USE OF DESTRUCTIVE AND NON-DESTRUCTIVE METHODOLOGIES TO ESTIMATE STEM BIOMASS ACCUMULATION AND CARBON STOCK IN AN EUCALYPTUS FOREST

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ABSTRACT – Predicting wood biomass and carbon stock contents in planted forests can vary due to limitations associated with the measurement of parameters. Therefore, reducing possible errors generated over biomass and carbon stock quantification is an important step in obtaining reliable data. The study aimed to compare the use of destructive and non-destructive methodologies for predicting biomass and carbon stock in a planted Eucalyptus forest. Scaling was performed on 21 trees and 3 methodologies for carbon stock estimation were compared. For methodology 1, a control sample was harvested, sectioned, weighted in the field, and the carbon stock calculated based on these data. Methodology 2 was also destructive, as trees were harvested, scaled and the carbon stock predicted based on these data. Methodology 3 was non-destructive, as trees were scaled upright with the aid of equipment and the predicted carbon stock was based on these data. Biomass and carbon stock were compared by Test F and no statistical difference was observed. The data were separated according to diametric classes and compared by the Kolmogorov-Smirnov test, and again no significant difference was observed. Furthermore, three equations were generated based on the Schumacher & Hall model and compared by the identity test model and no differences between the methodologies were observed. Thus, both non-destructive and destructive methodologies herein evaluated were effective and showed equal results to the control sample. Moreover, the use of the non-destructive methodology reduces time and cost destined to predicting biomass and carbon stock.

Keywords: Basic wood density; Forest plantation; Stem volume.

USO DE METODOLOGIAS DESTRUTIVAS E NÃO DESTRUTIVA PARA ESTIMAR ACÚMULO DE BIOMASSA NO TRONCO E ESTOQUE DE CARBONO EM UMA FLORESTA DE EUCALIPTO

RESUMO – A previsão de biomassa de madeira e estoque de carbono em florestas plantadas pode variar devido a limitações associadas à medição de parâmetros. Portanto, reduzir possíveis erros gerados na quantificação de biomassa e estoque de carbono é um passo importante na obtenção de dados confiáveis. O objetivo do estudo foi comparar o uso de metodologias destrutivas e não destrutivas para a previsão de biomassa e estoque de carbono em uma floresta plantada de eucalipto. As análises foram realizadas em 21 árvores e 3 metodologias para estimativa de estoque de carbono foram comparadas. Para a metodologia 1, uma amostra controle foi colhida, seccionada, pesada em campo e o estoque de carbono calculado com base nesses dados. A metodologia 2 também foi destrutiva, pois as árvores foram cortadas, cubadas e o estoque de *carbono previsto com base nesses dados. A metodologia 3 foi não destrutiva, pois as árvores foram cubadas com auxílio de um equipamento e o estoque de carbono estimado foi baseado nesses dados. A biomassa e o estoque de carbono foram comparados pelo Teste F e nenhuma diferença estatística foi observada. Os dados foram separados de acordo com as classes diamétricas e comparados pelo teste de Kolmogorov-Smirnov, e novamente não foi observada diferença significativa. Além disso, três equações foram geradas com base no modelo de Schumacher & Hall e comparadas pelo modelo de teste de identidade e não foram observadas diferenças entre as metodologias. Assim, tanto as metodologias não destrutivas quanto as destrutivas aqui avaliadas foram eficazes e apresentaram resultados iguais à amostra controle. Além disso, o uso da metodologia não destrutiva reduz o tempo e o custo destinados à previsão de biomassa e estoque de carbono.*

Palavras-Chave: Densidade básica da madeira; Florestas plantadas; Volume do tronco.

1. INTRODUCTION

Greenhouse gas (GHG) emissions have increased over the years and have caused an imbalance on Earth and, consequently, climate changes on a global scale (Olorunfemi et al., 2019). The principal anthropogenic sources of GHG are the burning of fossil fuels and the change in land use (IPCC, 2014). Given this situation, the development of strategies to reduce the concentration of atmospheric CO_2 is a consensus. Forests are essential mitigators with a stock potential of 2-4 $PgCO_{2e}$ from the atmosphere (Qureshi et al., 2012), because they are able to store carbon as part of their biomass (Zhang et al., 2019).

