Intra-Tree Models of Juvenile Wood in Norway Spruce as an Input to Simulation Software

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Juvenile wood found in the first 5–25 growth rings of a conifer has a structure and properties that differ from mature wood. Juvenile wood is therefore said to influence processing and the end-use of sawn products. Consequently, models describing the juvenile wood content, within and between trees, could be useful in improving the utilisation and value of wood as an industrial raw material. The objective of the present study was to develop juvenile wood models, based on Norway spruce trees, which 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 medium, and two large diameter 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 large end of each log and from the top end of the top log. Image analysis was used to determine growth ring development on sampled discs. Using tree and growth variables, the juvenile core radius and the logarithmic value of juvenile wood percentage were modelled. The two models had an R^2Adj of 0.71 and 0.88 respectively.

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

1.1 Juvenile Wood in Conifers and its Influence on Processing and Value of Forest Products

In recent decades, forestry management has aimed to produce fast growing trees, which can be harvested at an early age. Therefore, it is argued that the future wood resources will have a high juvenile wood percentage (*JWP*) (Bendtsen 1978, Thörnqvist 1993, Kennedy 1995, Zobel and Sprague 1998). The scenario of an increasing *JWP* has caused concern within the forest industry as it would have a negative influence on the production, properties, and product value of forest products (Cown 1992, Kennedy 1995, Zobel and Sprague 1998).

1.2 Utilising Information on Wood Variation in a Conversion Software Tool

Wood properties such as basic density (*BD*), microfibril angle, spiral grain, compression 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). From this perspective, it would be beneficial to develop models or tools that could be used to differentiate and select trees that are suited for a specified end-use (Todoroki 1997, Uusitalo 1997, Lönner and Björklund 1999, Meredieu et al. 1999, Usenius 1999). 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, Walker and Nakada 1999). Consequently, it is argued that accurate models of wood variation should be employed to ensure that the quality and specifications of the end-user are met (Eriksson and Kyrkjeeide 1992, Tian et al. 1995, Persson 1997). Zobel and Sprague (1998) and West (1998) claim that models of juvenile wood can find application primarily in two areas:

– Classification and pricing of logs
– Utilisation of wood as an industrial raw material

In recent years, some model systems, e.g. AUTOSAW (Todoroki 1997), SOPT (Lönner and Björklund 1999), CAPSIS©$_{\text{INRA}}$/WinEpifn©$_{\text{INRA}}$.(Meredieu et al. 1999) have been developed to integrate information on wood and knot properties in conifer tree stems into the production processes of wood-based products. Such systems have the potential to establish the link 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.

1.3 Attempts to Define the Juvenile Wood Boundary

Biological life forms have to pass through a juvenile stage before reaching maturity. In conifer trees, this age dependent transformation can be traced in the tracheid structure seen in successive growth rings from the pith. More specifically, the first growth rings from the pith contain tracheids that are relatively short, with a small diameter and a large microfibril angle. With the maturation of the vascular cambium a gradual change in tracheid characteristics occurs until a more mature wood structure is produced.

The duration of juvenile wood formation in a conifer tree will of course depend on the juvenile wood definition used. Jane (1956) writing in a period dominated by wood production from virgin forests claimed that the boundary between juvenile and mature wood could be set at growth ring number 50 from the pith, whereas more recent studies indicate a much shorter phase, reflecting the commercial interest of owners of plantation resources. The current interpretation seems to be that wood formed in the first 5–25 growth rings from pith in conifers can be named juvenile or core wood (Megraw 1985, Harris and Cown 1991, Kucêra 1994, Saranpää 1994, Lindström et al. 1998, Walker and Nakada 1999). Consequently, the demarcation between juvenile and mature wood, in terms of a specified growth ring number from the pith, is flexible. The wide definition range is most certainly a result of the fact that the rate of wood maturation will vary within and between trees, sites, and species. Furthermore, efforts to demarcate a juvenile wood boundary are complicated by the fact that individual wood characteristics seem to mature at non-constant progression rates. As an illustration of the gradual wood maturation process, a density gradient profile of loblolly pine (*Pinus taeda* L.), can be viewed in Fig. 1. The three zones used in the figure to denote the phases of transition from juvenile to mature wood in loblolly pine confirm that the gradual transition from juvenile to mature wood is of a non-rigorous character.

