Intra-Tree Models of Basic Density in Norway Spruce as an Input to Simulation Software

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Basic density is said to influence aspects of conversion, properties, and end-use of forest products. Consequently, it is argued that accurate models of basic density variation, within and between trees, could be used to improve the utilisation of wood as an industrial raw material. The objective of the present study was to develop basic density models based on Norway spruce trees, that could be used within a model system for conversion simulation studies. Nineteen stands of Norway spruce (*Picea abies* (L.) Karst.) were selected throughout Sweden. Based on dbh, two small, two moderate, and two large timber trees were taken from each stand. Dbh varied between 180–470 mm, tree height between 17–34 m, and total age between 51–152 years. Each selected tree was cross-cut into logs; discs were prepared from the butt end of each log and from the top end of the top log. Computed tomography scanning and image analysis were used to determine basic density and growth ring development on sampled discs. Basic density development in 20-mm segments from pith outwards was modelled in models based on ring width, tree and growth condition data. The resulting models had an adjusted R^2 of 0.37–0.51 and a RMSE of 37–41 kg/m^3.

Keywords basic density, growth conditions, image analysis, *Picea abies*, wood density
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1 Introduction

1.1 Utilising Information on Wood Variation in a Conversion Software Tool

Wood properties such as basic density (*BD*), microfibril angle, spiral grain, compression wood, juvenile wood, and large knots influence the properties, end-use and value of sawn wood (Cave and Walker 1994, Kliger et al. 1995, Danborg 1996, Persson 1997, Björklund and Julin 1998, Forsberg 1999, Ormarsson 1999). In this perspective, it would be beneficial to develop tools that could be used to differentiate and select trees that are suited for a specified end-use (Uusitalo 1997). In fact, a more refined selection and differentiation of the timber resource will be increasingly emphasised with the gradual emergence of a more fast-grown conifer wood resource (Thörnqvist 1993, Kennedy 1995). Consequently, it is argued that accurate models of wood variation could be employed to ensure that the quality and specifications by the end-user are met (Eriksson and Kyrkjeeide 1992, Tian et al. 1995, Persson 1997). In recent years, some model systems, e.g. AUTOSAW (Todoroki 1997) and SOPT (Lönner 1996) have been developed to integrate information of wood- and knot properties in conifer tree stems into the production process of wood-based products. It is indicated that such systems can be used to establish a linkage between raw material properties, end-use requirements, and product value, thereby providing a better utilisation of the given wood resource. The input to the simulation software may consist of empirical data or a set of non-destructive general models of wood variation. In the latter case, it will be necessary to derive general models of wood variation.

1.2 Modelling Basic Density Variation in Tree Stems

Wood formation in a conifer tree stem can be viewed as a combination of genetics (Zhang and Morgenstern 1995, Hylen 1997, Rozenberg and Cahalan 1997, Shelbourne et al. 1997, Hannrup 1999) and the individual tree's growth environment (Kärkkäinen 1984, Kučera 1994, Lindström 1997, Bergqvist 1999, Pape 1999). The outcome will be a tracheid structure that efficently meet water-transport and mechanical criteria (Niklas 1992, Mattheck and Kubler 1995). With the notion that wood structure variation in conifers is partly an outcome of growth conditions, there have been attempts to construct *BD* models based on growth-related variables. These studies are unfortunately limited to relatively few trees and are often taken from a restricted geographical area (Olesen 1976, Kärkkäinen 1984, Kyrkjeeide 1990, Danborg 1994, Kučera 1994, Eikenes et al. 1995, Lindström 1997). Nevertheless, these studies based on Norway spruce, show that a growth environment, which favours rapid crown development, yield trees with wide growth rings and low *BD*. In contrast, trees that grow more slowly due to a more moderate crown development will have more narrow growth rings and higher *BD*.

In the present study the aim is to develop *BD* models of Norway spruce trees grown under a wide range of growth conditions. The objective was to model *BD* (kg/m^3) in 20-mm segments, from pith outwards, at different stem heights.

