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Correlations between dendrometric and allometric variables of *Eucalyptus benthamii* under agroforestry systems in the subtropic of Brazil

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ABSTRACT: The growing interest in integrated agricultural production systems has increased the search for information about the arboreal component, thus, information about the correlations and associations between dendrometric and allometric variables are important. This study investigated the results obtained through simple correlation analysis and its breakdown via path analysis of dendrometric and allometric variables of *Eucalyptus benthamii* under different integrated systems and monoculture. The following variables were evaluated: diameter at 1.3 m above ground, total height, volume with and without bark, crown radius and biomass components stem wood and bark, branches, leaves and total aboveground biomass. Descriptive statistics showed the great variance of the data with coefficients of variation from 18 to 85.08%. All correlations (Spearman) between allometric and dendrometric variables were positive and 89% were statistically significant ($p < 0.05$). For the total aboveground biomass as dependent variable, the variables with the greatest direct effects were wood biomass (0.26), volume with bark (0.17) and branch biomass (0.15). With the results of the simple correlation any variable can be used in the modeling of the total aboveground biomass. However, the path analysis makes it clear that some variables have weak associations even with significant correlations of great magnitude.

Correlações entre variáveis dendrométricas e alométricas de *Eucalyptus benthamii* em sistemas integrados no subtrópico do Brasil

RESUMO: O crescente interesse por sistemas integrados de produção agrícola tem aumentado a busca por informações sobre o componente arbóreo, portanto, informações sobre as correlações e associações entre variáveis dendrométricas e alométricas são importantes. Este estudo investigou os resultados obtidos por meio de análises de correlação simples e sua decomposição por meio de análise de trilha de variáveis dendrométricas e alométricas de *Eucalyptus benthamii* sob diferentes sistemas integrados e monocultivos. Foram avaliadas as seguintes variáveis: diâmetro a 1,3 m acima do solo, altura total, volume com e sem casca, raio da copa e componentes da biomassa madeira e casca do caule, galhos, folhas e biomassa aérea total. A estatística descritiva mostrou grande variância dos dados com coeficientes de variação de 18 a 85,08%. Todas as correlações (Spearman) entre as variáveis alométricas e dendrométricas foram positivas e 89% foram estatisticamente significativas ($p < 0,05$). Para a biomassa total acima do solo como variável dependente, as variáveis com maiores efeitos diretos foram biomassa de madeira (0,26), volume com casca (0,17) e biomassa de ramos (0,15). Com os resultados da correlação simples, qualquer variável pode ser usada na modelagem da biomassa total acima do solo. No entanto, a análise do caminho deixa claro que algumas variáveis apresentam associações fracas mesmo com correlações significativas de grande magnitude.

Introduction

The growing worldwide interest in integrated agricultural production systems as a strategy to diversify, increase and improve the quality of food, in addition to increasing income, decreases the impacts on the environment and, consequently, the effects of climate change (Lemaire et al. 2014, Moraes et al. 2014, Pontes et al. 2018). In order to have all these beneficial effects, the insertion of the tree component becomes essential, not only because it increases the resilience of the productive systems (Quandt 2020) and increases the diversity of products, but also because it reduces the anthropic pressure on native forests. In the last three decades, global forest cover has decreased by 1.7% (FAO 2020; FAO and UNEP 2020), evidencing the growing demand for food and forest products, the continents Africa and South America are responsible for more than 90% of net deforestation between the years 2010 and 2020 (FAO 2020).

The conversion of livestock and conventional agriculture to integrated systems that contain trees, can bring great benefits to the human being and to the environment, with this, the species of the genus *Eucalyptus* present great potentials. However, in subtropical regions the occurrence of low temperatures limits the use of the main species of *Eucalyptus* cultivated in Brazil. Thus, it is necessary to choose a species that is tolerant or resistant to frost, in this sense *Eucalyptus benthamii* Maiden et Cambage has great potential, resisting negative temperatures (Maier et al. 2017; Kruchelski et al. 2021). There are few studies with this species, generally based on the characteristics of the wood (Kruchelski et al. 2021), or physiological (Maier et al. 2017), with this, it remains to study the behavior of the dendrometric and allometric relationships of *Eucalyptus benthamii* trees.

