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Growth modelling in the Heureka system

The Heureka forest planning system comprises three applications:

- Regwise, for simulation of regional forest development under different treatment scenarios
- Standwise, for simulation of stand and tree development and value production under different silvicultural options
- Planwise, for optimisation of forest management at the ownership level

Heureka replaces the former planning systems Hugin and Forest Planning Package, and the growth models from those systems are available in Heureka. However, the default options for growth modelling in Heureka are mainly based on new functions which will be presented here. All growth functions are common for the three applications and predictions can be based on single plot data or data from several plots representing a stand.

Two stages are distinguished at the growth modelling: the stand establishment period (h<7 m) and the development of established stands (h>7 m). Predictions of stand establishment and development of young stands are based on data from the Hugin young stand survey. For un-stocked areas (in initial inventory data or on areas that are clear-cut during the growth predictions) the expected stocking 12 years after clear-cut in natural regenerations or 12 years after sowing or planting is calculated as a function of site conditions and prescribed regeneration measures. With stocking, regeneration type and site conditions as indicators, data on height- and species distribution in the new stand is either imported from a data-base with measured plots or estimated with functions based on data from this data-base. Probabilities for all trees to become a future crop tree are calculated, and from this the mean height of different species in this population. Those probabilities are also used for stem selection at pre-commercial thinning.

Inventory data from young stands are often given in aggregated form as number of trees per hectare and mean height for different species. Then a list of single trees is created for each plot by use of distribution functions

Mean age is solved from species, mean height and site index with functions for mean height development. Age at breast height is also calculated for all trees as well as probabilities for survival and severity of damages by different agencies. Height growth is then estimated with the height development curves and differentiation functions, including effects of damages, for all trees in 5-year steps until mean height exceed 7 m. At this stage the stand is considered as established. All trees are then given a diameter as a function of species, height, stand density and other variables and the continued development is predicted with functions for established stands.

Growth of established stands is predicted with separate functions for basal area growth and height growth. Initial data should contain a tree list with species and diameter for all trees with dbh≥4 cm. Minimum input variables are also stand age , data on performed thinning, latitude, altitude, field vegetation type, soil moisture and site index according to site factors. Stand age is defined as basal-area weighted total mean age of the main stand (excluding standards). The stand must also be classified as even- or uneven-aged, where the latter is defined by having less than 80 % of the main stand volume within a 20-year age-span.

At start of prediction, if not given in initial data, height and age at breast height are calculated for all trees and a new stand age is calculated on basis of this. Time to reach breast height is calculated with a function that assimilates figures given in a table from the NFI field work instruction that has been practiced since 1983. Volumes are calculated with single-tree functions based on data from the Great Yield Investigation performed in the period 1940-1963. Also biomasses in roots, stem, branches and needles are calculated.

Stand development is predicted with 5-year steps. Basal area growth is calculated both tree-wise with functions for single trees and for the whole stand with a stand-level function. The latter function has the highest precision and is used to calibrate the growth level, while the individual-tree functions distribute growth between trees in a realistic manner.

Height growth is predicted with top-height development functions (site curves). For each tree height after 5 years is estimated as a function of initial height and age. Recruitment of new trees with dbh≥4 cm in established stands is calculated with in-growth functions. Mortality is estimated as a proportion of the basal area before growth with area-based functions and distributed on single trees with models for mortality probability of single trees. Thinning is distributed on species and trees with the same algorithms that were used in the Hugin system. The thinning response is calculated with specific thinning response functions. Effects of whole-tree utilisation at harvest are also considered. The effect of nitrogen fertilisation is initially given in the form of total response in m^3sk/ha as function of dose and stand parameters. Stand growth is predicted with ordinary functions until the predicted volume including fertilisation effect is reached and that stand conditions are then used as stand status when fertilisation effect has ceased, that is at a lower age (the age scale is shifted). The effect of genetic improvement is included by an increased site index. The amount of rot on spruce is estimated and taken into account at the valuation of the yield. Effects of global warming can be predicted by selection among different SWECLIM-scenarios. Correction factors for volume growth are available from tables produced with the mechanistic model BIOMASS. Adjustments are made to site and stand conditions.

Shelter trees, seed trees and retention trees can be selected with the thinning algorithms or with specific rules, and the mortality of those trees is predicted with a specific function. For old trees also an age-related mortality factor acts to avoid that trees become unrealistically old. The break-down of dead trees is followed. Competing effects of retained trees on the new stand are also calculated. The output features are very flexible and the development can be followed on the single-tree level. In this document the various sub-models are superficially described, more detailed (technical) descriptions are found in the Heureka model database.

Appendices Page

Appendix 1.

Functions for regeneration results

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Regeneration stocking 12 years after final cut in natural regenerations and 12 years after sowing or planting in cultivations (sown or planted areas) was expressed as function of site conditions and regeneration measures. The functions were based on data from regeneration surveys of about 15 000 regenerations performed in the period 1960-1968 by the Forestry Board Organisation (Forshell et al 1966). The survey covered 75 % of the productive forest area in Sweden. The state forests with 25 % of the area were not included. In allotted aerial photos clear-cuts larger than a minimum area, older than a minimum age and with a mean height below 1.3 m were identified. The minimum values were 0.3 ha - 2 years in southern Sweden and 0.5 ha - 4 years in the north. A specified amount of objects in each photo fulfilling the demands were allotted for survey.

The survey was performed as a circular plot inventory with about 20 evenly spaced plots á 10 m² per regeneration. The forest owner was generally interviewed regarding regeneration history. On the plots all seedlings were counted and the number of well-spaced seedlings judged capable to form future crop trees was annotated with species, origin (natural or cultivated) and height. Also the number of empty seedling spots ("missing seedlings") was counted, and the sum of existing and missing seedlings indicated the demand for full stocking. The quotient between existing and demanded seedling numbers (the stocking, SLH) was used as dependent variable in the regression analysis.

Beside site factors and variables expressing performed regeneration measures also time from stand establishment and demanded number of seedlings were included as independent variables, Tab. 1-2. The demand decreased from south to north, from start to end of the survey period and with increasing stand height, and this had of course a large impact on the registered stocking. By inclusion of the demand as an independent variable the results were stabilized. Stocking increased with age in natural regenerations and decreased in cultivations. This must also be taken into account at evaluation of regeneration results. In the final regressions only data from the years 1964-1968, with higher quality, was included.

Functions for species distribution and proportion of cultivated seedlings in cultivations were also developed but not utilized in the general prediction system. All functions were presented in Swedish by Elfving 1992.

In similar regeneration studies in Norway, the "zero-plot count" (proportion of 4 m²-plots without acceptable seedling) was used as dependent variable (Braathe 1966)

References

Braathe, P. 1966. Registrering av gjenvekst 1962-1964. MNS 21:78

Elfving, B. 1992. Återväxtens etablering och utveckling till röjningstidpunkten. SLU, inst för skogsskötsel. Arbetsrapporter nr 67.

Forshell, WP., Johansson, F. & Sillerström, E. 1966. Skogsstyrelsens återväxttaxering 1960-1965. SST nr 3.

Table 1. Function for regeneration stocking (SLH) in natural regenerations. The dependent variable is arcsin-transformed, see variable explanations. Bias correction: SLHcorr = 0.056 + 0.887·SLHest

Indep. variables	Mean	Coefficient	F-value
Constant		1.7413	529
alt2xNS	6.893	-0.0163	139
age-f	0.860	0.6863	96
propcult	0.028	0.6663	47
N-full	2.634	-0.1500	
mapxdry	3.680	0.0218	40
moist	0.048	0.2702	36
gotland	0.007	-0.7552	41
T-area	0.029	0.3310	29
SYZ-area	0.253	-0.1275	31
scarif	0.063	0.2692	40
burnt	0.028	0.2030	12
no-treat	0.147	-0.1484	23
uncleaned	0.268	-0.0947	15
N-seedtrees	0.263	0.1596	19
mapxno-seedtrees	4.112	0.0175	29
Jonsbon	4.801	-0.0379	8
invarea	0.380	0.1888	9
NS	0.748	0.1075	6
map	17.580	-0.00619	4
n		2462	
R^2		0.492	
s-res		0.475	
dep. mean	1.8585		

Variable	Definition
SLH	Stocking, varying between 0-1
asinslh	2·arcsin($SLH^{0.5}$), expressed in radians, asinslh varies between 0 and π
	Retransformation: SLH=sin²(asinslh/2). Estimated values must be bias-corrected, see table text
alt2xNS	(Altitude/100)² times "northern Sweden". Altitude is given in meter above see level and NS is
	an indicator variable with the value 1 for areas north the latitude 60 ºN, otherwise 0
age-f	a function of age, age-f=2·[1/(1+exp(-0.3·age))^-0.5] ; age= vegetation periods between cut and inventory
propcult	proportion of cultivated seedlings according to inventory. Some natural regenerations were partly planted.
N-full	number of demanded seedlings per ha for full stocking
mapxdry	map refers to map number in the Swedish system and is related to the distance north of the equator
	(X, km) according to the formula: map=(X-6050)/50
	dry is an indicator variable for dry site conditions (more than 2 m to the ground water).
moist	indicator variable for moist site conditions (les than 1 m to the ground water)
gotland, SYZ-area	indicator variables for the counties Gotland and Värmland-Medelpad-Jämtland
scarif	indicator variable for scarification, generally by manual patch-hacking
burnt	indicator variable for prescribed burning after the final felling
no-treat	indicator variable for totally un-treated areas (no measures done to promote regeneration)
uncleaned	indicator variable for where bushes and small trees remain after the clear-felling
N-seedtrees	number of seed-trees per hectare
mapxno-seeedtrees	map as explained above, no-seedtrees is indicator variable for natural regeneration without seed-trees
Jonsbon	site index according to the Jonson system in the scale 1-9. The relation to the productivity (MAImax) is:
	MAImax = 8·0.75(x-2), where x is site index according to Jonson
invarea	1/area, where area is the size of the regeneration area in hectare
NS	indicator variable for northern Sweden, see above
map	a value linked to the latitude, see above

Table 2. Function for regeneration stocking (SLH) in cultivations. The dependent variable is arcsin-transformed, see variable explanations. Bias correction: SLHcorr = 0.037 + 0.926·SLHest

Indep. variables	Mean	Coefficient	F-value
Constant		3.0707	828
invage	0.1826	0.4358	34
Jonsbon	3.5434	-0.0614	50
altxNS	0.7274	-0.0514	25
spacing	1.7320	-0.3591	83
spruce	0.5479	0.0760	18
burnt	0.0887	0.1141	19
scarif	0.4663	0.0757	27
sown	0.0683	-0.0675	6
NS	0.2236	0.2597	43
invmap	0.0786	4.7901	130
T-area	0.0244	0.2178	25
N-full	3.2650	-0.1500	
n		3528	
R^2		0.492	
s-res		0.391	
dep. mean	2.3059		

invage	1/age, where age is number of vegetation periods between sowing/planting and inventory
Jonsbon	site index according to the Jonson system in the scale 1-9. The relation to the productivity (MAImax) is: MAImax = 8·0.75(x-2), where x is site index according to Jonson
altxNS	altitude/100 times "northern Sweden". Altitude is given in meter above see level and NS is an indicator variable with the value 1 for areas north the latitude 60 ºN, otherwise 0
spacing	the average square spacing used at sowing/planting
spruce	indicator variable for regenerations cultivated with spruce
burnt	indicator variable for prescribed burning after the final felling
scarif	indicator variable for scarification, generally by manual patch-hacking
sown	indicator varialbe for sown regenerations
NS	indicator variable for northern Sweden, see above
invmap	1/map, where map refers to map number in the swedish system and is related to the distance north of the equator (X, km) according to the formula: map=(X-6050)/50
T-area	indicator variable for the county Örebro
N-full	number of demanded seedlings per ha for full stocking

At application of the functions in Tab. 1-2 age was set to 12 and N-full to 2.5. Increased efficiency in provenance selection and scarification has also been considered by assumed influence on the cofficients. For cultivations the negative effect by increasing height above see level has been reduced from -0.0514 to -0.0257 and the positive effect by scarification has been increased from 0.0757 to 0.2. For natural regenerations the effect by scarification has been modified to 0.30 on mesic sites and 0.15 on other sites.

Appendix 2.

The Hugin young stand survey: database and functions

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The Hugin young stand survey was performed in the period 1976-1979 and comprised 799 young stands in the whole country (Elfving 1982). The stands were mainly selected as a stratified sample among the 15 000 regenerations surveyed by the Forestry Board Organisation in the period 1960-1968. One aim with the stratification was to get a representative database of different sites and regeneration types (both successful and failed) that would reflect stand initiation under different treatment scenarios.

In each stand five circular plots á 100 m^2 were randomly located within the network of about 20 equidistant plots measured in the earlier regeneration survey. On each plot the up to 40 largest objects (remaining and cut trees and seedlings) were mapped and measured. If the number of objects was>40 a lower dimension limit was established and the number of smaller objects was counted with division on conifers and broad-leaves. If the stand had been pre-commercially thinned also stumps were registered. Before mapping a selection (strip-marking) of future crop trees was done, aiming at 16 well spaced objects per plot (1600 per ha) with potential to become future crop trees.

For each mapped object the variables type, species, height, diameter and damage (location, cause and severity) were registered. The variable type distinguishes future crop trees, other trees, stumps and standards. Age, diameters at breast- and stump height and 5-year height growth was measured on sample trees. The plot centre was marked with a 0.5 m high impregnated wooden pole. Most plots were re-measured after 5 years.

As a measure of the stand potential for future production the "young stand quality" (W) was calculated for each plot, based on the number, species composition, height stratification and damage degree of the future crop trees. W varies between 0-1 with value 1 corresponding to 16 even-sized and undamaged trees of the most suitable tree species. Average W per stand was related to the regeneration stocking (SLH) by the following functions:
Natural regenerations: $W = \sin^2(-0.11 + 1.671 \cdot asinslh - 0.583 \cdot asinslh^2)$
Cultivations: $W = \sin^2(-0.058 + 1.380 \cdot asinslh - 0.315 \cdot asinslh^2 - 0.031 \cdot NS)$
where $asinslh = \arcsin(SLH^{0.5})$ expressed in radians and NS=1 if latitude>60 °N, else =0

Data from the Hugin young stand survey was used to create the data-base NYSKOG and to construct the following functions:

1. Functions for prioritizing trees at pre-commercial thinning
2. Functions for mean height development in young stands
3. Functions for age determination of young trees
4. Functions for damage and mortality in young stands
5. Functions for estimation of dbh from height, stand density etc.
6. Functions for reconstruction of the state of young stands (species- and height distributions)

References:

Elfving B. 1982. Hugins ungskogstaxering 1976-1979. SLU, Projekt Hugin, Rapport 27.
Nyström, K. & Söderberg, U. 1987. Tillväxtberäkningen för ungskog i Hugin-systemet. SLU, inst. för skogsskötsel, Arbetsrapporter nr 18.

Overview of the data-base NYSKOG

The table below shows the distribution of 100 m²-plots in the HUGIN young stand survey. Regenerations were mainly selected by stratification from 16 000 regenerations surveyed by the Forestry Board in the period 1960-1968 and measured in the period 1976-1979. For the data-base NYSKOG the height distribution (and other variables) was reconstructed to represent the conditions before pre-commercial thinning (at a mean height of 2-3 m).

At simulation of regeneration in the Heureka system expected young stand quality (W) is calculated and representative plots (regeneration type, site conditions, expected W) are selected to represent the new stand. The time scale is synchronized with the actual timescale for the plot (years from clear-cut or cultivation). Alternatively, the state of the young stand can be reconstructed with functions (Appendix 2:6).

Southern Sweden (lat<60 ºN)

Regeneration type	Soil moisture			
	dry	mesic	moist	Sum
Natural regeneration	182	329	65	576
Sowing	77	95	13	185
Pine plantation	110	223	19	352
Spruce plantation	49	459	65	573
Sum	418	1106	162	1686

Northern Sweden (lat 60+ ºN)

Regeneration type	Soil moisture			
	dry	mesic	moist	Sum
Natural regeneration	189	439	108	736
Sowing	30	96	28	154
Pine plantation	100	322	68	490
Spruce plantation	26	327	64	417
Sum	345	1184	268	1797
Contorta				228
Total in the country				3711

2.1 Functions for prioritizing trees at pre-commercial thinning

Based on the nomination of future crop trees on the plots, the probability (p) for a tree to become a future crop tree is estimated:

Conifers: $p = \sin^2(0.7433 + 1.4339 \cdot H - 0.4902 \cdot H^2 - 0.1070 \cdot RB - 0.1097 \cdot RB \cdot H + 0.0587 \cdot RB \cdot H^2)$
Broad-leaves: $p = \sin^2(0.0185 + 1.0991 \cdot H - 0.2665 \cdot H^2 - 0.1615 \cdot RB + 0.0453 \cdot RB \cdot H^2)$

The values for the sin-functions are expressed in radians. H = relative tree height, h/HA, where h is height of the subject tree and HA is the arithmetic mean height of all mapped trees on the plot. $RB = B^{0.5}$, where B is the number of mapped conifers on the plot (100 m²).
For thinning to N stems per ha, multiply B by N/1600.

2.2. Functions for mean height development in young stands

Functions for mean height development were based on sample-tree data on height and total age from future crop trees (1600 stems per ha)) in the Hugin young stand survey. In total about 15 000 trees were measured. General functional form: $H = SI/(\exp(Y)+1)$. In this function Y is an expression of site index (SI, m) and X =ln(Atot), Atot=total age. For spruce SI=H100spruce. For pine, pub. birch (Betula pubescens) and aspen SI=H100pine.

Pine:	$Y= b0 + b1\cdot X + b2\cdot X^2$;	$b0=7.0$; $b1=-0.57-0.05\cdot SI$; $b2=-0.28+0.0094\cdot SI$
Spruce:	$Y= b0 + b1\cdot X + b2\cdot X^2$;	$b0=6.27+12.1/SI$; $b1=-0.262-0.0575\cdot SI+0.00088\cdot SI^2$; $b2=-0.323-0.134\cdot b1$;
Pub. birch:	$Y = b0 + b1\cdot X$;	$b0=6.836+0.03165\cdot SI-0.002757\cdot SI^2$; $b1=-2.694+0.4937\cdot b0-0.05331\cdot b1^2$;
Aspen:	$Y = b0 + b1\cdot X$;	$b0=10.024-0.1664\cdot SI$; $b1=-4.093+0.1605\cdot SI-0.0025\cdot SI^2$

Beech: Spruce function with $SI = 7.4 + 0.755\cdot H100Beech - 0.00268\cdot(H100beech)^2$

Oak: Birch function with $SI = 6.5 + 0.5\cdot H100oak$

Contorta: Pine function with $SI = 0.888 + 1.336\cdot H100pine - 0.0094\cdot(H100pine)^2$

Pend. birch: Pub. birch function with $SI = H100pine + 1.5$

2.3. Functions for age determination of young trees

Functions for determination of age at breast height for young trees were presented by Nyström & Söderberg (1987). They were based on data from un-damaged sample-trees with h>1.3 m from the Hugin young stand survey, in total about 10 000 trees. Sampling probabilities were used as weights in the regressions

Table 2.3. Functions for age at breast height (tbh, years) of young trees

Indep. Variables	Pine Coefficient	Pine std.err. %	Spruce Coefficient	Spruce std.err. %	Birch Coefficient	Birch std.err. %
ln(h-12)	2.548	1.2	2.643	1.5	1.988	2.0
$(h/SI)^2$	68.23	2.3	78.64	2.5	61.89	2.6
h·SI/10	-0.003	4.6	-0.002	5.1		
$(HA/SI)^2$	24.54	6.7	28.86	8.2		
(h-HA)/HA	0.572	17.8	0.510	24.0		
HA/SI					-1.490	27.3
peb·$(h/SI)^2$					-15.72	10.9
sp·(h-50)					0.014	22.1
R^2	0.96		0.92		0.91	
Sres	2.1		3.0		3.1	

Variable	Explanation
h	total tree height, dm
HA	arithmetic mean height of future crop trees (1600 stems per ha)
SI	site index, H100spruce for spruce, H100pine for pine and birch, dm
peb	indicator variable for birch species, peb=1 for pendula birch, else pb=0
sp	indicator variable for origin (sprout or seed), sp=1 for sprout, else sp=0

2.4. Functions for damage and mortality in young stands

Functions for estimation of probability for mortality and growth reduction due to damages on single trees were presented by Näslund (1986). They were based on data from re-measured plots in the Hugin young stand survey. About 100 000 trees were followed in a five-year period of which 18 % were damaged at the start of the period and 28 % were dead or damaged at the end of the period. In total 85 different functions were developed in the form of logistic regressions. At application, calculations are performed in five steps:

1. The probability for damage on different tree species on a given plot is calculated as function of mean height and stem number for each species, total mean height, site index and climate variables.

2. Damaged trees are distinguished with estimated probabilities and random numbers

3. For each tree nominated as damaged, probabilities for damage by different agents (moose, snow, frost etc) are calculated as functions of tree height, and an acting agent is allotted with a random number.

4. Depending on tree species, type of damage and tree height, the probability for different damage degrees are calculated (slight damage, heavy damage, dead) and the actual severity is decided by a random number

5. Depending on species and damage severity a growth reduction is calculated, expressed as number of years of lost height growth

To demonstrate the importance to take the effects of damage and mortality in young stands into account, the following example was given.

The initial stand was assumed to keep 4000 seedlings per ha at an age of 7 years, with 1000 each of pine, spruce, birch and aspen. Site index was H100pine=22, H100spruce=19. Growth predictions covered a 20-year period. In total the volume after 20 years was reduced by more than 50 % due to damages, Tab. 2.4. The reduction was largest for pine and aspen, mostly due to moose browsing.

Table 2.4. Estimated volumes after 20 years in an un-damaged and a normally damaged stand

Case	Volume after 20 years, m² per ha				
	pine	spruce	birch	aspen	total
without damage	23	4	12	23	62
with damage	10	4	11	2	27

Reference

Näslund, B-Å. 1986. Simulation of damage and mortality in young stands and associated stand development effects. SLU, Dept. of Silviculture. Report 18 (147 pp, in Swedish with English summary).

2.5. Functions for estimation of dbh from height, stand density etc.

Functions for estimation of breast height diameter from tree height and other variables were presented by Nyström & Söderberg (1987). They were based on data from the plots in the Hugin young stand survey re-measured 1981-1983 and checked with data from plots re-measured 1984. Functions were developed for pine, spruce and birch, and are presented in Tab. 5.1.

Table 5.1. Functions for estimation of single tree dbh from height and other variables. Dependent variable: $\ln(dbh^2)$, cm^2

Indep. variable	Pine		Spruce		Birch	
	coefficient	std.error %	coefficient	std.error %	coefficient	std.error %
ln(h-k)	2.098	0.6	1.868	0.4	2.25	0.8
h					0.0119	50
$(h-k)^2$			0.0147	18		
dat·(1-h)	3.474	12	1.582	12		
sh^2	-0.1473	10	-0.0525	16	-0.0166	8
$\ln(sh^2+0.1)$	-0.176	12	-0.109	13		
ln(cf)	-0.098	6	-0.058	9	-0.119	6
sin(ldel)	0.136	13	0.081	15		
nat	-0.312	14	-0.052	14		
$nat\cdot h^{0.5}$	0.0759	22				
roj/(1+ar)	-0.171	16	-0.093	25	-0.071	71
roj·ln(10+ar)	0.022	21	0.013	22	0.033	25
$stsk\cdot h^2$					-0.00029	29
lat	0.014	16	0.014	14		
alt/100	-0.0466	26	0.068	8		
$(alt/100)^2$	0.0126	19	0.0045	13		
ak	0.096	22	0.103	16	0.120	26
H100pine					-0.0096	20
grass	0.088	11				
shrub			-0.053	18		
constant	0.261		0.186		0.867	
corr. log-bias	+0.068		+0.061		+0.090	
n	9524		11706		5476	
R	0.91		0.95		0.93	
sf	0.42		0.36		0.47	

Variable	Definition
$\ln(d^2)$	dependent variable, d=dbh including bark, cm
k	constant, varies with species: pine=1.0 spruce=1.0 birch=1.1
h	tree heigth, m
Hmax	mean height of the three highest trees on the plot (100 m^2), m
hd	height difference: Hmax-h, m. If hd<0.1 then hd=0.1
sh2	10^{-5} ·(sum of squared heights per ha, m^2)
cf	1+10·hd·(sh2+0.1)
ldel	(proportion broadleaves of sh2)·1.5708 (expressed in radians)
stsk	number of sprouts higher than half max-height in stump sprout bunches

nat	indicator variable with value 1 in natural regenerations, else value 0
roj	indicator variable with value 1 if precommercial thinning was done<10 years ago
ar	number of growing seasons since precommercial thinning was done
lat	latitude, ºN
alt	altitude, meter above see level
Ak	indicator variable with value 1 if the distance to coast is <5 km, else value 0
H100p	site index for pine, m
grass	indicator variable with value 1 if the field vegetation type is grass, else value 0
shrub	indicator variable with value 1if the field vegetation type is dwarf-shrubs, else value 0
dat	indicator variable with value 1 if the measurement was done before 20/7, else value 0 current top shoot was not included in tree heigth before 20/7. This variable is only for accounting in the regression, should have the value 0 at application

2.6. Functions for reconstruction of the state of young stands (species- and height distributions)

Functions for reconstruction of the state of young stands were based on data from the database NYSKOG. The reconstruction is performed in six steps with separate functions for the five distinguished regeneration types: natural regenerations, pine sowings, pine plantations, spruce plantations, lodgepole pine plantations. The most important independent variables are young stand quality (W), mean height and site factors (site index, soil moisture, field vegetation type). Stands are reconstructed at a mean height for the dominating species of 2-3 m.

1. Estimate total stem number per hectare (trees and seedlings)
2. Estimate the proportion of conifers
3. Estimate the proportion of dominant conifer (pine in nat. reg., otherwise cultivated species)
4. Estimate heights (mean, var. coeff.) of secondary species (broadleaves, conifers)
5. Estimate shape and scale parameters for Weibull-distributed tree heights
6. Create stem lists (species, heights) by comparing random numbers with probabilities according to the Weibull distributions

All functions were developed independent of each other. Variances within and between stands were separated, using mixed modeling technique. The models are described in detail in the Heureka model data base (Nyström 2008).

Appendix 3

Construction of tree populations from aggregated young stand data

In forest inventories, the description of young stands is often given by stand-level data like mean height, total number of stems per hectare and species proportions of the number of stems. When such data is imported to Heureka a reconstruction on the plot level of single trees (species and height) is needed. A set of functions have been developed for this purpose by Kenneth Nyström, based on data from the Hugin Young Stand Inventories. For each plot mean height (H) and the coefficient of variation of tree heights (CVH) were computed, over all trees and per species. Furthermore, the two-parameter Weibull distribution was adapted to describe the height distribution on the plots and the parameters were fit to the data using the maximum-likelihood method. Then the estimated distribution parameters were expressed as functions of H and CVH and estimated simultaneously with seemingly unrelated regression techniques (SUR). The functions are documented in the Heureka model database and are applied as follows.

In the first step the stand type is identified by stem number proportions of different species. Seven stand types are distinguished:

1. Pine stands:	if p(pine) ≥ 0.7
2. Spruce stands:	if p(spruce) ≥ 0.7
3. Contorta stands:	if p(contorta) ≥ 0.7
4. Mixed conifer stands:	if p(conifer) ≥ 0.7
5. Species mixed stands:	if p(broadleaves) ≥ 0.4 and p(broadleaves) < 0.7
6. Broadleaf stands:	if p(broadleaves) ≥ 0.7 and p(leaf-tree[1]) < 0.5
7. Leaf-tree stands:	if p(broadleaves) ≥ 0.7 and p(leaf-tree) ≥ 0.5

If mean heights are given per species, coefficients of variation for height and Weibull parameters for the height distributions are calculated for each species. If only the total mean height of the stand is given, the corresponding distribution parameters are calculated as functions of stand type, stand origin (cultivation or natural regeneration), mean height, and species composition.

With the estimated distributions the heights of the specified number of trees are created. The frequency form (f(h)) and the integral form (F(h)) of the Weibull function are as follows:

$$f(h) = \frac{\lambda}{\beta}\left(\frac{h-\alpha}{\beta}\right)^{(\lambda-1)} \times \exp\left[-\left(\frac{h-\alpha}{\beta}\right)^{\lambda}\right] \qquad h-\alpha \geq 0$$

$$F(h) = 1-\exp\left[-\left(\frac{h-\alpha}{\beta}\right)^{\lambda}\right]$$

[1] Leaf trees: Oak, Beech, Elm, Linden, Ash, Mapel and Cherry

In the formulas λ>0 is the shape parameter which determines the skewness of the distribution, β is the scale parameter which is related to the range of the distribution, and α is the minimum value of the distribution, in our applications always is set equal to 0.1 m. The parameter h is a random variable, in our case representing tree height.

The set of functions for naturally regenerated pine stands are presented below as an example.

