Scientific Article

MODELING DIAMETER DISTRIBUTION OF TREE SPECIES IN A SEMIDECIDUOUS FOREST FRAGMENT

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ABSTRACT – Modeling diameter distribution in natural forests is an important tool for understanding the native woody species dynamics, supporting decision-making for degraded lands management and restoration. Therefore, this work aimed to fit probabilistic density functions to evaluate the diameter structure of three tree species with economic interest, such as *Campomansesia xanthocarpa* Marl. Ex. O. Berg, *Piptadenia gonoacantha* (Mart.) J.F. Macbr. and *Zeyheria tuberculosa* (Vell.) Bureau ex Verl., in a Semideciduous Seasonal Forest fragment at São Paulo State, Brazil. The data came from 83 temporary plots of 10 m x 20 m systematically distributed along 164 ha. Log-normal, Gamma, and Weibull functions were fitted to the three species using the fitdistrplus-package in the R program. Kolmogorov-Smirnov's adherence test was used to evaluate the fits at a 5% probability level. The functions were selected employing Akaike's Information Criterion (AIC) and Schwarz's Bayesian Information Criterion (BIC), in addition to a graphical analysis of the fitted functions. The results indicated that the three species diameter structure is positively asymmetric, representing the exponential pattern, representing continuous natural regeneration. AIC and BIC statistics indicated the Log-normal function to describe the diameter distribution of *C. xanthocarpa* and *Z. tuberculosa*, while the Gamma function was the most appropriate for *P. gonoacantha*. For the three species, the graphical analysis showed the Gamma function results in the best fit without tendency for estimating frequency density per diameter class.

Keywords: Diameter structure; Probabilistic density functions; Adherence test.

MODELAGEM DA DISTRIBUIÇÃO DIAMÉTRICA DE ESPÉCIES ARBÓREAS EM FRAGMENTO DE FLORESTAS ESTACIONAL SEMIDECIDUAL

RESUMO – A modelagem da distribuição diamétrica em florestas naturais é uma ferramenta importante para compreender a dinâmica de espécies nativas lenhosas, auxiliando na tomada de decisão para o manejo e a recuperação de áreas degradadas. Dessa forma, o objetivo deste trabalho foi ajustar funções de densidade probabilística para avaliar a estrutura diamétrica de três espécies arbóreas de interesse econômico, como ***Campomansesia xanthocarpa*** *Marl. Ex. O. Berg,* ***Piptadenia gonoacantha*** *(Mart.) J.F. Macbr. e* ***Zeyheria tuberculosa*** *(Vell.) Bureau ex Verl., em um fragmento de Floresta Estacional Semidecidual no estado de São Paulo, Brasil. Os dados foram provenientes de 83 parcelas temporárias de 10 m x 20 m distribuídas sistematicamente ao longo de 164 ha. As funções Log-normal, Gamma e Weibull foram ajustadas para as três espécies por meio do pacote fitdistrplus no programa R. O teste de aderência de Kolmogorov-Smirnov foi aplicado a 5% de probabilidade para avaliar os ajustes. As funções foram selecionadas por meio do Critério de Informação Akaike (AIC) e do Critério de Informação Bayesiano de Schwarz (BIC), além da análise gráfica das funções ajustadas. Os resultados indicaram que a estrutura diamétrica das três espécies é assimétrica positiva, as quais apresentam o padrão exponencial, sugerindo uma regeneração natural contínua. As estatísticas de AIC e BIC indicaram a função Log-normal para descrever a distribuição diamétrica de* ***C. xanthocarpa*** *e* ***Z.***

tuberculosa, *enquanto a função Gamma foi a mais adequada para* ***P. gonoacantha***. *Para as três espécies, a análise gráfica mostrou que a função Gamma resultou no melhor ajuste, não apresentando tendências nas estimativas da densidade de frequências por classe de diâmetro.*

Palavras-Chave:Estrutura diamétrica; Funções de densidade probabilística; Teste de aderência.

1. INTRODUCTION

The Seasonal Semideciduous Forest, also known as Atlantic Interior Forest and Semideciduous Seasonal Forest, is one of the forest typologies that compose the Atlantic Forest biome, especially in the western region of Serra do Mar. This forest has expansive in São Paulo State, Brazil, with remnants of 1,744,701 ha (7.0%) in medium to advanced succession stages (Ramos et al., 2015). The Seasonal Semideciduous Forest covers a smaller area than the Dense Ombrophylous Forest, with 3,512,662 ha (10.1%), in larger size of the São Paulo State territory (Ramos et al., 2015; SIMA, 2020).