Forests located in the tropics are in constant focus due to their high volumetric productivity and rapid growth (Achard et al., 2008). Therefore, accurate estimates of biomass production are needed to reduce uncertainties in the carbon stock potentials in those areas (Djomo et al., 2011). Estimates of volume, biomass, and carbon stock may have discrepancies associated with limitations in measuring parameters (Baccini et al., 2012). Therefore, reducing eventual errors generated in the quantification is a significant step in obtaining reliable data (Stovall et al., 2017).

Producing precise and accurate biomass forecasts is challenging for several reasons. First, an impartial forest inventory project is required, with reliable measurements of trees' attributes; further, requires biomass estimation models to accurately represent forest inventory data (Dutcâ et al., 2020). The methodologies usually used are defined as destructive, when trees inside a plot or trees previous selected from diametric classes are harvested and measured (Singh et al., 2011); and non-destructive, when is not necessary to cut trees (López-López et al., 2017). Non-destructive methodologies for estimating biomass are faster, cheaper, and avoid environmental problems resulting from tree felling (Mòntes, 2009).

Studies on forest biomass are carried out for different purposes, including knowing its energy potential, quantifying nutrient cycling (Silveira et al., 2008), monitoring tree growth (Zhao et al., 2018), and carbon stock potential (Chieppa et al., 2020). Destructive sampling, at the highest cost, is limited by capital, labor, logistics and bureaucracy, in the case of native forests.. Samples can be underrepresented in areas of complex topography and unfavorable climatic conditions (Picard et al., 2012). Therefore, testing the accuracy of a faster, cheaper and simpler methodology for estimating biomass and carbon accumulation in forests becomes important.

Thus, this study aimed to compare the use of destructive and non-destructive methodologies for estimating biomass and carbon stock in a forest with a hybrid of *Eucalyptus urophylla* x *Eucalyptus grandis*. The hypothesis that motivated this study was the possibility of differences between the non-destructive methodologies concerning the destructive ones in the estimation of biomass and carbon.

2. MATERIAL AND METHODS

2.1. Characterization of the study site

The study was conducted on a charcoal-producing rural property in Lamim, Minas Gerais (20°47'08.56" S and 43°26'37.78" O), in the Zona da Mata (Figure 1). The tree component is a hybrid of *Eucalyptus grandis* x *Eucalyptus urophylla*, planted at a spacing of 3.0 m x 2.0 m. The plantation was 5 years old in the forest inventory and the silvicultural operations performed in the area were fertilizing and ant's control. According to the Köppen's classification, the climate of the region is Cwa, that is, subtropical with dry winter and hot and rainy summer. Precipitation occurs mainly between October and March, with averages of 1,435 mm per year. June and July present the lowest temperatures (12ºC), and January the highest temperatures (25ºC) (Sá Junior et al., 2012).

2.2. Forest inventory and methodologies for estimating biomass and carbon stock

The forest inventory used simple random sampling, with 27 georeferenced plots of 300 m^2 (20 x 15 m). All trees had the circumference at 1.30 m above the ground (*cap*) measured, converted to the diameter at 1.30 m above the ground (*dbh*), and separated into seven diametric classes with an amplitude of 2.5 cm. Three sample trees (chosen outside the sample units) were selected by diametric class, to perform the rigorous scaling through the destructive and non-destructive methods. A total of 21 trees were selected for strict scaling and used in the evaluated methodologies.

2.2.1. Methodology 1 - Destructive by Weighing - control

Methodology 1 was considered a control to compare with other methodologies, as it is the most accurate (Chave et al., 2014). The sample trees were felled, and their stem was cut and weighed in the field. It is important to mention that the branches were not used. Wooden discs of 2.5 cm thickness at 0% (base), 25%, 50%, 75%, and 100% of tree's commercial height, were removed and weighed immediately. The same samples were placed in a forced circulation oven with controlled temperature (100ºC for stem, and 40ºC for leaves) at the Madeira Panel and Energy Laboratory (LAPEM UFV) and weighed until dry weight stabilization.

Figure 1 – Rural property in Lamim, MG, where the forest inventory was conducted to estimate volume, biomass, and carbon.
Figura 1 – *Propriedade rural em Lamim, MG, onde foi realizado o inventário florestal para estimativa de volume, biomassa e carbono.*

The proportionality method was used to calculate the total dry biomass in the field, by section of the tree, after harvest, according to the following equation:

$$W(f) = WW(f)*DW(s) / WW(s) \qquad \text{Eq,1}$$

Where: DW(f) = Field dry weight, in g; WW (f) = Field wet weight, in g; DW (s) = Sample dry weight, in g; WW (s) = Sample wet weight, in g.

