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Accumulation of carbon and age of thinning of the tree component in agroforestry systems

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ABSTRACT: Agroforestry systems (AFS) are considered large sinks of greenhouse gases (GHG) in the atmosphere. However, little is known about the dynamics of carbon accumulation in tree individuals over the years and the Age Thinning Technique (ATT) to potentialize GHG mitigation. The objective of the study was to predict the growth in carbon and determine the age thinning Technique of the tree component in 3 AFS in the municipality of Viçosa, MG, Brazil, in which System A is composed of eucalypt (*Eucalyptus saligna*) + pasture (*Brachiaria decumbens*) and systems B and C with eucalypt (*Eucalyptus urophylla* x *Eucalyptus grandis*) + pasture (*Brachiaria decumbens*). The Gompertz and Logistic models were employed to predict the timber volume and carbon growth. The ATT was determined based on the maximum productivity in timber volume per unit area. The curve asymptotic values of the systems A, B and C were 450, 221 and 226 m^3 ha^{-1} for the volume and 104, 51 and 52 MgC ha^{-1} for the carbon, respectively. Stabilization of carbon accumulation will occur close to 100 months for systems A and B and at 80 months for system C. As the ATT ranged 64-80 months, the thinning is recommended before this age to promote the carbon accumulation of the remaining arboreal individuals.

Key words: growth; crop-livestock-forest; modeling; production; prognosis

Acúmulo de carbono e idade técnica de desbaste do componente arbóreo em sistemas agroflorestais

RESUMO: Os sistemas agroflorestais (SAFs) são considerados grandes sumidouros de gases de efeito estufa (GEE) da atmosfera. No entanto, pouco se conhece sobre a dinâmica de acúmulo de carbono nos indivíduos arbóreos ao longo dos anos e a Idade Técnica de Desbaste (ITD) para potencializar a mitigação dos GEE. O objetivo do estudo foi prognosticar o acúmulo de carbono e determinar a idade técnica de desbaste do componente arbóreo em 3 SAFs no município de Viçosa – MG. O Sistema A é composto por eucalipto (*Eucalyptus saligna*) + pastagem (*Brachiaria decumbens*) e os Sistemas B e C com eucalipto (*Eucalyptus urophylla* x *Eucalyptus grandis*) + pastagem (*Brachiaria decumbens*). Empregou-se os modelos Gompertz e Logístico para projetar o volume e carbono. A ITD foi determinada baseando-se na máxima produtividade em volume de madeira por unidade de área. O valor assintótico da curva dos sistemas A, B e C foi de 450, 221 e 226 m^3 ha^{-1} para volume e 104, 51 e 52 MgC ha^{-1} para carbono, respectivamente. A estabilização do acúmulo de carbono ocorrerá próximo aos 100 meses para os sistemas A e B e aos 80 meses para o sistema C. Como a ITD variou de 64 a 80 meses, recomenda-se o desbaste previamente a esta idade para favorecer o acúmulo de carbono dos indivíduos arbóreos remanescentes.

Palavras-chave: crescimento; lavoura-pecuária-floresta; modelagem; produção; prognose

Introduction

In recent years, the Brazilian Government has adopted measures to mitigate greenhouse gas (GHG) emissions arising mainly from the agricultural sector and land use change (MCTIC, 2016), as well as to promote the creation of conditions to deal with the impacts of global climate change.

In this context, the Low Carbon Agriculture (LCA) program was created with the goal of encouraging the adoption of sustainable practices that guarantee the reduction of GHG emissions, as well as the increase of income of rural producers especially with the expansion of the following technologies: recovery of degraded pastures; No-tillage System - NTS; Biological Nitrogen Fixation - BNF; even-aged forests; crop-livestock-forest integration - CLFi; and Agroforestry Systems - AFSs (Brasil, 2012).