$\hat{CVH}$ = exp(– 0,2391 – 0,1662·H – 0.0375·ln(H) – 0.4973· ln(1+Pdec) – 0.0932·PL) ;
Pdec= proportion broadleaves, PL = 1 for plantation, else = 0

$\hat{\lambda}$ = exp(0,14337 + 0,00550·H – 0,20988·CVH – 1,02617·ln(CVH))

$\hat{\beta}$ = 0,30369+ 1,05814·H – 0,42533·CVH

The expected height distributions for stands with the mean heights 2 and 5 meters, respectively, are illustrated in figure 1(3):

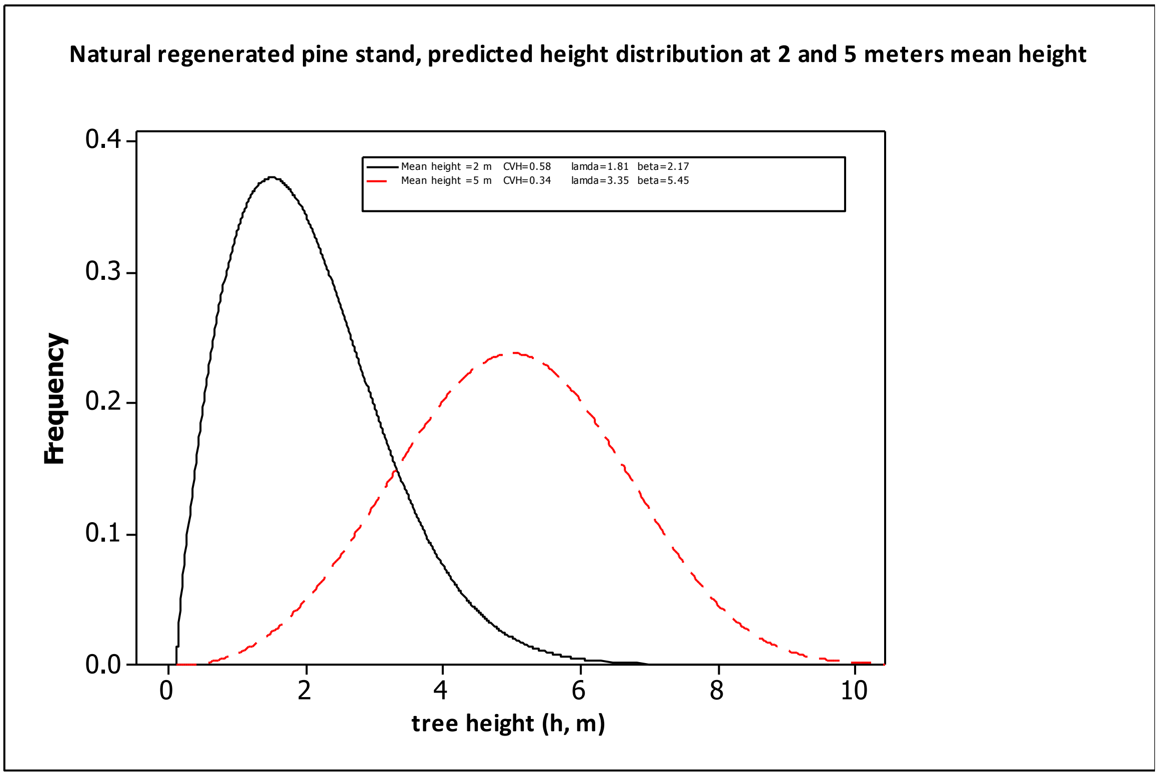

Figure 1(3) Predicted height distribution at 2 and 3 meters mean height. Stand type: Pine stand, naturally regenerated (PL=0), proportion broadleaves, Pdec=0.0

Appendix 4

Functions for basal area growth

PM for Heureka 2009-10-19 by Björn Elfving

General functions for basal area growth in Sweden were presented by Ekö (1985, stand level) and Söderberg (1986, tree level). The functions were based on data from temporary NFI-plots measured 1973-1977. Growth was registered on increment cores from sample trees. Separate functions were developed for different species, age/site classes and regions. One draw-back with those functions was discontinuities at borders between classes. Another drawback was related to an inconsistency found in the system for site index determination. Estimation from site factors gives lower values than estimation from age and height in young stands. Site index was included as an independent variable in the growth functions and it was thought that the varying value due to method for determination could cause a bias.

When data from re-measured permanent NFI-plots became available new functions were developed. The first approach was to develop tree-level functions without age and site index as independent variables. Those functions were presented at a conference on growth modelling in Vancouver in 2001. They were however never published since it was found that observed and estimated growth on long-term permanent plots deviated. Anyhow the manuscript is enclosed here because it gives a detailed description of data and methods used.

Inclusion of age as an independent variable stabilized the long-term predictions. It was also found that inclusion of site index according to site factors abbreviated the list of independent variables without essential loss in accuracy. The final tree-level functions were presented 2004. A preliminary stand-level function for basal area growth was presented in 2005. It was based on the same data set as the tree-level functions and indicated almost the same accuracy for growth predictions as the tree-level functions.

The inclusion of age as an independent variable in the growth functions forced the development of functions for single tree ages, se a following appendix. In 2008 a test of the stand-level function was conducted with data from measurements 1999/2004 and 2000/2005 on the permanent NFI-plots. At the same time the programming of the different basal area growth functions in the Heureka system was checked and the accuracy of the functions compared. It was found that the tree-level functions presented 2004 underestimated growth, probably due to bias in the year ring indices. Extensive nitrogen fertilization in Swedish forests in the period 1976-1990 probably increased the indices and caused a too large correction downwards of the observed growth. The stand-level function from 2004 was based on observed (un-corrected) values and gave accurate predictions for the test data. There was however indications of some discrepancies between species and an adjusted function was presented 2009 as the final solution for Heureka. In growth predictions the tree-level functions are used for distribution of growth on species and tree sizes and the stand-level function is used to calibrate the growth level.

Appendices:

Elfving. B 2001. Individual-tree basal area growth functions based on data from permanent inventory plots in Sweden. SLU, Dept of Silviculture. Manuscript 080801.

Elfving, B. 2004. Individual-tree basal area growth functions for all Swedish forests. SLU, Dept. of Silviculture. Manuscript 2004-01-26.

Individual-tree basal area growth functions based on data from permanent inventory plots in Sweden.

Manuscript briefly presented at a conference in Vancouver in August 2001 under the title: Elfving, B 2001. Framework for modelling of forest development in Sweden. Abstract in: LeMay, V. and Marshall, P. 2001. (Eds.) Forest modelling for ecosystem management, forest certification and sustainable management. Proceedings, UBC, Canada.

Abstract

General growth functions are fundamental tools in forestry planning systems and for evaluation of alternative silvicultural regimes. Functions for 5-year basal area growth of single trees were developed for 8 species and species groups on basis of data from 14 341 re-measured inventory plots in the Swedish National Forest Inventory. The large measurement error at growth estimation by repeated callipering forced the use of non-linear weighted regression. Observed growth was corrected for measurement error and annual growth variation. Functions were developed with and without stand age and vegetation indicators as independent variables. Influences of tree sizes, stand density, development stage, species mixture, site location, soil conditions and treatments were accounted. All species grew faster in mixed than in pure stands. The plots had 10 m radius, and differences in stand density inside and outside the plot were taken into account. Treatments included were ditching, thinning and nitrogen fertilization. Thinning could only be included superficially and its influence in the model must be moderated with data from thinning experiments. Residual variation at the plot level was estimated at about 40 % of the growth.

Introduction

Growth functions are important tools for evaluation of the wood production at alternative silvicultural regimes and the sustainability of forestry. The modern multipurpose forestry, which often aims at uneven-aged and mixed-species stands, stress the need for accurate and generally applicable single-tree growth functions.

Too little is known about the mechanisms behind tree growth to allow construction of mechanistic growth functions for single trees that are useful for detailed quantification. It is still needed to rely on empirical functions, describing how trees grew in the past under various conditions and assuming that the natural growing conditions will remain constant in the future. Even if the latter assumption seems to have been violated over the last decades (Spiecker et al 1996) this is not a strong argument to discard empirical models. It is even possible to incorporate growth trends into these model types.

The most important factors to consider in a single-tree growth function are the size and condition of the tree itself, its competitive situation and the site conditions. The resolution of growth models is dependent on available data at both construction and application of the models. Tree diameter at breast height is the most common variable for tree and stand description, and functions for diameter growth are fundamental. To estimate volume growth static form height functions can be used, but it is also possible to develop separate functions for form height growth. The natural variation in tree growth is big and must be considered in some applications.

General growth simulators have since long been available in several countries (Stage 1973, Ek & Monserud 1974, Hägglund 1981, Siitonen 1995). Söderberg (1986) developed the single-tree basal area growth functions most widely used for long-term planning in Sweden.. Functions were developed for 6 species in 2 age-classes and 2-3 regions on basis of year-ring measurements on increment cores, gathered from sample trees on temporary plots in the National Forest Inventory. The functions describe 5-year growth and at construction the stand condition 5 year before measurement had to be reconstructed. Individual tree basal area and age at breast height were among the most important independent variables. Before application of these functions, age has to be imputed to non-sample trees.

These functions have proved to be accurate in many applications, but they have some drawbacks:

1. The need to impute age to every tree
2. Incorporation of site index as independent variable: an inconsistency in site index system has been discovered (Elfving & Nyström 1996)
3. Incorporation of the species mixture effect in an inconsistent way
4. Incorporation of relative tree size in a less dynamic way
5. Discontinuities between functions for different areas

The aim of this work has been to develop new basal area growth functions for single trees to overcome the listed problems.

Material and methods

Data consisted of re-measured trees on permanent plots in the National Forest Inventory (NFI; Ranneby et al 1987). In total about 18 500 circular plots with radius 10 m were established on forest land in the period 1983-1987 and re-measured 1988-1992. Some plots were also re-measured in the period 1993-1997. The whole country was covered each year and the plot density increased from north to south. Coordinates, tree species and diameter at breast height (1.3 m above ground) were registered for each tree with diameter ≥10 cm. Smaller trees were registered on a reduced plot and coordinates were registered for fewer trees. Of trees <10 cm only representative sample trees were re-measured. Breast height was located with a stick and the diameter was registered by callipering in mm in direction to the plot centre.

A lot of stand and site describing variables were also registered, among others relascope-measured basal area, estimated basal-area weighted total age of the dominating tree strata, period and type of performed silvicultural operations, latitude, altitude, field vegetation type, soil depth, texture and moisture, slope inclination and direction and forest owner.

Only data from the first growth period was used for calibration of the model. Trees with registered diameter at start and end of the growth period were included. Plots without trees and divided plots with area less than half of full size (<158 m^2) were discarded. The remaining 14 341 plots contained 225 973 measured trees, Table 1. Norway spruce (Picea abies (L.) Karst) was the most abundant species, followed by Scots pine (Pinus sylvestris L.) and the birch species (Betula pendula Roth., Betula pubescens Erh. and pubescens ssp tortuosa Ledeb.). Aspen (Populus tremula L.), beech (Fagus sylvatica L.) and oak (mainly Quercus robur L.) were also represented in noticeable amounts. Residual deciduous species were grouped as noble (ash, elm linden, maple, hornbeam and wild cherry) and trivial (mostly alder, rowan and willow).

As dependent variable the five-year basal area growth on bark (BAI5, cm^2) was chosen in principle. In practice the increase in squared diameter (ID2, cm^2) was used in the calculations, related to BAI5 as follows: $BAI5 = ID2 \cdot \pi/4$. Since this was estimated from two consecutive measurements it is highly influenced by measurement errors. About 3 % of the trees had in fact lower registered diameter at re-measurement (D2, cm) than at the first inventory (D1, cm).

Identification of outliers is one of the most difficult problems in a study like this. The measurement errors were studied with data from independent check measurements, made on about 8 % of the plots within a week after the ordinary measurement. For 5475 sample trees checked in 1983-1987 the standard deviation for the diameter measurement (in the following called the measurement error, EMD, cm) was calculated in different diameter classes. It was found to be linearly related to the diameter (D, cm): $EMD = 0.118 + 0.0087 \cdot D$. The species did not differ in this aspect. Twenty-four observations were excluded from the calculation, depending on very large deviations. This indicates that the proportion of outliers is of the magnitude 0.4 %.

The measurement error for basal area growth (EMID2, cm^2) was approximated with the formula: $EMID2 = (8 \cdot D^2 \cdot EMD^2)^{0.5}$. For EMD according to the function above the following empirical expression was found: $EMID2 = 0.026 \cdot (D+5)^2$.

In order to avoid bias in estimated growth, D1 must be corrected for the measurement error. The diameter distributions peaks in the 10-cm class and the stem frequency (N) show an approximately logarithmic linear decline with increasing diameter: $\ln (N) = b0 - b1 \cdot D$. The appropriate correction is directly related to this decline and was for each tree calculated as: $-b1 \cdot EMD^2$. The coefficient b1 was estimated at 0.13 for pine, 0.16 for spruce and 0.19 for birch.

Diameter growth varies a lot between growth periods and geographical areas, mostly due to varying weather conditions. Year ring indices for different geographical areas and observation periods were used for adjustment of observed growth to "normal" growth, Fig.1. These indices were based on year ring measurements on increment cores from the sample trees in 1995-1997 on the temporary plots in the NFI. They were constructed according to Jonsson & Stener 1986. For pine and spruce 17 different areas were separated, in most cases with 100-500 sample trees in each area. For broadleaves only northern and southern Sweden were separated.
During the actual observation period (1983/87-1987/91) the growth level was above normal for pine and spruce and approximately normal for birch, as indicated in Fig. 1.

Dates of first and last measurement did not always correspond to an exact 5-year period. Adjustments were performed in the following way. The growing season was assumed to extend the period 20/5-29/8 = 100 days, cf Zumer 1969, Valinger 1992, Söderberg et al 1993. During this period the fulfilment of the year ring (y, $0<y<1$) was assumed to increase according to the function $y = 1/(1+\exp(5-10 \cdot x))$, where x = number of days passed of the growing season divided by length of growing season (= 100). Calculated difference in fulfilled growth between first and last measurement was used to adjust observed growth.

Competition was expressed with the total basal area on the plot level (BA, $m^2 \cdot ha^{-1}$) and with the basal area of larger trees on the tree level (BAL, $m^2 \cdot ha^{-1}$). The aim was to exclude age as an independent variable in the growth model, but stand age was anyhow used in the study in order to evaluate its performance. Two expressions for stand age were available: the value estimated in the field and a value based on age imputation. All trees were supplied with age from pairing with cored sample trees on temporary plots, and mean age was calculated as the basal area weighted mean. In this study the average of those values was used as expression for stand age (A, years from seed).

Temperature sum (TSUM, day-degrees >5 ºC) was calculated from altitude and latitude according to Odin et al (1983) and used as an expression for climatic conditions. Vegetation types according to Hägglund & Lundmark (1977) were used as indicators of site fertility and moisture. Alternatively, and sometimes in addition, primary site variables like soil type, texture, depth and moisture and topographic conditions were used to characterize the site. Also site index according to site factors (SIS, m ; Hägglund & Lundmark 1977) was calculated but only used in the preparatory work, not as an independent variable in the final model.

Of registered treatments only thinnings were accounted. Performed thinnings were classified in the field according to estimated time period before the measurement and indicator variables for thinnings in different periods were used to catch the thinning response. Nitrogen fertilisation has been performed in large scale in Sweden and fertilised plots were identified with year for fertilisation through a questionnaire to the larger forest owners practising this treatment. Based on the known response curve over time after fertilisation (e.g. Valinger et al 2000) and the timing of the actual growth period in relation to year for fertilisation the expected response in the scale 0-1 was estimated and used as a variable FERT. The algorithm for giving a value to FERT was as follows: T = year for fertilisation – year for I1.
If T<-1 : FERT = 1 + 0.3·(T+2) ; If T>-2: Fert = 0.8 - 0.2·T ; If FERT<0: FERT=0 ;

Growth and its variability could be expected to be more or less proportional to tree size and site fertility, and a logarithmic transformation of the dependent variable has often been practised to homogenize the variance. However, the large measurement errors that cause frequent observations of negative growth exclude this solution. Instead non-linear weighted regression has been applied with the following model:

$$ID2 = \exp(const + bTREE \cdot fTREE + bSTAND \cdot fSTAND + bSITE \cdot fSITE + bTREAT \cdot fTREAT)$$

where ´"const" is a scaling parameter, bTREE stands for the coefficients to tree variables, fTREE stands for expressions of tree variables, and corresponding for stand, site and treatment variables.

The weights should be inversely proportional to the expected residual variance S2RES, consisting of a biological component that is related to expected growth (ID2EST) and the measurement error that is related to the tree size, according to the model:
$$S2RES = b1 \cdot ID2EST^2 + b2 \cdot (D1+5)^4$$
A complication is that the variation in growth is expected to have a log-normal distribution, while the distribution of the measurement error is expected to be normal. In this study the resulting residual distribution has been regarded as approximately normal.

In a first step a plot of D2 on D1 revealed the most obvious outliers, and these observations were discarded. Next the following linear model was smoothed with ordinary linear regression without weighing: ID2 = b0 + b1·D1+b2·D1·SIS. The squared residuals from this function (S2RES(1)) were then smoothed according to the formula above, and the first approximation of the weight was set to W = 1/S2RES(1).

In the next step the original model was smoothed with non-linear, weighted regression. Proper expressions for the different tree, stand, site and treatment variables were recursively found by residual analysis. The most deviating outliers were removed, with even distribution on positively and negatively deviating observations. New weights were calculated for the reduced data set and the final model was smoothed with these weights.

Functions were developed for the eight species and species groups accounted in Table 1 and four different versions were produced for each group: functions with and without the independent variables stand-age (AGE, years) and vegetation type (VEG, indicators for different field vegetation types). The different functions are referenced as follows:
FA includes both AGE and VEG, FB only VEG, FC only AGE and FD neither AGE nor VEG. All calculations were performed with the SAS statistical package.

Results

Individual tree basal area growth functions of type FD are compared in Table 2. Definitions and abbreviations of variables are given in Table 3. The proportion of the total weighted variance that is accounted for by these functions varies between 0.531-0.727 for the different species. The partial relations of growth (ID2) to tree size (D), developmental stage (MD) and density (BA and BAL) are similar for the main species and their combined action is illustrated for pine in Fig. 2.

The partial relation of diameter to growth is sigmoid, with an exponential increase for smaller trees and a somewhat uncertain decline for larger trees. Addition of 1 to the diameter in the logarithm produce more realistic growth predictions for small trees even if the lack of small trees in data give little support to this formulation.

The differentiation of growth within the stand due to “competition” was expressed by the variable BALGDP1. It was highly significant for all species. The over-all density effect was expressed as a function of stand basal area (BA). Different expressions were tried for this relation, and it was found that the formulation INVBAP10 gave a robust approximation of the over-all density effect. This effect was complemented with data on density in the surrounding stand (edge effects). The logarithm of the quotient between basal area on the plot to the basal area of surrounding stand according to relascope measurements (LNBAREL) was highly significant in all functions and make them less dependent on plot size. On divided plots the relascope measurements concern the stand to which the actual part belongs. For plots on roadsides and field borders the indicator EDGEFF catches the border effect. Also other divided plots indicated significantly higher growth than undivided plots (the variable PART).

All explicitly extinguished species indicated higher growth in mixed than in pure stands. The best expression for effect of site location varied between species. The general trend was decreased growth with decreasing temperature sum. Birch and other trivial deciduous were most sensitive close to the alpine tree limit, and birch also grew better close to the coast than in the inland. Birch was also the only more frequently represented species on Gotland that not indicated lower growth level. The island Gotland in the Baltic Sea is dominated by shallow, lime-rich soils and other species indicated lower growth levels there, even if the relative response to other independent variables in the functions seemed to be the same as in other parts of Sweden.

The alternate response of birch to location is probably related to the distribution of different birch species. There are three species/subspecies with different growth rate and distribution, and they were not separated in the inventory, since this is difficult to do with higher precision. The pendula birch is most productive and dominates southern lowlands, dry and mesic sites. Pubescent birch is medium productive and more common on moist sites and on higher altitudes and latitudes. Closer to the alpine tree limit it turns over to the low-productive subspecies tortuosa.

Among soil factors shallow soil was significantly connected to low growth for all species. Factors indicating moist conditions were negative for the main species, but less negative for spruce than for the others. A soil texture with a mean particle size of fine sand – silt (texture class 6-7) indicated optimum for the main species growth. Trees in thinned stands indicated higher growth than trees in un-thinned stands under similar conditions. For the main species also the treatments ditching and fertilization indicated strong positive effects.

Inclusion of stand age and vegetation type in functions FA increased the explained part of the original variance with 2-4 % for most species, but only marginally for beech and oak. Age was highly significant and its inclusion substantially reduced the effect of most other variables, probably because the combination of age and diameter implicitly reflected the growing conditions. The vegetation types were introduced as indicator variables and their coefficients showed a smooth trend when sorted in expected order of fertility, Fig. 3. Thus, fertility could be regarded as a continuous variable measured in discrete classes. Pine was less sensitive to site fertility than spruce and birch.

In a special study a continuous fertility variable, ranging from 0 for poor types to 7 for tall herbs according to Fig. 3, was related directly to the site conditions. Only plots >157 m^2 on mineral soil with field vegetation were included, in total 14 264 plots. About one third of the variance was explained by soil texture, depth and moisture, topography and temperature sum. Stand density had low significance in this function. Introduction of pine- and broadleaves proportions increased the proportion of explained variance with 8 percent units. A high pine proportion indicated low fertility and the contrary for broadleaves.

The relation of observed to predicted growth at plot level was examined over species mixture and density on plot compared to surrounding stand. Plots with more than 7 trees were grouped on pure (main species >90 % of BA), moderately and highly species mixed (no species >70% of BA). In total 6 775 plots were pure, 3359 moderately and 4 264 highly mixed. The quotient of observed and predicted growth was close to 1.00 in all groups, indicating that the effect of species mixture was properly included in the model. Also the border effect seemed to be properly included, Table 4. The form of the plot distribution on relative density classes indicates a slight underestimation of basal area with relascope and a quite large variation in relative density.

The residual variation in plot growth decreased asymptotically with increasing tree numbers on the plot to a level around 0.4, Fig. 4. For plots with more than 7 trees the correlation between predicted and observed growth on plot level was 0.56 for FD-functions and 0.63 for FB-functions.

Discussion

The big measurement error in growth data from repeated callipering forced the development of a special evaluation technique in this study. Measurement errors have seldom explicitly been taken into account in growth analysis. In analysis based on year ring measurement on increment cores there is no problem with negative growth observations and the measurement error could be expected to be proportional to the growth. But the measurement error is still not negligible, around 20 % for 5 years basal area growth according to Matérn (1961). In the NFI-data the measurement error varied between less than 10 up to over 100 % of the growth, depending on tree size and growth level. For an average tree, with DBH=18 cm and ID2=50 cm^2 the measurement error (100·EMID2/ID2) can be estimated to about 30 %. The proportion of the residual variance explained by the weighing function varied around 0.2. For inclusion in the weighing function expected growth should not be calculated with a more detailed function than that the weights will be applied on, since this will give biased results.

To handle the errors properly the variation within and between plots should be separated. A proper method could be a random parameter retrieval technique, where the model is subsequently evaluated with different parameter upsets and the one with highest efficiency is finally chosen. This is however a very time-consuming technique and was considered impossible to use with the large data sets and many parameters to handle in this study. The effect of neglecting separation of within- and between-plot variation is probably small since the plots were small and numerous.

Four model variants were developed in this study (FA-FD), but only the FD functions were explicitly presented. They are thought to be the most useful for long-term predictions. The special study of vegetation type as fertility indicator showed that it only to a minor extent could be directly related to site factors, and that it was little influenced by stand density. The study also verified the well-known fact that pine thrives on poor sites and broadleaves on more fertile sites. This means that the species mixture effect probably was overestimated for pine and underestimated for broadleaves in FD-functions, since this variable caught both the mixture and the fertility effects. In FB-functions, where vegetation indices reflecting fertility were present, the mixture effect came out substantially smaller for pine and larger for spruce and birch, in line with what could be expected. Thus FB functions seem to be more reliable than FD functions for long-term predictions if detailed information on vegetation type is available.

In short-term predictions, for instance for prescribing data in stand registers used in operational forestry, the FA functions are probably most accurate, if reliable data on stand age and vegetation type is available.

The correction of observed growth with year-ring indices leads to a reduction of observed growth in the actual 5-year periods with 11 % for spruce and around 5 % for the other species. Indices varied between regions and it is probable that the latitudinal effect (temperature sum) comes up more reliable with than without the year ring correction.

The functions presented here are similar to those presented by Wykoff (1990) and Monserud & Sterba (1996). In these studies the stand level competition was however expressed with the crown competition factor (CCF) instead of basal area, and crown ratio was used as an expression for tree vitality. The latter variable was not available in the NFI data.

CCF (Krajicek et al 1961) is related to the maximum crown width of free-growing trees of actual diameters and expresses the crown coverage in the stand. Curtis(1970) showed that maximum crown width can be approximated with an allometric expression of the form b0·d^b1, where b1 varies around 1.6. An alternative way to interpret this is, that sapwood area is proportional to the expression, and crown biomass is proportional to sapwood area. In my model CCF was not more efficient than BA, probably because stand mean diameter was also included. It seemed moor consistent to use BA in both the overall density expression and in the stratifying expression BAL.

The thinning indicator was strong for all species. This means that the thinning response could not be captured only by the decrease of competition. The extra effect can be interpreted as a mix of three effects: a selection effect, a fertilisation effect and a stem-form-change effect. At thinning slow-growing trees of given size are cut and thus the remaining in average indicate higher growth. The fertilisation effect depends on the nutrient release from roots and slash of cut trees. The stem-form-change effect reflects the change of growth allocation to lower parts of the bole after thinning in order to increase the stability. All effects could be expected to decrease over time, but it was not possible to model this with the NFI data. The response level should also be dependent on the thinning grade. Data from thinning experiments will be used to modify the functions in these aspects at a later stage.

The clear species-mixture effect found in this study was unexpected and difficult to interpret. It says that, given the growing conditions with respect to tree size, density situation and site factors, trees grows faster in mixed than in pure stands. One explanation could be that minor components in the stand are special in some respect, for instance are growing in gaps or have outstanding qualities and for these reasons were left at thinning. On the stand level it seems as if species-mixed stands can grow up to 15 % more than the average of what pure stands would grow on the same site.

