BASIC DENSITY OF NORWAY SPRUCE. PART II. PREDICTED BY STEM TAPER, MEAN GROWTH RING WIDTH, AND FACTORS RELATED TO CROWN DEVELOPMENT

Håkan Lindström

Graduate Student
Department of Forest-Industry-Market Studies,
Swedish University of Agricultural Sciences,
S 750 07 Uppsala, Sweden

(Received May 1995)

ABSTRACT

In a fertilization trial near Stråsan, central Sweden, six net parcels of Norway spruce (*Picea abies*) planted in 1957 and clear-felled in 1989 were used to evaluate basic density in relation to growth rate. Growth rate had been regulated by annual dressings of nitrogen, phosphorus, and potassium. The six parcels represented two unfertilized, two medium, and two heavily fertilized treatments. Various thinning procedures were applied to each stand in 1982 and 1988. Based on the author's published paper of cambial activity regulation, this study focused on variables related to crown development and basic density. Three sets of predictors were used: stem taper, mean ring width, and factors related to crown development. Stem taper was found to be a significant predictor of basic density, with r^2 varying from 0.34 to 0.60, depending on the form of the model. Mean ring width was found to be a significant predictor of basic density, with $r^2 = 0.61$. Mean ring width was found dependent on factors related to crown development. Tree height, diameter outside bark, tree height × diameter outside bark, site quality, stand density, and thinning procedure were found to be significant predictors of growth ring width, with $r^2 = 0.95$. Factors related to crown development were used in a multivariate regression model in which tree height, tree height × diameter on bark, and thinning procedure were found to be significant predictors of basic density, with $r^2 = 0.68$ at tree level. At stand level, volume production, stand density, and thinning procedure were found to be significant predictors of basic density, with $r^2 = 0.99$.

Keywords: Crown development, *Picea abies*, stem taper, growth ring width, basic density, wood density.

INTRODUCTION

Based on a recent literature review (Lindström 1996), it has been indicated that crown development acts as a primary regulator of basic density in conifers. Environmental factors were reported to act through the tree crown. Moreover, factors connected to crown development, directly or indirectly, were used in basic density models. Most models were built upon factors such as stem taper or growth ring width, factors that indirectly relate to crown development. (Klem 1934; Klem et al. 1945; Burger 1939, 1953; Nylinder 1953, Hildebrandt 1954; Trendelenburg and Mayer-Wegelin 1955; Schultze-Dewitz 1960; Schniewind 1962; Ericson 1966; Persson 1975; Hakkila 1979).

Studies have also evaluated the effect on basic density in *Picea abies* of growth conditions, within-stand competition, tree characteristics, and tree social status, all factors thought to be related to crown development (Kärkkäinen 1984; Kyrkjeeide 1990; Johansson 1993; Kucera 1994). Regulation of crown development through silvicultural treatment has been shown to alter growth ring width and basic density (Pechmann and Schaite 1955; Madsen et al. 1978; Madsen et al. 1985; Moltesen et al. 1985).

This study focuses on variables that are related to basic density, through their influence or dependence on crown development. Two

TABLE 1. *Fertilizer applications applied to the 'optimum fertility experiment' E26A at Stråsan. Nitrogen was added as ammonium nitrate, phosphorus as superphosphate and potassium and magnesium as 'Kalimagnesia'.*

Nutrient added (kg ha^{-1}) Year	N1	N2	N3	P1	P2	K	Mg	B	Co	Zn	Cu	Mn	Mo
1967	60	120	180	20	40	80	22	0.23	0.01	0.20	0.34	0.77	0.01
1968	60	120	180	—	—	—	—	—	—	—	—	—	—
1969	60	120	180	20	40	80	22	0.80	0.05	0.72	1.20	2.70	0.05
1970	40	80	120	10	20	—	—	—	—	—	—	—	—
1971	40	80	120	—	—	—	—	—	—	—	—	—	—
1972	40	80	120	—	—	—	—	—	—	—	—	—	—
1973	40	80	120	—	—	—	—	—	—	—	—	—	—
1974	40	80	120	20	40	80	22	0.58	0.04	0.51	0.86	1.93	0.04
1975	40	80	120	—	—	—	—	—	—	—	—	—	—
1976	40	80	120		—	—	—	—	—	—	—	—	—
1977	30	60	90	20	40	80	22	1.17	0.07	1.03	1.72	3.86	0.07
1978	30	60	90	—	—	—	—	—	—	—	—	—	—
1979	30	60	90	—	—	—	—	—	—	—	—	—	—
1980	30	60	90	20	40	80	22	1.17	0.07	1.03	1.72	3.86	0.07
1981	30	60	90	—	—	—	—	—	—	—	—	—	—
1982	30	60	90	—	—	—	—	—	—	—	—	—	—

well-known approaches are evaluated: stem taper and growth ring width. A third approach was tested using a set of factors thought to be more directly related to crown development. The study reported herein is the second in a series of papers relating environmental influence to wood properties and how these are associated with end-use properties.

