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Estimating biomass and carbon stock in orange trees (*Citrus sinensis* L. Osbeck) of the São Paulo and southwestern Minas Gerais citrus belt, Brazil

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Abstract

The living biomass and carbon stock of *Citrus sinensis* (L. Osbeck) orchards from the citrus belt in the states of São Paulo and southwestern Minas Gerais, Brazil, is receiving increasing attention due to its role in the carbon balance of citrus production and in climate change mitigation. Orange trees were analyzed to develop allometric equations to estimate the carbon stock of living biomass at citrus orchards in Brazilian citrus belt. Above- and belowground living biomass and biometric variables were measured directly for 80 harvested orange trees, considering the Pera and Valencia orange varieties and four age classes (3–5, 6–10, 11–15, >15-year old). Considering the 80 orange trees evaluated by direct method, the biomass ranged between 22 and 224 kg tree^{-1}, with the branches (54%) being the main compartment, followed by the roots (28%), leaves (10%), and trunk (8%). Allometric equations were developed using stepwise backward regression analysis. For carbon stock estimation, the allometric equation was applied in a sample of 1321 orange trees distributed inside the citrus belt studied. This sample represents the 162 million orange trees that are more than 3 years old in 337,091 ha, and has stocked more than 8.4 million Mg C in the living biomass. We show for the first time that orange tree biomass can be estimated by allometric equations and that these equations can be used to estimate the biomass of orange trees, and can be recommended for carbon biomass inventories for similar regions, orchards, tree size ranges, and site characteristics.

Abbreviations: BAPB, basal area of the primary branches; BASB, basal area of the secondary branches; BAT, basal area of the trunk; BB, branch biomass; CD, canopy diameter; CV, canopy volume; LB, leaf biomass; OTB, orange tree biomass; OTC, orange tree carbon; PBD, primary branch diameter; RB, root biomass; SBD, secondary branch diameter; TB, trunk biomass; TD, trunk diameter; TH, total height.

Plain Language Summary

In Brazil, the agricultural sector responsible for producing oranges has been developing strategies to adapt to and mitigate the effects of climate change. Estimating how much carbon (C) an orange orchard stores in its living biomass has become increasingly important to reduce greenhouse gas (GHG) emissions. Using biometric measurements and biomass data from orange trees in orange orchards, we estimated that 8.4 million Mg of C are stored in around 162 million orange trees within the world's largest orange juice production region. On average, an orange tree contains 52 kg of C. The average amount of C stored in 1 ha of orange orchards is 25 Mg. One orange tree can fix approximately 4.28 kg of C per year on average, and 1 ha of orange orchards can store 2.04 Mg of C per year. Equations developed to estimate orange tree biomass and gross C sequestration can help companies and farmers in the orange production sector account for C stocks and GHG emission balance.

1 | INTRODUCTION

The potential negative impacts of global warming on human health and well-being, water availability, food production, biodiversity, ecosystems, and the global economy, among others, have mobilized society to identify possible alternatives for reducing greenhouse gas (GHG) emissions and increasing atmospheric carbon sequestration (Forest Trends' Ecosystem Marketplace, 2022; IPCC—Intergovernmental Panel on Climate Change, 2023b; The World Bank, 2022). Agriculture can be one of these possible alternatives, but in Brazil, the national GHG inventory estimates that agriculture emitted 21.8% of GHGs in 1990 and 28.5% in 2020 (MCTI—Ministério da Ciência, Tecnologia e Inovações, 2022). Given the growing trend in GHG emissions from the agricultural sector, some Brazilian agribusiness chains, such as citrus, have sought to reduce GHG emissions and store more carbon in plant biomass and soil. This will certainly help mitigate the potential negative effects of global warming.

The only study on the carbon stock in the biomass of orange trees carried out in Brazil (Ronquim, 2007), with a sample of 20 plants evaluated, showed values of 12.8 and 47.3 Mg C ha^{-1} for 7- and 18-year-old orchards, respectively, with a density of 340 trees ha^{-1}. Studying the carbon sequestration potential of tree plantations in Ghana using the allometric equation of Schroth et al. (2002), Kongsager et al. (2013) presented a value of 76 Mg C ha^{-1} for orange orchards that were 25 years old with a density of 267 trees ha^{-1}. For the estimates of GHGs for the National Inventory (MCTI—Ministério da Ciência, Tecnologia e Inovações, 2022) and the Inventory of the State of São Paulo (São Paulo, 2019), the reference value of 21 Mg C ha^{-1} (IPCC—Intergovernmental Panel on Climate Change, 2003a) was used for areas with perennial agriculture, which is the case for citrus production areas, regardless of the age of the citrus plantations. These data are an example of the heterogeneity of information on carbon stock in orange orchards.

Due to the lack of accurate information on carbon stocks in above- and belowground living biomass in orange orchards in Brazil, it is of particular interest to the Brazilian citrus production chain to develop an understanding of the capacity of these trees to absorb atmospheric carbon dioxide (CO_2), thus strengthening their role as carbon sinks. The estimation of carbon stocks in citrus orchards requires the application of methods to accurately estimate tree biomass at different ages and in different varieties. In addition to being necessary for estimating carbon stocks in citrus orchards, orange tree biomass (OTB) is an important characteristic of production systems, as it reflects soil organic carbon accumulation, fruit production, and net primary productivity (NPP) (Escanhoela et al., 2019; Iglesias et al., 2013; Morgan et al., 2006; Quiñones et al., 2013). In a study of the carbon balance of orange orchards in Spain, Iglesias et al. (2013) presented net C fixation values of approximately 10 Mg C ha^{-1} year^{-1}, indicating the great capacity of orchards to fix CO_2 from the atmosphere and contribute to climate change mitigation.

There are indirect methods for estimating tree biomass, such as allometric equations, which are an essential tool for calculating and understanding carbon stock in forests and perennial crops (IPCC—Intergovernmental Panel on Climate Change, 2003a). Allometric equations or allometric models use a combination of predictor variables such as trunk diameter (TD), basal area of the trunk (BAT), total height (TH), wood density, and canopy volume (CV) (Brown, 1997; Chave et al., 2005, 2014; Cole & Ewel, 2006; Kuyah et al., 2012; Overman et al., 1994; Quiñones et al., 2013; Saldarriaga et al., 1988). Specifically, for orange trees, Quiñones et al. (2013) established allometric equations to estimate the annual NPP of orange trees in Spain at different ages based on the relationship between NPP and biometric variables (TD, trunk basal area, CV, and leaf area index) and were thus able to measure the annual increase in C content in plant biomass. However, to obtain an allometric equation, it is necessary to carry out direct or destructive sampling of a set of plants that can represent the target population of the estimate.

