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# Wood Density Variations between Tree Components Should Be Considered to Correctly Estimate Tree Biomass Available for Different Uses

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## Abstract

Although biomass depends as much on volume as on density, in the case of trees, only the volume of the stem and the density at breast height have been studied quite extensively. The rare existing works and our preliminary analyses showed that, according to the species, the density could vary strongly between and within tree components.

There is a need to better know the forest resource in terms of wood density and biomass of the different tree components (clear wood, knots, bark, branches). Such work will contribute to refine biomass estimates to evaluate carbon sequestration in forests and to optimize the use of wood resource (lumber, pulp, panel, fuelwood, new utilisations such as extractives for chemistry), with a particular attention paid to the recovering of “waste” woods.

Wood samples of stem, knots and branches were X-rayed in oven-dried state with a medical CT scanner. For each type of sample, a specific image analysis procedure was developed under ImageJ software to measure wood density.

We present here our results for the stem and knot components for three major softwood species in France. This was done within the frame of a project about the development of a chemical industry. Knots are particularly rich in lignans, used in the cosmetics, medicine and nutrition industries. Knots have a much greater wood density than stem wood, whereas most wood density measurements, on which wood density databases are based, were performed at breast height. Depending on the species, it would be necessary to take into account these variations to estimate correctly the biomass of tree components.

Keywords: computed tomography, knots, extractives, forest resource

## Introduction

Accurate and non-biased estimate of biomass is necessary to meet several objectives. It is for example usual to estimate carbon sequestration of forest trees directly from total tree biomass. However, in the context of sustainable development, it becomes necessary to optimize the use of our resources. To optimize the use of forest biomass, it is needed to better know how it is distributed between and within the different tree components (stem, bark, knots, and branches). This last point is important to know if there is a need and an opportunity to develop a wood chemistry industry based on waste wood recovery. Bark and knots contain an important quantity of extractives (Kebbi-Benkeder, 2017). In particular, knots are a source of lignans, which can be used in cosmetics, medicine and alimentation. Such chemistry industry must not interfere with the already existing wood industry.

Today, we are not able to estimate correctly the amount of biomass of the different tree components for two main reasons. We are not able to estimate the volume of some tree components due to a lack of available measurements. It is in particular the case for the knots. For all tree components, we have a lack of knowledge on the wood density variations (most density measurements were done at breast height and the number of trees per species in the databases is quite limited). Moreover the methods used for density measurements are often questionable (Williamson and Wiemann, 2010).

Recent studies (Repola, 2006; Nogueira and al., 2008; Wiemann, 2013; Wassenberg, 2015; Wiemann and Williamson, 2014; Bastin et al., 2015) have proved that it was important to consider the variability of the wood density within the tree to have a good estimation of the biomass

The density of knots was little studied. For spruce, Gartner (1995) showed that the knots are denser than the stem. A mean oven-dried density calculated from the article is  $766 \text{ kg/m}^3$  in comparison with the wood density provided for this species by the Global Wood Density Database of  $370 \text{ kg/m}^3$  (Chave et al. 2009, Zanne et al. 2009) for example. Lehtonen (1979) has studied pine and spruce of Finland. He found that the knots are denser than the stem of  $351 \text{ kg/m}^3$  for pine and  $490 \text{ kg/m}^3$  for spruce. Also, he found for pine that bigger is the knot, denser it is. It is the opposite for spruce. Boutelje (1966) obtained the same results for the density of the same species.

In this study we measured the wood density of stem and knots for three softwood species (Norway spruce, silver fir and Douglas fir). We also estimated biomass for the knot component in our trees and compared our results with what would be done with breast height density measurement on our trees or with the usual wood density databases.

## Materials and methods

Three softwood species were studied: *Abies alba*, *Picea abies* and *Pseudotsuga menziesii*. Each species was sampled in different experimental forests in France.