Because of the breadth of the subject, I used a selective approach towards the literature and acknowledge the extensive literature that I was not able to cite.

OBJECTIVES

The dependence of basic density in *Picea abies* at stand and tree level is thought to be regulated by crown development. In this study, two well-known factors depicting crown development were evaluated: stem taper and growth ring width; additional factors thought to be more directly related to crown development were also evaluated. Focus was on the following five relationships: 1. basic density and stem taper, 2. basic density and mean growth ring width, 3. regression of mean growth ring width on external stem characteristics and stand variables, 4. regression of basic density on external stem characteristics and stand variables, and 5. average stand basic density and stand variables.

MATERIAL AND METHODS

The material was obtained from a fertilizing experiment located on glacial till at Stråsan, Gästrikland, in central Sweden, 350 meters above sea level. The treatment included different levels of fertilization intended to obtain an optimum fertility trial. The trial was established to provide information on volume production in response to altered site quality (Tamm et al. 1974). It was assumed that this material would provide biological data reflecting varying growth rates (Tamm et al. 1974; Mead and Tamm 1988). The Stråsan fertilizing trial was established in a plantation-grown stand of *Picea abies* with the same seed source. This stand had roughly reached breast height (1.3 m above stump height) when it was chosen as suitable for the fertilizing treatment. Established in 1967, the trial consisted of a 4 × 3 × 2 factorial experiment in nitrogen (N), phosphorus (P), and other nutrients (K+) with two blocks. The K+ fertilizer consisted of K, Mg, and micro-nutrients. The N dressings were repeated each spring; all other nutrients were applied at less frequent intervals. The level and

TABLE 2. *Initial stand characteristics of each parcel in 1966.*

Parcel	Treatment	Number of seedlings ha^{-1}	Mean height (m)
P34	Unfertilized	2,525	1.15
P51	Unfertilized	1,750	1.14
P10	N1P1	3,025	1.19
P36	N1P1	2,775	1.32
P18	N3P2	2,625	1.58
P41	N3P2	2,625	0.94

timing of the nutrient applications were adjusted every few years on the basis of foliar analyses in order to maintain constant fertility differences between treatments (Table 1). Plots had a gross area of 0.09 hectare with a central measured plot of 0.04 hectare.

In 1966, at the start of the fertilization treatment, the number of seedlings within each parcel ranged from 1750 to 3250 seedlings per hectare; average height ranged from 0.94 to 1.54 m (Table 2). In 1989 the diameter distribution of trees within each parcel was a fairly normal distribution (Fig. 1.1 to 1.6). In 1989, 353 trees without rot or other injuries were clear-felled. Tree height was measured on 153 randomly selected trees on about half the stems of each parcel (Personal communication, Professor C. O. Tamm and Doctor of Forestry A. Aronsson, both from the Department of Ecology and Environmental Research, The Swedish University of Agricultural Sciences, Uppsala).

Survey sampling

A bolt approximately 0.5 m long was cut from each tree about 1.0 m above stump height. Two knot-free discs, 2–4 cm in width, were cut from the center of each bolt. The discs represented a height near 1.3 m, close to breast height. These discs were transported to the Norwegian Forest Research Institute, Wood Technology Section, to determine wood characteristics.

Variables used in the statistical models

The diameter of each tree was calipered to the nearest millimeter outside bark at breast height (1.3 m above ground). The average diameter outside bark on height measured trees of each stand can be seen in Table 3. Each disc was debarked and the diameter calipered to the nearest millimeter. Mean growth ring width was calculated by dividing the diameter inside bark by twice the number of annual rings.

The height of about half the trees in each parcel was measured to the nearest decimeter (Table 3). Tree height × diameter outside bark was calculated as tree height multiplied by diameter outside bark. Volume production, defined as total stem volume production per hectar (m^3sk ha^{-1}), was measured in each parcel (Eriksson 1976; Aronsson and Tamm 1991) (Table 3).

Stand density was calculated similarly to Baker's (1950) interpretation of stand density. Baker's definition was modified here in that the average tree height and average tree diameter were based on the trees subjected to height measurement within each parcel. In this case, stand density = average tree height of height measured trees/average diameter outside bark of height measured trees (Table 3). Stem taper of height measured trees was calculated as individual tree height divided by individual tree diameter outside bark.

The parcels were subject to thinning in 1982 and 1988. In 1988, only 4 of the stands were thinned. To allow an interpretation of the effect of thinning procedure on wood density, Ericson's definition (1966) of selective thinning ratio (α), defined as a ratio between stem of mean basal area of removed trees and stem

FIG. 1. (**1**) Diameter distribution for control parcel 51 unfertilized (n = 55) (**2**) Diameter distribution for control parcel 34 unfertilized (n = 69) (**3**) Diameter distribution for parcel 36 medium fertilized (n = 72) (**4**) Diameter distribution for parcel 10 medium fertilized (n = 56) (**5**) Diameter distribution for parcel 41 heavily fertilized (n = 50) (**6**) Diameter distribution for parcel 18 heavily fertilized (n = 51).

