "Close to nature forestry" is prevailing, where heterogeneous and uneven aged forests are promoted (*cf* Bruciamacchie & Turckheim, 2005; Helliwell & Wilson, 2012; Pro Silva, 2017). In Scandinavia models have been tried where oak is mixed with spruce during the first part of the rotation, with the incentive to improve the economy in young oak stands. (Schaffalitzky de Muckadell, 1983; Ståål 1986). However, the current study focuses only on the traditional management of even aged oak stands.

Yield tables and growth simulators are important for planning issues, for outlining silviculture programmes and for studying relationship between growth and site factors. Yield tables for Swedish conditions have been constructed by Carbonnier (1975), based on material from 29 permanent plots in southern Sweden. (26 with at least one observed growth period). Yield tables were calculated for different site indices, different content of fine earth and for two different thinning programmes. The main components of Carbonnier's simulator contains top height development curves, functions for estimation of initial stands, functions for estimation of relative basal are growth and functions for estimation of stand volume. A growth simulator for has also been calculated by Ekö (1985) based on the data from the National Forest Inventory (NFI), were oak is one of the handled species. The NFI data were collected from sample plots (10m radius) without reference to the actual stan d and stand history. The use of this simulator for pure and well managed stands could therefore yield biased results.

Most of the stands included in Carbonnier's (1975) study still exist and have been inventoried on a regular basis for another 40-year period. In addition, new plots in oak have been established.

The aim of this study is to construct an updated growth simulator for oak based on available data from permanent plots in Sweden and on data collected from a special inventory of young stands.

Materials and methods

Data from permanent plots

Data from permanent oak plots have been collected with an almost consistent practice since 1898. Early collections of data on tree level exists only on paper and would unfortunately require a workload far beyond the budget of this project to be digitized. Consequently, data for individual trees could not be used as growth objects in this study. Instead stand data was extracted from SLU's database containing data from long term permanent plots. Some early inventories had to be excluded due to lacking information on the existents of other species than oak present on the plots.

In total the selected data includes 55 plots on 38 sites. The plot size varies between 0.25 and 0.5 ha. The observation period per plot is from 6 to 91 years with a median of 31 years. In total the number of growth periods are 301, with a median length of 5 years. The distribution of study sites is most dense in the south-west of Sweden, and on the island of Visingsö in lake Vättern (Figure 1)

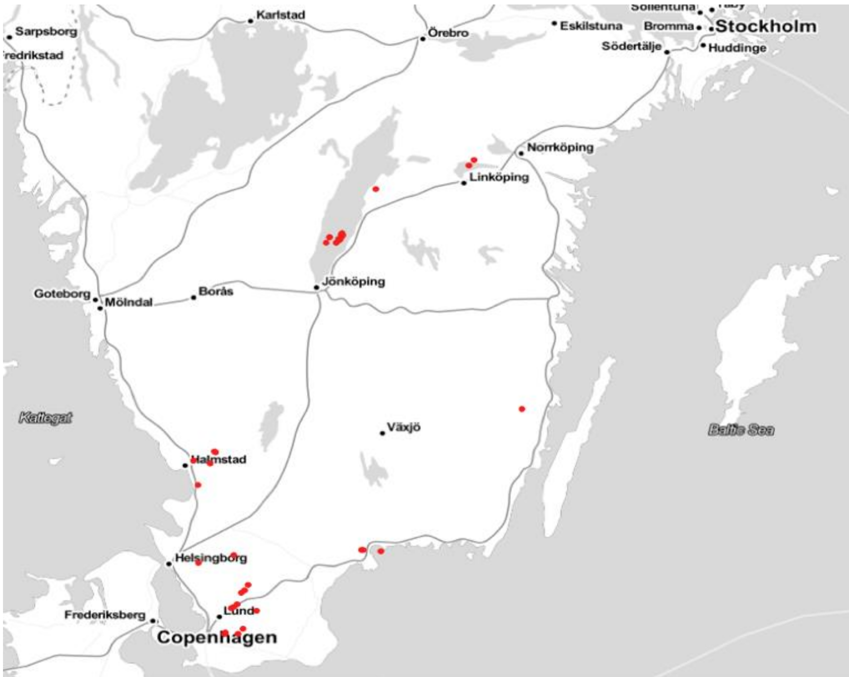

Figure 1. Location of the 37 study sites (some markers overlap).

About half of the plots (28) were used in the study by Carbonnier (1975) and are well documented with descriptions of establishment and management. Carbonnier has also reported detailed data about soil texture, base mineral index and species composition in the field layer. However, these variables could not be used in this study, since the information is not available for the new added plots. Furthermore, inclusion of such variables in the simulator would also complicate the practical application.

