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Modelling the Volume of Bark from Thickness Measurement Obtained by Swedish Gauge— Application to the Quantification of Extractives

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Abstract

Today, climate change, scarcity of fossil fuels and new regulations (as the European REACH regulation) lead chemical industry to find new resources in order to make its conversion toward green chemistry. Use of forest resources makes this conversion possible. Indeed, in addition to the ligno-cellulosic material, wood contains molecules, called extractives. These molecules, of little size compared to the wood polymers, lignin and cellulose, are easy to recover and can be used as a feedstock for the fine chemistry, for example pharmaceuticals or cosmetics. In order to assess the feasibility of installing regional extraction plants, the quantity of available extractives must be first estimated. This study, aims to estimate the volume of bark in *Pseudotsuga menziesii*, *Picea abies* et *Abies alba*, and combine it subsequently with density and concentration in extractives. Several French bark databases have been merged including a total of 12 000 trees measured. Both stem diameter were measured regularly all along the stem. A modelling approach is presented to predict bark volume from tree measurements, like DBH or tree height. This model is applied to the forests of North-Eastern France measured by the National Forest Inventory service (IGN). A first estimation of the resource of bark extractives is delivered from our bark volume estimates, density values and extractives concentrations.

Keywords: volume, bark, extractives, modeling, X-ray scanner

Introduction

Modelling tree volume is at the base of research approaches in the fields of forest and wood sciences. Indeed, the ability to know precisely the quantity of wood within each tree component (bark, knot, branch), directly from external tree measurement, like Diameter at Breast Height (DBH) or total Height (H) of the tree, allows forest manager to predict how much wood he is able to provide for several types of demand. In order to achieve this purpose, two ways of modelling have been explored. First, several studies developed models that allows to know directly the volume of the stem without bark from these external measurements (*Dhôte et al 2000, Jenkins et al 2003*). The advantage of this method is that it directly predict the volume of wood saleable without intermediary calculations; but, in the other hand, it is not very useful to describe the other compartment of the tree (like bark). The second approach to predict stem volume is to develop a model of bark volume and associate it with a model of stem volume with bark. Several studies follows this path and produce different models (

Meyer (1946), Loetsh et al (1973), Gordon (1983), Stängle et al (2017)), predicting either bark thickness at different heights or directly bark volume.

It turns out that, bark very rich in extractives (Trivelata et al (2016)). Extractives are molecules which can be extract by organic solvents or water from wood. They are naturally produced by the tree in order to defend himself against outdoor aggression, like bacteria, fungus or parasite (Theander O. (1985)). These molecules can become a new source for green chemistry in pharmaceutical and medicinal industry (Andersson (1955)), replacing with a serious ecological advantage, the use of petroleum-base products. This is the context of the project ExtraFor_Est in which this work takes place. The final purpose of this project is to predict the quantity of these molecules available in the forest resources of North-East of France. And in order to achieve this goal, knowing the volume of tree component containing a lot of these molecules is an essential work, along with the density and the extractives concentration of these parts.

In order to measure bark thickness alongside the tree trunk, the most common measurement method used is the Swedish bark gauge (Meyer (1946), Gordon (1983)) even if its accuracy have already been discussed (Stängle et al (2016)). With the progress of engineering it is possible today to pass sample in a X-ray scanner and so obtain more precise data (Stängle et al (2017))

Finally this studies has three purposes: 1. Deliver a model in order to describe more precisely the internal structure of stem, 2. allow a faithful estimation of extractives resources and 3. determine the statistical difference between X-ray measurement and bark gauge measurements. The studies deals weight five species: Silver fir (*Abies alba*), Norway spruce (*Picea abies*), Douglas fir (*Pseudotsuga menziesii*), Beech (*Fagus sylvatica*) and Oak (*Quercus petraea* et *Quercus robur*).

Materiel and method

Database

Different databases have been used to provide enough measurements. All databases include bark thickness measurements obtained at different heights along the stem (including 1.3m) and tree measurement. Several methods for measuring bark thickness were used. Table 1 summarises all these sources.