For studies with modeling of allometric variables, it is essential to study correlations (Zianis et al. 2016; Trautenmüller et al. 2019). However, simple correlations can result in mistakes in the choice of variables to be used in modeling allometric variables, as their estimate and magnitude may not reflect the true associations between the variables under study (Trautenmüller et al. 2019). To better understand the cause-and-effect relationships between variables Wright (1921) proposed a method called Path Analysis, which breaks down simple correlations into direct and indirect effects. This technique has been used on a large scale to explain the associations between agricultural crop variables (Dewey and Lu 1959; Toebe and Cargnelutti Filho 2013; Sari et al. 2017; Olivoto et al. 2017), in species assessment studies using this technique are rarer (Hermy 1987; Salla et al. 2015; Trautenmüller et al. 2019).

The great utility of the path analysis is related to the detailed study of the associations between the dependent and independent variables of the models, based on coefficients that describe the cause-and-effect relationship (Trautenmüller et al. 2019). However, the estimation of these coefficients is highly sensitive to the presence of multicollinearity between the independent variables of the adjusted model (Gujarati and Porter 2009). When the coefficients are estimated based on variables that show multicollinearity, their variance makes values excessively high, obtaining unreliable estimates (Montgomery et al. 2012). To avoid the problems caused by multicollinearity, the literature offers two alternatives, (i) identification and exclusion of the variable that provides collinearity, and (ii) the use of crest regressions (Trautenmüller et al. 2019), for situations where the elimination of the variable cannot be an option.

The simple correlation between variables is important to verify the degree and the meaning of this association, however, it may not identify the independent variables with true cause and effect associations on the dependent variable (Salla et al. 2015). Thus, the hypothesis of this study was that the direct and indirect effects via dismembered path analysis may show different results when compared with simple correlation analysis. Thus, the objective of the present work was to analyze the results obtained through the analysis of simple correlation and its breakdown into direct and indirect effects by the path analysis of dendrometric and allometric variables of *Eucalyptus benthamii* under different cultivation systems, in addition to indicating variables that should be used for modeling the tree biomass of this species.

Material and Methods

This work was conducted in the experimental area of the Center for Technological Innovation in Agriculture (NITA), and this experiment has different production systems, as follows: in isolation and all combinations crop-livestock-forest. This area of approximately 36 ha, belongs to the Federal University of Paraná, located on the experimental farm Canguiri (25 ° 23'30 "S, 49 ° 07'30" O, at 920 m altitude), in the municipality of Pinhais, state of Paraná, Brazil (Figure 1). The experimental farm is located in the Environmental Protection Area (APA) of the Iraí River (PARANÁ 1996), on the banks of the Iraí dam. The region's climate is Cfb, according to the Köppen-Geiger classification. The average annual precipitation varies from 1,600 to 1,900 mm, with no defined dry season, and the annual average temperatures vary from 16 to 18 ° C (Alvares 2013). The soils in the area were classified as Cambisols, Oxisols and their associations, with smaller portions of Organosols and Gleisols, according to the Brazilian Soil Classification System (Santos et al. 2018).

