PREDICTION MODELS FOR DENSITY IN STEMS OF *PICEA ABIES* (L.) KARST. AND *PINUS SYLVESTRIS* L. IN SOUTHERN NORWAY

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ABSTRACT

Random coefficient mixed models were developed to predict vertical and horizontal density variations in stems of Scots pine and Norway spruce. Modeling and validation were based on investigations of 132 spruce and 60 pine trees in southern Norway. Density was measured on discs and small clearwood samples that were taken from 4 different tree heights (stump, 25%, 50%, and 75%). In pine, the common vertical trend in disc density increased with approx. 100 kg m-3 from the stump to the top; the level of this trend, however, varied strongly among trees. The horizontal density trend was less clear than the vertical one and considerably differed between pine trees. Within trees, it was strongly dependent on the tree height position. The most accurate model for density in pine included the following explanatory variables: the ratio of tree height to diameter at breast height, diameter of stem disc with bark, bark volume on disc, and ring width. Validation on independent material gave R2 of 0.45 for density of clearwood samples.

In spruce, the vertical difference of density was low as compared to pine. The average disc density was approx. 15 kg m-3 higher at 75% tree height than at the stump. In vertical direction, density varied considerably between spruce trees. Silviscan measurements revealed that density rapidly decreased by approx. 100 kg m-3 within the first 5 annual rings. Differences between the average densities of clearwood samples were not statistically significant at any tree height level. The most accurate model gave an R2 of 31% in the validation procedure. The model included sample position, site index, diameter at breast height, and bark volume as input variables.

Key words: density, random coefficient mixed models, wood quality prediction

INTRODUCTION

Wood density has a great importance for manufacturing processes and quality of forest-based products, which has aroused a growing scientific interest to create models for predicting density in recent years (Duchesne et al. 1997; Kellomäki et al. 1999; Lindström 2000; Wilhelmsson et al. 2002; Repola 2006; Mäkinen et al. 2007; Ikonen et al. 2008; Steffenrem et al. 2009).

In the sawmilling industry, only few factories have density measurement systems for green boards although technology is available in form of weighing methods or X-ray technology. Such equipment, however, needs some kind of moisture content approximations either through inline measurements or quality control of drying batches. This implies that the use of this equipment at an early stage in the process gives poor density estimates due to the strongly varying moisture content in logs and green boards (Brännström 2005). A prediction of density will consequently improve the saw milling process in terms of both grade yield and production efficiency. The simplest systems for a saw mill could be to predict density from the dimension of the boards and the position in the cross section. (Steiner and Øvrum 2010). More advanced prediction models could include forest data like stand variables, tree variables, and what log in the tree the logs come from (Duchesne et al. 1997; Bergstedt and Olesen 2000; Lindström 2000; Wilhelmsson et al. 2002; Mäkinen et al. 2007).

The present study has the objective to extend the knowledge on density variation in Norway spruce (*Picea abies* (L.) Karst.) and Scots pine (*Pinus sylvestris* L). In this context, linear mixed models were developed based on investigations of 132 spruce and 60 pine trees in southern Norway to predict horizontal and vertical density variations in stems. The investigations are part of the project "Wood quality predicting systems as a tool for differentiation and sorting of wood raw material" (Norwegian Research Council, project no. 178330) that aims to create better utilisation of Norwegian forest resources.

MATERIAL AND METHODS

Material

The sampling procedure included stratification with regard to stands, tree status, and sample extraction within the stem. The spruce material came from 22 stands (12 natural regenerated and 10 planted) and the Scots pine material from 10 stands (all natural regenerated) in southern Norway. For each stand, twenty-four trees were randomly chosen in an area of approx. 500 m^2. The tree diameter was measured at breast height (DBH, ~1.3 m above ground). The trees were grouped into tree diameter classes based on the diameter. One tree per diameter class was randomly sampled, resulting in 2 suppressed, 2 co-dominant, and 2 dominant tree per stand.

Eleven site variables, 26 exterior tree variables, and 28 variables describing wood properties were recorded. Site indexes (SIT) were calculated for each tree, based on tree height and age and the H40 functions for Scots pine and Norway spruce (Tveite and Braastad 1981). The site index of each stand (SI) was derived from the SIT of the dominant trees. Discs with a thickness of 30-50 mm were taken at 4 different heights of each tree (H_1 = stump, H_2 = 25%, H_3 = 50%, H_4 = 75%).