Table 1: Data summary

Database	Species	Data subset	Number of data	Number of trees	Measurement method
Emerge	Fir	CTFT	17 262	751	Swedish bark gauge
		INRA	3 959	173	Debarking
		Total	2 1221	924	
	Spruce	CTFT	20 536	836	Swedish bark gauge
		FCBA	1 198	155	
		INRA	924	41	Debarking
		Total	22 658	1032	
	Douglas Fir	CTFT	2 080	81	Swedish bark gauge
		FCBA	2 553	233	
		INRA	298	21	Debarking
		Total	4 931	375	

Emerge

Emerge was a project supported by French national research agency (ANR) and led by Office National des Forêts (ONF). The project, finished in 2013, aimed to estimate the available biomass in the French forests. It regrouped eight French research and development institutes. Several subsets of data collected during the past centuries by various partners were merged for the ExtraFor_Est project. Three of these subsets (CTFT, INRA and FCBA) contained bark thickness and stem circumference measurements performed at several heights, whereas INRA measurements were obtained from circumference measured before and after debarking the stem. Besides, for each tree, the total height and the DBH were measured.

Swedish bark gauge

CTFT and FCBA measured bark using a Swedish bark gauge. Relatively simple of utilization, it allows to produce rapidly a lot of measurements. However, its accuracy is weak (*Stängle et al (2016)*) and, therefore, it cannot be assumed that it gives the actual value of bark thickness. Indeed, there is only one measurement for one height and, therefore, the thickness variation around the stem cannot be considered. These measurements were done at different heights on the tree.

Debarking protocol

INRA measurements were performed with the debarking method. This method consists in measuring the trunk girth on bark then removing bark for measuring the circumference under bark. The subtraction between these two measurements give us the bark thickness. However, this thickness considers the bark but also space between bark's irregularity. Like previously, these measurements are done at different heights of the tree.

Bark volume calculation

In order to calculate the volume of bark, all the bark thickness data were converted to compute stem and bark area following, respectively, equation 1 and 2.

$$A_{ob} = \frac{D_{ob}^2}{4} \times \pi \quad (1)$$

With: A_{ob} the stem area over bark and D_{ob} the stem diameter over bark

$$A_b = A_{ob} - \frac{(D_{ob} - 2T_b)^2}{4} \times \pi \quad (2)$$

With: A_b the bark area and T_b the bark thickness

In order to calculate the bark volume from these areas, we considered the stem as a stack of truncated cones. Therefore, we used equation (3) to calculate the volume of each truncated cone.

$$V_{truncated\ cone} = \frac{H_c}{3} * (A_1 + \sqrt{A_1 \times A_2} + A_2) \quad (3)$$

With $V_{truncated\ cone}$ the volume of the truncated cone, H_c the truncated cone height, A_1 and A_2 the area of, respectively, the lower section and the upper section of the truncated cone.

There are two special cases: the top and bottom parts of the tree. For the first one, we assumed the top of the tree to be a cone, and so used the cone volume formula (equation 4)

$$V_{top\ cone} = \frac{H_c}{3} * A \quad (4)$$

With $V_{top\ cone}$ the volume of the top cone and A the area of the last sample disc

At the tree bottom, we extrapolated the stem area at ground level using the two lowest measured areas.