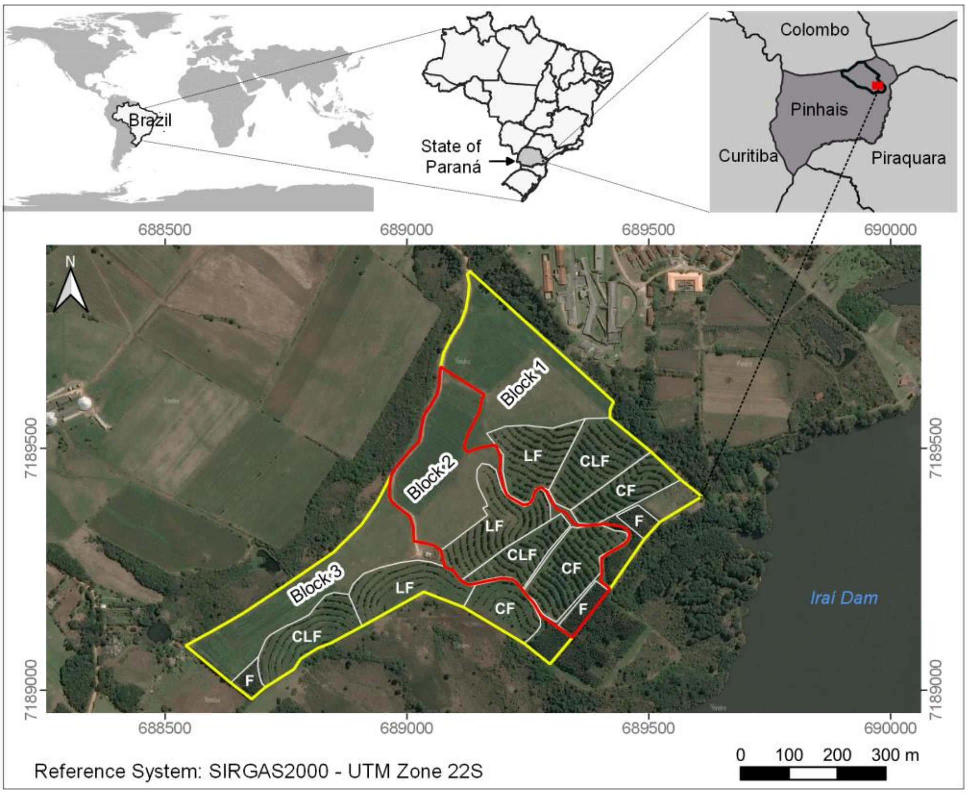


Figure 1. Location of the study area in the subtropical region of Brazil, being the treatments Livestock-Forest (LF), Crop-Livestock-Forest (CLF), Crop-Forest (CF) and only Forest (F). Source: Kruchelski et al. 2021.

First, the forest census of the area was carried out, in order to know the diametric amplitude of the trees, dividing them into five classes of diameter, with the trees being selected at random within each class of diameter. The collection of dendrometric and allometric data was carried out between the sixth and seventh year after the establishment of the experiment.

All sampled trees were evaluated for: diameter at 1.3 meters above ground (dbh) in cm, total height (h) in m and crown radius (CR) in m. The measured CR was the average of eight measurements collected from each tree. The diameters and their respective bark thickness were collected in the positions: 0.1, 1.3 m above ground and at 25, 50, 75 and 90% of the total height, to calculate the volume wood with bark (vwb) and without bark (vlb) in m³. The measurement of biomass was performed for the components of wood of the stem (WB), bark of the stem (BB), branches (BrB) and leaves (LB), all measured in kg, with the total above-ground biomass (TB) being the sum of the components of the tree.

After cutting the trees, the components were separated and weighed with the aid of a digital scale (dynamometer) with a capacity of 500 kg, with an accuracy of 100 g. To determine dry biomass, samples were collected from all components to determine moisture content, these samples were weighed with a precision digital scale (0.01 g). In the collection of samples for the wood and the bark of the stem three discs were collected, 0.1 m from the ground, 50% and 90% of the total height. For the branches and leaves, samples were collected in the three thirds of the crown, in the branches the maximum possible variation of diameters was collected. All samples were kiln dried with air circulation and renewal at 65 ± 5 ° C until constant mass.

With the data base, descriptive statistics and the Shapiro-Wilk test were performed to verify the adherence of the data to the normal distribution, the Spearman's correlation was applied if any of the variables did not show normality. With the application of the path analysis, the presence of multicollinearity was verified, among the independent variables of the linear regression model, through the condition number (CN) (Montgomery et al. 2012). Then, the path analysis was performed using the total aerial biomass and its components as a dependent variable, one at a time. When multicollinearity was verified in the model, the addition of a constant (k) chosen arbitrarily ($0 \leq k \leq 1$), the main diagonal was used, thus correcting the multicollinearity problem, as demonstrated by Trautenmüller et al. (2019).

All tests, diagnostics and analyzes were conducted with the aid of packages metan (Olivoto and Lúcio, 2020) the programs R 4.0.3 (R Development Core Team 2020).

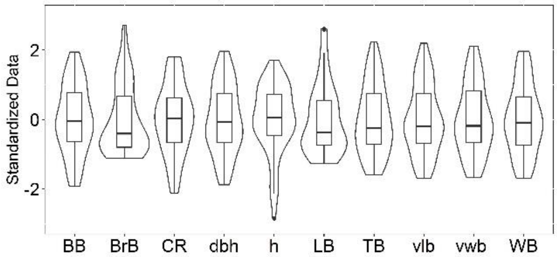
Results and Discussion

With the results of the descriptive statistics, it is possible to observe the great variance of the data with coefficients of variation from 18 to 85.08%, evidencing the great amplitude of the data (Table 1). In detailed analysis (Figure 1) the presence of outliers was verified in the variables total height and biomass of the leaf component.

