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Biometrics

Accurate Estimation of Commercial Volume in Tropical Forests

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Accurate estimates of commercial volume in tropical forests are key for the implementation of sustainable forest management plans. Because of the lack of local or generic volumetric equations, most forest managers and forestry services are still using traditional expansion factors (i.e., multiplication of the diameter by a given value) to estimate the volume of commercial tree species in the Amazon. Volumetric models were developed through a unique data set of 1,264 fallen trees fully measured in 150 sample plots located across a broad range of forests in Amapá, Brazil. Forest-specific volumetric models were developed and compared with a generic (i.e., across all forests) model and with published equations developed elsewhere in the Amazon. The generic equation performed well in all forest types and allowed precise predictions. The most efficient sampling design to develop volumetric models consists of measuring approximately 50 trees across four different size classes representing the whole population. The form factors (FF) developed locally generated substantial bias but performed better than the traditional FF (0.7). Overall, our results suggest that it is possible to develop accurate generic models to estimate commercial timber volume, and this study can serve as a guideline for forest managers or scientists interested in calibrating volumetric models in a cost-efficient way.

Study Implications: This work provides useful information on volumetric modeling methods for Brazilian Amazon tropical forests. Most of the studies in the literature only investigate the classical modeling using regression models considering only boom metrics with or without bark, and, in this way, they provide incomplete and biased total knowledge and estimates for a given population. Therefore, detailed and accurate analyzes are crucial tools for decisionmaking. If the harvesting interventions are carried out without considering the most appropriate method to estimate the total wood stock, there may be damages or even extinction of some species, as has happened with other forest domains in Brazil and in other rainforest regions in the world. In this work, the results clearly show the importance of testing different methodologies and selecting the one best suited for a particular site, as well as carrying out techniques for the sustainable and correct management of the forest. Because the analysis procedures provide only information on how methodologies behave statistically, our results may contribute to a more refined analysis to be applied in the future in similar environments. Currently, the Brazilian forestry sector is looking for alternatives to obtain forest resources within the concept of sustainability. For the Brazilian Amazon tropical forest domain, it is extremely important to achieve a sustainable management of resources through forest management. Most studies in the literature investigate the management of tropical rainforest, whereas there is a lack of scientific information on the transition range for the cerrado.

Keywords: Brazilian Amazonia, forest management, generic equations, form factor, tropical forest

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In the tropics, approximately 40 percent of the sawn wood traded annually comes from natural forests (Payn et al. 2015). Brazil is among the larger producers of tropical roundwood, with 81 million m^3 (48 percent of total production) of logs harvested annually (2005–2008) in natural tropical forests (Blaser and International Tropical Timber Organization 2011, da Silva et al. 2018). In its efforts to promote sustainable forest management, Brazil's government has enforced a set of regulations, defining notably a maximum allowable harvest of 30 m^3 per hectare when mechanized and 10 m^3 per hectare when operations do not involve heavy machinery, over a 35- and 10-year cutting cycle, respectively (Roma 2013). Accurate estimation of commercial volume at both tree and stand level is thus key to efficiently implementing such regulations and ensuring sustainable management of forest resources (Buongiorno and Gilless 2003, Burkhart and Tomé 2012). In a broader context, commercial timber volume (CTV) provides a rapid and easy way to estimate the monetary value of trees or forest stands, often referred to as commercial timber stock (Bettinger 2009).

In the field, CTV is generally estimated for the main trunk, as the multiplication of the diameter at breast height (DBH; 130 cm), the commercial height (Hc) of the trunk, and a form factor (FF). Hc is generally defined as the lowest main branch forming the base of the crown (Ploton et al. 2016, Rutishauser et al. 2016), and FF represents the ratio between the bole volume and that of a cylinder of the same girth and height (Gray 1956, Burkhart and Tomé 2012). FFs were shown to perform well when applied to a few commercial species, or when developed and used locally (Gray 1956, Colpini et al. 2009), and most forest services in the Brazilian Amazon are commonly applying a FF of 0.7 (Heinsdijk and Bastos 1963, Colpini et al. 2009). Indeed, volume, height, or shape of trees are known to greatly vary among and within species (Cannell 1984, Akindele and LeMay 2006), across large ecological gradients (Nogueira et al. 2008, Lines et al. 2012), or at smaller scale due to competition for light and nutrients (Iida et al. 2011, Rutishauser et al. 2016). To account for this variability, various volumetric equations have been developed across the Amazon (Rolim et al. 2006, da Silva and Santana 2014), and the use of a single FF at regional scale remains to be evaluated.

