Acta Scientiarum
http://periodicos.uem.br/ojs/acta
ISSN on-line: 1807-8621
Doi: 10.4025/actasciagron.v41i1.42626

BIOMETRY, MODELLING AND STATISTIC

Modeling the individual height and volume of two integrated crop-livestock-forest systems of *Eucalyptus* spp. in the Brazilian Savannah

Karen Keli Barbosa Abrantes[1*], Luísa Melville Paiva[2], Roberto Giolo de Almeida[3], Edilson Urbano[2], André Dominghetti Ferreira[3, 4] and Josmar Mazucheli[5]

[1]Programa de Pós-graduação em Agronomia, Universidade Estadual de Maringá, Av. Colombo, 5790, 87020-900, Maringá, Paraná, Brazil. [2]Universidade Estadual de Mato Grosso do Sul, Aquidauana, Mato Grosso do Sul, Brazil. [3]Centro Nacional de Pesquisa de Gado de Corte, Embrapa Gado de Corte, Campo Grande, Mato Grosso do Sul, Brazil. [4]Universidade Uniderp Anhanguera, Campo Grande, Mato Grosso do Sul, Brazil. [5]Departamento de Matemática, Universidade Estadual de Maringá, Maringá, Paraná, Brasil. *Author for correspondence. E-mail: kkelibarbosa@gmail.com

ABSTRACT. The aim of this study was to model the individual height and volume of eucalyptus wood in two integrated crop-livestock-forest systems ($ICLF_1$ and $ICLF_2$) in Campo Grande, a city in the state of Mato Grosso do Sul, Brazil. Classic nonlinear growth models were adjusted for height (Logistic, Gompertz, Richards, Weibull, Van Bertalanffy, Brody, Mitscherlich, and Chapman and Richards) and volume (Shumacher-hall nonlinear, Takata, Honner, Logistic, Gompertz, and Weibull) in two structural arrangements: $ICLF_1$, with a spacing of 14 x 2 m and density of 357 trees ha^{-1}, and $ICLF_2$, with a spacing of 22 x 2 m and density of 227 trees ha^{-1}. Diameter at Breast Height (DBH) measurements were performed in 100% of trees, with measurements of the total height of some individuals and a rigorous scaling procedure in diameter classes. According to the calculated value of Student's t-test, there was no significant evidence that DBH and the average height of the trees were different between $ICLF_1$ and $ICLF_2$. Based on the Akaike information criterion (AIC), the corrected Akaike information criterion (AIC_C) and the Bayesian information criterion (BIC), the Richards model was selected to estimate heights and the Takata model was selected to estimate the volume.

Keywords: nonlinear growth models; volumetric equations; hypsometric equations; agroforestry systems.

Received on October 24, 2017.
Accepted on March 16, 2018.

Introduction

Approximately 24 billion tons of fertile soils become useless annually, especially as a result of adopting agricultural systems that do not include soil conservation techniques (Heinrich-Böll-Stiftung, 2015). Integrated crop-livestock-forest systems (ICLFs) are presented as an alternative to those models because they integrate forestry and agricultural activities in the same area (Machado, Madari, & Balbino, 2010). The State of Mato Grosso do Sul, located in the Cerrado biome (Brazilian Savannah), has an estimated area of 500 thousand hectares of ICLFs in addition to the traditional vocation of livestock farming (Wruck, Behling, & Antonio, 2015).

The introduction of the forestry component in that system has many advantages, such as the improvement of the microclimate (Porfírio-da-Silva, 2015), animal welfare (Pires & Paciullo, 2015; Shibu, 2009), soil conservation (Benavides, Douglas, & Osoro, 2009), water conservation (Shibu, 2009), increasing the retention of soil nutrients and reducing the conduction of nutrients to water sources (Nair, Nair, Kalmbacher, & Ezenwa, 2007), in addition to increasing the wood supply (and other non-timber-products) for use in properties or commercialization (Porfírio-da-Silva, 2015).