Stem carbon stock was calculated using the 0.47 factor recommended for tropical forests (IPCC, 2006).

2.2.2. Methodology 2 - Destructive with scaling

Sample trees were felled, and their diameters with bark were measured at heights of 0 m, 0.30 m, 0.70 m, 1.00 m, and 1.30 m, using a tape measure. From this height on, measurements were taken every 1.00 meter until the minimum commercial diameter of 3 cm. The volume in each of the sections was calculated using Smalian's formula (Eq. 2).

$$Vb = (SA_1 + SA_2) /2 * L \qquad \text{Eq.2}$$

Where: Vcc – Volume with bark, in m^3; SA_1 – Sectional area of the stem lower part, in m^2; SA_2 – Sectional area of the upper stem, in m^2; L – Stem section length, in m.

At 0% (base), 25%, 50%, 75%, and 100% of tree's commercial height, wooden discs of 2.5 cm thickness were removed. Their opposite wedges were used to determine the basic wood density according to ABNT NBR 11941 (ABNT, 2003). The average value of the basic wood density of the opposite wedges was used to estimate each wooden disc biomass. The biomass of the stem was obtained by multiplying its volume with bark by the average basic wood density; carbon stock was calculated using the 0.47 factor, recommended for tree species (IPCC, 2006).

2.2.3. Methodology 3 - Non-destructive with a Wheeler Pentaprism Caliper

Sample trees (still standing) had their diameters with bark at heights of 0 m, 0.30 m, 0.70 m, 1.00 m, and 1.30 m measured. From this height on, measurements were taken every 1.00 meter using a Wheeler® Pentaprism caliper until the minimum commercial diameter of 6.5 cm. The volume in each of the sections was calculated using Smalian's formula.

$$Vb = (SA_1 + SA_2) / 2 * L \qquad \text{Eq.3}$$

Where: Vb – Volume with bark, in m^3; SA_1 – Sectional area of the stem lower part, in m^2; SA_2 – Sectional area of the upper stem, in m^2; L – Stem section length, in m.

The volume of the stem tip (stem portion above the minimum commercial diameter of 6.5 cm) was calculated using the formula for the volume of a cone.

$$Vcone = (SA_1 * L) / 3 \qquad \text{Eq.4}$$

Where: Vcone – Cone volume, in m^3; SA_1 – Sectional area of the stem lower part, in m^2; L – Stem section length, in m.

The volumes obtained using equations 3 and 4 were summed up to obtain the stem's total volume. A wood sample was taken from each sampled tree using a manual auger at 1.30 m above the ground (*dbh*) to determine the basic wood density according to ABNT NBR 11941 (ABNT, 2003). The biomass of the stem was obtained by multiplying the volume with bark by the basic wood density of each individual. The calculated stem biomass was converted into carbon stock by multiplying by 0.47 (IPCC, 2006).

2.3. Data Statistical Analysis

The results were interpreted with the analysis of variance (ANOVA) to compare the carbon stock between methodologies 1, 2 and 3. In case of statistical difference in carbon stock, the Test F would be applied for methodologies 2 and 3 in relation to methodology 1, separately. If significant differences were detected in carbon stock, the values would be compared by the Test T for paired samples, at 95% probability. A residual analysis was performed to compare the means estimated values for carbon stock per diameter classes obtained using Methodologies 2 and 3 with the ones obtained in Methodology 1 (control).

Kolmogorov-Smirnov test was used to compare the statistical significance between the carbon stock obtained using methodology 1 (control) with the others, per diametric classes, at 95% probability.

$$D_{cal} = Max\ (F_0\ (x) - F_e\ (x)) \qquad \text{Eq.5}$$

Where: Dcal - value for 5% significance obtained; F_0 (x) = cumulative frequency observed; F_e (x) = expected cumulative frequency.

D_{cal} value for 5% significance was obtained according to equation 6. If $D_{cal} < D_{tab}$: H_o is accepted (observed distribution equal to projected); if $D_{cal} \geq D_{tab}$: Ho is rejected (observed distribution is not equal to the projected distribution).

$$D_{tab} = 1.35 / \sqrt{n} \qquad \text{Eq.6}$$

Where: D_{tab} = critical value at 5% significance and "n" is the number of observations.