Table 1. Descriptive statistics of dendrometric variables, components of biomass (stem wood, stem bark, branches and leaves) and total above-ground biomass in *Eucalyptus benthamii* trees in different integrated systems of agricultural and monoculture production, in a subtropical region in the Brazil.

Statistic	dbh (cm)	h (m)	CR (m)	vwb (m^3)	vlb (m^3)	BrB (kg)	LB (kg)	WB (kg)	BB (kg)	TB (kg)
Minimum	13.81	12.33	0.88	0.0846	0.0673	3.25	2.15	27.16	7.64	50.74
Mean	27.91	25.23	2.70	0.7479	0.6840	58.30	21.99	267.78	41.71	389.78
Maximum	42.65	33.00	4.25	1.5884	1.4856	192.94	62.96	547.60	76.17	867.63
Standard deviation	7.49	4.54	0.86	0.40	0.36	49.60	15.70	142.03	17.74	213.81
CV (%)	26.85	18.00	31.80	53.10	53.37	85.08	71.40	53.04	42.53	54.85
SW (Test)	0.976	0.949	0.980	0.967	0.967	0.881	0.913	0.967	0.980	0.962
SW (p-value)	0.43	0.04	0.61	0.20	0.21	0.00	0.00	0.21	0.58	0.14

SW is the Shapiro-Wilk test for normality, CV (%) is the Coefficient of Variation in%, dbh is the diameter at 1.3 m above ground, h is the total height, CR is the crown radius, vwb you are the volume of wood with bark, vlb volume of wood less bark, BrB is the biomass of the branches, LB is the biomass of the leaves, WB is the biomass of the stem wood, BB is the biomass of the stem bark and TB is the biomass total above-ground tree.

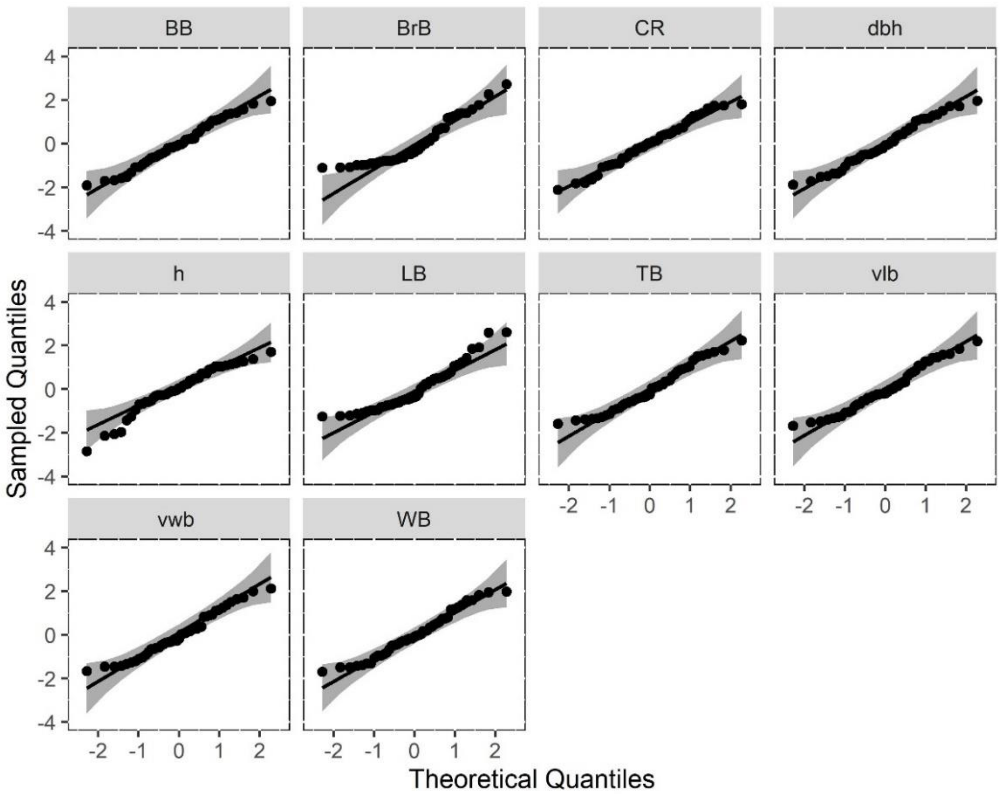


Where: BB is the biomass of the stem bark, LB is the biomass of the leaves, BrB is the biomass of the branches, WB is the biomass of the stem wood, TB is the total biomass above the tree soil, dbh is the diameter 1.3 m above ground, h is the total height, CR is the crown radius, vwb is the volume of wood with bark and vlb volume of wood less bark.