A tree is a dynamic biological organism that is constantly changing. This change is affected by the genetic capability of the species and its interactions with the environment, which vary according to age, the production capacity of the location, the degree of use of the productive potential and the silvicultural treatments applied (Campos & Leite, 2013). It is necessary to measure that change over the years using different techniques and methodologies, among which mathematical modelling can be highlighted as having played a very important role in forest management.

It is possible to elaborate a forest management plan by means of a forest inventory, which estimates wood volume using information about tree height, species and density. In view of the extent of these data, it is not possible to inventory 100% of the trees in most areas of the forest, and it is necessary to select representative samples of the population to produce an estimate with a value as close as possible to the population parameter (Soares, Paula-Neto, & Souza, 2012).

To estimate the stock of timber from even-aged or uneven-aged forests, it is necessary to estimate the tree height by using specific equations from hypsometric models (Campos & Leite, 2013). It is possible to obtain hypsometric equations with good stability using data such as the height and Diameter at Breast Height (DBH) of a parcel of the inventory (Andrade & Leite, 2011). For adjusting the volumetric equations, it is necessary to obtain data from the volume measurement of trees (Campos & Leite, 2013), which can be obtained by measuring the diameters at different heights.

Different methods have been used to estimate wood volumes of forests, mainly with eucalyptus species, such as the use of volumetric models (Azevedo, Mello, Ferreira, Sanqueta, & Nakagima, 2011b) and the form factor (Azevedo, Sousa, Barreto, & Conceição Júnior, 2011a). However, there is a lack of studies that model the individual height, volume and volumetric stock of timber in ICLF systems.

Therefore, the aim of this work was to model the hypsometric relation and the individual tree volumes in two integrated crop-livestock-forest systems ($ICLF_1$ and $ICLF_2$) in the Cerrado biome to quantify the total volumetric stock within each system. The hypothesis of the work is that the total height of individuals is directly related to DBH because the volume of wood of these systems is directly related to the height and DBH of the individuals and it is possible to use nonlinear growth models to adjust a hypsometric and volumetric equation for eucalyptus in crop-livestock-forest integration systems.

Material and methods

The experiment was conducted at Embrapa Gado de Corte in Campo Grande, a city of the state of Mato Grosso do Sul in the southwest of the Cerrado biome, with geographical coordinates of 20°27’ S and 54°47’ W at 530-m altitude in the watershed of the Piraputanga River. According to Köppen, the region’s climate is in the transition zone between Cfa and Aw humid tropical climates, with an average annual rainfall of 1,560 mm. The soil in the area is characterized as dystrophic Red Latosol (Oxisol) with clay texture.

The treatments consisted of two spatial arrangements of eucalyptus in two ICLF systems. $ICLF_1$ trees were spaced two meters in the crop row and 14 meters between lines (357 trees ha^{-1}) and piatã grass (*Urochloa brizantha* cv. BRS Piatã). $ICLF_2$ trees were spaced two meters in the crop row and 22 meters between lines (227 trees ha^{-1}) and piatã grass (*Urochloa brizantha* cv. BRS Piatã). Each treatment area consisted of six hectares comprising four repetitions of 1.5 ha each. Soy cultivation was used in a cycle to replenish the grazing lands, with a four-year rotation system.

In September of 2008 the soil preparation consisted of plowing and harrowing, followed by liming (3.0 tons ha^{-1}), gypsum application (1.0 ton ha^{-1}) and subsoiling in eucalyptus crop rows with the aim of implanting the experiment.

Chemical analysis of the soil before the experiment implantation at a depth of 0-20 cm presented a clay content of 41 ± 5%, P (Mehlich^{-1}) from 0.29 to 0.42 mg dm^{-3}, base saturation from 26 to 34% and aluminum saturation from 10 to 23%. Before the soybean planting, 400 kg ha^{-1} of 5-25-15 (NPK) fertilizer was applied, and the soybean planting was made at the end of November 2008 (cv. BRS 255 RR) with a line spacing of 0.45 m and a seeding density of 30 seeds m^{-1}, with two meters of space left for planting eucalyptus seedlings.

