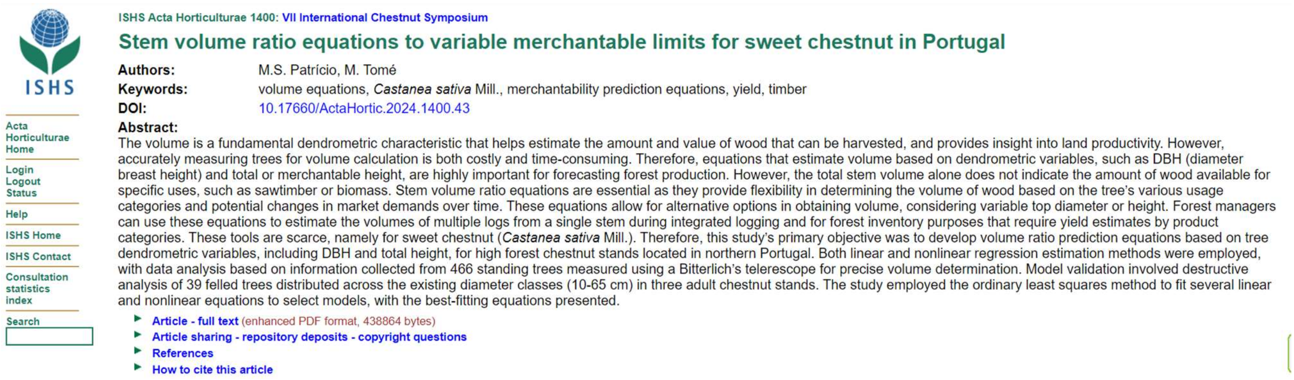

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Stem volume ratio equations to variable merchantable limits for sweet chestnut in Portugal

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Keywords: volume equations, *Castanea sativa* Mill., merchantability prediction equations, yield, timber
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The volume is a fundamental dendrometric characteristic that helps estimate the amount and value of wood that can be harvested, and provides insight into land productivity. However, accurately measuring trees for volume calculation is both costly and time-consuming. Therefore, equations that estimate volume based on dendrometric variables, such as DBH (diameter breast height) and total or merchantable height, are highly important for forecasting forest production. However, the total stem volume alone does not indicate the amount of wood available for specific uses, such as sawtimber or biomass. Stem volume ratio equations are essential as they provide flexibility in determining the volume of wood based on the tree's various usage categories and potential changes in market demands over time. These equations allow for alternative options in obtaining volume, considering variable top diameter or height. Forest managers can use these equations to estimate the volumes of multiple logs from a single stem during integrated logging and for forest inventory purposes that require yield estimates by product categories. These tools are scarce, namely for sweet chestnut (*Castanea sativa* Mill.). Therefore, this study's primary objective was to develop volume ratio prediction equations based on tree dendrometric variables, including DBH and total height, for high forest chestnut stands located in northern Portugal. Both linear and nonlinear regression estimation methods were employed, with data analysis based on information collected from 466 standing trees measured using a Bitterlich's telerescope for precise volume determination. Model validation involved destructive analysis of 39 felled trees distributed across the existing diameter classes (10-65 cm) in three adult chestnut stands. The study employed the ordinary least squares method to fit several linear and nonlinear equations to select models, with the best-fitting equations presented.

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Stem volume ratio equations to variable merchantable limits for sweet chestnut in Portugal

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Abstract

The volume is a fundamental dendrometric characteristic that helps estimate the amount and value of wood that can be harvested, and provides insight into land productivity. However, accurately measuring trees for volume calculation is both costly and time-consuming. Therefore, equations that estimate volume based on dendrometric variables, such as DBH (diameter breast height) and total or merchantable height, are highly important for forecasting forest production. However, the total stem volume alone does not indicate the amount of wood available for specific uses, such as sawtimber or biomass. Stem volume ratio equations are essential as they provide flexibility in determining the volume of wood based on the tree's various usage categories and potential changes in market demands over time. These equations allow for alternative options in obtaining volume, considering variable top diameter or height. Forest managers can use these equations to estimate the volumes of multiple logs from a single stem during integrated logging and for forest inventory purposes that require yield estimates by product categories. These tools are scarce, namely for sweet chestnut (*Castanea sativa* Mill.). Therefore, this study's primary objective was to develop volume ratio prediction equations based on tree dendrometric variables, including DBH and total height, for high forest chestnut stands located in northern Portugal. Both linear and nonlinear regression estimation methods were employed, with data analysis based on information collected from 466 standing trees measured using a Bitterlich's telerescope for precise volume determination. Model validation involved destructive analysis of 39 felled trees distributed across the existing diameter classes (10-65 cm) in three adult chestnut stands. The study employed the ordinary least squares method to fit several linear and nonlinear equations to select models, with the best-fitting equations presented.