Small clearwood samples with a dimension of 20 x 20 mm (radial x tangential) were taken along an axis from pith (R_1) to bark (R_n) from the west face of the discs (H_1-H_4). The basic density of the clearwood samples was determined according to Skanorm 4 (Kučera 1992) in order to map the density variation in radial and vertical direction along the stems.

In addition to the clearwood samples, a pith-to-bark bar was sawn from the west face of discs of 30 pine and 30 spruce trees. Samples were free of knots and obvious compression wood. The mean density and width of each annual ring was measured with the SilviScan-system (Evans 1997) at Innventia (formerly STFI-Packforsk) in Sweden and The Commonwealth Scientific and Industrial Research Organisation in Australia.

Models for density in spruce and pine stems

The variation in density was modeled, by linear mixed models, using the individual tree as a random effect. The random and fixed effects were assessed by using the Restricted Maximum Likelihood (REML) estimation of the software JMP (Version 7.0.0. SAS Institute Inc.) in compliance with Littell et al. (2006). The random elements were assumed to follow a normal distribution.

The models were stepwise developed on the dataset of 13 spruce stands and 6 pine stands. Initially, the horizontal and vertical profile of density in the stem was described with the radial position (R) and vertical position (H) of the clearwood samples.

The variable ln (H+1) was used instead of ln (H) to avoid a zero value when H=1. Random effects for the intercept and the R-elements were tested by log-likelihood ratio tests (χ^2; $p \geq 0.05$).

After modeling the vertical and radial density variation in stems, fixed effects were gradually added according to their type and the effort, which is necessary to measure them: Step I=site variables, Step II=Step I and exterior tree variables, and Step III=Steps I and II and interior tree variables.

The variables were rejected at the 5% level. The Coefficient of Determination (R^2) and the Root Mean Square Error (RMSE) were computed based on both random and fixed effects. This is equivalent to a situation in which each tree is individually fit. Subsequently, R^2 and RMSE values also were calculated from residuals of the random coefficient mixed model outputs, where only the fixed effects were included.

The models were validated based on independent datasets from 9 spruce stands and 4 pine stands. The intercept and the slope of the linear regression between predicted and measured values were constrained to 0 and 1, respectively, to include the model bias and to enable valid comparisons to be made between the model step and the validation. R^2 and RMSE were calculated from the residuals from these regressions.

RESULTS

In pine, the common vertical trend in disc density increased with approx. 100 kg m^{-3} from the stump to the top (Fig. 1a); the level of this trend, however, varied strongly among trees. The vertical stem position solely explained 95% (random and fixed effects) in modeling and 69% (only fixed effects) in validation, respectively, of the density variation on disc level. The horizontal density trend was less clear than the vertical one and differed considerably between trees. Within trees, density profiles strongly depend on the height position in the tree. At stump and 25% tree height, density increased by approx. 30 kg m^{-3}

within the first radial 75 mm from pith; afterwards, it decreased slightly towards the bark. In comparison, density showed very little radial variation in upper parts of the pine stems. The radial position became insignificant in models that included both the radial and the vertical stem position as independent variables. The most accurate model for density in pine (Table 1, model IIIa P) included as explanatory variables the ratio of tree height (TH) to diameter at breast height (DBH), diameter of stem disc with bark (DDB), bark volume on disc (BVB), and ring width (RW). A similar model including an estimation of RW with diameter of disc without bark (DD) and ring number (RN) gave lower R^2 (Table 1, model IIIb P). Validation on independent material gave R^2 of 0.45 (Table 2, model IIIa P) and 0.36 (Table 2, model IIIb P) for density of clearwood samples, respectively.

For spruce, the vertical variation in density was low compared to what was found for pine. The average disc density was approx. 15 kg m^{-3} higher at 75% tree height than at the stump. The vertical profiles varied considerably between the trees, and several trees showed no increase or even a negative trend in density towards the top of the stem. Silviscan measurements revealed that density rapidly decreased by approx. 100 kg m^{-3} within the first 5 annual rings. In the following, density slightly decreased by further 20 kg m^{-3}. A radial trend was however scarcely seen in the comparison of densities of clearwood samples. Differences between the average densities of clearwood samples (R-positions) were not statistically significant at any tree height level (Tukey HSD test, p = 0.05). The most accurate model gave an R^2 of 31% in the validation procedure. The model included sample position, site index, diameter at breast height, and bark volume as input variables (Table 2, model II S). The use of inner tree variables, such as ring width (RWD) or ring number (RN), did not result in more accurate predictions (Table 2, model III S).