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Table 1 . NFI-data used for the construction of growth functions. Distribution of trees on species and plots, and some species characteristics

Characteristic	Species / species group								
							Other deciduous		
	Pine	Spruce	Birch	Aspen	Beech	Oak	Noble	Trivial	Total
Number of trees	80 023	105 024	29 072	2 339	1 493	2 143	565	5 312	225 973
Proportion, %	35.4	46.5	12.9	1.0	0.7	0.9	0.2	2.4	100.0
Presence on plots	9 565	10 201	6 707	760	273	659	153	1 459	14 341
Prop. of total, %	66.7	71.1	46.8	5.3	1.9	4.6	1.1	10.2	100.0
DBH, mean (max)	19 (71)	17 (69)	15 (54)	18 (58)	25 (96)	21 (100)	19 (80)	16 (58)	
ID2, “	52	53	32	73	102	77	68	46	
LAT ºN “	61 (68)	60 (68)	61 (68)	60 (68)	56 (58)	57 (60)	57 (62)	59 (68)	
AGE “	74 (295)	74 (212)	68 (208)	60 (176)	71 (144)	62 (168)	67 (168)	55 (178)	

Table 2. Growth functions for single trees of type FD, without age and vegetation indicators as independent variables. Dependent variable: 5-year increment of squared dbh, cm² (ID2). Functional form: ID2 = exp (b0 + b1·x1 + b2·x2 …..), the table gives the coefficients b0, b1, b2 etc. For variable definitions, see Table 3

Effect type	Variable	Species / species group							
								Other deciduous	
		Pine	Spruce	Birch	Aspen	Beech	Oak	Noble	Trivial
	constant	-1.6952	-2.2827	-0.2269	-0.8198	0.2081	0.2348	0.4850	1.9814
Tree size	lndp1	1.1617	1.4354	1.1891	1.4839	1.7491	1.2141	1.0318	0.8401
	d	-0.0354	-0.0389	-0.0435	-0.0240	-0.2167			
	d2gt	0.2791	0.3106	0.5620					
Develop-ment stage	mdf	0.6119	0.7199	1.2991					
	md2gt	0.3932	0.3524	0.3278					
Density	balgdp1	-0.4422	-0.3729	-0.4742	-0.3978	-0.2644	-0.2878	-0.1973	-0.2753
	invbap10	13.54	11.96	13.06	10.58	26.34	20.15	21.98	13.51
Species mix.	propos2	0.2521	0.2125						
	propa05			-0.2213	-0.5368	-1.1407	-0.5726		
Site location	gotland	-0.2943	-0.6700				-0.3863	-0.3283	
	ts	1.6333	1.1974		0.9511				
	ts2	-0.2446							
	invtsm03			-0.5906					-1.3582
	invdcp30			8.590					
	lat					-0.2375			
	alt						0.3281		
	alt2						-0.1899		
Soil conditions	peat	-0.2606	-0.0817	-0.2180	-0.4642				
	shallow	-0.1036	-0.1177	-0.1381	-0.2292	-0.2266	-0.1514	-0.3453	-0.2880
	moist	-0.1750	-0.1089	-0.1343					
	wet	-0.5560	-0.3227	-0.5031					
	mswat		0.0635	0.1559					
	expos	0.0355							
	text	0.1103	0.1070	0.0806		0.0649			
	text3gt	-0.8317	-0.8334	-0.6127					
Treatments	ditch	0.1025	0.1674	0.1820	0.2323				
	thin	0.1895	0.2219	0.2740	0.2462	0.2078	0.1217	0.2616	0.2230
	fert	0.2529	0.2016	0.3448					
Edge effects	part	0.0493	0.0613	0.0799		0.1937			
	edgeff	0.1508	0.1428	0.1497			0.3993		
	lnbarel	0.1930	0.2486	0.3420	0.4106	0.2847	0.1898	0.4226	0.2052
Variance proportion ”explained” (r^2)		0.727	0.712	0.531	0.712	0.715	0.725	0.623	0.553

Table 3. Abbreviations and definitions of variables used in the growth functions. The variables are listed in the order they appear in Table 2

Abbreviation	Definition
d	diameter at breast height (1.3 m above ground) including bark, cm
d2gt	d^2 /1000
lndp1	ln (d+1)
md	basal area weighted mean diameter of the trees on the plot, cm ($\Sigma d^3 / \Sigma d^2$)
md2gt	$(md)^2$ /1000
mdf	$1 - 1 / \exp((14/md)^2)$
ba	basal area, m^2 / ha
bal	basal area of larger trees, i.e. trees on the plot with d> than that of the target tree, m^2 / ha
balgdp1	bal / (d + 1)
invbap10	1 / (ba + 10)
propos2	$(\text{ba proportion of other species on the plot})^2$
propa05	$(\text{ba proportion of actual species})^{0.5}$
gotland	indicator for the island Gotland in the Baltic sea
tsum	temperature sum, day-degrees > 5 ºC during vegetation period = 4835 - 57.6·la t - 0.9·alt
ts, ts2	0.001·tsum, ts2 = ts^2
invtsm03	1 / (ts-0.3)
invdcp30	1 / (dc + 30), where dc is distance to coastline, km
lat	latitude, ºN
alt, alt2	altitude, m a.s.l. , alt2 = alt^2
peat	indicator for plots covered by peat to more than 50 %
shallow	takes the value 1 if soil depth is 20-70 cm or very variable and the value 2 if depth < 20 cm
moist, wet	indicators for moist and wet sites, respectively
mswat	presence of movable soil water, never=0, seldom =1, often =2
expos	exposition of slope, se-w = 1, nw-e = -1
text	soil texture, eight classes from coarse-textured (stone=1) to fine-textured (clay=8)
text3gt	$text^3$ /1000 ; for peat-land the variable text should have the value 5
ditch	indicator for plot with ditch within 25 m from plot centre
thin	indicator for plots thinned within 15 years before end of the five-year growth period
fert	Takes a value between 0-1 on fertilised plots, according to expected response, see text
part	indicator for a partitioned plot where the other part not is open land
edgeff	indicator for a partitioned plot where the other part is open land
lnbarel	ln [(ba+1) / (bar+1)] , where bar is ba in surrounding stand measured with relascope

Table 4. The quotient between observed and predicted growth per plot in different classes of stand density on the plot compared to the surrounding stand (LNBAREL)

	Basal area on plot compared to surrounding stand						
	< (-.6)	(-.6) - (-.4)	(-.4) - (-.2)	±0.2	(+.2) - (+.4)	(+.4) - (+.6)	> +.6
No of plots	101	265	953	7490	1600	461	169
ID2REL	1.04	0.99	1.00	1.01	1.00	1.00	0.98

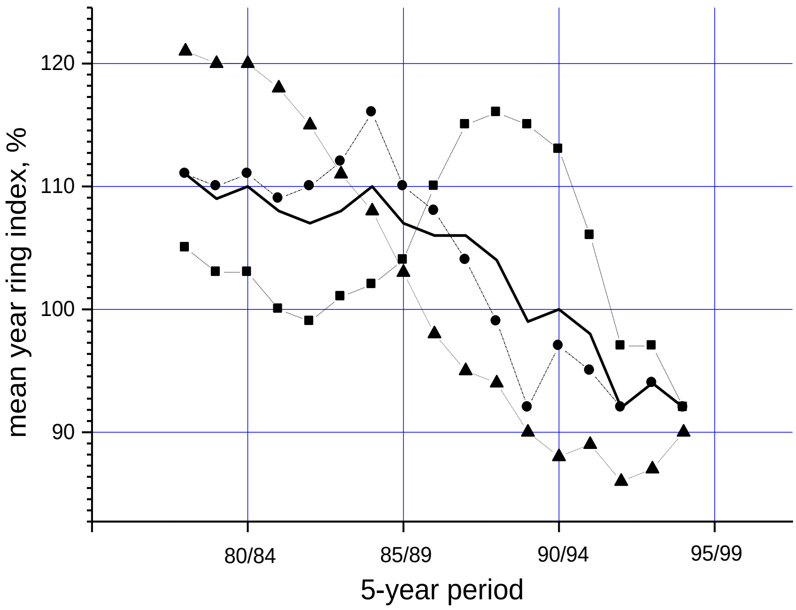

Fig. 1. Moving averages of year ring indices for 5-year periods during a 17-year period. Arithmetic means for pine (ν), spruce (σ) and birch (λ) in the whole country, and weighted grand mean (—) according to total growth of different species.

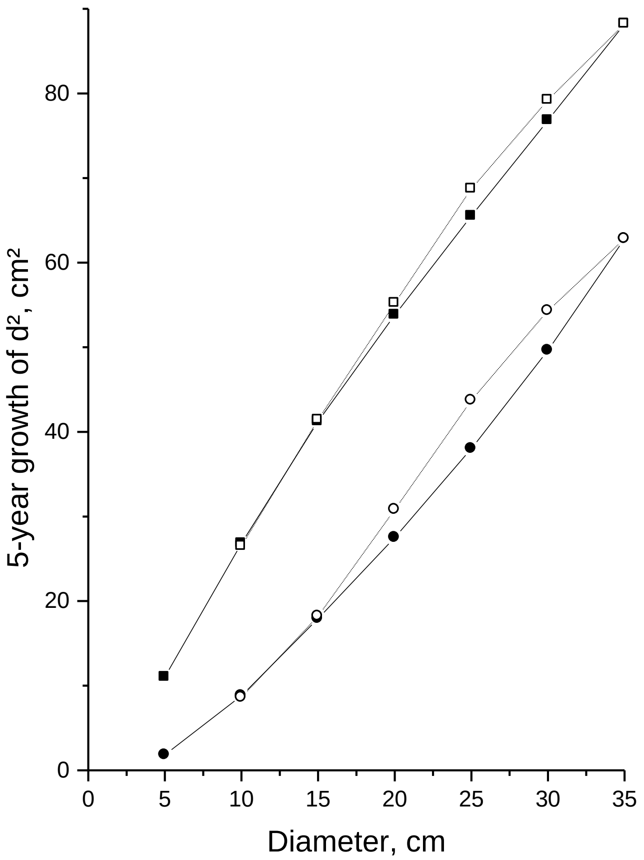

Fig. 2. Growth at given diameters and stand densities on average sites, as estimated by the function FD for pine. Two different diameter distributions were assumed as follows:

Diameter, cm	5	10	15	20	25	30	35
Distribution 1 (—)	1	1	1	1	1	1	1
Distribution 2 (- - -)	0	2	4	6	4	2	1

Assumed basal areas are 10 m²/ha (circles) and 30 m²/ha (squares).

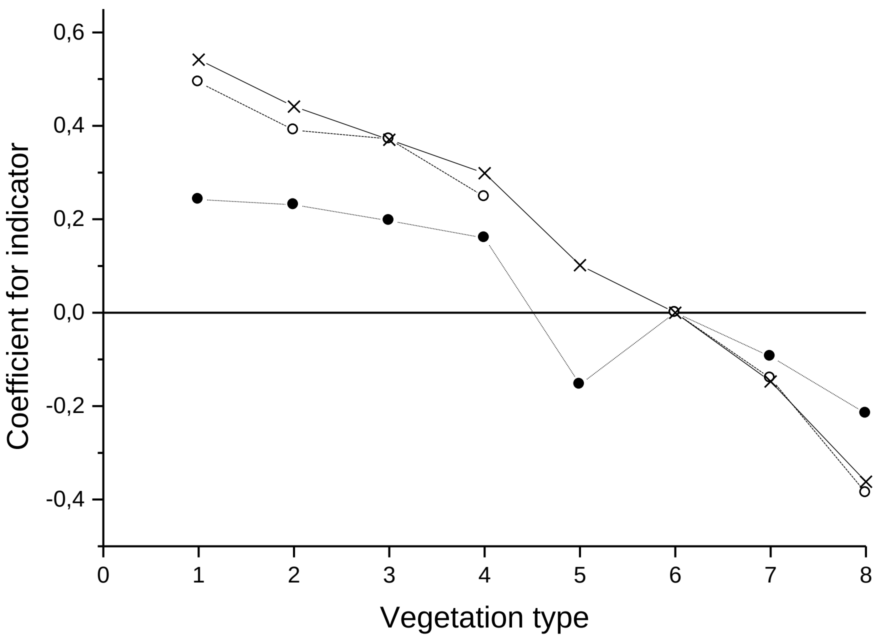

Fig. 3. Coefficients for vegetation indices in FB-functions for the main species:
Pine (• - - - •), spruce (○ – – ○), birch (+ ---- +) The vegetation types are:

1 Tall herbs
2 Low herbs
3 Herbs with dwarf-shrubs, wide-leafed grasses
4 Narrow-leafed grasses
5 Carex- and equisetum types
6 Vaccinium myrtillus (reference)
7 Vaccinium vitis idea
8 Poor (empetrum, calluna, lichens)

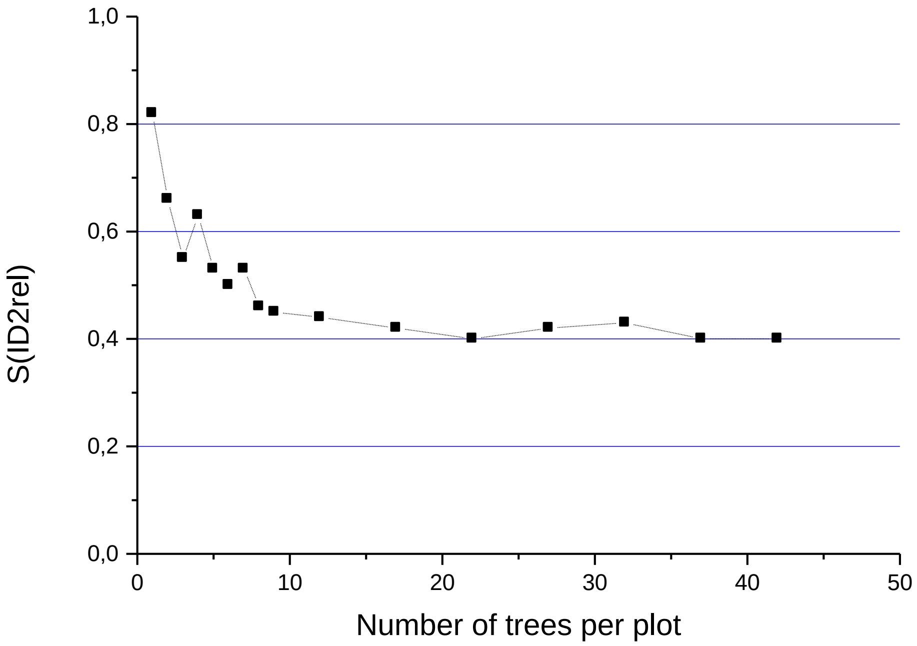

Fig. 4. Decrease of residual variation between plots (from FD functions) with increasing stem number on the plot

Individual-tree basal area growth functions for all Swedish forests

A translated and partly re-formulated PM 2010 of a manuscript written in Swedish 2004-01-26 for Heureka by Björn Elfving

Individual-tree basal area growth functions for Swedish forests were presented in a manuscript by Elfving (2001). They were based on data from permanent plots at the National Forest Inventory (NFI). Those functions represented an effort to avoid age as an independent variable in growth predictions. Later tests with data from long-term field experiments on spacing and thinning indicated that it was necessary to include age in the functions to get realistic long-term predictions. Single-tree ages were available in the NFI-data, based on calculations with less suitable functions. As a first step, new functions for age determination were developed (appendix 7) and applied on the initial data-set. After that new functions were developed, using the same data-set as 2001 (Elfving 2001, Table 1) and including estimated age at breast height among the independent variables. The description of data and methods in Elfving 2001 is fully relevant also for this study.

Two functions were developed for each species: a shorter variant with site conditions mainly represented by site index according to site factors (SIS) and a longer variant with only primary site factors included. The gain with the longer variant was marginal so the shorter variant was recommended for practical use, Tab. 1-2. For all species except pine and spruce coefficients in the final functions were estimated with the SAS-procedure NLMIXED, separating variances within and between plots. For pine and spruce the computer did not manage to perform those calculations despite several efforts, due to long running-times and disturbances in the computer. The effect of using NLMIXED for those species was expected to be marginal, since they were represented on so many plots.

Average year-ring indices and measured and corrected growth on plots representing different growth periods are compared in Tab. 3. Mean index is above normal for all species. The measured growth varies strongly between the periods for pine but much less for spruce and birch. The corretion decreased the variation for pine but increased it for spruce and birch. The usefulness of the correction can thus be questioned. The main reason for using corrected growth as dependent variable was that this should give a reasonable balance of the growth level between different regions in the country.

The status of the single tree was described with its diameter, competitive condition and computed age at breast height. Division of the basal area of larger trees by the tree diameter gave a stable expression for the competitive condition. For spruce the effect of larger trees was reduced if the larger trees consisted of other species than spruce and if the stand was uneven-sized. The latter factor was quantified by the relative difference between the basal area weighted mean diameter and the diameter of the basal area mean tree.

In residual studies all species indicated higher growth than expected in uneven-aged stands. Comparison of trees from even- and uneven-aged stands in different diameter and site index classes revealed that they had the same competitive condition and growth but differed in estimated age. Trees were 10 % older in uneven-aged stands. When the age of trees in uneven-aged stands was reduced by 10 %, the functions worked well also for trees in uneven-aged stands.

Table 1. Individual-tree basal area growth functions. Dependent variable: 5-year increase of squared diameter, cm² (ID2). Functional form: ID2 = exp (b0 + b1·x1 + b2·x2 …..), the table gives the coefficients b0, b1, b2 etc. For variable definitions, see Table 2

Type of effect	Variable	Tree species/species group							
								Other broadleaves	
		Pine	Spruce	Birch	Aspen	Beech	Oak	Noble	Trivial
	constant	3.4176	3.4360	5.9648	0.9945	1.7005	1.9047	2.3316	2.1108
Tree	lndp1	1.0149	1.5163	1.2217	1.9071	2.5823	1.3115	0.8250	0.9418
	dg10		-0.1520		-0.3313	-0.3758			
	balgdp1	-0.3902	-0.4024	-0.3998	-0.3040	-0.2079	-0.2640	-0.2877	-0.2599
	ejgdbal		0.1625						
	dif3bal		0.4702						
	lnap20	-0.7731	-0.7789	-0.9226	-0.4058	-0.4478			-0.3026
	ost	0.2218	0.4034	0.4772					
Plot	mdg10	0.1843							
	md2gt		0.1914						
	lngp3	-0.3145	-0.2342	-0.2090	-0.1981	-0.5348	-0.5056	-0.4010	-0.2280
	ejxdel2	0.1391	0.1754						
	rtxdel			-0.5821	-0.5967	-0.9304	-0.6001		
Climate	gotland	-0.0844	-0.3264				-0.4615	-0.3809	
	tsum		-0.6923	-0.5386	0.4408				
	tsum2	0.1178	0.2568						
	invtsm03			-0.4505					
	invkap3			0.8801					
	latm50					-0.1906			
	altgh						0.3833		
	altgh2						-0.1938		
Site	sisg10	1.0890	0.2903			0.3055			0.2595
	sis2gh	-0.2164							
	rich	0.1011	0.1965	0.3439	0.4759		0.2635		
	ort							0.9397	0.4392
Treatment	fertris	0.2790	0.4034	0.3844					
	hu0t10	0.1245	0.1309	0.1814	0.2143	0.2200	0.1034	0.2410	0.1561
	hu11t25	0.0451							
Environment	delad	0.0487	0.0561			0.2009			
	kanteff	0.1368	0.1126	0.2258			0.3551		
	lngrel	0.0842	0.0770	0.1321	0.2427	0.2669	0.1897	0.4676	
Variance proportion ”explained” (r^2)		0.758	0.753	0.555	0.723	0.722	0.729	0.639	0.569

Tabell 2. Abbreviations and definitions of the variables that are used in the growth functions. Variables are presented in the order they appear in Table 1

Beteckning	Definition
d	diameter at breast height (1.3 m above ground) including bark, cm
lndp1	ln (d+1)
dg10	d/10
bal	basal area of larger trees, i.e. trees on the plot with d> than that of the target tree, m^2 / ha
balgdp1	bal / (d + 1)
ejgdbal	balgdp1· (proportion of basal area that not is spruce)
dif3bal	balgdp1· $((md-(\Sigma d^2/\Sigma n)^{0.5})/md)^3$
lnap20	ln(a13+20), where a13 is computed tree age at breast height (uneven-aged: reduce 10 %)
ost	Indicator for a standard, separated at the age computation: if standard: ost=1 ;else ost=0
md	basal area weighted mean diameter of the trees on the plot, cm (Σd^3 / Σd^2)
mdg10	md/10
md2gt	$(md)^2$ /1000
lngp3	ln(g+3), where g=basal are on the plot, m^2 per ha
ejxdel2	(ba proportion of other species on the plot)^2
rtxdel	(ba proportion of actual tree species on the plot)$^{0.5}$
gotland	indicator for the island Gotland in the Baltic sea
tsumma	temperature sum, day-degrees > 5 ºC during vegetation period = 4835 - 57.6·la t - 0.9·alt
tsum, tsum2	tsum = 0.001·tsumma, tsum2 = $tsum^2$
invtsm03	1 / (tsum-0.3)
invkap3	1 / (ka+3), where ka is distance to coast, km/10
latm50	latitude, ºN - 50
altgh, altgh2	(altitude, m a sl)/100 , altgh2 = $altgh^2$
sis	site index according to site factors (m), mean of measurements at I1 and I2
sisg10, sis2gh	sis/10, sis^2/100
rich	indicator for grass and herb types
fertris	takes a value between 0-1 on fertilised plots of dwarf-shrub type, see text
hu0t10	indicator for plots thinned within 10 years before start of the five-year growth period
hu11t25	indicator for plots thinned within 11-25 years before start of the five-year growth period
delad	indicator for a partitioned plot where the other part not is open land
kanteff	indicator for a partitioned plot where the other part is open land
lngrel	ln [(ba+1) / (bar+1)] , where bar is ba in surrounding stand measured with relascope

Table 3. Average year-ring indices and measured and corrected growth on plots representing different growth periods

Tree species	Variable	Growth period					
		1983/87	1984/88	1985/89	1986/90	1987/91	Mean
Pine	Numb. obs.	15 174	16 668	16 318	15 916	15 795	
	Index	100.6	102.5	105.5	110,6	116.1	107.1
	ID2obs	45.3	49.2	53.0	58.1	56.3	52.4
	ID2norm	45.6	48.5	51.3	53.4	48.6	49.5
	ID2ber	49.0	50.0	48.2	49.5	48.9	49.1
	Rel.res. %	-6.9	-3.0	6.4	7.9	-0.6	0.8
Spuce	Numb obs.	21 073	21 280	19 812	21 199	21 457	
	Index	112	116	111	108	105	110.4
	ID2obs	53.0	51.3	54.9	54.9	53.1	53.4
	ID2norm	46.5	43.4	48.9	49.9	49.9	47.7
	ID2ber	46.9	46.4	48.2	47.5	48.3	47.5
	Rel.res. %	-0.8	-6.5	1.5	5.0	3.3	0.4
Birch	Numb obs.	5 659	6 100	5 401	5 627	6 232	
	Index	109.5	107.1	102.7	99.0	96.0	102.9
	ID2obs	31.4	30.3	30.9	33.7	31,3	31.5
	ID2norm	27.7	27.6	29.7	34.0	32.9	30.4
	ID2ber	29.6	20.0	30.0	30.7	29.6	29.8
	Rel.res. %	-6.4	-4.8	-1.0	10.7	11.1	1.9

Appendix 5

One basal area growth function for all species in Sweden

Translation of a manuscript in Swedish for Heureka by Björn Elfving, dated 2005-05-27.

Single-tree basal area growth functions were presented by Elfving (2004). They were based on data from permanent sample plots at the National Forest Inventory (NFI). About 18500 circular plots with 10 m radius were established on productive forest land in annually country-covering samples in the period 1983-1987 (I1). They were re-measured after five years in the period 1988-1992 (I2). The growth functions concerned observed growth in this period, adjusted for annual growth variations according to year-ring indices. The same data-set has now been used for a stand-level basal area growth function with observed (un-adjusted) growth as dependent variable (iG5, m² per ha).

The stand-level function (Tab. 1) has the following form:
iG5 = exp(b0 + b1·X1 + b2·X2 …..+bn·Xn), where b0, b1 etc are the coefficients under the heading "estimate" in Tab. 1 and X1, X2 etc are the independent variables under the heading "parameters". The value of the dependent variable iG5 is expressed in m² per ha during a 5-year period for the trees on the plot that were alive and measured at both I1 and I2.

Plots on stand borders were divided, and only plots larger than 50 % of full size (314 m²) with remaining trees at I2 were included in the study, in total 14232 plots. About 0.2 % of the plots were classified as obvious outliers and excluded. The standard deviation for the growth measurement as a difference between two caliperings is relatively large and negative growth observations exists. For that reason the coefficients of the function were estimated by non-linear weighted multiple regression. The weights were estimated according to residuals from a preliminary linear regression, with the aim to homogenize the final, residual variance. The residual mean square value below 1 in Tab. 1 means that the final function explained more of the total variance than the preliminary function.

The most important independent variables were age, basal area and vegetation type. The age (a) concerns the basal-area weighted total mean age of the stand. It is estimated in the field and concerns the tree layer signifying the cutting class. As a basis for growth prediction this age can be misleading, for instance in a seedling stand with standards, where only the standards produce basal area. Among available variables there is also an estimated, basal-area weighted mean age based on all trees on the plot. As expression for age the mean of the two available values turned out to be most useful. A problem with the mean age is that it seldom increases with 5 years in a 5-year period. Old trees die and young trees grow into the tree layer. Thus age is no ideal variable for growth predictions. It is necessary to include in order to stabilize the function but might cause problems at application in long-term growth predictions.

The basal area is included in two shapes in the function: as g and g0, both given in m² per ha. The variable g concerns the basal area for the trees included in the growth measurement while g0 concerns the total basal area before growth. For thinned stands the difference between those values might be quite large. The stem number per ha (sn) concerns the trees included in the measurement.

The variable indicating vegetation type (veg) is scaled in the interval -5 to +4 as follows. The field layer code (Fskod) is the code used at the NFI. The scaling is from 1=tall herbs without dwarf-shrubs via 9=narrow-leafed grasses and 13=bilberries to 18=lichens.

Fskod	1	2	3	4	5	6
Meaning	H-ört u ris	H-ört m blå	H-ört m ling	L-ört u ris	L-ört m blå	L-ört m ling
Index	4	2.5	2	3	2.5	2

Fskod	7	8	9	10	11	12
Meaning	Utan fs	Breda gräs	Smala gräs	Högstarr	Lågstarr	Fräken
Index	3	2.5	1.5	-3	-3	1

Fskod	13	14	15	16	17	18
Meaning	Blåbär	Lingon	Kråkb/ljung	Fattigris	Lavrik	Lav
Index	0	-0.5	-3	-5	-0.5	-1

The definitions for the other variables included in Table 1 are as follows.

lna	= ln(a), a is age at I1 according to definition in the text
barrdga	= [conifer proportion of basal area (0-1)] / a
tdveg	= (pine proportion of basal area) · veg
bjdel2	= (birch proportion of basal area)^2
lng	= ln(g), g is basal area at I1 (m^2/ha) for followed trees
g0	= total basal area (m^2/ha) at start of the growth period
lnsn	=ln(sn), sn is stem number per ha for followed trees
veg	= code according to definition in the text
torvveg	= veg if there is peat on the plot, else = 0
moist	= 1 if the plot is moist, else = 0
wet	= 1 if the plot is wet, else = 0
sis	= site index according to site factors for site-indicative species (m), mean of independent measurements at i! and I2
bjdkyl	= bjdel·"cold climate" = exp[-0.01·(tsumma-300)], where tsumma = temperature sum, day-degrees>+5 ºC = 4835 - 57.6·latitude – 0.9·altitude
dikat	= 1 if there is a ditch within 25 m from plot centre, else = 0
fertris	= takes a value between 0-1 on fertilized plots with veg<12, see Elfving 2001
kant	= 1 if there is a border to open area within 20 m from plot center, else = 0
delad	= 1 if the plot is divided, else = 0
hu0t10	= 1 if the plot was thinned within 10 years before start of the growth period
hu10t30	= 1 if the plot was thinned 11-25 years before start of the growth period
lngrel	= ln(g0/G), where G is basal area in surrounding stand according to relascope
a3	= 1 if the plot was established 1983, else = 0
a4	= 1 if the plot was established 1984, else = 0
a6	= 1 if the plot was established 1986, else = 0

Basic data for this function was not corrected with year-ring indices. In average the growth has been 8 % higher than normal during the observation period why estimated growth should be reduced in accordance to this. The indicator variables a3-a6 shows that the growth level in those periods differed significantly from that in the other periods.

The residuals in Tab. 2 over estimated growth show that the weighing has resulted in a relatively homogenous residual variance (resw). The real variation coefficient (relres) is 3 times higher at low than at high estimated growth. The residuals over number of trees per plot shows that that relres decrease sharply with increasing number of trees per plot, from 0.56 with one tree per plot to a level around 0.3 with more than 40 trees per plot. The latter value is probably an estimation of the true precision of the growth function.

Residuals over soil texture indicate a systematic pattern over the scale, with negative deviations on coarse-textured and fine-textured soils and positive deviations in the middle of the scale. The variable soil texture was however not included as an independent variable since soil texture is seldom registered in practical inventories.

Residuals over geographical areas show a relatively large regional variation. As an example have 310 plots in the county Uppland grown 15 % less than calculated while 276 plots in the county Södermanland have grown 10 % more. The causes for those deviations are difficult to find out. If there will be an opportunity, the stability over time for regional variations should be examined when data from more measurement periods becomes available.

In the function, the thinning response was represented by two simple indicator variables. In a special residual study over site index and time after thinning a more fine-tuned pattern was revealed, Fig. 1.

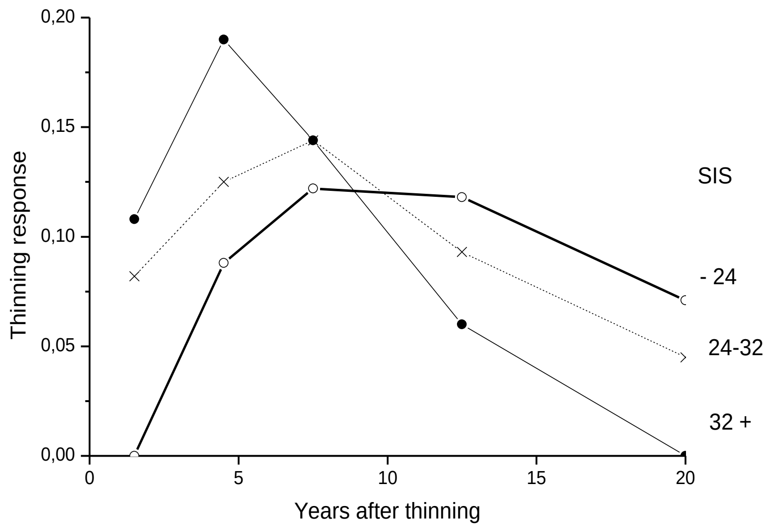

Figure 1. Patterns of thinning response (ln(iG5thinned) – ln(iG5unthinned)) over time after thinning on sites with different site indices according to a residual study.

At I1 type and year were noted for treatments performed in the last 30 years and at I2 the same data were noted for treatments in the last 5-year period. In total 65 % of the plots were noted as cut in some form. The basal area at I1 was in average the same for those plots as for those not noted as cut.

Fig. 1 shows that the distribution of thinning response over time varies with site index. At SIS<24 there is no response in the first years after cutting. The respons culminates after about 10 years and seems to last for more than 30 years. On the fertile spruce sites (SIS>32) a considerable response is noted directly after cut. The response culminates after about 5 years and lasts in 20 years. The response pattern on sites with intermediate site indices is between that of sites with high and low site indices. When the thinning response was modelled according to the pattern in Fig. 1 the residual variation was marginally reduced. Since the function will be complicated to use with this model only the function with the simple variables hu0t10 and hu11t30 is reported.

The residual variation of the stand-level function is shown in Fig. 2 over stem number per plot. For comparison also the residual variation from predictions with the single-tree growth functions for the same tree populations is shown. The figure shows that the residual variation is strongly reduced when the number of trees on the plot increases from 1 to 10. Then the reduction slows down and approach a value around 0.3. The form of the curve corresponds to the expectation with a relative variation of 0.7 within plots and 0.3 between plots. The curve for the tree-based calculation is marginally below that of the stand-based calculation. This shows that the tree-based functions not give essentially sharper predictions than the stand-based function. Despite the facts that both prediction systems contains the same independent variables and in average gives accurate predictions, they can give substantially different predictions for single plots. The variation coefficient for predictions on the plot level is about 0.1. One could expect that the mean of the two predictions per plot would give a better estimation than either system alone. The residual variance is however marginally reduced if the mean of the two predictions is used as predicted value. It is probably possible to improve the growth models if the differences between predictions on the plot level are scrutinized.