This seems also to be true for other soft wood species, eg. as stated by Harris and Cown (1991): "*for, sawn timber, its (corewood) most damaging features will be confined to the first 3–5 annual*

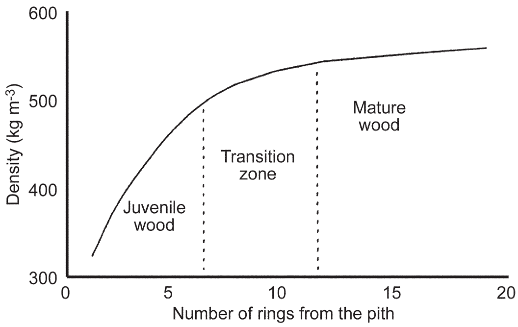


Fig. 1. Density profile in loblolly pine (*Pinus taeda* L.), redrawn after Zobel and Buijtenen (1989).

growth layers from the pith – yet outerwood in which all wood properties including density have stabilised may not develop until after the 25–30 growth layers. For practical convenience, corewood is often referred to as the first 10 annual growth layers; the wood contained within this region has most of the adverse qualities of corewood while outside it has few".

In studies attempting to demarcate the juvenile wood boundary in Norway spruce (*Picea abies* [L.] Karst) differing definitions of juvenile wood have resulted in a range of proposed demarcation boundaries. For instance, Kucêra (1994) claimed that the peak in annual height increment coincided with the cessation of juvenile wood formation. Using this method, trees grown at 1.25–2.25 m spacing were considered to produce juvenile wood at stump height until ring number 17–18. In comparison, trees grown at a spacing of 5.5 × 3.0 m continued to produce juvenile wood at stump height until ring number 28–30 from pith. Alternatively, in other studies the inflexion points of one or a set of wood characteristics has been used to define the juvenile–mature wood boundary. Boutelje (1968) used the presence of spiral thickenings that indicated a boundary between ring number 3 (at 1% of total tree height) and ring number 32 (at 90% of total tree height). Olesen (1977) and Madsen et al. (1978) used density levels to argue that the boundary is situated somewhere between ring number 11–20. Lewark (1981) took the maximum growth ring width to give a boundary between ring number 15–20. Kyrkjeeide (1990) evaluated the development of a set of wood characteristics, then argued that the boundary could be set at ring number 20. Danborg (1994) used the mean of the 5% lowest density records in an annual ring (*D5*) and found that the boundary could be set to ring number 10 where *D5* became stabilised.

Given these perspectives, the juvenile wood concept seems to have differing interpretations, and it should be recognised that "any accepted definition is arbitrary and is justified only if practically convenient" (Walker and Nakada 1999).

1.4 Used Definition of JWCR and JWP

Models of the juvenile wood core radius (*JWCR*) and *JWP* of trees require a definition of the boundary between juvenile and mature wood. However, in a retrospective evaluation of earlier studies, (Boutelje 1968, Lewark 1981, Madsen et al. 1986, Kyrkjeeide 1990, Danborg 1994, Kucêra 1994), it seems impossible to establish an absolute limit for the boundary between juvenile and mature wood in *Picea abies*. These reports only make it clear that the selection of a juvenile wood boundary will differ with differing methods of demarcation. That is, a definition based on the maturation of a single wood character will inevitably mean a particular distinct determination, and this value may not coincide with the maturation of other wood characteristics. Moreover, it has to be recognised that attempts to define the boundary are almost invariably based on data from planted trees i.e. location of the boundary in naturally regenerated trees could be different.

So, to establish yet another semi-rigid juvenile boundary, based on the empirical material used in this study, seems counterproductive because:

a) The existing wide range definitions of juvenile wood boundaries are based on restricted empirical material. The more extensive material in this study, in terms of geographical origin and number of observations, would probably generate an even wider definition span.
b) The second more fundamental problem is that a boundary deduced from the current empirical material would be confined to this study, which leaves any derived model of limited value.

Instead one can contemplate the many reports of wood maturation in *Picea abies* in terms of tracheid dimension (Olesen 1977, 1982, Kucêra 1994, Lindström 1997), tracheid length (Kucêra 1994, Saranpää 1994, Lindström 1997), microfibril angle (Lindström et al. 1998) and wood properties in terms of shrinkage and modulus of elasticity (Saranpää 1994, Persson 1997). These studies indicate that much of the wood maturation takes place in the first 10 growth rings. This fact together with the previous statements a) and b) underlie the decision to use a juvenile wood boundary set at ring number 10 from the pith in this study.