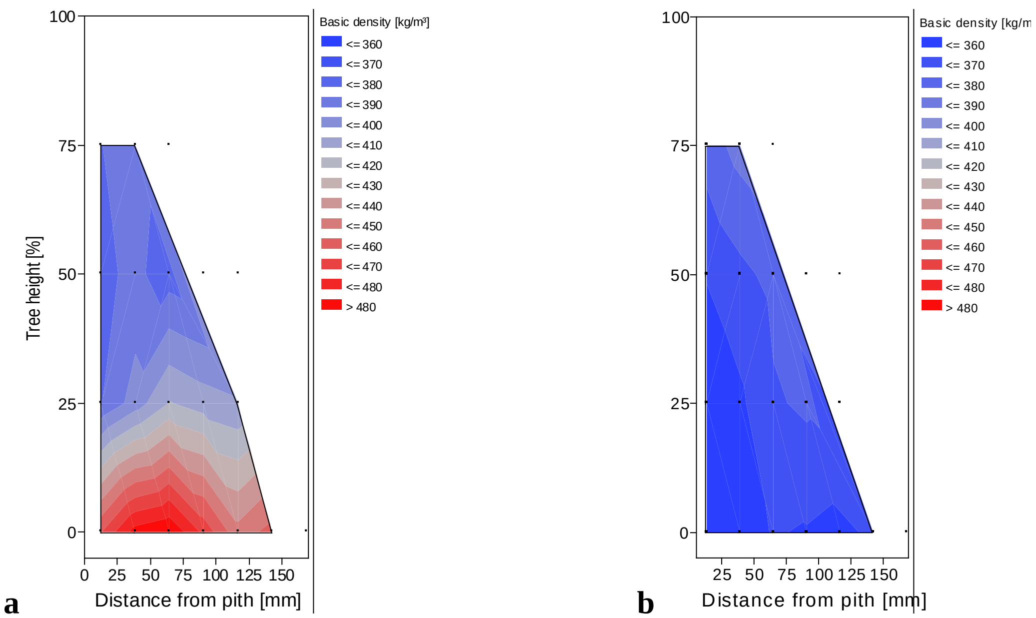

Fig. 1: Mean density variation in stems of Scots pine (a) and Norway spruce (b) derived from basic density measurements on clearwood samples. Each stem position is represented with n ≥ 10.

Table 1: Models for density with variance components and summary statistics for the comparison of modelled and measured values of density. Only models with significant variance-component estimates and significant parameter estimates of fixed effects are presented.

Variance components and summary statistics

Variance components	Step (model no.)						
Source	I P	II P	IIIa P	IIIb P	I S	II S	III S
Tree	825.89	746.48	666.83	745.12	453.05	344.62	444.72
H * tree					164.84	145.46	101.87
R * tree					144.98	146.69	148.05
ln (H+1) * tree	38.96						
Residual	904.25	1046.13	914.83	1033.61	1243.58	469.23	471.07
Summary statistics. including fixed and random effects							
R^2_{adj}	0.79	0.75	0.78	0.75	0.71	0.72	0.72
RMSE [°]	30.07	32.34	30.25	32.15	21.90	21.66	21.70
Summary statistics. including fixed effects							
R^2_{adj}	0.38	0.53	0.57	0.52	0.09	0.18	0.15
RMSE [°]	46.93	42.28	40.37	42.77	34.48	32.76	33.27

Models without random effects

I P	548.22 – 24.92 * ln (H+1) + 5.23* H40
II P	302.27 - 5.83 * H40 + 113.81 * TH/DBH + 0.26 * DDB + 4.1 BVD
III Pa	273 + 89.29 * TH/DBH + 0.26 * DDB + 3.87 BVD – 18.85 * RW
IV Pb	350 + 0.22 * DDB + 4.54 BVD – 28.75 * (0.5 * DD/RN)
I S	392.27 + 7.24 * H + 5.09 * R - 2.83 * H40
II S	390.72 + 4.07 * H +5.95 * R – 2.49 * H40 – 0.12 * DBH + 3.42 * BVD
III S	409.07 + 9.31 * H + 5.93 * R – 0.11 * DBH – 22.30 * RWD

Table 2: Validation statistics on models for pine (P) and spruce (S).

Model	Fixed-effects	R^2	RMSE [°]
I P	ln (H +1), H40	0.36	47.70
II P	H40, TH/DBH, DDB, BVD	0.40	46.83
IIIa P	TH/DBH, DDB, BVD, RW	0.45	45.59
IIIb P	TH/DBH, DDB, BVD, DD, RN	0.36	50.80
I S	H, R, H40	0.23	34.84
II S	H, R, H40, DBH, BVD	0.31	32.93
III S	H, R, H40, DBH, RWD	0.23	34.20

DISCUSSION

The results reveal that the density of a wood piece from a pine log can be quite accurately predicted just by using the information on the vertical origin of the piece (Table 1 and 2, model I P). The addition of information about site index of the stand, tree height, diameter of breast height, and bark volume at specific height increased the R^2 values with 4 % (Table 2, model II P). Such variables are available though the forest inventories and can also be derived from the information a harvester measures during processing the tree.