An agroforestry system can be defined as any system of land use that involves the deliberate use of trees or other perennial woody plants with agricultural crops, pastures and/or animal raising in order to reap benefits from the resulting ecological and economic interactions (Nair, 1993). These systems represent an important strategy to promote, among other environmental services, carbon stock in view of their potential for storing atmospheric carbon in the various components of the system, especially the arboreal (Grace et al., 2014). However, scientific information on the actual carbon sequestration potential of these systems is still needed, as well as the improvement of their management to make them effective CO_2 sinks.

For the management of AFSs, as well as of any type of forest production system, it is fundamental to predict the growth and Technical Thinning Age (TTA) of the tree component at future ages (Binoti et al., 2015). Functions known as growth and production models, which include attributes of the population such as age, basal area and site index, are used for this purpose, to obtain information of interest (Campos & Leite, 2013).

Prognosis in even-aged stands can be accomplished by means of two approaches: minimum stratification followed by fitting models with a greater number of explanatory variables, and maximum stratification by fitting simple models, including only age as independent variable (Campos & Leite, 2013). The second approach is the most used in Brazil, due in part to the great diversity of genotypes. In this case, the use of sigmoidal Logistic, Gompertz, Richards models or exponential models is common (Ratkowsky, 1983; Seber & Wild, 1989).

Many studies on growth and production modeling have already been conducted in AFSs. Salles et al. (2012) studied the best way of using Clutter model to estimate the growth and production of eucalypts clones; Lopes (2007) sought to develop and evaluate a diameter distribution model for eucalypts clones; and Souza et al. (2005) proposed to make the prognosis of the present and future production of eucalypt clone stands subject to planting in open spaces in agroforestry systems.

In the specific case of carbon, the vast majority of studies are related to the potential carbon sequestration at one specific time (Tsukamoto Filho et al., 2004; Müller et al., 2009). In turn, the scientific knowledge about the dynamics of carbon accumulation over the years in the various components of AFSs, especially the arboreal, is incipient. This same need for scientific evidence is perceived in the determination of TTA, because the best time to the thinning in agroforestry systems in their different types of arrangements is not known (Oliveira Neto & Paiva, 2010).

In this sense, the objective of this study was to predict the carbon accumulation and determine the technical thinning age of the tree component in three agroforestry systems in the city of Viçosa, MG.

Material and Methods

Study area

The city of Viçosa, MG, Brazil, has an average altitude of 650 m and its climate is of the Cwa type according to the Köppen system, with dry winter and rainy summer (Alvares et al., 2013). The average annual rainfall is approximately 1,200 mm and the average annual temperature is 19.4°C, with a minimum of 14.8°C and a maximum of 26.4°C (Ramos et al., 2009). According to Golfari (1975), the Thornthwaite and Mather Water Balance from May to September showed the occurrence of water deficit and absorption of water from the soil to supply the physiological needs of plants.

The study area was subdivided into 3 AFSs according to their year of implantation of the AFS and the components used (Table 1). The spacing of the tree component was 8 m x 3 m (24 m^2 $plant^{-1}$) in all systems, and 0.20 kg pit^{-1} of NPK was used at planting (year 0) (06-30-06). After 3 months, cover fertilization consisted in the application of 0.16 kg NPK $plant^{-1}$ (05-20-20).

Data collection and analysis

Sampling was random in all three systems, using 750 m^2 (25 x 30 m) sample units. In total, 22 plots (System A: 4 plots; System B: 7 plots; System C: 11 plots) were distributed proportionally to the planting area.

In all the plots, tree circumference at 1.3 m height (DBH) and total tree height were estimated using a Vertex IV digital hypsometer. Measurements were carried out from 2012 to 2015, always in the months of September and October.

Table 1. Year of implantation, tree component and pasture type of the agroforestry systems evaluated.

System	Year of implantation	Area (ha)	Tree component	Pasture
A	2007	0.93	*Eucalyptus saligna*	*Brachiaria decumbens*
B	2008	2.63	*Eucalyptus urophylla* × *Eucalyptus grandis*	*Brachiaria decumbens*
C	2009	4.95	*Eucalyptus urophylla* × *Eucalyptus grandis*	*Brachiaria decumbens*

In the initial and final years (2012 and 2015), a diametric distribution with amplitude of 2 cm was made to define the sampling range for modeling of tree volume. Three sample trees were felled and their volume per DBH class was estimated. Tree volume was obtained by applying the Smalian formula, measuring bark diameter and thickness at 0.30 m, 0.70 m, 1.00 m, 1.30 m height and from then every 2 m up to a minimum diameter of 3.0 cm.

