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Artificial neural networks and regression analysis for volume estimation in native species[1]

Redes neurais artificiais e análise de regressão para estimativa de volume de espécies nativas

Lucas M. Amorim[2*], Elton da S. Leite[2], Deoclides R. de Souza[2], Liniker F. da Silva[2], Carlos R. de Mello[3] & José M. de Lima[2]

[1] Research developed at Recôncavo region, Bahia, Brazil
[2] Universidade Federal do Recôncavo da Bahia/Centro de Ciências Agrárias, Ambientais e Biológicas, Cruz das Almas, BA, Brazil
[3] Universidade Federal de Lavras/Departamento de Recursos Hídricos, Lavras, MG, Brazil

HIGHLIGHTS:

Artificial neural networks (ANNs) provide a more robust and accurate estimate of timber volume than simple regression models.
Estimates improve as the number of neurons in the hidden layer increases, thereby reducing errors.
The ANNs models are more robust to estimate the volumes of the trees with greater accuracy than using simple regression ones.

ABSTRACT: Modeling is an important tool to estimate forest production in planted areas. Although this issue has been studied worldwide, knowledge regarding volume measurement in specific locations such as Northeast Brazil is still scarce. The present study aimed to evaluated the effectiveness of artificial neural networks (ANNs) and regression analysis in estimating the timber volume of homogeneous stands of *Anadantera macrocarpa, Genipa americana, and Mimosa casalpinifolia*, in order to better predict the growth and production of these species. Both methods were suitable for estimating the individual volume in 7-year-old stands with different spacing. The Spurr regression model showed better statistical results and dispersion of unbiased errors for *Anadantera macrocarpa* and *Genipa americana*, whereas the Shumacher-Hall model provided more accurate volume estimates for *Mimosa caesalpinifolia*. The ANNs calibrated with two neurons in the middle layer exhibited the best fit for all three species. As such, artificial neural networks can be recommended to estimate the individual volumes of the species analyzed in the study area.

Key words: native forest, production volume, prediction models, ANNs

RESUMO: O uso de modelos para estimar a produção florestal é uma importante ferramenta em áreas plantadas. Embora esse assunto tenha sido estudado em todo o mundo, ainda falta conhecimento a respeito da medição de volume para locais específicos, como os do Nordeste do Brasil. Desta forma, objetivou-se com este estudo avaliar o potencial de predição de redes neurais artificiais e regressão para a estimativa do volume de madeira em povoamentos homogêneos de *Anadantera macrocarpa, Genipa americana* e *Mimosa caesalpiniflolia*. Os métodos de regressão e de redes neurais artificiais (RNAs) mostraram-se aplicáveis para a estimativa do volume individual dos povoamentos em diferentes espaçamentos, aos sete anos de idade. O modelo de regressão de Spurr apresentou melhores resultados estatísticos e dispersão dos erros não tendenciosos para as espécies *Anadantera macrocarpa e Genipa americana.* Já o modelo de Shumacher-Hall foi mais preciso para a estimativa do volume da espécie *Mimosa caesalpinifolia*. As RNAs, com dois neurônios na camada intermediária, proporcionaram melhores ajustes para as três espécies, portanto, são recomendadas para estimar os volumes individuais das espécies avaliadas, por mostrar maior precisão, em relação à regressão, na estimativa do volume das espécies nativas avaliadas.

Palavras-chave: florestas nativas, volume de produção, modelos de predição, RNAs

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* Corresponding author - E-mail: lukasmamorim@gmail.com
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Introduction

Forest inventories to estimate timber volume typically use a set of data to estimate the height, volume and number of trees per hectare (Machado et al., 2000). However, in the literature, data on volume estimates and uniformity in tree species native to Northeastern Brazil are still scarce in the literature. Further research is needed to provide new knowledge and improve the management, planning and sustainability of native species in this region.

When adequately managed, many native species are a potentially important source of income. These include *Anadantera macrocarpa Bent*., used in construction and as charcoal for energy production (Carvalho, 2003) and *Mimosa caselpinifolia* Bent., whose timber is used in poles, stakes, charcoal, as a living barrier against strong winds and in restoring degraded areas in urban regions. The species is also an important source of income in the semiarid region (Ledo, 1980). *Genipa americana* L. is widely used in the production of curved parts, carpentry, and in the civil and naval construction sectors, and its fruits in juices and beverages (Lorenzi, 2002). As such, these native species are economically important in Northeastern Brazil.