Keywords: *volume equations, Castanea sativa Mill., merchantability prediction equations, yield, timber*

INTRODUCTION

In Europe, the sweet chestnut (*Castanea sativa* Mill.) encompasses over 2.5 million hectares of forested land, with the majority situated in the Mediterranean and Sub-Mediterranean regions (Conedera et al., 2021). In Portugal, the sweet chestnut (henceforth, chestnut) covers an area larger than 48,000 ha (ICNF, 2015), including both traditional orchards or groves and forest woodlands (high-forest and coppice) (Patrício et al., 2022). Chestnut stands can be categorized as either nut-oriented, timber-oriented or a combination of both. The chestnut is a multipurpose species that plays a multifaceted role, encompassing economic, ecological, social, and cultural aspects in the areas where it is present.

The multifunctional management of sweet chestnut stands offers valuable ecosystem services, many of which are supported by chestnut timber production. Chestnut timber is considered a provisioning service that contributes to boosting the bioeconomy. The species has the potential to produce high-quality timber that serves a variety of purposes. By adopting a tree-oriented silviculture approach centered on single-stem selection, chestnut has the potential to yield timber of excellent quality, characterized by desirable technological properties and durability (Manetti et al., 2016; Patrício and Nunes, 2017). The timber obtained from sweet chestnut is widely recognized for its durability, strength, and appealing aesthetics, making it suitable for diverse applications such as construction, furniture making, flooring, and joinery.

Efforts aimed at maximizing the quality of roundwood contribute to an increased proportion of harvested wood that is suitable for long-lived products, thereby promoting environmental sustainability (Patrício et al., 2020) and enhancing potential income for landowners. Engineered wood products such as Glulam beams and pillars used in building construction, as well as Cross Laminated Timber and Wood-processed Boards, highlight the potential for sustainable construction practices where chestnut wood could play a significant and renewed role. Wood sourced from less productive stands or those that have been unmanaged or poorly managed can also be effectively utilized as biomass for bioenergy purposes. Additionally, by prioritizing the selection of suitable trunks and focusing on the best logs in this context, it can be efficiently utilized within the wood industry to fully maximize its potential.

Having a reliable estimate of the volume categorized by classes of use is crucial for effective wood utilization. This allows for better planning and allocation of resources, ensuring that wood is utilized in the most efficient and appropriate manner for various purposes. Accurate volume estimations by classes of use help in making informed decisions regarding wood allocation, ensuring optimal utilization and minimizing waste. Additionally, these estimations also contribute to maximizing profitability in forests.

Therefore, there is a need to develop tools that enable reliable estimations of tree volume. Individual equations are one example of a tool used for estimating tree volume. Growth and yield studies typically focus on total stem volume; however, this measure alone does not provide specific information about the amount of wood available that meets a particular utilization standard (Alemdag, 1988; Menéndez-Miguélez et al., 2014). There are some methods available to obtain estimates of the sawtimber portion of the stem in order to meet a utilization standard, such as the volume ratio method (Alemdag, 1988). By employing volume ratio equations, it becomes feasible to acquire highly accurate estimates of the quantity of timber present from the stump level up to a specified diameter or height of the trunk (Tomé et al., 2001) as a percentage of total volume. Volume ratio equations offer flexibility to volume tables while preserving logical relationships (Avery and Burkhart, 1994). In order to estimate volumes by timber use category using a volume ratio equation, it is assumed that a volume equation already exists for calculating total volumes (Tomé, 1990).

The scarcity of tools for estimating the volume ratio of high-forest chestnut based on specific trunk diameter or height, coupled with the necessity for such tools, has motivated this research. The objective of this study was to develop precise volume ratio equations that can provide accurate estimates of merchantable stem volume for a specified trunk diameter or height. The study uses data from high-forest chestnut stands in North Portugal as a baseline.