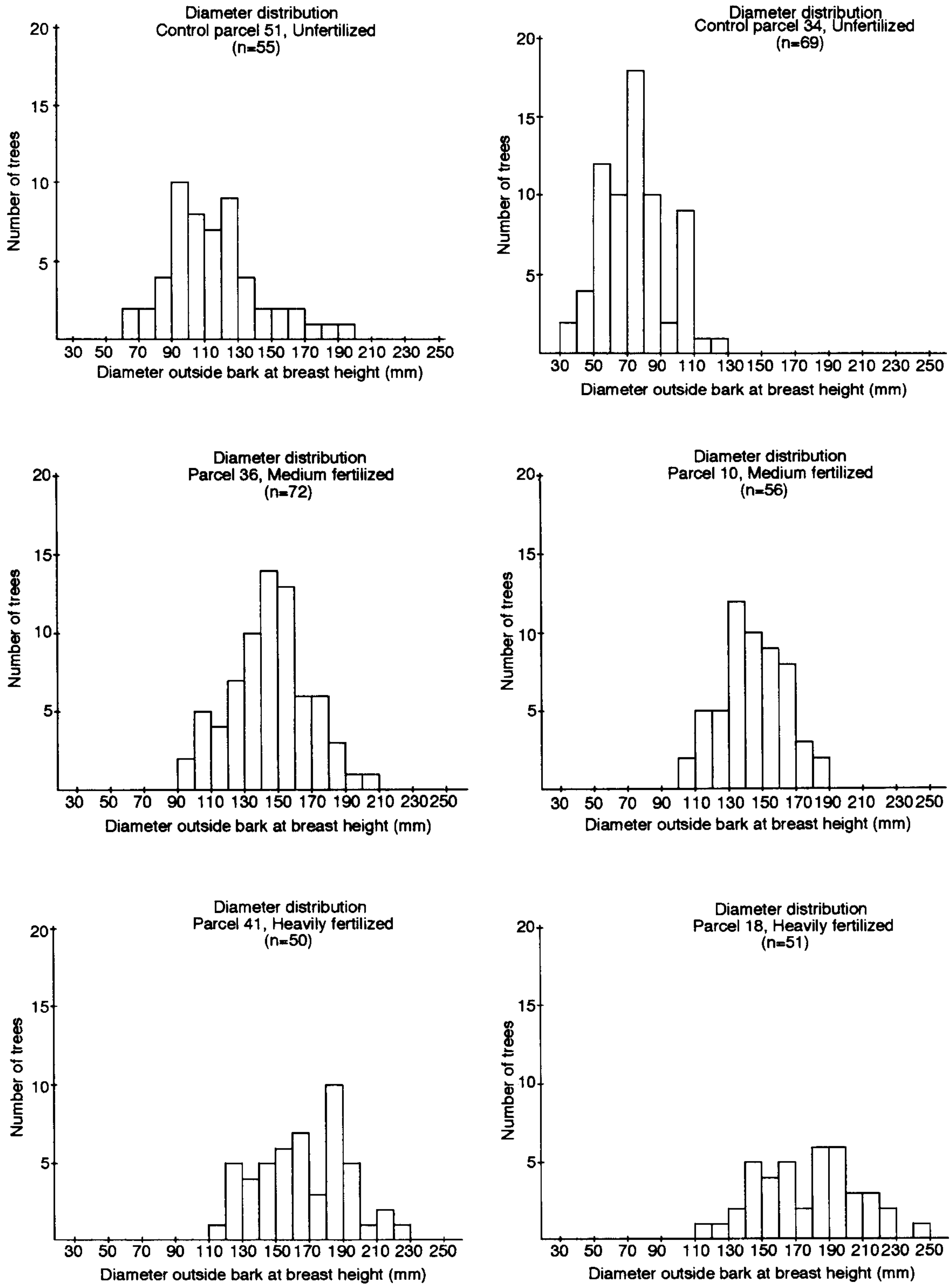
Diameter distribution
Control parcel 51, Unfertilized
(n=55)
Diameter distribution
Control parcel 34, Unfertilized
(n=69)
Diameter distribution
Parcel 36, Medium fertilized
(n=72)
Diameter distribution
Parcel 10, Medium fertilized
(n=56)
Diameter distribution
Parcel 41, Heavily fertilized
(n=50)
Diameter distribution
Parcel 18, Heavily fertilized
(n=51)
Number of trees
Diameter outside bark at breast height (mm)
0
5
10
15
20
30 50 70 90 110 130 150 170 190 210 230 250

TABLE 3. *Stand characteristics and thinning procedure registered in 1989.*

Parcel	α_{tot}	Volume production (m^3sk ha^{-1})[a]	Stand density	Average height (dm)	Average diameter (o.b.) of height measured trees (mm)
P34	1.0196	39.5	0.893	69	78
P51	0.7175	87.2	0.831	109	131
P10	0.6781	218.8	0.876	130	148
P36	0.8595	249.5	0.865	128	148
P41	0.7247	227.5	0.738	127	172
P18	0.7292	321.3	0.753	143	189

[a] m^3sk ha^{-1} is total produced bole volume above stump height per hectare.

of mean basal area of remaining trees, was used after a modification. The thinning ratio in the study reported herein was calculated as the thinning ratio of 1982 multiplied with the thinning ratio of 1988 to obtain total thinning procedure, $\alpha_{tot} = (\alpha_{1982}) \times (\alpha_{1988})$(Table 3).