Eight trees per species were harvested: four in an intensive thinning plot and four in a control plot which was not thinned. Trees were chosen in different diameter classes. The girth at 1m30 and the height of the crown base (the first whorl with at least 3/4 of living branches) were measured.

For each tree, 15 stem discs were sampled along the stem avoiding knots. The height of the first three discs was fixed at 0.3m, 0.8m and 1.3m. The 12 other discs were evenly spaced along the stem. Radial cut was done within each disc for avoiding cracks. Seven short logs containing each a whorl of knots were sampled in addition. Five were taken above the crown base and two below the crown base.



**Figure 1** - Stem discs in the X-ray CT scanner

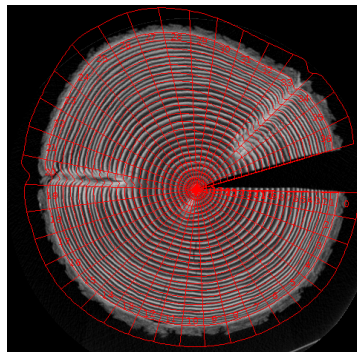
A medical CT scanner at INRA Grand Est-Nancy was used for all density measurements.

The stem discs were scanned in green and oven-dried states. CT images were produced and grey levels corresponding to Hounsfield numbers were converted into wood density (Freyburger et al. 2009). The method described by Longuetaud et al. (2016) was used to obtain the oven-dried density and the basic density of stem discs.

This method requires a good matching between CT images in green and oven-dried states. This is obtained by using the radial cut as a starting point and by manually recording the boundary between wood and bark. The discs were then divided into sectors.

The sectors including knots (even if knots were avoided by the choice of stem discs along the stem) were removed in order to compute wood densities in clear of knots areas.

For each tree, basic density of the clear of knots stem wood component was computed as the mean basic density of the 15 stem discs weighted by the wood volume of the clear of knots stem disc.

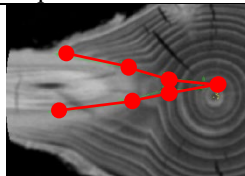


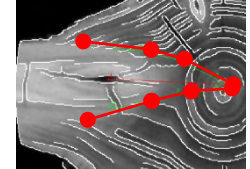
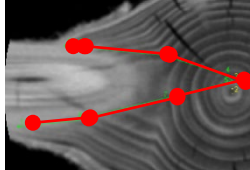
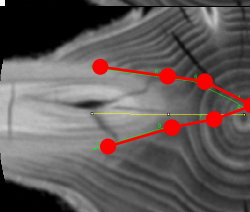
**Figure 2** - Sectorisation on a Douglas fir stem disc

The short logs containing each a whorl of knots were scanned only in oven-dried state. Only one of the eight Douglas-fir trees and six of the eight Norway spruce trees were scanned at this stage.

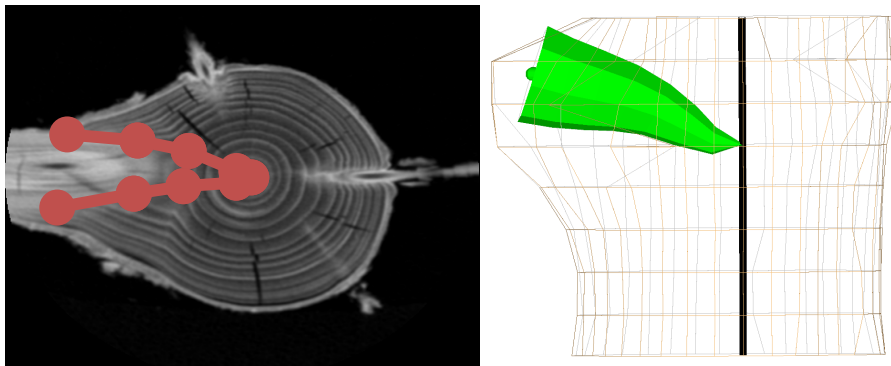
All the knots were manually segmented in each log by placing markers along the stack of CT images with a plugin developed for ImageJ called Gourmand (Colin et al., 2010). The segmentation results were visually checked thanks to a 3D viewer (Figure 3). In a preliminary step, four methods for guiding the manual segmentation were tested (Table 1).