Recently, the state of Amapá (Figure 1) declared 2.3 million hectares (16.5 percent of its area) of natural old-growth forests as state forests to tackle rapid deforestation and forest degradation and promote a sustainable timber harvest (Instituto Estadual de

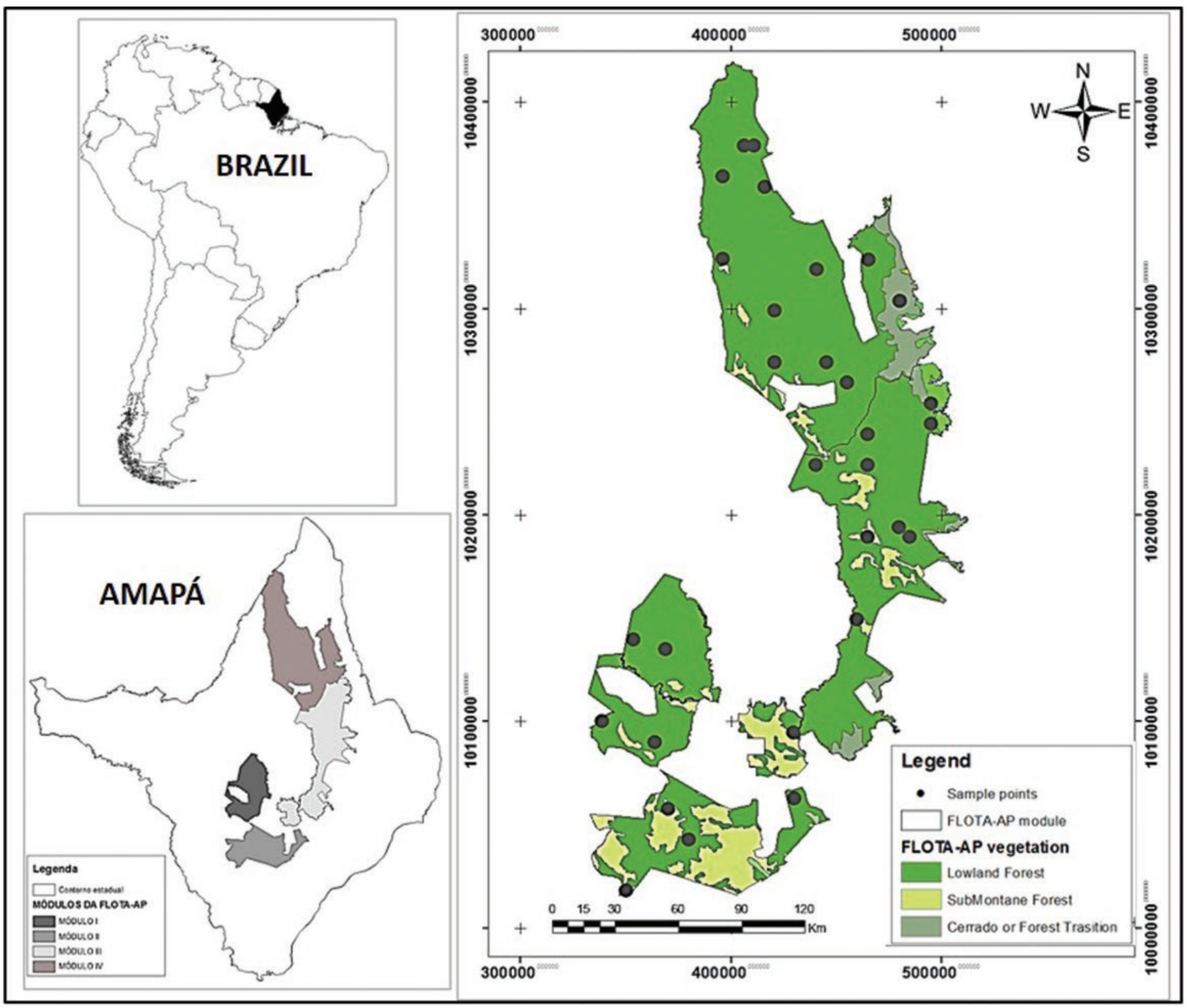

Figure 1. Location of state forests in Amapá, Brazil (left panel). Sample units (points) were randomly located in the different forest types, after stratification in function of the area of each forest type (right panel).