Basic density was determined by the water displacement method using one of the two discs cut from breast height of each tree. The discs then were saturated in water for 24 h. Thereafter, the discs were pierced with a needle attached to a tripod and lowered into distilled water in a container placed on a Mettler-scale, PM 30-K. Reading of the weight was made with 0.1 g accuracy, and a transformation into volume was made. Green volume data of the discs were collected and registered together with parcel number, tree number, and disc number. The discs then were placed into an air-ventilated oven at 103 ± 3°C, for 24 h, after which four discs in every oven were sampled and weighed. This procedure continued until the weight of the discs did not change after an additional 2 h of oven-drying (Kucera 1992). The discs were then regarded to have attained oven-dry weight, which was registered together with parcel number, tree number, and disc number. Basic density, expressed as kg/m³ was then calculated.

Statistical analysis using multivariate regression methods was carried out with the SAS statistical software version 6.09 (Anon. 1994).

RESULTS

Relationship between basic density and stem taper

Linear regression was used to determine the relationship between stem taper and wood density. SAS PROC REG was used to build three linear models of the following form:

Model

(1) $y = a + bx$ (Fig. 5)

(2) $y = a + bx_2$ (Fig. 6)

(3) $y = a + bx_3$ (Fig. 7)

where y = basic density at breast height; x = (tree height)/(diameter outside bark); x_2 = (log (tree height)/(diameter outside bark); x_3 = log (x_2). Correlation, statistical significance, and values of a and b for models 1 to 3 are given in Table 4. Residual plots for each model can be seen in Figs. 2–4.

Relationship between basic density and growth ring width

Linear regression was used to determine the relationship between basic density and growth ring width. SAS PROC REG was used to build a model of the following form:

$$y = a + bx \qquad n = 353$$

where y = basic density at breast height; x = average growth ring width at breast height. Correlation, statistical significance, and values of a and b can be seen in Table 5; a residual plot of the model can be seen in Fig. 5.

Regression of mean ring width on external tree characteristics and stand variables

The SAS REG procedure was used to determine an optimal model. Three selection techniques were used: stepwise regression, best ADJRSQ, and best Mallows' CP. All three yielded the following model:

$$y = a + b_1x_1 + b_2x_2 + b_3x_3 + b_4x_4 + b_5x_5 + b_6x_6$$

TABLE 4. *Relationship of basic density and stemtaper using models 1 to 3.*[a]

Regression equation	r^2	a	s_a	b	s_b
y = a + bx	0.3434	211.11***	16.61	173.56***	19.53
$y = a + bx_2$	0.5084	288.16***	5.88	1,895.34***	151.68
$y = a + bx_3$	0.6022	657.05***	19.91	89.18***	5.90

[a] For each model; *, ** and ***, indicate $P \leq 0.05$, $P \leq 0.01$ and $P \leq 0.001$, respectively (Anon. 1994).

where y = average growth ring width; x_1 = tree height; x_2 = diameter outside bark; x_3 = tree height × diameter outside bark; x_4 = site quality; x_5 = stand density; x_6 = thinning procedure. Correlation, statistical significance, and values of a, b_1, b_2, b_3, b_4, b_5, and b_6 can be seen in Table 6. A residual plot can be seen in Fig. 6.

Regression of basic density on external tree characteristics and stand variables

The SAS REG procedure was used to determine an optimal model. Three selection techniques were used: stepwise regression, best ADJRSQ, and best Mallows' CP. All three yielded the following model:

$$y = a + b_1x_1 + b_2x_2 + b_3x_3$$

where y = basic density at breast height; x_1 = tree height; x_2 = tree height × diameter outside bark; x_3 = thinning procedure. Correlation and statistical significance and values of a, b_1, b_2, and b_3 can be seen in Table 7; residual plot for the model can be seen in Fig 7.

Relationship between average stand basic density and stand variables

The SAS REG procedure was used to determine an optimal model. Three selection techniques were used: stepwise regression, best ADJRSQ, and best Mallows' CP. All three yielded the following model:

$$y = a + b_1x_1 + b_2x_2 + b_3x_3$$

where y = average basic density of each parcel; x_1 = stand density; x_2 = volume production; x_3 = thinning procedure. Correlation, statistical significance and values of a, b_1, b_2 and b_3 can be seen in Table 8; residual plot for the model can be seen in Fig. 8.