Campomansesia xanthocarpa Ex. O. Berg (Guabiroba), *Piptadenia gonoacantha* Mart. J.F. Macrbr. (Pau-jacaré), and *Zeyheria tuberculosa* Vell. Bureau ex Verl. (Ipe-tobacco) are considered as typical species of the Seasonal Semideciduous Forest (APG IV, 2016; Cole et al., 2019). *C. xanthocarpa* has potential for conservation and genetic improvement programs due to the commercial use of its fruits (Kampa et al., 2020) and for health treatment, such as reducing blood glucose (Biavatti et al., 2004). In contrast, *P. gonoacantha* species is used for firewood and charcoal (Carvalho, 2003), in addition to its pharmacological potential, while *Z. tuberculosa* is recommended for landscaping due to its crown appreciation (Lorenzi, 2008).

The diameter distribution allows understanding its ecological aspects of forest species, providing subsidies for forest management and monitoring (Dardengo et al., 2017). Therefore, diameter distribution analyses are fundamental as an indicator of forest structure. In addition, it is possible to identify different typologies and the intensity of natural regeneration at the species and forest level, as well as to measure the growth stock (Scolforo, 2006).

The probabilistic density functions provide a mean to analytically describe the diameter structure of species and forests. In the literature, there are some functions used for this purpose, in which we highlight the Log-normal, Gamma, and Weibull for natural forest formations (Machado et al., 2009; Dalla Lana et al., 2013). Therefore, this work aimed to fit probabilistic density functions to evaluate the diameter structure of three tree species with economic interest in a Semideciduous Seasonal Forest fragment at São Paulo State, Brazil.

2. MATERIAL AND METHODS

This study was carried out in 164 hectares (ha) of a Semideciduous Seasonal Forest fragment in Assis, São Paulo State, Brazil. The area is located in the Middle Paranapanema region, between coordinates 22° 29' 17" S and 50° 25' 26" W, at an altitude of approximately 500 m above sea level. The region's relief ranges from flat to gently undulating.

According to the Köppen's classification, the region's climate is represented by a transition between humid subtropical climate types, warmer and with a defined dry season, and subtropical hot summer climate (Durigan, 2010). The rainfall is concentrated in the summer, with average annual precipitation around 1,400 mm, and the winter is dry, with average temperatures of 21.8 °C and the possibility of severe frosts (Brando and Durigan, 2005).

The fixed area sampling method and the systematic sampling process were used in this study, with the allocation of 83 temporary sampling units of 10 m x 20 m. The total area sampled was 16,600 m^2, representing 1.01% of the forest fragment. Data were collected between March and July 2020. The first plot was randomly established and, subsequently, the other sampling units were allocated at distances of 100 m from each other on the East-West axis and 200 m on the North-South axis.

The diameter of 5 cm was established as the minimum value to include a tree in the sample.

Table 1 – Probability density functions fitted for tree species in a Semideciduous Seasonal Forest fragment.
Tabela 1 *– Funções de densidade de probabilidade ajustadas para espécies arbóreas em um fragmento de Floresta Semidecídua Estacional.*

Function	Model	Equation
Log-Normal	$f(x) = \frac{e^{-\frac{1}{2}\left(\frac{\ln x-\mu}{\sigma}\right)^2}}{x\left(\sqrt{2\pi\sigma^2}\right)}$ $x \geq 0$	1
Gamma	$f(x) = \frac{x^{\alpha-1}\, e^{-x/\beta}}{\beta^{\alpha}\, \Gamma(\alpha)}$ $x \geq 0$	2
Weibull	$f(x) = \frac{c}{b}\left(\frac{x}{b}\right)^{c-1} e^{-\left(\frac{x}{b}\right)^{c}}$ $x \geq 0, \quad b > 0 \quad e \quad c > 0$	3

x is the diameter variable cm; *μ* is the mean of *x*, *σ* is the standard deviation of *x*, *α,β,γ,b* e *c* are the estimated parameters.
x é a variável diâmetro em cm; μ é a média da variável x, σ é o desvio padrão da variável x, α,β,γ,b e c são os parâmetros estimados.