MATERIALS AND METHODS

General Characteristics of the Sites

This study was based on tree volume information collected in the three mature chestnut high forest stands located in three mountains of northern Portugal: Bornes (41º 29’ 42’’ N, 6º 55’ 12’’ W and 800 m a. s. l.), Marão (41º 14’ 46’’ N, 7º 55’ 04’’ W and 900 m a. s. l.) and Padrela (41º 31’ 47’’ N, 7º 35’’ 22’’ W and 850 m a. s. l.) which have been monitored over time. Sampling followed a west-to-east transect across to northern Portugal from a more-Atlantic-to-less-maritime influence. General characteristics of these sites can be found in (Patrício et al., 2009; Patrício et al., 2012, 2014).

Field data

In order to obtain tree volume data, 466 trees were submitted a rigorous cubing with telereslascope of Bitterlich device according to the existent diameter classes. From these trees (data set 1) a 1' data set with n = 3 690 observations was generated and used in the adjustment of the volume ratio equations with bark. An independent sample of 39 felled trees, rigorously cubed, was used for validation. This data set 2 generated another one 2', with n= 330 observations. Cubing was carried out based on diameter measurements made at the base, at breast height (1.30 m) and from this level every 2.25 m, both for felled trees and for standing trees, until the 7 cm tip, with the exception of the existing data where measurements were made every 2 m in length from the diameter to the height of the breast. For the tree volume calculation, Smalian's formula was used (Husch et al., 2003). The characterization of data sets 1 and 2 are shown in Table 1.

Table 1: Dendrometric characterization of data sets 1 and 2 for adjusting the volume ratio equations (volumes obtained through rigorous cubing with a telerelascope) and validation (volumes obtained through rigorous cubing in felled trees), respectively.

Site - plot	Tree variable	Nº Trees	Mean	s	Minimum	Maximum
Data set 1 (model fit)						
Bornes	d (cm)	76	20.80	5.81	10.30	34.00
	h (m)		19.05	2.67	11.94	24.01
	v (m^3)		0.33	0.22	0.04	1.09
Marão - A	d (cm)	26	28.35	5.45	19.70	41.50
	h (m)		14.14	2.48	11.06	21.39
	v (m^3)		0.38	0.15	0.16	0.70
Marão - B	d (cm)	29	37.28	8.98	22.50	54.10
	h (m)		27.77	2.84	22.91	33.90
	v (m^3)		1.20	0.66	0.33	2.50
Padrela - A	d (cm)	66	32.35	10.07	9.00	56.00
	h (m)		23.27	2.81	12.15	26.86
	v (m^3)		0.93	0.56	0.04	2.33
Padrela - C	d (cm)	269	37.30	12.16	9.00	69.30
	h (m)		20.34	4.76	6.11	30.92
	v (m^3)		1.11	0.74	0.02	4.02
Total (data set 1)	d (cm)	466	33.41	12.19	9.00	69.30
	h (m)		20.66	4.81	6.11	33.90
	v (m^3)		0.92	0.70	0.02	4.02
Data set 2 (model validation)						
Felled trees	d (cm)	39	34.81	13.61	10.25	64.20
	h (m)		22.28	4.51	11.55	30.40
	v (m^3)		1.20	0.91	0.05	3.38

Tree parameters: d, diameter at 1.30 m height with bark (cm); h, total height of the tree (m); v, total volume with bark (m^3); s, standard deviation.

Data Analysis

To model the volume rate (R), the following candidate equations (Table 2) were tested, where d represent the diameter breast height (DBH), di the stem diameter at height hi, h the total height of the tree, hi height of the tree to the diameter di, p = h-hi, z = (h-hi)/h relative tree height. The volume rate, denoted as R, is defined as the ratio of the merchantable volume of a tree (v_m) to the total volume (v).

Table 2: Models tested for the development of volume ratio equations as a function of topping diameter (di) or topping height (hi).