According to the "Inventory of trees in the citrus belt of São Paulo and Triangle/Southwest Mineiro: portrait of orchards in March 2023" (Fundecitrus et al., 2023), the orchards of the main orange varieties in this region cover an area of 387,633 ha. Of these orchards, the Pera and Valencia varieties account for 37% and 26% of the total number of trees, or 74.8 and 53.1 million trees, respectively. To determine the amount of carbon that is sequestered in orange trees for this large area of the citrus belt, it is necessary to arrive at an allometric equation that can be used to estimate the biomass and carbon stock of orange trees representative of this important citrus belt. In this context, the objective of this work was to define allometric equations that can be used to estimate the biomass and carbon stock of orange trees in the citrus belt of São Paulo and triangle/southwest Minas Gerais, as well as to support the estimation of carbon stocks of above- and belowground living biomass in potential carbon projects involving citrus.

2 | MATERIALS AND METHODS

2.1 | Study area and allometric equations development for OTB estimation

For the allometric equation development, the study was carried out in three citrus farms located in the municipalities of Espírito Santo do Turvo, Iaras, and Santa Cruz do Rio Pardo, in the central-southwestern region of the citrus belt of São Paulo and Minas Gerais, Brazil (Figure 1). According to the Köeppen classification, the climate in these municipalities is humid subtropical with hot summers (Cfa) (Alvares et al., 2013). The average annual rainfall is approximately 1300 mm, with the rainy season lasting from October to March. The average annual temperature is approximately 21˚C, with a minimum in July and a maximum in February. In the area of the farms, the local vegetation varies between savannah and seasonal semideciduous forest (IBGE—Instituto Brasileiro de Geografia e Estatística, 2018), and Latosols, Argissols, and Nitosols are the main soil classes (Rossi, 2017).

The findings enhance the readability and comprehension of the article, before showing the methodological procedures, and Table 1 lists some variables studied.

For the direct measurement of OTB, eight plots were selected from commercial orange orchards, one of which was irrigated. In each plot, 10 trees were evaluated. In total, 80 trees were evaluated by direct method, including the Pera ($n = 40$) and Valencia ($n = 40$) varieties, with four age classes, 3–5 ($n = 20$), 6–10 ($n = 20$), 11–15 ($n = 20$), and >15-year old ($n = 20$). Importantly, these two varieties of *Citrus sinensis* were selected because they represent approximately 63% of the orange trees in the citrus belt of southeastern Brazil (Fundecitrus et al., 2023). Here, we can highlight that the present study did not evaluate the annual leaf and pruner deposition to analyze the carbon deposition or turnover.

Core Ideas

- The biomass of orange trees can be estimated by allometric equations using biometric variables.
- These equations can be a useful tool to calculate the carbon stock potential in citrus orchards.
- In the Brazilian citrus belt, approximately 8.4 million Mg C is stored in the biomass of orange trees.
- This corresponds to 25 Mg C ha^{-1} per citrus orchard and 52 kg carbon per orange tree.
- Annually, an orange tree can fix 4.28 kg of carbon, and citrus orchards can store 2.04 Mg C ha^{-1}.

The following biometric variables were measured on the 80 orange trees evaluated: TH, canopy diameter (CD) at the planting line, and CD perpendicular to the planting line in meters and TD at 10 cm height, primary branch diameter (PBD), and secondary branch diameter (SBD) in centimeters. From the measurements of TD, PBD, and SBD, the basal area (BA) in cm^2 of these three evaluated variables was calculated using Equation (1):

$$\mathrm{BA} = \pi r^2 \tag{1}$$

The BA of primary branches and the BA of secondary branches are the sum of the BA of all the primary branches and all the secondary branches, respectively.

From the mean CD in meters given by Equation (2) and the TH, the CV in m^3 was calculated by Equation (3).

$$\mathrm{MCD} = \frac{\mathrm{CDpl} + \mathrm{CDppl}}{2} \tag{2}$$

where MCD is the mean CD; CDpl is the CD at the planting line; and CDppl is the CD perpendicular to the planting line.

$$\mathrm{CV} = \frac{2}{3}\pi r^2 \mathrm{TH} \tag{3}$$

where CV is the canopy volume, r is the MCD/2, and TH is the total height.

After measuring and calculating the variables, each tree was cut with a chainsaw, and the tree biomass was quantified by the direct method (Figure 2). To determine the weight of the biomass of each tree, four compartments were considered:

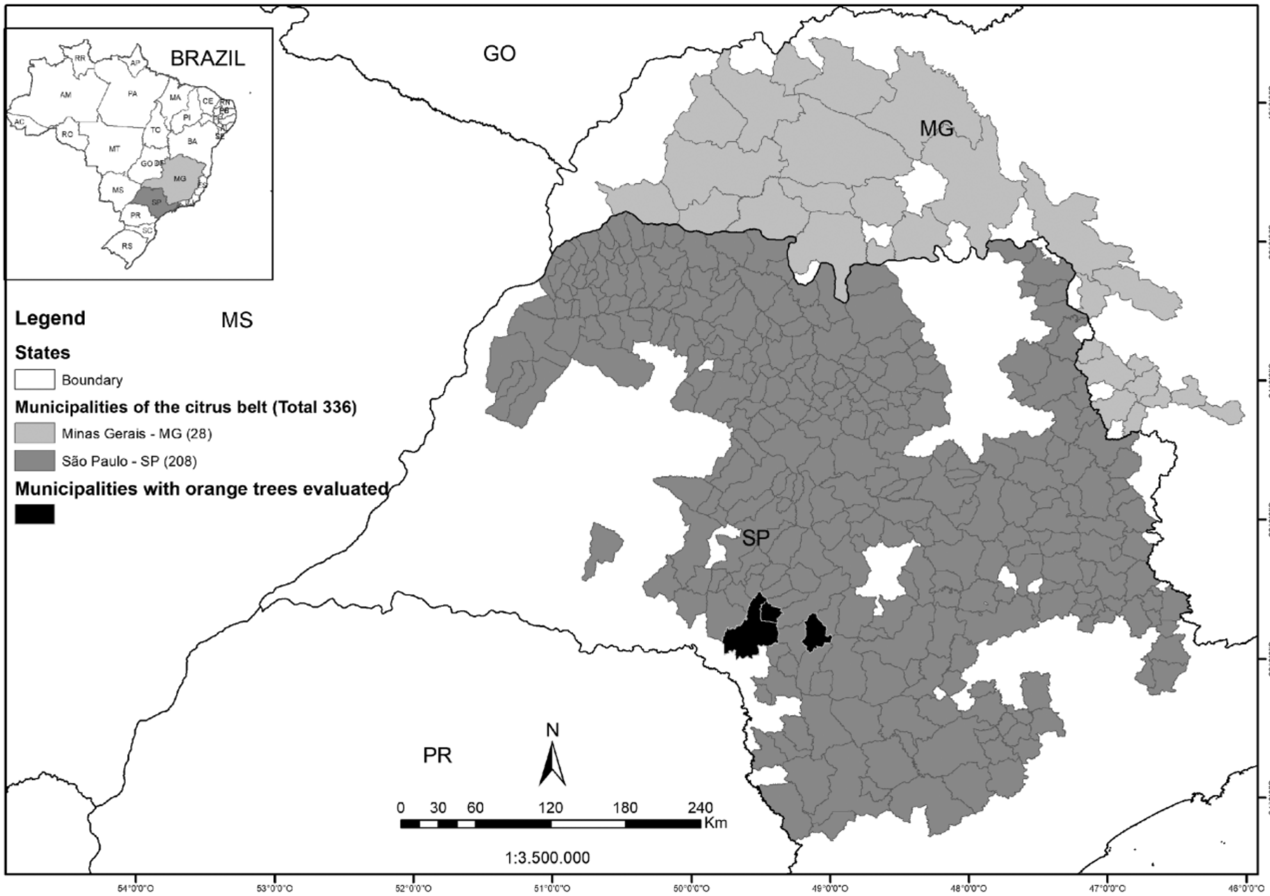

FIGURE 1 Location of the municipalities of the citrus belt of São Paulo and Minas Gerais and location of the municipalities (Espirito Santo do Turvo, Iaras, and Santa Cruz do Rio Pardo) with orange trees (*Citrus sinensis* L. Osbeck) that were evaluated.