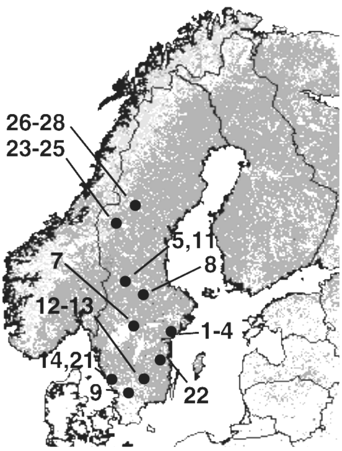
The aim of the derived models is that they, together with other wood property models e.g. Moberg 1999, will be implemented into the software SOPT – a model system for conversion simulation studies (Lönner 1996, Björklund and Julin 1998). In such an environment, the models could be applied to study the utilisation of wood.

2 Material and Methods

2.1 Selection of Trees and Stands

Norway spruce stands (*Picea abies* (L.) Karst.) were selected throughout Sweden in order to represent a wide range of growth conditions (Table 1). Data on silvicultural procedures such as thinning and initial spacing was only available on some sites. Based on tree diameter, a selection of two small, two moderate, and two large timber trees was made within each stand. Each selected tree was felled, and the stems were cross-cut and marked into logs. The minimum top diameter was 120 mm. In total 114 trees were sampled. These trees had a range in diameter of 180–470 mm at breast height, a tree height between 17–35 m, and a total age varying between 51–152 years. This variation in tree size was aimed to be representative of commercial timber trees of Norway spruce in Sweden. Tree and stand data was here pooled from, "Log Scanner Project" (FAIR-CT 96-1188), a pilot project and "Improved spruce timber utilisation" (FAIR-CT96-1915) (Moberg 1999).

Table 1. Description of selected stands.



Geographical location of stands in Sweden	Stand nr	Altitude m, a.s.l	Location (latitude, longitude)	Stand age	Site index (H100)	Standing volume m^3 ha^{-1}	Mean dbh mm	Mean tree height m
	1	40	58°49'N 16°56'E	51	G36	676	190	19
	2	40	58°49'N 16°56'E	51	G36	619	270	27
	3	40	58°49'N 16°56'E	51	G36	432	300	30
	4	40	58°49'N 16°56'E	51	G36	410	240	24
	5	220	60°53'N 14°23'E	105	G25	449	230	23
	7	80	59°10'N 14°12'E	110	G26	.	220	24
	8	260	60°31'N 15°08'E	140	G20	220	220	20
	11	220	60°53'N 14°22'E	135	G26	353	320	28
	12	225	57°08'N 14°44'E	120	G28	370	310	27
	13	185	57°09'N 14°46'E	110	G34	465	330	30
	14	170	56°56'N 12°47'E	61	G36	719	290	24
	21	95	56°41'N 13°06'E	101	G33	510	280	30
	22	120	58°12'N 15°56'E	76	G32	581	380	26
	23	310	63°13'N 14°30'E	82	G25	284	190	18
	24	310	63°13'N 14°30'E	82	G26	301	250	21
	25	310	63°13'N 14°30'E	82	G26	290	240	21
	26	270	64°04'N 16°15'E	152	G18	243	250	21
	27	270	64°04'N 16°15'E	152	G18	162	230	20
	28	270	64°04'N 16°15'E	152	G18	145	160	16

2.2 Ring Number and Ring Width

Tree discs of approximately 40-mm thickness were taken at stump height, and successively upwards close to each cross cutting point in each stem (Fig. 1). These discs were divided into disc pairs. The first disc in each disc pair was polished at original moisture content and a CCD camera with a 0.1-mm-pixel resolution was used to obtain digital images of the growth ring pattern. The images were analysed using WinDENDRO™ ver.6.3a (Fig. 1). The number of growth rings and ring width, in two opposite directions, were determined from pith outwards on each disc. The standard output was saved as a PC text file and imported into the SAS program ver. 6.12 (SAS Institute 1998).