When using information about ring widths, R^2 increased to 45% (Table 2, model IIIa P). It has been frequently reported that density is closely related to ring width and cambial age (Johansson 1993; Pape 1999; Molteberg and Høibø 2007; Jyske et al. 2008). Such variables are difficult to obtain in industrial processes. The challenge therefore is to create models with easily recordable variables (Wilhelmsson et al. 2002). This implies that variables, which are difficult to measure, must be explained by subjacent models, as it is seen at the models developed in the Indisputable Key project (Sixth Framework Programme, project no. 34732). The application of an expression for ring width with stem diameter and ring number (Wilhelmsson et al. 2002) reduced R^2 by 9% (IIIb P). Ring number must however be estimated by another sub-model. An alternative to sub-models is to use automated measurement for inner log properties, such as the BoardMaster-EndSpy of the company FinScan. Although the measurement algorithms of such scanning systems are still debated, the current development suggests that these systems will become state-of-the-art in industrial processes (Brüchert et al. 2008).

The vertical and horizontal trends for density in spruce comply with findings reported in most earlier studies (Nylinder and Hägglund 1954; Foslie and Moen 1968; Frimpong-Mensah 1987; Høibø 1991; Kučera 1994; Lindström 1996; Vestøl et al. 2001; Raiskila et al. 2006). The models for density in spruce trees gave poor estimations for density (models I-III S). This can probably be ascribed to the low in-tree and between-tree variation of density in the dataset, which is based on forest stands in southern Norway. Wilhelmson (2002), for example, developed a model explaining approx. 50% of the density variation in spruce, which was based on 252 trees coming from stands throughout Sweden.

Steiner and Øvrum (2010) carried out a case-study in a sawmill on the effect of pre-sorting of spruce boards with a dimension of 50 x 200 mm on density. The average density of inner boards, i.e., boards closer to the pith, was 18 kg m^3 greater than that of outer boards, which results in a theoretical reduction of drying time by approx. 10%. However, the low variation in vertical and especially in radial direction of spruce trees suggests that pre-sorting of spruce boards is of limited value. Further research is going on to investigate the applicability of pre-sorting and prediction models in industrial processes.

SUMMARY AND CONCLUSIONS

- the vertical position accounts for most of the density variation in stems of pine
- the density variation in vertical direction of spruce stems is much lower than in pine stems
- the radial position is of little importance for density prediction for both pine and spruce
- the most accurate prediction model for density in pine stems explained 45%
- the most accurate prediction model for density in spruce stems explained 31%
- all necessary input information for the models are obtainable from forest inventories, harvester measurements, and scanner technologies for industrial application

REFERENCES

Bergstedt, A. & Olesen, P.O. 2000. Models for Predicting Dry Matter Content of Norway spruce. Scandinavian Journal of Forest Research 15(6):633 - 644

Brüchert, F., Baumgartner, R. & Sauter, U.H. 2008. Ring width detection for industrial purposes - use of CT and discrete scanning technology on fresh roundwood. Conference COST E53, Delft, The Netherlands

Brännström, M. 2005. Establishing a model for the dry density of heartwood of Norway spruce by parameters industrially measurable on green logs. Master's thesis. Luleå University of Technology

Duchesne, I., Wilhelmsson, L. & Spangberg, K. 1997. Effects of in-forest sorting of Norway spruce (Picea abies) and Scots pine (Pinus sylvestris) on wood and fibre properties. Can J For Res-Rev Can Rech For 27(5):790-795

Evans, R. 1997. Rapid scanning of microfibril angle in increment cores bv x-ray diffractometry. In: Butterfield BG (ed). Microfibril in wood: Proc. of the IAWA/IUFRO Inter. Workshop on the significance of microfibril angle to wood quality University of Canterbury Press, Westport, New Zealand, p. 116-139

Foslie, M. & Moen, K. 1968. Norsk granvirkes styrkeegenskaper. 1. Bøyestyrke, elastisitetsmodul og strekkstyrke målt på 3"x8" og 2"x4" [Strength properties of Norwegian Spruce. 1. Bending strength, modulus of elasticity and tensile strength tested on the structural sizes 3"x8" og 2"x4"]. Oslo: NTI. Report nr Meddelelse nr. 33 [In Norwegian with English summary]. 40 p