1.5 Objectives of the Current Study

In the present study the aim is to model JWP of tree stems and *JWCR* at different stem heights of Norway spruce trees grown under a wide range of growth conditions in terms of site quality, silviculture, and geographic locality (Table 1). The aim with the derived models is that they, together with other wood property models e.g. Moberg 1999, will be incorporated into the software SOPT – a model system for conversion simulation studies (Björklund and Julin 1998, Lönner, and Björklund 1999). In such a context, the models could be applied to study the utilisation of wood.

2 Methods

2.1 Selection of Trees and Stands

This study utilises tree and stand data pooled from two earlier studies, "the log scanner project" (FAIR CT 96-1188) and "Improved spruce timber utilisation" (FAIR-CT96-1915, Moberg 1999).

This study is based on 19 Norway spruce stands (*Picea abies* [L.] Karst.) of which nine stands were naturally regenerated and ten stands were planted. Selections of stands were undertaken throughout Sweden in order to represent a wide range of growth conditions and corresponding growth rates (Table 1, 2). However, detailed data on silvicultural procedures such as thinning and initial spacing was only available for some sites. Within each selected stand, six tree stems were sampled to represent differing tree classes, with two stems from each class. The medium sized tree class was represented by the quadratic mean DBH of the stand. Small- and large tree size classes were defined by using a limit set at one-half standard deviation above and below the quadratic mean DBH. From each of the three classes, two stems with similar DBH were chosen randomly near each class mean. 114 selected trees were felled, the stems cross-cut into logs and marked with stand, tree, and log number. The logs had an average length of 4.5 m with a variation in length between 3.4–5.3 m to ensure:

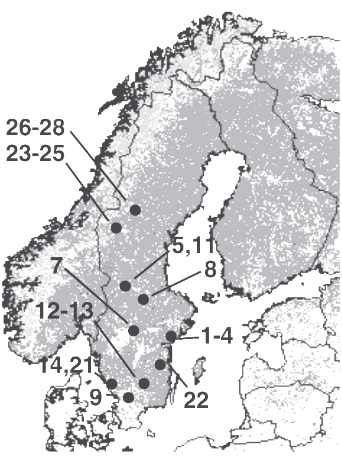
a) That logs did not exceed crook requirements set by the CT-scanner (Moberg 1999).
b) Complete utilisation of each stem up to a stem height that corresponded with the minimum log diameter of 120 mm (Fig. 1).

The trees used in the study had a range in diameter of 180–470 mm at breast height, a tree height between 17–35 m, and were between 51–152 years old. Here, the choice of stands was limited to stands close to final felling, and trees representative of Norway spruce timber trees in Sweden. It has to be emphasised that the current study is based on only 19 stands taken from 11 different locations. So, even if the material used in this study covers a reasonable range in Swedish growth conditions, this study is limited in material size with few replications of stand variability.

2.2 Ring Number and Ring Width

Tree discs of approximately 40-mm thickness were taken at stump height, and successively up each stem at the cross-cutting point of individual logs. The logs were cut to an approximate length close to 4.5 m with a variation in length between 3.4–5.3 m to ensure that each stem was utilised up to the minimum log diameter of 120 mm. (Fig. 1). Each sampled disc was polished at original moisture content and a CCD camera with a 0.1-mm-pixel resolution was then used to obtain digital images of individual growth ring patterns of each disc. The images were analysed using WinDENDRO™ ver.6.3a (Fig. 1). The number

Table 1. Description of selected stands.



Geographical location of stands in Sweden	Stand nr[a)]	Altitude m, a.s.l	Location (latitude, longitude)	Stand age	Site index (H100)	Standing volume (m^3)	Mean Dbh (mm)	Mean height (m)
	1	40	58°49’N 16°56’E	51	36	676	190	19
	2	40	58°49’N 16°56’E	51	36	619	270	27
	3	40	58°49’N 16°56’E	51	36	432	300	30
	4	40	58°49’N 16°56’E	51	36	410	240	24
	5	220	60°53’N 14°23’E	105	25	449	230	23
	7	80	59°10’N 14°12’E	110	26	.	220	24
	8	260	60°31’N 15°08’E	140	20	220	220	20
	11	220	60°53’N 14°22’E	135	26	353	320	28
	12	225	57°08’N 14°44’E	120	28	370	310	27
	13	185	57°09’N 14°46’E	110	34	465	330	30
	14	170	56°56’N 12°47’E	61	36	719	290	24
	21	95	56°41’N 13°06’E	101	33	510	280	30
	22	120	58°12’N 15°56’E	76	32	581	380	26
	23	310	63°13’N 14°30’E	82	25	284	190	18
	24	310	63°13’N 14°30’E	82	26	301	250	21
	25	310	63°13’N 14°30’E	82	26	290	240	21
	26	270	64°04’N 16°15’E	152	18	243	250	21
	27	270	64°04’N 16°15’E	152	18	162	230	20
	28	270	64°04’N 16°15’E	152	18	145	160	16