Figure 2. Boxplot of the standardized variables of a plantation of *Eucalyptus benthamii* in different integrated systems of agricultural and monoculture production, in a subtropical region in Brazil.

There are few scientific studies that use allometric variables and present descriptive statistics, because, for the biomass component variables, the coefficients of variation (CV) can exceed 80% (Table 1). In a study with a hybrid of *Eucalyptus urophylla* and *Eucalyptus grandis*, 5.5 years old in Brazil, Ribeiro et al. (2015) found a 58% CV for the leaves component. For above-ground total biomass and its components in subtropical forests in Brazil, Trautenmüller et al. (2019) found CV above 200%. With work carried out in the tropical forest of Dipterocarp in Vietnam Huy et al. (2016), found CV above 150% for the total biomass above ground. These results show the wide range of data when studying tree biomass. In the analysis of each biomass component independently, only the leaf component showed outliers (Figure 1). However, the biomass components of leaves and branches did not show adherence to normal distribution (Table 1; Figure 2). This lack of normality is often found in biomass data, making it a problem for modeling based on linear regression (Gujarati & Porter, 2009; Balbinot et al. 2019; Trautenmüller et al., 2019). The ways to overcome the lack of normality are: (i) transformation of the data, but not indicating when the additivity of the biomass component equations must be reached (Sanquetta et al. 2015; Behling et al. 2018), (ii) the use of non-linear regression (Huy et al. 2016; Trautenmüller et al. 2021) that employ other forms of adjusting the coefficients other than the Ordinary Least Squares or, (iii) applying stratification to the data, thus, each group presents normality (Behling et al. 2018; Balbinot et al. 2019).

The Shapiro-Wilk test was applied to allometric and dendrometric data and revealed the non-adherence of the data to the normal distribution for the variables total height and the biomass of the leaf and branch components (Figure 3). Therefore, correlations must be assessed by a non-parametric method, such as Spearman's correlation, to test the degrees of significance between the variables.



Where: BB is the biomass of the stem bark, LB is the biomass of the leaves, BrB is the biomass of the branches, WB is the biomass of the stem wood, TB is the total biomass above the soil of the tree, dbh is the diameter 1.3 m above ground, h is the total height, CR is the crown radius, bwv is the volume of wood with bark and vlb volume of wood less bark.

Figure 3. Evaluation of the normal distribution adjustment of dendrometric and allometric variables in *Eucalyptus benthamii* trees in different integrated systems of agricultural and monoculture production, in a subtropical region in Brazil.

All correlations between allometric and dendrometric variables were positive and 89% were statistically significant ($p < 0.05$) (Table 2). The variables bark volume and biomass of the stem wood show correlations of 0.99 with the total biomass above the ground, only the variables total height (0.55) and crown radius (0.30) showed correlations below 0.85.

Table 2. Spearman's correlation between dendrometric and allometric variables in *Eucalyptus benthamii* trees in different integrated systems of agricultural and monoculture production, in a subtropical region in Brazil.

	dbh	h	CR	bwv	vlb	BrB	LB	WB	BB	TB
dbh	1	0.38**	0.29*	0.96**	0.94**	0.92**	0.91**	0.93**	0.92**	0.96**
h		1	0.21^{ns}	0.59**	0.62**	0.20^{ns}	0.12^{ns}	0.64**	0.56**	0.55**
CR			1	0.29*	0.29*	0.37**	0.25^{ns}	0.27^{ns}	0.29*	0.30*
bwv				1	0.99**	0.85**	0.81**	0.99**	0.96**	0.99**
vlb					1	0.83**	0.80**	0.99**	0.95**	0.98**
BrB						1	0.93**	0.82**	0.84**	0.89**
LB							1	0.78**	0.78**	0.85**
WB								1	0.95**	0.99**
BB									1	0.96**
TB										1

** Significant at 1% probability of error by t test; * Significant at 5% probability of error; ns not significant at 5% probability of error; dbh = diameter at 1.3 m above ground, h = total height, CR = crown radius, vwb = volume wood with bark, vlb = volume of wood less bark, BrB = biomass of branches, LB = biomass of leaves, WB = stem wood biomass, BB = stem bark biomass and TB = total biomass aboveground the trees.