**Table 1** - Presentation of the different methods of manual segmentations of the knots

Method	Principe	Advantage/Drawbacks	Example
Regular	No instruction given to the operator	Unrepeatable results	

Canny Edge	The Canny edge detection algorithm is used to outline the contours in order to help the operator	No noticeable improvement in repeatability. Large variations in knot length measurements	
Triple points	The limit of the knot must be set at the triple points where bark meet normal wood and knot	More repeatable results. No triple point can be found in some cases	
Radius	The radius is estimated by looking at the stem above the deformation caused by the branch, then shifted at the knot end level to fix the length	Repeatable results but with underestimated knot length and volume	

Finally, we selected the “Triple points” method because it was repeatable and because Willför (2005) reported that a lot of extractives are present at the knot end (insertion bumper) that would be excluded in the volume given by the “Radius” method. The method was applied to measure the average density of knots for each tree.



**Figure 3** - Manual segmentation of a knot with the “triple point” method (left) and 3D representation with the Bil3D viewer (right)

To estimate the volume of knots, with the final objective to compute knot biomass in trees, we used another dataset issued from silver fir trees previously sampled in the same forest as the silver fir sampled for the present study. These trees were scanned integrally in logs of about 1.5 meter long. All the knots of the trees were manually segmented as described above. It was found that the knots represented 1% of the total stem volume measured over-bark. The same rate was used for Norway spruce and Douglas fir in the absence of other data.

As mentioned before, the knot logs were only scanned in the oven-dried state. We therefore used a linear relationship to convert the oven-dried density measured on the CT images into basic density. The following equation was fitted for each species by using oven-dry and basic densities measured on the stem discs:

$$BD = \alpha * D_0 + \beta$$

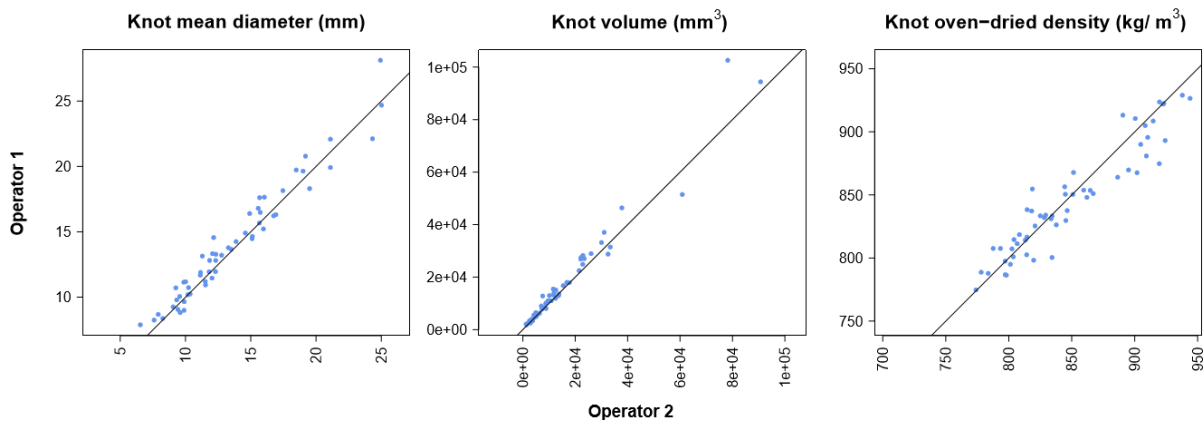
where BD is the basic density,  $D_0$  is the oven-dried density and  $\alpha$  and  $\beta$  are the parameters. Parameters of the equation are presented in the following table (Table 2).