Florestas do Amapá [IEF] 2016). Accurate and reliable estimates of CTV in those forests are required to define both maximum timber volume harvestable and efficient regulations that sustain wood production, incomes, and forest functioning in the long run. So far, no volumetric equation has been developed in the region of the Amapá state, and the ability of published models from other regions to be used remains untested. The present study aims to fill this gap by developing stand-specific and generic volumetric models based on an original data set of 1,264 commercial trees; testing the ability of various models (i.e., locally developed and published volumetric models and FF) to estimate CTV in Amapá; and proposing guidance regarding efficient ways to develop volumetric models.

Materials and Methods

Study Area

The data come from the State Forest of Amapá, which is located in the central region of Amapá (Figure 1), Amazon, Brazil (01°15′52.01″ N, 51°24′05.18″ W). The forest is composed of multiple parcels of land interspersed by a discontinuous area of 2,369,400 hectares of three main formations: lowland rainforest (54.86 percent), upland rainforest submontane (16.88 percent), and cerrado or forest transition (10.55 percent) (IEF 2016).

The climate of the region is humid equatorial, with average temperature of 25°C and annual precipitation of 2,800 mm. The rainiest period occurs from March to May (above 1,000 mm). The driest months (<400 mm) usually occur from July to December (known regionally as the Amazonian summer). The dominant forest types are described below in terms of tree species abundance, altitude, and geomorphology (Instituto Brasileiro de Geografia e Estatística 2012, IEF 2016).

Lowland forests (Low) are found at an altitude of 60 to 100 m, mainly on dystrophic red-yellow latosol. These dense forests are formed by tall canopy trees, up to 50 m, dominated by *Eschweilera coriacea*, *Pouteria caimito*, *Protium tenuifolium*, or *Minquartia guianensis.* Currently, 190 tree species are considered as potentially harvestable (DBH > 50 cm), representing on average 133 m^3 per hectare or approximately half the total wood volume (DBH > 10 cm).

Dryland submontane forests (Sub) are located on slopes up to 320 m, with an average elevation of 195 m. Dominant tree species are *Eschweilera coriacea*, *Pouteria caimito*, *Inga auristellae*, *Guarea pubescens*, and *Vouacapoua americana.* More than a hundred species found there are considered as commercial, representing 49 percent of the total volume (DBH > 10 cm).

Cerrado or cerrado transition forest (Trans) is located closer to the coast, with medium canopy height (up to 30 m). About 203 species of trees were recorded, among which *Pouteria caimito*, *Protium decandrum*, and *Guarea pubescens* are the most abundant.

Sampling Design and Data Collection

Inventory of living and dead fallen trees is carried out through stratified sampling: 30 sample units randomly located across the different forest types described above, proportional to the area of each type (23, 4, and 3 sample units in Low, Sub, and Trans, respectively) (Figure 1). Each sampling unit consists of 5 secondary units composed of four 20 × 200 m strips (tertiary units), forming a cross aligned in the four cardinal directions (Figure 2).

A total of 1,264 fallen trees with DBH ≥ 10 cm were measured. The trunk was divided into 10 sections of equal length, from the base to the lowest main branch, corresponding to the Hc. The diameter was measured at the center of each section and later converted into diameter. The CTV of each stem was estimated using a Smalian formula, as follows (Avery and Burkhart 2002):

$$CTV = \frac{A + a}{2} \times Hc \tag{1}$$

where A is the cross-sectional area of the large end of the log, a is the cross-sectional area of the small end of the log, and Hc is the commercial height of the trunk (meters).

Development of Volumetric Models

Because of differences in floristic composition, soil, and topography among forest types, volumetric models were first developed by forest type and further among all forests (referred to as "All") to develop and test the possibility of a generic equation for the whole region (e.g., Vibrans et al. 2015). Four models commonly used in forestry were used: two based on DBH only (Table 1) and two combining DBH and Hc (Table 1). Because volumes are always positive and have measurement uncertainties proportional to their values, we used a lognormal law to infer the model.

The parameters of the Husch, Hohenald-Krenn, Spurr, and Schumacher-Hall models were written in Stan and inferred through Hamiltonian Monte Carlo sampling (Carpenter et al. 2015, Monnahan et al. 2017).