Subsequently, descriptive statistics and histograms were calculated to evaluate the heterogeneity of the diameter structures. The number of diameter classes and their intervals were defined using the Sturges' method (1926).

Log-Normal, Gamma, and Weibull probability density functions (Table 1) were fitted by the Maximum Likelihood method using the fitdistrplus-package (Muller and Dutang, 2015) of the R program (R Core Team, 2021). The estimation quality of the fits was assessed by the Kolmogorov-Smirnov's adherence test (α = 0.05). In addition, Akaike's Information Criterion (AIC) and Schwarz's Bayesian Information Criterion (BIC) statistics were used to select the best function for each species.

3. RESULTS

3.1. Diameter distribution and descriptive statistics

In this study, a total of 61 *C. xanthocarpa* tree stems were measured in 36 sampling units, 88 *Z. tuberculosa* stems in 42 sampling units and 91 *P. gonoacantha* stems in 43 sampling units (Table 2). *C. xanthocarpa* showed the lowest number of stems, range, and maximum diameter, as well as the lowest values for other descriptive statistics. The sample of *Z. tuberculosa* resulted in the highest number of diameter classes between the three species and two times more than *C. xanthocarpa*.

Figure 1 shows the histograms of the studied species, in which positive asymmetry was verified with mean diameter greater than the median value (Table 2). In addition, the distributions present the pattern of a negative exponential curve for native forests. However, the first class for *C. xanthocarpa* and *Z. tuberculosa* showed lower frequency than the upper class (Figure 1). *Z. tuberculosa* showed some classes without tree stems for diameters greater than 30 cm, with only one individual in the 60 cm to 65 cm class (Figure 1).

P. gonoacantha showed more tree stems distributed in the upper diameter classes when compared to the other species, with 54% concentrated in the diameter classes lower than 20 cm (Figure 1). In addition, although there was a negative exponential distribution tendency, a second mode was observed for *P. gonoacantha* in the diameter class of 20 cm to 25 cm.

3.2 Fitting probability density functions

Log-normal, Gamma, and Weibull functions presented adherence to the observed species distributions, resulting in non-significance by the Kolmogorov-Smirnov's test (D) at the 5% probability level (Table 3). Log-normal function resulted in the lowest D value statistics for *C. xanthocarpa*, followed by Gamma and Weibull. In addition, the lowest D value resulted by Weibull function for *P. gonoacantha*, followed by Log-normal and Gamma. In contrast, lowest value was presented by the Log-normal for *Z. tuberculosa*, followed by Gamma and Weibull (Table 3).

Akaike's Information Criterion (AIC) and Schwarz's Bayesian Information Criterion (BIC) allowed us to score the functions according to the estimation quality of the fits (Table 3). Log-Normal function was the one that most minimized the loss of information for *C. xanthocarpa* and *Z. tuberculosa*. On the contrary, Gamma function presented the lowest AIC and BIC values for *P. gonoacantha*. In addition to the classification, the quality of the fits can be evaluated by fitted curves in Figure 2.

Log-normal function overestimated the frequencies in the second and third classes for *C. xanthocarpa*. Gamma function, although similar

Table 2 – Descriptive statistics of the variable diameter at 1.3 m above ground for tree species in a Semideciduous Seasonal Forest fragment.
Tabela 2 *– Estatística descritiva da variável diâmetro a 1,3 m do solo para as espécies arbóreas em um fragmento de Floresta Estacional Semidecidual.*

Statistics	*C. xanthocarpa*	*P. gonoacantha*	*Z. tuberculosa*
Number of sampled tree stems	61	91	88
Minimum diameter (cm)	5.09	5.09	5.09
Mean diameter (cm)	8.38	19.54	16.51
Median diameter (cm)	7.96	18.46	15.44
Maximum diameter (cm)	15.92	54.11	60.80
Diameter range (cm)	10.82	49.02	55.70
Coefficient of variation (%)	30.90	55.10	47.87
Number of diameter class	6	10	12