The following overall description of the material refers to all data in the study. The studied stands were established both on forest land and om former agriculture land. All stands were either planted or seeded with Pedunculate oak (*Quercus robur*), with the exception of three plots where Sessile oak (*Q. petraea*) was also present. In most cases the origin of the material is unknown. When documented, it shows that it is manly from Holland or of a local provenance. The establishment methods vary. In some cases, in the early development phase, larch (*Larix sp.)*, birch (*Betula sp.)* and grey alder (*Alnus incana*) have been blended into the new generation and used as a shelter, or with an intention of a more long-lasting mixture. An understory has often occurred naturally, but has in several cases been planted with spruce (*Picea abies*), beech (*Fagus sylvatica*) and hornbeam (*Carpinus betulus*). In some cases, planting of an understory was made in the middle-aged oak stand, mainly with spruce, but also with silver fir (*Abies alba*) and beech. It was hypothesized that the production could be increased by growing one or two generations of other species (primarily spruce) under an open canopy of oak. The development of this kind of mixtures has been evaluated by Carbonnier (1951).

In some stands pruning of main stems have been made, followed by removal of epicormic branches on irregular occasions.

Repeated pre-commercial thinnings have been documented in some cases. However, this treatment is assumed to have been applied in all stands. Commercial thinnings have been frequent. The interval between thinnings is on average 6 years in stands younger than 80 years and 8 years in older stands.

The strategy in thinnings has been to promote the development of potential future crop trees, aiming at well below 100 trees per ha in the final stand. Cuttings in early established stands has been less hard than in more recent establishments. On average the basal are removal in thinnings in ages below 80 was 16% and above 80, 8%. In most cases the basal are has been kept between 10 and 20 m^2ha^{-1} (Figure 2). With the exception of young stands, there has been no significant increase in basal are over time.

There is one exception from the general thinning strategy. One site (six plots) contains a thinning experiment, where the traditional thinning strategy is compared to no thinning and very hard thinning (Ekö *et al.* 2018).

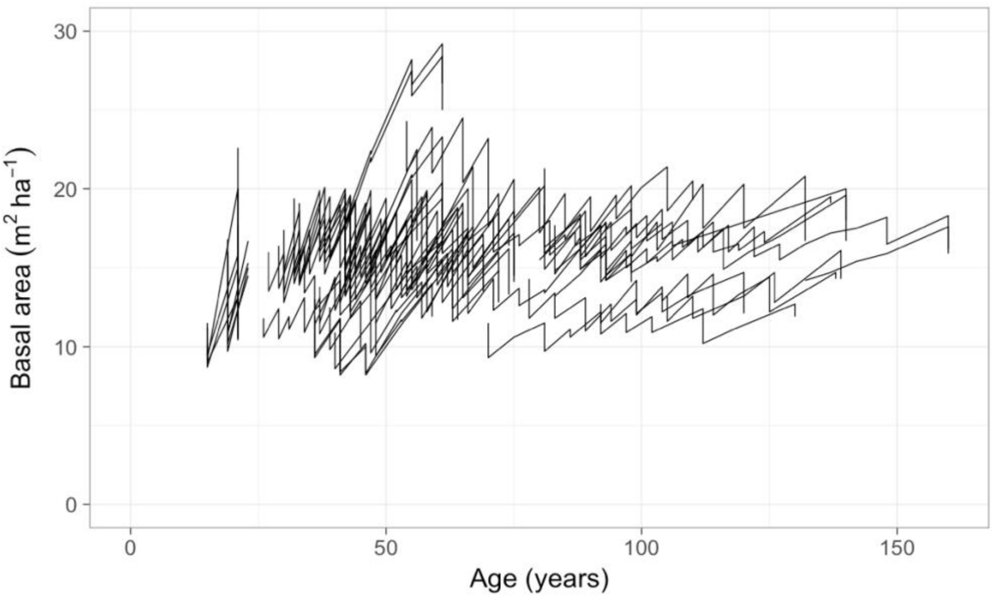

Figure 2. Basal area development on the study plots

Hard cuttings have been made to control spruce and beech in the understory, but the basal area of these species still remains quite high in some plots, even in old stands.

Naturally mortality is noted at every inventory. But, except for wind throw, the cause is not documented.

The stand variables in data include: age, top height, mean height, no of stems, basal are and volume. The tree heights refer to the stand after thinning. Top height refers only to oak, while mean height is calculated for all species. The other variables are given species-wise, before and after thinning. Only trees with a minimum diameter at breast height (dbh) of 50 mm are represented in data.

The volume comprises only to the stems on bark, from stump to top, and includes bark. Before 1947 the assessment of volume was made on felled sample trees. The volume was calculated section-wise, summed up and referred to the diameter class. From 1947 the tree volume was calculated by functions by Matérn (1975).

Basal are increment and volume increment was calculated as the difference between consecutive inventories. Correction of increment with tree-ring indices has not been made, since neither single tree data, nor indices for the whole observation period in data were available.