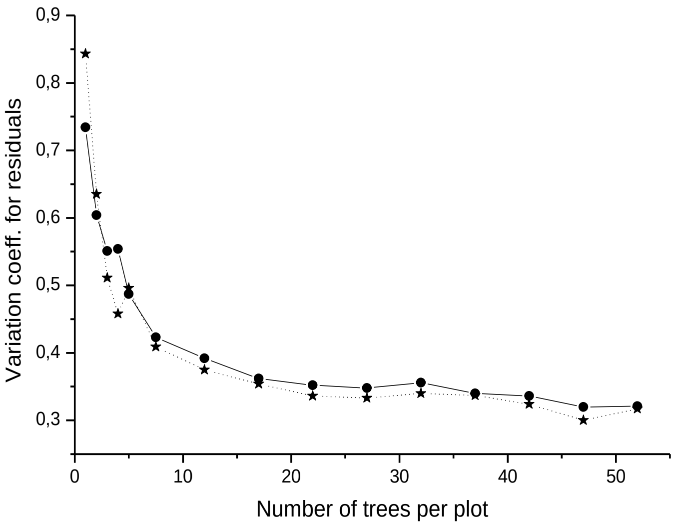

Figure 2. Relation between number of trees per plot and the residual variation at basal area growth predictions with stand-based (circles) and tree-based (stars) growth functions

Reference

Elfving, B. 2004. Individual-tree basal area growth functions for all Swedish forests. SLU, Dept. of Silviculture. Manuscript 2004-01-26.

Table 1. The stand-based basal area growth function as described in the text

Source	DF	Sum of Squares	Mean Square	F Value	Approx Pr > F
Regression	24	96211.1	4008.8	4984.68	<.0001
Residual	14208	11426.4	0.8042		
Uncorrected Total	14232	107637			
Corrected Total	14231	49404.2			

Parameter	Estimate	Approx Std Error	Approximate 95% Confidence Limits	
const	0.2702	0.0882	1.0160	1.2699
blna	-0.5819	0.0133	-0.6078	-0.5559
bbarrdga	8.1754	0.4544	7.2847	9.0661
btdveg	-0.0233	0.00454	-0.0322	-0.0145
bbjdel2	-0.3163	0.0300	-0.3750	-0.2576
bbjdkyl	-10.5278	1.7926	-14.0416	-7.0139
blng	0.5416	0.0112	0.5197	0.5635
bg0	-0.00932	0.000549	-0.0104	-0.00825
blnsn	0.1895	0.00897	0.1719	0.2071
bveg	0.0622	0.00293	0.0565	0.0679
btorvveg	-0.0252	0.00391	-0.0328	-0.0175
bmoist	-0.0476	0.00678	-0.0609	-0.0343
bwet	-0.1810	0.0353	-0.2501	-0.1118
bsis	0.0113	0.000875	0.00959	0.0130
bdikat	0.0533	0.00905	0.0356	0.0710
bfertris	0.3091	0.0505	0.2101	0.4082
bkant	0.0755	0.0127	0.0506	0.1004
bdelad	0.0621	0.00740	0.0476	0.0766
bhu0t10	0.1469	0.00717	0.1328	0.1609
bhu10t30	0.0624	0.00946	0.0438	0.0809
blngrel	0.1266	0.0172	0.0930	0.1603
ba3	-0.0610	0.00830	-0.0773	-0.0447
ba4	-0.0432	0.00809	-0.0591	-0.0274
ba6	0.0434	0.00762	0.0285	0.0584

Table 2. Residuals according to description in the text

Variable	N	Mean	Std Dev	Minimum	Maximum
IG	14232	2.174	1.557	-0.821	12.060
BERIG	14232	2.173	1.355	0.064	15.116
RES	14232	0.001	0.785	-3.852	5.948
RESW	14232	-0.002	0.896	-3.706	5.259

RELRES	14232	-0.006	0.405	-1.530	3.753

BERKL	N Obs	Variable	N	Mean	Std Dev	Minimum	Maximum
0	2539	IG	2539	0.601	0.418	-0.371	2.786
		BERIG	2539	0.632	0.239	0.064	1.000
		RESW	2539	-0.070	0.715	-2.390	3.500
		RELRES	2539	-0.058	0.558	-1.530	3.753
1	4928	IG	4928	1.517	0.702	-0.821	5.214
		BERIG	4928	1.508	0.288	1.000	2.000
		RESW	4928	0.010	0.894	-3.510	5.080
		RELRES	4928	0.002	0.418	-1.465	2.860
2	3689	IG	3689	2.495	0.881	-0.791	7.252
		BERIG	3689	2.441	0.283	2.000	3.000
		RESW	3689	0.059	0.940	-3.706	4.799
		RELRES	3689	0.022	0.344	-1.386	1.727
3	1765	IG	1765	3.432	1.012	0.505	8.823
		BERIG	1765	3.437	0.284	3.000	4.000
		RESW	1765	-0.004	0.933	-2.626	5.259
		RELRES	1765	-0.001	0.285	-0.836	1.371
4	743	IG	743	4.305	1.195	1.089	9.477
		BERIG	743	4.421	0.274	4.000	4.996
		RESW	743	-0.097	0.992	-3.326	4.510
		RELRES	743	-0.026	0.266	-0.761	1.198
5	319	IG	319	5.233	1.454	1.857	10.098
		BERIG	319	5.440	0.291	5.002	5.999
		RESW	319	-0.162	1.073	-2.601	3.274
		RELRES	319	-0.039	0.260	-0.654	0.838
6	126	IG	126	6.400	1.644	3.624	12.060
		BERIG	126	6.399	0.283	6.006	6.996
		RESW	126	-0.002	1.137	-2.034	4.199
		RELRES	126	0.000	0.254	-0.454	0.973
7	73	IG	73	7.598	1.427	4.829	10.918
		BERIG	73	7.410	0.279	7.003	7.977
		RESW	73	0.120	0.924	-1.861	2.214
		RELRES	73	0.025	0.188	-0.378	0.435
8	29	IG	29	8.292	1.308	4.647	11.045
		BERIG	29	8.456	0.300	8.006	8.937
		RESW	29	-0.104	0.858	-2.417	1.815
		RELRES	29	-0.018	0.161	-0.453	0.350
9	20	IG	20	9.762	1.497	6.729	11.859
		BERIG	20	9.380	0.244	9.029	9.785
		RESW	20	0.227	0.901	-1.529	1.674
		RELRES	20	0.042	0.163	-0.282	0.314

snkl	N Obs	Variable	N	Mean	Std Dev	Minimum	Maximum
1	691	IG	691	0.354	0.311	-0.141	1.857
		RELRES	691	-0.198	0.559	-1.325	2.074
2	486	IG	486	0.715	0.572	-0.140	4.328
		RELRES	486	-0.054	0.534	-1.352	2.631
3	394	IG	394	0.959	0.675	-0.261	3.997
		RELRES	394	-0.000	0.553	-1.216	2.164
4	377	IG	377	1.147	0.783	-0.435	5.233
		RELRES	377	0.053	0.524	-1.409	3.753
5	366	IG	366	1.292	0.923	-0.277	5.103
		RELRES	366	-0.017	0.490	-1.409	2.860
6-9	1738	IG	1738	1.661	1.046	-0.440	6.599
		RELRES	1738	0.016	0.419	-1.530	3.287
10-14	2699	IG	2699	2.069	1.233	-0.525	12.060
		RELRES	2699	0.026	0.389	-1.382	2.106
15-19	2741	IG	2741	2.395	1.362	-0.470	10.098
		RELRES	2741	0.007	0.361	-1.317	1.727

20-24	2063	IG	2063	2.676	1.492	-0.791	10.200
		RELRES	2063	-0.001	0.355	-1.386	3.224
25-29	1228	IG	1228	2.934	1.687	-0.346	12.033
		RELRES	1228	-0.022	0.333	-1.192	1.792
30-34	695	IG	695	3.061	1.835	-0.821	11.325
		RELRES	695	-0.023	0.357	-1.465	1.508
35-39	382	IG	382	3.469	1.964	0.292	11.859
		RELRES	382	-0.001	0.332	-0.855	1.567
40-44	210	IG	210	3.766	2.166	0.510	11.045
		RELRES	210	-0.007	0.305	-0.709	0.899
45-49	76	IG	76	3.842	2.056	0.623	9.355
		RELRES	76	-0.051	0.315	-0.728	0.895
50-54	58	IG	58	4.017	2.474	0.147	11.105
		RELRES	58	-0.043	0.324	-0.927	0.902
55-59	20	IG	20	4.843	2.875	1.152	11.293
		RELRES	20	-0.041	0.168	-0.489	0.211
60-64	6	IG	6	5.248	1.576	3.648	7.555
		RELRES	6	-0.088	0.160	-0.338	0.105
65-69	2	IG	2	4.215	1.925	2.854	5.576
		RELRES	2	-0.355	0.121	-0.440	-0.269

TEXTURe	N Obs	Variable	N	Mean	Std Dev	Minimum	Maximum
Sten	101	IG	101	1.443	1.001	0.046	5.059
		BERIG	101	1.500	0.776	0.198	3.671
		RELRES	101	-0.077	0.411	-0.865	1.052
Grus	97	IG	97	1.533	1.050	-0.141	4.322
		BERIG	97	1.692	0.864	0.106	4.453
		RELRES	97	-0.130	0.357	-1.197	0.716
Grovsand	655	IG	655	1.846	1.368	-0.440	11.333
		BERIG	655	1.894	1.151	0.148	9.632
		RELRES	655	-0.038	0.411	-1.361	1.778
Mellansand	3359	IG	3359	1.921	1.427	-0.525	12.033
		BERIG	3359	1.933	1.253	0.081	15.116
		RELRES	3359	-0.018	0.405	-1.530	2.099
Grovmo	6456	IG	6456	2.185	1.542	-0.821	12.060
		BERIG	6456	2.176	1.339	0.064	9.785
		RELRES	6456	0.002	0.402	-1.455	3.224
Finmo	2578	IG	2578	2.515	1.745	-0.479	11.859
		BERIG	2578	2.464	1.487	0.082	9.462
		RELRES	2578	0.012	0.412	-1.465	3.753
Mjäla	439	IG	439	2.260	1.423	-0.435	7.474
		BERIG	439	2.278	1.302	0.143	8.499
		RELRES	439	-0.002	0.407	-1.409	1.751
Lera	547	IG	547	2.572	1.599	-0.791	9.445
		BERIG	547	2.693	1.467	0.161	9.782
		RELRES	547	-0.045	0.374	-1.386	1.362

DLANSKOD	N Obs	Variable	N	Mean	Std Dev	Minimum	Maximum
BDL 1	581	IG	581	0.928	0.692	-0.470	4.155
		RELRES	581	-0.074	0.522	-1.409	3.753
BDK 2	855	IG	855	1.207	0.832	-0.479	4.492
		RELRES	855	-0.025	0.475	-1.530	1.778

ACL	3	553	IG	553	1.113	0.816	-0.310	5.359
			RELRES	553	-0.015	0.542	-1.273	3.287
ACK	4	649	IG	649	1.554	0.976	-0.346	6.092
			RELRES	649	-0.063	0.391	-1.247	2.074
ZJ	5	945	IG	945	1.603	1.061	-0.791	6.611
			RELRES	945	0.031	0.475	-1.407	2.631
ZH	6	282	IG	282	1.227	0.841	-0.163	4.026
			RELRES	282	-0.046	0.411	-1.207	1.412
YÅ	7	521	IG	521	1.763	1.057	-0.053	6.490
			RELRES	521	-0.001	0.377	-1.168	1.162
YM	8	240	IG	240	2.159	1.314	-0.351	7.592
			RELRES	240	0.069	0.413	-1.259	1.865
XH	9	714	IG	714	2.149	1.271	-0.153	7.989
			RELRES	714	0.045	0.387	-1.307	1.769
XG	10	201	IG	201	2.621	1.424	-0.030	8.077
			RELRES	201	0.053	0.349	-1.036	1.225
WSI	11	86	IG	86	0.923	0.655	0.000	4.055
			RELRES	86	-0.049	0.431	-1.000	1.458
WÖVR	12	1021	IG	1021	1.785	1.205	-0.718	9.477
			RELRES	1021	-0.039	0.390	-1.420	2.164
S	13	833	IG	833	2.176	1.450	-0.037	9.305
			RELRES	833	-0.038	0.375	-1.096	1.789
T	14	449	IG	449	2.421	1.421	-0.821	9.746
			RELRES	449	-0.031	0.406	-1.455	2.860
U	15	327	IG	327	2.464	1.452	-0.470	12.060
			RELRES	327	-0.047	0.358	-1.224	1.362
C	16	310	IG	310	2.266	1.333	-0.260	6.523
			RELRES	310	-0.156	0.325	-1.120	1.019
B	17	243	IG	243	2.427	1.266	0.062	6.793
			RELRES	243	0.004	0.310	-0.871	1.223
D	18	276	IG	276	3.035	1.604	0.263	10.098
			RELRES	276	0.111	0.362	-0.836	1.898
E	19	501	IG	501	2.778	1.579	-0.029	8.842
			RELRES	501	0.037	0.349	-1.037	1.384
R	20	295	IG	295	3.000	1.927	-0.001	11.333
			RELRES	295	0.053	0.354	-1.001	1.235
PD	21	188	IG	188	2.420	1.577	0.046	9.848
			RELRES	188	0.075	0.408	-0.865	1.480
PV	22	452	IG	452	2.588	1.458	-0.013	8.848
			RELRES	452	0.041	0.401	-1.040	1.838
F	23	543	IG	543	2.714	1.418	-0.090	7.406
			RELRES	543	0.022	0.364	-1.035	1.738
G	24	576	IG	576	2.646	1.550	-0.212	9.224
			RELRES	576	-0.053	0.345	-1.179	1.186
H	25	549	IG	549	2.803	1.530	0.000	10.918
			RELRES	549	0.034	0.361	-1.000	1.680
O	26	323	IG	323	2.798	1.948	-0.275	11.859
			RELRES	323	0.062	0.434	-1.325	1.627
N	27	523	IG	523	3.142	1.964	-0.262	11.325
			RELRES	523	-0.015	0.328	-1.146	1.183
L	28	504	IG	504	3.460	2.220	-0.140	11.293
			RELRES	504	0.024	0.352	-1.170	1.517
M	29	139	IG	139	3.653	2.219	-0.435	9.581
			RELRES	139	0.065	0.367	-1.409	1.171
K	30	317	IG	317	3.175	1.973	0.000	12.033
			RELRES	317	-0.014	0.349	-1.000	1.276
I	31	236	IG	236	1.725	1.091	0.022	6.287
			RELRES	236	-0.093	0.352	-0.972	1.078

SIS	N Obs	Variable	N	Mean	Std Dev	Minimum	Maximum
-16	1567	IG	1567	0.940	0.706	-0.821	6.326
		BERIG	1567	0.983	0.498	0.064	3.687
		RELRES	1567	-0.045	0.518	-1.530	3.753
-24	6348	IG	6348	1.717	1.083	-0.791	7.113
		BERIG	6348	1.703	0.834	0.081	6.599
		RELRES	6348	-0.004	0.416	-1.409	2.631
-32	4867	IG	4867	2.750	1.550	-0.586	12.060
		BERIG	4867	2.742	1.315	0.112	9.632
		RELRES	4867	0.005	0.364	-1.319	2.860
32+	1450	IG	1450	3.576	2.106	-0.435	12.033
		BERIG	1450	3.606	1.811	0.276	15.116
		RELRES	1450	-0.011	0.334	-1.409	1.371

Basalarea	N Obs	Variable	N	Mean	Std Dev	Minimum	Maximum
-10	4987	IG	4987	1.364	1.158	-0.525	9.329
		BERIG	4987	1.359	0.996	0.064	8.177
		RELRES	4987	-0.016	0.474	-1.530	3.753
-20	4692	IG	4692	2.297	1.532	-0.479	11.045
		BERIG	4692	2.297	1.293	0.287	9.782
		RELRES	4692	-0.007	0.369	-1.465	1.827
-30	3273	IG	3273	2.809	1.531	-0.821	12.060
		BERIG	3273	2.816	1.260	0.660	9.785
		RELRES	3273	0.002	0.350	-1.455	3.224
-40	1046	IG	1046	3.152	1.507	-0.470	12.033
		BERIG	1046	3.176	1.235	0.904	15.116
		RELRES	1046	0.005	0.356	-1.224	2.106
-50	202	IG	202	3.655	1.434	-0.260	9.526
		BERIG	202	3.548	1.183	1.794	7.596
		RELRES	202	0.064	0.379	-1.120	1.725
-60	26	IG	26	3.826	1.904	1.361	9.059
		BERIG	26	3.657	1.306	1.877	7.670
		RELRES	26	0.035	0.318	-0.577	0.720
-70	4	IG	4	5.644	3.083	2.034	9.477
		BERIG	4	3.887	1.252	2.497	5.401
		RELRES	4	0.478	0.736	-0.391	1.198
-80	2	IG	2	4.032	2.967	1.934	6.130
		BERIG	2	3.118	0.816	2.540	3.695
		RELRES	2	0.210	0.635	-0.239	0.659

Birchprop	N Obs	Variable	N	Mean	Std Dev	Minimum	Maximum
-0.2	10593	IG	10593	2.332	1.615	-0.821	12.060
		BERIG	10593	2.329	1.409	0.064	15.116
		RELRES	10593	-0.006	0.378	-1.455	2.860
-0.4	1906	IG	1906	1.895	1.310	-0.791	8.937
		BERIG	1906	1.905	1.088	0.105	7.181
		RELRES	1906	-0.011	0.431	-1.409	2.208
-0.6	887	IG	887	1.700	1.201	-0.479	9.031
		BERIG	887	1.685	1.001	0.111	6.323
		RELRES	887	0.010	0.469	-1.530	3.224
-0.8	453	IG	453	1.448	1.187	-0.371	6.910
		BERIG	453	1.490	1.025	0.101	5.284
		RELRES	453	-0.008	0.559	-1.407	3.753
-1.0	305	IG	305	1.240	1.139	-0.142	5.764
		BERIG	305	1.197	0.865	0.081	3.874
		RELRES	305	0.001	0.577	-1.260	3.287
1.0	88	IG	88	0.997	0.929	-0.262	4.211
		BERIG	88	1.032	0.826	0.109	3.071
		RELRES	88	-0.075	0.552	-1.168	2.062

Check and calibration of basal area growth functions for Heureka

PM for Heureka 2009-02-23 by Björn Elfving, Nils Fahlvik and Peder Wikström
Translated to English 2010-01-14.

Abstract
In the Heureka system the basal area growth is alternatively calculated with single-tree growth functions by Söderberg (1986) or Elfving (2004) or with the stand-based function by Elfving (2005). In the DT-system developed at the Southern Swedish Forest Research Centre the stand-based functions by Ekö (1985) are used. This study reports comparisons and tests of all those functions with new data from permanent plots at the National Forest Inventory (NFI). The test showed that all functions gave predictions with small deviations between each other and from the observed growth. The functions by Elfving, based on data from earlier measurements of the NFI plots, gave the lowest residual variation. Tests of the stand-based function with data from long-term field experiments indicated a need for a minor adjustment and the new, adjusted function is reported.

Even if the agreement between estimated and observed growth was good for the whole data-set, there were some differences for different tree species. A special analysis of the fluctuating growth-levels for different species over time indicates the problem to normalise the growth levels for different species. Test data was used to calibrate the growth levels for different species in the final growth function.

Introduction
Trees breast height diameters and their development over time are used to characterize stand development. The growths of single trees are quite variable and difficult to measure with a high accuracy. Growth functions for single trees can only give expected average development for trees with given character and position. The point with tree-wise accounting is that predictions from a given state can give both total production and its distribution on species and size classes. Elfving (2005) showed that the gain in precision at prediction of total growth with single-tree functions compared to area-based functions is marginal. The main strategy in Heureka is to use single-tree growth functions for distribution of growth and the area-based function to calibrate the growth level.

Since the interval between measurements of permanent plots generally has been 5 years the growth in a five-year period is used as dependent variable in growth functions. Growth is expressed as basal area growth instead of diameter growth for statistical reasons. In the Heureka system basal area growth is calculated either for single trees with the functions by Söderberg (1986) or Elfving (2004) or with the stand-level function by Elfving (2005). In the TT-system developed at the Southern Swedish Forest Research Centre in Alnarp the stand-level models by Ekö (1985) are used.

The old functions are based on data from temporary plots at the National Forest Inventory (NFI), measured in the period 1973-1977. Growth has been registered by year-ring measurements on increment cores from representative sample trees. The functions by Ekö give the growth per hectare for different species in the stand, with division on pine, spruce, birch, beech, oak and other broad-leaved trees. Separate functions were presented for different parts of the country and different site index classes. The single-tree functions by Söderberg enclose separate functions for different regions and age classes of the mentioned species. In total the Ekö functions include 682 estimated parameters, while the Söderberg functions include 449.

The functions by Elfving are based on data from the first observation period on the NFI permanent plots, established 1983-1987 and re-measured 1988-1992. The growth has been registered as the difference between measured diameters at start and end of the observation period for trees that were alive at the end of the period. The functions for single trees were divided on pine, spruce, birch, aspen, beech, oak, other noble broad-leaves and other trivial broad-leaves. In total those functions include 106 estimated parameters while the stand-level function only includes 21.

Residual studies have confirmed that all those functions are well adapted to the data they are based on. They have however not been tested with more extensive and representative data. The aim of this study was to test the functions with new NFI-data and make comparisons between the different functions. The stand-level model by Elfving has also been tested with data from long-term field experiments, corrected according to the results and calibrated with regard to the outcome of the test.

Material and methods

Data from the measurement periods 1999/2004 and 2000/2005 from the NFI permanent plots were prepared for another project and was used as test data in this study. Un-divided plots on productive forest land with mineral soil and mean stand height above 8 m were selected. To facilitate a simple analysis also plots that were thinned or had natural mortality in the observation period were excluded. The remaining data-set included 892 plots. Trees with d>99 mm at start of the growth period were individually followed and could be used in the test. Smaller trees were measured on smaller plots with different size at the two inventories and could not be included. The selected plots form a sample from the 18 500 permanent plots at NFI and are representative for the whole country. They are positioned in a systematic grid with higher density in the south than in the north.

The measured growth (iGobs, m^2/ha) was corrected for deviations from the nominal observation period 5 vegetation periods. For example, a plot measured in spring at period start and in autumn at period end the length of the observation period is 6 years and the corrected growth iGc =iGobs·5/6. For plots that were measured during the vegetation period the realized part y of the growth in current season was estimated as $y = 1/(1+\exp(5-10\cdot x))$, where x = number of days passed of the growing season (assumed start May 20, end Sept 10, length 100 days) divided by length of growing season. In average the length of the observation period was 4.97±0.58 years for the 892 plots.

The data-file also included year ring indices for the actual periods, species and regions. Indices states the growth level in the actual growth period in proportion to the normal and is based on ring series from cored sample trees on temporary NFI-plots with more than 60 rings at breast height. Indices are produced for different species and regions and are generally based on data from 20-200 trees per group. The value corrected for period length was further corrected for deviating growth level to iGcorr=iGc/index. Mean index was estimated as a weighted mean per plot for represented tree species with species proportion of basal area as weight. The fact that index was applied on basal area growth instead of diameter growth was especially considered. Mean indices on the country level for different tree species are given in

Tab. 1. For pine the growth level in the period was below normal, for spruce marginally above and for birch approximately normal.

Table 1. Five-year mean year-ring indices for different species in actual period

Period	Tree species			
	pine	spruce	birch	other desc.
1999-2003	95	103	95	98
2000-2004	90	99	104	100

For growth calculations with the Ekö functions the mean age at breast height of the two by diameter largest trees on the plot is demanded. Ages estimated according to Westerlund (1990) on basis of field-estimated stand age were given in the data-file and used for this purpose. Site-describing variable values were missing for 10 % of the observations for unknown reasons. Soil moisture was than given the value mesic and vegetation type the value blueberry type. To gain direct comparability with calculations according to Ekö, growth according to Elfvings initial (un-corrected) stand-level function was also calculated on basis of this data-file.

The growth calculations with the other functions were performed with a variant of Heureka Stand-Wise, importing data directly from the NFI data-base. Tree ages were calculated with functions presented by Elfving 82003). Thus the calculated and not the field-estimated stand age was used in this application.

Observed and estimated growth were compared both in absolute and relative terms. For the comparison in relative terms the transformation z=ln(iG+1) was applied in order to overcome the problem with negative values on measured growth and to homogenize the residual variance.

The initial stand-level function by Elfving was based on the observed growth corrected for deviating length of observation period but not with year-ring indices. The single-tree functions concerns index-adjusted growth and predict about 8 % lower growth than the stand-level function. Earlier tests of the single-tree functions have often indicated underestimations but the reason has been difficult to derive. The reason is probably that the index values have been influenced by fertilization. Almost 1 million hectares of the Swedish forest were under response to nitrogen fertilization during the observation period, forming a large part of the old conifer stands of interest to fertilize and where increment cores for the index series were captured. The growth level of the stand-level function has not been influenced to the same extent since the fertilized plots were identified and the fertilization response captured with a special indicator variable.

The stand-level function has also been tested with data from the un-thinned plots in the GG-trials (thinning and fertilization trials) comprising 48 blocks with 217 observation periods in pine stands and 23 blocks with 105 observation periods in spruce stands. The function indicated a heavy overestimation of the growth (almost 14 %) and a closer examination indicated that the reason was a too steep partial relation with the stem number per hectare. The function was recalculated with an asymptotic influence of the stem number. The reduction of the residual variance in the basic data was marginal but the adjusted function gave a proper growth level for the un-thinned GG-plots.

Results

The correction of measured growth in test data for deviating length of observation period and year-ring indices caused an increase of the average growth figure by 2,8 % while the standard deviation remained un-changed, cf. iGobs and iGkorr in Tab. 2. All functions except the single-tree functions by Elfving (BET) gave predictions in the neighbourhood of iGkorr (±2 %). The BET-functions underestimated growth by about 10 % which according to the MM-section is assumed to depend on influence of fertilization on the year-ring indices.

The residual standard deviation is lower for predictions with the Elfving functions than for that of the older and lowest for the recalculated and adjusted stand-level function (BEY2). This function explains 73 % of the absolute growth variance compared to 66-68 % for the older functions. In relative terms (z-values) the difference is smaller. One reason for this can be that the new functions are accounting growth in absolute terms and the old functions in relative terms.

Table 2. Comparison of observed and estimated basal area growth (iG, m²/ha, 5 år) z=ln(iG+1), res=obs-est, BEY1= initial, stand-level function by Elfving; BEY2= re-calculated and adjusted stand-level function by Elfving; PME= stand-level functions by Ekö; BET= the single-tree functions by Elfving ; UST= the single-tree functions by Söderberg ; R^2=proportion of total variance explained by the function

Variable	Mean	Std.dev.	z-mean	z-std.dev	R^2abs	R^2z
iGobs	2,239	1,506	1,079	0,434		
iGkorr	2,302	1,504	1,101	0,431		
iG-BEY1	2,344	1,288	1,143	0,351		
iG-PME	2,338	1,320	1,137	0,363		
iG-BEY2	2,285	1,228	1,128	0,344		
iG-BET	2,061	1,109	1,059	0,341		
iG-UST	2,263	1,398	1,106	0,383		
res-BEY1	-0,031	0,808	-0,040	0,231	0,711	0,713
res-PME	-0,036	0,854	-0,037	0,242	0,678	0,684
res-BEY2	0,017	0,778	-0,028	0,229	0,732	0,718
res-BET	0,241	0,810	0,041	0,233	0,710	0,708
res-UST	0,039	0,879	-0,005	0,245	0,658	0,677

Even if the predicted growth in average agreed with that measured there were differences between groups in the data. Functions BEY1 and PME gave proper growth for the 1999/2003 data but overestimation by 3.7 % for the 2000/2004 data. There were also differences between tree species. All functions gave overestimation for pine-dominated stands and underestimations for broadleaves-dominated stands. The function BEY2 is calibrated so that estimated growth corresponds to the measured (iGkorr) for stands with either pine, spruce, birch or other broad-leaves as dominating species (>70 % of the basal area). The recalculated function with an asymptotic function for the influence of stem number is shown in Tab. 3.

The calibrated function BEY2 suggested for application in Heureka is given below. The variable definitions are given in Tab. 4.

iG-BEY2 = exp(0,366 – 0,5842*lna + 8,374*barrdga – 0,0237*tdveg – 0,3192*bjdel2 – 10,8034*bjdkyl + 0,5002*lng – 0,00632*g0 + 1,376*nf + 0,0627*veg – 0,0244*torvveg – 0,0498*moist – 0,1807*wet + 0,0109*sis + 0,0542*dikat + 0,1396*hu0t10 + 0,0567*hu10t30 – 0,06*talldel – 0,03*grandel) ;

Table 3. Basal area growth function 2008-12-09 för for all tree species in Sweden, based on data from NFI permanent plots in the period 1983/87 – 1988/92. The dependent variable is ln(5-year growth, m²/ha). The independent variables are defined in Tab. 4.. The b in front of the variable name indicates that it is a coefficient that shall be multiplied with the variable value

Source	DF	Sum of Squares	Mean Square	F Value	Approx Pr > F
Regression	24	96286.0	4011.9	5021.50	<.0001
Residual	14208	11351.5	0.7989		
Uncorrected Total	14232	107637			
Corrected Total	14231	49404.2			

Parameter	Estimate	Approx Std Error	Approximate 95% Confidence Limits	
const	0.3531	0.0831	0.1903	0.5160
blna	-0.5842	0.0131	-0.6098	-0.5586
bbarrdga	8.3740	0.4542	7.4837	9.2643
btdveg	-0.0237	0.00452	-0.0325	-0.0148
bbjdel2	-0.3192	0.0300	-0.3779	-0.2605
bbjdkyl	-10.8034	1.8010	-14.3336	-7.2732
blng	0.5002	0.0121	0.4765	0.5238
bg0	-0.00632	0.000563	-0.00742	-0.00522
bnf	1.3760	0.0613	1.2559	1.4961
bveg	0.0627	0.00292	0.0570	0.0685
btorvveg	-0.0244	0.00389	-0.0320	-0.0168
bmoist	-0.0498	0.00676	-0.0630	-0.0365
bwet	-0.1807	0.0351	-0.2496	-0.1118
bsis	0.0109	0.000856	0.00919	0.0125
bdikat	0.0542	0.00902	0.0365	0.0719
bfertris	0.3065	0.0504	0.2077	0.4053
bkant	0.0760	0.0126	0.0512	0.1008
bdelad	0.0607	0.00737	0.0463	0.0752
bhu0t10	0.1396	0.00711	0.1257	0.1535
bhu10t30	0.0567	0.00938	0.0383	0.0750
blngrel	0.1163	0.0170	0.0831	0.1496
ba3	-0.0616	0.00827	-0.0778	-0.0454
ba4	-0.0429	0.00806	-0.0587	-0.0271
ba6	0.0433	0.00759	0.0285	0.0582

Table 4. Definition of the independent variables in the basal area growth function

The variable indicating vegetation type (veg) is scaled in the interval -5 to +4 as follows. The field layer code (Fskod) is the code used at the NFI. The scaling is from 1=tall herbs without dwarf-shrubs via 9=narrow-leafed grasses and 13=bilberries to 18=lichens.