[a)] The numbering of stands follows that given in Lindström (2000), where the omissions of stands number 6, 9, 10, 15–20 simply reflects the fact that some potential tree stands were never utilised. The current study is based on the tree and stand data pooled from three earlier studies, “the Log scanner project” (FAIR CT 96-1188) and “Improved spruce timber utilisation” (FAIR-CT96-1915, Moberg 1999).

of growth rings and ring width, in two opposite quadrants, 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 JWCR and JWP

In SAS, a program was written to determine the mean radius of *JWCR* based on the growth ring data (Fig. 2). Then, JWCR determinations at **n** differing stem heights, given by the cross-cutting locations of each a tree stem, were averaged and a juvenile core wood volume for each tree was calculated:

$$\text{Juvenile wood volume} = 100 \times \left[\pi \times \left(\frac{\left(\sum_{i=0}^{n} JWCR_i \right)}{n} \right)^2 \times \text{total tree height} \right] \quad (1)$$

The *JWP* is calculated as the ratio between the juvenile wood volume and total stem volume under bark for each individual tree:

$$\text{Juvenile wood percentage} = \frac{\text{Juvenile wood volume}}{\text{Total stem volume u.b. (Näslund 1947)}} \quad (2)$$

The min, max, and averaged values of *JWCR* and *JWP* of small, medium, and large trees arranged into three site quality classes can be seen in Table 2.

2.4 Statistical Analysis

A set of original variables (Moberg 1999) relating to tree and stand growth development of the used material was combined with calculated values of *JWCR*, *JWP*, and growth ring data using SAS. Furthermore, SAS was used to construct descriptive, combined and transformed variables, that together with original variables were merged into a large data set. The SAS REG procedure was used to build models of *JWCR* and *JWP* devel-