In light of their different applications, knowing the timber volume and uniformity of these species in a commercial plantation is crucial for production sustainability, in order to be economically advantageous. Production variables can be estimated by regression analysis and artificial neural networks (ANNs). Regression analysis is an efficient technique widely used to estimate volume in trees with fewer branches (Machado et al., 2002). However, estimating volume in species with many bifurcations and irregularities is far more complex. As such, specific adjustments to equations are needed for each stand (Binoti et al., 2013), meaning different approaches may be necessary in order to optimize forest inventories.

Artificial neural networks (ANNs) represent a new approach that could potentially provide better timber volume estimates (Gorgens et al., 2009; Leite et al., 2010) and are still little explored for this purpose in Brazil. In forestry inventories, ANNs can provide significant results for volume, hypsometric ratios and taper equations (Gorgens et al., 2009; Silva et al., 2009; Binoti, 2010; Leite et al., 2010; Binoti et al., 2012a; Binoti et al., 2012b; Binoti et al., 2013; Binoti et al., 2014). The present study aimed to assess the potential of ANNs and regression analysis in estimating the timber volume of *Anadantera macrocarpa* Bent., *Genipa americana* L. and *Mimosa caesalpiniflolia* Bent., native species in Northeastern Brazil.

Material and Methods

The study was conducted in the Recôncavo region, (12° 39' 22" S; 39° 5' 04" W; and altitude of 220 m) of Bahia state, Brazil, with three native species (*Anadenanthera macrocarpa* Benth. – Angico Vermelho, *Genipa americana* L. - Jenipapo, and *Mimosa caesalpinifolia* Benth. – Sabiá). According to Köppen-Geiger's classification the climate in the region is As, with the rainy season occurring in winter and fall (Köppen & Geiger, 1948), average annual rainfall of 1224 mm, mostly between March and June, 80% relative air humidity and an average temperature of 24.5 °C. The soil is classified as Oxisol.

Data were collected from three homogeneous stands of the native species studied, as follows: i) *Anadantera macrocarpa* (Angico Vermelho), 384 plants with spacing of 6 × 1.5, 6 × 2, 6 × 2.5 and 6 × 3 m; ii) *Genipa americana* (Jenipapo), 500 plants with spacing of 3 × 1.5 , 3 × 2, 3 × 2.5, 3 × 3, 3 × 3.5 m; and iii) *Mimosa caesalpinifolia* (Sabiá), 720 plants with spacing of 3 × 1.5, 3 × 2, 3 × 2.5, 3 × 3 and 3 × 3.5 m. The trees were planted in May 2009, in 0.3 × 0.3 × 0.3 m pits, with three seeds per pit, according to the spacing described above. Each pit was fertilized with 120 g of single superphosphate, keeping the soil between the pits undisturbed. Topdressing was carried out 90 days after planting, with 120 g of NPK 20-0-20 per pit. Manual weeding (for ant control) and harrowing were performed three times, the former within the rows and the latter between them. Seven years after germination, the height and circumference of each plant was measured, the latter at a height of 1.3 m (diameter at breast height - DBH).

Smalian's equation (Eq. 1) (Machado et al., 2002) was used to calculate individual volumes for each plot. A total of 25 trees were randomly selected from each stand and fit within five classes of diameters.

$$V = \frac{G_1 + G_2}{2} L \tag{1}$$

where:

V - volume of each plot according to Smalian's equation, m^3;
G_1 - sectional area at the base, m^2;
G_2 - sectional area at the top, m^2; and,
L - length of section, m.

Five linear regression models were used to analyze volume in the species studied, as described by Soares et al. (2011); Rocha et al. (2015); Silva et al. (2016). Timber volume was estimated based on the DBH and plant height, as shown in Table 1.

These equations were fit using linear regression. The results were compared based on the coefficient of determination (R^2) and root mean square error (RMSE) to measure the difference between predicted and observed values. Additionally, graphic distribution of the residuals made it possible to assess the homogeneity of residual distribution for each model.

Artificial neural networks (ANNs) were used to estimate volume in three steps: training, testing and validating. For that purpose, Statistica 10.0 software (Statsoft, 2010) and different training methods were used.