The only existing site variables are longitude, latitude (Figure 1) and site index. Assessment of site index was made at the inventory closest to 100 years using current top height development curves (Johansson *et al.*, 2014). There is a great variation in site index, from 17 m to 34 m, with a mean of 24.5 m)

Data from young unthinned stands

A special inventory was made in order to describe the structure of young unthinned stands to complement the permanent plot data.

Methods

The growth simulator is built on a set of regression functions for estimation of: height development, basal area increment, mortality and stand volume. The structure is in line with previous Swedish simulators (*cf.* Eriksson, 1976; Agestam,1985; Ekö, 1985; Hägglund *et al.*, 1979; Hägglund, 1981; Persson, 1992). Estimation of ingrowth, *i.e.* trees that will establish during the forecast period and will reach a certain minimum diameter, is not considered necessary since oak is a light demanding tree species, and since only single storied and managed stands are considered.

Top height development

Existing height development curves are used in this study (Johansson *et al.*, 2014).

Stand basal are increment

The growth regression model is based on the assumption that the effects of the growth factors interact multiplicatively (Baule, 1917). This assumption has been used for construction of several growth simulators (*cf.* Eriksson, 1976; Agestam,1985; Ekö, 1985; Hägglund *et al.*, 1979; Hägglund, 1981; Persson, 1992*)*. The development of the basic idea into the regression model is described by Jonsson (1969) and Hägglund (1981).

Stand basal area increment was chosen as the dependent variable, since it is measured with higher accuracy compared to stand volume increment. There is an obvious dependence within plots between observations of the increment in different periods. Thus, a mixed model was used with plot as a variance component. The choice of independent variables was restricted to variables that are possible to update when the growth simulator is applied recursively. Furthermore, top height could not be used since observations were missing for 81 growth periods. Different analytic expressions were tried to estimate the effect of the independent variables. A variable for length of the observation period was introduced for ages less than 80 years, since the growth is expected to decrease rapidly at younger ages and since the period length varies between 2 and 24 years in this interval. Different variables were tried to express the effect of trees competing with the oaks, among them $ba_c \cdot \frac{d_c}{d}$, where ba_c is the basal area of competing tree species, d and d_c are the are the quadratic means of the dbh of the oaks and of the dbh of the competing species

Regression model:

$$\ln\left(i_{ba_i}\right) = b_0 + \sum b_i \cdot x_i + \varepsilon_p + \varepsilon_o \qquad (1)$$

where:

i_{ba_i}: annual basal area increment

x_i: independent variables

b_i: coefficients

ε_o: is a random error term for variation between plots

ε_p: is a random error term for variation within plots

The random error terms were assumed to be independent and identical distributed, with distributional assumptions:

$\varepsilon_p \sim NID(0, \sigma_o^2)$, $\varepsilon_o \sim NID\left(0, \sigma_p^2\right)$, Residual plots were used to study systematic deviations and the assumption of normal distributed error terms was studied via Q-Q plots.

Parameters and variance components estimates were made with the package lme4 in R. The variance components were estimated with the REML procedure.

Stand volume

The regression function is based on the assumption that stand volume can be estimated from the relation; $v = ba \cdot h \cdot f$, where v Is stand volume, h is top height and f is a factor describing the relation between the sum of the individual tree volumes and the cylinder defined by basal area and top height. Thus, f reflects both the individual stem form and the diameter distribution. Data from all inventories could not be used since top height was missing in 85 cases. The remaining data consists of 268 observations.

Different independent variables reflecting the diameter distribution were tried to estimate the f factor. Thus, the following mixed regression model was used with plot as a variance component.

$$\ln(v_i) = b_0 + b_1 \cdot ba_i + b_2 \cdot h_i + \sum b_i \cdot x_i + \varepsilon_p + \varepsilon_o \quad (2)$$

where:
v_i: stand volume
ba_i: basal area
h_i: top height
b_i: coefficients
x_i: independent variables reflecting the form factor
ε_o: is a random error term for variation between plots
ε_p: is a random error term for variation within plots

The random error terms were assumed to be independent and identical distributed, with distributional assumptions:
$\varepsilon_p \sim NID(0, \sigma_o^2)$, $\quad \varepsilon_o \sim NID(0, \sigma_p^2)$,

Residual plots were used to study systematic deviations and the assumption of normal distributed error terms was studied via Q-Q plots.

Mortality

Mortality refers to the growth periods. It is possible to distinguish only between mortality due to wind throw and morality due to other causes. The annual mortality is calculated in different age intervals related to the times of the inventories.

Initial stands to be used in the simulator.