2.3 Determination of *BD*

The second disc in each disc pair was conditioned to eight percent moisture content and then CT (computed tomography)-scanned in a Siemens SOMATOM AR.T that produced images with 512 × 512 pixels. The settings were 110 keV, 50 mA/s, three seconds exposure, scanning width two mm, using a SP 9 standard filter. Dependent on log size, each image was scanned with a field of view of 350 mm, 400 mm, or 450 mm, corresponding to a pixel resolution of 0.68 mm, 0.78 mm, and 0.88 mm respectively (Lindgren 1992). *BD* analysis was performed on a Macintosh computer using the public domain NIH Image program ver. 1.59 (developed at the U.S. National Institutes of Health and available on the Internet at http://rsb.info.nih.gov/nih-image/). Using a CT-scanned image of a waterphantom (Lindgren 1992), the grayscale values of water and air were obtained and used as density references in the calibration of the NIH image analysis software. Each density image was imported into the image analysis software where *BD* from pith outwards of each disc was determined using a histogram function applied onto the image in four radii (Fig. 1). The x-, y-coordinates from each of the four histograms of each disc were copied into an Excel spreadsheet and saved as an individual text file. Programs written in Visual Basic ver. 5.0 were used to transform and manage the text files into usable PC-data.

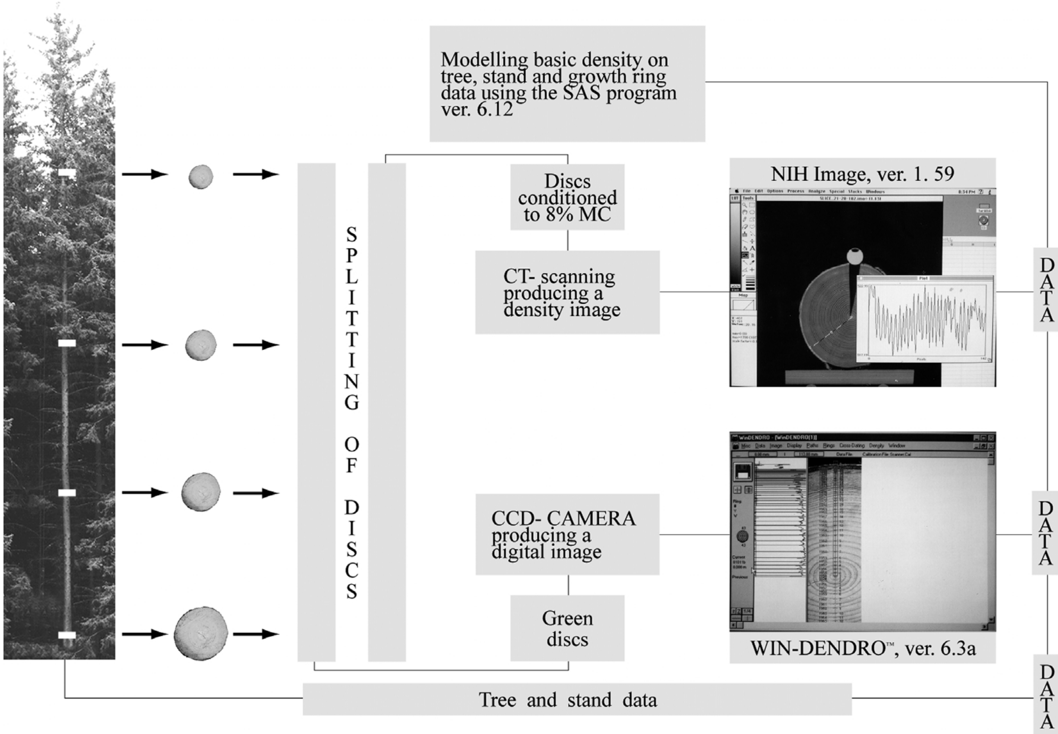


Fig. 1. Project description.