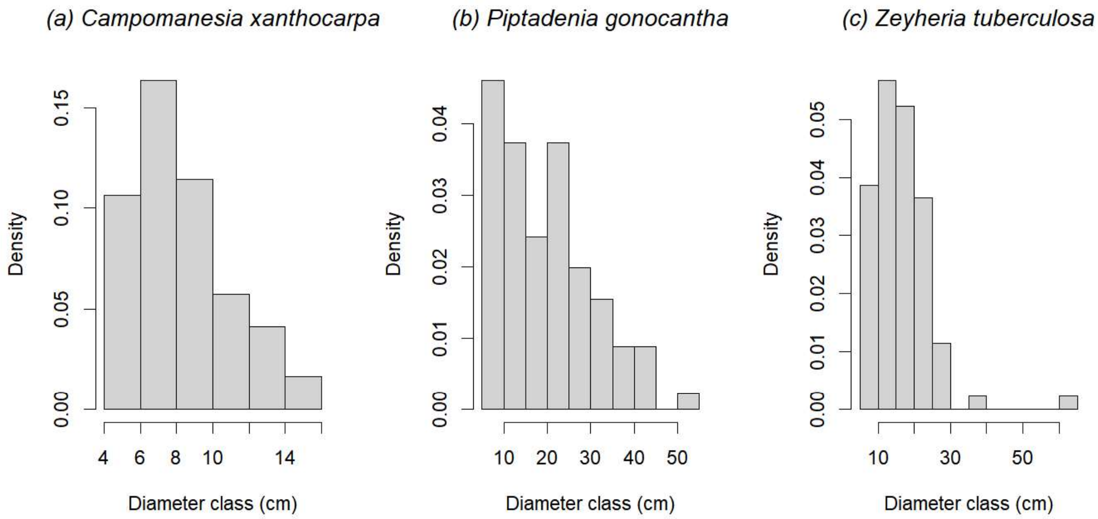

Figure 1 – Diameter distribution histograms of tree species in a Semideciduous Seasonal Forest fragment.
Figura 1 *– Histogramas da distribuição diamétrica de espécies arbóreas em um fragmento de Floresta Estacional Semidecidual.*

Table 3 – Parameters and statistics of probabilistic density functions fitted for tree species in a Semideciduous Seasonal Forest fragment.
Tabela 3 *– Parâmetros e estatísticas das funções de densidade probabilística ajustadas para as espécies arbóreas em um fragmento de Floresta Estacional Semidecidual.*

Function	*D*	$D_{5\%}$	*μ*	*σ*	*α*	*β*	*b*	*c*	Rank	AIC	BIC
					C. xanthocarpa						
Log-Normal	0.0920^{ns}	0.1728	2.0800	0.2976					1°	283.0209	287.2427
Gamma	0.0935^{ns}	0.1728			11.2909	1.3487			2°	284.7961	289.0178
Weibull	0.1186^{ns}	0.1728					9.3111	3.4382	3°	292.5229	296.7446
					P. gonoacantha						
Log-Normal	0.0732^{ns}	0.1415	2.8090	0.5947					3°	678.9135	683.9353
Gamma	0.0970^{ns}	0.1415			3.2182	0.1647			1°	676.5040	681.5257
Weibull	0.0641^{ns}	0.1415					22.1190	1.9403	2°	678.1911	683.2129
					Z. tuberculosa						
Log-Normal	0.0638^{ns}	0.1439	2.7062	0.4425					1°	586.5313	591.4860
Gamma	0.0726^{ns}	0.1439			5.2746	0.3195			2°	589.2075	594.1622
Weibull	0.0975^{ns}	0.1439					18.6459	2.1806	3°	603.312	608.2666

μ,σ,α,β,b and *c* are the estimated parameters, *D* is the Kolmogorov-Smirnov statistics, $D_{5\%}$ is the critical value of Kolmogorov-Smirnov test, at the 5% probability level, and *ns* is non-significance, AIC is Akaike's Information Criterion, and BIC is Schwarz's Bayesian information criterion.
μ,σ,α,β,b e c são os parâmetros estimados, D é a estatística do teste de Kolmogorov-Smirnov, $D_{5\%}$ é o valor crítico do teste de Kolmogorov-Smirnov, ao nível de 5% de probabilidade, e ns é não significativo. AIC é o Critério de Informação de Akaike, e BIC é o critério de informação Bayesiano de Schawarz.