(1) leaves; (2) branches, that is, the biomass between the trunk and the leaves; (3) trunk, that is, the biomass between the base of the trunk (close to the ground) and the beginning of the primary branches; and (4) roots, that is, the biomass between the base of the trunk and roots greater than 1.0 cm in diameter. Roots were dug up and removed manually using a chain hoist. The fresh biomass of the compartments of each tree was determined in the field using a balance with a capacity of 40 kg and an accuracy of 2 g. To determine the dry weight of each tree, we first determined the moisture content of each compartment by taking 0.5 to 1 kg (fresh weight) of leaves, branches, trunk, and roots.

In the laboratory, fresh samples of leaves, branches, trunks, and roots were dried in an oven at 70°C to a constant weight and then weighed. The dry biomass of each tree compartment was calculated from the fresh and dry weights of the samples. The total dry biomass of each tree (OTB) is the sum of the dry biomass of leaves, branches, trunk, and roots. The carbon content (%) by variety, age class, and compartment was determined by Nogueira et al. (2023) (Table 2).

For the allometric equation development, the dependent variables were OTB, leaf biomass (LB), branch biomass (BB), trunk biomass (TB), and root biomass (RB) in kilograms. The independent variables were TH, CV, TD, BAT, basal area of the primary branches (BAPB), and basal area of the secondary branches (BASB). The data of the dependent and independent variables of the 80 trees evaluated were subjected to the Shapiro–Wilk normality test. Data from the dependent variables (OTB, LB, BB, TB, and RB) were subjected to multiple regression analyses with stepwise backward selection to calculate the relative contributions of the independent variables (TH, CV, TD, BAT, BAPB, and BASB). The regression analysis was carried out in two steps. In the first step, the dependent variables were related to all the independent variables. In the second step, the resulting models were simplified by the program by removing all variables with a p value greater than 0.05 at each step. This allowed the identification of the independent variables that best explained the dependent variables, expressed by allometric equations.

2.2 | Proceedings for estimative of OTB and carbon stock in the São Paulo and southwestern Minas Gerais citrus belt

For the estimation of OTB and orange tree carbon (OTC) in the citrus belt, we evaluated the biometric variables (TH, TD, BAT, and BASB) of 1321 orange trees distributed inside the

TABLE 1 Variables studied and their acronyms and units.

Variables	Acronyms	Units
Age	–	years
Basal area of the primary branches	BAPB	cm^2
Basal area of the secondary branches	BASB	cm^2
Basal area of the trunk	BAT	cm^2
Branch biomass	BB	kg
Branch carbon	BC	kg
Canopy diameter	CD	m
Canopy volume	CV	m^3
Leaf biomass	LB	kg
Leaf carbon	LC	kg
Orange tree biomass	OTB	kg
Orange tree carbon	OTC	kg
Primary branch diameter	PBD	cm
Root biomass	RB	kg
Root carbon	RC	kg
Secondary branch diameter	SBD	cm
Total height	TH	m
Trunk biomass	TB	kg
Trunk carbon	TC	kg
Trunk diameter	TD	cm

citrus belt. This sample representing 162.013 million of different orange trees (Brazilian common name: Pera Rio, Valência, Hamlin, Natal, Valência Americana, Valência Folha Murcha, Rubi, Westin, Pineapple, Alvorada, and Seleta) with more than 3 years old planted in 337,091 ha (Fundecitrus et al., 2023). The allometric equations selected for estimating OTB, LB, BB, TB, and RB were applied in this sample. For carbon stock estimation by orange tree and its compartment, we multiplied the carbon content (Table 2) by the estimated biomass of 1321 orange tree and its compartment. Finally, for carbon estimation in the citrus belt, the OTC of each 1321 orange trees sample was concatenated with the inventory of orange trees in the citrus belt (Fundecitrus et al., 2023) considering the varieties (Pera Rio, Valência, and others—Hamlin, Natal, Valência Americana, Valência Folha Murcha, Rubi, Westin, Pineapple, Alvorada, and Seleta) at four age classes (3–5, 6–10, 11–15, and >15-year old).

2.3 | Statistical analysis and data sharing

For the 80 orange trees evaluated, Pearson correlation analyses were performed between the measured biomass and the independent variables selected in the stepwise backward multiple regression analyses, and were also performed for measured biomass and biomass estimated by allometric equations. R software (Dowle & Srinivasan, 2023; R Core Team, 2022; Wickham, 2016, 2022) was used for statistical analyses (Shapiro–Wilk normality test, Pearson correlation, and regression analysis) and graph generation. The primary data and basic statistical analyses are available at http://paineis.cnpm.embrapa.br/carbcitrus_biomass/.

3 | RESULTS AND DISCUSSION

3.1 | Allometric equations for OTB estimation

The direct evaluation of the 80 OTB resulted in an average of 95 kg tree^{-1} (Table 3), ranging from 22 to 224 kg, without outliers (Figure 3). Similar values were found in the study on OTB in São Paulo state, Brazil (Ronquim, 2007), that presented values of biomass (leaves, branches, trunk, and roots) varying between 48.9 and 278.1 kg. These values show that orange trees have a high capacity to biomass accumulation.

The branches, which include all the biomass between the trunk and the leaves, were the compartment with the highest contribution to the OTB, with an average of 52 kg tree^{-1} (54%), followed by the roots with an average of 27 kg (28%), the leaves with 9 kg (10%), and finally the trunk with 7 kg (8%). Considering the aboveground (leaves, branches, and trunk) and belowground (roots) living biomass, these percentages per tree (72% and 28%, respectively) is similar to 74% and 26% showed by Ronquim (2007).

This information on the biomass per compartment can be important for the management of citrus orchards, especially in the planning of operations to manage the dead biomass generated by pruning, as well as operations to target biomass in the renewal of orchards (López-Cortés et al., 2022). Other relevant information is related to the participation of roots in the OTB, which indicates a great capacity to incorporate organic carbon into the soil through the death of fine roots, as well as through the deposition of senescent leaves and the pruning of the canopy.

The Valencia variety had an average biomass of 109 kg, while the Pera variety had an average biomass of 82 kg tree^{-1} (Figure 4). In terms of age, orange trees older than 15 years had an average biomass of 156 kg, orange trees between 11 and 15 years had an average biomass of 150 kg, orange trees between 6 and 10 years of age had an average biomass of 46 kg, and orange trees between 3 and 5 years had an average biomass of 30 kg.