All statistical analyzes were performed using the R software (R CORE TEAM, 2021).

2.4. Model Identity

An equation based on Schumacher and Hall (1933) model was adjusted for each one of the tested methodologies to estimate carbon stock using diameter at breast height (*dbh*) and commercial height (Ht) from the sampled trees.

$$C = \beta_0 * dbh^{\beta 1} * Ht^{\beta 2} \qquad \text{Eq.7}$$

Where: C – carbon stock, in Mg; βn – model parameters; dbh – diameter with bark measured at 1.30 m from the ground, in cm; Ht – commercial height of the sample trees, in m.

The verification of the model adequacy was carried out based on the analysis of the adjusted determination coefficient (R^2_{adj}), Bias (%), and RMSE (%).

A model identity test (Graybill, 1976) was used to group the carbon stock estimation models, in relation to the control, to a significance of 5%. The

Table 1 – Values of volume (Vol, in m³), wood density with standard deviation as a function of the samples taken along the shaft (Dens, in g cm^{3-1}), and carbon stock (Carb, MgC) for the 21 sample trees evaluated using the methodologies 1 (Destructive with weighing - control), 2 (Destructive with scaling) and 3 (Non-destructive with Pentaprism).
Tabela 1 *– Valores de volume (Vol, em m³), densidade da madeira com desvio padrão em função das amostras tomadas ao longo do fuste (Dens, em g cm^{3-1}) e estoque de carbono (Carb, MgC) para as 21 árvores amostras avaliadas pelas metodologias 1 (Destrutivo com pesagem - controle), 2 (Destrutivo com cubagem) e 3 (Não destrutiva com Pentaprisma).*

Sample	Methodology 1	Methodology 2			Methodology 3		
	Carb	Vol	Dens	Carb	Vol	Dens dap	Carb
A1	0.0031	0.0163	0.4412	0.0034	0.0110	0.4480	0.0023
A2	0.0031	0.0166	0.4469	0.0035	0.0118	0.4418	0.0024
A3	0.0036	0.0180	0.4453	0.0038	0.0112	0.4452	0.0024
A4	0.0115	0.0492	0.4354	0.0101	0.0213	0.4314	0.0043
A5	0.0109	0.0451	0.4384	0.0093	0.0217	0.4389	0.0045
A6	0.0137	0.0671	0.4470	0.0141	0.0306	0.4347	0.0062
A7	0.0212	0.1121	0.4355	0.0229	0.0998	0.4350	0.0204
A8	0.0225	0.0898	0.4334	0.0183	0.0650	0.4265	0.0130
A9	0.0237	0.1229	0.4415	0.0255	0.1061	0.4520	0.0225
A10	0.0479	0.2480	0.4487	0.0523	0.1925	0.4564	0.0413
A11	0.0495	0.2516	0.4387	0.0519	0.2158	0.4307	0.0437
A12	0.0494	0.2552	0.4411	0.0529	0.2294	0.4327	0.0467
A13	0.0541	0.2826	0.4392	0.0583	0.2471	0.4412	0.0512
A14	0.0591	0.3058	0.4364	0.0627	0.3143	0.4384	0.0648
A15	0.0596	0.3128	0.4414	0.0649	0.3187	0.4507	0.0675
A16	0.0781	0.4126	0.4364	0.0846	0.3737	0.4325	0.0760
A17	0.0727	0.3824	0.4331	0.0779	0.3626	0.4479	0.0763
A18	0.0749	0.3975	0.4341	0.0811	0.3986	0.4376	0.0820
A19	0.1027	0.5466	0.4358	0.1119	0.5287	0.4408	0.1095
A20	0.0753	0.4091	0.4353	0.0837	0.3757	0.4354	0.0769
A21	0.0835	0.4544	0.4429	0.0946	0.4369	0.4398	0.0903
Average ±	0.0438	0.2284	0.4394	0.0470	0.2082	0.4399	0.0431
Stand Dev	0.0308	0.1671	0.0047	0.0343	0.1668	0.0078	0.0345

test consists of reducing the sum of squares, allowing to statistically verify, by the Test F, the significance of the difference between the total sums of squares of the regressions adjusted for each methodology alone (complete model) and the sum of the squares of the regression adjusted for the total data set (reduced model). The verification of the identity of models in the forest area becomes a useful tool in modeling analysis, in an attempt to reduce the number of equations without loss of precision in the estimates, in addition to reducing sampling costs and economy of operations in use cases of a common equation.