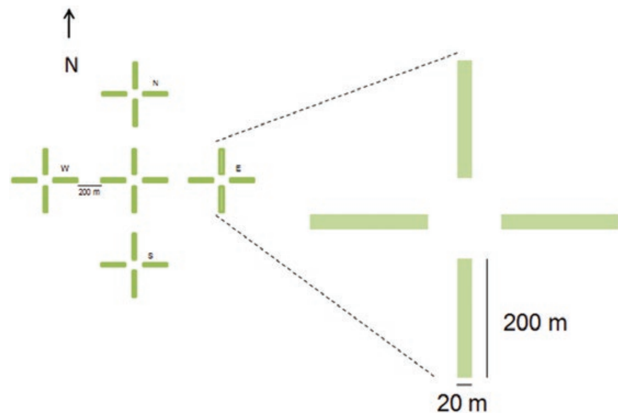

Figure 2. Sampling unit design to assess fallen trees in state forests of Amapá.

Table 1. Volumetric models used to estimate CTV in Amapá state forests.

Author	Model
Hohenald-Krenn	$\text{Log}(CTV) = \beta_0 + \beta_1.\text{Log}(DBH) + \beta_2.\text{Log}(DBH^2) + \varepsilon$
Husch	$\text{Log}(CTV) = \beta_0 + \beta_1.\text{Log}(DBH) + \varepsilon$
Spurr	$\text{Log}(CTV) = \beta_0 + \beta_1.\text{Log}(DBH^2.Hc) + \varepsilon$
Schumacher-Hall	$\text{Log}(CTV) = \beta_0 + \beta_1.\text{Log}(DBH) + \beta_2.\text{Log}(Hc) + \varepsilon$

Note: β_i, parameters to be estimated; CTV, commercial timber volume above bark (m^3); DBH, diameter at breast height (cm); ε, random error; Hc, commercial height (m); Log, logarithm natural.

To select the best model, the goodness of fit was compared through Akaike information criterion (AIC) coefficient of determination, root-mean-square error (RMSE), and bias (see Supplementary Materials). Once the best model was selected, we sequentially tested for a "forest type" effect on each model parameter adding a random "forest type" variable in place of the tested parameters. Using a "forward stepwise" selection based on AIC, we built the final model. Because of the difficulty of testing for a forest type effect on several parameters at once, the effect was tested parameter by parameter. A significant effect was detected if the likelihood improved >log(#trees) compared with the null model (without forest type; e.g., Vibrans et al. 2015). The same procedure is repeated for the remaining parameters. This ad hoc procedure is similar to a Bayesian information criterion forward procedure in a glm() framework.

Minimum Sample Size to Develop Accurate Volumetric Models

To provide some guidance regarding the development of volumetric models, we tested two sampling methods (simple random sampling and random sampling within the strata) and various sample sizes to propose an optimal strategy. We simulated a random sampling strategy consisting of randomly selecting N individuals among either all trees DBH ≥ 10 cm or only commercial trees (i.e., DBH ≥ 50 cm).

Appropriately, 2, 5, 10, 20, 50, and 70 percent of either all trees DBH ≥ 10 cm or all trees DBH ≥ 50 cm were selected randomly. Alternatively, we simulated a stratified random sampling in grouping trees into four size classes of equal strata size (5–20, 20–35, 35–50, and >50 cm for all trees DBH > 10 cm and 50–55, 56–65, 66–75, and >75 cm for commercial trees). Similarly 2, 5, 10, 20, 50, and 70 percent of trees within a given class were randomly chosen.

Table 2. Published equations used for comparison in the prediction of CTV. All models are of the form: $\text{Log}\,(CTV) = \beta_0 + \beta_1.\text{Log}\,(DBH) + \beta_2.\text{Log}\,(Hc) + \varepsilon$.

CTV_{ALT}	β_0	β_1	β_2	R^2	RSE	Ntrees
Thaines et al. (2010): Amazonas	–9.5452	2.1284	0.7221	0.92	0.7048	141
Silva and Santana (2014): Pará	–9.5084	2.0139	0.8788	0.94	0.1103	234
Silva et al. (1984): Pará	–8.8610	1.9318	0.7868	0.96	0.6294	905

Note: β_i, parameters to be estimated; CTV, commercial timber volume above bark (m^3); DBH, diameter at breast height (cm); ε, random error; Hc, commercial height (m); Log, logarithm natural; Ntrees, number of trees used in the study cited; RSE, residual standard error.

