Predicting individual tree and stand diameter increment responses of Norway spruce (*Picea abies* (L.) Karst.) after mountain forest selective cutting

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Abstract. Models for predicting diameter increment in multi-storey spruce stands following mountain forest selective cutting (MFS) were developed. They were based on increment cores, tree ring analyses and stump registrations. The presented models rely upon time series data from 1600 trees in thirty-one Norway spruce stands in south-eastern and central parts of Norway. The selective cuttings were heavy; on average two thirds of the standing volume were cut. The increment following the interventions was highly variable, resulting in large random variability in the models with R^2 varying between 0.18–0.31 for individual tree diameter growth and 0.40–0.50 for mean tree stand diameter growth. Dummy variables referring to three first 5-year periods after cutting were found to increase the precision and significantly reduce the random error. Selected models were validated using a test material from central Norway and also compared with the mostly applied Norwegian diameter increment models. Despite a large random variation in all models, the model performances appeared logical and the general fit to the data was acceptable. Based on tests, two diameter increment models are recommended for future yield prognoses in MFS. The models should also be of interest for wider use in other parts of the Nordic and Baltic boreal zone.

Key words: diameter growth, individual tree increment models, lowland forest, mountain forest, multi-storey stand, Norway spruce, *Picea abies*, selective cutting, stand increment models.

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Introduction

During the last three decades the implementation of alternatives to even-aged forestry, i.e. different forms of partial cutting systems and their performance, has been widely discussed in northern Europe (Nilsen, 1988; Lundquist, 1989; Ohlson & Tryterud, 1999; Hagner *et al*., 2001; Nilsen, 2001; Øyen & Nilsen, 2002; Lundquist *et al*., 2006; Tahvonen *et al*., 2010). This interest for continuous cover forestry has emerged from both forest managers and environmentalists, where important arguments have been to reduce the regeneration costs, to secure a more regular income from cuttings in small properties and to search for solutions that will lead to fewer conflicts between forestry, tourists and other recreational groups. Several investigations by the scientific community in Norway, Sweden and Finland have dealt with either the production potential or the regeneration aspects following various types of selection or conversion systems (e.g. Lindman, 1986; Bäckström, 1986; Nilsen, 1988; Andreassen, 1994; Lundqvist, 1995; Lähde *et al.*, 2002; Hagner *et al.*, 2001; Holgen *et al.*, 2003; Lundqvist, 2004; Eerikäinen *et al.*, 2007; Tahvonen *et al.*, 2010).

Growth and yield studies following "traditional" selection cutting (Plenterhieb) are frequent in Central Europe (e.g. Schütz, 1989), whereas reports that cover heavy interventions in Norway spruce forest are rare. To procure a sustainable timber supply, management decisions must be based on the best available projections or on reliable models. The forest stands resulting from partial harvests become more heterogeneous than even-aged stands and there are several questions to be answered concerning the growth of remaining trees (e.g. Andreassen & Tomter, 2003), ingrowth of small trees (e.g. Lexerød & Eid, 2005) and natural mortality (e.g. Eid & Tuhus, 2001; Eid & Øyen, 2003). One partial cutting system that was introduced in the late 1960s in Sweden and Norway is the mountain forest selective cutting system (MFS) (i.e. Børset, 1994; Suadicini & Fjeld, 2001; Øyen & Nilsen, 2004). MFS cutting has been practised in several high elevation areas in the north and mid-boreal forest regions in Norway and Sweden. In Norway it has also occasionally been used on low fertility areas in the lowlands and at medium elevations. The system is based on natural regeneration and a cutting, mainly of the largest trees and trees with injuries and low quality. A prerequisite is that small, medium and large trees are intimately intermixed. There is a lack of knowledge concerning long-term yield from forest areas subjected to MFS. For the classical selection cutting system the yield level is estimated to be some 80–90% of what could be achieved in an even-aged stand (Lundqvist, 1995; Andreassen & Øyen, 2002b; Lundqvist *et al.*; 2006) under Nordic conditions. Due to lack of long-term experimental MFS plots, reliable data for yield evaluations and long term prognoses are missing. The need for updated growth models to strengthen the fundament for forest management is therefore large.

Since long-term experiments following development after MFS in Norway was first established in the late 1990s and only few increment periods are available, an alternative approach was to use data from temporary plots and reconstructed plots gathered under different conditions and periods. The purpose of this study was firstly to validate well-known Norwegian growth models by use of data from mountain forest selective cut areas in Norway, and secondly, if necessary, develop preliminary individual tree and stand diameter increment models applicable for use in MFS-cut areas for yield projections.