DISCUSSION

Material

The material for this study consisted of even-aged planted trees that represented a wide range of growth rate. The material provided an opportunity to evaluate the influence of growth

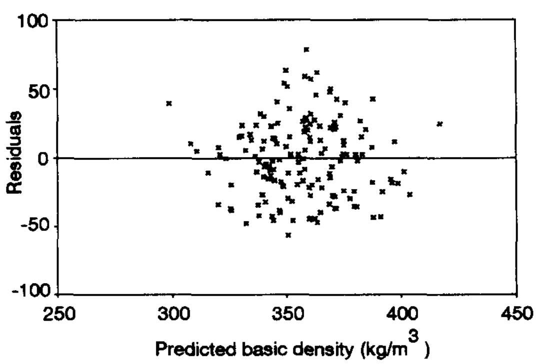

FIG. 2. Residuals from the regression of basic density on stem taper using model 1 (y = a + bx).

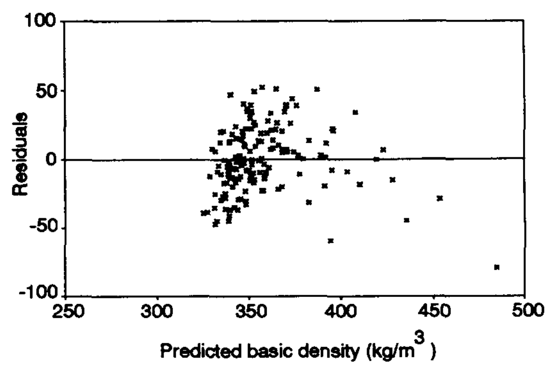

FIG. 3. Residuals from the regression of basic density on stem taper using model 2 ($y = a + bx_2$).

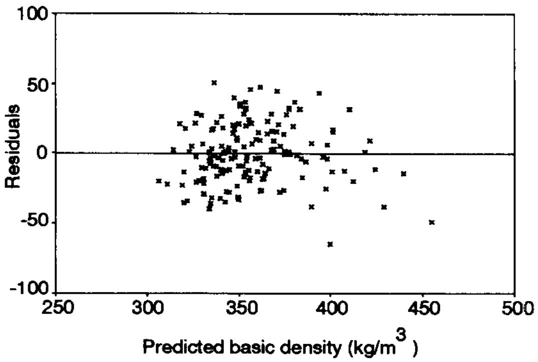

FIG. 4. Residuals from the regression of basic density on stem taper using model 3 ($y = a + bx_3$).

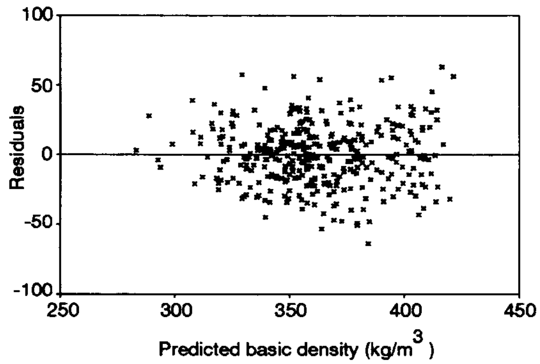

FIG. 5. Residuals from the regression of basic density on mean growth ring width ($y = a + bx$).

conditions on basic density development in even-aged planted stands of *Picea abies.*

However, some intrusion of the growing conditions occurred that can impact the results. The Stråsan fertilization trial was established as a plantation with the same seed source. Genetic variation of the evaluated trees is therefore thought to be reduced. If genetic variation is reduced, it is still possible that basic density variation caused by genetic differences remains. This view is strengthened by the fact that natural regeneration, to some extent, is likely to have taken place in all parcels of the fertilization trial. So, even if the parcels were planted and considered even-aged, variation in the number of growth rings at breast height will occur. Of the clear-felled trees, seven were removed from the material because of stem injuries and stem rot, something that is believed to cause abnormal basic density. Also, interaction effects of crown development likely occurred, given that fertilization treatment began when the trees attained about 1.3 m. Crown development, growth rate, and growth allocation were then abruptly altered. Changes in growth rate from low to high, as a result of fertilization, were likely to lead to conditions not exhibited in forests where growth rate is naturally high. However, because the wood sample was taken at breast height, only minor deviations from natural stand development are to be expected.

Also, note that the trial had been initialized with the primary aim on volume production studies. Therefore, a limited number of variables, necessary in such studies, were recorded and the number of variables to evaluate the relationship of crown development and basic density became limited. Indirect variables known to be connected with crown development, instead of direct measurement of crown length and diameter, were therefore used in the statistical evaluation.

In any case, the trees of each parcel did provide a valuable opportunity to examine how general growth conditions alter basic density. This is the first modern fertilization trial of *Picea abies* in Sweden where the design of the experiment in terms of parcel size and number of replications are fully acceptable. This view is also based on the belief that intrusion factors in the trial only slightly affect basic density.

TABLE 5. *Relationship of basic density and mean growth ring width.*[a]

Regression equation	r^2	a	s_a	b	s_b
$y = a + bx$	0.613	458.59***	4.27	−35.29***	1.49

[a] *, ** and ***, indicate $P \le 0.05$, $P \le 0.01$ and $P \le 0.001$, respectively (Anon. 1994).