The current data for estimation of basal increment functions and stand volume functions cover stand development from about the first thinning (app. 10 - 12 m) and onwards. Thus, there is need for data describing initial stands, which should serve as starting points for simulations. The initial stands in Carbonnier's (1975) yield tables are constructed from the relationship:

$$d_{ba} = 2.3377 + 6322 \cdot \frac{1}{n} + 0.3617 \cdot h_{dom}$$

where:

d_{ba}: quadratic diameter (cm)
n: number of stems per ha
h_{dom}: top height (m)

Results

Function for estimation of basal area increment
There is a high correlation (-0.79) between age and basal area increment (Figure 3). The correlations between age and other independent variables are also great, number of stems (0.63) and quadratic mean diameter (-0.75).

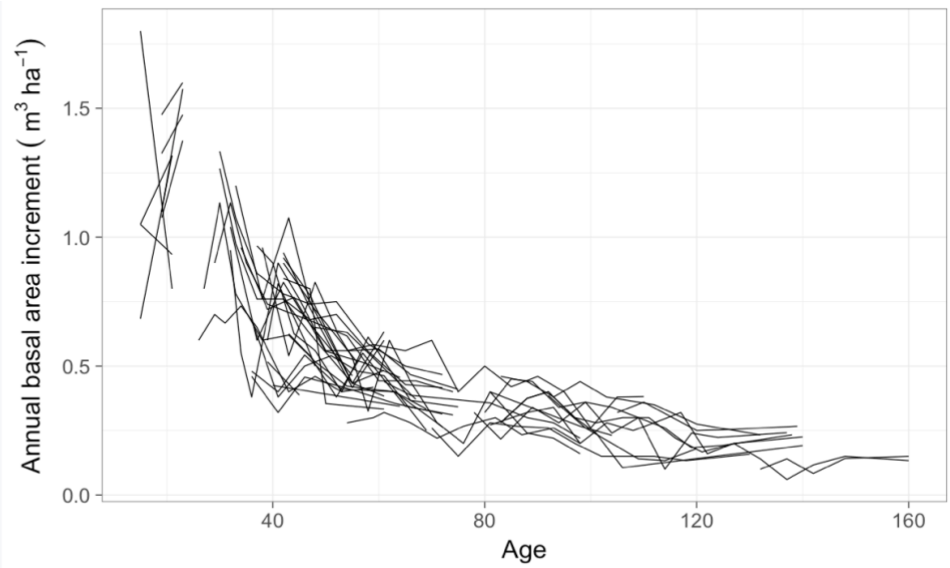

Figure 3. Relationship between age and annual basal area increment for the individual plots.

The parameter estimates for the final chosen independent variables in Model 1 are shown in Table 1. Several analytic expressions for the variables were studied and insignificant variables were excluded, *e.g.* variables describing thinnings and location of the stand.

Table 1. Estimated function for annual increment of stand basal area. Dependent variable: *ln(Annual basal area growth)*(m^2ha^{-1})

Variable	Coefficient	Std. Error
Intercept	0.808144	0.775970
ln(Age)	-0.599776	0.169742
ln(Basal area) (m^2ha^{-1})	0.158495	0.121190
Diameter (cm)*	-0.019810	0.004021
(No of stems)$^{1/2}$ ($no \cdot ha^{-1}$)	-0.004325	0.003019
*Comp.*** (m^2ha^{-1}))	-0.012269	0.005893
Site index (m)	0.046161	0.011595
*Pl80****	-0.020299	0.007210
σ_o^2 random variation between plots	0.01187	
σ_p^2 random variation within plots	0.05309	

** quadratic mean diameter*
*** $d_c/d * ba_c$, d: quadratic mean diameter, ba: basal area, index c: competing tree species.*
**** Pl80: length of observation period for ages below 80 years*
The intercept is corrected for logarithmic bias

Studies of residuals over fitted values and over the independent variables showed no trends of bias and did not violate the requirement of homoscedasticity. In four cases the model heavily overestimated the observed increment, where the residuals exceeded the standard deviation more than three times. However, these observations were not excluded since there could be natural causes for a relative low increment in periods, *e.g.* due to defoliation by frost or by moths. (*Tortrix viridana* or *Operophtera brumata*). Besides the outliers, QQ-plots of the residuals did not display significant deviation from the normal distribution. Furthermore, the assumption of additive errors seemed appropriate. Studies of residuals were also made plot wise over age and revealed no trends of systematic deviation in any case.