Frimpong-Mensah, K. 1987. Fibre length and basic density variation in the wood of Norway spruce (*Piceas abies* (L.) Karst.) from northern Norway. Ås: Norsk institutt for skogforskning. 25 p

Høibø, O.A. 1991. The quality of wood of Norway spruce (Picea abies (L.) Karst) planted with different spacing. Doctoral. Agricultural University of Norway. Ås, Norway [In Norwegian with English summary]

Ikonen, V.-P., Peltola, H., Wilhelmsson, L., Kilpeläinen, A., Väisänen, H., Nuutinen, T. & Kellomäki, S. 2008. Modelling the distribution of wood properties along the stems of Scots pine (Pinus sylvestris L.) and Norway spruce (Picea abies (L.) Karst.) as affected by silvicultural management Forest Ecology and Management 256(6):1356-1371

Johansson, K. 1993. Influence of initial spacing and tree class on the basic density of Norway spruce. Scandinavian Journal of Forest Research 8(1):18-27

Jyske, T., Mäkinen, H. & Saranpää, P. 2008. Wood density within Norway spruce stems. Silva Fennica 42(3):435-455

Kellomäki, S., Ikonen, V.-P., Peltola, H. & Kolström, T. 1999. Modelling the structural growth of Scots pine with implications for wood quality. Ecological modelling 122:117-134

Kučera, B. 1992. SKANORM 4: Determination of density for physical and mechanical tests. Norwegian Forest Research Institute, Department of Forestry, Agricultural University of Norway

- 1994. A hypothesis relating to annual height increment to juvenile wood formation in Norway spruce. Wood and Fiber Science 26(1):152-167

Lindström, H. 1996. Basic density in Norway spruce, Part III. Development from pith outwards. Wood and Fiber Science 28(4):391-405

- 2000. Intra-tree models of basic density in Norway spruce as an input to simulation software. Silva Fennica 34(4):411-421

Littell, R. 2006. SAS for mixed models. SAS Publishing, p. 814
Molteberg, D. & Høibø, A. 2007. Modelling of wood density and fibre dimensions in mature Norway spruce. Canadian Journal of Forest Research 37(8):1373-1389
Mäkinen, H., Jaakkola, T., Piispanen, R. & Saranpaa, P. 2007. Predicting wood and tracheid properties of Norway spruce. Forest Ecology and Management 241(1-3):175-188
Nylinder, P. & Hägglund, E. 1954. The influence of stand and tree properties on yield and quality of sulphite pulp of Swedish spruce (Picea excelsa). Report Forest Research Institute of Sweden 44(11)
Pape, R. 1999. Influence of thinning and tree diameter class on the development of basic density and annual ring width in Picea abies. Scandinavian Journal of Forest Research 14(1):27-37
Raiskila, S., Saranpaa, P., Fagerstedt, K., Laakso, T., Loija, M., Mahlberg, R., Paajanen, L. & Ritschkoff, A.C. 2006. Growth rate and wood properties of Norway spruce cutting clones on different sites. Silva Fennica 40(2):247-256
Repola, J. 2006. Models for Vertical Wood Density of Scots Pine, Norway Spruce and Birch Stems, and Their Application to Determine Average Wood Density. Silva Fennica 40(4):673-685
Steffenrem, A., Kvaalen, H., Høibø, O., Edvardsen, Ø.M. & Skrøppa, T. 2009. Genetic variation of wood quality traits and relationships with growth in Picea abies. Scandinavian Journal of Forest Research 24(1)
Steiner, Y. & Øvrum, A. 2010. Pre-sorting for density in drying batches of Norway spruce. The final conference of COST Action E53 - The future of quality control for wood & wood products,
Tveite, B. & Braastad, H. 1981. Bonitering for gran, furu og bjørk. Norsk Skogbruk 27(4):17-22
Vestøl, G.I., Høibø, O., Slotnæs, T. & Værnes, K. 2001. Egenskaper til trelast med store dimensjoner fra grov gran på Vestlandet. Ås: Norsk institutt for skogforskning. Report nr 1/2001. 27 s. p
Wilhelmsson, L., Arlinger, J., Spångberg, K., Lundqvist, S.O., Grahn, T., Hedenberg, O. & Olsson, L. 2002. Models for predicting wood properties in stems of Picea abies and Pinus sylvestris in Sweden. Scandinavian Journal of Forest Research 17(4):330-350