The eucalyptus seedlings (hybrid *Eucalyptus urophylla* x *E. grandis*, clone H13) were planted in January 2009 in accordance with proposed treatments. On planting, seedlings had an average height between 15 and 20 cm and an average diameter at the stem of 2 mm. The tree rows were planted in the direction of the sun (westbound). Eighty grams of 5-25-15 (NPK) fertilizer per sulcus linear meter were applied on the top-dressing. Additionally, 300 grams of gypsum, 60 grams of MAP (monoammonium phosphate), 30 grams of potassium chloride, 50 grams of ammonium sulfate, six grams of zinc sulfate and six grams of borax were added per plant in the base fertilization (which was carried out at six, twelve and eighteen months after planting).

Soybeans were harvested in the first half of April 2009. Sorghum grains were seeded (cv. BRS 310) together with piatã grass (*Urochloa brizantha* cv. BRS Piatã) in the second half of April. Broadcast fertilization was carried out with 200 kg ha^{-1} of 5-25-15 (NPK) fertilizer; however, sorghum was not harvested because of the low productivity achieved, which is explained by a water deficit that occurred soon after seeding.

In April 2010, 80% of the eucalyptus trees showed DBHs over six cm, which allowed the first pruning up to two meters height, which allowed the entrance of nelore heifers during their period of reproduction in May 2010. The grazing method used was the continuous stocking system, with a variable stocking rate until July 2012.

To obtain higher quality wood, two additional prunings were carried out, the second in July 2011 up to four meters height and the third in July 2012 up to six meters height.

From September 2012 to March 2013 the step was repeated for the soybean crop, the implanting of piatã grass and the use of heifers for grazing.

Data Collection

Six years after planting, a census of treated trees was carried out considering the circumference at breast height (CBH) in centimeters of all individuals with bark. The measurements were made with the help of a tape measure; afterwards, the results of the CBH measurements were converted into DBH. The total height (h) in meters was measured for groups of 20 individuals in the crop rows with the help of a haglof compass clinometer.

The diametric data were distributed in seven classes for the scaling procedure with standing trees (a non-destructive method because this was an experiment) using a Criterion RD 1000 Electronic Dendrometer, Laser Technology, Inc, USA. Ten trees were selected based on diameter class and randomly distributed to cover the class range, producing 36 trees in the $ICLF_1$ system, 35 trees in the $ICLF_2$, and a total of 71 cubed trees in both systems.

The Hohenadl's volume calculation method (5 sections) was used. Based on the total height of the trees, heights and diameters were obtained in the following proportions: 10%, 30%, 50%, 70%, and 90%.

Statistical analysis of collected data

The Student's t-test was considered significant at the 95% level for the variables DBH and total height. The test led to the definition of how the modeling of height and volume of each tree would be taken, by treatment or for the experiment as a whole.

A second Student's t-test was applied after calculating the individual tree volumes and the volumetric stocks per hectare to verify if there was a difference between treatments.

Modeling of height and volume

The nonlinear growth models were fitted to the DBH and height by the statistical package SAS (Statistical Analysis System) PROC NLIN; the parameters of the models were estimated by the Gauss-Newton method. For modeling, the eight nonlinear growth height models selected from the forest literature were fitted (Table 1).

Table 1. Nonlinear growth models tested for modeling the height.

Model	Equation	
Logistic	h = β0 /(1 + exp((β1 - β2*d)	(1)
Gompertz	h = β0 * exp(- exp(β1-β2 * d))	(2)
Richards	h = β0 / (1 + exp((β1 - β2*d)) * (1/β3)	(3)
Weibull	h = β0 - β1 * exp(- β2 * d β3)	(4)
Van Bertalanffy	h = β0 * (1 - β1 * exp(-β2 * d))^3	(5)
Brody	h = β0 * (1 - β1 *exp(-β2 * d))	(6)
Mitscherlich	h = β0 * (1 - exp(β1 * d))	(7)
Chapman and Richards	h = β0 * (1 - exp(β1 * d))^(1/(1-β2))	(8)

Legend: h = total height of the tree (m); d = diameter situated 1.30 m from the ground (cm); exp = exponential; βi = coefficients of models.

To estimate the volumes, six nonlinear growth models selected in the forest literature were tested (Table 2). The obtained data from the rigorous scaling procedure of five to seven trees per diameter class (which must be selected to faithfully represent the forest diametric distribution) are necessary for the adjustment of the volumetric equations (Campos & Leite, 2013).