Table 1. Linear regression models used to estimate timber volume

Equation (Author)	Model
Spurr (1952)	$V = \beta0 + \beta1DBH^2 * H$
Shumacher & Hall (1933)	$Ln (V) = \beta0 + \beta1Ln (H) + \beta2Ln (DBH)$
Brenac (Machado, 2002)	$Ln (V) = \beta0 + \beta1Ln (DBH) + \beta2 (1/DBH)$
Hush (1963)	$Ln (V) = \beta0 + \beta1Ln (DBH)$
Hohenald-Krenm (Machado, 2002)	$V = \beta0 + \beta1DBH + \beta2DBH^2$

V - Tree volume, m^3; β0, β1, β2 - Model coefficients; DBH - Diameter at breast height (1.30 m from the soil surface), cm; H - Tree height, m

In the first method, ANNs were trained separately for each tree species. The observed data were input through a specific target variable, which was established during the cubing process (volume measurement), estimated using plant height and DBH. The data set was randomly divided into 70% for training, 15% for testing and 15% for validating. The input layer consisted of two neurons, one for each predictor variable. The ANNs were either a 2-2-1 or 2-1-1 network and contained half or one intermediate (hidden) layer for each numeric variable, which had one or two neurons with a logistic or exponential activation function.

Only one ANN was trained to estimate volume for the species studied. In this case, only one input variable, which consisted of all the tree species, was considered. Due to the addition of this categorical variable, the ANN architecture consisted of five neurons in the input layer, one or two in the intermediate layer and one in the output layer (volume) in a 5-1-1 or 5-2-1 configuration.

In order to separate shapes, traces and patterns, 200 multi-layer perceptrons (MLP) were trained. The results of the four best-performing ANNs are presented in this paper and were selected based on the correlation between estimated and measured volumes, and residual plots as a function of the estimated volume, analyzing the root square mean error (RSME, %). It is important to note that the lower the RMSE, the more accurate the estimated values.

Results and Discussion

The Spurr and Hohenald-Krenm models showed the best fit for *Anadantera macrocarpa* when compared to the Shumacher and Hall, Brenac, and Hush models, which exhibited little or no difference between R^2 and RMSE (Table 2). The Spurr model was the best fit for *Genipa Americana,* with the remaining models obtaining higher RMSE values, close to 50%. The Shumacher and Hall model exhibited the best fit for *Mimosa caesalpinifolia* in relation to the other models, which recorded lower R^2 values and RMSE close to 32%.

Melo et al. (2013), Rocha et al. (2015), and Silva et al. (2016) used models to estimate volume in homogeneous stands of *Genipa americana*, *Khaya ivorensis*, and *Pinus caribaea*, respectively, and concluded that the Spurr model showed the best fit, with little dispersion between estimated and observed values. The results found in the present study for *Genipa americana* and *Anadantera macrocarpa* are similar to those obtained in the aforementioned investigations. This similarity is due to the trunk shape of these species. However, different results were recorded for *Mimosa caesalpinifolia*, with a low R^2 due to the highly branched pattern of this species. There was no relationship between R^2 and RMSE values for *Anadantera macrocarpa* and *Genipa americana*, a finding similar to results reported by Barros et al. (2002), due to the different shapes of these two species.

Despite the irregular trunk shapes, the residual distribution of all the models tested showed some dispersion, with no difference between species (Figure 1). These results corroborate the findings of Silva et al. (2016) in *Khaya ivorensis*, which has similar architecture to the species studied here. The Hush model showed more uniform distribution for *Mimosa caesalpinifolia* when compared to the other models, providing the most accurate volume estimate for this species. Encinas et al. (2009) also reported that this model performed best in estimating volume in Cerrado species, whose shape and branching pattern is similar to that of the species in the present study.

Based on the coefficient of correlation and RMSE, the ANNs provided satisfactory volume estimates for *Anadantera macrocarpa, Genipa americana,* and *Mimosa caesalpinifolia* (Table 3). Silva et al. (2009) reported results similar to those obtained here.

The statistical results of the ANNs trained for the three species are presented in Table 4. The best results were obtained by ANN-3, due to the two neurons in the intermediate layer. This model was also successfully used by Binoti et al. (2013) and Gorgens et al. (2014) in eucalyptus plantations.