Fskod	1	2	3	4	5	6
Meaning	H-ört u ris	H-ört m blå	H-ört m ling	L-ört u ris	L-ört m blå	L-ört m ling
Index	4	2.5	2	3	2.5	2
Fskod	7	8	9	10	11	12
Meaning	Utan fs	Breda gräs	Smala gräs	Högstarr	Lågstarr	Fräken
Index	3	2.5	1.5	-3	-3	1
Fskod	13	14	15	16	17	18
Meaning	Blåbär	Lingon	Kråkb/ljung	Fattigris	Lavrik	Lav
Index	0	-0.5	-3	-5	-0.5	-1

The definitions for the other variables included in Table 3 are as follows.

lna	= ln(a), a is age at I1 according to definition in the text
barrdga	= [conifer proportion of basal area (0-1)] / a
tdveg	= (pine proportion of basal area) · veg
bjdel2	= (birch proportion of basal area)^2
lng	= ln(g), g is basal area at I1 (m^2/ha) for followed trees
g0	= total basal area (m^2/ha) at start of the growth period
nf	=sn/(sn+80), sn is stem number per ha for followed trees
veg	= code according to definition in the text
torvveg	= veg if there is peat on the plot, else = 0
moist	= 1 if the plot is moist, else = 0
wet	= 1 if the plot is wet, else = 0
sis	= site index according to site factors for site-indicative species (m), mean of independent measurements at i! and I2
bjdkyl	= bjdel·"cold climate" = exp[-0.01·(tsumma-300)], where tsumma = temperature sum, day-degrees>+5 ºC = 4835 - 57.6·latitude – 0.9·altitude
dikat	= 1 if there is a ditch within 25 m from plot centre, else = 0
fertris	= takes a value between 0-1 on fertilized plots with veg<12, see Elfving 2001
kant	= 1 if there is a border to open area within 20 m from plot center, else = 0
delad	= 1 if the plot is divided, else = 0
hu0t10	= 1 if the plot was thinned within 10 years before start of the growth period
hu10t30	= 1 if the plot was thinned 11-25 years before start of the growth period
lngrel	= ln(g0/G), where G is basal area in surrounding stand according to relascope
a3	= 1 if the plot was established 1983, else = 0
a4	= 1 if the plot was established 1984, else = 0
a6	= 1 if the plot was established 1986, else = 0

At the calibration of the basal area growth function for Heureka the variables in Tab. 3 not included in the final function except fertris were given their mean values in the basic data. The variable fertris was given the value 0. The reason for deleting the variables kant and delad from the final function is that those variables not are predictable at application of the function in Heureka. The proportion of plots with those properties is assumed to remain about the same in the future. The calibration has been done so that the estimated growth corresponds to the corrected growth observation in a limited data set during a limited growth period. Since the growth levels for different species varies substantially over time (Fig. 1) and the year-ring indices for the last years are relatively uncertain the growth function should successively be checked with new data from the NFI permanent plots. This is relatively easy to do in accordance with this study.

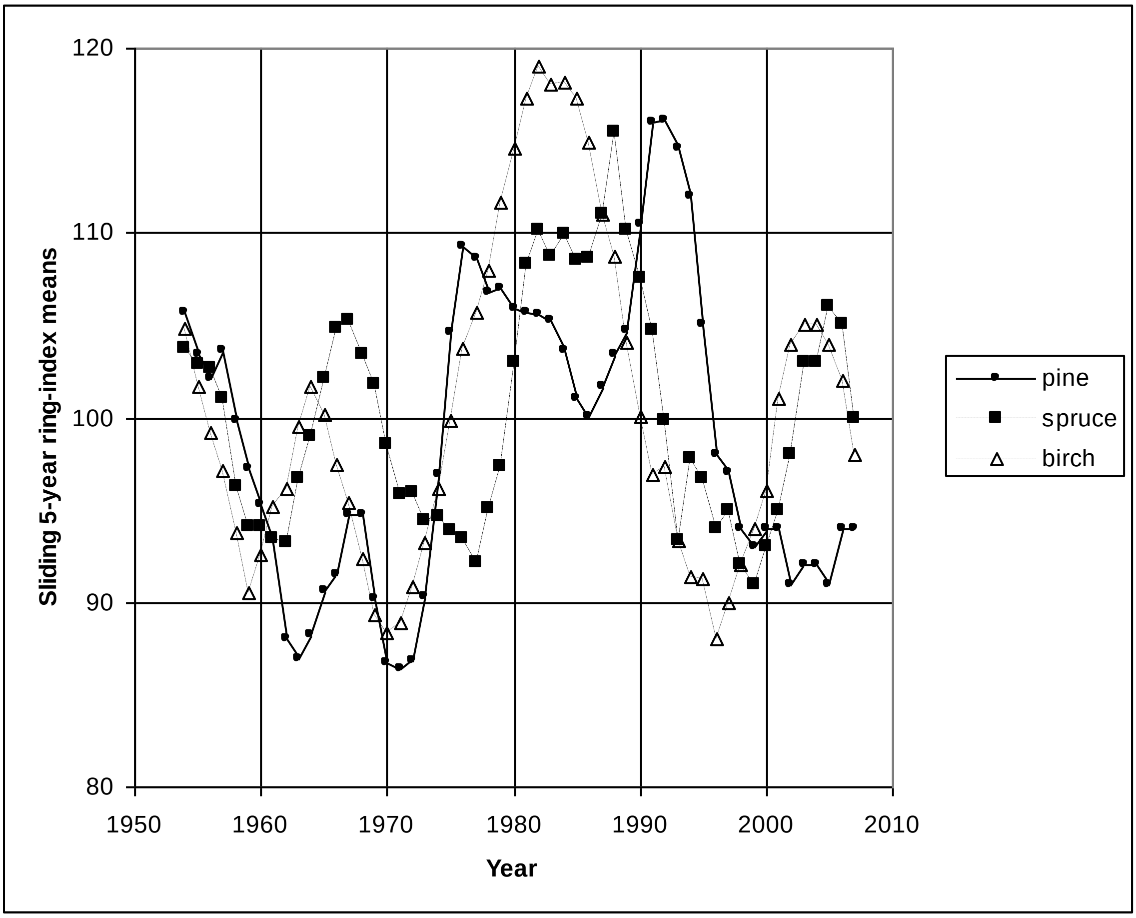

Figure 1. Variation in growth level for different tree species over time. Given values concern means for the last 5-year period. The relatively high values in the period 1975-1995 are probably partly depending on fertilization.

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Appendix 6

Functions for estimation of single-tree ages at breast height

Functions for estimation of single tree ages at breast height were presented by Elfving (2003). They are based on sample tree data from temporary NFI-plots measured 1992-2001. Age at breast height (a13) was measured on increment cores from 46 054 trees. Mean diameter of co-dominant trees (Dm, cm) was estimated as a function (1) of total stand age, site index and stand density, and used as a basis for expressing tree size in relative terms. Trees with dbh>1.8·(Dm+8) were distinguished as standards (remnant trees from a former stand) and trees with d<0.4*Dm as undergrowth. Separate functions were constructed for 8 different tree groups as follows. The dependent variable was ln(a13):

2. Total data set, with stand age included as independent variable
3. Total data set, without stand age included as independent variable
4. Uneven-aged stands
5. Pines in even-aged stands
6. Spruce in even-aged stands
7. Birch in even-aged stands
8. Other broad-leaved trees in even-aged stands
9. Standards

1. lnd=-0.9231+1.0032*lnbald-0.00701*bald-4.005/sis+0.0186*sis-1.882/Gf +0.036

2. lna13=-1.4692+0.2989*lnd-0.01132*d+0.2594*d/Dm+1.019*lnbald-0.0948*tall-0.0980*ljuslov+0.00465*sis-0.00372*sis*gran+0.3350*ts-0.1551*ts2+0.5684*ost-0.2103*sma-0.0312*likald+0.0449*lng+0.0344*gotland-0.1388*rich+0.0614*poor +0.028

3. lna13=2.2552+1.2108*lnd-1.5115*reld+0.3962*red2-0.1822*tall+0.1416*bokek-0.1276*ljuslov-0.0278*sis-0.00471*sis*gran-0.00000304*sis2-0.3921*ts+0.1621*ost+0.2950*sma+0.1908*ln(Gf+1)+0.1994*gotland-0.2071*rich+0.0320*poor-0.0918*dike+0.1410*torv +0.062

4. lna13=0.4181+0.5572*lnd-0.01803*d+0.1713*d/Dm+0.3923*lnbald+0.00367*bald +0.1051*bokek-0.2228*ljuslov-0.01171*sis+0.0002851*sis*d-0.00135*sis*gran+0.8362*ts-0.4469*ts2+0.0469*lng-0.0668*rich+0.0313*poor-0.0379*dike+0.1449*gotland +0.042

5. lna13=-1.6957+0.2982*lnd-0.00801*d+0.0726*d/Dm+1.1587*lnbald-0.0007699*bald+0.0310*lng +0.012

6. lna13=-1.3834+0.3790*lnd-0.01003*d+0.1283*reld+1.0201*lnbald+0.0175*lng +0.018

7. lna13=0.1006+0.5207*lnd-0.00793*d-0.0814*reld+0.6701*lnbald-0.01053*sis-0.0990*rich+0.0394*ln(Gf+1) +0.038

8. lna13=0.138+0.6469*lnd-0.265*d/Dm+0.5053*lnbald+0.1939*slov-0.1787*ljuslov +0.034

9. lna13=1.7993+1.1489*lnd-0.01841*d+0.00634*bald-0.0346*sis-0.2254*ljuslov +0.045

The last term in the different functions is the correction for logarithmic bias.

Variable definitions

bald	total stand age, as estimated in the field
d	diameter at breast height of the tree, cm
dg	diameter of the basal area mean tree on the plot, cm
reld	d/dg
g	total basal area on the plot, m^2/ha
Gf	total basal area of the stand, as estimated with relascope in the field, m^2/ha
sis	site index according to site factors, given as top height at age 100, m
sis2	sis^2
ts	temperature sum/1000, estimated as a function of latitude and altitude
ts2	ts^2
tall	indicator variable for pine (0-1)
gran	indicator variable for spruce (0-1)
ost	indicator variable for standards (0-1)
sma	indicator variable for undergrowth (0-1)
rich	indicator variable for sites with herbs and grass (0-1)
poor	indicator variable for sites with poor field vegetation (lichens, heather etc) (0-1)
dike	indicator variable for sites with a ditch within 20 m from the plot (0-1)
torv	indicator variable for sites on peat-land (0-1)
likald	indicator variable for even-aged stand: > 80 % of volume within a 20-year age class(0-1)
Gotland	indicator variable for sites in the county/island Gotland (0-1)
bokek	indicator variable for the tree species beech and oak (0-1)
ljuslov	indicator variable for the tree species elm, linden, maple, cherry and sallow (0-1)
slov	indicator variable for the tree species hornbeam and rowan (0-1)

Reference

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Appendix 7

Function for time to reach breast height

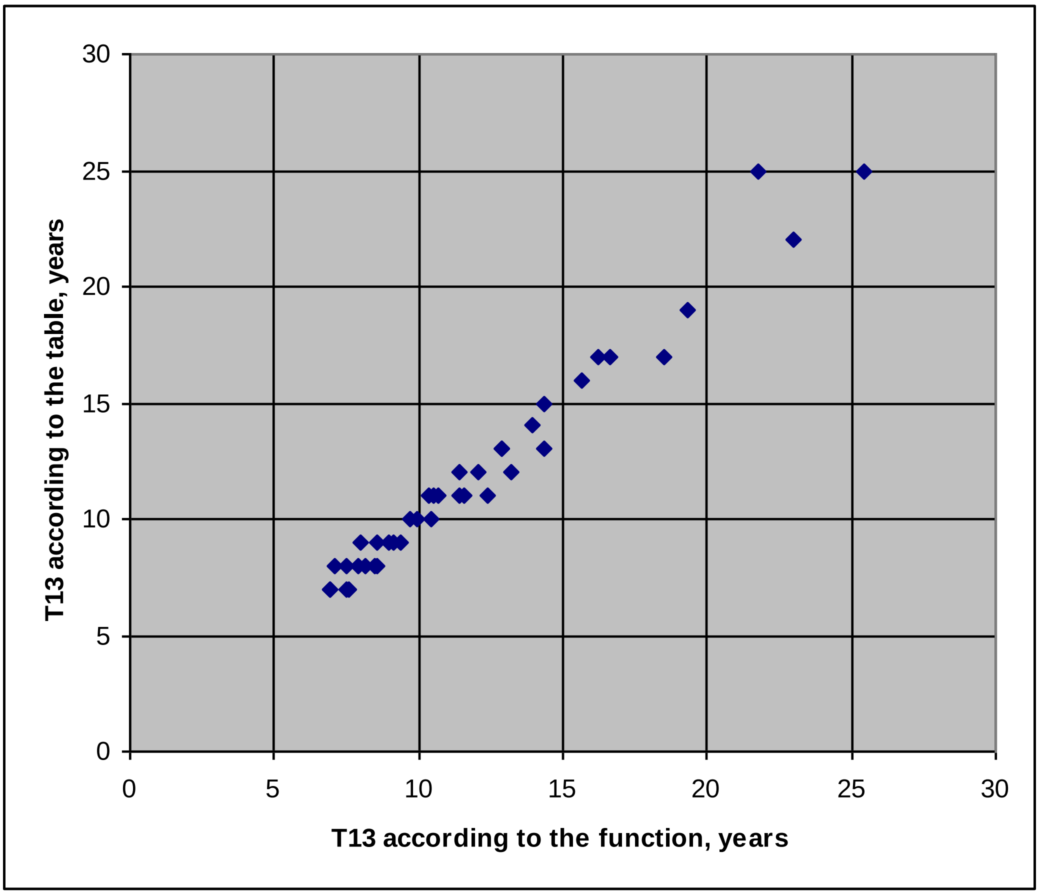
PM for Heureka 2009-01-14 by Björn Elfving

At the National Forest Inventory the determination of stand age is generally based on counting of year rings on increment cores taken at breast height from basal area mean trees. To get total stand age a value for “time to reach breast height” is added. This value (T13) is selected from a table and depends on species, site index according to site factors (SIS, m) and latitude (LAT, °N). The values in this table have been smoothed with the following regression:

T13 = 37 – 0.605*LAT – 1121/SIS + 21.92*LAT/SIS + 29.5*SPRUCE/SIS ;
n=40; r^2adj=0.970; sres=0.86 ;

Values according to the table and to the function are compared in the diagram below. Function values concern pine and spruce. For prominent broadleaves the spruce values are applied. For other broad-leaves (birch, aspen etc.) the following relation is applied:

T13 = 150/SIS



Appendix 8

Functions for estimation of heights of individual trees

Functions for estimation of heights of individual trees were presented by Söderberg (1992). They are based on sample tree data from the 1973-1977 inventories by NFI, in total including 31 000 sample trees. Trees on the island Gotland with very specific site conditions, and trees with apparently large measurement errors and disturbing damages were excluded. Separate functions were developed for pine in northern, middle and southern Sweden, for spruce and birch in northern and southern Sweden, for beech and oak (only growing in the south) and for other broadleaved tree species in the north and in the south.

As an example the function for pine in northern Sweden is shown below. The dependent variable is ln(h), where h is total tree height, dm.

$$\ln(h) = - 8.2981 - 27.995/(d+5) + 678.16/(d+5)^2 - 8.0059/(t+10) + 100.56/(t+10)^2 - 0.001899 \cdot t - 0.66679 \cdot d/t + 0.014142 \cdot H100p + 0.011473 \cdot G - 0.00012937 \cdot G^2 - 0.15662 \cdot d/dmax + 0.02292 \cdot (d/dmax)^2 + 0.45084 \cdot lat - 0.0035449 \cdot lat^2 - 0.002026 * (alt/100)^2 + 0.12172 \cdot pprop + 0.06390 \cdot sprop - 0.026745 \cdot coast - 0.047547 \cdot div - 0.016487 \cdot mar ;$$

$n=3785$; $R=0.94$; $sres=0.128$;

d	dbh including bark, cm
t	number of year-rings at brest height
H100p	site index for pine, m (top height at age 100)
G	basal area, m²/ha
dmax	dbh of largest tree on the plot (314 m²)
lat	latitude, ºN
alt	altitude, meter above see level
pprop	pine proportion of basal area
sprop	spruce proportion of basal area
coast	indicator variable with value 1 if distance to coast is <50 km
div	divided plot (plot on stand border)
mar	plot within area with maritime climate

Reference

Söderberg, U. 1992. Functions for forest management. Height, form height and bark thickness of individual trees. SLU, Dept. of Forest Survey, Report 52.

Appendix 9 PM for Heureka 2009-03-11 by Björn Elfving

Height development functions

Height development functions (site index equations) have been developed for pine, spruce, birch, aspen oak, beach and larch with a special solution of the difference equation method. This means that height H2 at age A2 is directly estimated as a function of height H1 at age A1 and A2 according to the following algorithms. The parameters, estimated with non-linear regression with data for the different species (Table 1), are asi, beta and b2.

$d = beta \cdot asi^{b2}$; $r = [(H1-d)^2 + 4 \cdot beta \cdot H1 \cdot A1^{b2}]^{0,5}$;
$H2 = (H1+d+r)/[2 + (4 \cdot beta \cdot A2^{b2}) / (H1-d+r)]$

Table 1. Parameter values for different tree species in the site index equations. For spruce and birch: see remarks in the text

	Tree species						
Parameter	pine	spruce	birch	aspen	beech	oak	larch
asi	25	10	7	7	15	1000	17,97
beta	7395,6	1495,3	394	693,2	4239,3	8841,4	1529
b2	-1,7829	-1,5978	-1,3870	-0,9771	-1,7753	-1,4317	-1,3451

Those functions concerns top height increment over total age except for birch and spruce. For birch the equation gives height development above breast height as function of age at breast height. For spruce the age should be reduced by 3 years at calculation and the equation is not valid below age 10. For example, height at age 100 corresponds to the height value calculated with age=97. Parameters for pine are valid for both Scots pine and lodge-pole pine. Parameters for larch are valid for both European, Japanese and Russian larch as well as hybrids between those species.

Top height is defined as the height according to the height curve at the mean diameter of the 100 by diameter largest trees per hectare. The functions are applied for estimation of height growth for single trees based on their initial age and height. Only the functions for pine and birch have been scientifically reported. The function for pine was based on data from 156 permanent plots in even-aged Scots pine stands re-measured 1-6 times, in all 453 measurement periods. (Elfving, B. & Kiviste, A. 1997. Construction of site index equations for Pinus sylvestris L. using permanent plot data in Sweden. For. Ecol. Manage. 98:125-134.) The similarity of growth patterns for Scots pine and lodge-pole pine was reported in Swedish (Elfving, B. 1993. SLU, Dept. of Silviculture, Working Papers nr 71).

The function for spruce was based on data from 81 permanent sample plots in even-aged Norway spruce stands, re-measured 1-7 times, in all 293 measurement periods. The study was reported in Swedish (Elfving, B. 2003. SLU, Dept. of Silviculture, Working Papers 185).

The function for birch was based on data from 266 felled and sectioned top height trees, representing 155 different stands with Betula pendula (43 %) and Betula pubescens (57 %). No difference in growth pattern was found between the species. (Eriksson, H., Johansson, U. & Kiviste, A. 1997. A site index model for pure and mixed stands of Betula pendula and Betula pubescens in Sweden. Scand. J. For. Res. 12: 149-156).
The function for aspen was based on data from 10 sectioned trees per stand in 40 stands on 8 localities in Sweden (Johansson, T. 1996. Site index curves for European aspen growing on forest land of different soils in Sweden. Silva Fennica 30(4): 437-455). A similar study was

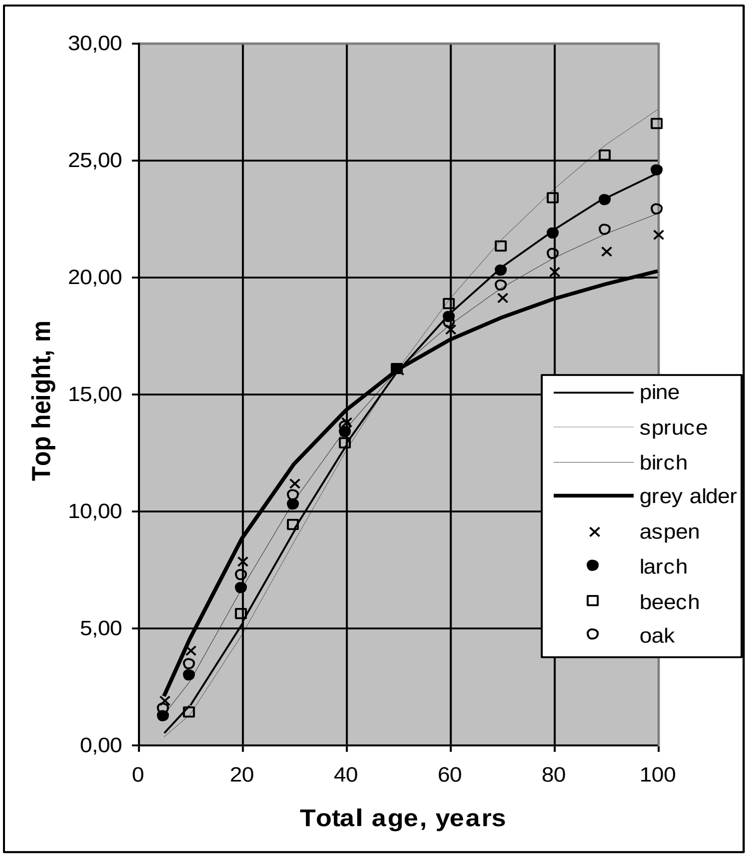
done for alder but not used in Heureka (Johansson ,T. 1999. Site index curves for common alder and grey alder on different types of forest soils in Sweden. Scand. J. For. Res. 14:441-).

The function for beech was based on data from 29 permanent plots in beech stands with long-term observations. For older stands with slow growth and for stands observed during a shorter period the period between first and last measurement was used as observation period while the other observation series were represented by two periods of approximately equal length. Data from those plots founded the yield tables constructed by Carbonnier, C. 1971. Yield of beech in southern Sweden. Stud. For. Suec. 91. For the new height growth study the former data-set was completed with later re-measurements.

The function for oak was based on data from 42 permanent sample plots in oak plantations followed with frequent re-measurements. As for beech, each stand was represented by 1-2 longer observations periods. Data from those plots formed basis for the yield tables constructed by Carbonnier, C. 1975. Yield of oak plantations in southern Sweden. Stud. For. Suec. 125. As for beech, data was completed with later re-measurements for the height growth study.

The function for larch was based on data from 77 permanent plots on 44 main sites, with 21 plots in European larch, 14 plots in Japanese larch, 31 plots in Russian larch and 11 plots in hybrid larch (euro-lepis). No significant difference in growth pattern was found between the different species.

Growth patterns of different species are illustrated below.



Appendix 10

Functions for estimation of in-growth in established stands

Functions for estimation of ingrowth in established stands were presented by Wikberg (2004). In-growth of trees above 39 mm dbh in established stands (mean height above 7 m) is estimated with a 4-step model as follows:

1. The probability for occurrence of small trees (dbh=1-39 mm) in a plot with 5-m radius is estimated for different tree species as a function of density and species distribution in the over-story, stand age, field vegetation type and other site characteristics.

2. The number of small trees per plot on plots with small trees is estimated as a function of the variables under (1).

3. The probability for a small tree to pass the in-growth limit during a 5-year period is estimated.

4. Mean diameter of ingrown trees at the end of the 5-year period is estimated.

Functions 1-2 were based on data from the first inventory (1983-1987) of the permanent NFI-plots, in total about 18 500 representative plots in the whole country. Functions 3-4 were based on data from revisions 2 and 3 of the permanent NFI-plots. Small trees within a quadrant of a 5-m radius plot (area about 20 m^2) were coordinated at revision 2 (1988-1992) and re-measured at revision 3 (1993-2002). In total 29 590 small trees were followed during a period of 5-10 years.

The functions are here only illustrated with graphs of partial relations. The detailed description is found in the primary publication.

Reference

Wikberg, P-E. 2004. Occurrence, morphology and growth of understory saplings in Swedish forests. Acta Univ. Agr. Suec., Silvestria 322.

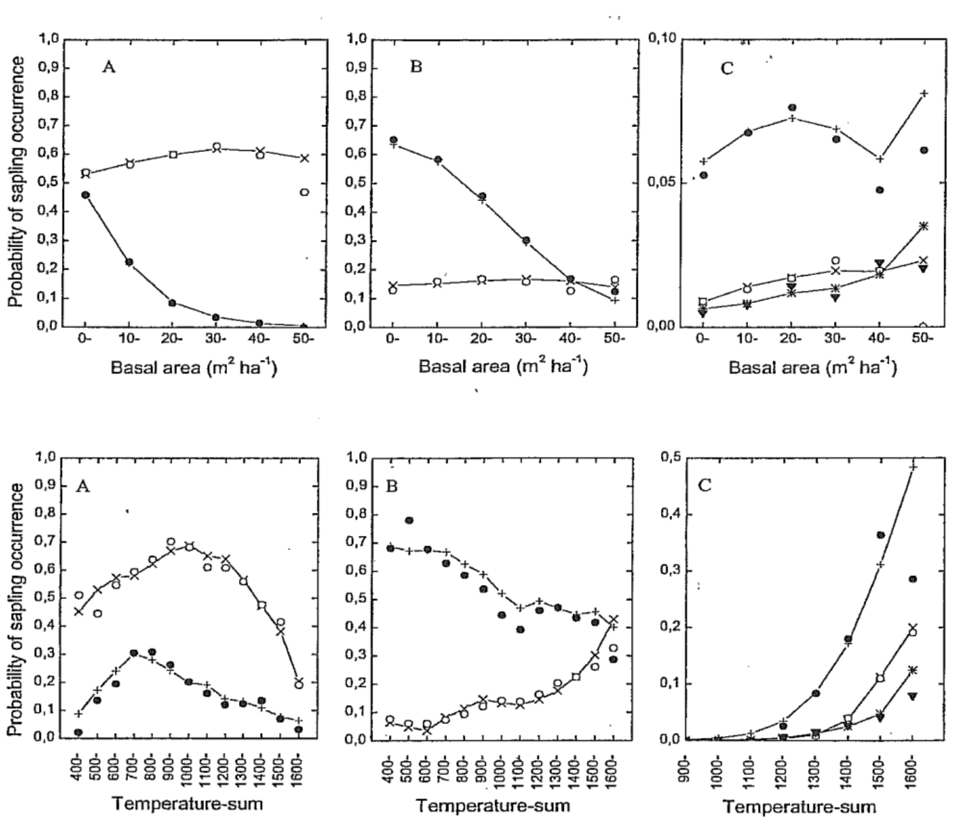


Figure 1. Calculated and observed mean values of probability of sapling occurrence in basal area classes (I) and temperature-sum classes (II). Dots, circles and triangles represent observed values and the connected plus, cross and star signs estimated values according to the models in Table 5. A = Scots pine (dots and plus signs) and Norway spruce (circles and cross signs), B = birch (dots and plus signs) and the class other boreal broad-leaves (circles and cross signs), C = oak (dots and plus signs), beech (circles and cross signs), and the class other hemiboreal broad-leaves (triangles and stars). Note the different value ranges on the y-axis.

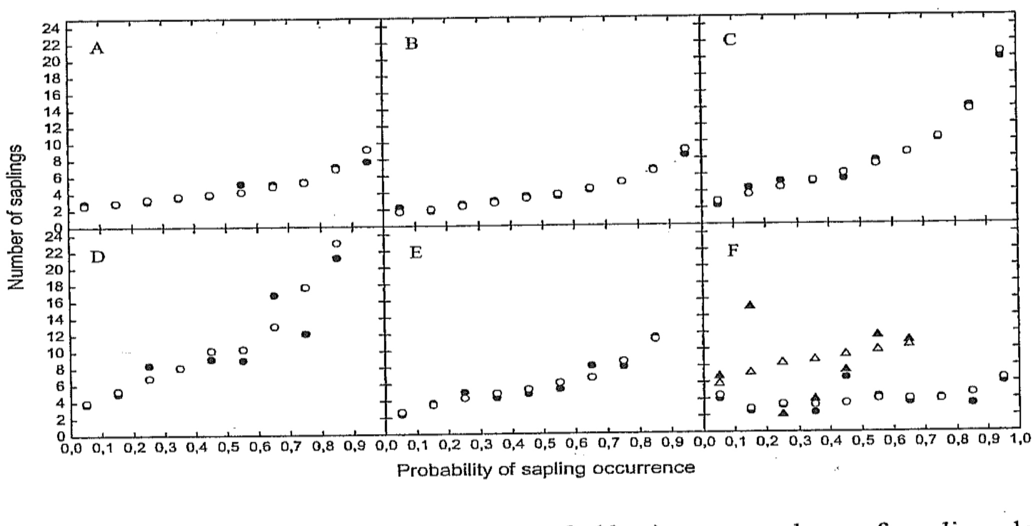


Figure 2. Calculated (circles) and observed (dots) mean values of sapling density in different occurrence classes in plots where sapling of target species occurred. The Y-values from model 1 were used as an independent variable in model 3, and were transformed to p-values in the graph. A = Scots pine, B = Norway spruce, C = birch, D = other boreal broad-leaves, E = oak, F = beech (dots and circles), and the class other hemiboreal broad-leaves (triangles).

