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ORIGINAL PAPER

Prognosis of aboveground woody biomass in a central Brazilian Cerrado monitored for 27 years after the implementation of management systems

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Abstract

Accurate estimation of biomass in natural vegetation sites remains a challenge. Modeling biomass growth and production in Cerrado areas is crucial to understanding the vegetation succession process, especially regarding the changes in biomass accumulation over time. Thus, our objective was to model the growth and production of woody aboveground biomass (living and total) in a cerrado *stricto* sensu monitored for 27 years after implementing management systems. As expected, the basal area (with a diameter taken at 30 cm from the ground level) is the most important predictor variable and showed a higher correlation with the biomass stocks and allowed accurate and consistent estimates of these accumulated stocks over time. Future estimates of biomass production, generated from growth models that estimate production as a function of parameters observed at previous ages, indicate that maximum stocks of living (25.86 ± 0.15 Mg ha^{-1} [mean ± standard deviation]) and total aboveground biomass (26.11 ± 0.15 Mg ha^{-1}) are expected for a period between 28 and 30 years after the implementation of the management systems, with maximum mean annual increment between 23 and 27 years. Furthermore, the systems of equations obtained simulated reductions up to 30% of biomass after the occurrence of a forest fire at 23 years. Thus, our study can be useful for the decision-making process and developing public policies and strategies for managing and conserving natural resources in the Cerrado biome.

Keywords Forest growth and production · Basal area · Natural regeneration · Forest fires · Biomass prediction

Introduction

Estimates of woody vegetation biomass stocks are essential to support decision-making related to forest resource management, use, and conservation. Hence, there has been growing interest in studies concerning the quantification of woody biomass in several ecosystems of the world (Djomo et al. 2011; González-García et al. 2014; Hofansl et al. 2020; Mukul et al. 2016; Rijal et al. 2020; Ryan et al. 2011; Wassihun et al. 2019; Zeng et al. 2017; Zhang et al. 2020). In Brazilian biomes, we highlight the studies in Amazonia (Avila et al. 2018; Barni et al. 2016; Fearnside 2018), Atlantic Forest (Rodrigues et al. 2019; Watzlawick et al. 2012), Caatinga (Albuquerque et al. 2015; Costa et al. 2014; Souza et al. 2019), and Cerrado (Azevedo et al. 2020a; Loiola et al. 2015; Morandi et al. 2018; Paiva et al. 2011; Ribeiro et al. 2011; Zimbres et al. 2020).

Some researches have shown that woody biomass stocks vary among different ecosystems. This variation may result from the interaction between several factors, such as succession stages, management system, site, species composition, climate, occurrence of fires, among others (Azevedo et al. 2020a; Hofansl et al. 2020; Mukul et al. 2016; Rijal et al. 2020; Rodrigues et al. 2019; Yadav et al. 2019; Zhang et al. 2020). Overall, the largest increases in biomass and CO$_2$

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absorption are recorded in native vegetation sites, which are in the process of succession, and also in young forest plantations, while in primary forests and mature plantations, the accumulation of biomass is in a state of equilibrium (Paulick et al. 2017; Souza et al. 2020). However, even in primary forests, there are numerous natural processes, such as leaf fall and regrowth influenced by natural disturbances (fires, drought, floods, among others), which shape plant mortality and recruitment rates as well as CO_2 accumulation (Ahlström et al. 2015; Pugh et al. 2019). Therefore, even primary forests maintain the dynamics of forest replacement in time (turnover) and space, which can influence the rates of biomass and CO_2 accumulation.

Despite the recognized importance of forest ecosystems for the global carbon cycle, changes in land use in these ecosystems, and especially the destruction of forests, have contributed significantly to increasing CO_2 emissions to the atmosphere. In this context, we highlight the Cerrado, the second largest biome in Brazil and one of the richest savannas in world (Gomes et al. 2018; Mendonça et al. 2008), highly endemic (Mendonça et al. 2008; Strassburg et al. 2017), pointed out as one of the world's hotspots for biodiversity conservation (Mittermeier et al. 2011; Strassburg et al. 2017), and providing a range of ecosystem services (Klink and Machado 2005). The anthropogenic influence that occurs in the Cerrado has caused various environmental damages that limit its sustainability and the socioeconomic future in its region of scope, especially in the face of climate change scenarios (Bustamante et al. 2012; Klink and Machado 2005; Sano et al. 2019).

Allied to this scenario, the behavior of natural regeneration in Cerrado sites that have undergone some anthropic intervention is still poorly known. Monitoring these areas is crucial to understand vegetation succession, especially regarding the changes that occur in the accumulation of biomass over time, and hence to better understand the impact of anthropogenic disturbances on the global carbon cycle. In this sense, mathematical models, such as empirical models of growth and production, emerge as a tool to evaluate the changes that occur in a forest community over time. These models can indirectly predict future production based on different management alternatives and forestry options, and provide essential information for the sustainable management of forest resources (Campos and Leite 2017; Cao 2014; Peng 2000; Qiu et al. 2020; Vanclay 1995; Yue et al. 2016).