For each subset, the best local model was developed and applied to the remaining data for cross validation. For each iteration, RMSE and bias were computed, and this procedure was carried out 1,000 times for each sample size. We report mean RMSE and bias with 95 percent confidence interval for both sampling strategies and population of trees (e.g., Sullivan et al. 2018).

Form Factors

FFs were computed at tree level, as the ratio between estimated CTV and that of a cylinder of diameter equal to DBH and height equal to Hc. FFs were developed for every tree and averaged by forest type and among all forests (FF_{ALL}). We also tested the performance of the traditional FF (FF = 0.7).

Applicability of Published Volumetric Models

Three alternative volumetric models (CTV_{ALT}) developed in other Amazonian regions were compared with measured CTV (CTV_{MES}) (Table 2).

For each equation, standard error (RSE) and coefficient of variation (CV; $p < .05$) were computed for each forest type (j) as follows:

$$RSE(j) = \sqrt{\frac{1}{N_j - p}\sum_{i=1}^{N}\left[CTV_{ALTij} - CTV_{MESij}\right]^2} \quad (2)$$

$$MCTV(j) = \frac{1}{N_j}\sum_i CTV_{MESij} \quad (3)$$

$$CV\ (j)\ \% = \frac{RSE\,(j)}{MCTV\ (j)} \times 100 \quad (4)$$

where CTV_{ALTij} and CTV_{MESij} are the volume estimates of tree i in forest type j. A large value of CV would be acceptable as long as the bias is low because, in general, the model is applied among many trees within a site, and therefore, random errors tend to cancel out (Chave et al. 2014). All computations and analyzes were performed using the statistical software R (R Development Core Team 2017).

Results

Development of Volumetric Models

Among the four adjusted volumetric models, models that include DBH and Hc (i.e., Schumacher-Hall and Spurr) presented better performance (lower AIC; Table 3), returned the best predictions, and explained more than 95 percent of the total variance (R^2adj; Table 3), despite large variations in Hc for a given DBH (Figures S1–S5).

Goodness of fit (RMSE) and prediction error (bias) roughly doubled when estimating CTV through DBH only (Table 3). Generally, CTV of trees DBH < 50 cm were well predicted by all models but tended to diverge for larger diameters (Figure 3). The

Table 3. Parameter estimates (fitted in a hierarchical framework) and indices of goodness-of-fit of four volumetric models across all and by forest types (lowland forests; submontane forests; cerrado/forest transition; Table S1). The best model is bolded.

Area	N	Model	$\hat{\beta}_1 \pm SE$	$\hat{\beta}_1 \pm SE$	$\hat{\beta}_2 \pm SE$	AIC	RSE	R^2adj	RMSE	Bias (%)
All forest types	1,264	Husch	–8.031 ± 0.081	2.210 ± 0.023		1471.87	0.43	0.88	0.8	20
		Hohenald-Krenn	–7.508 ± 0.384	1.898 ± 0.225	0.045 ± 0.033	1471.93	0.43	0.88	0.82	19
		Spurr	–8.899 ± 0.054	0.925 ± 0.006		263.87	0.27	0.95	0.49	7
		Schumacher-Hall	–8.889 ± 0.054	1.881 ± 0.016	0.875 ± 0.019	258.51	**0.26**	**0.96**	**0.48**	**6**

Note: Corresponds to the statistical parameters of the models and the confidence interval measured by the standard error of the estimate. AIC, Akaike information criterion; R^2adj, adjusted coefficient of determination; RMSE, root-mean-square error; RSE, residual standard error.