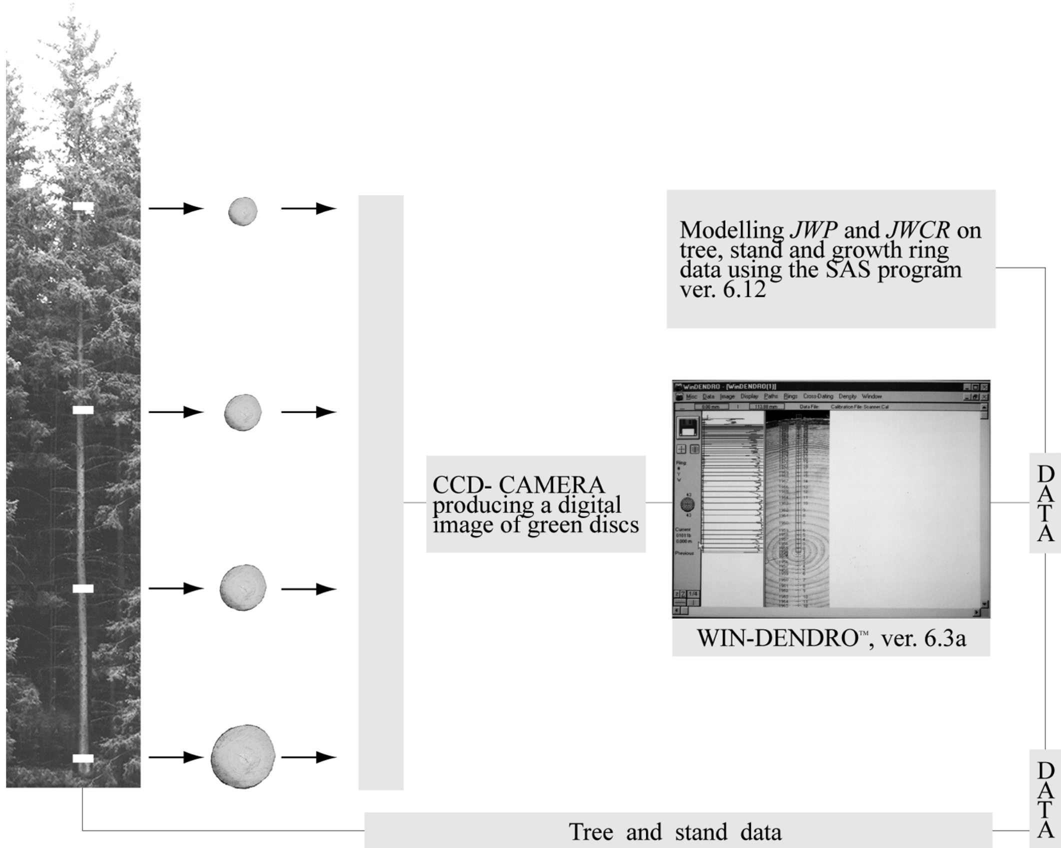


Fig. 2. Stem disc sampling at the stem cross-cutting points corresponding to a log length variation of 3.4–5.3 m, and the analytical technique to obtain determinations of JWCR and JWP.

opment. A first screening of alternative models was undertaken using stepwise regression, best RSQUARE, and best Mallow's CP. Then a set of statistical selection criteria (a–b) were chosen. These generated a number of models with similar RMSE and coefficient of determination. To correct for heteroscedasticity seen in the residual plots of the *JWP* models, logarithmic and square root transformations of JWP were utilised. Variables that intuitively seemed logical (c) had limited multicollinearity (d), and also are easy to record were selected in the final models of *JWCR* and *JWP*. Hence, a *JWCR* model (model 1) and a logarithmic *JWP* model (model 2) were developed based on tree and stand data variables:

$$Y_j = \sum_{i=1}^{n_j} b_{ji} x_{ji} + \varepsilon_j \qquad (1)–(2)$$

where j is models 1, 2. Variables included in both models had to meet the following criteria:

a) Variables should be significant at $p < 0.001$ level.
b) Each variable included should add a partial R^2Adj > 0.02 to the total R^2Adj of a model.
c) If very similar R^2Adj the variable combination was chosen that was presumed both easy to record or sample and also be intuitively related to growth development of stands and trees.
d) The variables selected in the final models should have a variance inflation factor < 3 to avoid severe problems with multicollinearity.

Table 2. The min, max, and averaged values of JWCR and JWP of small, medium, and large trees arranged into three site quality classes.

Site quality[a]		G 18–20		G25–28		G32–38	
Average stand age[a]		149 years		102 years		69 years	
Juvenile wood measurement		*JWCR*[b]	*JWP*[c]	*JWCR*[b]	*JWP*[c]	*JWCR*[b]	*JWP*[c]
Small	MIN	4.6	2.6	5.2	3.4	10.2	6.8
tree class	MAX	26.6	7.0	37.3	17.5	64.3	51.1
	MEAN	13.0	4.8	23.2	10.2	40.4	22.7
Medium	MIN	4.5	2.6	9.7	4.5	16.2	4.7
tree class	MAX	24.5	4.9	42.7	16.8	73.2	47.8
	MEAN	15.0	4.0	28.2	9.9	46.4	21.1
Large	MIN	6.9	2.7	6.0	4.1	21.6	5.5
tree class	MAX	33.7	6.1	50.5	13.3	74.9	42.2
	MEAN	18.0	3.9	31.5	8.8	50.0	17.5

[a]See further stand description in Table 1.
[b]Measured in mm.
[c]Measured in %.

Table 3. Variables used in the models

	Description of variables
Stand variables	
SiteR10	The average JWCR (mm) at stump height of the selected stems on each site.
Sitequal	Site quality (H100) (Hägglund and Lundmark 1981)
Mataht	*Average h*eight (m) on a s*ite* / Sitequal
Tree variables	
Idbh	Dbh (mm) measured as the arithmetric mean of diameter on bark i*n t*wo perpendicular directions
Iht	Tree height in dm (distance from stump *height t*o the top of the tree)
Hpercent	100 * (Height within tree (cm) / (Iht *10))

2.7 Variables Used in the Models

On each site and for each tree a wide range of data were recorded; only those used in the derived models have been listed in Table 3.

3 Results

3.1 Effect of Variables Used in the JWCR and JWP Models

The final model of *JWCR* was derived with 3 variables: *SiteR10*, *IDBH*, and *Hpercent*, which describe the growth and allocation of stem wood in individual trees. *SiteR10* can be seen as a stand level factor dependent on the site quality and silviculture used on each site which consequently depicts the growth rate of the entire stand. *SiteR10* was found positively correlated with *JWCR*. *IDBH* relates to average individual growth rate of each stem and was also found with a positive influence on *JWCR*. The positive correlation between *JWCR* and *Hpercent* indicates a higher radial growth rate of the first ten rings with increasing height in the tree. This could be the result of crown expansion with increasing height, due to less crown competition further up in the tree. It can be attributed to successive thinning and an indication of the altered stem growth allocation following a receding tree crown.