Table 2. Models tested for modeling the volume.

Model	Equation	
Schumacher and Hall	v = β0*d1^β1*h^β2	(1)
Takata	v = (d^2*h)/(β0+β1*d)	(2)
Honner	v = (d^2)/(β0+β1*1/h)	(3)
Logístic	v = β0 /(1 + exp((β1 - β2*d)	(4)
Gompertz	v = β0 * exp(- exp(β1 - β2 * d))	(5)
Weibull	v = β0 - β1 * exp(- β2 * d β3)	(6)

Legend: v = volume (m^3); d = diameter situated 1.30 m from the ground (cm); h = total height of the tree (m); exp = exponential; βi = coefficients of models.

Model Selection

The selection of the best regression model was based on the following statistical criteria:

Akaike information criterion (AIC), corrected Akaike information criterion (AIC_C), Bayesian information criterion (BIC), lower standard error of estimate in percentage (S_{yx}%) and coefficient of determination (R^2).

The Akaike information criterion (AIB) (Akaike, 1974), the corrected Akaike information criterion (AIC_C) and the Bayesian information criterion (BIC) (Akaike, 1978) were used to compare the adjusted models. The Akaike Information Criterion is defined by:

$$\mathrm{AIC} = -2 + 2\mathrm{r}$$

where: = log-likelihood maximized, r = p + 1, and p represents the number of model parameters.

The Bayesian information criterion is defined as:

$$\mathrm{BIC} = -2 + \frac{\mathrm{rlog}}{9\mathrm{n}}(\mathrm{n})$$

where: n = number of observations.

The lower the value of AIC and BIC, the better the explanation of the variability of the data by the model. The standard error of the estimation is a criterion widely used in the evaluation of the adjustment quality of dendrometric equations; it can be used in absolute dimensions (Syx) or percentages (Syx%) (Sanquetta et al., 2014).

Results and discussion

The data of height and diameter at breast height of the trees in both spatial arrangements are presented in Table 3. The treatments did not influence the evaluated characteristics ($p < 0.05$).

Table 3. Total height (h) and Diameter at Breast Height (DBH) of *E. urophylla* x *E. grandis* – clone H 13, in two integrated crop-livestock-forest systems, in Campo Grande, Mato Grosso do Sul, at six years old.

Treatment	h (m)	DBH (cm)
$ICLF_1$ (14 x 2 m)	20.66 a	21.98 a
$ICLF_2$ (22 x 2 m)	21.61 a	22.02 a

Averages followed by the same letter in the columns do not differ, according to the p-value ($p < 0.05$).

The tolerance to competition and the efficiency in the use of environmental resources are factors that influence the growth and development of trees (Binkley, 2004; Boyden, Binkley, & Stape, 2008). In a study of the influence of different spatial arrangements on the growth of different eucalyptus clones, Ferreira et al. (2016) concluded that space influences the behavior of eucalyptus clones and that there are differences in the growth of different genetic materials when they are implanted in the same space. However, the same genetic material, as well as the spacing, was used for both treatments in this study, which provided low stand plants; those facts thus justify the lack of significant differences in the evaluated characteristics in the present study.

The lack of significant differences between the variable averages (height and DBH) of the treatments provided a group of averages of height, DBH of cubed trees for unique databases; a single hypsometric equation was fitted that could estimate the height of trees that were not measured in both systems (Table 4).

Table 4. Parameter estimates and the criteria adopted to assess the model adjustment of the height of trees in both systems ($ICLF_1$ and $ICLF_2$).