These models can be developed with regression methods (linear or non-linear), providing a non-destructive and indirect estimation of biomass, in which the dependent variable biomass is estimated according to one or more explanatory variables more easily measurable, such as diameter, height, wood density, and structural characteristics of the stand (Chapagain et al. 2014; Wassihun et al. 2019). However, accurate predictions of biomass production in natural vegetation sites remain a challenge because the relationships between the dendrometric variables can be influenced by the type of vegetation and are still little known in the native vegetation of the Cerrado.

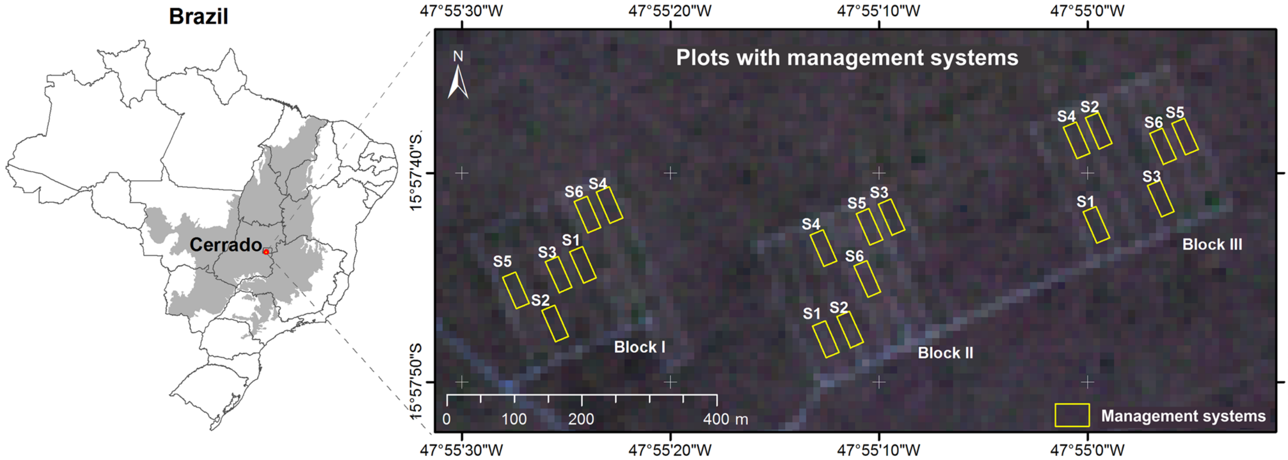
Given the above, we aim to model the growth and future production of aboveground woody biomass in a cerrado sensu stricto, the most common Cerrado phytophysiognomy, monitored for 27 years after the implementation of management systems. For this, we developed a system of equations to estimate the aboveground biomass per unit area at a future age as a function of stand variables projected from a known initial condition. In our study, we were concerned about the following research questions: (1) easily obtainable dendrometric variables in plot-level can be used as predictor variables of the aboveground woody biomass stocks, in future ages, of the cerrado sensu stricto subjected to different management systems; (2) the predictions of the growth and production models are consistent and allow estimates of the expected increase and production of biomass in each management system; and (3) the models can also be used to simulate the impact of events that modify the community structure, such as fires, on the biomass stocks.

Material and methods

Study site

This study was carried out on 18 experimental plots of 1000 m^2 each, implemented in a site of cerrado sensu stricto, surrounded by large extensions of natural vegetation of this phytophysiognomy and without evidence of anthropic interventions, at Ecological and Experimental Reserve of the University of Brasília, Água Limpa Farm (FAL), located in Brasília, Federal District, Brazil (Fig. 1). Started in 1988, six management systems based on different harvesting and extraction techniques have been implemented in a controlled experimental design (Fig. 1). The management systems were: S1—Chain sawing individuals with Db equal to or greater than 5 cm + removal of firewood; S2—Chain sawing individuals with Db equal to or greater than 5 cm + removal of firewood + fire; S3—Blade tractor cutting all individuals + removal of firewood; S4—Blade tractor cutting all individuals + removal of firewood + fire; S5—Blade tractor cutting all individuals + removal of firewood + 2 soil harrowing (24″); S6—Chain sawing all individuals + removal of firewood + fire + stump extraction + 2 soil harrowing (24″).