One highlight emerged from the analysis of the OTB by variety and age class (Figure 4). The highlight is related to the average OTB (148 kg) of the 11- to 15-year-old trees of the Pera variety, which is higher than that of the >15-year-old trees of the same variety (117 kg). This is due to the irrigation of the plot, but it does not affect the biomass analyses; it only indicates that irrigation favors higher biomass stock.

TABLE 2 Carbon content (%) by varieties and age class used for carbon stock estimation in the citrus belt.

		Carbon content (%)				
Varieties	**Age classes (years)**	**Orange tree**	**Leaves**	**Branches**	**Trunk**	**Roots**
Pera Rio	3–5	46.97	43.48	47.77	47.14	47.77
Pera Rio	6–10	46.69	44.06	47.31	47.02	46.77
Pera Rio	11–15	47.22	43.29	47.54	47.94	47.40
Pera Rio	>15	47.14	44.64	47.28	47.57	47.42
Valência	3–5	46.38	42.37	47.31	47.99	46.79
Valência	6–10	46.87	42.90	47.50	47.80	47.33
Valência	11–15	47.41	43.53	47.25	47.51	48.56
Valência	>15	46.81	43.38	47.22	47.67	46.81
Others	3–5	46.66	42.93	47.54	47.56	47.28
Others	6–10	46.80	43.48	47.40	47.41	47.05
Others	11–15	47.32	43.41	47.39	47.72	47.98
Others	>15	46.93	44.01	47.25	47.62	47.11

Note: Others in Brazilian common name are the Hamlin, Natal, Valência Americana, Valência Folha Murcha, Rubi, Westin, Pineapple, Alvorada, and Seleta. For others, the values of carbon content are the mean of Pera Rio and Valência. Data adapted by Nogueira et al. (2023).

FIGURE 2 Some pictures that illustrate the direct method used to quantify the living biomass (leaves, branches, trunk, and roots) of the 80 orange trees (*C. sinensis*) studied.

TABLE 3 Descriptive statistics of 80 orange trees harvested for biomass equation development.

Variables (n = 80)	Units	Minimum	First quarter	Median	Mean	Third quarter	Maximum
Total height	m	2.14	2.77	3.26	3.52	4.29	5.10
Canopy volume	m^3	4.91	7.70	12.98	14.00	21.23	25.45
Trunk diameter	cm	7.32	10.24	13.69	14.30	18.55	23.52
Basal area of the trunk	cm^2	42.10	82.51	147.14	176.49	270.24	434.59
Basal area of the primary branches	cm^2	53.00	87.57	192.15	228.50	345.11	573.36
Basal area of the secondary branches	cm^2	61.20	94.49	181.85	223.13	337.89	526.11
Leaf biomass	kg	2.45	5.17	7.38	9.11	13.04	20.94
Branch biomass	kg	6.89	14.18	45.82	51.78	79.45	125.99
Trunk biomass	kg	1.34	2.58	5.43	7.49	11.67	22.28
Root biomass	kg	5.13	9.83	20.75	26.93	38.02	77.10
Orange tree biomass	kg	22.16	32.88	85.84	95.32	150.24	223.90

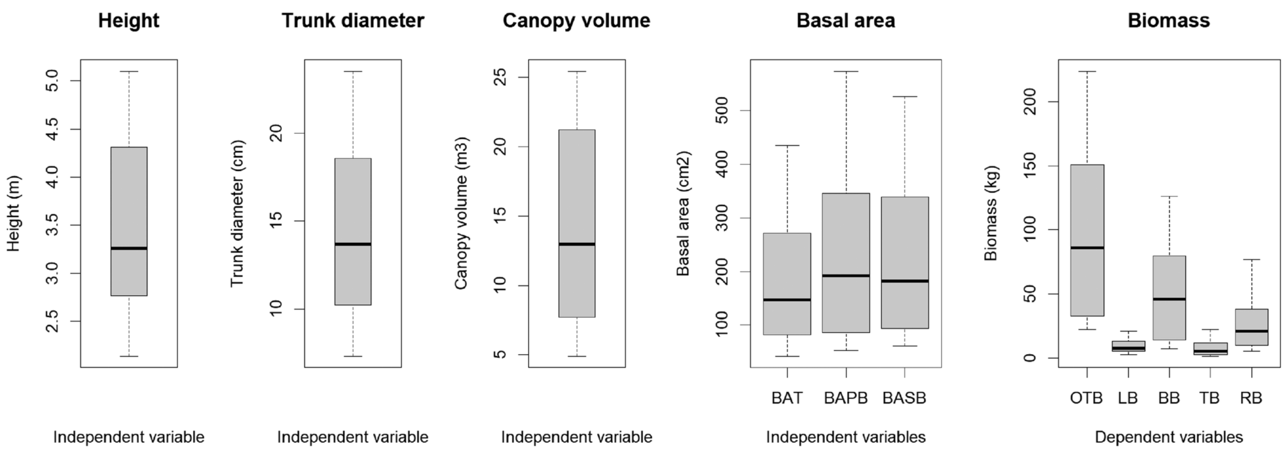

FIGURE 3 Boxplots of the variables analyzed for the 80 orange trees (*C. sinensis*) evaluated. BAPB, basal area of the primary branches; BASB, basal area of the secondary branches; BAT, basal area of the trunk; BB, branch biomass; LB, leaf biomass; OTB, orange tree biomass; RB, root biomass; TB, trunk biomass.

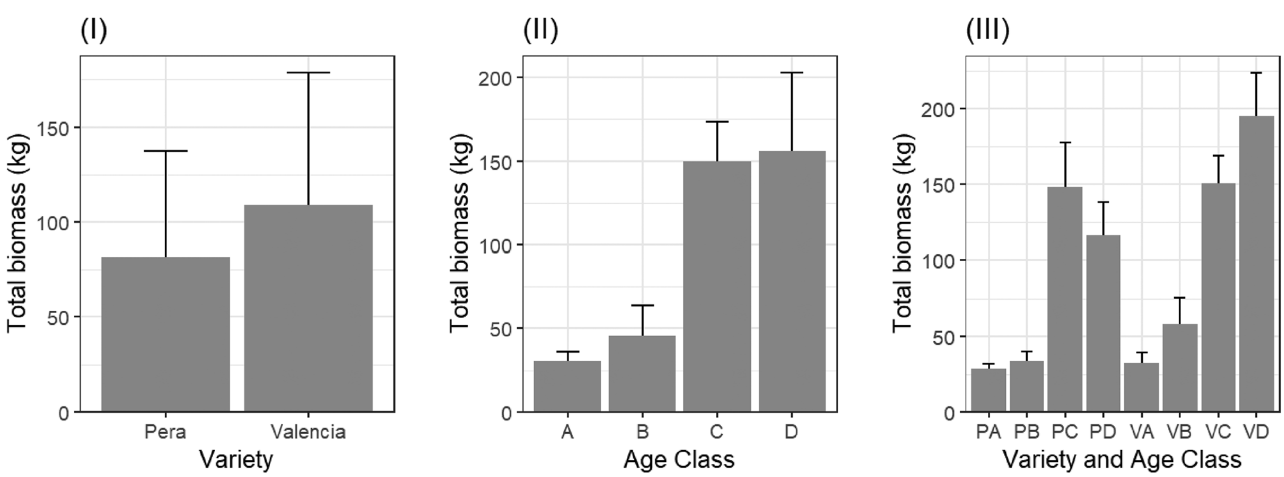

FIGURE 4 Bar graphs with the mean and standard deviations of the orange tree biomass (kg) by cultivar (I: Pera = P; Valencia = V), by age class (II: A = 3- to 5-year old; B = 6- to 10-year old; C = 11- to 15-year old; D = >15-year old), and by cultivar and age class (III) of the 80 orange trees (*C. sinensis*) evaluated. The plot with the sample of the Pera variety with 11- to 15-year old (PC) is irrigated.