Materials and Methods

Three different independent materials (A, B and C) from southeast and central parts of Norway (Fig. 1) have been used in this study. For detailed information about the plots, see Table 1. Materials A and B were

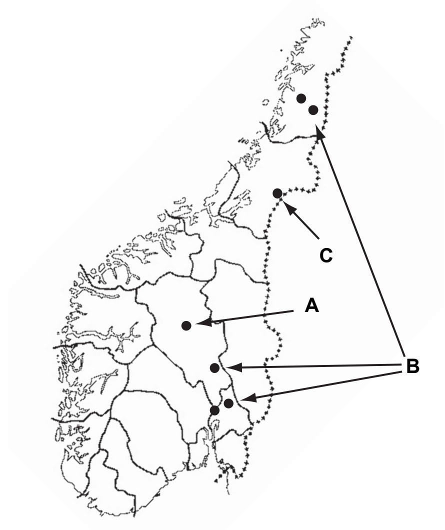


Figure 1. Location of the plots in southern Norway. For explanation of the letters, see Materials and Methods.

used for the development of the models whereas material C was chosen as test material for the individual tree models developed.

The MFS cutting had been heavy, with a substantial proportion of the standing volume removed. On average the standing volume was 224 m^3 ha^{-1} just before cutting and the removal was 68%. Corresponding figures for the stem numbers were 730 ha^{-1} just before cutting, while 42% was removed (Table 1).

Table 1. Stand data for the three materials included in the study.

Material	Plot no.	Latitude, Longitude	Alt. m	Veg. type*	Cutting year	Stand age**	Site Index H40, m	Volume, m^3 ha^{-1}	Volume removed, %	No. of trees ha^{-1}	No. of trees removed, %
A	1	61°10′, 9°55′	800	3	1974	73	7.0	100	42	650	19
	2	″	800	1	1974	98	6.0	113	76	700	61
	3	″	790	3	1974	91	6.0	105	59	675	37
	4	″	880	2	1975	66	6.5	223	50	750	27
	5	″	760	1	1975	86	7.5	132	72	625	40
	6	″	840	2	1974	101	7.0	121	56	725	35
	7	″	840	3	1974	88	6.5	155	75	925	35
	8	″	860	2	1975	86	7.5	144	68	675	33
	9	″	870	3	1975	71	7.0	122	72	500	45
	10	″	780	3	1975	114	6.5	110	80	575	52
	11	″	780	3	1975	118	5.5	134	80	850	38
	12	″	750	2	1975	99	6.5	146	92	700	54
	17	″	815	3	1974	68	7.0	131	83	450	44
	18	″	820	2	1974	98	6.5	150	70	700	46
	19	″	780	1	1975	39	6.5	150	88	500	75
	20	″	780	3	1975	77	8.0	210	87	700	75
B	276	60°39′, 11°12′	240	5	1962	53	23.0	650	59	480	33
	277	60°38′, 11°14′	240	5	1970	63	23.0	630	60	540	56
	278	60°40′, 11°14′	245	5	1962	60	20.0	570	58	670	43
	279	59°59′, 10°42′	450	3	1974	125	11.0	380	50	640	31
	280	″	450	2	1974	85	17.0	460	41	460	33
	281	60°00′, 10°42′	460	2	1966	124	11.0	480	29	590	41
	282	″	480	2	1966	82	11.0	440	55	810	41
	283	65°31′, 14°01′	250	2	1966	82	11.0	200	50	1210	26
	284	″	240	3	1963	80	11.0	200	65	1100	50
	285	″	250	4	1966	89	8.0	290	52	1250	27
	286	65°31′, 14°00′	240	2	1963	85	11.0	290	55	1080	56
	287	65°43′, 13°13′	110	2	1971	125	8.0	210	48	680	32
	288	65°36′, 13°10′	170	2	1967	63	8.0	200	80	1170	44
	290	65°41′, 13°09′	130	3	1948	66	11.0	180	48	1730	38
	292	60°24′, 10°57′	530	3	1973	102	11.0	310	58	800	46
C	12	64°05′, 12°52′	500	1	1949	60	12.0	291	77	1025	20
	13	″	500	3	1949	35	8.0	103	82	475	42
	14	″	500	3	1949	67	8.0	81	80	525	52
	15	″	500	3	1949	66	8.0	150	78	600	54
	16	″	500	3	1949	28	8.0	70	96	475	26
	17	″	500	3	1949	65	8.0	100	90	775	39
	18	″	500	3	1949	72	8.0	98	82	375	47
	19	″	500	3	1949	87	8.0	103	93	475	47
	30	″	500	3	1949	98	8.0	-	-	525	29

* 1-*Melico-Piceetum aconitetosum*, 4 plots, 2-*Eu-Piceetum dryopteridetosum*, 3-*Eu-Piceetum myrtilletosum*, 4-*Vaccinio-Pinetum*, 5-*Melico-Piceetum typicum*. (i.e. Kielland-Lund, 1981).