Tree volume data were used to fit a Schumacher-Hall volumetric model (Eq. 1) using the least squares method in the Statistica 13 software (Statsoft, Inc., USA). To evaluate the accuracy of the equation, the following statistics were used: adjusted coefficient of determination (R^2) and residual standard error ($s_{y.x}$).

$$V = \beta_0 \cdot DBH^{\beta_1} \cdot H_t^{\beta_2} \tag{1}$$

where:

V - volume , m^3;
DBH - diameter at breast height, cm;
H_t - total height, m; and,
β_0, β_1 and β_2 - parameters of the models.

Biomass and carbon stock were determined by the average carbon density and content of wood, respectively. These analyses were performed in pairs of opposite wedges (crossing the pith) from 2.5 cm thick wood discs collected at 1.30 m from the ground and at 0%, 25%, 50%, 75% and 100% of the commercial height of the stem (Torres et al., 2016). Basic wood density was determined by the water immersion method (Vital, 1984; ABNT, 2003), while wood C content was determined by the dry combustion method using an elementary determinant of C, H and N (TruSpec Micro CHN LECO Corp., St. Joseph, MI).

Besides volume (m^3 ha^{-1}), biomass (Mg ha^{-1}) and carbon content (MgC ha^{-1}), the quadratic diameter (cm), average height (m) and basal area (m^2 ha^{-1}) of systems A, B and C were determined for every year from 2012 to 2015.

Growth and production modeling

In order to predict growth and production at population level in terms of volume and carbon as a function of age, Gompertz (Eq. 2) and Logistic (Eq. 3) models were fitted using the DAPCurveFit software (version 0.7), made available free of charge by the NeuroForest project (http://neuroforest.ucoz.com/):

$$y = \alpha e^{\left(e^{(\beta - \gamma I)}\right)} + \varepsilon \tag{2}$$

$$y = \frac{\alpha}{\left(1 + \beta e^{(-\gamma I)}\right)} + \varepsilon \tag{3}$$

where:

y - variable of interest;
I - age, months; and,
α, β and γ - model parameters.

The best model was chosen with basis on the coefficient of determination (R^2) and residual standard error ($s_{y.x}$) besides graphical analysis of the fitted models.

Determination of technical thinning age (TTA)

Technical thinning age was based on maximum productivity in terms of wood volume per unit area. Annual Average Increment (AAI) is equal to Current Annual Increment (CAI) and indicates the best time of thinning (Campos & Leite, 2013).

Results and Discussion

Forest survey and carbon storage

The equation ($V = 0.000059 * DBH^{1.476661} * H_t^{1.469720}$) to estimate volume of trees of the system presented a satisfactory adjustment ($R^2 = 0.9825$ and $s_{y.x} = 0.0562$). Average values of density of 0.44 g cm^3 and carbon content of 52.3% were used in the calculation of carbon stock (Table 2).

Carbon stock values varying from 48.19 to 101.04 MgC ha^{-1} were found for the year 2015 (Table 2), corresponding to an Average Annual Increment of Carbon (AAIc) of 7.22 to 13.04 MgC ha^{-1} $year^{-1}$.

Müller et al. (2009) carried out a study in a mixed silvipastoral system located in the experimental field of Embrapa Cattle Milk in Coronel Pacheco - MG. The system was implanted in 10 m transects with rows of trees spaced 3 m x 3 m, interspersed with 30 m of pasture. At 10 years, after mortality and selective thinning, the final density was 105 trees ha^{-1}, being 60 of *Eucalyptus grandis* and 45 of *Acacia mangium*. The estimated stock values found were 14.29 MgC ha^{-1}, of which 11.17 MgC ha^{-1} were stored in *E. grandis* and 3.12 MgC ha^{-1} in *A. mangium,* corresponding to an AAIc of 1.43 MgC ha^{-1} $year^{-1}$. In Müller's study, despite the higher stand age, the low density of trees contributed to lower carbon storage when compared to the present study.