TABLE 4 Parameters, allometric equation models, and results (r^2, adjusted r^2, and p) of multiple regression analyses (stepwise backward regressions) for the biomass estimation of orange trees (*C. sinensis*).

Parameters (kg)	Allometric equation models	r^2	r^2 adjusted	p
Orange tree biomass	OTB = −82.454 + 36.801 TH − 0.265 BAT + 0.425 BASB	0.918	0.915	<0.001
Leaf biomass	LB = −3.881 + 3.224 TH − 0.039 BAT + 0.038 BASB	0.740	0.730	<0.001
Branch biomass	BB = −45.328 + 15.892 TH + 0.184 BASB	0.951	0.950	<0.001
Trunk biomass	TB = −2.635 + 3.833 TH − 1.026 TD + 0.036 BAT + 0.021 BASB	0.850	0.842	<0.001
Root biomass	RB = −50.438 + 11.471 TH + 4.698 TD − 0.389 BAT + 0.172 BASB	0.769	0.757	<0.001

Abbreviations: BASB, basal area of secondary branches; BAT, basal area of the trunk; BB, branch biomass; LB, leaf biomass; OTB, orange tree biomass; RB, root biomass; TB, trunk biomass; TD, trunk diameter; TH, total height.

The data for the independent and dependent variables presented in the Table 3 showed a normal distribution and no outliers (http://paineis.cnpm.embrapa.br/carbcitrus_biomass/), which shows the quality of the sample set for the determination of the models of the allometric equations by means of stepwise backward linear regression. It is important to highlight some information about the variables in the sample set (Table 3; Figure 3). The amplitude between the minimum and maximum values highlights the high variability of the data for all the variables analyzed. In this way, stepwise backward linear regression was used to select the independent variables that best explained tree biomass, which allowed the establishment of allometric equations for estimating OTB (Table 4).

TH and BASB were the two independent variables selected in the regression analyses that appeared in all five allometric equations. BAT was selected in the regression analyses for OTB, LB, TB, and RB. TD was selected in the regression analyses for TB and RB. CV and BAPB did not appear in the allometric equations, that is, they were the independent variables that were eliminated in all the regression analyses. Regarding CV, our study differs from that of Quiñones et al. (2013), in which CV was the best independent variable for predicting aboveground and belowground biomass. This is due to the fact that in the commercial orange orchards studied here, the canopy is systematically pruned. This drastically changes the volume of the canopy.

The results of the multiple regression analyses (stepwise backward) performed by Quiñones et al. (2013) for the estimation of fruit yield net primary production, aboveground net primary production, belowground net primary production, and total net primary production of 36 orange trees showed r^2 values between 0.97 and 0.82. In developing allometric models to quantify the residual biomass of uprooted citrus trees, López-Cortés et al. (2022) presented allometric equations with r^2 values between 0.78 and 0.52. In the present study, the r^2 of the presented equations ranged between 0.95 and 0.74, with a much larger sample size than that of López-Cortés et al. (2022) and Quiñones et al. (2013), who evaluated 37 and 36 trees, respectively.

Figure 5 shows the independent variables with $p < 0.05$ in the regression analysis and that were selected for use in the allometric equations. Although the stepwise backward regression used in the analyses produces multiple correlations between the independent variables and the dependent variables, Pearson's correlation analyses (r) showed the best results for the TH and BASB variables, accounting for all the dependent variables.

Figure 6 shows correlation graphs of the biomass data obtained by destructive sampling (x axis) and biomass estimated by allometric equations (y axis) for the 80 orange trees sampled. For the total values, that is, the sum of the 80 evaluated trees, the estimated biomass and the evaluated biomass were equal, reaching 7625 kg dry biomass in the 80 evaluated trees; this is also the case for the evaluated compartments. The best Pearson's correlations between the evaluated and estimated values occurred for OTB (r = 0.9585) and BB (r = 0.9753). This means that the best estimates can be obtained for orange tree and BB.

To better understand whether the allometric equation underestimates or overestimates biomass, Figure 7 was constructed. To do this, the data from the biometric variables were used in the allometric equation to estimate the biomass of each of the 80 orange trees evaluated. Thus, Figure 7 shows the trend of underestimation and overestimation of biomass. In general, an underestimation of biomass is observed for orange trees with higher biomass, and an overestimation is observed for orange trees with smaller biomass, even if it is small. This should be taken into account in future biomass estimates.

Although there is no other dataset with biometric and biomass data of orange trees to which the allometric equations can be applied to evaluate the accuracy of the estimates, the normality of the data analyzed (http://paineis.cnpm.embrapa.br/carbcitrus_biomass/), the biometric heterogeneity of the plants (Table 3; Figure 3), the r^2 of the regression analyses (Table 4), the Pearson's correlation analyses between the estimated and the measured biomass (Figure 6), and the error of estimated biomass (Figure 7) lead us to conclude that the allometric equations can be widely used in different orange orchards.