Utilising the same selection criteria gave a logarithmic model of *JWP* based on 3 variables:

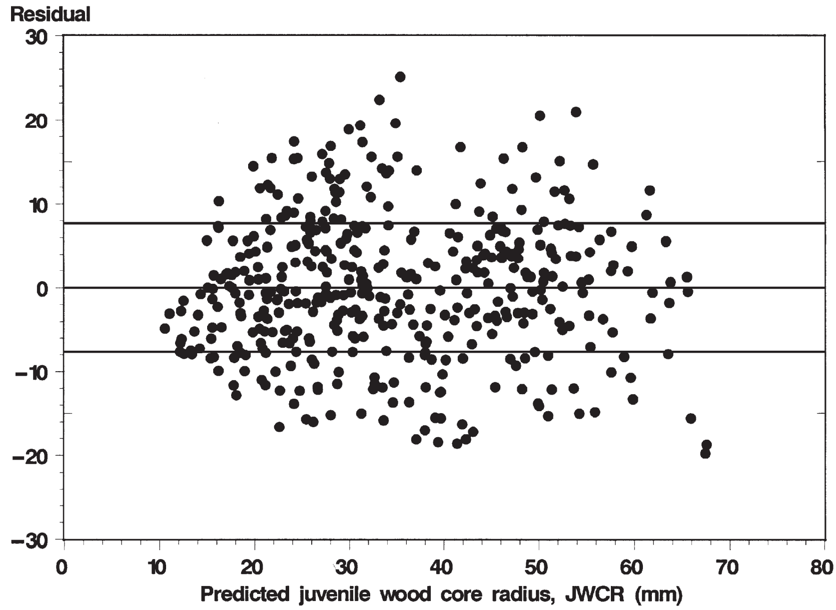


Fig. 3. Residual plot of JWCR model.

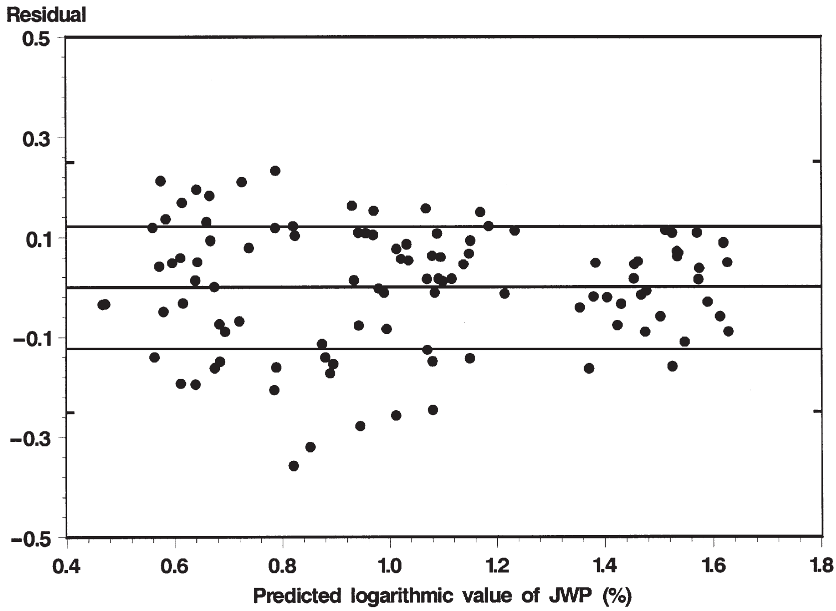


Fig. 4. Residual plot of JWP model.

SiteR10, *IDBH*, and *Mataht*. The first chosen variable, *SiteR10* depicted growth rate of the entire stand and was positively correlated with *JWP*. It indicates that the initial growth rate of the trees increased the *JWP*. The second variable *IDBH* was taken as an indication of tree size rather than growth rate, the argument being that with increasing stem volume the less proportion of the stem volume is made up of juvenile wood. The third variable used in the model was *Mataht*,

Table 4. Dependence of JWCR (Model 1), and the logarithmic value of JWP (Model 2), based on tree and stand data[a]

R^2Adj	RMSE	b_{i-n}	Sb_{i-n}	Variable
		Model 1		
0.71	8.4	–2.572	1.919	Intercept
		0.804***	0.027	*SiteR10*
		0.041***	0.006	*IDBH*
		0.128***	0.02	*Hpercent*
		Model 2		
0.88	0.124	1.643***	0.113	Intercept
		0.0131***	0.0013	*SiteR10*
		–0.6414***	0.0786	*Mataht*
		0.0012***	0.0002	*IDBH*

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

i.e. the ratio between average height and the site quality of a stand. *Mataht* was found to have a negative effect on *JWP*. *Mataht* can be seen as a measurement of stand maturity as increasing stand age increases the average tree height and stem volume in a stand. However, *Mataht* is also related to silviculture since average tree height of a tree stand can be assumed to be regulated by thinning and regeneration methods (Elfving and Tegnhammar 1996).