Model	β0	β1	β2	β3	R^2	AIC	AIC_C	BIC	S_{yx}(%)
Logístic	25.23	11.4886	4.3871		0.99	967.2	967.3	980.8	9.74
Gompertz	26.16	1.4448	0.1583		0.99	977.8	978	991.4	9.97
Richards	24.37	17.6562	2.4135	3.7174	0.99	961.8	962	978.9	9.58
Weibull	24.34	18.8228	0.000295	2.9786	0.86	962.2	962.5	979.3	9.59
Van Bertalanffy	26.72	0.967	0.1346		0.99	983.2	983.4	996.9	10.10
Brody	28.84	1.3859	0.0855		0.84	998.2	998.4	1011.9	10.44
Mitscherlich	37.75	0.0409			0.99	1031.8	1031.9	1042	11.29
Chapman and Richards	26.51	0.1369	0.673		0.99	983.3	983.5	997	10.10

Legend: βi = coefficients of models; R^2 = coefficient of determination; AIC = Akaike information criterion; AICC = corrected Akaike information criterion; BIC = Bayesian Information Criterion and S_{yx} (%) = lower standard error of estimate in percentage.

Except for the nonlinear growth models of Weibull and Brody, all the models tested presented 99% adjustments related to the data (Table 4). However, the equation that was adjusted in accordance with the Richards model was used for estimating the height of other trees that were not measured inside the population. The Richards nonlinear model presented the lowest values of AIC (961.8), AIC_C (962), BIC (978.9), and S_{yx}(%) (9.58) and was thus the model chosen to estimate the height of the unmeasured trees.

Models with biological realism are widely used in the forest environment to model the growth of forest stands (Vendruscolo et al., 2017), and studies have proven the efficiency of these models, such as the Gompertz model, and for hypsometric relationships (Vendruscolo et al., 2015). One study used nonlinear equations and neural networks to estimate the height of Crimean juniper trees and concluded that the nonlinear models of Gompertz and Bertalanffy-Richards, as well as neural networks, presented a valid solution for the data under study (Özçelik, Diamantopoulou, Crecente-Campo, & Eler, 2013)

For the adjustment of the volumetric models (Table 2), data were used from the volume calculation method of standing trees in accordance with the frequency in each DBH class (Table 5).

Table 5. Frequency and total number of cubed trees in both systems ($ICLF_1$ and $ICLF_2$), per each DBH class.

DBH Class	Frequency	Number of cubed trees
1	20	8
2	72	12
3	99	11
4	358	12
5	1.484	12
6	360	11
7	10	5
Total	2.403	71

All models achieved high values of R^2 (Table 6), with variations from 0.95 to 0.99 that demonstrated a high level of relation between the volume and the independent variables (DBH and h). In a study of the hybrid *Eucalyptus urograndis* in the State of Goiás, Brazil, the authors tested four volumetric models and found adjusted coefficients of determination with variations from 0.9561 to 0.9890 (Venturoli & Morales, 2014). The data also corroborated the findings of Lemos-Junior et al. (2016), who tested 8 models and found coefficients of determination between 0.8793 and 0.9953.

Table 6. Adjusted volumetric equations for both treatments and their statistics.

Model	β0	β1	β2	β3	R^2	AIC	AIC_C	BIC	S_{yx} (%)
Schumacher and Hall	0.000088	1.6615	1.0353		0.99	-242.4	-241.8	-233.3	14.75
Takata	19735.1	410.4			0.99	-243.6	-243.2	-236.8	14.84
Honner	237.3	24780.1			0.98	-229.4	-229.0	-222.6	16.39
Logístic	0.8454	227622	50.228		0.98	-198.3	-197.7	-189.2	20.12
Gompertz	11611	20439	0.0894		0.95	-202.2	-201.6	-193.1	19.57
Weibull	0.9934	10034	0.000121	27.019	0.95	-200.3	-199.4	-189.0	19.55

Legend: βi = coefficients of models; R^2 = coefficient of determination; AIC = Akaike information criterion; AIC_C = corrected Akaike information criterion); BIC = Bayesian Information Criterion and Syx (%) = lower standard error of estimate in percentage.

The nonlinear growth model of Takata presented the lowest values of AIC (-243.6), AIC_C (-243.2), BIC (-236.8), and Syx% (14.84%) (Table 6); the Takata model, as well as the model chosen to estimate the volume of trees measured and based on these parameters, is the most suitable for estimating the population volume. Miguel & Leal (2012), studying a stand of *Eucalyptus urophylla* S. T. Blake located in the Niquelandia in the state of Goias, verified that the Takata model produced a homogeneous distribution of residues with a standard error of a very considerable estimate (8.86%) and a determination coefficient ($R^2_{\%}$ = 98.9) very similar to that found in the present study ($R^2_{\%}$ = 99).