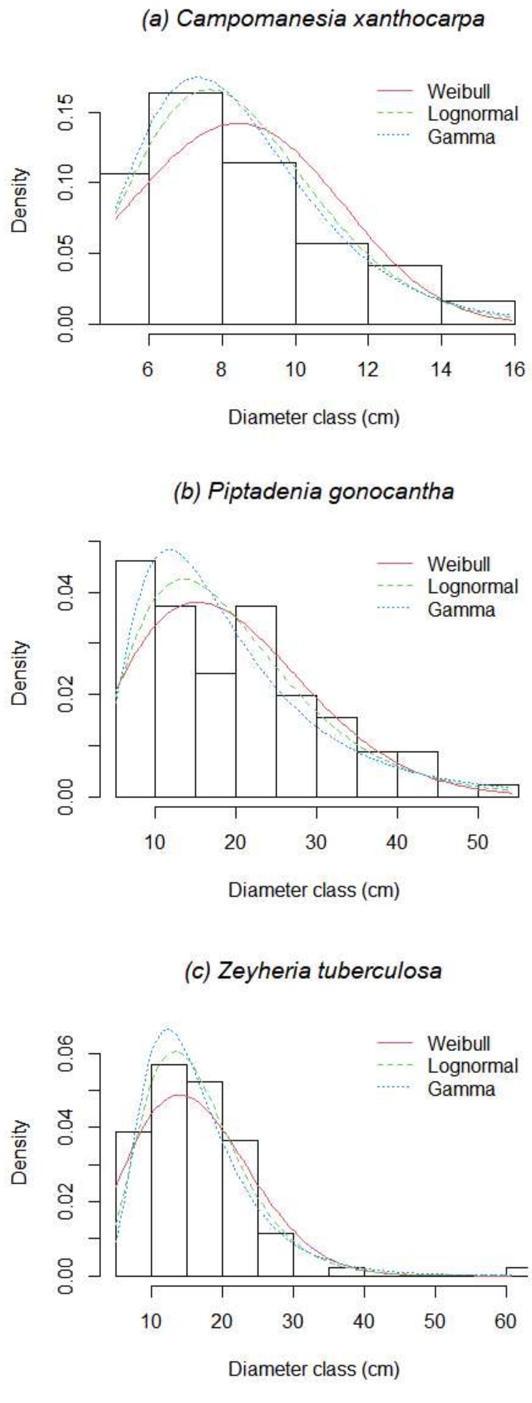

Figure 2 – Fitted curves of probabilistic density functions for tree species in a Semideciduous Seasonal Forest fragment.
Figura 2 *– Curvas ajustadas das funções de densidade probabilística para as espécies arbóreas em um fragmento de Floresta Estacional Semidecídua.*

to the Log-normal, showed better estimates for the first diameter classes. Weibull function resulted in a lower quality of the fit, underestimating the frequency density in the first classes and overestimating them in the third and fourth diameter classes (Figure 2).

Gamma function resulted in better statistical performance for *P. gonoacantha* compared to the other functions, although it underestimated the frequency density in the first diameter class. Log-normal function overestimated for the second and third classes, while it underestimated for the fourth, fifth and sixth diameter classes. In contrast, Weibull also showed good fit, but underestimated in the first diameter class (Figure 2).

Log-normal fit overestimated the frequency density in the second class and underestimated it in the fourth diameter class for *Z. tuberculosa*. Weibull underestimated in the second and third classes and overestimated in the fifth, while Gamma function provided the best fit in the classes up to 30 cm in diameter. However, it was not possible to describe the behavior after 40 cm, since trees in the upper classes were not sampled, with only one tree in the 60 cm to 65 cm class, which was not estimated by the three fitted functions (Figure 2).

4. DISCUSSION

Although the species *P. gonoacantha* and *Z. tuberculosa* showed similar stem numbers, *Z. tuberculosa* showed greater homogeneity than *P. gonoacantha* by means of variation, in which *P. gonoacantha* resulted in greater diameter variability (Table 2). In addition, we found that the mean diameter was higher than the median value, which is considered a positive asymmetric distribution (Table 2).

A tendency of negative exponential or "reversed-J" shapes were observed when the diameter distributions were evaluated (Figure 1). However, the first diameter class for *C. xanthocarpa* and *Z. tuberculosa* showed a lower frequency density compared to the upper ones (Figure 1). This result indicates the presence of factors that influence the regeneration of these species, such as different successional stages within the same area.

In addition to recent anthropic disturbances, it is noteworthy that the studied fragment is located in a region of ecological contact between the Cerrado and

Atlantic Forest biomes. This local characteristic may influence the species establishment and development in the site (Durigan and Leitão Filho, 1995; Durigan and Ratter, 2006).