2.4 Calculation of Average Ring Number from Pith, Ring Width, and *BD* in 20-mm Segments

Using the SAS program ver. 6.12 (SAS Institute 1998), routines were written to combine *BD*- and growth ring measurements with tree- and stand data. Here, routines were written that delineated 20-mm segments on the discs. Within each 20-mm segment, average ring number from pith, ring width, and *BD* was calculated. Subsequently, ring number-, growth ring-, *BD*-, tree-, and stand data were merged.

2.5 Number of Observations

During image analysis of *BD*, it was discovered that a great deal of discs contained cracks, and/or compression wood, knots, rot, and resin pockets. For instance, occurrence of compression wood was seen on the image as areas that differed in grayscale from surrounding "normal wood". These areas had distinctive high wood densities and could often be seen on images obtained from less circular discs. Density images that had deviating grayscale and/or high local densities were used to identify actual discs that after inspection were found to have corresponding patches of compression wood. No attempts to quantify the compression wood areas were undertaken. After removal of discs with excessive wood defects, the material consisted of 1597 segments on 277 discs taken from 104 trees.

2.6 Statistical Analysis

The SAS REG procedure was used to build models of *BD* development. A first screening of alternative models was undertaken using stepwise regression, best RSQUARE, and best Mallow's CP. The variables in the final models were selected with a set of selection criteria to avoid multicollinearity. When the selection criteria yielded a number of models with similar RMSE and coefficient of determination the variable combination presumed easiest to record was choosen.

Three sets of models were developed based on 1) Growth ring data, 2) Tree-, and stand data, and 3) Tree-, stand-, and growth ring data:

$$Y_j = a_j + \sum_{i=1}^{n_j} b_{ji} x_{ji} + \varepsilon_j \qquad (1)\text{–}(3)$$

where j is Models 1, 2, 3. Variables in models (1)–(3) were selected based on the following criteria:

i) Variables should be significant at $p < 0.001$ level.
ii) Each variable included should add a partial adjusted $R^2 > 0.02$ to the total adjusted R^2 of a model.
iii) If very similar adjusted R^2 the variable combination was chosen that was presumed easiest to record or sample.
iv) Variables in the final models should have a variance inflation factor < 3 to avoid severe problems with multicollinearity.

2.7 Variables Used in Model (1)–(3)

On each site and on each tree a wide range of data were recorded; only those used in the derived models have been listed in Table 2.

3 Results

3.1 Effect of Variables used in Model (1)–(3)

Coefficient of determination, statistical significance, and parameter values of b_{i-n} for each model (1)–(3) are in Table 3. Residual plots are provided in Figs. 2–4.

The first Model (1) was derived using growth ring data obtained from the discs. A set of growth ring data combinations such as ring width, the logarithm of ring width, ring age, inverse of ring age, and interactions were used. The model selection criteria resulted in using only two variables: *LogRw* and *MminvCa* (Table 3). Apparently there is a negative effect of *LogRw* and a negative composite effect of *MminvCa*.

The second attempt was to model basic density on a set of tree and stand data using the selection criteria for Model (2). Humidity of a site, here represented by the *Martonne* index (Eriksson 1986) had an effect on the basic density development, where sites with high humidity were found to produce less dense wood. *CalcRw* was found to have a negative effect on *BD*. A negative relationship was also found between *BD* and *Latitude*. The positive effect of *Dratio* (Table 3) reflects a descent in mean ring width and increasing ring age with increasing distance from pith.

Model (3) was similar to Model (1) but had also components describing stand data. Here,

Table 2. Variables used in the models.