** Basal area weighted age at breast height at time of MFS cutting.

The data material

Material A

This material consisted of sixteen long term plots (0.04 ha) in Norway spruce dominated stands in Mannstadlia, Gausdal municipality (61°N, 10°E), southeast Norway, about 800 m a.s.l. The plots were first investigated in 1983/84 (Nilsen, 1988) and re-measured in September 2000, 24–25 years after MFS cutting (Øyen & Nilsen, 2002). The cutting in 1974/75 was quite heavy, with a mean volume removal of 72%. A more detailed description about the site is given by Øyen & Nilsen (2002). The stand reconstruction method is according to Øyen & Nilsen (2004).

Material B

The dataset originates from an earlier investigation in old spruce forests from southeast and central Norway (Nilsen & Haveraaen, 1983). Most stands were from mountain forests or low productive areas at lower elevations, whereas four stands were situated on highly productive soils in the lowlands. The bulk of the stands were situated on moraine material and the vegetation types were mainly small fern and bilberry types. Most stands had an inverse J-shaped diameter distribution and a heavy selective cutting was performed 5 to 15 years before the registrations took place. Altogether 15 plots, varying from 0.040 to 0.105 ha in size, were investigated in 1980. A more detailed description about the plot and the stand reconstruction method is given by Nilsen & Haveraaen (1983).

Material C

Nine temporary plots of 0.04 ha in size in Holden State Forest in Snåsa municipality (64°N, 13°E), central Norway, about 500 m above sea level, were investigated in 1989. The plots were subjectively selected to cover different cutting strengths and stand properties in Norway spruce. The upper conifer timberline is about 550 m a.s.l. in the area. Eight of the plots were located in flat terrain on fluvial deposits, while one plot was situated on moraine material. The selective cutting was performed 40 years prior to the registration and was quite heavy, with a mean volume removal of 85% of the standing volume. The main vegetation cover was of the bilberry type. The registrations and calculations were otherwise similar to those described for material A. A more detailed description of the stand history and cutting is given by Gjellan & Nilsen (1990).

Functions applied

The following functions were applied for the tree and stand data and for reconstruction of the stand;

- Tree volume including bark for Norway spruce; Vestjordet (1967)
- Tree volume including bark for birch; Braastad (1966)
- Bark (Norway spruce); Eide & Langsæter (1941)
- Dbh from stump diameter; Øyen & Nilsen (2002)
- Site index (Norway spruce); Tveite (1977).

Model development

Stand level models

A multiple least square estimation (OLS) approach was used to elaborate the models. A total of 126 increment periods of 5 years' length were used. A combination of methods was used to select the variables. First, stepwise regression analyses were made with different combinations of variables to get primary knowledge about the independent variables. Secondly, selections of variables were made where several aspects were considered, i.e. common variables included in Norwegian inventories, variables that logically could explain increment and statistically significant variables. We used an approach with the basal area mean tree diameter increment as dependent variable (both linear and logarithmic) as commonly applied for even-aged stands in Norway (Braastad, 1974; Blingsmo, 1984):

id = b0 + b1*V1 + b2*V2 … + bn*Vn + c1*P1 + c2*P2 +c3*P3 + E (1)

lnid = b0 + b1*ln V1 + b2*ln V2… + bn* lnVn + c1*P1 + c2*P2 + c3*P3 + E (2)

where id is the basal area mean tree diameter increment (mm) in a stand in the coming 5-year period, b0, b1, b2...bn, c1, c2 and c3 are constants. V1, V2…Vn are stand variables from 1 to n, P1, P2 and P3 are dummy variables indicating 5-year period nos. 1, 2 or 3 after the selective cutting, ln is the natural logarithm and E is the random error term.

The bias of the logarithmic dependent variable in 2) was corrected by applying an iterative process and by adjusting the intercept term to harmonise the average of the residuals equal to zero for the transformed models.

Individual tree models

Both linear and log-transformed variables were used in a multiple OLS approach. The models were constructed as linear models with random plot effect similar to 1) and 2) for the stand level model, but they also included a variable expressing the competition from the other trees. The relationship between diameter of the subject tree (dbh) and the basal area mean diameter of the stand (Dg) was chosen in this study, a similar variable to those used in Andreassen & Tomter (2003). The number of increment periods included was 1600. The variables included in the models can be divided into the following main groups:

- Site productivity (site index, H_{40}),
- Development phase (age, dummy variables including 5-year growth period after MFS cutting),
- Tree size (dbh, tree height),
- Stand density (basal area, stem number),
- Competition (dbh/Dg).