TABLE 6. *The regression of mean growth ring width on external stem characteristics and stand variables*[a]

Regression equation	r^2	a	s_a	b_1	s_{b1}	b_2	s_{b2}	b_3	s_{b3}	b_4	s_{b4}	b_5	s_{b5}	b_6	s_{b6}
$y_1 = 1 + b_1x_1 + b_2x_2 + b_3x_3 + b_4x_4 + b_5x_5 + b_6x_6$	0.95	5,268.98***	598.40	−9.84***	1.76	9.96***	1.86	0.05***	0.01	−0.93*	0.38	−2,544.86***	451.67	−1,613.96***	198.39

[a] *, ** and ***, indicate $P \le 0.05$, $P \le 0.01$, and $P \le 0.001$, respectively (Anon. 1994).

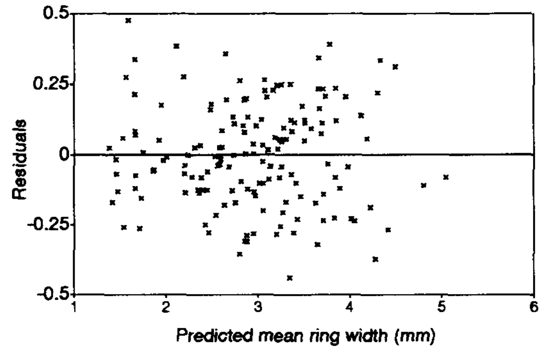

FIG. 6. Residuals from the regression of mean growth ring width on external tree characteristics and stand variables.

Results

This study focused on variables that are related to basic density, through their influence or dependence on crown development. The statistical evaluation was divided into three approaches.

The first approach was to focus on stem taper as a predictor of basic density. Stem taper has been seen as a function of crown development, where strongly tapering stems have been said to be the result of excessive crown development. Basic density was found statistically dependent on stem taper with $r^2 = 0.34$. Here, trees with strongly tapering stems were found to have lower basic density than trees with less stem taper. Residuals of each stem taper model suggest that correlation increases with use of the logarithmic value of height in the model. This implies that a differentiation of trees with the same stem taper but with different height increases correlation between basic density and stem taper. The best model expression found for a logarithmic transformation of stem taper gave an adjusted $r^2 = 0.60$. Based on the literature review, there is reason to believe that stem taper will differ and interact with site quality, stand density, and stand age. Therefore, stem taper should be used mainly as a predictor of basic density in young and even-aged stands.

The second approach used growth ring width

TABLE 7. *The regression of basic density on external stem characteristics and stand variables*[a]

Regression equation	r^2	a	s_a	b_1	s_{b1}	b_2	s_{b2}	b_3	s_{b3}
$y = a + b_1x_1 + b_2x_2 + b_3x_3$	0.681	296.57791***	23.99068	0.57744***	0.16786	−0.00436***	0.00051	90.12311***	18.52092

[a] *, ** and ***, indicate $P \le 0.05$, $P \le 0.01$, and $P \le 0.001$, respectively (Anon. 1994).

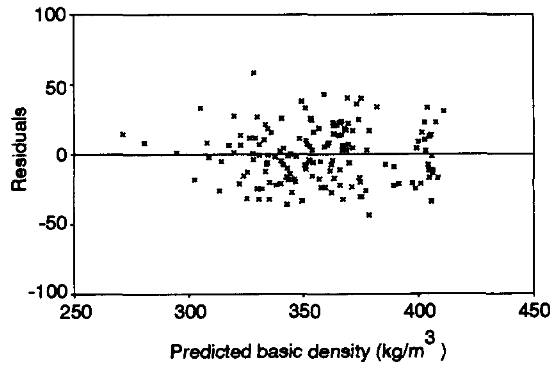

FIG. 7. Residuals from the regression of basic density on external tree characteristics and stand variables.

as a predictor of basic density. Growth ring width was found to be negatively correlated with wood density, with an adjusted $r^2 = 0.61$.

The regression of mean growth ring width on external stem characteristics and stand variables gave an $r^2 = 0.95$. Moreover, statistical significance was found on the dependence of mean ring width to factors related to crown development. The results suggest that mean growth ring width is dependent on factors related to crown development.

The third approach was to use variables related to crown development to predict basic density. In agreement with the literature review, a tree will adapt growth allocation and wood structure to meet mechanical, nutritional, and water conduction demand through hormonal growth regulation. The external relationship of height and diameter of a tree stem has been used to express relative dominance of a tree individual. A truly dominant tree with limited restriction of crown growth will have a greater proportion of diameter growth compared with intermediate and suppressed trees. From the perspective of crown development as a determinant of basic density, it can be argued that tree characteristics such as tree height and tree diameter could serve as variables correlated with basic density. In the study reported here, tree height was found positively correlated with basic density. This is in agreement with a similar study (Kärkkäinen 1984).