**Table 2** - Parameters of the linear relationship fitted using stem disc data to convert oven-dried density into basic density.

Species	$\beta$ (kg/m <sup>3</sup> )	$\alpha$ (Unitless)
Silver fir ( <i>Abies alba</i> )	38 **	0.790 ***
Norway spruce ( <i>Picea abies</i> )	67 ***	0.710 ***
Douglas fir ( <i>Pseudotsuga menziesii</i> )	- NS	0.879 ***

## Results

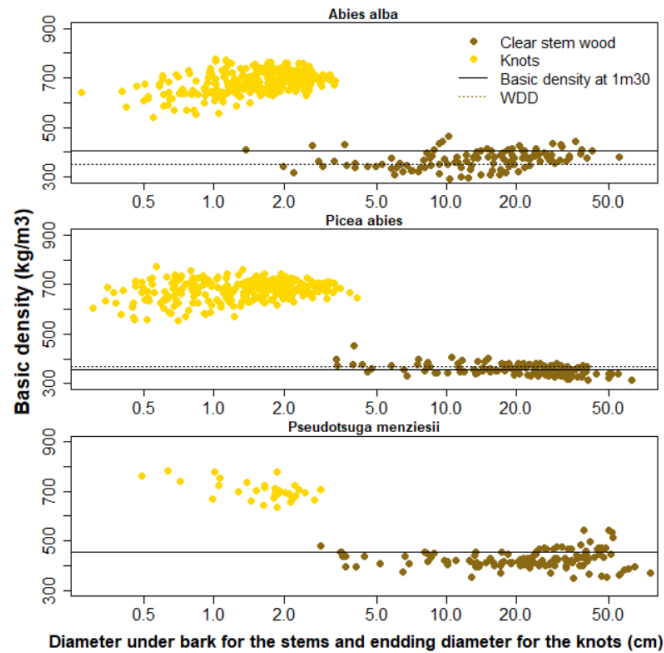
Differences in the manual segmentation of knots made by two operators with the “Triple points” method and the effects on basic density, mean diameter and volume are presented in Fig. 4. Very few discrepancies between operators were observed. It confirmed that the “Triple point” method was repeatable and efficient for assessing knot wood density and volume.



**Figure 4** – Mean diameters, volumes and oven-dried densities of knots obtained by two operators. The black line is the “y=x” line.

The basic density of knot wood and clear wood is represented for each species in Figure 5. It appears that the density of knots is much higher than the normal stem wood. In average, the basic density of knots was 685 kg/m<sup>3</sup> for silver fir, 676 kg/m<sup>3</sup> for Norway spruce, and 705 kg/m<sup>3</sup> for Douglas fir whereas the density of normal stem wood was 374 kg/m<sup>3</sup>, 353 kg/m<sup>3</sup>, and 430 kg/m<sup>3</sup>, respectively. Moreover, it would appear that there is no influence of the knot diameter on the knot basic density.

The effects of diameter at breast height and silvicultural treatment were assessed independently on the wood density of stem and knot components with regression and t-test, respectively. No effect of DBH was found. Only the effect of the treatment was statistically significant for silver fir with a greater density for thinning plot. The biomass values were computed by using the measured density of each component and compared with the biomass that would have been obtained with the basic density measured at 1m30. Table 3 shows the difference between both values. For the three species, applying the density of normal wood measured at 1.30 m to the knots would lead to underestimate by more than 60 % the available quantity of knot extractives.



**Figure 5** - Basic density of knot wood (yellow) and clear of knot stem wood (brown) as a function of the diameter of knots and stem discs, respectively. Each point represents the mean density of a knot or a stem disc. The solid black line indicates the mean basic density of the trees at 1m30 for each species. The dotted black line indicates the mean basic density of each species from the Global Wood Density Database (Chave et al. 2006).