Residuals for estimated volumes in *Anadantera macrocarpa*, *Genipa americana* and *Mimosa caesalpinifolia* are shown in Figure 2. The ANNs selected showed significant potential in accurately estimating the timber volume of the species studied. There were no differences between the ANNs

Table 2. Fitted regression models for timber volume in 7-year-old stands of *Anadantera macrocarpa, Genipa americana,* and *Mimosa caesalpinifolia* with different spacing, in Northeastern Brazil

Model	β_0	β_1	β_2	R^2 (%)	RMSE (%)
		Anadantera macrocarpa Bent.			
Spurr	0.01176**	0.00003**		87.9	31.56
Shumacher & Hall (Log)	-8.60458**	0.45913**	1.80458**	82.8	29.83
Brenac	-8.26207**	1.95163**	-0.16443**	79.8	31.11
Hush	-8.33343**	1.9723**		80.6	30.99
Hohenald-Krenm	0.0058	-0.00098	0.00026**	88.6	30.38
		Genipa americana			
Spurr	0.00029	0.00002**		86.2	41.88
Shumacher & Hall (Log)	-9.7054**	1.70072**	1.0821**	79.9	44.20
Brenac	-9.6727**	2.14012**	-2.3189	61.8	51.39
Hush	-11.069**	2.65894**		75.4	47.83
Hohenald-Krenm	0.00051	-0.0003	0.0001**	80.0	49.64
		Mimosa caesalpinifolia			
Spurr	0.02221**	1.13298		10.3	45.31
Shumacher & Hall (Log)	-13.74405**	5.57288**	0.06932	60.2	32.01
Brenac	-0.11627	-1.02279	-10.56400	25.3	42.62
Hush	-5.02573**	0.64529**		30.1	45.96
Hohenald-Krenm	-0.00793	0.00777	-0.00036	22.9	42.00

R^2 - Coefficient of determination; RMSE – Root mean square error; β0, β1, β2 - Model coefficients; ** - Significant at $p \leq 0.01$ according to the t-test

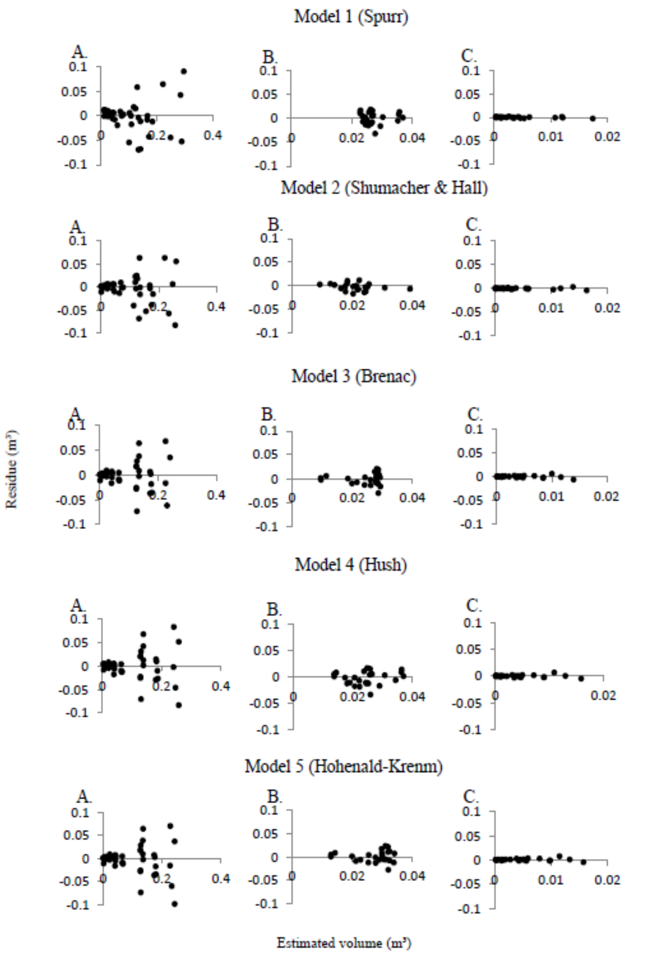

Figure 1. Residual distribution as a function of estimated volume for *Anadantera macrocarpa* (A), *Genipa americana* (B) and *Mimosa caesalpinefolia* (C) in five regression models