The existence of sites with clearings and lianas were verified in the forest fragment, in which forest fires remnants were also observed. These factors highlight the hypothesis of disturbance, as well as the re-establishment process of the forest structure. These facts also corroborate the lack of larger diameter stems for *Z. tuberculosa*, which is considered a late species in a forest succession (Carvalho, 2003).

For the *P. gonoacantha*, Marangon et al. (2008) and Machado et al. (2010) observed that more than 85% and 90% of the diameters, respectively, were present in classes lower than 20 cm. Since this species is classified as pioneer (Marangon et al., 2007; Gusson et al., 2009; Sá et al., 2012; Guedes and Krupek, 2017) or early secondary (Leite and Rodrigues, 2008), it is possible that the *P. gonoacantha* showed better development and reached higher diameters, due to the presence of clearings and areas in initial succession stage. In addition, the second mode for *P. gonoacantha* (Figure 1) can be explained by natural disturbances and anthropic interventions that resulted in a multimodal distribution for the same species (Ebling and Péllico Netto, 2015).

For the *C. xanthocarpa*, this species is expected to reach diameter classes greater than 16 cm, resulting in a longer tail for its diameter curve. New recruitment will depend on the presence of regenerating trees with diameters lower than 5 cm, in addition to a seedling bank and dispersing organisms. This seedling bank is essential for a community's perpetuation and represented by many trees in tropical regions (Durigan et al., 2010). In addition, a good fruiting of adult trees is also important for the continuity of these species, ensuring a considerable number of seeds. Furthermore, the presence of dispersers is necessary for *C. xanthocarpa*, since this species depends on the zoochory for fruits and seeds dispersions.

For the conservation purposes, non-disturbance tends to support the forest development to higher succession strata, as well as the canopy closure in gaps. According to Durigan and Ratter (2006), climate evidence and field observations indicate that the forests would be expanding rapidly at the present over the absence of anthropic impacts, such as fires and cattle raising. Therefore, non-pioneer species, such as *C. xanthocarpa* (Klauberg et al., 2010) and *Z. tuberculosa* (Crepaldi and Peixoto, 2013), tend to develop better at these sites in short-to medium-term.

Since *P. gonoacantha* is considered a pioneer species, it will present a decrease in frequency density in the upper classes in medium-to-long-term, due to the mortality and successional forest fragment evolution. Consequently, considering an undisturbed ecosystem, the species tends to its characteristic distribution, in which more than 85% of the diameters are concentrated under 20 cm (Marangon et al., 2008; Machado et al., 2010).

The diameter distribution can be one of the criteria to define the sustainable management. Therefore, the species *P. gonoacantha* is potential for firewood, while it is possible to obtain sawmill diameters for *C. xanthocarpa* in a long-term. In addition, it is possible to manage *Z. tuberculosa* trees of higher diameter classes for sawmill in medium-to-long-term. Although there are examples in the literature of *C. xanthocarpa* with maximum diameters of approximately 40 cm (Bianchini et al., 2003, Andrzejewski et al., 2020), 50 cm (Lorenzi, 2008; Orellana et al., 2014; Trautenmüller et al., 2019), and 70 cm (Carvalho, 2003), trees with diameters greater than 15.92 cm were not found in the present study (Table 2).

5. CONCLUSION

By means of the diameter structures, the species *Campomanesia xanthocarpa*, *Piptadenia gonoacantha* and *Zeyheria tuberculosa* showed positive asymmetry approximately similar to the negative exponential pattern of native forests. This evidence indicates a natural regeneration in continuous flow and stability.

Log-normal, Gamma, and Weibull functions were statistically adequate for the three species, resulting in adherence between observed and estimated values. Based on Akaike and Bayesian information criteria, Log-normal function was appropriate for *C. xanthocarpa* and *Z. tuberculosa*, while Gamma was indicated for *P. gonoacantha*. Therefore, Gamma function was recommended for the three species, considering the graphical fit analyses.

AUTHOR CONTRIBUTIONS

Flaick Rodrigo de Lima Ferreira e Allan Libânio Pelissari redigiram o artigo e discutiram os resultados.Vinicius Costa Cysneiros and Carla Krulikowski Rodrigues assisted the data analysis. Lucas Araujo Moura and Eduardo Resende Girardi Marques assisted in writing the paper.

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