Function for estimation of stand volume
Stand volume has a high correlation with top height (0.87), with basal area (0,76) and has a very high correlation with the product of these variables (0.99) (Figure 4)

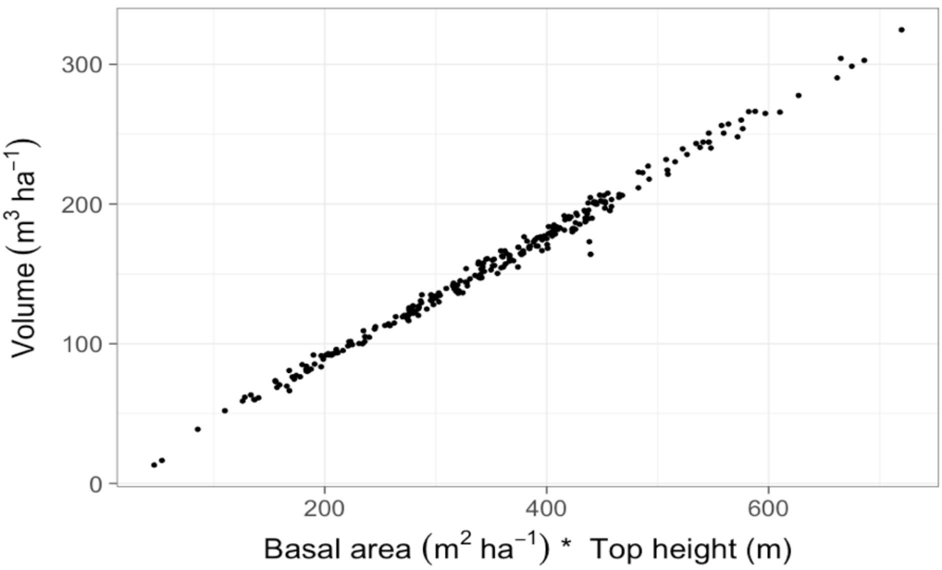

Figure 4. Relationship between stand volume and the product of basal area and top height.

Model 2 was estimated from 268 observation where top height was registered. (Table 2). The quadratic mean diameter was used for estimation of the form factor in Model 2. Other included variables did not significantly reduce the residual variation. Residuals were investigated in the same way as for the basal area increment function. No violations of the requirements for regression were found. However, four cases were observed where volume was heavily overestimated, with residuals greater than three times the standard deviation. Three of these cases came from heavily thinned plots. The data was not excluded from the analysis.

The assumption of additive errors could not be falsified.

Table 2. Estimated function for stand volume. Dependent variable: *ln(stand volume) (m^3/ha)*

Variable	Coefficient	Std. Error
Intercept	-0.64483	0.05168
ln(Basal area)(m^2/ha)	1.05670	0.01588
ln(Top height) (m)	0.74567	0.03512
Ln(Quadratic mean diameter) (m)	0.12826	0.01916
σ_o^2 random variation between plots	0.0054086	
σ_p^2 is a random variation within plots	0.0005194	

The intercept is corrected for logarithmic bias

Mortality

The average annual mortality in the material was 0.027 m^3ha^{-1}, but varied in different age intervals and was greatest in very old stands. (Figure 3). Wind throw more than 10 m^3ha^{-1} occurred in four cases, observation periods less than 15 years. The most extensive wind throw felled 47.3 m^3ha^{-1}.

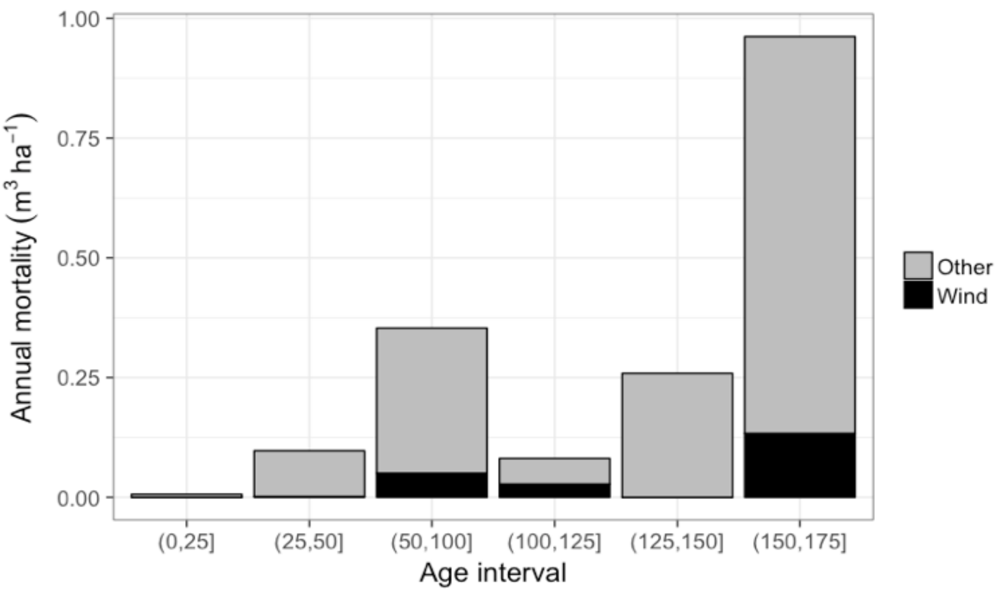

Figure 3. Mean annual mortality in different age intervals. Mortality caused by wind throw and other causes. Means calculated for the whole material.