For both stand and single-tree models there was one main criterion for selecting the final modifications of the variables: to develop models with unbiased behaviour throughout the range of the data. Additionally, if possible, the models should also perform logically outside the range of the basic data. SAS, release 8.02 (SAS 1999), was used for statistical analyses and data treatment. If nothing else is stated, only variables meeting the 5% level of significance were included in the models.

Evaluation of the models

The primary requirement for the presented increment models was their capability to produce unbiased predictions for the development of common MFS-cut Norway spruce stands. The evaluation work consisted of three sequential steps:

1) Comparisons with selected Norwegian increment models (i.e. Braastad, 1974; Blingsmo, 1984; Andreassen & Øyen, 2002; Holte & Solberg, 1988; Andreassen & Tomter, 2003). If necessary, new models should be suggested.
2) Calculating average model bias (and standard deviation) for selected models and using the residuals from the predictions to perform a visual inspection of the plotted graphics, by each variable in turn.
3) Validation of the proposed diameter increment models using the independent material C.

Results

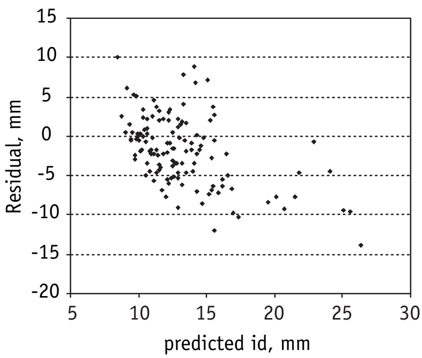
Comparison with existing stand diameter increment models

Two increment models for even-aged stands (No. 9 of Blingsmo, 1984 and No. 16 of Braastad, 1974), and one model for selection forest stands (No. Bled-2 of Andreassen & Øyen, 2002b) was tested by use of the present material (A+B). A substantial bias was detected in all models compared to the observed increment (Table 2).

The best fit for the MFS-cut stands was found when applying model No. Bled-2. This model gave on average an underestimation of 5.3%. However, some bias

Table 2. Estimates of diameter increment (mm) in the coming 5-year period (materials A and B) by applying three independent models (No. 9 of Blingsmo (1986), No. 16 of Braastad (1974) and No. 2 of Andreassen & Øyen (2002b)) and the percentage difference (%, diff) between estimated and measured values and standard deviation of the differences.

Model	Measured mean	Number of observations	Estimated	Diff	% diff	Std (diff)
Blingsmo, No. 9	11.4	126	13.3	-1.9	116.7	4.4
Braastad, No. 16	11.4	126	15.7	-4.3	137.7	5.1
AndOyb, No. 2	11.4	126	10.8	0.6	94.7	4.2



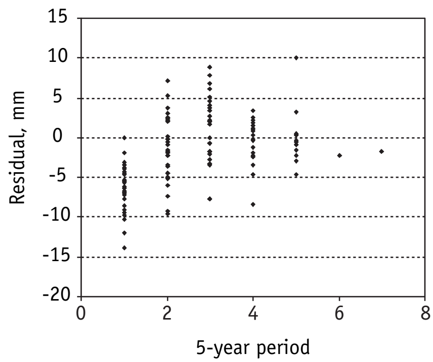


Figure 2. Residual plots for predicted diameter increment (id, mm) (Blingsmo No. 9) and the various 5-year periods after cutting.

existed in the model: the residual analyses revealed strong differences for the different 5-year periods. In the first 5-year period a 43% overestimation was found, while an underestimation of the increment in the other periods in the order of 10-25% was detected. Model No. 16 (Braastad, 1974) was found to give an average overestimation of almost 38%. The largest overestimation was revealed in the first 5-year period. Model No. 9 (Blingsmo, 1984) overestimated the increment by some 17% (Fig. 2). This model too overestimated highly the diameter growth in the first period. The overestimation increased with increasing mean diameter of the stand.

New stand diameter increment model

Six models containing simple biometric data were selected (Table 3). Judged from the contribution to the multiple correlation coefficients (R^2), the most important independent variables were site index and stand basal area.

The squared correlation coefficients varied between 0.38 and 0.50, and the coefficient of variation was in the range from 25 to 27%. There seemed to be a small gain in predictive value by including weighted stand age in the models of both logarithmic (FII, FIII) and linear type (FV, FVI). Model FI was chosen for further analyses since it contained no age variable and since basal area, stem number and site index are usually determined in forest inventories.