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

4 Discussion

4.1 Material

The current study consist of 114 trees selected in 19 stands from 11 different locations (Table 1). This material has been chosen to represent typical mature stands and tree types grown in Sweden. The material selection will not mirror young trees under 50 years of age, truly suppressed trees, trees exceeding 45 cm in DBH, crooked or damaged trees, or trees grown at extreme northerly locations. Moreover, this study does not contain information on how some of the recorded variables such as tree height and diameter might have been influenced by genetics (Hylen 1997, Rozenberg and Cahalan 1997, Flæte 1999). In conclusion, the used material can be viewed as a restricted representation of typical commercial timber stands and tree types used in Swedish sawmills. Because of the restrictions in material size and representation, the derived models in the current study should only be applied to similar material.

4.2 The Use of JWP and JWCR Models in Simulation Software

Using a conifer wood resource with a high proportion of juvenile wood is believed to impair the properties and value of solid forest products (e.g. Cown 1992, Thörnqvist 1993, Kennedy 1995, West 1998, Walker and Nakada 1999). In these reports, it is argued that the end use properties and corresponding value will differ substantially between stands and trees with differing juvenile proportion. Consequently, it has been argued that a better knowledge of *JWCR* and *JWP* of individual trees would allow for improved selection and conversion of solid forest products (West 1998). The aim of the present study was to derive practical models of *JWCR* and *JWP* which together with other models of wood variation e.g. knot and basic density models (Moberg 1999, Lindström 2000) could be fed into a conversion simulation software SOPT (Lönner and Björklund 1999). The SOPT software is designed for strategic planning, especially in selecting raw material for sawn products. This integrated approach offers the prospect of better utilisation of a given timber resource thereby creating economic benefits.

4.3 Interpretation of JWCR and JWP Models

Definitions

A number of studies partly or entirely devoted to the demarcation of juvenile wood in Norway spruce (Boutelje 1968, Lewark 1981, Madsen et al. 1986, Kyrkjeeide 1990, Danborg 1994, Kucêra 1994) have indicated that the juvenile wood boundary, dependent on used definition, can be set anywhere between 3–32 growth rings from pith. This discrepancy is reflecting the dependency on used maturation criteria and the non-constant progression rates within and between trees. Similar results can be found for other softwood species where sometimes the boundary has been extended to growth ring number 50 (Jane 1956). Jane's study also emphasises that the definition of juvenile wood seems to change with the successive shift from a natural forest resource towards a fast-grown man-made wood resource. For instance, if early definitions such as the one set by Jane (1956) were kept it would mean that the concept would progressively cover much of the timber volume produced in stands of high site quality where commercial tree size is reached at low tree age. The difficulty in defining a juvenile wood boundary is also compounded by the use of disparate and sometimes limited empirical material. With this background it is not surprising that, although there is an acceptance of the juvenile wood concept, the derived definitions found in the literature are broad and non-affirmative.

Of course the definition of the juvenile wood boundary can be improved if only one single wood character is considered to represent the gradual multifaceted development into mature wood (Danborg 1994). Nevertheless, the wood maturation pattern is likely to vary between planted and naturally regenerated trees (Eikenes et al. 1995, Bergqvist 1999). Moreover, independent of regeneration method, the wood maturation will differ with growth conditions (Lindström 1997), spacing (Kucêra 1994), and genetics (Flæte 1999). Further, drastic changes in wood structure development in young trees can be caused by unforeseen events such as heavy frosts, silviculture, and damages caused by animals or insects. Such changes will interfere with the objective to find an indisputable definition. From this perspective, the prospect of defining a decent juvenile wood boundary based on the current material with differences in geographical location, regeneration, growth rates, and silviculture is slim. The second more fundamental problem would be that a boundary deduced on the current empirical material would be confined to this study, which leaves any derived model less useful.