Discussion

Comparisons with Carbonnier's (1975) yield tables

Volume estimates

Carbonnier's (1975) functions for estimation of stand volume were applied to current data set. The estimates were on average 1.7% (sd 4.1%) higher compared to the estimates in this study. The ratio between the estimates were studied over basal area, quadratic diameter and top height. No trends for were found except for stands in the early development phase. For top heights less than 10 m Carbonnier's estimates were on average 14.7% higher than the current. It should be noted that Carbonnier's material did not include such early observations.

Estimation of basal area growth

It was not possibly to directly apply Carbonnier's (1975) growth function to the current data set, since information on content of fine earth (soil fraction equal or less than 0.06 mm) and information on thinnings before the observation period was missing. Instead the function in this study was applied to the 12 yield tables published by Carbonnier (1975). The tables cover site indices (h100) from 20 to 28. Two thinning programmes are applied, with different intervals between thinning. The tables are also differentiated depending on the content of fine earth.

The estimated annual basal area increment was on average 16% lower (sd 20%) compared to Carbonnier's (1975) yield tables. The difference between the estimates varies between the 12 yield tables (Figure 4). There is a tendency of a greater difference with increasing age. Also, site index and content of fine earth have an influence on the observed differences.

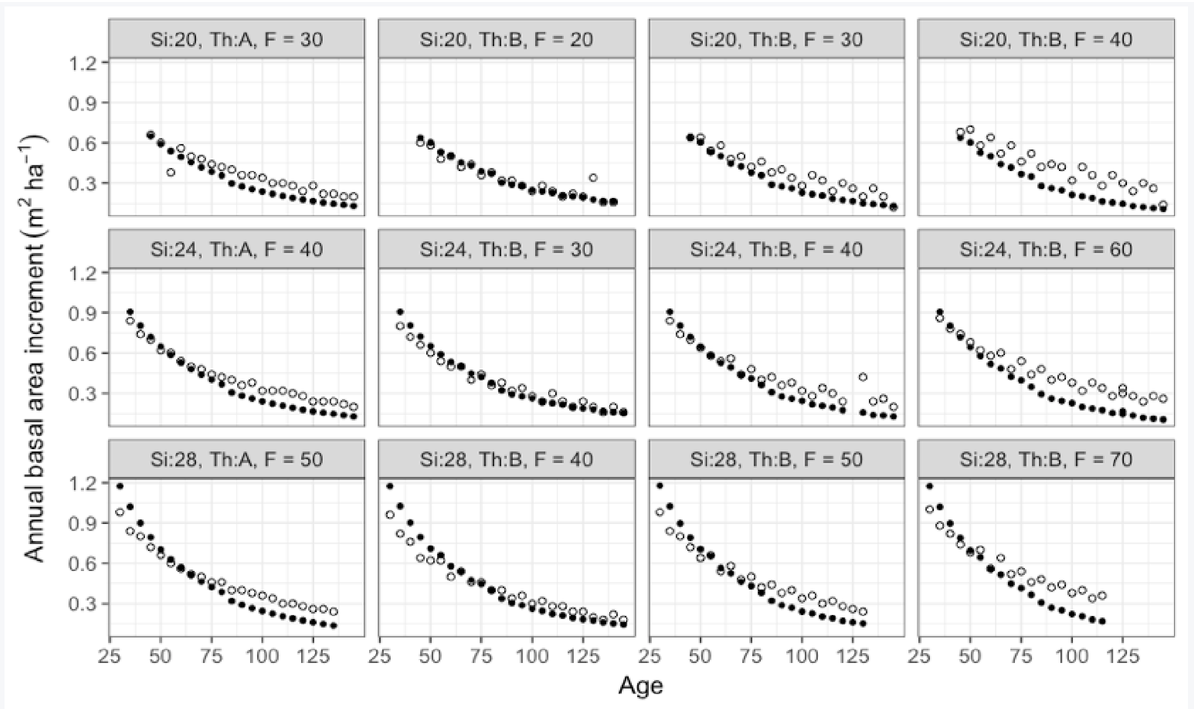

Figure 4. Estimated basal area increment by the current function (solid circles) compared to the values in Carbonnier's (1975) yield tables (open circles). Si: site index (m); Th: applied thinning programme, A: short thinning intervals, B: longer intervals; F: content of fine earth (%), fraction equal or less than 0.06 mm

Residuals for the current basal increment function were studied over the content of fine earth, using only the plots present in Carbonniers's (1975) study (Figure 5). There is a small correlation (0.12). However, the results indicate that there would only be a minor gain if this variable could be included. Still, in text books it is vindicated that the optimal soil conditions, especially for pedunculate oak, should be loam or clay (*cf*. Evans, 1984)