Model evaluation, new stand diameter increment model

Residual plots from model FI are shown in Fig. 3. The plots indicate that the chosen model was appropriate. Only 6 residuals were outside the range of ± 6 mm in a 5-year period. Removing these outliers gave only small effects on the model parameters.

Table 3. Diameter increment (mm) in the coming 5-year period. H_{40} in m, basal area (BA) in m^2 ha^{-1}, $T_{1.3}$ is basal area weighted age at breast height in years. N is number of trees ha^{-1}. All figures are for the beginning of the increment periods. P1 and P3 are dummy variables for the first and third 5-year periods after cutting, respectively. P1 takes the value 1 if the calculation is for the first period, otherwise the value is 0, and P3 takes the value 1 for period 3, otherwise 0.

Model Independent variable	FI lnid	FII lnid	FIII lnid	FIV id	FV id	FVI id
Constant+	2.0103	5.6011	5.1290	10.5606	17.2752	19.0288
$\ln H_{40}$	0.4985		0.1005*			
lnBA	-0.2416					
$\ln T_{1.3}$		-0.6931	-0.6354			
H_{40}				0.5424	0.3211	0.2755
BA				-0.2731	-0.1741	-0.1457
$T_{1.3}$					-0.0636	-0.0672
N						-0.0027
P1 (dummy)	-0.4481	-0.4462	-0.4503	-4.2882	-4.5997	-4.6105
P3 (dummy)	0.1437	0.1443	0.1420	2.1944	2.0775	2.0860
N (obs)	126	126	126	126	126	126
R^2	0.38	0.46	0.47	0.42	0.49	0.50
	0.40	*0.41*	*0.42*			
CV (%)	12.0	11.2	11.1	26.8	25.0	24.7
	27.1	*26.9*	*26.6*			

+ Correlation coefficient and CV for the logarithmic functions *in italic letters* are on retransformed figures.
* Pr > | t | < 0.16. Example FII: $id = \exp(5.6011 - 0.6931 \cdot \ln T_{1.3} - 0.4462 \cdot P1 + 0.1443 \cdot P3)$

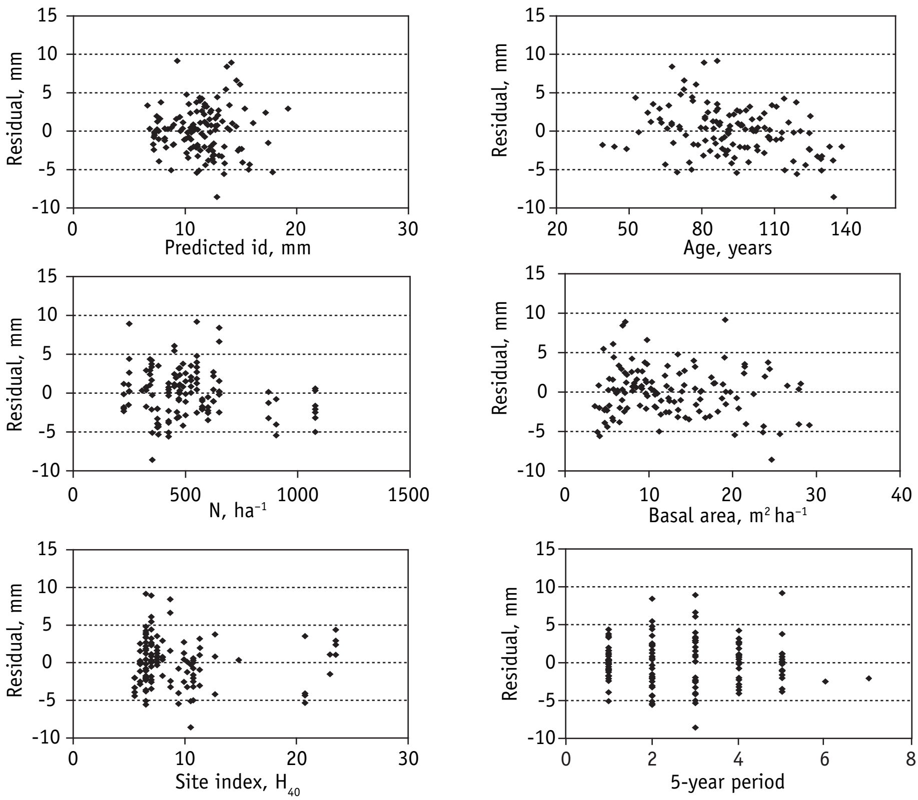


Figure 3. Residual (in mm per 5 years) plots for function FI.