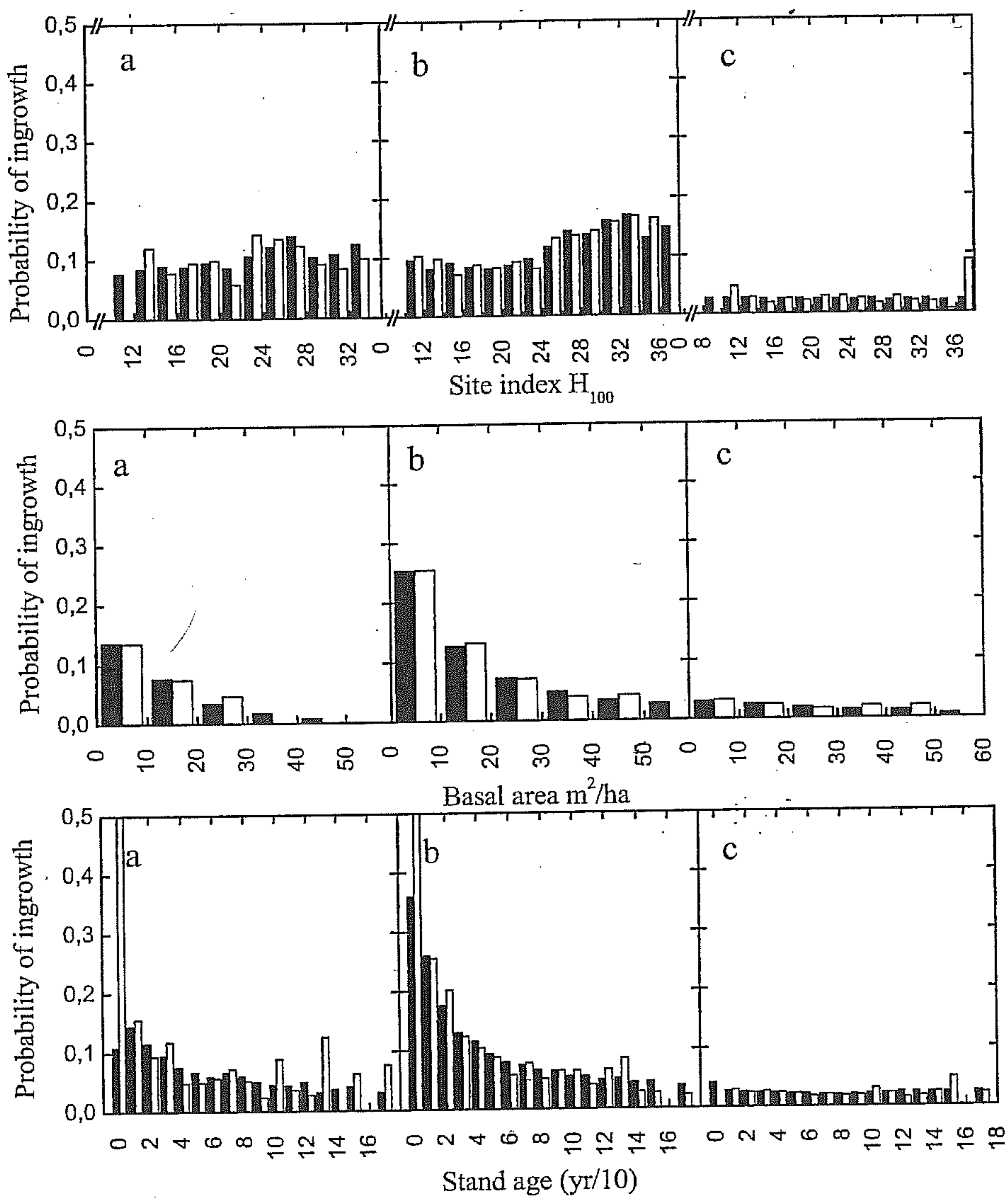


Figure 2. Mean estimated (black bars) and mean observed (white bars) probability of ingrowth during 5-year, by classes of: site index, basal area ha^{-1}, and stand age, measured on the10 m plot. a=Scots pine, b=Norway spruce, c=birch.

Table 4. *Coefficients, standard error and p-values for Model 3 for estimation of diameter at the end of the end of the 5-year period for ingrowth trees. Dependent variable was ln(d). The coefficients have been corrected for logarithmic bias* d in mm !

Variable	Scots pine. Adj. R^2: 0.134			Norway spruce. Adj. R^2: 0.13			Birch. Adj. R^2: 0.174		
	Estimate	SE	p	Estimate	SE	p	Estimate	SE	p
intercept	3.5650	0.0594	<0.0001	3.6223	0.0229	<0.0001	3.5579	0.0377	<0.0001
INV5BA	3.7675	0.6614	0.0001	2.5129	0.2837	<0.0001	1.8171	0.4743	0.0002
SI	0.0158	0.0021	0.0072	0.0147	0.0008	<0.0001	0.0179	0.0012	<0.0001

Appendix 11

Functions for estimation of mortality in established stands

The mortality level in self-thinning stands is predicted with functions presented by Söderberg (1986) and in stands of lower density with functions presented by Bengtsson (1978).
The distribution of the mortality on species and dimensions is based on functions presented by Fridman & Ståhl (2001). Mortality of old trees and shelter trees is especially accounted.

Söderberg (1986) presented one function for basal area and one function for mortality in self-thinning stands. Mortality was expressed as annual percent of the basal area that is self-thinned. At application in Heureka mortality is a weighted average of predictions by Söderberg and Bengtsson, depending on the relative density of the stand. Relative density is actual basal area related to basal area of self-thinning stands according to Söderberg.

The functions by Söderberg were based on data from 532 observation periods on 82 yield plots in non-thinned stands.

1. Basal area in self-thinned stands. Dependent variable is ln(basal area), m²/ha

Variabel *Variable*	Beteckning *Symbol*	Koefficient *Coefficient*	Formellt medelfel, % *Standard error, %*
1/(totalålder + 10)	1/(T + 10)	−18.612	42.0
1/(totalålder + 10)²	1/(T + 10)²	−765.295	32.4
Ståndortsindex, gran, m	SI(G)	0.04798	5.2
Ståndortsindex, tall, m	SI(T)	0.05589	4.5
Stamantal 1/ha	N	0.6717E−04	10.1
Stamantal²	N²	−0.2864E−08	10.1
Granandel	GP	0.7204	15.5
Granandel²	GP²	−0.4879	24.8
Lövandel	LP	0.1062	184.8
Lövandel²	LP²	−0.2073	97.8
Konstant	C	2.5225	2.1

Multipel korrelationskoefficient	0.87
Spridning kring funktionen, s_f	0.15
s_f/spridning kring medeltalet, %	50.2
Antal observationer	532

Symbols for the variables used in the basal area function and mortality function.

T	*total age, years*
G	*basal area, m²/ha*
SI(G)	*site index, spruce. The variable is 0 if site index is based on pine*
SI(T)	*site index, pine. The variable is 0 if site index is based on spruce*
N	*number of stems/ha*
GP	*basal area of spruce/total basal area*
LP	*basal area of broadleaves/total basal area*
c	*constant*

Table 7.2 Mortality function. Symbols are explained in section 7.4

Materialgrupp: fasta försöksytor, orörda parceller /*Data set: unthinned permanent plots*
Beroende variabel: årlig andel av grundytan som självgallras /*Dependent variable: mortality as annual proportion of basal area*

Variabel *Variable*	Beteckning *Symbol*	Koefficient *Coefficient*	Formellt medelfel, % *Standard error, %*
1/(totalålder + 10)	1/(T + 10)	0.60949	46.4
1/(totalålder + 10)²	1/(T + 10)²	−12.5903	76.2
Grundyta m²/ha	G	0.3317E−03	42.6
ln grundyta	ln G	−0.01006	52.9
Ståndortsindex, gran, m	SI(G)	0.173E−03	60.8
Ståndortsindex, tall, m	SI(T)	0.156E−03	71.0
Granandel	GP	−0.0130	33.6
Granandel²	GP²	0.0119	39.1
Lövandel	LP	0.0189	40.1
Lövandel²	LP²	−0.0174	44.8
Konstant	C	0.0232	60.7

Multipel korrelationskoefficient	0.40
Spridning kring funktionen, s_f	0.0059
s_f/spridning kring medeltalet, %	92.7
Antal observationer	532

Den beroende variabelns medelvärde i materialet är 0.0079
/*Mean of the dependent variable in the data set is 0.0079*

2. The functions by Bengtsson (1978) were based on the NFI inventory of dead trees in the period 1973-1975. Dead trees with dbh>49 mm were classified according to the season when they died and trees that died in the last 3-year period were accounted. For technical reasons data was grouped before regression which limits the interval for application to mean dbh (D) 7-30 cm and stand age (A) 30-120 years. For D and A values outside the valid values the use of closest limit value is recommended. For pine in southern Sweden site productivity, expressed in m²sk per hectare and year (MAI) was included as an independent variable. Dependent variable is annual mortality in percent of standing volume.

Variable	Coefficients, northern Sweden			Coefficients, southern Sweden		
	pine	spruce	descidous	pine	spruce	descidous
constant	0,437	0,39	1,005	0,76	0,66	0,46
D	-0,0847	-0,061	-0,0843	-0,043	-0,013	-0,02
D²	0,00214	0,0016	0,00176			
A	0,0104	0,005	-0,000174	0,0047	0,0043	0,0046
A²	-0,0000317		0,0000591			
MAI				0,048		

The mortality level during the observed period was judged to have been higher than normal so at application the mortality given by the functions was reduced with 40 % in northern Sweden and 25 % in southern Sweden.

3. Fridman & Ståhl presented a mortality model with three steps:

Step 1. Predict probability of mortality on a plot during the next 5 yr period
Step 2. Predict proportion of basal area that die on plots with mortality
Step 3. Predict probability of mortality for trees of different species and size

The functions were based on data from the second and partly from the third observation period on the permanent NFI-plots, up to the 1998 inventory. Only trees with dbh> 99 mm were included. In Heureka only step3 functions are utilised. Estimated mortality as a function of diameter for different species is shown below.

The mortality of old trees is calculated as a function of their nearness to maximum age. The latter was expressed as a function of tree species and site index as described in the following document.

References:

Bengtsson, G. 1978. Beräkning av den naturliga avgången i avverkningsberäkningarna för 1973 års skogsutrednings slutbetänkande. I: Skog för framtid, SOU 1978:7, bilaga 6.

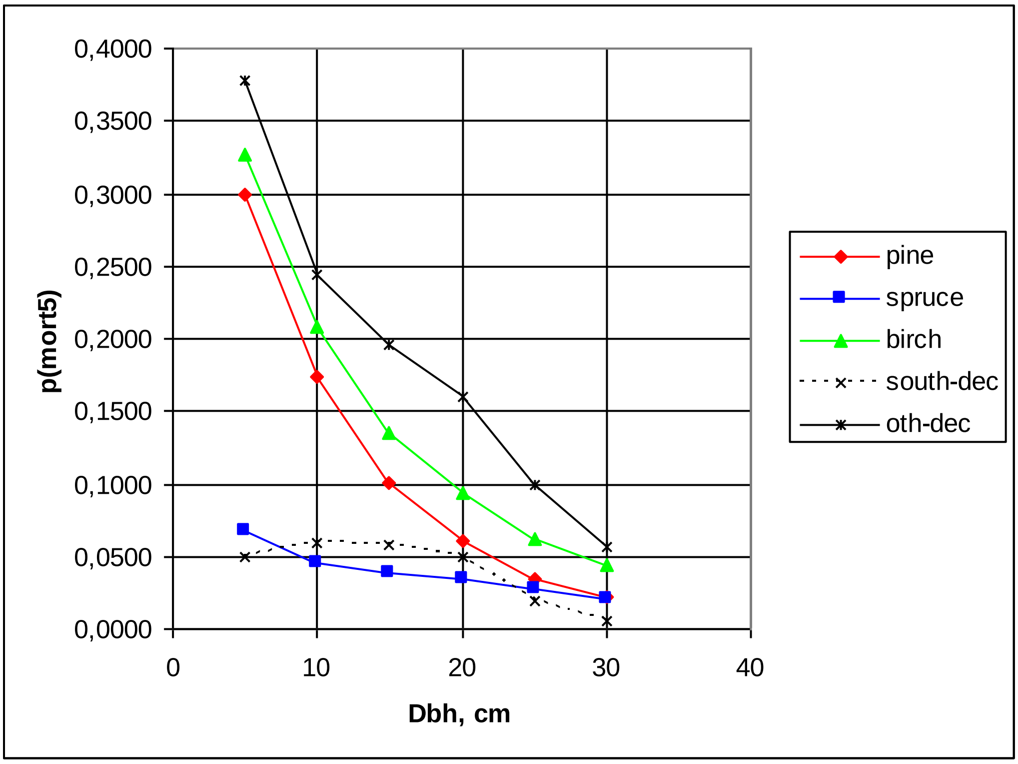
Fridman, J. & Ståhl, G. 2001. A three-step approach for modelling tree mortality in Swedish forests. Scan. J. For. Res. 16: 455-466.

Söderberg, U. 1986. Functions for forecasting timber yields. SLU, Section for forest mensuration and management, Report 14.

Distribution of mortality on species and tree sizes –an example

The step 3-functions of Fridman & Ståhl 2001 were applied with "average values" for most independent variables in order to study the partial relation with tree size. Selected fixed values were latitude=60 ºN, altitude=300 m a.s.l, pine-dominated stand with basal area 20 m²/ha and mean diameter 20 cm, normal diameter distribution, mesic site >20 m from stand borders, not newly thinned. The values of the variables latitude and altitude are too high for southern deciduous species but that does not matter since those variables were not included in the function.

At application mortality probabilities are calculated for all trees on a plot and the estimated total mortality is distributed according to those probabilities. Trees with dbh<10 cm were not represented in the basic data for the functions. Still those functions are applied also for smaller trees and the figure shows results of extrapolation downwards.



On the maximum size and age of trees

PM for Heureka 2008-11-14 by Björn Elfving

There are few trees in the data-set funding the growth functions that are very large and old. Also, the standard deviation for the growth measurement is very big for large trees so there is a risk for bias in prediction of their growth. The following study was performed in order to examine which maximum tree sizes and ages that are reasonable for different species and site types. Two sets of inventory data were used:

1. The basic data for the growth functions (first inventory of NFI permanent plots, Tab. 1)
2. The basic data for the functions for age determination (sample trees from temporary plots measured by NFI in the period 1992-2001, Tab. 3)

Table 1. Number of trees in different species- and diameter classes in the data-set tax83-87

Species	Number of trees in diameter classes of width 10 cm										Sum
	-10	-20	-30	-40	-50	-60	-70	-80	-90	-100	
Pine	1308	49050	22315	6287	788	48	2	1	-	-	79709
Spruce	2055	73953	22670	5178	754	90	10	-	-	-	104710
Birch	2316	21420	3368	506	53	5	-	-	-	-	27668
Aspen	20	1623	486	117	26	4	-	-	-	-	2276
Alder	4	700	166	22	1	1	-	-	-	-	894
Beech	5	635	400	279	132	29	6	1	-	2	1489
Oak	27	1237	522	205	89	31	13	1	4	2	2131
Oth-noble	6	364	130	46	7	4	1	1	-	-	559
Oth-trivial	47	4096	990	133	23	3	-	-	-	-	5292

Both inventories were restricted to productive forest land. The low number of trees in the smallest size class (4-10 cm, Tab. 1) depends on the fact that trees with dbh below 10 cm were measured on smaller plots than the larger trees. Otherwise the tree frequency decrease sharply with increasing diameter. The decrease is with high precision described by the function $\ln(n) = b0 + b1 \cdot \ln(d) + b2 \cdot d$.

The degree of explanation (r^2) was above 0.999 for pine, spruce, birch and aspen and above 0,99 for the other species. The random occurrence of some large trees disturbed the oak function. When the distribution is truncated at the diameter 70 cm r^2 is above 0.999 even for oak. Estimated functions were used to roughly estimate the occurrence of trees with dbh=87-97 cm in Sweden in the following way. At the country level each measured tree on the plots represents in average 38 000 trees. Due to lower sampling density in northern than in southern Sweden the weight varies in the interval 15 000 – 73 000 from south to north. The values at d=90 cm of the species-wise functions were multiplied with 38 000 for all species except oak and beech. Since those species only are growing in the south they should have lower weights. Selected values were 15 000 for beech and 26 000 for oak. Results are given in Tab. 2.

Table 2. Estimated occurrence of large trees (d=87-97 cm) of different species in Sweden

Trädslag	Tall	Gran	Björk	Asp	Al	Bok	Ek
Antal	2	359	12	106	18	858	22 719

Data in Tab. 2 are of course quite uncertain but they represent reasonable results from an objective and well specified examination. For pine there is a clear underestimation. The largest pine in Sweden is reported from the county Västergötland with a dbh of 148 cm (Skogen 1/06, p. 51). In the county Västerbotten at least four pines have been registered with dbh in the interval 87-97 cm and five pines that are thicker. Many thick trees grows on non-forest land and are for that reason not represented in the inventory data.

The data-set of age-determined sample trees comprised 46 054 trees, Tab. 3. Age is here defined as number of year-rings at breast height (1.3 m). The sample trees were selected on temporary plots in proportion to their basal area. This means that a larger proportion of the thick than of the thin trees were age-determined. Number of sample trees and highest age was registered in 8 classes of latitude and 8 classes of site index for each species. Then highest age (AMAX) was expressed as a function of latitude (LAT, ºN), site index according to site factors (SIS, m) and number of sample trees in the class (n) according to the following model:

$$\ln(AMAX) = b0 + b1 \cdot SIS + b2 \cdot \ln(n) + b3 \cdot \ln(LAT) \quad \text{(F1)}$$

Table 3. Some data on the species level in the data-set pt9201. b0-b2 are coefficients in F1

Species	No trees	Max-age	Max-diam	b0	b1	b2
Pine	19 369	360	76	5,1650	-0,04526	0,2007
Spruce	20 548	340	79	5,3823	-0,04884	0,1703
Birch	4 040	240	53	4,6246	-0,02192	0,1742
Aspen	387	137	53	-	-	-
Oak	412	211	67	-	-	-
Beech	233	162	63	-	-	-
Oth broadl.	711	136	66	-	-	-

The regression was only performed for the main species (pine, spruce and birch) and classes with n<20 were not included. The variable LAT was not significant and thus excluded from the model. With those functions (Tab. 3) the value of AMAX at n=10 000 was calculated for different SIS-classes, Fig. 1. For the species with fewer observations the registered AMAX in different SIS-classes were corrected according to the following expression: AMAX-corr = $\exp[\ln(AMAX) + 0.175 \cdot (\ln(10000)-\ln(n))]$ The figure 0.175 corresponds to an approximate average of the values of b2 in Tab. 3.

The results indicate that the differences in AMAX between species are relatively small and that site productivity (SIS) has a large impact on the maximum ages that trees can attain, Fig. 1. I practice pines grow older than spruces mainly because pines are growing on sites with lower SIS. The maximum age of birch was less sensitive to SIS than that of the conifers. The maximum ages of aspen were about 10 % lower than that of spruce. The maximum ages of beech and oak were approximately the same (340 year) and insensitive to SIS. Oak is known to be able to reach very high ages (around 1000) but that is not expressed in this study. The highest registered age for oak was 211 years (Tab. 3). For other descidous species the tren over SIS was opposite that of the other species., depending on shifts in species composition over the age-scale. The function for this group is: AMAX = $98 + 6 \cdot SIS$ (not shown in Fig. 1).

In Heureka the AMAX-values in Fig. 1 are used as target values. The model used in the Finnish MELA/MOTTI-system to estimate mortality due to ageing (Hynynen et al 2002) is also used here:

$p = 1/(1 + \exp(10 - 12 \cdot A/AMAX))$, where p is the probability that a tree has died by age weakening at age A. The proportion estimated to die in the next 5-year period is:

$p(m5) = [p(A+5) - p(A)] / [1 - p(A)]$

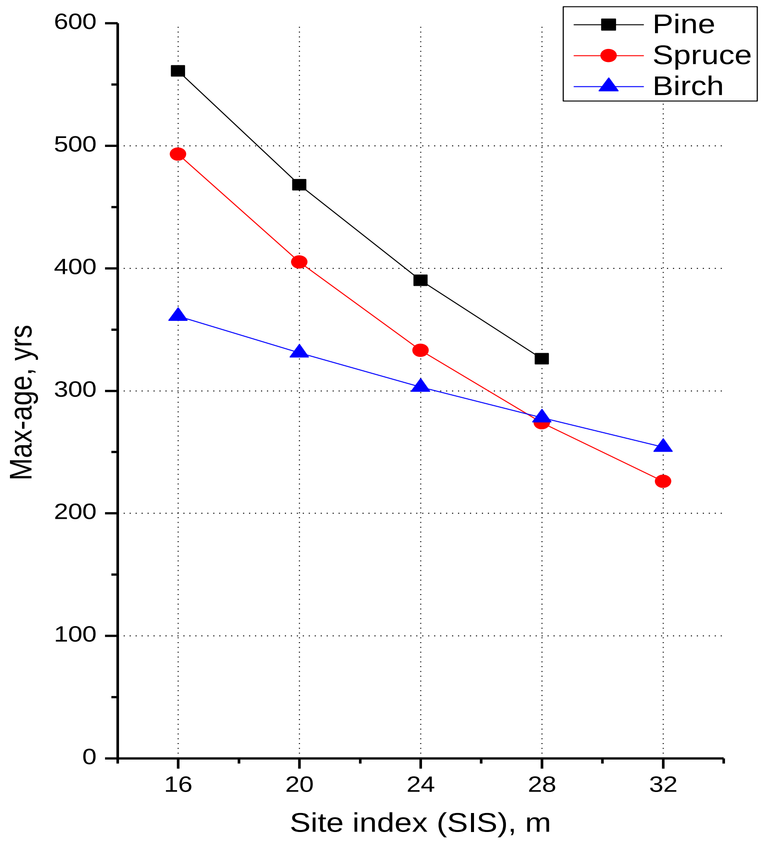


Figure 1. Estimated max-ages for pine, spruce and birch on sites with different site index

An example:

For a pine with A=300 on a site with SIS=20 the probability that it will die in the coming 5-year period is estimated as follows:

$AMAX = \exp[5.1650 - 0.04526 \cdot 20 + 0.2007 \cdot \ln(10000)] = 449.58$

$P(300) = 1 / [1 + \exp(10 - 12 \cdot 300/449.58)] = 0.11999$

$P(305) = 1 / [1 + \exp(10 - 12 \cdot 305/449.58)] = 0.13481$

$P(m5) = (0.13481 - 0.11999) / (1 - 0.11999) = 0.01684$

Reference

Hynynen, J., Ojansuu, R., Hökkä, H., Siipilehto, J., Salminen, H. &Haapala, P. 2002. Models for predicting stand development in MELA System. METLA Research Paper 835, p 50-

Appendix 12

Algorithm for distribution of thinning on species and diameter classes

PM for Heureka 2009-03-04 by Björn Elfving

The algorithm for distribution of thinning is imported from the Hugin system. The distribution of thinning is specified as proportion of basal area in different species- and size classes. In a first step the differentiation between broadleaved trees (B) and conifers (C) is specified:

$th\%(B) = th\%(A) + b \cdot C\%$
$th\%(C) = th\%(A) - b \cdot B\%$

th%(A) is the thinning proportion of total basal area, %
th%(B) is the thinning proportion of broadleaves basal area, %
th%(C) is the thinning proportion of conifers basal area, %
B% is the basal area of broadleaves in proportion of total basal area, %
C% is the basal area of conifers in proportion of total basal area, %
b is a coefficient for differentiation of the thinning on species groups, defined in the interval $-1<b<1$, with positive values leading to stronger thinning of broadleaves and vice versa. The maximum and minimum value of b (blim) represents the largest possible differentiations: thinning cannot exceed 100 % or be below 0 %.
If b is positive then blim1=[100-th%(A)]/C% and blim2=th%(A)/B%.
If b is negative then blim1=th%(A)/C% and blim2=[100-th%(A)]/B%.
If the absolute value of the preset b is larger than blim then it should be replaced by blim.

Example: assume that th%(A) = 40, B% = 20 and b=0,5.
Then blim1=60/80=0.75 and blim2=40/20=2.0.
Since both limit values are above preset b then:
$th\%(B) = 40+0{,}5 \cdot 80 = 80$ and $th\%(C) = 40-0{,}5 \cdot 20 = 30$

Thinning distribution on pine (P) and spruce (S) can be differentiated accordingly.
$th\%(P) = th\%(C) + b \cdot S\%$
$th\%(S) = th\%(C) - b \cdot P\%$
th%(P) is thinning proportion of pine basal area, %
th%(S) is thinning proportion of spruce basal area, %
P% is the basal area of pine in proportion of conifer basal area
S% is the basal area of spruce in proportion of conifer basal area
b is the differentiation coefficient

Size distribution is characterised by 4 relative diameter classes, defined by the diameter of the smallest tree (dmin), basal area mean diameter (dg) and diameter of the largest tree (dmax) as follows, where ul stands for upper limit:

Class	1	2	3	4
Lower limit	dmin	ul1	ul2	ul3
Upper limit	dg/2 *	dg	(dg+dmax)/2	dmax

* if $dmax<2 \cdot dg$: $(3 \cdot dg-dmax)/2$

Differentiation parameters are specified in the same dichotomy way as for species, first between the classes small (<dg) and large (>dg) and then between the classes small within small (1) - large within small (2) and small within large (3) – large within large (4).

Example: a species-mixed stand with 87 % pine and 13 % birch is thinned 35 % with all differentiation factors = 0.2. Proportions of total basal area in different species- and relative size classes are:

Species	Size class				
	1	2	3	4	sum
pine	0.005	0.132	0.435	0.296	0.868
birch	0.030	0.063	0.039	0.000	0.132

Calculations:

th%(birch) = 0.35 + 0.2·0.868 = 0.524 (blim1=0.65/0.868=0.749)
th%(pine) = 0.35 - 0.2·0.132 = 0.324 (blim2=0.35/0.132=2.652)

th%(small birch) = 0.524 + 0.2·0.039/0.132 = 0.583
th%(large birch) = 0.524 - 0.2·0.093/0.132 = 0.383

th%(small pine) = 0.324 + 0.2·0.731/0.868 = 0.492
th%(large pine) = 0.324 - 0.2·0.137/0.868 = 0.294

th%(small of small birch) = 0.583 + 0.2·0.063/0.093 = **0.718**
th%(large of small birch) = 0.583 - 0.2·0.030/0.093 = **0.518**
th%(small of large birch) = 0.**383**

th%(small of small pine) = 0.492 + 0.2·0.132/0.137 = **0.685**
th%(large of small pine) = 0.492 - 0.2·0.005/0.137 = **0.485**
th%(small of large pine) = 0.294 + 0.2·0.296/0.731 =**0.375**
th%(large of large pine) = 0.294 - 0.2·0.435/0.731 = **0.175**

Figures in bold gives the thinning proportions in different classes, leading to a total thinning proportion of 35 %.

This way to specify thinning works well but it is hard to know how chosen differentiation coefficients work in different populations and how realistic they are. Empirical studies are needed to guide the selection of coefficients. As a guide for distribution on diameter classes the following figures can help. Thinning quotient qth = dg(thinned) / dg(remaining).

b	qth(normal dbh-distribution)	qth(j-shaped dbh-distribution)
0.1	0.947	0.933
0.2	0.899	0.873
0.3	0.855	0.819
0.4	0.823	0.772
0.5	0.798	0.724
-0.2	1.121	1.170
-0.5	1.300	1.541

Appendix 13

Influence of thinning on stand basal area growth

PM for Heureka 2009-05-18 by Björn Elfving

In forest growth models height growth and basal area growth are generally estimated with separate functions. This is also how it is done in Heureka, and the basal area growth function for spruce has the following principal form. Other species are modelled accordingly with minor deviations.

iG = exp(b0 + b1*ln(age) + b2* 1/age + b3*ln(G) – b4*G + b5*N/(N+80) + b6*SIS + b7*path

In this expression b0–b7 are coefficients with values estimated by regression on data from permanent plots at the National Forest Inventory (NFI). The dependent variable iG is defined as 5 year basal area increment (m^2/ha). Age is total basal area-weighted mean age, G is basal area (m^2/ha), N is stem number (st/ha), SIS is site index according to site factors (m), and path is an indicator variable, indicating period after thinning. In practice, two different periods are distinguished: stands that were thinned within 10 years before the start of the period concerned (path0-10=1) and stands that were thinned 11-30 before (path11-30=1). The values of those variables are 0 for stands that not full-fill the criteria for thinning period. The result of the regression tells that thinned stands are expected to grow 14 % more in the first 15 years after thinning and 6 % more in the following 15 years, compared to un-thinned stands with the same age, density and site conditions.