Instead, as most of the gradual wood maturation in Norway spruce seems to occur in the first 5–10 growth rings from pith, this study used ring number 10 to define the boundary between juvenile and mature wood. Another reason to choose this definition is that it is simple, yet it can be assumed roughly consistent with other demarcation boundaries. That is, should another growth ring number have been denoted to be the "true" boundary such as growth ring number 3, 15, or 18 it is likely that the resulting models would still remain dependent on variables which are assumed to be related to tree and stand development.

Interpretation of Derived Models

The variables used in the derived models are assumed to mirror growth development of trees and stands. The first model of *JWCR* utilises variables that mirror stand, tree, and within-tree growth development, while the second model of *JWP* is restricted to stand and tree variables. After the initial screening of the used data, some statistical selection criteria were applied to produce a number of viable models with similar R^2Adj and RMSE. The final decision on model structure required that the selected variables should have limited multicollinearity, be intuitively related to tree growth and be easy to record. In addition, the chosen variables should ensure some compatibility between the two models without much loss in predictive ability.

It is obvious that the *JWCR* and *JWP* models are dependent on several interacting variables controlling or describing the wood production and allocation of wood along the tree stem. In the case of naturally regenerated, low site quality stands, seedlings will have been grown under a sheltering canopy leading to retarded diameter growth. With the removal of the canopy, wood production in the stand is transferred to the understorey seedlings. The result will be tree growth acceleration, where a narrow core of juvenile wood, will be successively surrounded by an increasing volume of mature wood. This study indicated that naturally generated trees at the age of ca 150 years would have a *JWP* of about 5% (Table 2).

In contrast, planted seedlings grown on a fertile site experience a different growth environment. At first there is no sheltering by older trees, so the trees respond quickly by building a large crown that promotes high radial growth rate leading to wide growth rings. Consequently, planted trees grown on a high site quality will reach a commercial tree size at an early age with higher stem *JWP* compared with trees grown on less fertile sites and harvested when the trees are older (Table 1, 2). However, the combination of growth rate and clear felling age only offers a partial explanation of *JWP*. That is, at the time of stand closure the radial stem growth decelerates in the basal part of the stem as increasing crown competition promote growth allocation higher up the stem. In fact, there is an interesting tendency, as seen in Table 3, for a small tree class to yield a higher JWP compared with a more dominant tree class. My interpretation is that the smaller trees will obtain a lower relative growth rate in the basal stem part compared with more dominant trees when crown competition commences. The result will be that the smaller trees in a stand, when the mature wood is starting to form, will have a more marked deceleration in basal stem growth while more dominant trees are able to put on a larger stem volume of mature wood that surround the juvenile wood core.

In this study, it was found that forest management aiming for fast growth on a high site index could cause stem *JWP* to exceed 50% in a 51 year old stand (Table 2). In contrast, much older naturally regenerated stands contained some trees with a *JWP* less than 3%. Such results are in agreement with the assertions of Larson (1963), Thörnqvist (1993), and Kennedy (1995). In other words, man-made forests will cause a drastic increase of juvenile wood production in absolute and relative terms.

Model Application

The aim of the present study was to derive practical *JWCR* and *JWP* models based on variables that directly or indirectly relate to a tree's growth conditions. Based on the selection criteria it was possible to build models on variables that describe stand, tree, and within-tree development. These variables are related to either the regulation of tree growth or descriptions of tree growth rate. The study strongly suggests that if a general definition of the juvenile wood concept is used a given wood resource could be assessed for *JWCR* and *JWP*. The possibility to model such differences could allow strategic decisions in forestry management and the utilisation of a given wood resource. However, the models derived herein are based on a limited data set, meaning that the models should be used with care. A future priority would be to validate the models against independent data. Another future priority, to reach truly general models of *JWCR* and *JWP*, would be to broaden the range in selected material.

5 Conclusions

The objectives of the study were to create models of *JWCR* and *JWP* in Norway spruce stems which, together with other tree models, could be used as an input into conversion simulation software. This would enable strategic selection of stands and trees suitable for a certain range of wood products. Material thought to represent typical commercial timber stands and tree types was used to construct individual tree models of the radius of a juvenile wood core (*JWCR*) and the juvenile wood percentage (*JWP*) of tree stems based on easily measured variables related to conifer wood formation. The *JWCR* model had an R^2Adj of 0.71, while the logarithmic *JWP* model had an R^2Adj of 0.88. The derived models are limited to a restricted data set and should be used with care. Some future priorities would be to validate the derived models against an independent data set and broaden the modelling approach of *JWCR* and *JWP* by including more replications of stand and tree development variability.

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