Test of individual-tree diameter increment models

Model 1a for multi-storied stands with 100% spruce (Andreassen & Tomter, 2003) was chosen for a test together with a individual tree model for spruce, Model I1 (Holte & Solberg, 1989). The comparisons were made on trees more than 5 cm dbh and the increment estimated by the two models was compared to the measured increment from materials A and B (1600 trees). The average underestimation for the two models was 1.2 cm^2 and 1.6 cm^2, respectively (Table 4). Residual plots showed an increased random error with increasing diameter of the trees. The periodic increment was highly overestimated in the first 5-year period

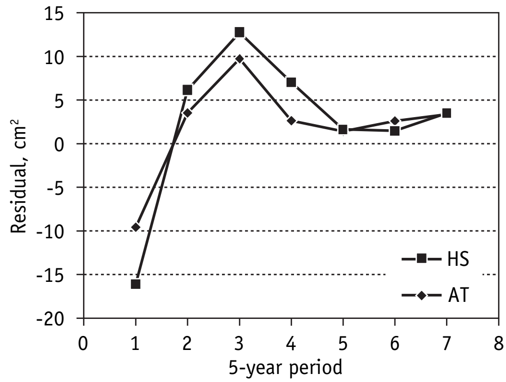


Figure 4. Mean residuals of basal area increment (iba) in different 5-year periods after selective cutting as given by the functions of Andreassen & Tomter (2003), AT, and Holte & Solberg (1989), HS.

Table 4. Diameter increment (mm) in the coming 5-year period for individual trees. H_{40} in m, stand basal area (BA) in m^2 ha^{-1}, $T_{1.3}$ is basal area weighted age at breast height in years. N is the number of trees ha^{-1}, Dg is the basal area mean diameter, dbh is the individual tree diameter at breast height, h is the individual tree height. All figures are for the beginning of the increment periods. P1, P2 and P3 are dummy variables for the first, second and third 5-year periods after cutting, respectively. P1 takes the value 1 if the calculation is made for the first period, otherwise the value is 0. P2 takes the value 1 if the calculation is made for the second period, otherwise the value is 0, and P3 takes the value 1 for period 3, otherwise 0.

Model Independent variable	VII lnid	VIII lnid	IX lnid	X id	XI id	XII Id
Constant+	1.6870	-3.1288	2.3440	11.1254	13.3268	17.9128
lnH_{40}	0.6612	-0.6114	0.2516			
lndbh	0.1577	-0.9653	0.6061			
lnT_{13}			-0.6845			
lnBA	-0.5379	-0.7138	-0.4822			
lnN		0.1510	0.1105			
Lnh		2.6506				
ln(dbh/Dg)		-0.6531				
H_{40}				0.6450		0.3009
$T_{1.3}$						-0.0846
BA				-0.4816	-0.5517	-0.4373
Dbh				0.0111	-0.0304	0.0281
dbh/Dg					-2.0005	
H					0.1097	
P1 (dummy)	-0.4901	-0.4375	-0.42221	-4.2695	-4.2562	-4.3223
P2 (dummy)	-0.0986	-0.1066	0.1539			
P3 (dummy)	0.1009	0.0782		2.1692	2.0126	2.1392
N (obs)	1599	1599	1723	1599	1599	1599
R^2	0.17	0.25	0.29			
	0.18	*0.25*	*0.23*	0.19	0.23	0.31
CV (%)	25.4	24.1	23.1			
	52.4	*50.1*	*50.3*	52.3	50.8	48.2

+ Correlation coefficient and CV for the logarithmic functions *in italic letters* are on retransformed figures.
Example FVI: id = exp(1.6870 + 0.6612*lnH40 + 0.1577*lndbh – 0.5379*lnBA – 0.4901*P1 – 0.0986*P2 + 0.1009*P3)

after cutting, thereafter slightly underestimated (Fig. 4). This was most pronounced for the model by Holte & Solberg (1989).

New diameter increment model on individual tree level

A large number of id-models were constructed, and a selection of the six 'best' models was made (Table 4).

The growth variations within the base material were substantial. The squared correlation coefficients of the models were in the range 0.18–0.31, and the coefficient of variation was about 50%. The non-transformed models displayed a slightly lower coefficient of variation and a slightly higher R^2 than the log-transformed models. The gain when including tree age was significant, but rather moderate if looking at the coefficient of variance and R^2. The dummy variable P2 was significant in all log-transformed models and not significant in the non-transformed models.

Model evaluation, diameter increment functions

The two models FVII and FX were chosen for further evaluation, due to their simplicity and the reasonableness of the results obtained. Residual plots displaying observed versus predicted increment and diameter at breast height are presented (Fig. 5).

Residual plots for most combinations of trees and stand variables displayed no indication of serial correlations, dependencies on initial conditions or other systematic patterns. The tendency for residuals to decrease with increasing predicted diameter was not significant.