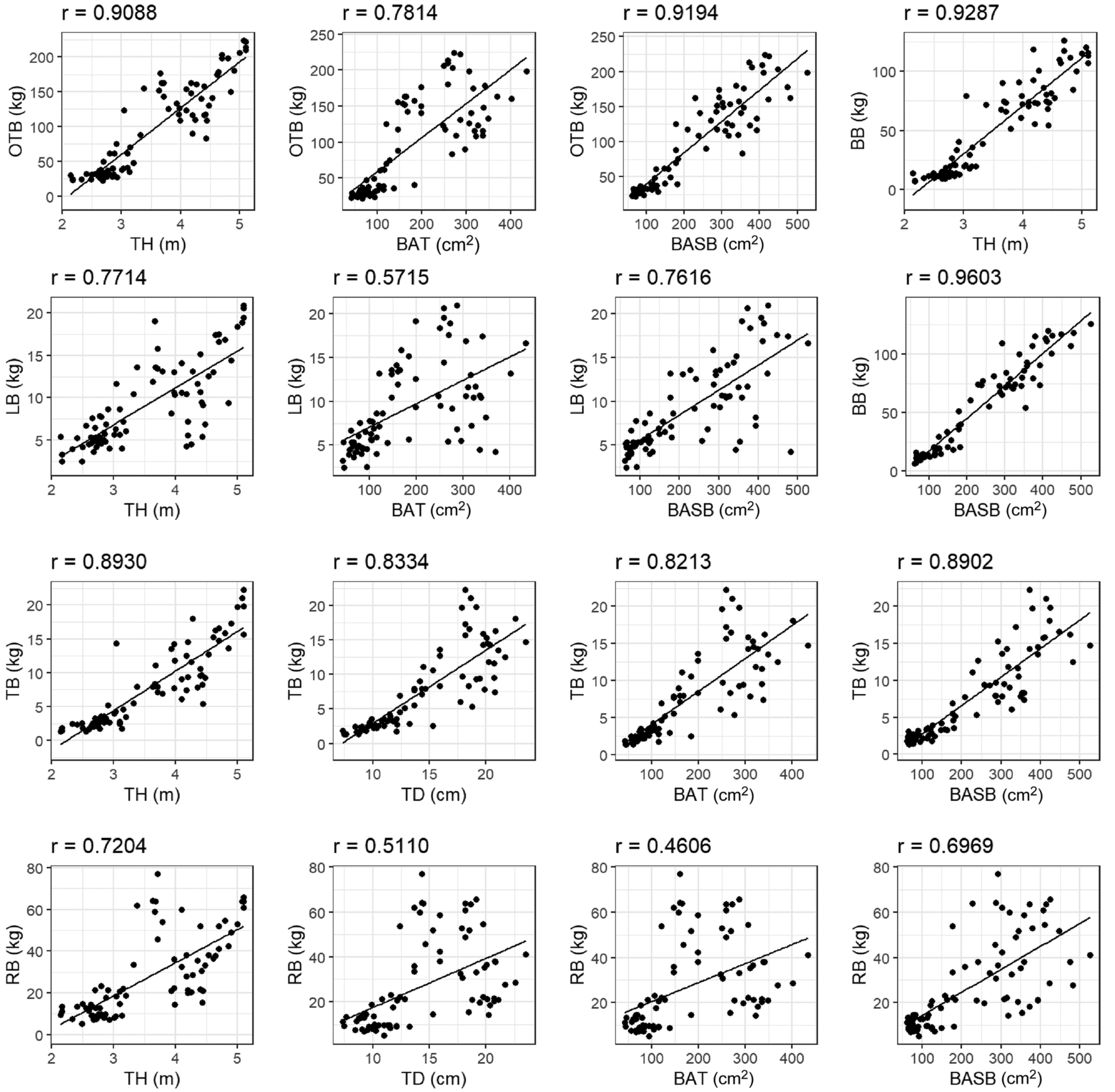

FIGURE 5 Results of Pearson's correlation analyses (r) of the independent variables (x axis) with the dependent variables (y axis) ($p < 0.05$) in the stepwise backward regression analysis. BASB, basal area of secondary branches; BAT, basal area of the trunk; BB, branch biomass; LB, leaf biomass; OTB, orange tree biomass; RB, root biomass; TB, trunk biomass; TD, trunk diameter; TH, total height.

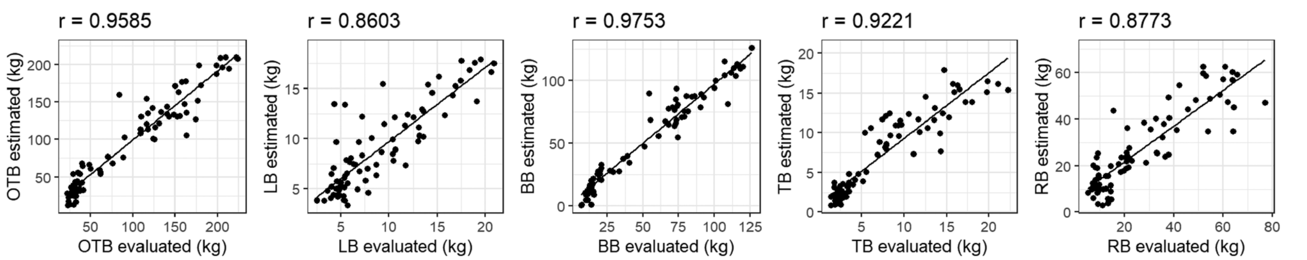

FIGURE 6 Pearson's correlation graphs (r) of the biomass obtained by destructive sampling (x axis) and the biomass estimated by the allometric equations (y axis) for the 80 orange trees evaluated. BB, branch biomass; LB, leaf biomass; OTB, orange tree biomass; RB, root biomass; TB, trunk biomass.

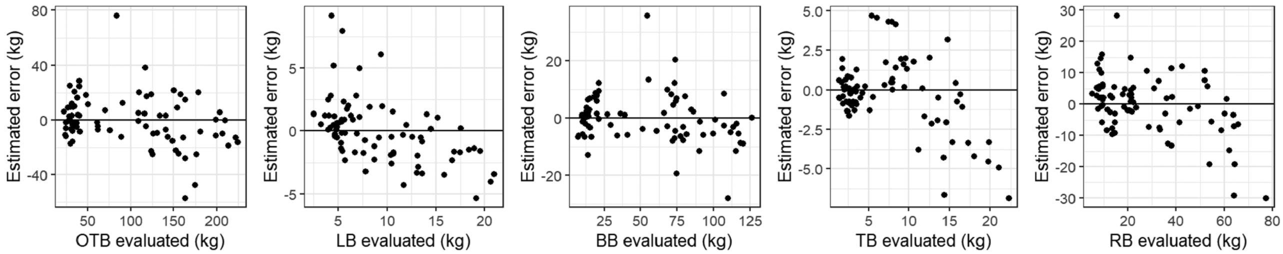

FIGURE 7 Estimated error distribution graphs of the application of the allometric equation in the 80 orange trees evaluated. Estimated error = estimated biomass − evaluated biomass. BB, branch biomass; LB, leaf biomass; OTB, orange tree biomass; RB, root biomass; TB, trunk biomass.