This is a crude way to describe influence of thinning on growth and depends on lack of detailed information on performed thinning in the NFI data. The aim of this report is to document a sharper model for prediction of the thinning response.

When a stand is thinned the space for remaining trees increases and they expand in order to utilize the increased amount of light and nutrients. This part of the growth increase after thinning is expressed by changes of the density expressions (N and G). After a uniform thinning with 50 % removal of both N and G the basic function (without indicators for thinning) express a relative growth increase for remaining trees from 50 % to 73.5 % of the growth before thinning, that is with 100*(73,5/50-1) = 47 %. (Fig. 1). After a thinning from below with the thinning quotient qth=0.8 the corresponding response is estimated at 43 % and after a thinning from above with qth = 1.2 it is estimated at 49 %. The thinning quotient is the quotient between basal area mean diameters of thinned and remaining trees.

Significant positive influences of the indicator variables for thinning response indicate that the response of remaining trees is even larger. The reasons for this larger effect can be increased nutrient release and availability after the disturbance caused by the thinning, increased priority for stem growth of slender trees that need to stabilize and removal of slow-growing trees.

In the presented calculation, age was assumed to be un-altered by the thinning. In uneven-aged stands a thinning from below increase the stand age and a thinning from above decrease it. In Heureka all trees are given an age so those age effects are also included in the growth predictions.

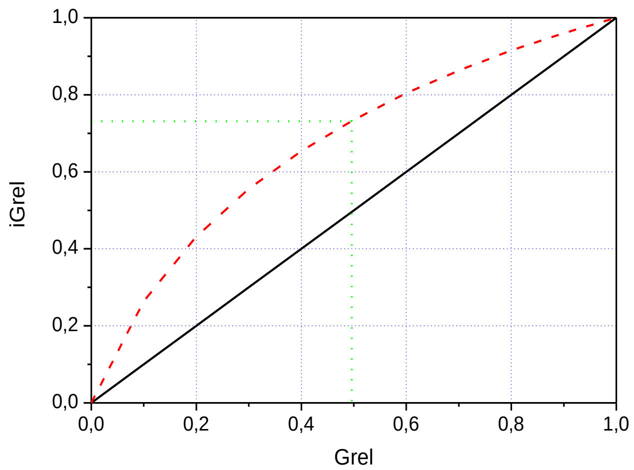


Figure 1. Thinning response – a principal diagram. In a closed stand (Grel=1) also the basal area growth is full (iGrel=1). If trees grew equal after thinning as before then iGrel should decrease in proportion to the reduction of Grel along the full drawn line. According to the basic growth function (except indicators for thinning) trees grow faster in more open stands as indicated by the dashed curve.

The Swedish GG-trials offer an ideal data source for a closer examination of the thinning response. The GG-trials comprise 23 blocks in spruce stands and 47 blocks in pine stands with an even distribution on different site types all over the country. They were established in the period 1966-1983 and have been followed during in average 30 years. Represented treatments are un-thinned control, moderate thinning from above and below, early and late first thinning, and heavy thinning from below with different frequency. Observed and predicted growth in three treatments are compared in Fig. 2-3. Predictions were made with the functions quoted above, without inclusion of the expression for thinning respons. For un-thinned stands there is a good agreement between observed and predicted growth. For the thinned stands there are big deviations related to the thinning respons.

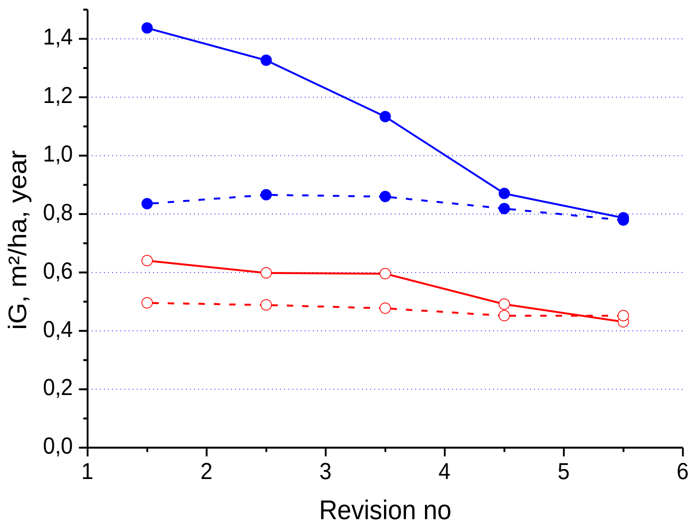


Figure 2. Basal area growth in the treatment ”one heavy thinning” of the GG-trials. Observed (full-drawn) and estimated (dashed) means for 6-year periods for spruce (blue) and pine (red).

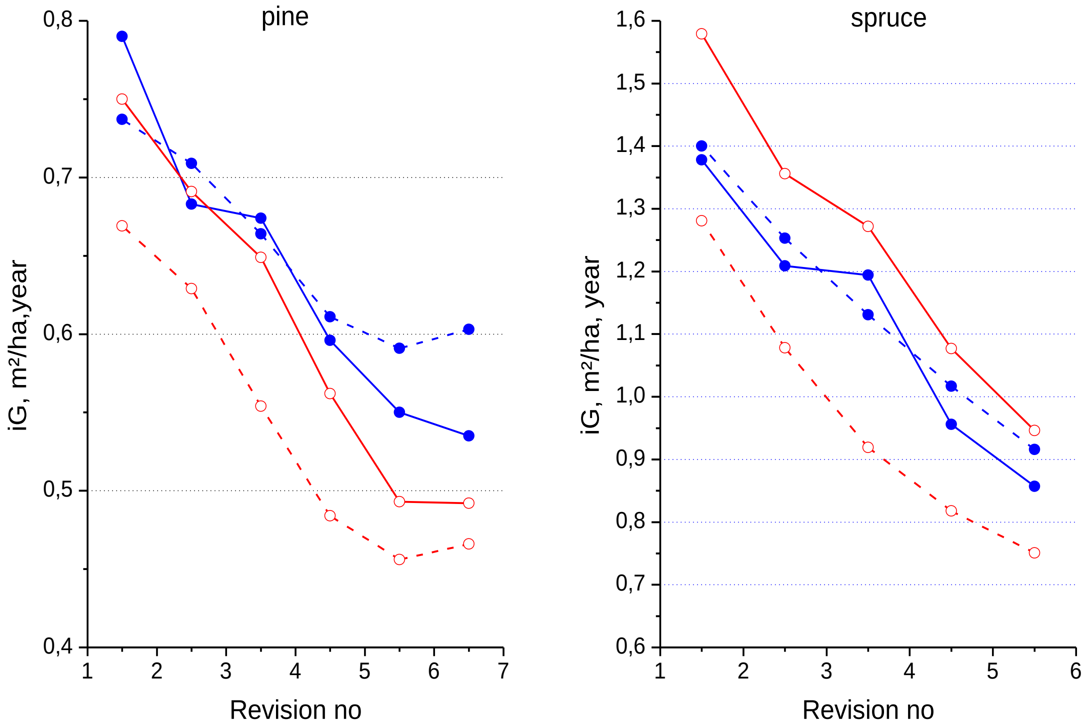


Figure 3. Basal area growth in the GG-trials in different observation periods in the treatments "un-thinned"(blue) and "standard thinning from below" (red). Observed (full-drawn) and estimated (dashed) means for 6-year periods.

The thinning response was expressed with functions in the following way. For each observation period on thinned plots the thinning response (THRESP) was expressed as:
THRESP = ln(iGobs) – ln(iGpred) + Cblock,
where iGobs is observed and iGpred is predicted basal area growth (by presented functions with path=0). Cblock is a block correction factor based on the difference between observed and predicted growth for the treatment "un-thinned": Cblock = ln(iGobs)-ln(iGpred)

The independent variables were proportion of basal area thinned at the last thinning (THPROP), time after thinning (TATH, number of years from last thinning to the midpoint of the actual growth period), and residual release effect after earlier thinning (RRE). The estimation of residual release effect was based on preliminary calculations indicating that initial thinning response was proportional to THPROP and decreased linearly during a 30-year period, that is RRE = sum[THPROP*(1-0.0333*TATH)} for thinning before the last one. Pine and spruce indicated different response patterns so separate functions were needed for those species. For pine there was a delay before full response was attained. This pattern was captured by the indicator variable newly thinned (NEWTH) with the value 1 if TATH<4, otherwise =0. The response after thinning with a given THPROP was also higher after thinning from above than after thinning from below. This was captured by the indicator variable thinning from above (THFA). For spruce those variables were insignificant. Coefficients of the final models (Table 1) were estimated with the SAS-procedure Mixed, with block number as random variable.

Table 1. Functions for thinning response, based on data from the GG-trials

Species	Variabel	Coefficient	std. dev.	t-value	p-value
pine	intercept	0,0585	0,0160	3,5	0,0010
	THPROP	0,4617	0,0325	14,2	<0,0001
	RRE	0,2843	0,0522	5,4	<0,0001
	THPROP*TATH	-0,01832	0,0014	13,7	<0,0001
	NEW	-0,0943	0,0104	9,1	<0,0001
	THFA	0,1172	0,0377	3,1	<0,0019
spruce	intercept	0,0589	0,0294	2,0	0,0582
	THPROP	0,8478	0,0547	15,5	<0,0001
	RRE	0,4821	0,0500	9,6	<0,0001
	THPROP*TATH	-0,0333	0,0024	13,9	<0,0001
Background data		no of obs.	dep. mean	sres	r^2adj
pine		958	0,144	0,129	0,398
spruce		498	0,275	0,147	0,556

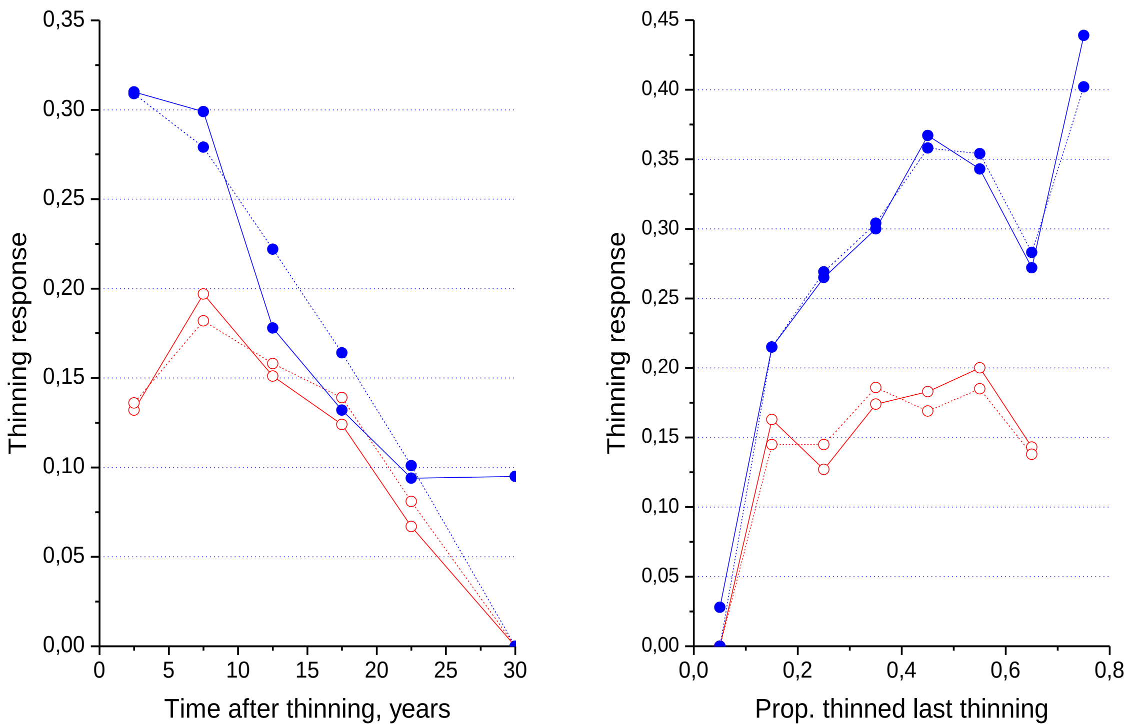


Figure 4. Observed (full-drawn) and estimated (dashed) thinning response in the GG-trials for pine (red, open circles) and spruce (blue, filled circles).

The partial relations over time after thinning and thinning proportion (Fig. 4) indicates fairly good agreement between observed and predicted values despite the relatively low degree of explanation (r^2adj). The large difference in response between pine and spruce may partly be due to differences in site fertility. The spruce plots were mainly located to fertile sites in southern Sweden. Residual studies over site index and field vegetation type did however not indicate any tendencies in this direction.

In contrast to this study the thinning response seems equal for pine and spruce in the NFI-data. The coefficients for the path-variables got the same values for pine-dominated as for spruce-dominated stands. Plausible causes could be that the thinning proportion in average is larger at thinning of pine than at thinning of spruce (less probable) and that the spruce stands more often are uneven-aged and that the influence of thinning on the stand age catches some of the thinning response (more probable). On the other hand, in a study of growth response on the single tree level after strong cutting it was found that pine and spruce growing in the same stands had a quite similar response, Fig. 5.

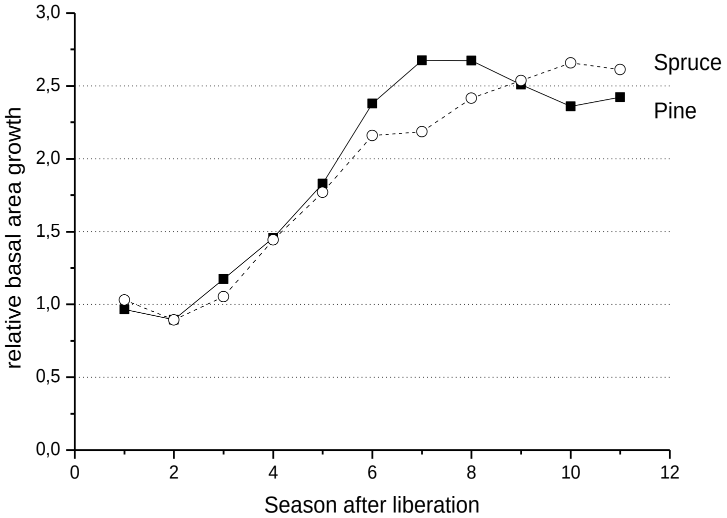


Figure 5. Thinning response on the tree level after heavy thinning from above. Averages for about 100 trees per species on 8 different sites. After Ågren, D. 2005. SLU, Dept. of Silviculture, Master thesis 2005-15.

The thinning response functions are applied for even-aged stands in Heureka. The values calculated with the functions in Table 1 shall replace the path-values in the initial basal area growth functions. The spruce function is used if the spruce proportion of basal area is > 50 %, otherwise the pine function is applied. When the estimated value is <0 it must be set to 0. For uneven-aged stands no direct expression for thinning response is applied. Those stands are generally thinned from above and the decrease of stand age will increase predicted growth. So far this effect seems to be proper, but this must be examined further with new data.

The influences of thinning on height growth and stem form development have not been separately handled in Heureka. A study of top height development in the GG-trials (Elfving in prep) showed that thinning from below did not influence top height growth for spruce. For pine height growth was clearly retarded in proportion to the thinning proportion, lasting for a period of 5-15 years. After that height growth in thinned stands exceeded that in un-thinned stands and tended to regain the loss. A thinning effect is also built into the site index/height growth functions for pine, since most stands in the basic data for those functions were thinned. For the volume estimations also the stem form changes should be taken into account. My judgement is that those influences on the growth estimation in the Heureka system are relatively small.

Appendix 14

Growth effects of whole-tree harvesting

PM for Heureka 2008-09-22 by Björn Elfving

At thinning and final felling tree tops, branches and small trees (GROT) are harvested to increasing extent as a profitable assortment for energy production. After conventional harvesting of stem-wood above least profitable diameter GROT is left on the site and the soil is supplied with this organic substrate that successively breaks down and release nutrients. The harvesting of GROT can thus be expected to decrease the site productivity.

Experimental studies (Egnell & Leijon 1999, Jacobsson et al 2000) have shown that growth after GROT-harvesting is reduced by 5-6 % during a 10-year period in thinned stands and by up to 17 % in the first 15 years after clear-cut. When needles were left on the clear-cut no growth loss was found. In the latter case the survival of planted seedlings was increased by GROT-harvesting, despite careful scarification and planting even where GROT was left. In practice the scarification and planting are facilitated after GROT-harvesting so the positive effects on resulting regeneration density could be expected to be even larger. Sinclair et al (1992) interpreted the long-term effect of GROT harvesting at final felling as a retardation of the start of the new stand by 1-4 years.

GROT-harvesting at thinning is so far not practiced to any larger extent but it is expected to increase when the demand for bio-energy increase. Cutting of un-limbed tree-parts is of special interest at thinning of dense stands with small trees and of stands with poor quality for saw-timber.

In GROT-harvesting at final felling the practical recovery has been found to be about 70 % of the total GROT amount (Rudolphi & Gustafsson 2000). Needles were not included in the study and it is probable that the recovery of needles is lower than that of the other GROT components. The authors also stated that GROT harvesting decreased the amount of remaining trees and dead wood. The extent of hauling damages on the soil increased due to increased transportation quantity and decreased arming of the strip roads. According to official statistics (Skogsstyrelsen 2005) GROT was harvested on about 30 % of the clear-felled area in 2004. The potential maximum utilization is judged to be 80 % of the annual cutting area (Jacobsson 2005).

For Heureka the effects of GROT harvesting are specified as follows:
GROT harvesting at thinning induce a 5 % reduction of basal area growth in the three following growth periods
GROT harvesting at final felling prolong the time for stand establishment with one year, leading to a long-term growth reduction with about 1 %.

References

Egnell, G. & Leijon, B. 1999. Survival and growth of planted seedlings of Pinus sylvestris and Picea abies after different levels of biomass removal in clear-felling. Scand. J. For. Res. 14: 303-311.

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Rudolphi, J. & Gustafsson, L. 2005. Effects of forest-fuel harvesting on the amount of deadwood on clearcuts. Scand. J. For. Res. 20: 235-242.

Sinclair, E., Leijon, B. & Albrektson, A. 1992. Plantöverlevnad och tillväxt efter helträdsutnyttjande – sammanställning av fälförsök. Vattenfall, Utveckling & Miljö, Bioenergi. Projektrapport 1992-7.

Appendix 15

Growth response to nitrogen fertilisation

PM 2009-10-26 by Björn Elfving

Functions expressing the response (increased volume growth) to nitrogen fertilisation were presented by Pettersson (1994 a, b). In a first step the response in the five-year period after fertilisation is calculated and in a second step the total growth response of one application. The total response period varied between 6 and 12 years, depending on species and site index.

Step 1. The function was based on data from 961 plots on 230 experimental sites in stands dominated by pine or spruce.

$$
\begin{aligned}
iV5 = 10\text{^}(&- 5.1130 + 0.1191\cdot LAT{>}61 + 0.0586\cdot LAT5861 + 1.7192\cdot \log(ALT+100) \\
&- 0.000030\cdot LAT\cdot ALT - 0.2155\cdot \log(LAT\cdot ALT) + 0.0106\cdot SIH - 0.0518\cdot PCAI \\
&+ 0.7810\cdot \log(PCAI) + 0.3063\cdot \log(SCAI) + 1.3353\cdot \log(Nan) - 0.00009\cdot Nan\cdot SIH \\
&+ 1.2261\cdot Nur - 0.000057\cdot Nur\cdot SIH)\ ;\ \ n = 961\ ;\ sres = 3.54\ ;\ r^2 = 0.45\ ;
\end{aligned}
$$

iV5 = increased volume growth in the first 5-year period after fertilisation, that is growth in treated minus growth in un-treated stand, m^3 per hectare.
ALT = altitude, m above see level, varies in data in the interval 5-625.
LAT = latitude, degrees north, varies in data in the interval 56-67.
LAT>61 = index variable with value 1 at LAT>61, otherwise 0.
LAT5861 = index variable with value 1 if LAT is in the interval 58-61, otherwise 0.
SIH = site index according to site curves from measured age and top height, m.
PCAI = pine current annual volume increment excluding the fertilisation effect, $m^3\cdot yr^{-1}\cdot ha^{-1}$.
SCAI = spruce "
Nan = amount of nitrogen applied as ammonium-nitrate, kg per hectare.
Nur = amount of nitrogen applied as urea, kg per hectare.

Step 2. The function was based on data from 301 plots in 117 experimental sites in stands dominated by pine or spruce.

$$
\begin{aligned}
iVtot = 10\text{^}(&- 0.1158 + 0.9735\cdot \log(iV5) + 0.01954\cdot (LAT-54) + 0.004166\cdot (ALT+100) \\
&- 0.3597\cdot \log(ALT+100) - 0.000057\cdot LAT\cdot ALT - 0.005493\cdot SIH - 0.1055\cdot PINE \\
&+ 0.3140\cdot \log(Ntot)\ ;\ \ n = 301\ ;\ sres = 2.80\ ;\ r^2 = 0.88\ ;
\end{aligned}
$$

iVtot = total increased volume growth after a single fertilisation, m^3 per hectare
iV5, KALT, LAT, SIH: see step 1.
PINE = index variable with value 1 if the stand is pine-dominated, otherwise 0.
Ntot = total amount of applied nitrogen, irrespective of fertiliser, kg per hectare.

References

Pettersson, F. 1994a. Predictive functions for impact of nitrogen fertilization on growth over five years. Skogforsk, Report 3.

Pettersson, F. 1994b. Predictive functions for calculating the total response in growth to nitrogen fertilization, duration and distribution over time. Skogforsk, Report 4.

Appendix 16

Incidence of rot in spruce and its influence on the wood value

PM for Heureka 16/10/2009 by Björn Elfving

Thor et al (2005) presented functions for estimation of rot incidence in spruce in Sweden, based on data from breast height increment cores gathered from 45 587 trees by the National Forest Inventory (NFI) in the period 1983-2001. Functions were developed both for whole Sweden except the north-western part (region 1) and separate for southern and northern Sweden except region 1. The reasons for exclusion of region 1 were that data was scarce and that the rot in this region is mainly caused by other fungi than in other parts of Sweden.

The estimated probability for decay at breast height (p(dc13)) was correlated to rot observations on 7893 stumps, gathered by NFI in the period 1993-2002. In this way the probability for decay at stump height (p(dcst) could be estimated. The function for whole Sweden got the following form:

p(dcst)=2.037*p(dc13) = 2.037*[exp(z)/(1+exp(z)], where
z = -31.839 – 0,3741*age + 5.792*ln(age) + 0.05725*age*ln(age) + 0.01553*sis + 0.3348*(1-tsn) – 0.3099*alt>99 – 0.06151*dbh + 3.3909*ln(dbh) + 0.007669*dbh*ln(dbh) – 0.2683*moisture + 0.1510*(1-sand) + 0.1370*ln(sprucepart*10+0.1) ; (f1)

age is total stand age ; sis is site index according to site factors, m at age 100 ; tsn=1 if 800< temp.sum<1099, otherwise=0 ; alt>99=1 if altidude>99 m, otherwise=0 ; dbh is tree diameter at breast height, mm ; moisture: dry=1, mesic=2, mesic-moist=3, moist=4, wet=5; sand=1 if soil texture is sandy-silty till/sand, otherwise=0 ; sprucepart is spruce proportion of basal area.

Sjöberg (1994) studied the rot frequency also in region 1 on NFI breast height cores and found it marginally larger than average in other parts of the country. In the light of this, extrapolation of the function given above to region 1 seems to give reasonable values.

Predicted p(dcst) is 0.275 with lat=60, alt=50, age=80, sis=26, dbh=200, moisture=2, sand=0, sprucepart=1. This can be compared to the values reported by Tamminen (1985) and Piri et al (1990) for southern Finland. Tamminen examined 29 900 spruce stumps in 146 clear-cuts of which 18.5 % had rot. The rot frequency was higher along the southern coast (around Helsinki) than further to the north. Piri et al. examined 12 102 spruce stumps in 34 clear-cuts along the southern coast of which 27.6 % had rot.

Norokorpi (1979) examined 9 old spruce stands in northern Finland (age>150 years). Of 6275 felled trees 30 % were decayed by rot. Most trees (27 %) had rot at the stump level, only 5 % had stem rot developed from wounds higher up in the stem. In total 4.9 % of the volume was affected by rot.

In a Norwegian study Huse & Solheim (1994) reported a rot frequency of 26.8 % for 271 023 spruce stumps measured in 4914 clear-cuts all aver the country. The rot frequency was lower in western and northern parts than in other parts of the country. 3.8 % of the bottom logs were wrecked and 23 % of the logs with timber dimensions were classified as pulpwood instead of saw timber due to rot.

Tamminen (1985) expressed the loss of timber volume (sawloss, %) as a function of mean diameter of cut trees (dg, cm) and volume proportion of decayed trees (vp, %, volume of decayed trees as proportion of the total volume). The function has the following form:
Sawloss = vp*[0.682 – 0.01577*dg + 0.04375*vp^0.5] (f2)

In Heureka functions f1 and f2 are combined to estimate the value loss due to rot in spruce.

The practiced way to include the rot effect in Heureka is crude. Root rot (*Heterobasidion annosum*) is the main cause for rot in most parts of Sweden except region 1. This rot infects fresh stumps after summer-cutting of spruce and can spread via root contacts from infected stumps in both prevailing and preceding stand. Infection can be counteracted by stump treatment and around the year 2000 about half of the summer-thinned spruce area was treated (Samuelsson & Örlander 2001) so the incidence of rot can probably be lowered in the future.

References

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Appendix 17

Formation and handling of shelters and seed tree stands

PM for Heureka 2008-09-22

According to a proposal by Albrektsson et al (2008) a shelter is defined as a stand thinned to a volume level between the 10§5-curve and the 5§1-curve in the diagram for stocking levels (volume over mean height) in the Forestry Act. Those curves corresponds approximately to the stocking levels 0.5 and 0.3. If the stocking of the remaining stand is below 0.3 it is defined as a seed tree stand if it has been cut from below and a residual stand if it has been cut from above. This paper concentrates on formation of shelters and seed tree stands aiming at regeneration in connection to the final felling. The role of a shelter can be seed production, frost protection, drainage, moderation of field vegetation and invasion of broadleaves, and promotion of environmental values.

In Heureka the following specifications are applied as default for natural regeneration of pine and spruce. Natural regeneration of pine can only be applied if the number of pines per hectare in the main stand is >100 before cut. A shelter is formed by thinning from below to a basal area (m^2/ha) corresponding to 0.4*hgv, where hgv is the stand mean height before cutting (m). A seed tree stand is formed accordingly by thinning to the basal area 0.25*hgv. The shelter and seed trees are cut after 5 years. Natural regeneration of spruce can only be applied for pure spruce stands (>85 % spruce) on fertile sites (field vegetation code <6, SIS>20). The shelter is formed in the same way as for pine. The shelter trees are cut after 10 years. The proportion of trees blown down (and lost) are 12 % after 5 years and 18 % after 10 years, cf. enclosed appendix.

Reference

Albrektson, A., Elfving, B., Lundqvist, L. & Valinger, E. 2008. Skogsskötselns grunder och samband. Skogsstyrelsen, Skogsskötselserien nr 1. Web-dokument på: http://www.skogsstyrelsen.se/episerver4/templates/SNormalPage.aspx?id=36530

Appendix: On the mortality of shelter trees

On the mortality of shelter trees

This appendix summarises some studies on the mortality in shelters in order to estimate the normal mortality level for Heureka.

According to the National Forest Inventory the annual natural mortality of the standing volume is 0.25 % (Skogsdata 2000). Other data indicate that the mortality in closed forests is considerably higher. Analysis of the mortality in Finnish and Swedish thinning experiments (Mäkinen & Isomäki 2004, Elfving 2008) indicates mortality levels of 0.3-0.9 % depending on stand height and density. The normal mortality level in stands ready for final cutting can on basis of this be estimated at 0.6 % for pine and 0.9 % for spruce, expressed as annual mortality of the stem number.

The mortality increases after shelter formation as shown by the following studies.

Hagner (1962) examined the wind-through in 129 pine shelters in middle North Sweden at the end of the 1950th. The study was performed in average 3.5 years after the shelter formation. The number of wind-thrown trees per hectare was estimated at 2.5, corresponding to about 2 % of the stem number.

Andersson & Fries (1979) reported 8 % wind-thrown trees 12 years after shelter cutting in a trial at Siljansfors Research Forest.

Hånell & Ottosson (1994) examined 9 experimental spruce shelters á two densities on fertile peatland and reported 40 % wind-thrown trees after 6 years.

Örlander (1995) reported the wind-throw in 25 shelters in Småland to in average 20 % after 5 years and 27 % after 10 years. Similar results were reported from a shelter experiment at the Asa Research Forest.

Sikström (1997) examined 52 spruce shelters in middle and south Sweden in average 4.5 years after shelter formation and estimated the mortality of shelter trees at in average 15 %.

Huggard et al (1999) performed an extensive cutting trial in Canada and found that a 30 %-thinning doubled the mortality in the first 3 years compared to un-thinned stand, from 0.45 to about 1 % per years of the stem number.

Sikström & Pettersson (2005) examined 27 spruce shelters in middle Sweden and found that 7 % of the volume had blown down and 3 % had dried after 5 years. In total, the mortality of the stem number was 12 %.

Nilsson et al (2006) studied spruce planting in clear-cut and shelter on 22 sites all over the country. The shelters were mainly formed by pine. In 6 years 11 % of the shelter trees blew down.

Elfving (2006) examined a spruce shelter in Jämtland 10 years after formation and found that 12 % of the trees had blown down or dried.