Venturolli (2014) studied the volumetry of a hybrid of *Eucalyptus grandis* x *E. urophylla* in the Cerrado and observed that the four models studied presented a correction of data superior to 95%, which stood out like the model of Takata (R^2 = 0.96). In a study of *Eucalyptus grandis x urophylla* in a 6-year-old crop-livestock-forest integration system in the city of Cachoeira Dourada, Goiás State, using several nonlinear growth models, the Takata model presented a 99% adjustment (Lemos-Junior et al., 2016).

After gathering the tree height data and the DBH measures of all trees from the census, it was possible to calculate (using the adjustment equation in accordance with the Takata model) the estimates for the individual volume of wood (m^3 tree^{-1}) and for the wood volume per hectare (m^3 ha^{-1}) at six years of age for each treatment. The Student´s t-test was used to verify if there were any differences between the average volumes of individual trees and per hectare volumes in both treatments (Table 7).

Table 7. Productivity of *E. urophila* x *E. grandhis* – H 13m clone in two integrated crop-livestock-forest systems, Campo Grande, Mato Grosso do Sul, at six years old.

Treatment	Volume (m^3 tree^{-1})	Volume (m^3 ha^{-1})
$ICLF_1$ (14 x 2 m)	0.4178 a	149.20 a
$ICLF_2$ (22 x 2 m)	0.4144 a	93.9417 b

Averages followed by the same letter, in columns, do not significantly differ according to the p -value ($p < 0.01$).

Because there was no significant difference between heights and between DBHs of both systems, it was expected that the wood volume per plant would present a similar behavior; therefore, there was no significant difference ($p < 0.01$) between the wood productivity of individual trees in both systems.

Lemos-Junior et al. (2016) studied an arrangement of eucalyptus in triple lines in a crop-livestock-forest integration system with 845 trees ha^{-1} and found a volume of 259.93 m^3 ha^{-1}. It was observed in the present study that in the $ICLF_1$ arrangement, the volume found was only reduced by 28%, although this system presented a lower tree value than the mentioned study (58%). For the $ICLF_2$ arrangement, with an even greater reduction in the number of individuals (73%), the reduction in volume was only 36%.

According to Oliveira, Macedo, Venturin, and Higashikawa (2009), the production capacity of a small farm is achieved at first by planting with denser spacing compared with broader plantings. However, the initial differences of production tend to decrease over the years, although they become similar when the plants with more space completely use the available natural resources, which results in equivalent production per area for all spacings of the planting (Berger, Schneider, Finger, & Haselein, 2002). Therefore, because of the huge spacings between eucalyptus rows in the present study, the production capacity of small farms has not yet been reached, which is highlighted by the similarity of wood productivity per tree between treatments.

Table 7 shows that the production of wood per hectare in the $ICLF_1$ treatment was higher than the productivity presented in the $ICLF_2$, which confirms the view that higher densities of trees give larger volumes of wood per area (Muller, Couto, Leite, & Brito, 2005; Ferreira et al., 2016).

However, according to Ferreira et al. (2016), the differences in the wood volume per hectare between less-dense and more-dense populations tend to decrease with the increase in the average age of the population because of increased competition for water, lighting, nutrients and space among individuals in the more-dense population, which thus reduces their growth rate. It is important to note that in large spacings, such as those of the present study, it is necessary to use a longer period of time so that the productivities of different spatial arrangements can become similar and the necessary resources for the growth of plants will be available for a long time.

Conclusion

The characteristics of total height, Diameter at Breast Height (DBH) and wood volume per tree were not influenced by spatial arrangements of simple lines until six years after the planting, but the number of plants heavily influenced the wood volume per hectare. The Richards nonlinear model estimated the individual heights of trees with greater accuracy, and the Takata nonlinear model estimated the individual volume of wood with bark with greater accuracy. There is a relationship between the height of the individuals and the DBH in crop-livestock-forest integration systems, as well as a relationship between volume and height and DAP.