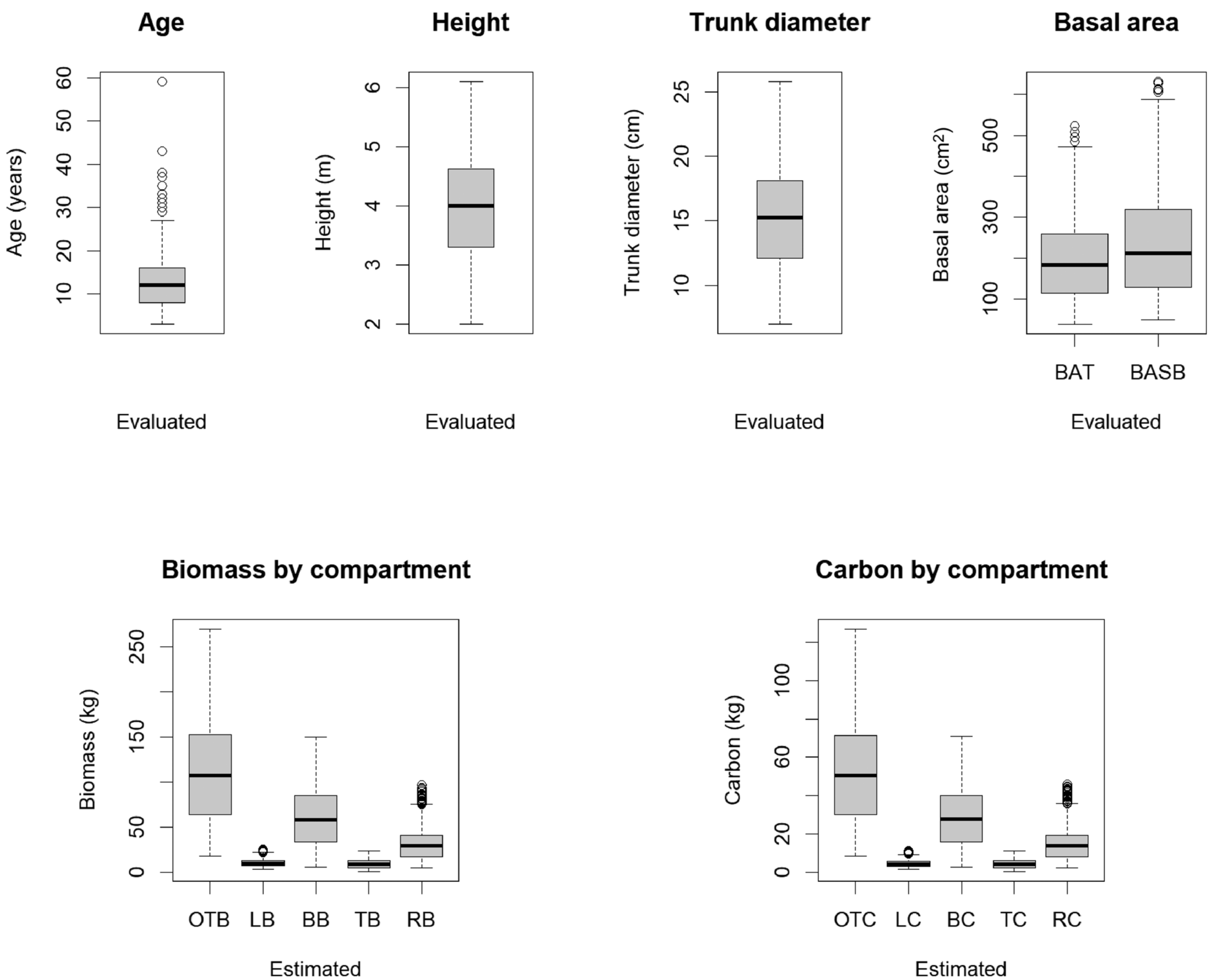

FIGURE 8 Box plots of the evaluated and estimated variables analyzed for the 1321 orange trees (*C. sinensis*) assessed within the citrus belt. BASB, basal area of secondary branches; BAT, basal area of the trunk; BB, branch biomass; BC, branch carbon; LB, leaf biomass; LC, leaf carbon; OTB, orange tree biomass; OTC, orange tree carbon; RB, root biomass; RC, root carbon; TB, trunk biomass; TC, trunk carbon.

3.2 | Estimative of OTB and carbon stock in the São Paulo and southwestern Minas Gerais citrus belt

The data of the estimated and evaluated variables for the 1321 orange trees showed normality (http://paineis.cnpm.embrapa.br/carbcitrus_biomass/). However, the data had some outliers (Figure 8) for age (years), BA (trunk and secondary branches), biomass by compartment, and carbon by compartment (leaves and roots). This is due to the fact that some orange trees over 28 years old had a larger BA, which may reflect outliers for leaf and RB and carbon estimates. Although this is not a prob-

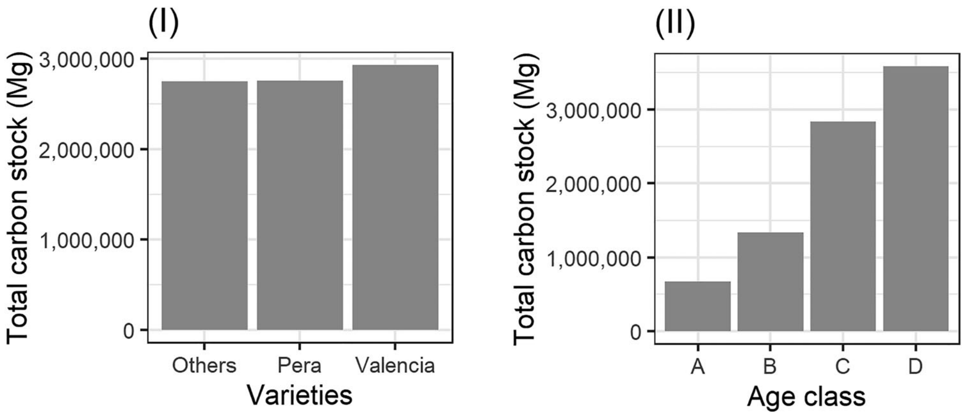

FIGURE 9 Carbon stock by varieties (I: others in Brazilian common name are the Hamlin, Natal, Valência Americana, Valência Folha Murcha, Rubi, Westin, Pineapple, Alvorada, and Seleta) and age classes (II: A = 3- to 5-year old; B = 6- to 10-year old; C = 11- to 15-year old; D = >15-year old) in the citrus belt.

lem for estimating carbon stocks of orange trees in the citrus belt, it reinforces the idea that the average of the variables included in the sample set should be used with caution when comparing with data from other studies.

Here, we highlight that, considering the 1321 orange tree sample (Figure 8), the age average was 12.28 years and the carbon stock average was 52.59 kg, of which the branches were responsible for 55.36% of the carbon stock, the roots 27.87%, the leaves 8.57%, and the trunk 8.2%. In general terms, these represent an annual average of 4.28 kg of carbon fixed per orange tree.

According to our results, at 2023, the citrus belt of São Paulo and southwestern Minas Gerais has 8.44 million Mg C stock in the living biomass of 162.013 million of productive orange trees (≥3 years) on 337,091 hectares of productive orchards. The Pera variety stocked approximately 2.759 million Mg (32.68%), the Valência variety 2.931 million Mg (34.72%), and the other varieties of orange trees accounted for 2.751 million Mg (32.59%) (Figure 9). These results can highlight that the carbon stocks were fixed proportionally in different varieties of orange trees. This fact is important because it can improve the biodiversity associated with these orchards.

The orange trees with more than 10 years (age class 10–15 and >15 years old) stocked around 6.429 million Mg, 76.17% of the total carbon stocked in the citrus belt. Here, we can consider that the age class below 10 years that represent 23.83% of the carbon stock will increase over the time and will increase the total carbon stock in the citrus belt at the next years.