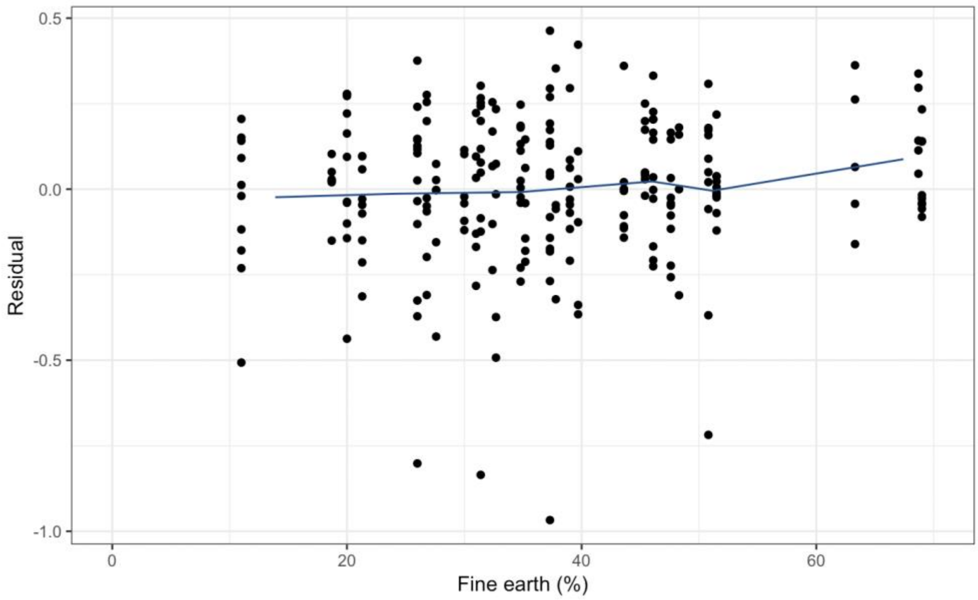

Figure 5. Residuals for the basal area increment function plotted over content of fine earth content of fine earth, fraction equal or less than 0.06 mm. Only plots in Carbonnier's (1975) study included. The solid line shows the mean residual calculated in classes of 10% fine earth.

Simulations of oak productivity in southern Sweden

Simulations were made with the current set of functions for site indices 20 to 32 (Figure 6, Table 5). The simulations started from 12 m height and continued until the stand reached an age of 150 years. The number of stems was set to 1400 per ha after the pre-commercial thinning phase. Thinnings were made at the start (12 m) and thereafter when the top height had increased by at least one meter since the last thinning. The thinning programme ended if the number of stems became less than 50 per ha. The thinning grade varied between 15% and 18% of the basal area. The applied thinning programme resulted in basal area development well represented in the data. Mortality was not included in the simulations, thus it was assumed that dead trees were removed at thinnings.

The maximum simulated mean annual increment (Mai) was 3.0, 4.1, 5.7 and 8.0 m^3ha^{-1}, for site index 20, 24, 28 and 32 m, respectively. This is on average 0.3 m^3ha^{-1} less than estimated by Carbonnier (1975). The current annual increment (Cai) decreases rapidly over time, especially on high site indices (Figure 6). This is likely due to frequent thinnings, keeping the stand density at a low level.

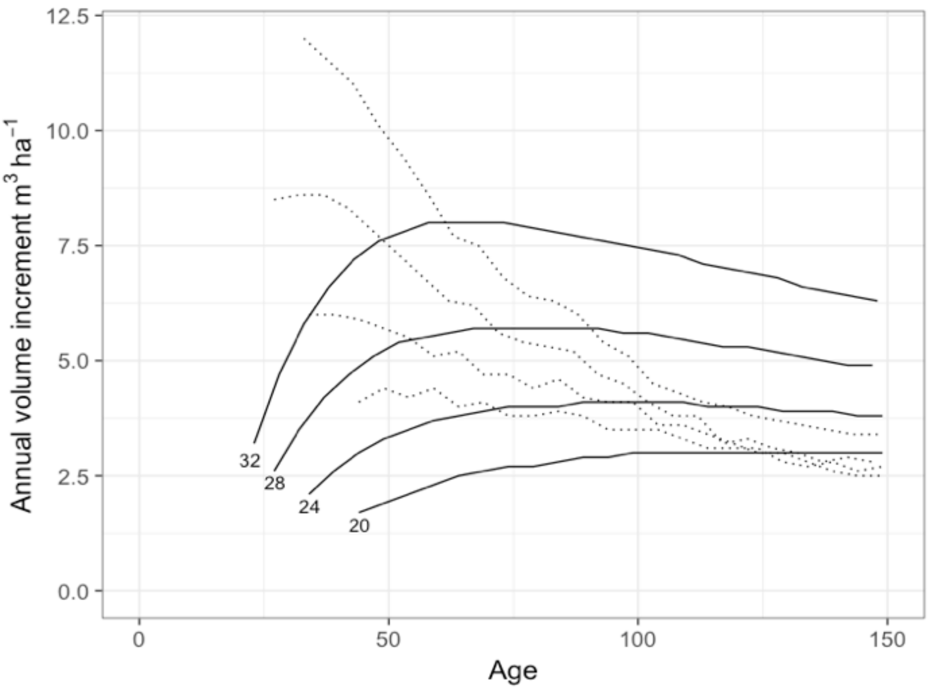

Figure 6. Simulated current annual volume increment (dotted line) and mean annual volume increment (solid line), for site indices 20, 24, 28 and 32.