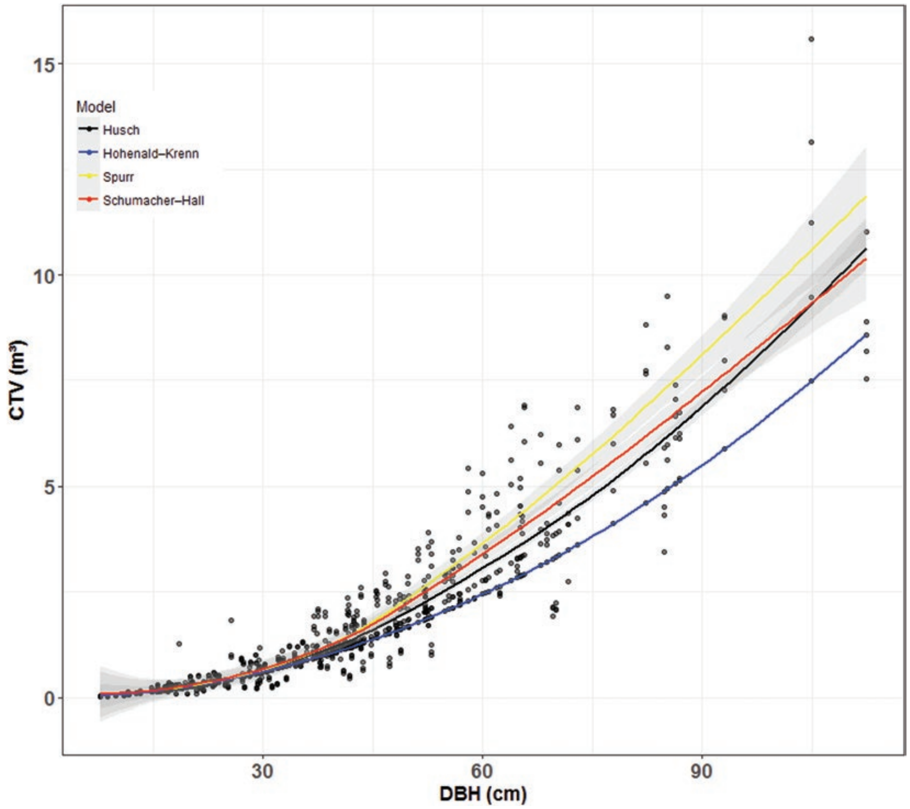

Figure 3. Regression curves (colored lines) and 95 percent confidence intervals (gray shading) of four models (detailed in Table 1) relating commercial timber volume (CTV) and diameter at breast height (DBH) for overall forest types ("all forests types").

Schumacher-Hall model was found to return the best estimates in both Sub and Trans forests (Table S1 and Figure S6, and across all forest types (Table 3). This model generally captured variations well in DBH and Hc, resulting in a mean bias of only 6 percent (Table 3). No significant effect of forest type on the estimated parameters was detected (Table 4), pointing out the genericity of this model at regional scale.

Minimum Sample Size

The model parametrization carried out above already revealed that stratification by forest type was unnecessary. Regarding the minimum sample size needed to develop such an accurate generic model, all strategies tested tended to plateau above 20 percent (approximately 250 trees) of the whole population sampled (Figure 4a). Although the error on individual CTV estimates was on average higher when models were developed solely with trees DBH > 50 cm (Figure 4a), errors tended to cancel out at stand level when large trees were sampled in a stratified manner (Figure 4b). Overall, the best option to estimate CTV is sampling approximately 50 trees across four different size classes representing the full DBH (≥10 cm) distribution. However, results from simulations show that a stratified sampling among large commercial trees returns fair stand-level CTV estimates (<5 percent difference).

Comparing Published Volumetric Equations and Form Factors

Predictions of the model proposed by Silva et al. (1984) were similar with those of our best model (Figure 5). The average CV was 32.2 percent and 31.9 percent using the best local model and Silva's model, respectively (Table 5). The regional models of Thaines et al. (2010) and da Silva and Santana (2014) underestimated CTVs in smaller trees across all forest types (Figure 5). Yet, this trend remained when considering the forest types independently, with greater evidence in submontane forests and forest transition (Figure S7).

Table 4. Parameter estimates of the Schumacher-Hall model [$CTV \sim \log(\beta_0.DBH^{\beta_1}.Hc^{\beta_2}, \varepsilon)$], when including forest types (Low, lowland forests; Sub, submontane forests; Trans, cerrado/forest transition). RMSE and likelihood of the whole model. Note that the null-model (i.e., without forest type) likelihood is 1,029.8.

	$\hat{\beta}_0$	$\hat{\beta}_1$	$\hat{\beta}_2$
Low	0.786	1.872	0.878
Sub	0.779	1.904	0.864
Trans	0.786	1.900	0.867
RMSE	0.267	0.267	0.267
Likelihood	1,029.6	1,025.5	1,029.5

Note: Corresponds to the statistical parameters of the models obtained by generalized linear modeling. β_i, parameters to be estimated; CTVlog, logarithm of the commercial timber volume; DBH, diameter at breast height (cm); ε, random error; Hc, commercial height (m); RMSE, root-mean-square error.

FFs were generally close to 0.87 in all forest types but overestimated actual CTV by 38 percent (Figure 5 and Table 5). CTV predictions through FFs showed greater variation and errors in all forest types (Table S2 and Figure S7).