The correlations between the variables dbh and h with the biomass components and the total biomass are generally significant with great magnitudes and positives, being reported in several studies (Burger and Delitti 2008; Magalhães 2015; Trautenmüller et al. 2019). No studies were found that report the correlation coefficient of the stem volume variable with the total biomass and its components. In the present study, all coefficients were significant (p-value> 0.01) and positive, with a magnitude greater than 0.80. For the correlations of the biomass components with the total biomass, the coefficients were significant and positive, with a magnitude greater than 0.85. These high correlations between the biomass allometric variables are biologically expected, since the sum of the biomass components results in the total biomass (Trautenmüller et al. 2019).

With the analysis of literature that aim to model biomass according to easily obtainable variables (dbh and h), these high correlations may not generate equations with acceptable errors (especially in native forests), as discussed in detail by Trautenmüller et al. (2019). For forest plantations these errors are minor, for obvious reasons, as the only species of cultivation, they are often clones and the trees are the same age. In general, the literature shows that the errors in the biomass equations for native forests (tropical and subtropical) are above 20% (Trautenmüller et al. 2021) and for planted forests they are below 20% (Ribeiro et al. 2015). With the analysis of the errors in the biomass equations for native and planted forests, it is evident that the diametric amplitude has a great influence on the errors, confirming that the variance of the biomass is proportional to the average diameter, as discussed by Behling et al. (2018) and Trautenmüller et al. (2021).

Table 2 shows Spearman's simple correlations. However, these do not express the real causes and effects between the variables, as can be revealed by dismembering the direct and indirect effects of the independent variables on the dependent ones, in all the proposed combinations presented in Table 3. With the analysis of biomass total above-ground (TB) as a dependent variable, the real contribution of the independent variables was verified due to the high coefficient of determination ($R^2 = 0.98$) and the low residual effect (pe = 0.13). Multicollinearity correction was necessary for all dependent variables (biomasses), for TB the use of the constant k (0.07) was possible to correct the effects of multicollinearity based on the CN (92.9). The variables with the greatest direct effects on TB were WB (0.26), vwb (0.17) and BrB (0.15).

Table 3: Split of direct and indirect effects via path analysis of dendrometric and allometric variables in *Eucalyptus benthamii* trees in different integrated systems of agricultural and monoculture production, in a subtropical region in Brazil.

Variable		Direct	Indirect effect										$\hat{\rho}$	R^2	p_e	k	CN
Dep	Ind	effect	dbh	h	CR	vwb	vlb	BrB	LB	WB	BB	TB					
BrB	dbh	0.16	-	-0.08	0.03	0.06	0.02	-	0.30	0.04	0.14	0.25	0.92	0.90	0.31	0.08	88.4
	h	-0.21	0.06	-	0.02	0.04	0.01	-	0.03	0.03	0.08	0.14	0.20				
	CR	0.13	0.04	-0.03	-	0.02	0.01	-	0.08	0.01	0.04	0.07	0.37				
	vwb	0.06	0.15	-0.12	0.03	-	0.02	-	0.27	0.05	0.14	0.25	0.85				
	vlb	0.02	0.15	-0.13	0.03	0.06	-	-	0.26	0.05	0.14	0.25	0.83				
	BrB	-	-	-	-	-	-	-	-	-	-	-	-				
	LB	0.33	0.15	-0.02	0.03	0.05	0.02	-	-	0.04	0.11	0.22	0.93				
	WB	0.05	0.14	-0.13	0.03	0.06	0.03	-	0.25	-	0.14	0.25	0.82				
	BB	0.14	0.14	-0.12	0.04	0.06	0.03	-	0.25	0.06	-	0.24	0.84				
	TB	0.25	0.15	-0.11	0.04	0.06	0.03	-	0.28	0.05	0.14	-	0.89				
LB	dbh	0.30	-	-0.10	-0.01	0.03	0.15	0.34	-	0.03	-0.03	0.20	0.91	0.88	0.34	0.08	89.2
	h	-0.26	0.11	-	-0.01	0.01	0.10	0.06	-	0.02	-0.03	0.12	0.12				
	CR	-0.02	0.08	-0.05	-	0.01	0.05	0.12	-	0.01	-0.01	0.06	0.25				
	vwb	0.02	0.29	-0.15	-0.01	-	0.16	0.31	-	0.03	-0.05	0.21	0.81				
	vlb	0.16	0.28	-0.16	-0.01	0.02	-	0.30	-	0.04	-0.04	0.21	0.80				
	BrB	0.37	0.29	-0.05	-0.01	0.01	0.13	-	-	0.03	-0.04	0.20	0.93				
	LB	-	-	-	-	-	-	-	-	-	-	-	-				
	WB	0.03	0.28	-0.16	-0.01	0.02	0.16	0.30	-	-	-0.05	0.21	0.78				
	BB	-0.05	0.28	-0.15	-0.01	0.02	0.15	0.40	-	0.03	-	0.20	0.78				
	TB	0.21	0.29	-0.14	-0.01	0.03	0.16	0.32	-	0.03	-0.04	-	0.85				
WB	dbh	0.09	-	0.05	-0.01	0.19	0.22	0.03	0.02	-	0.07	0.27	0.93	0.97	0.15	0.07	95.4
	h	0.14	0.03	-	-0.01	0.12	0.14	0.02	0.01	-	0.04	0.15	0.64				
	CR	-0.03	0.03	0.03	-	0.06	0.07	0.01	0.02	-	0.02	0.08	0.27				
	vwb	0.20	0.09	0.08	-0.01	-	0.23	0.03	0.02	-	0.07	0.28	0.99				
	vlb	0.23	0.09	0.08	-0.01	0.21	-	0.02	0.02	-	0.08	0.27	0.99				
	BrB	0.02	0.08	0.04	-0.01	0.17	0.19	-	0.02	-	0.06	0.25	0.82				
	LB	0.02	0.08	0.03	-0.01	0.16	0.18	0.02	-	-	0.06	0.24	0.78				