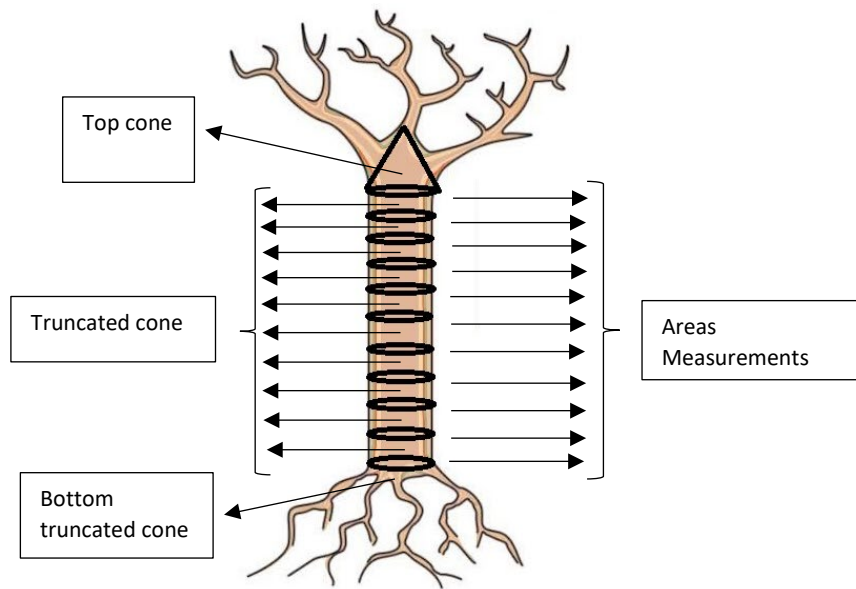


Figure 3 : Schema of a sequence of truncated cone modelling a stem

The sum of the over bark and under bark volume gave the volume of stem over and under-bark. The bark volume was therefore obtained by subtraction. Figure 3 summarises this protocol.

Results and discussion

Bark model

The first objective of our research was to obtain a model of Bark Thickness at Breast Height (BTBH). This variable give precious information over bark. However, used it need a more complicated protocol in order to obtain this measure. An accurate model will allows us to use BTBH without strongly increase the sample protocol. Moreover, we will also be able to use other database, which did not measure BTBH, to achieve ExtraFor_Est purpose.

We tested different models with candidates variables like, DBH, H/DBH, DBH²/H, DBH²*H, H being the total height of the tree. The two most accurate models follow equation (5) and equation (6).

$$BTBH = a \cdot DBH + b \quad (5)$$

$$BTBH = a \cdot BDH^b \quad (6)$$

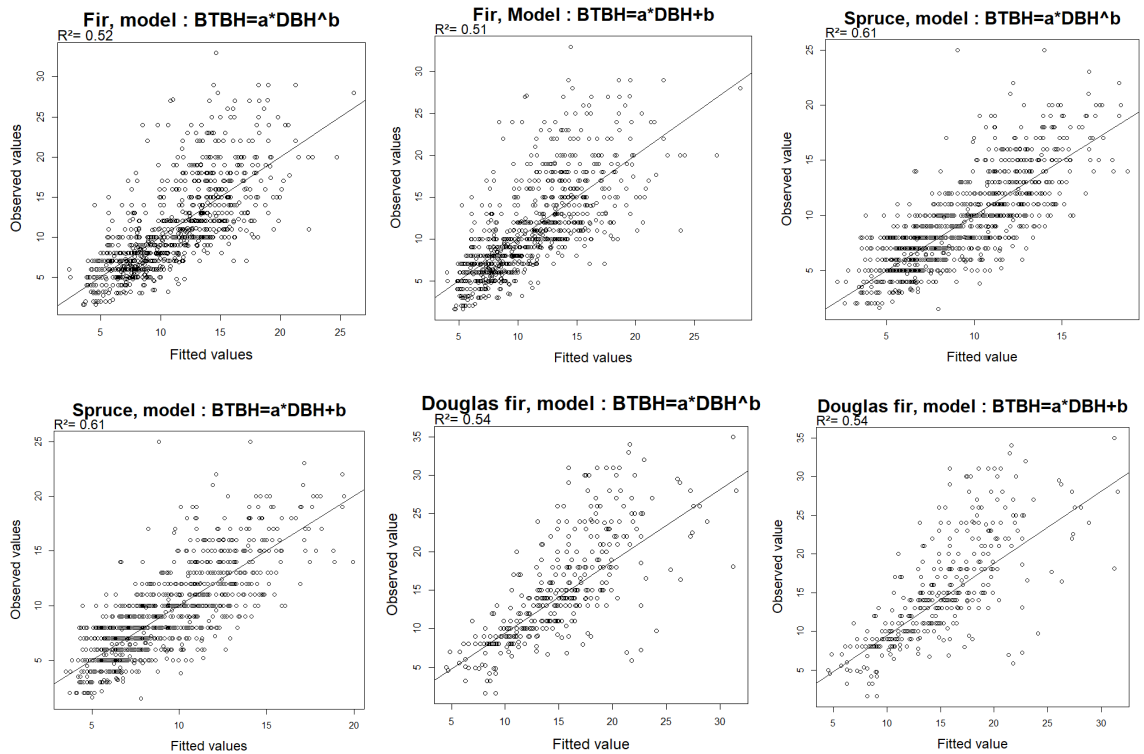


Figure 4 : Modelling result for $BTBH=a*DBH^b$ (left side) and $BTBH=a*DBH+2$ (right side) for Fir, Spruce and Douglas fir. Black line is the line of equation observed values=fitted values ($y=x$). Observed and fitted value are expressed in mm.