Table 5. Statistic for simulated stand developments. The stand after thinning.

	Start of simulation				Age close to 50 years			
Site index (m)	20	24	28	32	20	24	28	32
Age	44	34	27	23	49	49	52	48
Top height (m)	12.0	12.0	11.8	12.1	13.0	16.2	20.2	22.5
No of stems per ha	1040	1040	1040	1040	1040	484	291	291
D_{ba}[1] (cm)	11.8	11.8	11.7	11.8	13.0	18.5	25.9	28.5
Basal area (m^2ha^{-1})	11.3	11.3	11.2	11.4	13.9	13.0	15.3	18.6
Volume (m^3ha^{-1})	60	60	58	60	80	91	134	180
Cai[2]	4.0	5.9	8.3	11.4	4.3	5.5	7.1	9.9
Mai[3]	1.7	2.1	2.6	3.2	1.9	3.3	5.3	7.5
	Age close to 100 years				**At app. 150 years**			
Site index (m)	20	24	28	32	20	24	28	32
Age	99	99	102	98	149	149	147	148
Top height (m)	19.9	23.9	28.2	31.8	23.0	27.2	31.3	35.5
No of stems per ha	291	135	63	63	175	63	49	49
D_{ba}[1] (cm)	27.2	40.9	55.4	61.4	39.6	60.0	73.0	81.2
Basal area (m^2ha^{-1})	16.9	17.7	15.2	18.7	16.9	17.8	20.5	25.4
Volume (m^3ha^{-1})	148	187	188	259	224	219	289	403
Cai[2]	3.4	4.0	4.0	5.0	2.7	2.5	2.8	3.4
Mai[3]	2.9	4.0	5.4	7.3	2.9	3.7	4.8	6.2

[1] *Quadratic mean diameter*
[2] *Current annual increment*
[3] *Mean annual increment*

The difference between Carbonnier's (1975) results and the current outcome could have several causes. The functions for assessing site index are not the same. The new and updated material is more extensive and includes both younger and older observations. In the current study the increment is not corrected with climate indices. The analyse methods differ between the two studies.

Application of the simulator

According to the various studies of residuals the simulator seems to be well adapted to the data and should thus provide a good description of the material. The simulator is easy to implement in planning programs, since it only requires variables which are normally present in inventory data. However, precautions have to be made since the background material is small and restricted concerning the applied silviculture. All plots, except four plots in the earlier mentioned thinning experiment, are managed according to the general belief of how oak forestry should be conducted in southern Sweden. Forecast for long periods with no thinning should be avoided, especially since estimations of natural mortality are not available. In general, to make forecasts based on stand data outside the limits of the material, as it is previously described, are extrapolations and should be regarded with great precaution.

Even if the oak stands have been grown on land belonging to long term owners it should be noted that it is difficult to pursue a consistent management over a very long period, due to lack of knowledge and outer circumstances, In the current data the introduction of other species as an under story has sometimes been too extensive. Furthermore, weather variations, defoliation by insects and frost, economic circumstances etc. have influenced the management and the stand development (*cf.* Schotte1923; Kardell, 1977). This has both advantages and disadvantages. The advantage being that similar events will happen during the course of a rotation and that the material therefore represent realistic conditions, the disadvantage it is that it is difficult to get a good picture of what kind of forests and silviculture the material really represents.

Future research

The current material is gathered with great efforts over a hundred-year period. Thus, to extend the material cannot be made over-night and would require great costs. Hopefully new experiments in oak, testing modified silviculture practices, will be established in the future. Such experiments are important for the understanding of how stand development can be influenced and for improvement of methods for growth prognoses.

The economy in oak is highly dependent on the yield of high-quality sawn timber of great dimensions. In the current material there is no observations on quality traits. However, it would not be a very extensive work to supplement the data with a survey of the quality of the main stems.

As mentioned, early collected data are not digitized. Access to individual tree data would be valuable for estimations of stem distributions. Moreover, it would be interesting to follow the development of final crop trees, since there are different opinions on when main stems should be appointed. (*cf.* Holten, 1995; Holten & v. Diest, 1966; Chroust, 2007; Nagel, 2007)

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