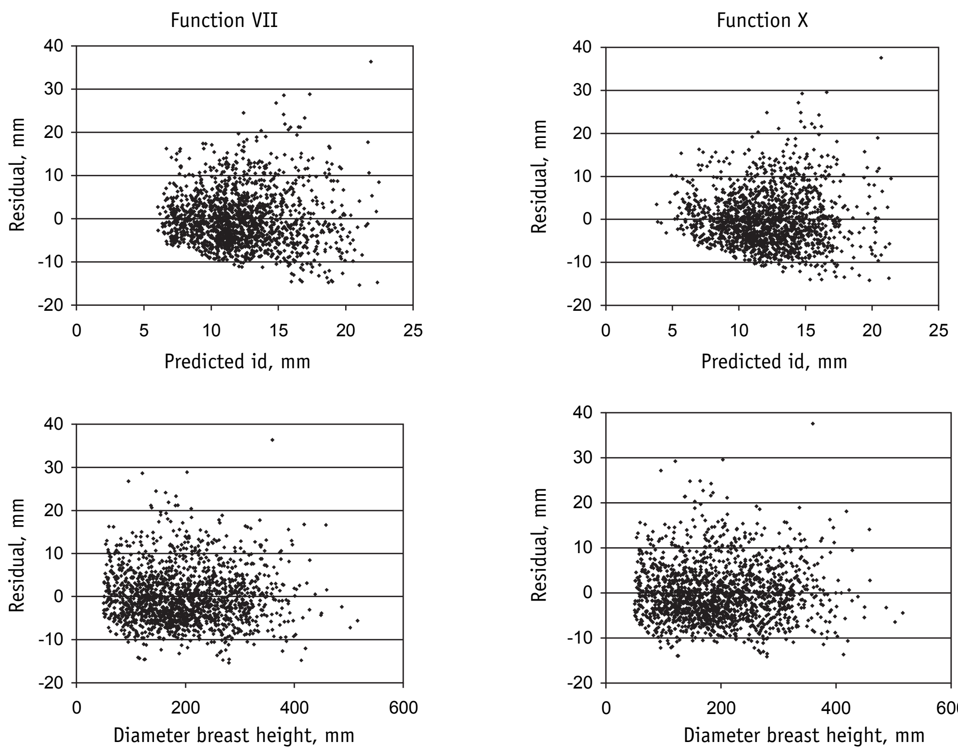


Figure 5. Plot of residuals (mm) against predicted diameter increment (id) and breast height diameter for functions FVII and FX.

Table 5. Measured basal area increment, i_{ba} (cm^2 in 5 years) on individual trees and estimated increment from two functions (Andreassen & Tomter (2003), Holte & Solberg (1989)) and the mean, maximum, minimum and standard deviations of residual values.

Model	N	Measured i_{ba}	Estimated i_{ba}	Residual mean	Minimum	Maximum	Std.
Andreassen & Tomter (2003)	1600	39.7	38.5	1.2 (3.0%)	-111.1	235.0	27.3
Holte & Solberg (1989)	1600	39.7	38.1	1.6 (4.0%)	-137.8	274.5	26.4

Test of individual tree model, accuracy of short term projections

The two models (FVII and FX) were tested on the independent material C from central Norway, containing 96 trees and 765 increment periods of 5 year. For trees larger than 5 cm dbh, the predicted increment was on average 101.2% and 90.1% of measured increment for FVII and FX, respectively. Both models gave a small overestimation at high increment values. The model FVII worked well within the range of diameters, basal areas and site indices found in the base material. Model FVII did not predict any increment below 8 mm in a 5-year period and model FX did not give higher values than 20 mm in a 5-year period judged from the available test material.

Discussion

Individual-tree based growth models in northern Europe (e.g. SILVA, Pretzsch *et al*., 2002; MOTTI, Hynynen *et al*., 2005) now offer great possibility and flexibility to explore stand management options beyond the range of treatments represented in the empirical data base. However, care must be taken if such models are generalized and applied outside the intended forest management regime, growth conditions and/or geography. Empirical growth models purely based on data from MFS-cut stands has, to our knowledge, not been available in Europe. From the evaluation of growth models, originally constructed for use in even-aged stands (e.g. Braastad, 1974; Blingsmo, 1984), this study has clearly demonstrated that mean tree diameter increment models are less suitable for growth prognosis in areas where mountain forest selective cutting is applied. There was a systematic overestimation of increment of a magnitude of about 20%, and the largest deviation was found in the first periods after cutting and at low increment rates.