The tested hypotheses were:

-H_0: the reduced model adjusted for the total data set obtained using methodologies 2 and 3 in relation to the control (methodology 1) does not statistically differ from the adjusted complete models.

-H_1: H_0 is rejected.

These analyses were performed using the Microsoft Excel.

3. RESULTS

The average carbon stock obtained using methodology 1 was 0.0438 ± 0.0308 MgC, a value similar to those found using methodologies 2 (0.0470 ± 0.0343 MgC) and 3 (0.0431 ± 0.0345 MgC) (Table 1).

The comparison using ANOVA between methodologies 2 (Value F – 0.102 < Value P – 0.751) and 3 (Value F – 0.006 < Value P – 0.941) with the control (Methodology 1), showed no significant difference between the carbon stock data.

The residual analysis plots showed methodology 2 performed better than methodology 3, with a steady trend around the identity line (Figure 2). Methodology 3 had an overestimation of data in the two lower-class centers (6.25 and 8.75 cm).

Kolmogorov-Smirnov test's evaluation resulted in a non-statistical difference between the carbon stock by diametric class for the methodologies 2 (Dcalc – 0.010 < Dtab – 1.407) and 3 (Dcalc – 0.023 < Dtab – 1.407) in relation to the control – Methodology 1.

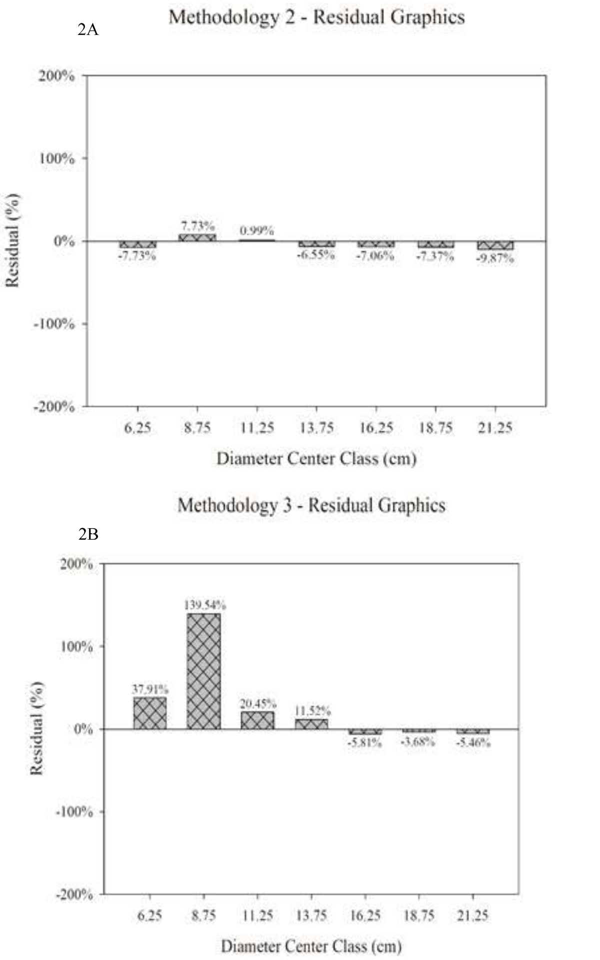

Figure 2 – Residual analysis plots for methodology 2 (2A) and 3 (2B).
Figura 2 – *Gráficos de análise de resíduos para as metodologias 2 (2A) e 3 (2B).*

The adjustment of the equations to estimate the carbon stock using data of each one of the tested methodologies was considered adequate, with satisfactory R^2_{adj}, RMSE (%), and Bias (%) values (Table 2).

The model identity test showed the same behavior for the combination of Methodologies 2 and 3, that is, a single equation can be used to estimate biomass and carbon stock.

4. DISCUSSIONS

The quantification of biomass accumulation is an essential step to understand the carbon dynamics in forests and their ecosystem services (Houghton et al., 2009), as it is a relevant component of carbon stocks and assessment of climate changes potential mitigation (Huy et al., 2016). Thus, reliable biomass estimations are essential to monitor forest conditions and support decision-making under forest management (Ubuy et al., 2018).