	Description of selected model variables
Growth ring variables	
LogRw	log (Average ring width (mm) within a 20-mm segment)
MminvCa	Distance (mm) from pith to a specific 20-mm segment × (1/ Average cambial age (growth ring number counted from pith, yrs) within a 20-mm segment)
Tree variables	
Dratio	Distance (mm) from pith to a specific 20-mm segment / maximum diameter of the disc under bark (mm)
CalcRW	Dbh (mm) on bark / Stand age
Stand variables	
Latitude	Geographical latitude
Martonne	Humidity index for the summer period based on the years 1951–1980 calculated according to a formula suggested by *Martonne*, extrapolated values (Eriksson 1986)

Table 3. Dependence of *BD* on tree-, stand-, and growth ring data [a]).

Model	Adjusted R^2	RMSE (kg/m^3)	b_{i-n}	Sb_{i-n}	X_{i-n}
1)	0.37	41	500.167***	2.417	*Intercept* = a_1
			–43.258***	2.732	*LogRw* = x_{11}
			–7.977***	1.237	*MminvCa* = x_{12}
2)	0.40	40	1048.28***	30.107	*Intercept* = a_2
			–1.563***	0.234	*Martonne* = x_{21}
			46.646***	3.760	*Dratio* = x_{22}
			–7.906***	0.488	*Latitude* = x_{23}
			–24.742***	0.848	*CalcRw* = x_{24}
3)	0.51	37	1007.915***	25.368	*Intercept* = a_3
			–1.686***	0.206	*Martonne* = x_{31}
			–6.830***	0.429	*Latitude* = x_{32}
			–45.508***	2.411	*LogRw* = x_{33}
			–18.193***	1.200	*MminvCa* = x_{34}

[a]) *, **, and ***, indicate $p \le 0.05$, $p \le 0.01$, and $p \le 0.001$, respectively (SAS Institute 1998).

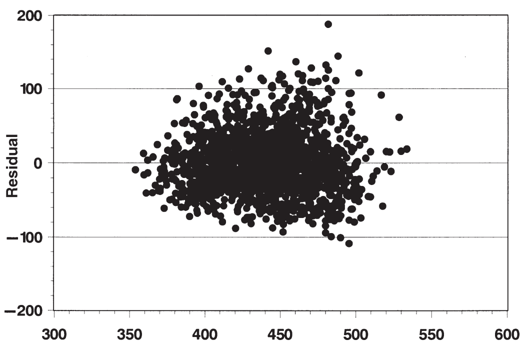


Fig. 2.. Basic density (kg/m^3) predicted by Model 1.

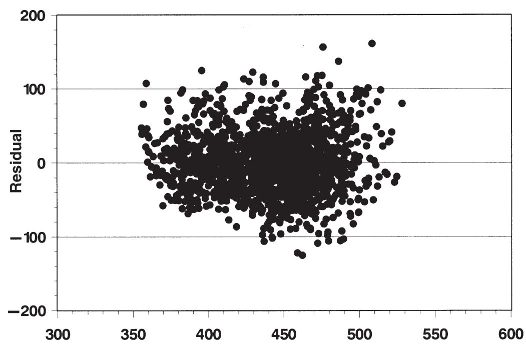


Fig. 3. Basic density (kg/m^3) predicted by Model 2.

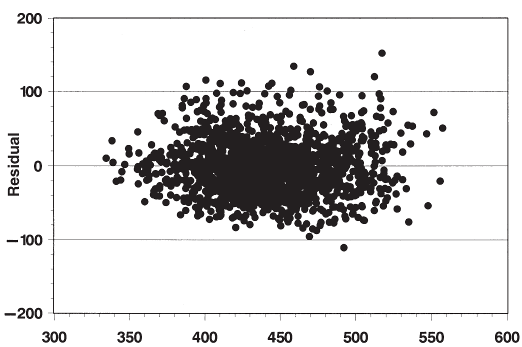


Fig. 4. Basic density (kg/m^3) predicted by Model 3.

Martonne was confirmed to have a negative effect on *BD*. A negative relationship was also found between *BD* and *Latitude*. (Table 3).