**Table 3** - Difference between biomasses computed with the specific density of each component and biomass computed with the average density of our trees at 1.30m

Species	Clear of knots stem wood	Knot wood
Silver fir ( <i>Abies alba</i> )	-7.8 %	68.9 %
Norway spruce ( <i>Picea abies</i> )	-0.9 %	89.9 %
Douglas fir ( <i>Pseudotsuga menziesii</i> )	-5.1 %	64.1 %

## Discussion and conclusion

The mean basic density of knots was found to be 83% above normal wood for silver fir, 92 % for Norway spruce and 64 % for Douglas fir. In table 3, the negative value of the clear of knots stem wood basic density can be explained by the fact that the basic density at DBH is higher than the rest of stem. So, the mean basic density of the stem is little than the DBH mean.

The results are in agreement with the literature. For knot wood of spruce, a mean oven-dried density calculated from Gartner (1995) was 766 kg/m<sup>3</sup> and that is equivalent, when applying the conversion equation presented above, to a basic density of 611 kg/m<sup>3</sup>, in the same order of magnitude than our value of 676 kg/m<sup>3</sup> for spruce. A mean oven-dried density calculated from Boutelje (1966) was 1040 kg/m<sup>3</sup>, which is equivalent to a basic density of 805 kg/m<sup>3</sup>. In both studies, density of knot wood was found to be much higher than density of clear wood. Moreover, Lehtonen (1979) found for spruce that dense knots are little and it would appear that it is not validate in this study.

The volume of knots was not measured. Based on measurements performed on six silver fir trees from another study (not published yet), it was fixed in this paper to 1% of the total stem volume over-bark whatever the species. Up to now, no data are available for Douglas fir and Norway spruce. According to the bibliography, the knot rate varies between 0 and 4% (Polge et Illy, 1967; Andersson 1987 in Lula 2017; Pinto et al. 2002; Fredriksson, 2012). Most of these studies focused on pine.

In this study, it was considered that the knot volume can be entirely used for the chemical extraction process. In reality, all the knots will not be used because the wood of knots is usually not separated from

normal wood in the industrial process (except in paper industry). Moreover, it was shown that the boundary between wood and knots is not clearly defined. This is probably not a serious problem, since in the case where knot extraction would be performed for feeding a chemical process, the wood around the knot would certainly be included into the extracted volume. The “Gourmand” plugin makes it possible to modify the diameter of the manually segmented knots to compute density with including more or less wood framing knots.

Other tree components (bark and branches) will be analysed in a further study. Until now, the analyses were mainly descriptive, but in the future we intend to model the density of each component as a function of tree characteristics. The density variations within tree components will also be studied.

In conclusion, the lack of volume data of the knots and the utilisation of the stem wood density for the knots make it hard to have a good estimation of the basic density of the knots and underestimate the biomass of knots.

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## References

- Bastin, J.F.; Fayolle, A.; Tarelkin, Y.; Van Den Bulcke, J.; De Haulleville, T.; Mortier, F.; Beeckman, H.; Van Acker, J.; Serckx, A.; Bogaert, J.; De Canniere, C. 2015. Wood specific gravity variations and biomass of central african tree species: the simple choice of the outer wood. *PloS one*. 10(11).
- Boutelje, J.B. 1966. On anatomical structure moisture content density shrinkage and resin content of wood in and around knots in Swedish pine (*Pinus Silvestris* L) and in Swedish spruce (*Picea Abies* Karst). *Svensk Papperstidning-Nordisk Cellulosa*. 69(1): 1-10.
- Chave, J., Coomes, D., Jansen, S., Lewis, S. L., Swenson, N. G., & Zanne, A. E. 2009. Towards a worldwide wood economics spectrum. *Ecology letters*, 12(4), 351-366.
- Colin, F.; Mothe, F.; Freyburger, C.; Morisset, J.-B; Leban, J.-M.; Fontaine, F. 2010. Tracking rameal traces in sessile oak trunks with X-ray computer tomography: biological bases, preliminary results and perspectives. *Trees*. 24(5): 953-967.
- Fredriksson, M. 2012. Reconstruction of *Pinus Sylvestris* knots using measurable log features in the Swedish Pine Stem Bank. *Scandinavian journal of forest research*, 27(5): 481-491.
- Freyburger, C.; Longuetaud, F.; Mothe, F.; Constant, T.; Leban, J.M. 2009. Measuring wood density by means of X-ray computer tomography. *Annals of forest science*. 66(8), 804.