The generation of reliable data on the carbon stock potential of forests is relevant in the current political momentum, in which the Paris Agreement is already in force, and some countries that have ratified it, such as Brazil, have emission reduction targets in the forestry sector (Azevedo-Ramos et al., 2020). The Brazilian government estimates that by the year 2030, the area of commercial forests will be increased by 3 million hectares, with varied stock potential, which highlights the importance of validation of biomass and carbon estimation methodologies (Brasil, 2015).

The equivalence between the results of the tested methodologies with the control one is evidenced by the low difference between the carbon stock numbers presented in the results. This fact can be explained by the number of sections measured in the rigorous scaling, which contributes to a reduction in the estimation error, due the increase in the control of the tree taper (Tonini et al., 2019). The use of a Wheeler's Pentaprism (methodology 3) also allowed the generation of reliable results for carbon stock estimation. The use of this device is recommended for scaling Eucalyptus trees up to 50 m height, with

Table 2 – Parameters and adjustment of models to estimate carbon stock.
Tabela 2 – *Parâmetros e ajuste de modelos para estimar o estoque de carbono.*

Methodology	β_0	β_1	β_2	R^2_{adj} (%)	Bias (%)	RMSE (%)
1	0.0000280	1.368	1.195	99.25	-0.084	5.932
2	0.0000187	1.458	1.264	99.60	-0.082	4.499
3	0.0000017	1.493	1.942	99.06	1.228	7.590
1x2	0.0000228	1.415	1.23	98.89	-7.790	7.379
1x3	0.0000079	1.431	1.53	98.25	-4.659	9.729

a good precision in the generated estimations (Avery and Burkhart, 1997). However, tree size can affect the results obtained with the Pentaprism due to the difficulty in collecting the diameter of the section in the correct position. Another important factor to be mentioned is the importance of operator training to maintain the estimates accuracy.

The residuals values found in the lowest diameter classes for methodology 3 (37.91% and 139.54%, respectively for the 6.25 cm and 8.75 cm classes), despite having great magnitude, does not negatively impact carbon stock estimation because these values represent classes with less biomass accumulation. In a diametric distribution for a eucalyptus plantation, most individuals are concentrated in the middle-center diameter classes. Therefore, the impact of residuals values in the population's carbon stock estimation is not so important because it affects a smaller number of trees (Nogueira et al., 2005).

The destructive method has some negative points when compared to indirect methodologies. The time required to carry out fieldwork is longer than in indirect methods (Flombaum and Sala, 2007). Destructive methodologies are also limited to smaller areas with a small number of trees to be felled (Lu et al., 2014). Sampling errors can also be a problem in direct methodologies, with trees selected wrongly (Brown et al., 1989), which would lead to tendency errors and subsequent overestimation or underestimation of biomass accumulation (Ribeiro et al., 2009).

For Eucalyptus forests, the pentaprism proved to be a reliable tool for carbon stock estimation, with no observed statistical difference for estimates for population or diameter classes. The search for non-destructive methodologies that reliably estimate the accumulation of biomass and carbon stock is the focus of the researchers due to faster service execution and lower cost of data collection (Huff et al., 2018; Kramer et al., 2018) and, despite the possible uncertainties surrounding them, the need for data from direct methodologies demonstrates the importance of these methods in research related to the topic.

5. CONCLUSIONS

There are no differences, according to the data, in the biomass and carbon stock estimation between destructive and non-destructive methodologies in an Eucalyptus forest.

The non-destructive methodology and the destructive one with rigorous scaling is effective, with statistically similar results to the reference methodology, which reduces time and cost in estimating biomass and carbon in eucalyptus forests without compromising the result.

AUTHOR CONTRIBUTIONS

B. L. S. Schettini: data analysis and text writen, L. A. G. Jacovine: research superfi sion and text review, C. M. M. E. Torres: conception and data analysis, A. C. O. Carneiro: technical review, R. V. O. Castro: data analysis and technical review, P. H. Villanova: text review, S. J. S. S. Rocha: text review and data analysis, M. P. M. X. Rufino: text review, S. N. Oliveira Neto: text review, V. T. M. M. Júnior: text review.

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