As recommended by *Piñeiro et al (2008)*, figure 4 represented the observed values vs. predicted values in order to establish the relevance of the model, and the R^2 presented is the result of regression between both values. We can see that the linear model fits relatively well with the data, especially for Spruce.

Table 2: Results of the model predicting BTBH from DBH. All presented models are significant with a p -value < 0.05. All trees of data set were used for adjusting. DBH and BTBH are expressed in mm.

Species	Model	a	b	Significance a	Significance b	R ²	RMSE(mm)	Relative RMSE	AIC
Fir	aDBH+b	0,0220	3,0660	2,58E-146	8,41E-26	0,51	3,849	35%	5119
Fir	aDBH^b	0,1706	0,7122	4,65E-11	8,09E-132	0,52	3,835	35%	5112
Spruce	aDBH+b	0,0194	2,6665	2,44E-217	6,05E-47	0,61	2,501	27%	4883
Spruce	aDBH^b	0,1532	0,7076	1,57E-18	5,52E-200	0,61	2,512	28%	4892
Douglas fir	aDBH+b	0,0480	0,5446	9,40E-64	4,56E-01	0,54	4,592	31%	2190
Douglas fir	aDBH^b	0,0727	0,9349	4,29E-04	1,51E-58	0,54	4,584	31%	2189

With: $RelativeRMSE = RMSE/mean(B_v)$

For Fir, the model seems, visually, to be good, even if the R^2 is lower than for the others models. For Douglas fir the data seem to follow an exponential model. The non-linear model does not seem better than the linear model. However, it is more logical because it does not predict a bark thickness at 1.30m for tree with a DBH=0. In the particular case of Fir, we can also see, in table 2, that the significance of parameter b for the linear model is not relevant and so this parameter cannot be kept in

the final model. We can select this model without a constant parameter, which seems more biologically relevant as it predict a null BTBH for a null DBH.

It must be mentioned that we tried to model the non-linear model with a constant, but it appeared not significant. In addition, of these work, we also try to fit the residuals of these models, on H.

Nevertheless, there were no more variation with H. This was a non-surprising result, according to the relation already shown between H and DBH (*Mehtatalo et al (2015)*).

Bark volume model

The purpose of this study is to model the volume of bark along the stem. To do this, we used a geometric approach, considering bark as the difference between two cones, represented by eq. (7.1).

$$B_V = V_{ob} - V_{ub} \quad (7.1)$$

$$= \frac{1}{3} \cdot H \cdot \frac{\pi}{4} \cdot DBH_{ob}^2 - \frac{1}{3} \cdot H \cdot \frac{\pi}{4} \cdot DBH_{ub}^2 \quad (7.2)$$

$$= \frac{\pi}{12} \cdot H \cdot (DBH_{ob}^2 - DBH_{ub}^2) \quad (7.3)$$

$$= \frac{\pi}{12} \cdot H \cdot (DBH_{ob} - DBH_{ub}) \cdot (DBH_{ob} + DBH_{ub}) \quad (7.4)$$

$$= \frac{\pi}{12} \cdot H \cdot BTBH \cdot (2 \cdot DBH_{ob} - BTBH) \quad (7.5)$$

$$\approx \alpha \cdot H \cdot BTBH \cdot DBH_{ob} \quad (7)$$

With denoting X_{ob}, the variable X over bark, X_{ub}, the variable X under bark, V the volume of stem and B_v the bark volume.

In equation (7.5), we assumed BTBH insignificant before DBH_{ob}.

Equation (7) was the equation we used to model bark volume. In this model, we can add the two previous models over BTBH in function of DBH, like in equation (8) and (9).

$$B_V = \alpha * DBH * (b * DBH + c)H + b \quad (8.1)$$

$$= \alpha b * DBH^2 * H + \alpha c * DBH * H + d \quad (8.2)$$

$$= \alpha' * DBH^2 * H + b' * DBH * H + c' \quad (8)$$

$$B_V = \alpha * DBH * (b * DBH^c)H + b \quad (9.1)$$

$$= \alpha b * DBH^{1+c} * H + d \quad (9.2)$$

$$= \alpha' * DBH^{1+b'} * H + c' \quad (9)$$

Finally, we tested three models. In order to control the heteroscedasticity of the data, we used the varPower form, following equation (10) to account of the variance structure:

$$Var = \sigma^2 D^2 H^{2\theta} \quad (10)$$

With Var the variance, D²H defined as DBH²*H and σ and θ two parameters.