- Gartner, B.L. 1995. Patterns of xylem variation within a tree and their hydraulic and mechanical consequences. In: *Plant stems*: 125-149.
- Kebbi-Benkeder, Z.; Manso, R.; Gérardin, P.; Dumarçay, S.; Chopard, B.; Colin, F. 2017. Knot extractives: a model for analysing the eco-physiological factors that control the within and between-tree variability. *Trees*. 31(5): 1619-1633.
- Lehtonen, I. 1978. Knots in Scots pine (*Pinus sylvestris* L.) and Norway spruce (*Picea abies* (L.) Karst.) and their effect on the basic density of stemwood. *Communicationes Instituti Forestalis Fenniae*.
- Longuetaud, F.; Mothe, F.; Fournier, M.; Dlouha, J.; Santenoise, P.; Deleuze, C. 2016. Within-stem maps of wood density and water content for characterization of species: a case study on three hardwood and two softwood species. *Annals of Forest Science*. 73(3): 601-614.
- Lula, M. (2016). Knots properties of lodgepole sawn boards from unthinned stands planted in different initial spacings.
- Nogueira, E.M.; Fearnside, P.M.; Nelson, B.W. 2008. Normalization of wood density in biomass estimates of Amazon forests. *Forest Ecology and Management*. 256(5): 990-996.
- Pinto, I.; Pereira, H.; Usenius, A. 2003. Analysis of log shape and internal knots in twenty maritime pine (*Pinus pinaster* Ait.) stems based on visual scanning and computer aided reconstruction. *Annals of forest science*, 60(2), 137-144.
- Polge, H. ; Illy, G. 1967. Observations sur l'anisotropie du Pin maritime des Landes. *Annales des Sciences Forestières*. 24(3): 205-231. EDP Sciences.
- 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.
- Wassenberg, M.; Chiu, H. S.; Guo, W.; Spiecker, H. 2015. Analysis of wood density profiles of tree stems: incorporating vertical variations to optimize wood sampling strategies for density and biomass estimations. *Trees*. 29(2): 551-561.
- Wiemann, M.C., Williamson, G.B. 2013. Biomass determination using wood specific gravity from increment cores. USDA Forest Service, Forest Products Laboratory, General Technical Report, FPL-GTR-225, 2013: 9 p., 225, 1-9
- Wiemann, M.C.; Williamson, G.B. 2014. Wood specific gravity variation with height and its implications for biomass estimation. Research Paper FPL-RP-677. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 9 p.
- Willför, S.M.; Sundberg, A.C.; Rehn, P.W.; Holmbom, B.R.; Saranpää, P.T. 2005. Distribution of lignans in knots and adjacent stemwood of *Picea abies*. *Holz als Roh-und Werkstoff*. 63(5): 353-357.
- Williamson, G.B.; Wiemann, M.C. 2010. Measuring wood specific gravity...Correctly. *American Journal of Botany*. 97(3): 519-524.
- Zanne, A.E.; Lopez-Gonzalez, G.; Coomes, D.A.; Ilic, J.; Jansen, S.; Lewis, S.L.; Miller, R.B.; Swenson, N.G.; Wiemann, M.C.; Chave J. 2009. Data from: Towards a worldwide wood economics spectrum. Dryad Digital Repository.