	WB	-	-	-	-	-	-	-	-	-	-	-	-				
	BB	0.08	0.08	0.07	-0.01	0.19	0.22	0.03	0.02	-	-	0.27	0.95				
	TB	0.28	0.09	0.07	-0.01	0.20	0.23	0.03	0.02	-	0.08	-	0.99				
BB	dbh	0.13	-	0.03	-0.01	0.20	0.14	0.13	-0.03	0.12	-	0.21	0.92	0.91	0.30	0.08	87.3
	h	0.07	0.06	-	-0.01	0.12	0.09	0.04	-0.01	0.08	-	0.12	0.56				
	CR	-0.01	0.04	0.02	-	0.06	0.04	0.05	-0.01	0.04	-	0.06	0.29				
	vwb	0.21	0.12	0.05	-0.01	-	0.15	0.12	-0.02	0.13	-	0.21	0.96				
	vlb	0.15	0.12	0.05	-0.01	0.20	-	0.12	-0.02	0.13	-	0.21	0.95				
	BrB	0.14	0.12	0.01	-0.01	0.18	0.13	-	-0.03	0.11	-	0.19	0.84				
	LB	-0.04	0.11	0.02	-0.01	0.17	0.12	0.13	-	0.10	-	0.18	0.78				
	WB	0.14	0.12	0.05	-0.01	0.20	0.15	0.11	-0.02	-	-	0.21	0.95				
	BB	-	-	-	-	-	-	-	-	-	-	-	-				
	TB	0.22	0.12	0.05	-0.01	0.20	0.15	0.12	-0.03	0.14	-	-	0.96				
TB	dbh	0.08	-	0.04	-0.01	0.16	0.11	0.14	0.09	0.24	0.11	-	0.96	0.98	0.13	0.07	92.9
	h	0.07	0.04	-	-0.01	0.10	0.06	0.04	0.02	0.17	0.06	-	0.55				
	CR	-0.01	0.02	0.01	-	0.05	0.03	0.05	0.04	0.07	0.04	-	0.30				
	vwb	0.17	0.08	0.05	-0.01	-	0.11	0.13	0.09	0.26	0.11	-	0.99				
	vlb	0.11	0.09	0.05	-0.01	0.17	-	0.12	0.08	0.26	0.11	-	0.98				
	BrB	0.15	0.08	0.03	-0.01	0.14	0.09	-	0.10	0.21	0.10	-	0.89				
	LB	0.10	0.07	0.03	-0.01	0.14	0.08	0.14	-	0.21	0.09	-	0.85				
	WB	0.26	0.08	0.05	-0.01	0.17	0.12	0.12	0.09	-	0.11	-	0.99				
	BB	0.12	0.08	0.05	-0.01	0.16	0.11	0.12	0.08	0.25	-	-	0.96				
	TB	-	-	-	-	-	-	-	-	-	-	-	-				