Tsukamoto Filho et al. (2004) studied carbon sequestration in an AFS with eucalypts clones (*Eucalyptus* sp.) planted at a spacing of 10 m x 4 m, rice (*Oriza sativa* L. cv. Guarany), soy (*Glycine max* (L.) Merr. cv. Conquista) and brachiaria (*Brachiaria brizantha* stapf.) in the municipality of Paracatu, MG, and observed a carbon stock in tree shoots of 49.5 MgC ha^{-1} at 8 years of age, and an AAIc of 6.18 MgC^{-1} $year^{-1}$. In this case, although planting age was close to that of the system A, for example, this study presented lower carbon stock, which can be explained by the smaller number of trees per unit of area.

Growth and production modeling

Based on data of the forest survey, Logistic and Gompertz models were fitted for the three systems studied as a function of age. There was a satisfactory adjustment for volume and carbon in both models. However, the logistic model was the one that best described growth despite presenting a coefficient of determination (R^2) and residual standard error

Table 2. Quadratic diameter (q), average height (h), basal area (G), volume (V), biomass (B) and carbon (C) of the tree component of Agroforestry Systems, where: System A: eucalypts (*Eucalyptus saligna*) + pasture (*Brachiaria decumbens*); Systems B and C: eucalypts (*Eucalyptus urophylla* × *Eucalyptus grandis*) + pasture (*Brachiaria decumbens*).

Systems	Age (months)	q (cm)	h (m)	G (m^2 ha^{-1})	V (m^3 ha^{-1})	B (Mg ha^{-1})	C (MgC ha^{-1})
				2012			
A	57	22.00	25.80	14.40	258.20	113.61	59.42
B	44	13.40	16.00	5.45	61.40	27.02	14.13
C	32	12.20	13.30	4.56	43.50	19.14	10.01
				2013			
A	69	23.90	30.10	17.00	361.90	159.24	83.28
B	56	17.40	20.40	9.30	134.50	59.18	30.95
C	44	17.30	20.20	9.30	132.00	58.08	30.37
				2014			
A	81	24.20	31.20	17.50	432.50	190.30	99.53
B	68	19.20	21.50	11.30	180.80	79.55	41.60
C	56	18.80	23.50	10.90	192.40	84.66	44.28
				2015			
A	93	24.50	33.10	18.50	439.10	193.20	101.04
B	80	20.60	22.50	12.80	209.40	92.14	48.19
C	68	20.00	24.00	12.40	223.70	98.43	51.48

($s_{y.x}$) similar to the Gompertz model. However, the behavior of the curve to estimate growth at the lower ages and the biological interpretation were determinant factors for choosing the model (Figure 1).