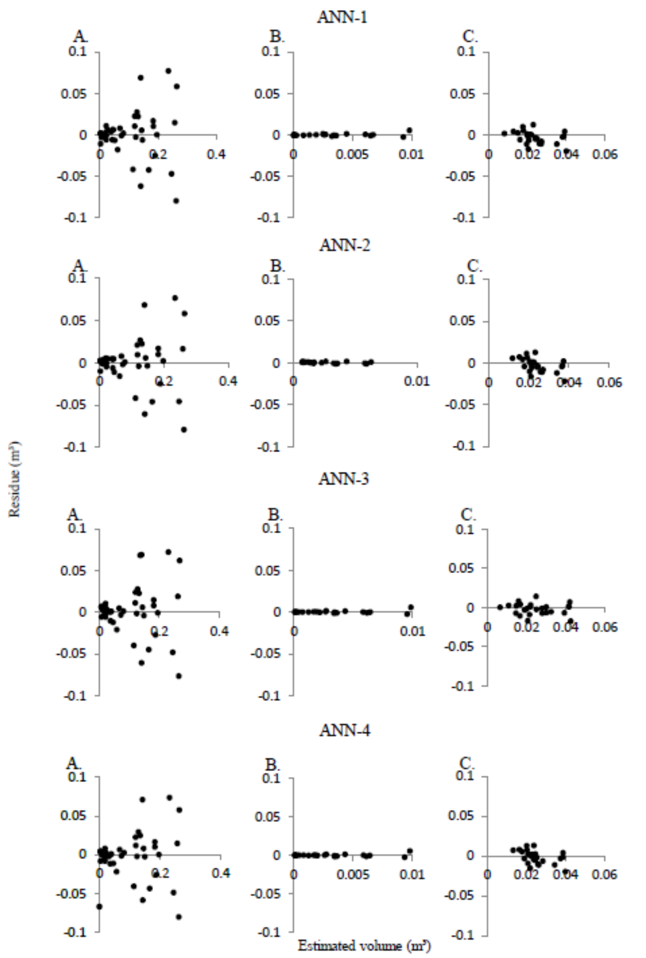

Figure 2. Dispersion of absolute errors of individual timber volume estimated by four ANNs in *Anadantera macrocarpa* (A), *Genipa americana* (B) and *Mimosa caesalpinefolia* (C)

Table 3. Artificial neural networks (ANNs) selected to estimate the timber volume in *Anadantera macrocarpa. Genipa americana, and Mimosa caesalpinifolia*

ANN	Architecture	R^2 (%)			RMSE (%)		
		Training	Test	Validation	Training	Test	Validation
			Anadantera macrocarpa Bent.				
1	MLP 2-2-1	93.8	96.7	99.6	29.33	17.39	12.52
2	MLP 2-2-1	93.8	96.9	99.6	29.36	17.25	12.50
3	MLP 2-2-1	93.8	96.4	99.7	29.34	17.46	12.90
4	MLP 2-1-1	93.8	97.0	99.6	29.44	17.46	12.86
			Genipa americana				
1	MLP 2-2-1	91.5	99.0	99.9	40.68	19.54	28.36
2	MLP 2-2-1	90.9	96.6	99.9	42.64	23.37	27.36
3	MLP 2-2-1	91.6	99.5	99.9	40.70	19.10	23.56
4	MLP 2-1-1	91.9	98.5	99.9	37.43	18.68	20.34
			Mimosa caesalpinifolia				
1	MLP 2-2-1	80.8	93.1	99.9	30.75	12.44	34.27
2	MLP 2-2-1	80.2	92.4	99.9	32.12	10.62	49.81
3	MLP 2-2-1	81.9	98.8	99.9	27.93	14.10	39.82
4	MLP 2-1-1	78.0	88.7	99.9	32.14	12.44	43.64

RMSE - Root mean square error; R^2 - Coefficient of determination; MLP - Multiple layer perceptron

Table 4. Artificial neural networks (ANNs) selected to estimate the individual timber volume of native species in 7-year-old homogeneous stands

ANN	Architecture	R^2 (%)			RMSE (%)		
		Training	Test	Validation	Training	Test	Validation
1	MLP 5-1-1	84.2	87.1	92.9	78.94	75.24	86.34
2	MLP 5-1-1	83.7	87.0	92.8	69.13	77.60	91.23
3	MLP 5-2-1	95.6	97.9	98.6	22.70	39.51	33.97
4	MLP 5-1-1	84.2	86.5	92.8	93.66	73.62	79.07