TABLE 8. *Relationship of average stand basic density and stand variables*[a]

Regression equation	r^2	a	s_a	b_1	s_{b1}	b_2	s_{b2}	b_3	s_{b3}
$y_1 = a + b_1x_1 + b_2x_2 + b_3x_3$	0.998	182.896**	14.068	142.030*	16.143	−0.111**	0.010	102.510**	8.064

[a] *, **, and ***, indicate $P \le 0.05$, $P \le 0.01$, and $P \le 0.001$, respectively (Anon. 1994).

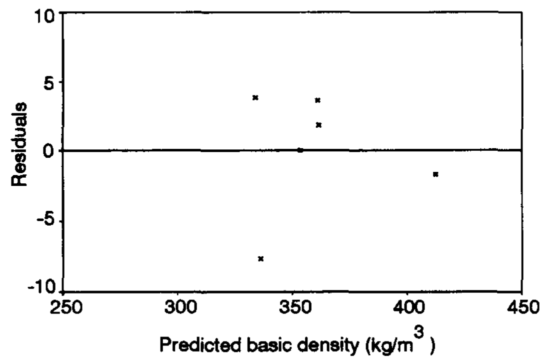

FIG. 8. Residuals from the regression of average basic density on stand variables.

It can be argued that external tree characteristics such as tree height × diameter and tree height describe general crown size and crown allocation. Another factor thought to be related to crown development is the thinning procedure. In the study reported here, thinning procedure is defined as a ratio between mean basal area of stems in removed trees and mean basal area of stems in remaining trees. Based on that, tree diameter in an even-aged stand is dependent on crown size. It can be presumed that a thinning ratio will depict the relative crown size of the trees removed. In the long-term, the choice of thinning procedures is likely to change the course of crown competition and crown development at stand level. At tree level, tree height, height × diameter, and thinning procedure were found significant predictors of basic density with $r^2 = 0.68$.

At stand level, the third approach was also used, where average basic density was evaluated with factors thought to regulate crown development. Factors related to lateral crown competition and crown development, such as volume production, stand density, and thinning procedure, were found significant, where the model yielded an adjusted $r^2 = 0.99$. This correlation coefficient seems to provide an almost perfect explanation of basic density variation at stand level. To predict average basic density by factors thought to influence crown development seems to give an accurate description of average basic density. However, since this study contained a limited data set in which only six parcels were available, this result should be treated with caution. This study only suggests that growth conditions thought to regulate crown development play a major part in basic density development at stand level.

CONCLUSIONS

From the literature review and the results of this study, the following conclusions can be drawn:

- In young even-aged stands of *Picea abies*, stem taper can be seen as a predictor of basic density. The best model expression yielded an $r^2 = 0.60$.
- Growth ring width was found significant to basic density, where the best model yielded an adjusted $r^2 = 0.61$.
- Tree height, diameter outside bark, tree height × diameter outside bark, volume production, stand density, and thinning procedure were found significant predictors of mean growth ring width with $r^2 = 0.95$.
- At tree level, tree height, tree height × diameter outside bark, and thinning procedure were found significant predictors of basic density with $r^2 = 0.68$. In the best model at stand level, volume production, stand density, and thinning procedure were found significant predictors of basic density with $r^2 = 0.99$.
- There is a relationship between variables related to crown development and basic density. Increased accuracy would probably be seen if this reasoning could be further quantified. In an effort to meet these objectives, we need a silvicultural concept that connects environmental variables, tree age, stand competition, and silvicultural treatment to crown development and wood structure.

ACKNOWLEDGMENTS

For general guidance and discussions, I thank Associate Professor Bohumil Kucera, Norwegian Forest Research Institute; Associate Professor Thomas Thörnqvist, SÖDRA Timber; and Dr. of Forestry Torbjöm Elofsson, Department of Forest Products, Swedish University of Agricultural Sciences. For encouragement and proofreading, I thank Professor Göran Lönner and graduate student John Arlinger at the Department of SIMS, Swedish University of Agricultural Sciences, Uppsala.

From the USDA Forest Service, Forest Products Laboratory, in Madison WI, I thank Dr. Steve Verrill, Mathematical Statistician, and Mrs. Cherilyn Hatfield, Statistician, for their invaluable statistical help, and Library Technican Mary Kemp for her help with the literature search. For discussions and valuable comments, I thank Dr. Said Abubakr, Supervisory Chemical Engineer; Mr Daniel Caulfield, Research Chemist; Mr John Klungness, Chemical Engineer; and M. F. Gary Myers, Research Forest Products Technologist. Finally I would like to thank Jean Livingston, Technical Publications Editor, for editing assistance.

This study was funded by Skogstyrelsens Forskningsfond, Knut och Alice Wallenbergs stiftelse, Sverige-Amerika stiftelsen, and Jacob Wallenbergs Forskningsstiftelse/Lars-Erik Thunholms stiftelse för främjande av vetenskaplig forskning.

REFERENCES

ANON. 1994. SAS/STAT User's Guide, Version 6.09, 4th ed. vol. 1, 2.