To show more details about the carbon stock in the citrus belt orchards, we calculated the average of carbon stock per orange tree and per hectare (Figure 10), considering the different varieties and age classes. Even using the values of carbon content per varieties and age classes suggested by Nogueira et al. (2023), which is smaller than proposed by the *Good practice guide for land use, land-use change and forestry* of Intergovernmental Panel on Climate Change (IPCC—Intergovernmental Panel on Climate Change, 2003a), the average carbon stock per hectare of orchard was 25.039 Mg. This is 4 Mg bigger than the reference value of 21 Mg C ha^{-1} suggested by the IPCC—Intergovernmental Panel on Climate Change (2003a), and used for the estimates of GHGs for the National Inventory (MCTI—Ministério da Ciência, Tecnologia e Inovações, 2022) and the Inventory of the State of São Paulo (São Paulo, 2019) in citrus productive areas. It is important to highlight than this average of carbon stock per hectare was estimated with an average density of 480 orange trees per hectare (Fundecitrus et al., 2023), calculated without taking into account replanting.

Extrapolating the average of 4.28 kg of carbon annually fixed per orange tree to the 162.013 million of productive orange trees in the citrus belt, 693,618 Mg C are fixed annually by the living biomass of orange trees. For 1 ha, the carbon annually fixed is approximately 2.04 Mg. These results and others discussed above highlight the importance of studies of carbon stocks in perennial crops, possibly more accurate GHG inventories, with a confidence biomass base line, and explain the importance of the orange orchards for carbon balance in agricultural lands. These results can be showed how the baseline about carbon stock in the Brazilian citrus belt.

4 | CONCLUSIONS

The direct evaluation of the OTB resulted in an average of 95 kg tree^{-1}, ranging from 22 to 224 kg. With an average of 52 kg tree^{-1}, the branches were the compartment with the highest contribution (54%) to the OTB, followed by the roots with an average of 28%, the leaves with, 10% and finally the trunk with 8%. Using regression analyses,

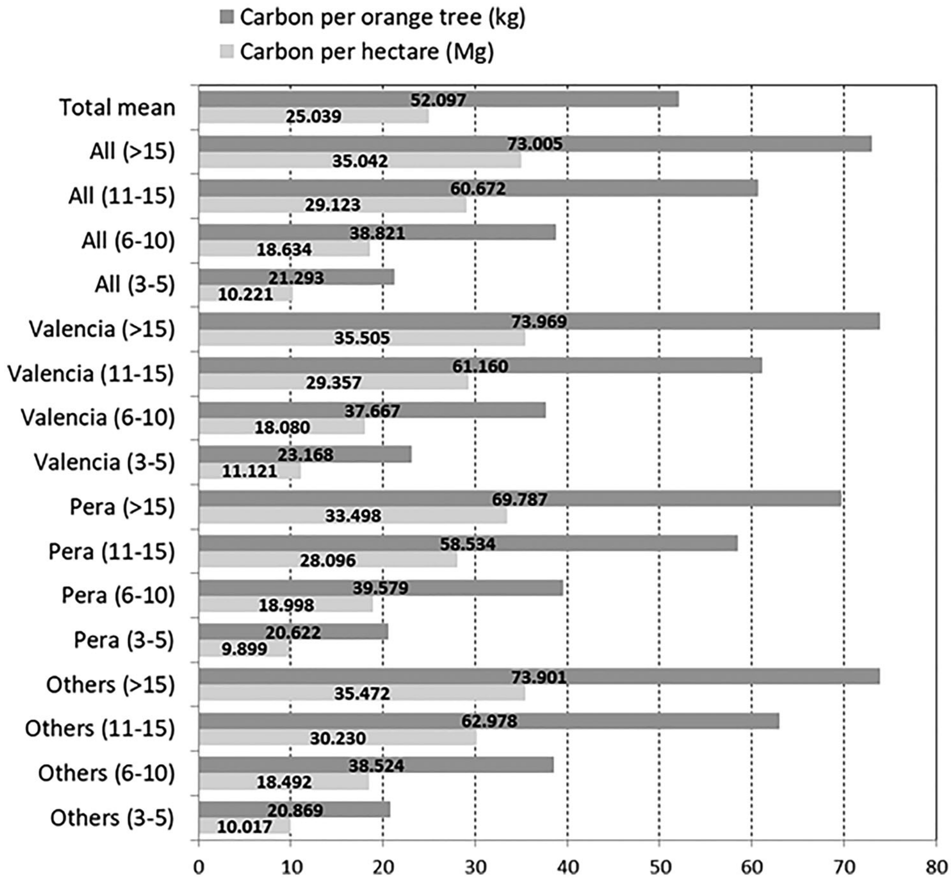

FIGURE 10 Total carbon stock in the living biomass by orange tree and hectare in the Brazilian citrus belt, considering different varieties and age classes (3- to 5-year old; 6- to 10-year old; 11- to 15-year old; >15-year old). All is the average of Valência, Pera, and other varieties (others in Brazilian common name are the Hamlin, Natal, Valência Americana, Valência Folha Murcha, Rubi, Westin, Pineapple, Alvorada, and Seleta).

we developed allometric equations to estimate OTB and its parts (leaves, branches, trunk, and roots) by means of biometric variables (TH, TD, BAT, and BASB). These equations were developed as a nondestructive approach to measure living biomass and carbon stock (aboveground and belowground) in 337,000 hectares of orange orchards in the citrus belt of São Paulo and Minas Gerais states. These equations can be a useful tool to calculate C stock potential in citrus at different scales (orchards, farms, municipalities, and regions) and can be used by farmers, citrus companies, technicians, agricultural societies, researchers, students, and so forth. But one should consider similar orchards, age classes, tree sizes, and local characteristics, measuring easily measurable biometric variables. In addition, the equations can support carbon inventories in voluntary market projects or payment for ecosystems services initiatives. In the Brazilian citrus belt, approximately 8.4 million Mg C are stored in the living biomass of orange trees. This corresponds to a stock of 25.2 Mg C in living biomass per hectare of citrus orchards and 52 kg of carbon per orange tree. On average, one orange tree can fix about 4.28 kg of carbon per year in the living biomass, and 1 ha can stock an average of 2.04 Mg C in the living biomass of orange trees. These results can be used as a baseline for carbon stocks in the Brazilian citrus belt.

AUTHOR CONTRIBUTIONS

Lauro Rodrigues Nogueira Jr.: Conceptualization; data curation; formal analysis; funding acquisition; investigation; methodology; project administration; resources; supervision; validation; visualization; writing—original draft; writing—review and editing. **Carlos Cesar Ronquim**: Conceptualization; data curation; formal analysis; investigation; methodology; validation; writing—original draft. **José Carlos Barbosa**: Data curation; formal analysis; methodology; validation; writing—original draft. **Vinicius Gustavo Trombin**: Conceptualization; data curation; formal analysis; funding acquisition; investigation; methodology; resources; validation; visualization; writing—original draft. **Roseli Reina**: Methodology. **Fernando Alvarinho Delgado**: Methodology. **Fernando Antônio de Pádua Paim**: Data curation; formal analysis; methodology.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The datasets generated and analyzed during the current study are available at http://paineis.cnpm.embrapa.br/carbcitrus_biomass/.

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