Ref.	Model	Designation	Obs.
	Volume ratio equations as a function of topping height, hi		
EVPH1	$R=1+[\beta_1(h-hi)^{\beta2}/h^{\beta3}]$	Cao *et al.* (1980)	Non-linear
EVPH2	$R=1-z+\beta_2(z^2-z)+\beta_3(z^3-z)+\beta_4(z^4-z)+\beta_5(z^5-z)+\beta_6(z^6-z)$	Cao *et al.* (1980)	
EVPH3	$R=1-[1-\exp(-\beta_1\tan(\beta_2 h^{\beta3}z))]]^{\beta4}$	Matney e Sullivan (1980)	
EVPH4	$R=1-z^{\beta1}$	Reed e Green (1984)	
EVPH5	$R=\exp(\beta_1 z^{\beta2})$	Parresol *et al.* (1987)	
EVPH6	$R=\exp[\beta_1(p^{\beta2}/h^{\beta3})]$	Parresol *et al.* (1987)	
EVPH7	$R=1+\beta_1(hi/h-1)+\beta_2(hi^2/h^2-1)$	Honer (1967)	Linear
	Volume ratio equations as a function of topping diameter, di		
EVPD1	$R=1+\beta_1(di^{\beta2}/d^{\beta3})$	Burkhart (1977)	Non-linear
EVPD2	$R=1-\beta_1(di^{\beta2}d^{\beta3})$	Clutter (1980)	
EVPD3	$R=1-[1-\exp(-\beta_1\tan(\beta_2 h^{\beta3}(di/d)))]^{\beta4}$	Matney e Sullivan (1980)	
EVPD4	$R=\exp[\beta_1(di/d)^{\beta2}]$	Deusen *et al.* (1981)	
EVPD5	$R=1+\beta_1 di^{\beta2}/(d^{\beta3}h^{\beta4})$	Reed e Green (1984)	
EVPD6	$R=1+\beta_1(di/d)^{\beta2}(\beta_3 h+\beta_4)^{\beta5}$	Reed e Green (1984)	
EVPD7	$R=\exp[\beta_1(di^{\beta2}/d^{\beta3})]$	Parresol *et al.* (1987)	
EVPD8	$R=1+\beta_1(di/d)+\beta_2(di/d)^2+\beta_3(di/d)^3+\beta_4(di/d)^4+\beta_5(di/d)^5+\beta_6(di/d)^6$	Cao *et al.* (1980)	Linear

The Equations were fitted using the ordinary least squares method (OLS) with both the PROC REG (linear models) and PROC NLIN (non-linear models) procedures of SAS/STAT. The modified Gauss-Newton iterative method was employed for fitting the non-linear models.

The models were assessed based on various measures of fit and prediction ability, including modelling efficiency (EM), which is analogous to adjusted R^2 in linear models, mean square error (MSE), significance of model parameters, prediction R^2 (R^2pred), mean of PRESS residuals (m_PRESS), mean absolute values of PRESS residuals (ma_PRESS), as well as the 95th percentile (P95) and 5th percentile (P5) of the PRESS residuals. Collinearity was evaluated by examining the correlation matrix between parameters, variance inflation factor (VIF) for linear models, and the matrix condition number (NCOND) for nonlinear models. The normality of studentized residuals was assessed using normal QQ plots. Heteroscedasticity associated with the error term in the models was checked by plotting studentized residuals against predicted values.

The departure from regression assumptions was addressed by applying non-linear iteratively reweighted least squares (IRWLS) using the Huber function (Myers, 1986), with a maximum value of r=1.

For the selection of models, an index was assigned to each statistic used, with a value of 1 corresponding to the 'best' value, 2 to the second-best value of that statistic, and so on. The final index of each model corresponds to the sum of the partial indexes of each statistic, all of them weighted equally. This procedure was applied both in the adjustment phase and in the validation phase to rank the models, with the lowest sum corresponding to the best equation.

RESULTS AND DISCUSSION

Equations EVPH1 to EVPH7 and EVPD1 to EVPD8 were fitted to the volume data as described in the methodology. Table 3 presents fitting, precision, and bias statistics for the selected models. The plot analysis of the studentized residuals was also taken into consideration in model selection.

Table 3: Measurements of adjustment and prediction for the volume ratio models over bark as a function of height at the top (hi) and at the top (di), after applying IRWLS.