The models (8) and (9) were tested and compared to model (7) using the measured value of BTBH in view to evaluate the extra-accuracy obtained by measuring bark thickness at breast height. Figure 5 presents the results for these three models for each species and table 3 shows the model statistics.

We can see on figure 5 that the three models are rather good since the data cloud is close to the line of equation y=x. As expected for Spruce and Fir, results show a decrease of prediction accuracy for models without BTBH compared to models with, although this drop is not very important (R² : 0.93 VS 0.86 and 0.87 for Fir, 0.94 VS 0.9 and 0.9 for Spruce, relative RMSE: 30% VS 43% and 41% for Fir, 29% VS 34% and 33% for Spruce).

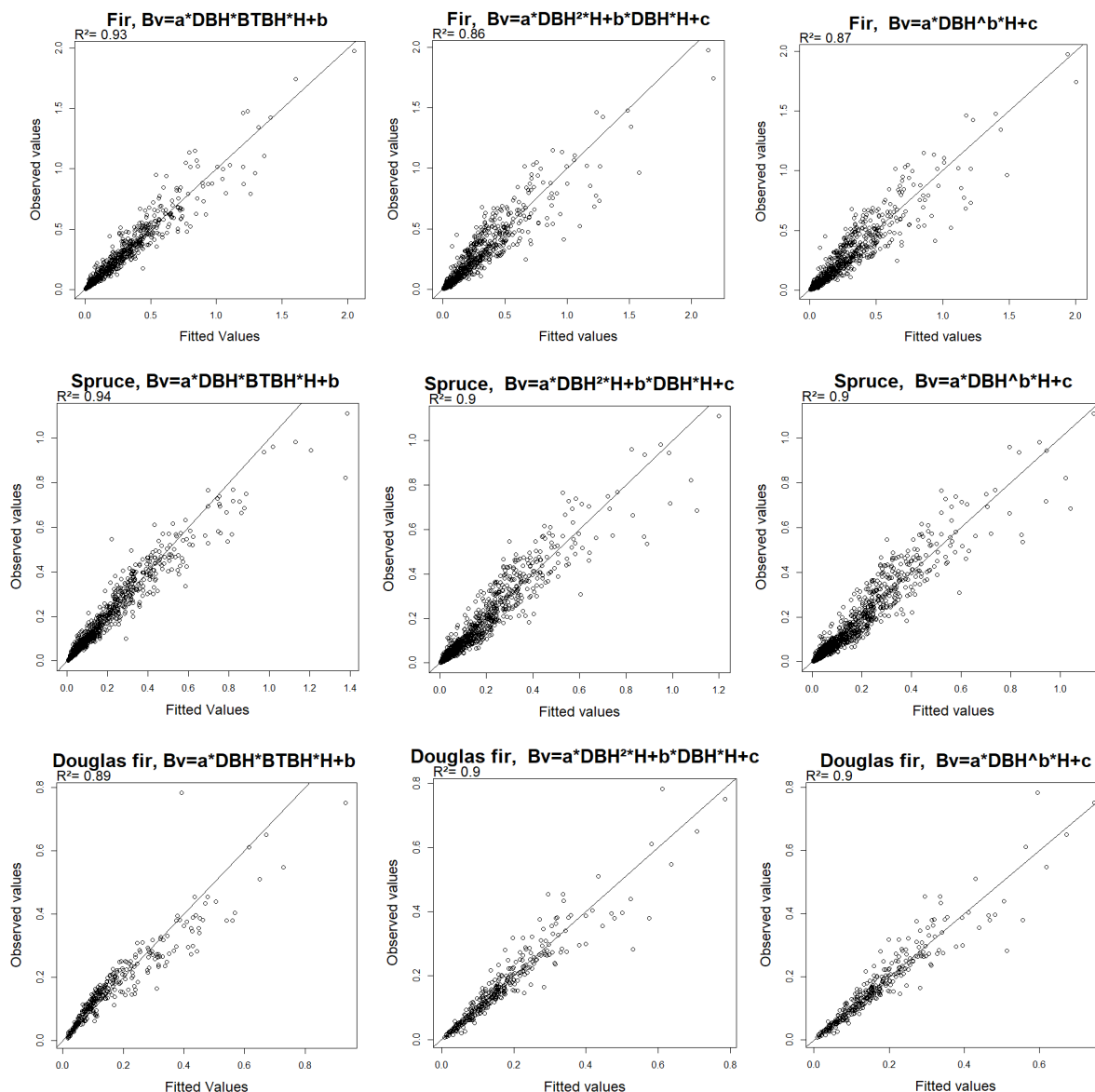


Figure 5: Observed vs Fitted values for Fir, Spruce and Douglas fir, for the models (7) (left side), (8) (middle) and (9) (right side) Black line is the line of equation observed values=fitted values (y=x).

Table 3: Results of the relationship between B_v and DBH, H and BTBH. All presented models are significant with a p-value<0.05. All trees of data set were used for adjusting. Model A : $a \cdot DBH \cdot BTBH \cdot H + b$; Model B : $a \cdot DBH^2 \cdot H + b \cdot DBH \cdot H + c$; Model C : $a \cdot DBH^b \cdot H + c$

Species	Model	a	b	c	Significance a	Significance b	Significance c	RMSE	Relative RMSE	AIC	R ²
Fir	(A)	1,64E-06	2,99E-03	/	0,00E+00	2,43E-33	/	6,71E-02	30%	-3825	0,9
Fir	(B)	3,65E-08	5,15E-06	2,83E-03	2,86E-94	5,51E-15	3,56E-07	9,47E-02	43%	-3093	0,9
Fir	(C)	2,64E-07	1,72E+00	3,73E-03	3,89E-07	5,47E-286	5,79E-14	9,15E-02	41%	-3102	0,9
Spruce	(A)	1,50E-06	4,88E-03	/	0,00E+00	1,65E-36	/	4,58E-02	29%	-4816	0,9
Spruce	(B)	2,07E-08	8,15E-06	5,68E-04	5,70E-66	1,21E-49	0,44	5,30E-02	34%	-4327	0,9
Spruce	(C)	7,35E-07	1,52E+00	2,62E-03	3,39E-08	7,94E-291	3,37E-04	5,16E-02	33%	-4319	0,9
Douglas fir	(A)	1,11E-06	1,27E-02	/	2,09E-181	1,60E-31	/	4,76E-02	30%	-1448	0,9