References

Akaike, H. A. (1974) A new look at the statistical model identification**.** *IEE Transactions on Automatic Control, 19*(6), 716-723. DOI: 10.1109/TAC.1974.1100705

Akaike, H. A. (1978) A new look at the Bayes procedure. *Biometrika*, *65*(1), 53-59. DOI: 10.2307/2335276

Andrade, V. C. L., & Leite, H. G. (2011). Hipsometric relationship modeling using data sampled in tree sacaling and inventory plots. *Revista Árvore*, *35*(1), 157-164. DOI: 10.1590/S0100-67622011000100019

Azevedo, G. B., Sousa, G. T., Barreto, P. A. B., & Conceição Júnior, V. (2011a) Estimativas volumétricas em povoamentos de eucalipto sob regime de alto fuste e talhadia, no sudoeste da Bahia. *Pesquisa Florestal Brasileira*, *31*(68), 309-318. DOI: 10.4336/2011.pfb.31.68.309

Azevedo, T. L., Mello, A. A., Ferreira, R. A., Sanqueta, C. R., & Nakagima, N. Y. (2011b) Equações hypsometrice volumétricas para um povoamento de *Eucalyptus* sp. localizado na FLONA do Ibura, Sergipe. *Revista Brasileira de Ciências Agrárias*, *6*(1), 105-112. DOI: 10.5039/agraria.v6i1a861

Benavides, R., Douglas, G. B., & Osoro, K. (2009). Silvopastoralism in New Zealand: review of effects of evergreen and deciduous trees on pasture dynamics. *Agroforest Systems*, *76*(2), 327–350. DOI 10.1007/s10457-008-9186-6

Berger, R., Schneider, P. R., Finger, C. A. G., & Haselein, C. R. (2002). Efeito do espaçamento e da adubação no crescimento de um clone de *Eucalyptus saligna* Smith. *Ciência Florestal*, *12*(2), 75-87. DOI: 10.5902/198050981682

Binkley, D. (2004). A hypothesis about the interaction of tree dominance and stand production through stand development. *Forest Ecology and Management*, *190*(2), 265–271. DOI: 10.1016/j.foreco.2003.10.018

Boyden, S., Binkley, D., & Stape, J. L. (2008). Competition among Eucalyptus trees depends on genetic variation and resource supply. *Ecology*, *89*(10), 2850–2859. DOI: 10.1890/07-1733.1

Campos, J. C. C., & Leite, H. G. (2013). *Mensuração florestal*: perguntas e respostas. Viçosa, MG: UFV.

Ferreira, A. D., Serra, A. P., Laura, V. A., Ortiz, A. C. B., Araújo, A. R., Pedrinho, D. R., & Carvalho, A. M. (2016). Influence of spatial arrangements on silvicultural characteristics of three eucalyptus clones at integrated crop-livestock-forest system. *African Journal of Agricultural Research*, *11*(19), 1734-1742. DOI: 10.5897/AJAR2016.10990

Heinrich-Böll-Stiftung (2015) *Soil Atlas*: Facts and figures about earth, land and fields. Berlin, GE: Heinrich-Böll-Stiftung, Institute for Advanced Sustainability Studies.

Lemos-Junior, J. M., Silva- Neto, C. M., Souza, K. R., Guimarães, L. E., Oliveira, F. D., Gonçalvez, R. A., ... Calil, F. N. (2016). Volumetric models for *Eucalyptus grandhis* x *urophylla* in a crop-livestock-forest integration (CLFI) in the Brazilian cerrado. *African Jounal of Agricultural Research*, *11*(15), 1336-1343. DOI: 10.5897/AJAR2016.10806

Machado, P. L. O. A., Madari, B. E., & Balbino, L. C. (2010). Manejo e conservação do solo e da água no contexto das mudanças ambientais-Panorama Brasil. In R. B. Prado (Ed.), *Manejo e conservação do solo e da água no contexto das mudanças ambientais* (p. 41-52). Rio de Janeiro, RJ: Embrapa Solos.

Miguel, E. P., & Leal, F. A. (2012). Seleção de equações volumétricas para a predição de volume total de *Eucalyptus urophylla* S. T. Blake na região Norte do Estado de Goiás. *Enciclopédia Biosfera*, *8*(14), 1372-1386.