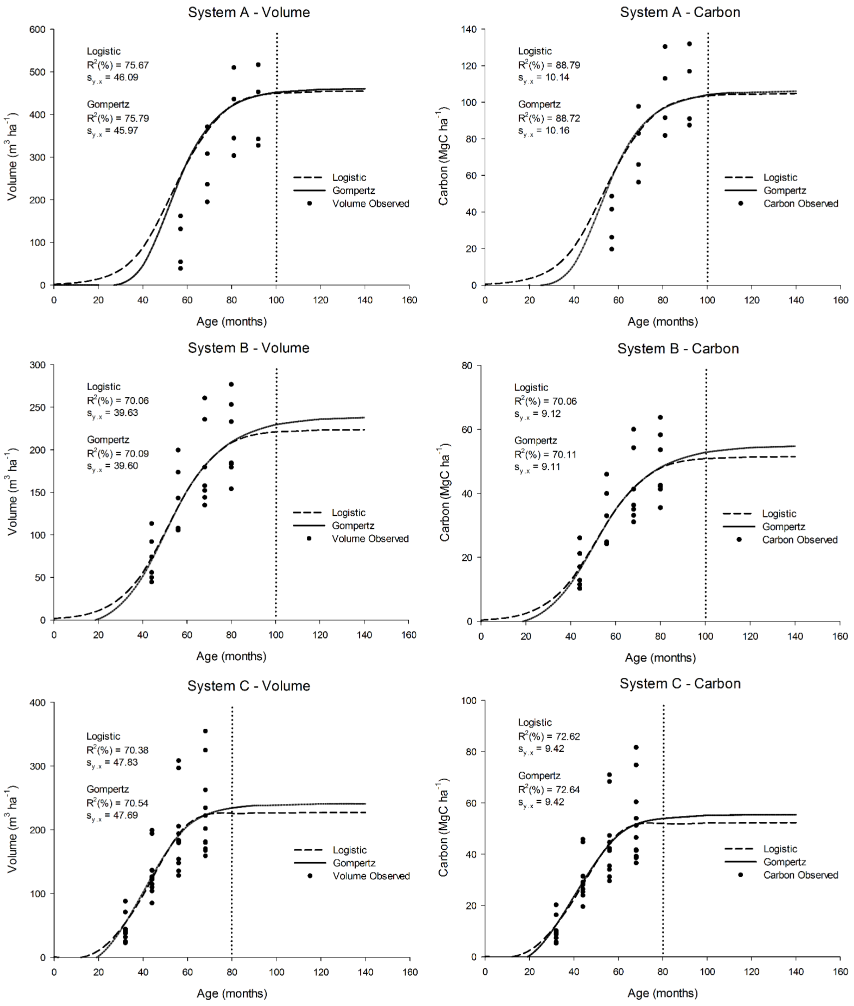

Figure 1. Volume (m^3 ha^{-1}) and carbon (MgC ha^{-1}) growth curve according to Logistic and Gompertz models for Agroforestry Systems, where: System A - eucalypts (*Eucalyptus saligna*) + pasture (*Brachiaria decumbens*); Systems B and C - eucalypts (*Eucalyptus urophylla* × *Eucalyptus grandis*) + pasture (*Brachiaria decumbens*).

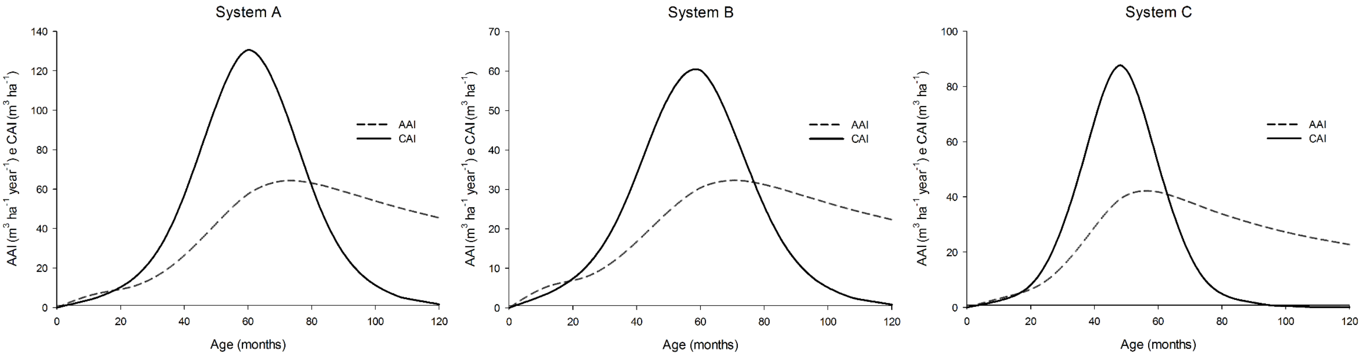

Figure 2. Current Annual Increment (CAI) and Annual Average Increment (AAI) of Agroforestry Systems, where: System A - eucalypts (*Eucalyptus saligna*) + pasture (*Brachiaria decumbens*); Systems B and C - eucalypts (*Eucalyptus urophylla* × *Eucalyptus grandis*) + pasture (*Brachiaria decumbens*).