Douglas fir	(B)	3,48E-08	1,05E-05	-2,10E-03	7,60E-23	2,24E-16	0,19	3,82E-02	24%	-1559	0,9
Douglas fir	(C)	9,64E-07	1,54E+00	5,64E-04	1,08E-03	1,35E-96	0,71	3,71E-02	23%	-1566	0,9

However, for Douglas fir results are unexpected. Indeed, for R^2 , AIC, RMSE and relative RMSE the models (B) and (C) that do not require BTBH are even better than model (A) using the measured value for BTBH. We can explain this considering the roughness of Douglas fir's bark at breast height. This property can introduce a high variability between measures from the same tree. A single measurement is thus probably not very representative of the mean BTBH.

It can be seen also that the constant parameter (c) is not significant (p-value superior of 0.05) for three models (third models for Spruce and second and third ones for Douglas fir). It make sense from a biological point of view since it predicts a null bark volume for a null DBH.

In addition, with the results presented in table 2, we can compare both models for predicting BTBH. The accuracy is not very different between the two models and for each species. Finally models (C) seem the more suitable for predicting bark volume for the three species

Conclusion and perspectives

In this study we tested several models in order to predict bark thickness at breast height BTBH and and bark volume B_v . The models predicting BTBH are quite good even if modelling estimators (especially R^2) could be improved. The models predicting B_v , on the other hand, fits strikingly good with the data measured with or without the use of BTBH. These models can thus bring more knowledge on bark of these species. However, the work is not finished yet. The models have to be validated using a cross-validation procedure or using an independent dataset. At least, these results are very encouraging and can lead us to very interesting models.

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