The residual plots of Model (1)–(3) (Figs. 2–4) suggested that there was a slight bias towards positive deviation.

4 Discussion

4.1 The Use of *BD* Models in Simulation Software

The notion that models of wood and knot variation can be used as an input to simulation software (Lönner 1996) has initiated this study. If this information is fed into conversion simulation software, it could be used for strategic planning; i.e. how to select stands and trees suitable for a specific wood based product. Hopefully, this would lead to a better utilisation of a given timber resource and thereby create economic benefits. In some of the following sections some major biological and technological issues are mentioned.

4.2 Material

Results of the current study are based on nineteen stands taken from eleven different locations. The choice of stands was limited to stands close to final felling, and trees considered representative of Norway spruce timber trees in Sweden were selected. It can be assumed that the *BD* variation registered on stand- and tree level is largely a result of genetics (Hylen 1997, Rozenberg and Cahalan 1997, Hannrup 1999). The found *BD* variation can therefore be taken as the compounded effect between growth conditions and genetic constitution that varies between stands and among individuals.

4.3 *BD* Measurements

In comparison with traditional *BD*-determination, the method described herein is faster and probably exceeds the precision given by conventional methods (Lindgren 1992). In addition, measurements are flexible in that they can be defined to cover a specific range e.g 20 mm segments. Moreover, using image analysis allows screening of discs that contain rot, cracks, compression wood, or knots to an extent that discourage measurements.

In the current study, discs with wood defects seemed to have been randomly distributed among sites, I do not believe they caused any bias. Nevertheless, one should be aware that measurements are not entirely objective as the operator has to make decisions where to place the histogram functions and whether wood defects are serious enough to cause rejection. This is illustrated by the slightly positive deviations seen in the residual plots as an indication that the measurements included some local compression wood. Moreover, there are no adjustments for less cylindrical stem sections with more irregular pith position.

4.4 Unrecorded Events

Tree injuries or drastic changes of growth conditions to a conifer can be caused by e.g. peeling and browsing by animals, frost, silviculture, and insects. Whatever caused the tree injury or drastic change in growth environment, there will not be a record kept of what took place in a certain year for a particular tree. But we can be sure that there will be changes in the wood formation processes of the living tree as a response to such events. For instance, a tree injury could initiate resin production that would impregnate the tracheids and thereby influence *BD*. In addition, less drastic changes in the tree's environment (e.g. thinning) may change the allocation and physical structure of the wood formed (Pape 1999). Thinning causes varying individual responses of the trees within a stand. For instance, released trees will increase their amount of foliage and thus increase their growth rate, while other trees in the same stand remain almost unaffected due to less decrease in crown competition. In summary, unrecorded events may have contributed to the wood variability in the present study, but could not be accounted for in the model due to lack of information.

4.5 Interpretation of Results

BD has been found correlated with variables describing or regulating the wood formation processes of the vascular cambium. Such variables can be divided into those that can be gathered easily and those not so easily accessible. In addition such variables are often if not always correlated with each other. Consequently, evaluation of *BD* based on a set of variables related to tree growth raises the questions of multicollinearity. To avoid severe problems with multicollinearity, the used variable selection criteria was rather rigid. That is, only highly significant variables adding more than two percent to the coefficient of determination and having a variance inflation factor of less than three were included in the final models. Nevertheless, the models should be validated to give an indication of sensitivity and their usefulness for estimation.

In contrast with other studies (Nylinder and Hägglund 1954, Ericson 1966, Björklund 1984, Johansson 1993, Danborg 1994) where a height effect was reported, the effect of height or height percentage in the tree stem was not included in Model (1)–(3). This could in part be explained in that studies which identify a height effect often are based on the *BD* of the entire stem section. With increasing stem height the number of growth rings decreases while the mean growth ring width tend to increase; both these variables are correlated with *BD*. In this study where each disc is divided into 20-mm segments, the changes in growth ring structure associated with increasing stem height will not be as influential.