As for estimates of the parameters obtained and the behavior of the growth curves (Figure 1), it was observed that the asymptotic value of the curve for volume will be 450 m^3 ha^{-1} in system A, 221 m^3 ha^{-1} in system B and 226 m^3 ha^{-1} in system C, and stabilization of growth will occur in around 100 months in the systems A and B and around 80 in the system C. Thus, it is verified that the AFSs are already close to their stabilization in the current conditions of management of the area.

In the studies of Paula et al. (2013) and Barbosa (2015) in the city of Vazante - MG, an asymptotic curve value of 109.84 m^3 ha^{-1} was found for volume at a spacing of 9 m x 3 m (27 m^2 $plant^{-1}$) at 54 months and 99.32 m^3 ha^{-1} at a greater spacing of 9.5 m x 4.0 m (38 m^2 $plant^{-1}$) at 84 months. Apart from the clones used in each AFS, the nutritional factors and the edaphoclimatic factors of each area, it is noticed that, compared to the present study, the larger the useful area of the plant, the smaller is the asymptotic value of the curve. However, regularity in the age of growth stabilization was not observed.

As for carbon, the asymptotic value of the curve corresponds to 104 MgC ha^{-1}, 51 MgC ha^{-1} and 52 MgC ha^{-1} in systems A, B and C, respectively. The age of stabilization was the same as for growth in volume. Considering the carbon stock values found in 2015 (Table 2), minimum increases are expected for the three systems until reaching their maximum potential for carbon storage.

Technical thinning age (TTA)

The average annual increment (m^3 ha^{-1} $year^{-1}$) and the current annual increment (m^3 ha^{-1}) for determining technical thinning age were estimated based on the logistic model (Figure 2).

When analyzing the meeting point of the IMA and ICA of each system, the ITD was exceeded. Thus, the competition is already affecting the growth of the arboreal component of the system (Campos & Leite, 2013). The thinning of these systems should have been performed close to 80 months for systems A and B and close to 64 months for system C.

In the studies conducted by Paula et al. (2013) and Resende et al. (2004) in forest monocultures of *Eucalyptus* sp. planted at denser spacing, TTA ranged from 48 to 59 months depending on the site index of the area. When comparing these results with the present study, it is noticed that the TTA of the AFSs tend to be higher than that of more dense systems.

On the other hand, in both the more dense systems and the AFSs, thinning should be done before reaching the TTA if better quality wood is desired, such as wood to be used for sawing and/or electrification. This practice is an important strategy for the resumption of growth of forest stands, concentrating the production potential in an ever smaller number of individuals (Silva et al., 2012). Thinning is also important to increase the transmittance of photosynthetically active radiation for higher forage production in AFSs (Oliveira Neto et al., 2010).

According to Ofugi et al. (2008), AFSs with a population density of 250-350 trees ha^{-1} have a greater gain in diameter when compared to forest monocultures with 1,666 trees ha^{-1}.Utility poles can be harvested at 8 years and logs for sawing at 12 years.

Thinning at the correct time is essential for future production not to be compromised (Campos & Leite, 2013), and to favor carbon storage in the remaining trees.

Conclusions

Stabilization of volume and carbon increment in AFSs with a spacing of 8 m x 3 m occurs at around 80 and 100 months of age. The trees present in the study area have a high carbon stock capacity, demonstrating their important role for the mitigation of GHG emission.

Technical thinning age ranges from 64 to 80 months. It is recommended to intervene (thinning) in the AFSs before this age is reached in the case of wood destined to electrification poles or for sawing and to promote the accumulation of carbon in the remaining tree individuals.

Literature Cited

Alvares, C.A.; Stape, J.L.; Sentelhas, P.C.; Moraes, G. de; Leonardo, J.; Sparovek, G. Köppen's climate classification map for Brazil. Meteorologische Zeitschrift, v. 22, n. 6, p. 711-728, 2013. https://doi.org/10.1127/0941-2948/2013/0507.