RMSE - Root mean square error; R^2 - Coefficient of determination; MLP - Multiple layer perceptron

Table 5. Best-performing artificial neural networks (ANNs) and volumetric regression models for estimating the individual timber volume of *Mimosa caesalpiniifolia. Genipa americana* and *Anadantera macrocarpa*

Method species		R^2 (%)			RMSE (%)*		
		Training	Test	Validation	Training	Test	Validation
ANNs	*Anadantera macrocarpa*	93.8	96.9	99.6	29.36	17.25	12.50
	Genipa americana	91.9	98.5	99.9	37.43	18.68	20.34
	Mimosa Caesalpinifolia	80.8	93.1	99.9	30.75	12.44	34.27
	All species	95.6	97.9	98.6	22.70	39.51	33.97
Regression	*Anadantera macrocarpa*		94.1			30.30	
	Mimosa caesalpinifolia		63.4			41.80	
	Genipa americana		92.8			44.20	

RMSE - Root mean square error; R^2 - Coefficient of determination

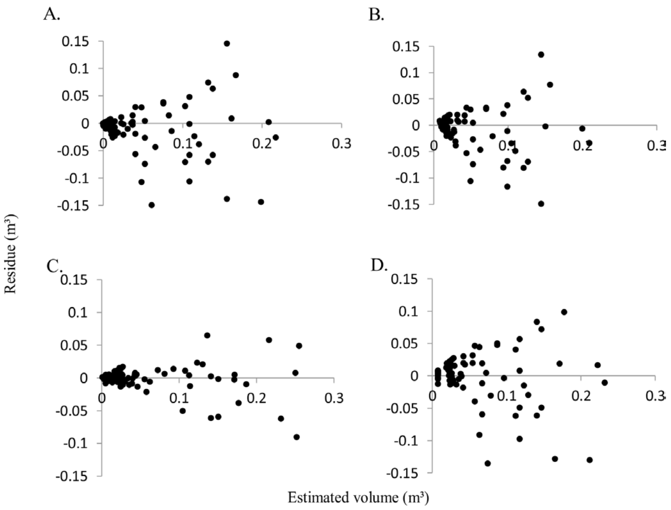

Figure 3. Dispersion of absolute errors of individual timber volume estimated by four ANNs in 7-year-old homogeneous stands of native species

for *Anadantera macrocarpa,* whereas the best estimates for *Genipa americana and Mimosa caesalpinifolia* were obtained byANN-2 and ANN-3, respectively.

Figure 3 presents the estimation of the dispersion error obtained by the selected ANNs for the three species studied. Although unbiased results were obtained, ANN-3 showed the best fit, with better distribution of the errors for all three species assessed. This is due to the presence of an additional neuron in the hidden layer, reducing errors and improving the accuracy of estimates. These results are similar to those reported by Gorgens et al. (2009) and Binoti et al. (2013) in experiments with exotic clonal species in different locations, demonstrating the efficient use ANNs in forest science.

Table 5 presents a comparison between the regression and ANN models. Based on the precision statistics in this Table, there is a clear improvement in volume estimates by ANNs. The ability to train ANNs for several species in a single model is one of the main advantages of these networks when compared to regression models, which are individually fit to each species, clone, or stand (Binoti et al., 2013). Thus, the ANNs were able to estimate timber volume more accurately than the regression models. This corroborates the findings of Leal et al. (2015) in eucalyptus trees and Rodrigues et al. (2010) in *Schizolobium parahyba var. amazonicum.*

Conclusions

1. Regression and artificial neural network (ANNs) methods are suitable for estimating timber volume in 7-year-old homogenous stands of *Mimosa caesalpiniifolia, Genipa americana* and *Anadantera macrocarpa* with different spacing.

2. The Spurr regression model obtained the best statistical results with unbiased dispersion of the errors for *Anadantera macrocarpa* and *Genipa americana*, while the Schumacher and Hall model provided more accurate predictions for *Mimosa caesalpinifolia*.

3. The best-fitting ANNs were those with two neurons in the intermediate layer. Additionally, ANNs can be used to estimate the volume of individual trees, showing better accuracy.

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