ARONSSON, A, AND C-O TAMM. 1991. Continuous measurement of stand and tree parameters at Strasan fertilization experiment. (Unpublished). Dept. of Ecology and Environmental Research, The Swedish University of Agricultural Sciences, Uppsala, Sweden.

BAKER, F. S. 1950. Principles of silviculture. McGraw-Hill Book Company, Inc., New York, Toronto, London.

BURGER, H. 1939. Baumkrone und Zuwachs in zwei hiebsreifen Fichtenbeständen. Mitt. Schweiz. Anstalt forstl. Versuchsw. 21:147–176.

———. 1953. Holz, Blattmenge und Zuwachs. XIII. Fichten im gleichalterigen Hochwald. Mitt, Schweiz. Anstalt forstl. Versuchsw. 29:38–103.

ERICSON, B. 1966. Gallringens inverkan på vedens torrråvolymvikt, höstvedhalt och kärnvedhalt hos tall och gran. Dept. of For. Yield Research. Res. Note No. 10.

ERIKSSON, H. 1976. Production of Norway spruce (*Picea* *abies*) in Sweden. Swedish Univ. of Agricultural Sciences, Dept. For. Yield Res., Res. Note No. 51.

HAKKILA, P. 1979. Wood density survey and dry weight tables for pine, spruce, and birch stems in Finland. Communicationes Instituti Forestalis Fenniae 96.3:1–59.

HILDEBRANDT, G. 1954. Untersuchungen an Fichtenbeständen über Zuwachs und Ertrag reiner Holzsubstanz. Deut. Verlag Wissenschaften, Berlin, Germany.

JOHANSSON, K. 1993. Influence of initial spacing and tree class on the basic density of *Picea abies*. Scand. J. Forest Res. 8:18–27.

KÄRKKÄINEN, M. 1984. Effect of tree social status on basic density of Norway spruce. Silva Fennica. 18(2): 115–120.

KLEM, G. G. 1934. Undersökelser av granvirkets kvalitet. Medd. Norske Skogsforsøksv. 5(2):197–348.

———, F. LOSCHBRANDT, AND O. BADE. 1945. Undersökelser av granvirke i forbindelse med slipe- og sulfit kokeforsök. Medd. Norske Skogsforsøksv. 31:1–127.

KUCERA, B. 1992. Skandinaviske normer for testing av sma felfrie prover av heltre. Skogforsk, Norwegian Forest Research Institute, Dept. of Forestry, Agricultural University of Norway.

———. 1994. A hypothesis relating current annual height increment to juvenile wood formation in Norway spruce. Wood Fiber Sci. 26(1):152–167.

KYRKJEEIDE, P. A. 1990. A wood quality study of suppressed, intermediate, and dominant trees of plantation grown *Picea abies*. USDA Forest Products Laboratory, Madison, WI.

LINDSTRÖM, H. 1996. Basic density in Norway spruce: Part I. A literature review. Wood Fiber Sci. 28(1):15–27.

MADSEN, T. L., P. MOLTESEN, AND P. O. OLESON. 1978. The influence of thinning degree on basic density, production of dry matter, branch thickness and number of branches of Norway spruce. Det Forstl. Forsøgsv. Danm. 36:181–204.

———, ———, AND ———. 1985. Effect of fertilization on the basic density and production of dry matter in Norway spruce. Det Forstl. Forsøgsv. Danm. 40(2):141–172.

MEAD, D. J., AND C. O. TAMM. 1988. Growth and stem form changes in *Picea abies* as affected by stand nutrition. Scand. J. Forest Res. 3:505–513.

MOLTESEN, P., T. L. MADSEN, AND P. O. OLESON. 1985. The influence of spacing on the production of dry matter and wood quality of Norway spruce. Det Forstl. Forsøgsv. Danm. 40:53–76.

NYLINDER, P. 1953. Volymviktsvariationer hos gran. Medd. Statens Skogsforskningsinstitut. 43(3):1–44.

PECHMANN, H. V., AND O. SCHAITE. 1955. Die auswirkung der waldbaulichen Behandlung auf die holzeigenschaften der Fichte. Fw.Cbl. 74:305–318.

PERSSON, A. 1975. Wood and pulp of Norway spruce and Scots pine at various spacings. Swedish Univ. of Agricultural Sciences, Notes 37.

SCHNIEWIND, A. P. 1962. Horizontal specific gravity variation in tree stems in relation to their support function. Forest Science. 8(2):111–118.

SCHULTZE-DEWITZ, G. 1960. Wie wirkt der Einfluss der Stellung eines Baumes im Bestand auf seine Holzstruktur aus ?. Holzforsch. u. Holzverwert. 12:30–33.

TAMM, C. O., A. ARONSSON, AND H. BURGTORF. 1974. The optimum nutrition experiment Stråsan. A brief description of an experiment in a young stand of Norway spruce (*Picea abies* Karst.) Res. Note. 17, Royal Coll. For. Dept. of Forest Ecology. Stockholm, Sweden.

TRENDELENBURG, R., AND H. MAYER-WEGELIN. 1955. Das Holz als Rohstoff. Carl Hanser, Munich, Germany.