Associação Brasileira de Normas Técnicas - ABNT. Normas técnicas NBR 11941. Brasília: ABNT, 2003. 5p.

Barbosa, R.A. Crescimento de clone de eucalipto em espaçamentos amplos com variação na distância entre plantas na linha de plantio. Viçosa: Universidade Federal de Viçosa, 2015. 37p. Dissertação Mestrado. http://www.locus.ufv.br/handle/123456789/7298. 22 Jun. 2017.

Binoti, M.L.M.S.; Leite, H.G.; Binoti, D.H.B.; Gleriani, J.M. Prognose em nível de povoamento de clones de eucalipto empregando redes neurais artificiais. Cerne, v. 21, n. 1, p. 97-105, 2015. https://doi.org/10.1590/01047760201521011153.

Brasil. Ministério da Agricultura, Pecuária e Abastecimento. Plano setorial de mitigação e de adaptação às mudanças climáticas para a consolidação de uma economia de baixa emissão de carbono na agricultura. Brasília, DF: MAPA; ACS, 2012. 173p. http://www.agricultura.gov.br/assuntos/sustentabilidade/plano-abc/arquivo-publicacoes-plano-abc/download.pdf. 26 Mai. 2017.

Campos, J.C.C.; Leite, H.G. Mensuração florestal: perguntas e respostas. Viçosa: Editora UFV, 2013. 605p.

Golfari, L. Zoneamento ecológico do estado de Minas Gerais para reflorestamento. Belo Horizonte: Centro de Pesquisa Florestal da Região do Cerrado, 1975. 65p.

Grace, J.; Mitchard, E.; Gloor, E. Perturbations in the carbon budget of the tropics. Global Change Biology, v. 20, n. 10, p. 3238–3255, 2014. https://dx.doi.org/10.1111/gcb.12600.

Lopes, P.F. Modelo de distribuição de diâmetros para clones de eucalipto em sistema agroflorestal. Viçosa: Universidade Federal de Viçosa, 2007. 42p. Dissertação Mestrado. http://locus.ufv.br/handle/123456789/2966. 07 Jun. 2017.

Ministério da Ciência, Tecnologia, Inovação e Comunicações - MCTIC. Estimativas anuais de emissões de gases de efeito estufa no Brasil. 3.ed. Brasília: MCTIC, 2016. 83p. https://bit.ly/2rVWgWj. 22 Jun. 2016.

Müller, M.D.; Fernandes, E.N.; Castro, C.R.T.; Paciullo, D.S.C.; Alves, F.F. Estimativa de acúmulo de biomassa e carbono em sistema agrossilvipastoril na Zona da Mata Mineira. Pesquisa Florestal Brasileira, v. 1, n. 60, p. 11-17, 2009. https://dx.doi.org/10.4336/2009.pfb.60.11.

Nair, P.K.R. An Introduction to agroforestry. Dordrecht: Kluwer Academic Publishers, 1993. 499 p.

Ofugi, C.; Magalhães, L.L.; Melido, R.C.N.; Silveira, V.P. Integração lavoura-pecuária-floresta (ILPF), sistemas agroflorestais (SAFs). In: Trecenti, R.; Oliveira, M.C.; Hass, G. (Eds.). Integração lavoura-pecuária-silvicultura: boletim técnico. Brasília: MAPA, 2008. p. 20-25.

Oliveira Neto, S.N.; Paiva, H. N. Implantação e manejo do componente arbóreo em sistema agrossilvipastoril. In: Oliveira Neto, S. N.; Vale, A. B.; Nascif, A. P.; Vilar, M. B.; Assis, J. B. (Orgs.). Sistema agrossilvipastoril - integração lavoura, pecuária e floresta. Viçosa: Editora Arka, 2010. v. 1, p. 15-68. http://www.bibliotecaflorestal.ufv.br/handle/123456789/3307. 26 Mai. 2017.