Dep = Dependent, Ind = Independent, dbh = diameter at 1.3 m above ground, h = total height, CR = crown radius, vwb = volume of wood with bark, vlb = volume of wood less bark, BrB = biomass of branches, LB = biomass of leaves, WB = stem wood biomass, BB = stem bark biomass and TB = total biomass above the tree's soil; $\hat{\rho}$ = Spearman's correlation coefficient; R^2 = coefficient of determination; p_e = Effect of the residual variable; k = constant k included to correct multicollinearity; CN = Condition number, to check multicollinearity.

With the analysis of branch biomass (BrB) as a dependent variable, R^2 of 0.90 and residual effect of 0.31 were verified using the constant k = 0.08, the CN was 88.4, the variables with the highest direct effects on BrB were LB (0.33), TB (0.25) and tree height (-0.21). For leaf biomass (LB) using constant k = 0.08 the analysis resulted in CN of 89.2, R^2 of 0.88 and residual effect of 0.34, it was evidenced that the variables BrB (0.37), dbh (0.30) and h (-0.26) showed the greatest direct effects on LB. In the analysis of the biomass of the stem wood (WB) as a dependent variable and using a value of k = 0.07, CN of 95.4, R^2 of 0.97 and residual effect of 0.15 were found, and the variables with the highest direct effect on WB were TB (0.28), vlb (0.23) and vwb (0.20). For the biomass of the bark of the stem (BB) an CN of 87.3, R^2 of 0.91 and residual effect of 0.30 was found, using a k of 0.08, in this analysis the variables with the greatest direct effect were TB (0.22), vwb (0.21) and vlb (0.15).

In the path analysis, it was evidenced that the use of the constant k (ranged from 0.07-0.08) was sufficient to overcome the problem of multicollinearity, since the CNs were below 100, as mentioned by Montgomery et al. (2012), who mentioned, in this condition, the multicollinearity is weak, not causing problems in the linear regression analysis. The dismemberment of the direct and indirect effects of the dendrometric and allometric variables for the total biomass above ground showed that the biomass of the stem wood (0.26) and the volume with bark (0.17) should be included in the total biomass models. above ground, or even replace the traditionally used variables (dbh and h).

With the analysis of the results of the simple correlations (Spearman) and the direct effects (Path analysis) with the total biomass above ground as a dependent variable, the variable components of biomass leaves, branches and bark obtained simple correlations equal to or less than dbh, however, dbh had less direct effect when compared to these variables. Similar patterns of behavior can be observed for the components of biomass leaves and branches when used as a dependent variable in modeling through path analysis. For the stem biomass (wood and bark) the volume of wood (vwb and vlb), presented significant direct effects, indicating its inclusion in the regression models.

All of these direct effect results are biologically consistent, because the biomass components added together are the total aboveground biomass. The amount of leaf biomass is closely related to the diameter and height of the tree, and consequently, a greater number of branches (greater biomass of branches) in integrated systems (spacing greater than 14x2m), similar patterns can be observed for the biomass of the branches. For the components of biomass, wood and stem bark, the greatest direct effect was of the total biomass above ground, followed by volume (for WB o vlb and for BB o vwb), all expected results, since the sum of the wood biomasses and the bark of the stem, on average, represent approximately 80% of the total biomass above ground. In the analysis of the biomass variables, other biomasses have high direct effects may be related to the unit of measurement (kg) as mentioned in the literature (Péllico Netto and Behling, 2018, Trautenmüller et al. 2019). With this, it is evident the need to include some biomass variable (stem, branches and leaves) independently in the regression models to estimate the different biomass components of the trees. This need becomes possible with the use of the method of adjusting the regression coefficients by the Method of Two-Stage Least Squares, as presented in Gujarati and Porter (2009).

Conclusions

With the results of the simple correlation (Spearman) any variable can be used to have significant correlations between the total biomass above ground with the other variables analyzed. However, the trail analysis makes it clear that both associations are weak even though they have significant correlations and of great magnitudes.

In future work with modeling of total biomass and its components with *Eucalyptus benthamii* in integrated agricultural production systems, allometric variables (volumes and biomass) must be inserted or even replace dendrometric variables in the modeling. Thus, equations with minor errors can be achieved.

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