Tjernell (2007) examined an experiment in Medelpad with spruce shelters of different density and formed by dominant or co-dominant trees. The average mortality was 24 % in the first 5 years and 32 % after 13 years. It was significantly higher in shelters formed by co-dominant trees. In shelters formed by dominant trees the mortality was 5 % after 5 years and 12 % after 13 years.

Lundqvist et al (2007) reported the development in a 10-year period after thinning with different form and strength in two uneven-aged spruce stands in Jämtland and Norrbotten. Total mortality of the stem number after 10 years was 6 % in un-thinned stands and increased with increasing thinning strength to 13 % in the strongest thinning.

The average mortality level varies strongly between the different studies. The low mortality reported by Hagner is probably due to low stand densities before shelter formation and low wind speeds during the observation period. The high mortality in the study by Hånell & Ottosson might depend on high stand densities before shelter formation, weak anchorage in the peat for shelter trees and the fact that shelter trees (as reported) were selected among co-dominant trees. The study by Tjernell showed that dominant trees are more stable.

For spruce shelters the studies by Sikström are most significant. They report a mortality level of 12-15 % in the first 5-year period. For pine shelters, the studies by Örlander and Nilsson et al are judged to be most significant. They indicate mortality levels of 11-20 % in the first 5-6 years after shelter formation. Based on this the average mortality in the first 5-year period is assumed to be 12 %. Available data give no reason to differentiate the mortality on species or parts of the country. Some studies indicate that the mortality in the second 5-year period after shelter formation is about half of that in the first period. Thus the mortality after 10 years is estimated at 18 %. If the shelter period is prolonged the mortality in the following periods is assumed to be the same as in un-thinned stands.

In the given review only mean figures are reported. The variation in time and space is of course large. The distribution of stands on mortality proportion is “J-shaped” with a larger proportion of stands with low mortality and a smaller proportion of stands with very high mortality. The gain by applying a stochastic model is however assumed to be small. Things that could be affected are degree and costs for harvesting of blow-down trees, the need for complementary regeneration measures and the growth of remaining trees. All those effects can be considered in over-arching specifications.

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Appendix 18

Influence of retained trees on growth of the new stand

PM for Heureka 2009-05-14 by Björn Elfving

Retained trees on clear-cuts compete with the new seedlings growing up in their neighbourhood. Elfving & Jacobsson (2006) constructed the following function on basis of data from 60 retained trees with surrounding seedlings on 25 sites in the whole country:

$$Vrel=0,1725+0,8275\cdot[1-\exp\{(-0,0883-0,0189\cdot SFI)\cdot DIST^2\}]$$

Vrel express the volume in the new tree generation at distance DIST (m) from the retained tree in proportion to the volume in undisturbed stand. SFI stands for site fertility index and is a coverage-weighted mean of species-specific index values of indicator species in the field vegetation more than 7 m from the retained tree as follows:

Species	herbs	grasses	bilberry	cowberry	heather	lichens
Index value	8	4	1	-1	-4	-8

For average pine sites SFI is close to 0 and it varies between 4 and -4 in the basic data. The area occupied by the retained tree is estimated as the integrated value of $\pi\cdot(1\text{-}Vrel)\cdot DIST^2$ and gives the following values at different site fertilities:

SFI	4	2	0	-2	-4
Area occupied, m²	15,9	20,6	29,5	51,5	205

Thus the growth reduction with 10 remnant trees per ha on sites with SFI=0 is $10\cdot 29,5/10000=0,0295$ or 2,95 %.

For practical application in Heureka, SFI is translated to the field vegetation code VEG as: SFI=VEG+1, and the growth reduction RED (%) with N remnant trees per hectare can be estimated as $RED=0,01\cdot N\cdot\exp[4,8647+0,4582\cdot 1/(VEG+6)-0,9782\cdot(VEG+6)]$

Reference: Elfving, B. & Jakobsson, R. 2006. Effects of retained trees on tree growth and field vegetation in *Pinus sylvestris* stands in Sweden. Scand. J. For. Res. 21(Suppl 7): 29-36.

Appendix 19

Influence of a changing climate on stand development

In Heureka the effect of global warming on forest growth can be accounted for based on results from the process-based model BIOMASS (cf. Zheng et al 2002). This model is computationally demanding and not suitable to directly include in Heureka's growth simulator. Instead, BIOMASS was used by Michael Freeman to compute growth correction factors (a,b,c, available from a table) for different climate scenarios, locations, soil moisture conditions and tree species. A primary growth correction factor was calculated as:

$$Cp = a + b \cdot \exp(-c \cdot LAI)$$

where LAI =leaf area index, calculated from leaf biomass according to biomass functions for the actual stand. The primary correction concerns optimal conditions and it is modified with regard to site fertility, as expressed by a field vegetation index.

The adjusted growth correction factor is multiplied with the estimated 5-year growth without global warming. Then the growth period is prolonged until the corrected growth has been obtained. The stand conditions at the end of the prolonged period form the starting point for the next 5-year growth period. Thus two age scales are used: the biological age following the faster ageing of the stand due to climate change and the actual age following the calendar.

Other temperature-related independent variables in the growth functions are also successively updated: temperature sum, field vegetation index (VIX) and site index according to site factors (SIS). The wide amplitude of climate conditions in Sweden (temperature sums from below 500 at the alpine timber line to over 1600 in the south) made is feasible to make functions expressing VIX and SIS as functions of temperature sum.

Reference

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Appendix 20

Volume and biomass functions for single trees

PM for Heureka 2004-01-20 by Björn Elfving

Volume estimation

For pine, spruce and birch the volume functions by Brandel (1990) are used (function group 100). Form: $v = 10^\wedge(b0 + b1\cdot\log(d) + b2\cdot\log(d+20) + b3\cdot\log(h) + b4\cdot\log(h-1.3)$

v =volume (dm^3) for stem-wood including bark above stump; d = dbh with bark, cm ; h = height, meter ; log = 10-logarithm. There are different functions for northern and southern Sweden (north = latitude> 60 ºN except the parts of Uppland and Västmanland north of 60 ºN.

Species	country part	constant	log(d)	log(d+20)	log(h)	log(h-1.3)
pine	south	-1,38903	1,84493	0,06563	2,02122	-1,01095
pine	north	-1,20914	1,94740	-0,05947	1,40958	-0,45810
spruce	south	-1,02039	2,00128	-0,47473	2,87138	-1,61803
spruce	north	-0,79783	2,07157	-0,73882	3,16332	-1,82622
birch	south	-0,89359	2,27954	-1,18672	7,07362	-5,45175
birch	north	-0,44224	2,47580	-1,40854	5,16863	-3,77147

Function for aspen according to Eriksson (1973):

$v = 0.01548\cdot d^2 + 0.03255\cdot d^2\cdot h – 0.000047\cdot d^2\cdot h^2 - 0.01333\cdot d\cdot h + 0.004859\cdot d\cdot h^2$

Function for beech (and hornbeam) according to Matérn (1975):

$v = 0.01275\cdot d^2\cdot h + 0.12368\cdot d^2 + 0.0004701\cdot d^2\cdot h^2 + 0.00622\cdot d\cdot h^2$

Function for oak (and ash and elm) according to Matérn (1975):

$h\geq 10$ m: $v = 0.03522\cdot d^2\cdot h + 0.08772\cdot d\cdot h – 0.04905\cdot d^2$

$h<10$ m: $v =$ ” $+ (1 - h/10)^2 \cdot(0.01682\cdot d^2\cdot h + 0.01108\cdot d\cdot h – 0.02167\cdot d\cdot h^2 + 0.04905\cdot d^2)$

For other broadleaved tree species the function for birch is used.

Function for larch according to Carbonnier (1954):

$v = 0.04801\cdot d^2\cdot h + 0.08886\cdot d^2 - 0.01012\cdot d^3 - 0.08406\cdot d\cdot h + 0.1972\cdot h$

Function for lodgepole pine according to Eriksson (1973), updated by Elfving (1985):

$v = 0.98\cdot(0.1121\cdot d^2 + 0.02870\cdot d^2\cdot h – 0.000061\cdot d^2\cdot h^2 - 0.09176\cdot d\cdot h + 0.01249\cdot d\cdot h^2)$

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Biomass estimation

Different biomass functions are used for young stands (mean height < 7 m) and established stands. The functions for young stands were presented by Claesson et al 2001. They were based on data from 193 trees in six dense stands in northern Sweden. Species distribution pine-spruce-birch was 44-22-34 %. For each species group functions were elaborated for the dry biomass of stem-wood, stem-bark, living branches, foliage and dead branches. The functional form was: ln(dry weight) = f (dbh, h). The estimation method was mixed linear regression.

For established stands the biomass is calculated with functions presented by Petersson (1999, above-stump components) and Petersson & Ståhl (2006, stumps and roots). Petersson (1999) used data gathered by Marklund 1983-1985 in whole Sweden. In total almost 1200 trees from 123 stands were measured with the approximate species distribution 40-40-20 % (pine-spruce-birch) (Marklund 1988). Functions were presented for the following components: stem including bark, stem bark, living branches including foliage, foliage, dead branches, total tree above stump, total tree including stump and roots with d> 5 cm. All functions were made for pine and spruce. For birch no data on stumps and roots were measured.

Model form: ln(dry weight) = f(dbh, id5, a13, SIH, Lat, Long, Alt)

d	diameter at breast height including bark
id5	width of the last five year-rings at breast height
a13	number of year-rings at breast height
SIH	site index estimated from height and age of top height trees
Lat	latitude, expressed by co-ordinate in the national system
Long	longitude, “
Alt	altitude, m a.s.l.

The new functions for stump and root biomass presented by Petersson & Ståhl (2006) included both Marklunds data (600 stumps) and a new dataset, comprising 80 trees from 12 stands at latitudes 57-65 ºN. The new dataset included both birch and all roots with d > 2 mm. Diameters of broken roots on Marklunds stumps were used to update those data with functions relating cut-off diameter to remaining biomass of root with d>2 mm in the new dataset. The dry mass of stump and roots >2 mm was expressed as function of dbh and age. Functions ere also presented for stumps and roots with d >5 mm, and with more independent variables.

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Appendix 21

Combined effects of genetic improvement, climate change and fertilization

PM for Heureka 2009-04-14 by Johan Sonesson. (Translated, initially written in Swedish)

Introduction
At the meeting with Heureka steering committee March 5 2009 the following question was asked: What happens after simultaneous fertilization, use of genetically improved material and influence of climatic change. The question can be split in two parts, on one hand the question on what knowledge we have on how these factors interact, on the other hand how Heureka models the interaction.

What knowledge do we have on this interaction?

Fertilization of genetically improved material
Experiences from other countries and species indicate relatively small differences in fertilisation response between families while the differences between clones can be substantial. There are studies with spruce in climate chambers and young clone experiments pointing in the same direction. The knowledge for our tree species is defective, especially at fertilization of older stands. We can assume that the interaction has no practical influence as long as we use seed-origin material. At use of single clones however, the interaction effects must probably be taken into account. This is probably best done by clone selection in fertilized experiments, as practiced in countries with more intense forestry than in Sweden. In counties where fertilization is used as a standard treatment also in young stands the genetic selection is done in fertilized trials. The interaction of genetic improvement and fertilization has there been found to be of more multiplicative rather than additive nature. This agrees with results from Skogforsk in spruce-clone trials indicating larger than additive (moderately multiplicative) effects.

Warmer climate and genetically improved material
The empirical knowledge on how a given genetic material grows at different altitudes and latitudes is fairly good. There are also results from studies in climate chambers. In the tool "plantval", available at the internet site "kunskap direkt" from the Skogforsk home-page, the best available knowledge has been used on how a latitude transfer affect the growth of genetically improved material compared to seed-origin material. According to this tool 1-2 percent units of the improvement effect is lost when a material is transferred one latitude-degree (e.g. from 10 % increased growth to 8-9 %). If a climate change has the same effect as a transfer we can expect interaction effects of this magnitude. At the same time it is probable that the forestry successively move the planting material northwards when the climate becomes warmer so the effect of un-optimal material in future climate can be expected to be small.

Warmer climate and fertilization
The fertilization trials founding the functions for fertilization effect show increasing effect with increasing latitude and decreasing site index but also with increasing current annual increment. How a changed climate will influence this complex is very hard to predict.

How do Heureka calculate this interaction?

Climate- and fertilization effect
Fertilization effects are calculated with the functions by Folke Pettersson. They give the effect as volume increase in the stand and current annual increment is included as an independent variable (for pine there is a culmination at CAI=6 m^2/ha, year, for spruce there is no culmination). Since the functions for climate response gives increased growth this will cause a multiplicative effect. The climate model also adjust the site index, even included as independent variable giving higher effect in the Pettersson model. This enhance the multiplicative effect. Thus, the larger the climate effect, the larger will the fertilisation effect be. How large the total effect will be is not yet examined.

It is also clear that the results of the models depend on each other. At estimation of the climate effect the tree ages are adjusted. Since the fertilization model affect the size-age relationship also the age correction in the climate model will be affected. In which way and how much is not known. Neither is the importance of which model is applied first: the climate model or the fertilization model. It seems most logical to first apply the climate model since this model adjust the growth curve itself (implicitly through the mentioned age adjustment). The fertilization effect is somehow added afterwards.

Climate and young-stand effect
We have not planned to use the climate model in the management system “intensive forestry”. Climate effects are not modelled at all during stand establishment. New stands are only initiated with the higher site index predicted by the climate model.

Appendix 22

Assignment of thinning intensity over sample plots

Appendix 23

Specification of continuous cover forestry

PM for Heureka 2008-10-07 by Ulf Söderberg

Four different treatment units are identified for continuous cover forestry:

1. Selection cutting in spruce stands
2. Two-storied pine stands
3. Urban forests
4. Deciduous-rich marches

Definitions

1. Selection cutting in spruce stands

Potential stands/plots are defined by a spruce proportion >0,7, a field vegetation type equal to Vaccinium myrtillus or better and cutting class C or D (stands in the thinning or final felling stages). The diameter distribution is defined by 4 classes with the width of Dmax/4, where Dmax is the dbh of the thickest tree on the plot. If the number of stems in the classes from lowest to highest are called n1-n4, then decreasing distribution means n1>n2>n3>n4. Those restrictions are completed with a figure on largest allowable area.

2. Two-storied pine stands

Potential stands/plots are defined as cutting class D with >50 % pine, field vegetation type V. myrtillus or poorer and soil moisture mesic or dry. If the vegetation type is V. myrtillus, then the altitude must be <300 m a.s.l.

3. Urban forests

Specifications are related to applications. Selection of stands/plots can be done by using an appropriate GIS-layer: distance to dense-populated centers or direct mapping.

4. Deciduous-rich marches

This treatment unit contains stands/plots on wet sites with the proportion of deciduous trees > 70 %. Fiels vegetation type must be better than V. myrtillus and swamp mosses must dominate in the bottom layer.

Treatment programs for the treatment units

1. Selection cutting in spruce stands

The treatment is specified as a thinning from above. The so called 10§-curve in the Forestry Act define the lowest allowable volume in the stand after a cutting aiming at improving forest development. This curve is used as a guide curve. Thinning is done when at least 30 % of the volume can be cut without falling below the curve, that is when Vact>1.43*Vmin. Vact is actual volume and Vmin is volume from the guide curve:

$Vmin = 0{,}1875 \cdot h^2 + 6.5 \cdot h - 33.75$, where h is basal area weighted mean height.

The parameters for distribution of the thinning shall be:

Deciduous/conifers	p = 0.0	Spruce/pine	p = 0.0		
Small/large	p = -0.1	Within small	p = 0.0	Within large	p = -0.2

2. Two-storied pine stands
Selection of seed trees is performed as a thinning with highest priority to cut other tree species than pine. Remaining basal area of pine after thinning shall be 5 m^2 /ha at SIS≤T20 and 7 m^2 /ha at higher site indices.

The parameters for distribution of the thinning of pine shall be:
Small/large p = 1.0   Within small p = 1.0   Within large p = 0.3

3. Urban forests
Stands in this treatment unit are thinned 20 % from above each 30 years. The parameters for distribution of the thinning shall be:

Deciduous/conifers	p = 0.0	Spruce/pine	p = 0.0		
Small/large	p = -0.5	Within small	p = 0.0	Within large	p = -0.3

4. Deciduous-rich marches
No treatments are done in this treatment unit

Treatments for nature preservation

Treatments for nature preservation are performed on different levels: stand level, plot level, tree level. Different specifications are needed for the different levels. If information on area for nature preservation is given in initial data, this area is referred to the treatment unit "border zones".

Specification of treatments

Stand level
The user can define treatment units, for instance deciduous-rich stands, signified by >60 % deciduous species in cutting class B and >30 % in classes C and D. Treated by promotion of deciduous trees at thinning.

Plot level
Two cases are distinguished that can be treated in different ways: border zones and other tree groups. Border zones are areas bordering waters and bogs. They are gathered in a separate treatment unit. Other tree groups are randomly distributed on plots and plot parts.

Tree level
The leaving of single trees at the final harvest can be specified on "eternal trees" (large trees) and trees for diversity preservation (generally deciduous trees). The user must specify the number of trees per hectare that shall be left. Selection of trees is done in the prioritized order:
1. Oak > 20 cm
2. Beech > 20 cm
3. Other leaf trees > 15 cm
4. Sallow > 10 cm
5. Rowan > 10 cm
6. Aspen > 25 cm
7. Birch > 20 cm
8. Pine > 25 cm
9. Spruce > 25 cm

Technical solutions

For tree groups specifications are dependent on application.

In Regvis the user specify the proportion of the area that shall be allocated to nature preservation. Plots within 25 m from waters an bogs are referred to the treatment unit border zones. The remaining area allocated to nature preservation is allocated to a random part per plot (0-100%) of the proportion of plots needed to fill up the specified area.

In Planvis the solution depends on type of owner/ company and the following cases are distinguished:
1. As in Regvis. Information of border zones may be collected from a GIS-layer. If no information is available it is possible to make a totally random distribution.
2. All information is collected from GIS-layers
3. The user gives specific rules for nature preservation

In cases when plots are divided the different parts will get different treatments. The preserved part is left unmanaged while the other part is regenerated. Area weighting is done corresponding to proportion of initial plot.

For single trees the number of trees per hectare to be left (N) is specified by the user. In Regvis the proportion (p) of plots is estimated on which to leave a tree as $p = N*A/10000$ where A is the plotsize in m^2. A tree can be left equidistant on each 1/p plot or randomly with the probability p. In Planvis the growth modeling of young stands demands whole trees (not parts of trees) to be left on the plot ….

Beståndsvis as Planvis.

Appendix 24

Determination of stand age and site index on the NFI permanent plots

PM 2009-11-09 by Björn Elfving

In this PM the determination on the NFI-plots of two important independent variables in the growth functions will be examined: stand age and site index.

For the permanent plots at the National Forest Inventory (NFI) the stand age is defined as the total age of the main stand (the tree layer signifying the cutting class). When mean height is below 7 m, age is determined as the arithmetic mean of the future crop trees. When mean height is above 7 m age is determined as the basal-area weighted mean age. I possible the age determination is performed by whorl-counting and addition of 2-3 years for seedling age. Otherwise increment cores are taken at breast height on at least two representative trees outside the plot, the number of year-rings are counted and the time to reach breast height according to a table in the field instruction is added. Before 2003 the measured age was noted for stands younger than 40 years. For older stands only a 10-year age-class was given up to age 160 years. Older stands were given the value 175. From 2003 the measured age is always given.

The precision of the age determination has been examined for the 1547 plots that were selected for testing of the basal area growth functions. Data concerns plots that were measured 1999/00 and 2004/05. As support for the age determination the earlier given value was available at the field work. Mean stand age was estimated at 76.5 years in 1999/00 (a1) and 83.0 years in 2004/05 (a2). This means that the stands were estimated to increase their age with 6.5 years in a 5-year period. One could expect that age should increase little less than 5 year in a 5-year period due to death of old trees and in-growth of younger trees. On the other hand the grouping on age-classes before 2003 means a slight underestimation of the mean age since the class-middle was used at calculation of mean age. The number of stands over age class is descending so mean age in a certain class is lower than the class-middle. More-over, thinning from below cause a slight age increase since the thinned. Smaller trees normally are younger than the remaining trees. For the 20 % of the plots that were thinned between the measurements the age increase was 6.03 years in the 5-year period. Also, the year-ring counting in the field is known to underestimate the real number of rings, as measured in the lab, by 1-2 years. An overall conclusion is that the stands were classified as about 1 year older at the latter measurement than at the former.

Since the earlier determined value for stand age was available at the re-measurement this could be expected to influence the new age determination. For 31 % of the plots age has been registered to increase with 5 years in the 5-year period. At observed deviations between the measurements (Fig. 1-2) the expected proportion of observations with 5 years age increase is about 5 %. For the 69 % of observations with more or less than 5 years age increase (probably independent age-determinations) the difference in estimated age (adiff=a2-a1-5) increase with stand age, expressed as the mean of the two determinations, am), Fig. 1.

The standard deviation for the age determination (S(adiff)) was estimated as:
$S(adiff) = [(a2-a1-5-0.03 \cdot am)^2 / (2 \cdot n) - 9]^{0.5}$, wherea1 and a2 are estimated stand ages in 1999/00 and 2004/05, am is (a1+a2)/2 , n is number of observations and the figure 9 come from the fact that a1 concerns class-grouped data. The calculation was performed for different

am-classes and the relation between S(adiff) and am was: S(adiff) = 0.076·am. This means that the variation coefficient for the age determination was 0.076.

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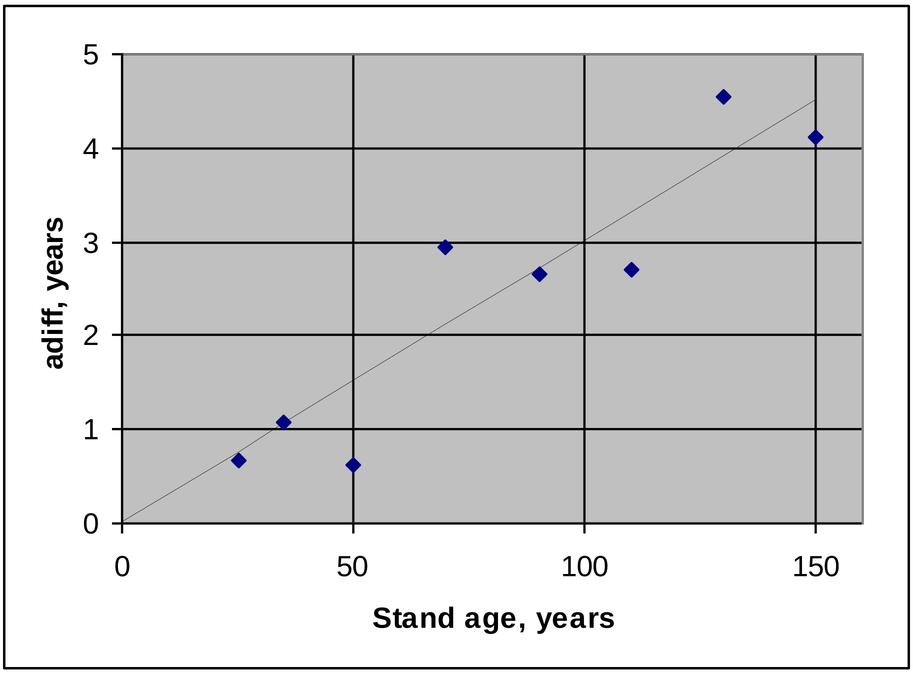

Figure 1. Difference in stand age according to determinations 99/00 and 04/05 as function of average initial stand age: adiff=0,03*am

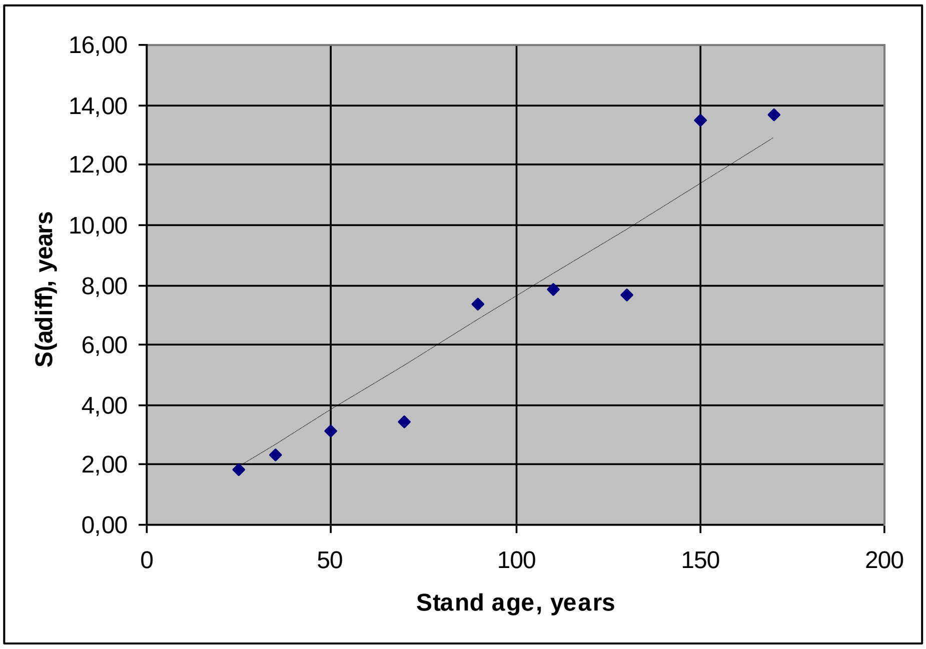

Figure 2. Standard deviation for the age determination as function of average initial age: S(adiff)=0,078·am

Site index according to site factors (SIS, m) is calculated with functions presented by Hägglund & Lundmark (1977) and revised by Hägglund (1979). There are five functions for pine and three functions for spruce according to groupings on site moisture and fertility as indicated by the field vegetation. At the field work the SIS-indicating species (pine or spruce) is first determined, generally according to dominating species but also with regard to expected productivity and suitability on the site. The species assumed best adapted is selected.

The independent variables included in the functions are latitude, altitude, climate region, soil depth and texture, topographic location and vegetation type. The vegetation types comprise 18 classes based on occurrence of indicator species and coverage of different species in the field and bottom layers. The standard error for the SIS-determination has been studied with the same test-data set that was used for check of basal area growth functions (appendix 5), comprising 1547 representative NFI-plots measured 1999/00 (I1) and 2004/05 (I2). Independent SIS-determinations were made at the two measurements of each plot.

In average the difference between the two measurements (SIS1-SIS2) was 0.003 m with the standard deviation 2.09 m. Different SIS-indicating species were given for 90 plots (5.8 %). For this group the SIS-difference was 0.42 ± 4.31 m. Of those 90 plots 59 were changed from spruce to pine as indicator species and the SIS-difference was +1.37 m. For the 31 plots changed from pine to spruce the difference was -1.38 m.

Excluding the plots with different SIS-indicating species, the mean and standard deviation for the SIS-difference was -0.023 ± 1.87 m. The standard deviation for the SIS-determination is thus estimated at $(1.87^2/2)^{0.5}$ =1.32 m.

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Appendix 25

On the accuracy of growth predictions

PM for Heureka 2008-05-15 by Björn Elfving

Growth simulators linked to a site index system principally gives the average volume development at a given course of height development. For pure and even-aged stands with given initial density the variation coefficient for volume production to a given height is about 0.15 (Assman 1963). A growth prediction includes both this variation and the residual variation in the height growth prediction.

In order to estimate the total prediction error the following study was performed. Data consisted of long-term thinning trials (the GG trials) that were established in the period 1966-1983 and had been followed for an average period of 30 years. There were 23 blocks in Norway spruce and 47 blocks in Scots pine. Each block contained 4-12 treatments. For this study only the treatments un-thinned control and one heavy thinning from below were selected. The volume growth during the observation period (iV) was regressed on initial stem number per hectare (N1), top height (H1) and height increment during the observation period (iH), either the observed value (iHobs) or the value predicted with site curves (iHpred). There was a difference between the species also that could be modeled by a dummy variable for spruce. The regressions were as follows:

ln(iV)= -0.5954+1.1476·ln(**iHobs**)+0.4264·ln(N1)-
0.000158·N1+0.0623·H1+0.2249·SPRUCE;
n = 136 ; R^2adj =0.934 ; s(res) =0.144 ;

ln(iV)= -1.2310+1.2432·ln(**iHber**)+0.5300·ln(N1)-
0.000227·N1+0.0488·H1+0.2079·SPRUCE;
n = 136 ; R^2adj =0.881 ; s(res) =0.192 ;

The residuals of those functions had normal distributions and indicated a smooth fit over included variables and no significant correlation with some other tested variables (site index, latitude). An effort was made to also include an expression for “local yield class” but it was not significant. As expression for local yield class the residuals from the function lnG1=f(lnH1, lnN1) were used, where G1 is initial basal area.

The prediction error for the function with iHobs was exp(0,144)=0,15 as expected. The total prediction error (from the function with iHpred) was estimated at exp(0,192)=0,21.

Eriksson (1976) also estimated the prediction error for volume growth at 0.21, based on data from spruce stands in the Great Yield Investigation. Söderberg (1986) compared predicted and observed basal area growth on 18 yield plots that had been followed during 44 years. Observed growth was adjusted to “normal weather conditions” with year-ring indices. The prediction error for adjusted basal area growth was estimated at 0.12. The same prediction error for volume growth was estimated for 26 pine plantations in northern Sweden that had been followed in 20 years. Pretzsch (2002) estimated the prediction error of the model SILVA with data from German long-term yield plots. The error was 0.19 for oak, 0.20 for spruce, 0.29 for beech and 0.39 for pine.

My conclusion of this examination is that the variation coefficient of predicted growth in growth predictions (the prediction error) generally can be expected to be about 0.2.

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