It must be stressed that the base material for a construction of new models and the material for validation is rather small, and the limited size of the plots adds another source of error when figures are up-scaled. Small plots imply that a relatively large portion of the trees is affected by the conditions outside the plot. This problem is particularly relevant for basal area and number of trees per ha, since these variables are certainly affected by competitors outside the plot. Top height (and site index) is defined at a 1 hectare level, and at smaller plots and in areas where top height trees are removed in cuttings there is a slight risk of a systematic underestimation. Great changes in site index over time are another source of error. A study from the mountain forest spruce in Norway comparing plantations and old semi-natural stands has revealed that the functions of Tveite (1977), applied outside the base material, underestimates the site index for planted stands by 4.2 m on average (Bøhler & Øyen, 2011). Methods for more accurate determination of a site index for stands cut from above should therefore be further explored.

In our study 126 growth periods reflecting different climatic conditions from the 1950s to 2000 are represented; with plots on both high and low site index classes, even though the latter are best covered. The range of mean tree diameters is also rather restricted, from 7 to 27 cm. The selected stand models had a R^2 of about 0.50 and a CV of 25%. This is a slightly lower R^2 and a higher coefficient of variation than reported in previous diameter increment models in spruce for homogenous even-aged stands in Norway (e.g. Braastad, 1974; Blingsmo, 1984), but on the same level as in models for mixed stands (Strand, 1983; Gobakken & Næsset, 2000; Bollandsås, 2007). It is, however, likely that within-plot-errors are correlated due to repeated measurements so the measure of fit should be interpreted with care. Periodic variables are important for depicting the growth response during the time period after MFS cutting, because the stand variables that are sensitive to growing space do not immediately reflect sudden changes in stand density, and therefore cannot reflect growth response properly. The highest increment was found in the third growth period after cutting, and the lowest in the first period after cutting. A similar dynamic response has also been shown in previous studies in Sweden (Näslund, 1942) and Finland (Sarvas, 1944). Part of the unexplained residual variance of the model could be ascribed to soil factors, climatic variations and genetic components, which are not included in the model.

The new individual tree models showed that the variable selected for competition is of less importance than the variables describing tree size and site index. This could be interpreted as a result of the heavy cutting and because some of the increment variation could be an effect of competition liberation, rather than actual competition with remaining trees (e.g. Nilsen & Haveraaen, 1983). In other European studies on individual tree growth a variety of tools have been used to develop competition indices (e.g. Biging & Dobbertin, 1995).

On average, the test results for the individual tree models were opposite to those for the stand level models in the way that a small underestimation was identified. This was mainly due to large underestimation at low diameter increment for the first 5 year period after cutting. The results also demonstrated that the previous individual tree models for spruce forest in western parts of Scandinavia have several shortcomings for predictions in MFS-cut stands.

Model FVII seemed to cover the range in site index conditions, the small and medium tree diameters and various development phases rather well, but the random variation was large. Also, there was a risk of extrapolation errors at a single tree level owing to the limited data on which the model was based. This could lead to pronounced uncertainty when predicting e.g. economic return from MFS cutting, especially in smaller stands. Based on the model type and the variables included we also recommend to avoid use of the models for trees greater than 40 cm dbh, due to sparse representation of higher diameter classes in the material (Fig. 4). Although the multiplicative model ensures that the functions will never yield illogical predictions in terms of negative values, one should pay special attention when predicting growth by extrapolation.

In spite of the uncertainties related to the model development, validation tests and data material discussed previously, the presented model, FVII, can be applied for predicting diameter growth of spruce in MFS-cut stands, up to 50 years after cutting. Considering the general uncertainty in growth models and representative data, the presented models seem to have an appropriate level of reliability. On the other hand, the models could be improved in several directions. With re-measurements of plots, the models could be revised.

Lundquist *et al*. (2006) point out the large variability in volume growth dependency of standing volume after selection cutting in different European investigations. From this perspective the presented models, with the inclusion of significant periodic variables, should be of interest for testing outside Norway too.

Distance dependent models for MFS-cut stands will also be evaluated in the future, but the practical use of such functions seems restricted until remote sensing techniques are further developed. Work on the development of the LiDAR remote sensing technology is in the direction of registration of individual tree positions and dimensions, which could add a new dimension to spatially explicit models.

Prediction of diameter growth is only one part of predicting growth and yield of MFS-cut stands. Complete growth and yield predictions are also dependent on designated models for height development or tariff tables (e.g. Fitje & Vestjordet, 1977; Øyen & Andreassen, 2002; Bollandsås, 2007), recruitment (e.g. Lexerød & Eid, 2005) and mortality (e.g. Eid & Tuhus, 2001; Eid & Øyen, 2003). With new revisions of permanent plots the model system should be evaluated and, if necessary, revised or calibrated.

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