Oliveira Neto, S. N.; Reis, G. G.; Reis, M. G. F.; Leite, H. G. Arranjos estruturais do componente arbóreo em sistema agrossilvipastoril e seu manejo por desrama e desbaste. Informe Agropecuário, v. 31, n. 257, p. 47-58, 2010. http://www.epamig.br/download/informe-agropecuario-257-integracao-lavoura-pecuaria-floresta-2010/#. 12 Jun. 2017.

Paula, R.R.; Reis, G.G.; Reis, M.G.; Neto, S.N.O.; Leite, H.G.; Melido, R.C.N.; Lopes, H.N. S.; Souza, F.C. Eucalypt growth in monoculture and silvopastoral systems with varied tree initial densities and spatial arrangements. Agroforestry systems, v. 87, n. 6, p. 1295-1307, 2013. https://doi.org/10.1007/s10457-013-9638-5.

Ramos, A.M.; Santos, L.A.R.D.; Fortes, L.T.G. Normais climatológicas do Brasil 1961-1990. Brasília: INMET, 2009. 465p.

Ratkowsky, D.A. Nonlinear regression modeling: a unified practical approach. New York: Marcel Dekker, 1983. p. 61-73.

Resende, R.R.; Vale, A.B.; Soares, T.S.; Silva, M.L.; Couto, L.; Vale, R.S. Emprego de um modelo de crescimento e produção para determinação da rotação em povoamentos de eucalipto. Revista Árvore, v. 28, n. 2, p. 219-225, 2004. https://doi.org/10.1590/S0100-67622004000200008.

Salles, T.T.; Leite, H.G.; Oliveira Neto, S.N.; Soares, C.P.B.; Paiva, H.N.; Santos, F.L. Modelo de Clutter na modelagem de crescimento e produção de eucalipto em sistemas de integração lavoura-pecuária-floresta. Pesquisa Agropecuária Brasileira, v. 47, n. 2, p. 253-260, 2012. https://doi.org/10.1590/S0100-204X2012000200014.

Seber, G.A.F.; Wild, C.J. Nonlinear regression. New York: John Wiley, 1989. 792p.

Silva, J.V.; Nogueira, G.S.; Santana, R.C.; Leite, H.G.; Oliveira, M.L.R.; Almado, R.P. Produção e acúmulo de nutrientes em povoamento de eucalipto em consequência da intensidade do desbaste e da fertilização. Pesquisa Agropecuária Brasileira, v. 47, N. 11, p. 1555-1562, 2012. https://doi.org/10.1590/S0100-204X2012001100001.

Souza, A. N. Crescimento, produção e análise econômica de povoamentos clonais de *Eucalyptus* sp em sistemas agroflorestais. Lavras: Universidade Federal de Lavras, 2005. 203p. Tese Doutorado. http://repositorio.ufla.br/jspui/handle/1/4054. 29 Mar. 2017.

Torres, C.M.M.E.; Oliveira, A.C.; Pereira, B.L.C.; Jacovine, L.A.G.; Oliveira Neto, S. N. de; Carneiro, A.D.C.O.; Torres, C.M.M.E. Estimativas da produção e propriedades da madeira de eucalipto em Sistemas Agroflorestais. Scientia Forestalis, v. 49, n. 109, p. 137-148, 2016. https://doi.org/10.18671/scifor.v44n109.13.

Tsukamoto Filho, A.D.A.; Couto, L.; Neves, J.; Passos, C.; Silva, M.D. Fixação de carbono em um sistema agrossilvipastoril com eucalipto na região do Cerrado de Minas Gerais. Agrosilvicultura, v. 1, n. 1, p. 29-41, 2004. http://www.sbag.org.br/03-SBAG-v1-n1-2004-29-41.pdf. 10 Jun. 2017.

Vital, B.R. Métodos de determinação da densidade da madeira. Viçosa: Sociedade de Investigações Florestais, 1984. 21p. http://www.eucalyptus.com.br/artigos/outros/1984_Metodos_determinacao_densidade.pdf. 29 Mar. 2017.