Discussion

Accurate Estimation of CTV in Northern Amazonian Forests

The present study investigates the ability of a newly developed generic volumetric model, along with three published ones,

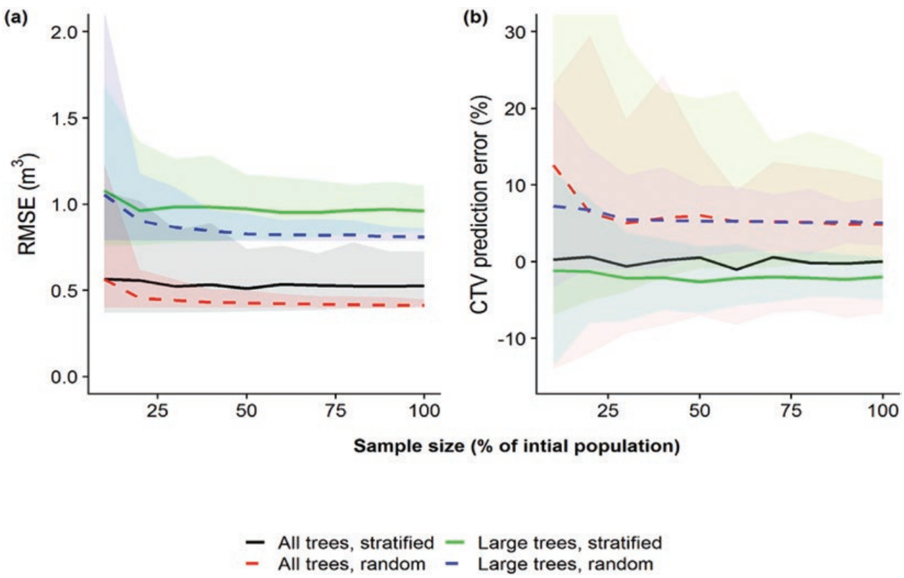

Figure 4. Effect of different sampling strategies to estimate a generic volumetric model, where model performance was assessed as (a) root-mean-square error (RMSE) and (b) difference between estimated and measured commercial timber volume (CTV prediction error in %). Sample size defined as the ratio (%) of initial population sampled either randomly or in a stratified manner by size classes, across (a) all trees diameter at breast height (DBH) > 10 cm or (b) commercial trees (DBH > 50 cm) only. Mean (lines) and 95 percent confidence intervals (ribbons) of 1,000 bootstrap simulations are shown (see "Methods").

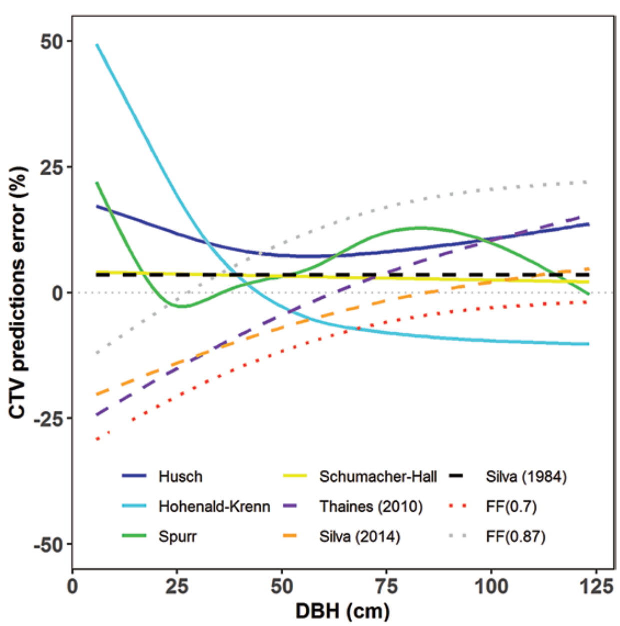

Figure 5. Relative error of commercial timber volume (CTV) estimated through different methods (i.e., local models [solid lines], published equations [dashed lines], and using expansion factors [dotted lines]) plotted as a function of tree diameter at breast height (DBH). Smoothed curves represent the mean value for each method.

Table 5. Mean, 95 percent confidence intervals (CI), residual standard error (RSE), and coefficients of variation (CV in %) of estimated commercial timber volume for all models tested across all forest types.