Model	MSE	EM	mPRESS	maPRESS	R^2_{pred}	P95	P5	NCOND
Nº of observations (n=3690)								
Volume ratio equations as a function of topping height, hi								
EVPH1	$0.868\ 10^{-3}$	0.9872	0.0025	0.0271	0.9792	0.0683	-0.0544	3090.5862
EVPH2	$0.866\ 10^{-3}$	0.9872	0.0018	0.0269	0.9788	0.0713	-0.0527	$1.7879\ 10^{8}$
EVPH3	$0.868\ 10^{-3}$	0.9872	0.0017	0.0270	0.9790	0.0683	-0.0544	1934.8555
EVPH4	$0.963\ 10^{-3}$	0.9856	0.0034	0.0285	0.9771	0.0721	-0.0573	1.0000
EVPH5	0.0011	0.9830	-0.0028	0.0306	0.9737	0.0766	-0.0631	10.1603
EVPH6	0.0011	0.9834	-0.0030	0.0304	0.9742	0.0740	-0.0628	2326.2828
EVPH7	0.0010	0.9843	0.0011	0.0307	0.9752	0.0814	-0.0488	180.3401
Volume ratio equations as a function of topping diameter, di								
EVPD1	0.0025	0.9629	$0.2896\ 10^{-4}$	0.0441	0.9376	0.1122	-0.1076	4279.3834
EVPD2	0.0025	0.9629	$0.2896\ 10^{-4}$	0.0441	0.9376	0.1122	-0.1076	4279.3848
EVPD3	0.0022	0.9671	$0.1156\ 10^{-4}$	0.0416	0.9431	0.1087	-0.1051	1841.9179
EVPD4	0.0028	0.9571	-0.0037	0.0476	0.9320	0.1233	-0.1049	6.0185
EVPD5	0.0022	0.9673	-0.0005	0.0415	0.9437	0.1083	-0.1068	6154.2454
EVPD6	0.0022	0.9674	-0.0005	0.0414	0.9437	0.1080	-0.1069	$4.1826\ 10^{12}$
EVPD7	0.0027	0.9585	-0.0036	0.0470	0.9333	0.1257	-0.1039	3188.4573
EVPD8	0.0026	0.9615	0.0005	0.0451	0.9362	0.1138	-0.1066	$3.9845\ 10^{8}$

As shown in Table 3, the adjustment of the prediction equations for the R ratio between the merchantable volume for a specific height/diameter of topping and the total volume, including bark and stump, generally revealed that models with higher complexity were associated not only with better-fit quality and predictive ability, although not significantly pronounced, but also with increased collinearity.

One of the effects of multicollinearity is the instability of the regression coefficients, meaning that the coefficients become highly dependent on the specific dataset from which they were derived (Myers, 1986). However, according to the author, it is still possible to achieve good predictions within the limits of the available data.

To obtain a more comprehensive evaluation of the models' predictive performance, validation was conducted using the previously mentioned 2' dataset. The results of the model validation for this dataset are presented in Table 4. The validation process involved comparing the observed and estimated volume ratio values (R=vm/v) generated by the models.

Table 4: Measures of predictive capacity obtained from the validation process for the volume ratio equations over bark as a function of the height at the top (hi) or the diameter at the top (di).

Model	MSrp	R^2rpred	mrp	marp	Vrp
Number of observations – data set 2' (n=330)					
Volume ratio equations as a function of topping height, hi					
EVPH1	0.0012	0.9842	-0.0218	0.0269	0.0007
EVPH2	0.0007	0.9905	-0.0044	0.0225	0.0007
EVPH3	0.0012	0.9842	-0.0226	0.0271	0.0007
EVPH4	0.0013	0.9828	-0.0218	0.0272	0.0008
EVPH5	0.0016	0.9785	-0.0284	0.0324	0.0008
EVPH6	0.0016	0.9796	-0.0273	0.0288	0.0008
EVPH7	0.0013	0.9833	-0.0256	0.0313	0.0006
Volume ratio equations as a function of topping diameter, di					
EVPD1	0.0027	0.9646	-0.0034	0.0370	0.0027
EVPD2	0.0027	0.9646	-0.0034	0.0370	0.0027
EVPD3	0.0024	0.9684	-0.0076	0.0346	0.0024
EVPD4	0.0034	0.9564	-0.0002	0.0406	0.0034
EVPD5	0.0023	0.9689	-0.0068	0.0341	0.0023
EVPD6	0.0024	0.9687	-0.0067	0.0342	0.0024
EVPD7	0.0032	0.9584	0.0013	0.0399	0.0032
EVPD8	0.0038	0.9505	0.0024	0.0391	0.0029

Prediction residuals (rp); mean square of prediction residuals (MSrp); mean of prediction residuals (mrp); mean absolute values of prediction residuals (marp); variance of prediction residuals (Vrp).