Model (1) was derived based on a set of growth ring variables that contained transformed (logarithmic, inverse, and squareroot) mean values and untransformed mean values of growth ring width and cambial age within each 20-mm segment on each sampled disc. Based on the selection criteria and the residual plots, the resulting model only contained two variables. The negative effect of *LogRw* on *BD* is assumed to depict growth rate at a given stem height. Variation in growth ring width is believed set by the amount of photosynthesising foliage and the growth allocation along the tree stem (Larson 1963). In addition, the composite effect of distance from pith to a specific 20-mm segment and the inverse of cambial age of that segment *MminvCA*, had a negative effect on *BD*. Although studies of *BD*-development show significant effects of cambial age and distance from pith (Kučera 1994, Lindström 1997), this composite effect was difficult to interpret. It could be that the BD patterns of planted and naturally regenerated trees differ so that growth ring width and cambial age can only provide a limited explanation. In that case, adding additional stand and tree data to the growth ring data as in Model (3) would improve model fit.

Model (2) was based on available tree and stand data. Unfortunately, many sites lacked important silvicultural variables, such as spacing and thinning, which could have changed the correlation and model expression of Model (2). Based on the selection criteria the following variables were to be included in the model: *Martonne*, *Dratio*, *Latitude,* and *CalcRw*. Humidity of a site, the *Martonne* index (Eriksson 1986) had an effect on the basic density development, where sites with high humidity were found to produce less dense wood. There are few studies on how precipitation and humidity might affect the tracheid structure of Norway spruce. However, Fritts et al. (1991), proved that e.g. cell wall thickness and tracheid diameter are correlated with precipitation. The positive effect of *Dratio* is assumed to reflect lesser mean ring width and increasing ring age with increasing distance from pith. Similar results has been obtained in many other studies (Danborg 1994, Kučera 1994, Lindström 1997). *Latitude*, with it's negative effect on *BD*, can be regarded to describe the climate of a site e.g. length of growing season, temperature, or sun radiation, which all will decrease with increasing latitude (Morén and Perttu 1994). So, other things being equal, a colder climate as depicted by latitude would mean a decrease in *BD*. Similar results have also been found by Saranpää (1983) and Björklund (1984). *CalcRw*, which can be seen as a crude measurement of a tree's average growth ring width, had a negative correlation with *BD*-development. Hence, even an easily obtained measurement of growth ring width will add explanation to the model.

Model (3), which in addition to growth ring data also contained tree and stand variables, yielded a model composed of four variables where the effect of *LogRw*, *MminvCa*, *Martonne*, and *Latitude* has been discussed earlier. Thus, Model (3) can be interpreted as follows: two trees can have the same mean *LogRw* and *MminvCa* in a given 20-mm segment, but they can be grown under differing growth conditions and will therefore not have the same tracheid structure within that segment. Here the unequal *BD* can be the result of unequal cell wall thickness and/or mean tracheid diameter. Adding tree and stand data would to some extent depict this relationship. Consequently, Model (3) attained lowest RMSE and the highest coefficient of determination among the models.

4.6 Future Work

Accurate models of *BD* development in Norway spruce trees require comprehensive information on variables related to wood formation such as genetics, silviculture, growth conditions and tree injuries. Still, such models have to be based on variables that are easily accessible to be of practical value. Is this compromise possible, or are there to many obstacles involved? There is no definite answer to this question, but it is likely that more efficient methods would create more unrestrained approaches.

4.7 Model Application

The aim was to create models of *BD* development which, together with other tree models, could be used as input into conversion simulation software. This could enable strategic selection of stands and trees suitable for a certain range of wood products. In the current study, it was possible to build general *BD* models in 20-mm segments for Norway spruce stems based on factors related to the wood formation of a conifer with an adjusted R^2 between 0.37–0.51 with a RMSE = 37–41 kg/m^3.

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