Area	Models	Mean	CI ($p \geq .05$)	RSE	CV%
All forest types	Husch	1.42	(1.33–1.51)	0.43	52.16
	Hohenald-Krenn	1.28	(1.20–1.35)	0.43	58.56
	Spurr	1.54	(1.43–1.64)	0.27	34.05
	Schumacher-Hall	1.47	(1.37–1.57)	0.26	32.25
	Thaines et al. (2010)	1.39	(1.29–1.49)	0.51	33.64
	da Silva and Santana (2014)	1.36	(1.26–1.45)	0.52	34.09
	Silva et al. (1984)	1.47	(1.38–1.57)	0.48	31.95
	Local form factor (0.87)	1.62	(1.51–1.74)	0.58	38.06
	Form factor 0.7	1.30	(1.21–1.40)	0.55	36.54

to estimate CTV in tropical forests at a regional scale (approximately 2×10^6 hectares). With known variation of diameter-height relationships at various scales (Nogueira et al. 2008, Feldpausch et al. 2011), volumetric equations are often confined to a few commercial species or the extent of timber concessions (Higuchi and Ramm 1985). Yet, most forestry services and concessionaires still rely on simple FFs to estimate CTV and overcome the lack of generic volumetric models. Our analysis tests for the best alternative if no volumetric equation is available at a site: Is it better to use a generic model developed elsewhere, apply a standard FF, or develop a site-specific model?

Our results show that the development of a generic model that includes both diameter and height returns the most accurate estimates and remains valid across a wide range of forest types. The model developed by Silva et al. (1984) is a fair alternative instead, with little mean bias (CV% = 31.95 percent) and across the whole range of DBH tested (Figure 5). On the contrary, FFs tend to have large bias at either ends of the DBH distribution.

Models including both diameter and height were shown to better depict tree shape and volume in tropical (Vibrans et al. 2015) and subtropical forests (Segura and Kanninen 2005, McRoberts et al. 2015). Accurate CTV estimates are key to the implementation of sustainable management plans (Domke et al. 2013, Sagang et al. 2018). For instance, in Brazil, timber concessionaires are now constrained by law to estimate CTV through volumetric equations developed locally (Conselho Nacional do Meio Ambiente [CONAMA] 2009). However, no recommendation is made about the minimal size or design (i.e., random versus stratified) of the sample, impeding efficient implementation of this regulation.

Although total height measurements are often time consuming and sometimes hard to achieve in tall tropical forests (Sullivan et al. 2018), measuring trunk height is less difficult and is often routinely done by forestry services. However, instead of measuring the trunk height of all trees, we suggest measuring a stratified sample of the whole stand. Our results tend to show that models developed through a stratified random sample are generally more accurate than those based on simple random samples, when all trees DBH > 10 cm are considered. The likely reason is that random sampling skews sampling toward small stems, resulting in larger errors across larger trees that are underrepresented (Duncanson et al. 2015). Stratified sampling lessens CTV errors and tending to zero, even when a small fraction of the whole population is measured (Figure 4b). Subsequently, our results suggest that choosing 50 trees across the different size classes (stratified sampling) is the most efficient way to develop a generic volumetric model.

The inclusion of total height was shown to improve whole live-tree biomass (Chave et al. 2005); our results confirm that trunk heights vary across forests and should be systematically measured. Accounting for both DBH and Hc captured the variability among plots and forest types, up to the point that a single generic model performs better than forest-specific models. Interestingly, the parameters related to trunk volume (i.e., β_1 and β_2) of our generic model were very close to other models developed in Amazon forests (Thaines et al. 2010, da Silva and Santana 2014). This indicates that, contrary to trunk height, trunk volume does not vary greatly at regional scale and that our generic model could be applied elsewhere in the Amazon basin.

Conclusion

Accurate volume estimates can be obtained by the Schumacher-Hall equation for the forest in Amapá. Estimates with valid confidence intervals can be obtained using only a generic equation without the need to include forest type.

The FFs produced less reliable estimates than the local equation and suggest larger prediction errors when used for large scales (live-tree inventory), where specific volume estimates are required.

Our study pointed out that, contrary to what is generally thought, generic models to estimate CTV can be developed. Integrating volumetric data at the scale of the whole Amazon basin could potentially lead to the development of a single model integrating, for instance, DBH, Hc, and key climatic information. Such a generic model could then be used reliably by the forestry sector to enforce a sustainable forest management of the remaining natural forests in the region.

Supplementary Materials

Supplementary data are available at *Forest Science* online.

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