To provide a clearer understanding of the predictive ability of the models, an analysis of their accuracy and bias was performed based on top height (hi) classes (not shown). The objective of this analysis was to identify the equation that demonstrated the best performance when applied to an independent dataset.

Among the evaluated models, EVPH1 and EVPH2 displayed a certain degree of superiority. These models exhibited a larger number of classes in which the predictions obtained have lower bias compared to the other models. Generally, the analyzed models tended to overestimate the volume ratio (R) as a function of the top height, with the exception of the EVPH2 model. However, the mean deviations were less than 3%. Specifically, for the EVPH1 model, the average bias of the volume ratio per hi class was less than 1.5% for top heights above 12 m. Similarly, for the EVPH2 model, the average bias was less than 2.5% within the same top height range.

On the other hand, the models with lower collinearity, namely EVPH4 and EVPH5, demonstrated lower predictive capacity compared to EVPH1 and EVPH2. Consequently, they exhibited more bias and lower accuracy compared to the latter models.

The equations that demonstrated the best performance in predicting the volume ratio with bark as a function of top height were as follows:

$$EVPH1: \quad R=1+[-0.8075(h-hi)^{2.7922}/h^{2.7359}]$$

$$EVPH4: \quad R=1-((h-hi)/h)^{2.9340}$$

Despite having higher collinearity, the EVPH1 equation exhibited superior predictive capacity. On the other hand, the EVPH4 equation, which had lower collinearity, also showed good performance in predicting the volume ratio.

Regarding the volume ratio with respect to a specific top diameter (di), the models EVPD5, EVPD6, and EVPD4 occupy the top positions in descending order.

In order to provide a clearer understanding of the predictive capacity of the models, an analysis of their accuracy and bias was performed by topping diameter (di) classes. The objective of this analysis was to select the equation with the best performance when applied to an independent dataset.

Among the two preselected models with the lowest collinearity, EVPD3 and EVPD4, the EVPD4 model demonstrates a greater number of classes with less bias. On the other hand, the EVPD3 model exhibits a greater number of classes with higher precision. Consequently, the EVPD4 model is considered to have lower bias but lower accuracy compared to the EVPD3 model, although it does exhibit higher extreme bias values.

The previously selected equations for predicting the volume ratio over bark as a function of topping diameter were as follows:

$$EVPD3: R = 1 - [1 - \exp(-0.8525 * \tan(0.9682 * h^{0.0847} * (di/d)))]^{3.1504}$$

$$EVPD4: R = \exp[-1.4039 * (di/d)^{4.3716}]$$

To estimate volumes by timber use category using the volume ratio equations mentioned earlier, a total volume equation specific to high-forest chestnut must be used. In this regard, we propose the total volume equation over bark presented in Patrício (2006) and Patrício and Nunes (2017). The equation is as follows:

$$v = 0.015160 + 0.0000324\, d^2h$$

This equation enables the estimation of the total volume (v) over bark based on the diameter at breast height (d) and total height (h) of the tree. The variables are expressed in the units of centimeters (cm) for diameter, meters (m) for height, and cubic meters (m^3) for volume. The equation exhibits a high coefficient of determination ($R^2_{adj} = 0.98$), indicating its robust predictive capacity.

CONCLUSIONS

This study has provided valuable volume ratio equations that offer precise estimates of the merchantable stem volume over bark for high forest sweet chestnuts, utilizing specific trunk diameter or height as variables. The application of these volume ratio equations can lead to improved timber utilization practices, ensuring that a greater proportion of the harvested chestnut trees can be transformed into valuable products. This not only minimizes waste but also optimizes the economic and environmental benefits derived from forest resources. Landowners and forest managers can utilize the equations to estimate the volume of merchantable timber available in a given area, facilitating informed decision-making regarding harvesting.

By accurately estimating the volume of merchantable timber, landowners can better negotiate fair prices for their products and contribute to timber industry supply chains.

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