Muller, M. D., Couto, L., Leite, H. G., & Brito, J. O. (2005). Avaliação de um clone de eucalipto estabelecido em diferentes densidades de plantio para produção de biomassa e energia. *Biomassa & Energia*, *2*(3),177-186.

Nair, V. D., Nair, P. K. R., Kalmbacher, R. S., & Ezenwa, I. V. (2007). Reducing nutrient loss from farms through silvopastoral practices in coarse-textured soils of Florida, USA. *Ecological Engineering*, *29*(2), 192–199. DOI: 10.1016/j.ecoleng.2006.07.003

Oliveira, T. K., Macedo, R. L. G., Venturin, N., & Higashikawa, E. M. (2009). Desempenho silvicultural e produtivo de eucalipto sob diferentes arranjos espaciais em sistema agrossilvipastoril. *Pesquisa Florestal Brasileira*, *60*(esp.), 1-9. DOI: 10.4336/2009.pfb.60.01

Özçelik, R., Diamantopoulou, M. J., Crecente-Campo, F., & Eler, U. (2013). Estimating Crimean juniper tree height using nonlinear regression and artificial neural network models. *Forest Ecology and Management*, *306*, 52-60. DOI: 10.1016/j.foreco.2013.06.009

Pires, M. F. A., & Paciullo, D. S. (2015). Bem-estar animal em sistemas integrados. In F. V. Alves (Ed.), *Sistemas agroflorestais: a agropecuária sustentável.* (p. 117-133). Brasília, DF: Embrapa.

Porfírio-da-Silva, V. (2015) Ideótipo de espécie arbórea para sistemas de integração Lavoura-Pecuária-Floresta. In F. V. Alves (Ed.), *Sistemas agroflorestais: a agropecuária sustentável* (p. 134-147). Brasília, DF: Embrapa.

Sanquetta, C. R., Dalla Corte, A. P., Behling, A, Piva, l. R. O., & Sanquetta, M. N. I. (2014). Uso de critérios estatísticos de seleção de modelos alométricos para estimar biomassa individual de espécies. In A. P. Dalla Corte, C. R. Sanquetta, A. L. Rodrigues, A. S. Machado, S. Péllico Netto, A. Figueiredo Filho, & G. S. Nogueira (Ed.), *Atualidades em mensuração florestal* (p. 398-402). Curitiba, PR: UFPR.

Shibu, J. (2009). Agroforestry for ecosystem services and environmental benefits: an overview. *Agroforest Systems*, *76*(1), 1–10. DOI: 10.1007/s10457-009-9229-7

Soares, C. P. B., Paula-Neto, F., & Souza, A. L. (2012). *Dendrometria e inventário florestal*. Viçosa, MG: UFV.

Vendruscolo, D. G. S, Drescher, R., Souza, H. S., Moura, J. P. V. M., Mamoré, F. M. D., & Siqueira, T. A. S. (2015). Estimativa da altura de eucalipto por meio de regressão não linear e redes neurais artificiais. *Revista Brasileira de Biomassa*, *33*(4), 556-569. DOI: 10.13140/RG.2.1.1742.5684.

Vendruscolo, D. G. S, Chaves, A. G. S., Medeiros, R. A., Silva, R. S., Souza, H. D., Drescher, R., & Leite, H. G. (2017). Estimativa da altura de árvores de Tectona grandhis L. f. utilizando regressão e redes neurais artificiais. *Nativa*, *5*(1), 52-58. DOI: 10.5935/2318-7670.v05n01a09.

Venturoli, F., & Morales, M. M. (2014). Volumetria de um híbrido de *Eucalyptus grandis* x *E. urophylla* no cerrado: similaridade de estimativas. *Agrotrópica*, *26*(3), 167-174.

Wruck, F. J., Behling, M., & Antonio, D. B. A. (2015). Sistemas integrados em Mato Grosso e Goiás. In F. V. Alves (Ed.), *Sistemas agroflorestais: a agropecuária sustentável* (p. 169-194). Brasília, DF: Embrapa.