The experimental area is surrounded by vast extensions of native cerrado sensu stricto vegetation and, since the implementation of management systems, it is protected from anthropic interventions. Only the occurrence of three fires was recorded, occurring one, six, and 23 years after the implementation of the experiment. Additional information on the area history, implantation, and arrangement of the



CODE - DESCRIPTION OF TREATMENTS
S1 - Chain sawing individuals with Db equal to or greater than 5 cm + removal of firewood
S2 - Chain sawing individuals with Db equal to or greater than 5 cm + removal of firewood + fire
S3 - Blade tractor cutting all individuals + removal of firewood
S4 - Blade tractor cutting all individuals + removal of firewood + fire
S5 - Blade tractor cutting all individuals + removal of firewood + 2 soil harrowing (24″)
S6 - Chain sawing all individuals + removal of firewood + fire + stump extraction + 2 soil harrowing (24″)

Fig. 1 Map of cerrado *stricto* sensu area located at Água Limpa Farm (FAL), Brasília-DF, Brazil, indicating the distribution of experimental blocks and plots with management systems implemented in 1988. Description of management systems applied

management systems are described in Azevedo et al. (2020a, 2020b).

Database

The woody vegetation, resulting from the natural regeneration process, was monitored on eight occasions, i.e., 8, 10, 12, 14, 17, 20, 23 (before the fire), and 27 years after implementing management systems. Over this period, the individuals (living and standing dead), with a diameter taken at 30 cm from the ground level (Db), above or equal to 5 cm, as recommended by Felfili et al. (2005) were identified botanically and had the values of Db and total height (Ht) recorded. Individuals with more than one stem, bifurcated below 0.30 m from the ground, had each stem measured separately.

From the data collected, the following variables representative of the vegetation structure and average tree size were obtained: density of individuals per hectare (N); basal area, in $m^2\ ha^{-1}$ (G), calculated based on Db; mean squared Db, in centimeters (q); mean Db of the dominant trees, in centimeters (DD); Lorey's height, in meters (HL), and mean height of the dominant trees, in meters (HD) (Machado and Figueiredo Filho 2014; van Laar and Akça 2007). The dominant trees were defined as Assmann (1970).

The dry aboveground biomass of the individuals was estimated in each monitored period, from the product between the woody volume and the weighted mean density of the stem (wood + bark), as described in Azevedo et al. (2020a, 2020b). The wood volume (V) of each individual was estimated using an equation:$V = 0.000109Db^2 + 0.0000451Db^2Ht$, where V = volume (m^3), Db = diameter taken at 0,30 m from the ground level (cm), and Ht = total height (m). This equation was developed for the cerrado sensu stricto of the FAL and generates volume estimates that consider the stem and branch with a minimum top diameter equal to 3 cm (Rezende et al. 2006).

The weighted average density of the stem of each species recorded in the area was obtained from data on the dry mass and density of wood and bark from the area of the cerrado sensu stricto adjacent to the area of this experiment (Vale 2000). For species common to our study, the weighted average density of the stem was determined by the formula:$WADS = (DM_{wood}.DS_{wood} + DM_{bark}.DS_{bark})/(DM_{wood} + DM_{bark})$, where WADS = weighted average density of the stem ($kg\ m^{-3}$), DM = dry mass ($kg\ tree^{-1}$), and DS = density ($kg\ m^{-3}$). For species without information available, we consider the weighted average density of the stem equal to the average density of the common species. Common species accounted for 80% to 95% of the individuals sampled during the monitoring periods.

The aboveground woody biomass per unit area of each plot was obtained from the sum of stem biomass recorded in the plots. The value found was extrapolated to the $Mg\ ha^{-1}$. We modeling of the growth and production considering two conditions separately: living aboveground wood biomass (B_L) (only living trees) and total aboveground wood biomass (B_T) (living trees + standing deadwood). For this, we developed systems of equations to estimate the aboveground biomass per unit area, at a future age, as a function of stand variables projected from a known initial condition. As there was a fire 23 years after implementing the management systems, the data collected at 27 years were not used for model fit.

Data analyses

Selection of independent variables from biomass growth and production models To generate estimates of the dependent variable biomass production per unit area, we adjust a growth and production model at a total stand level in a future age (BL and BT). We selected the most adequate explanatory plot-level variables for predicting B_L and B_T, through the path analysis proposed by Wright (1921). This analysis allows for a better understanding of the association between variables by breaking correlation coefficients into direct and indirect effects on the main variable (Couto et al. 2017; Teodoro et al. 2015). It is a multivariate statistical technique used to assess the relationships between two variables and describe the impact of explanatory variables on a dependent variable (Jiang 2017), thus allowing selecting explanatory variables that have the greatest direct contribution with the dependent variable.

To perform the path analysis, we initially proceeded with the multicollinearity diagnosis of the X'X correlations matrix, based on its condition number (CN), obtained by the ratio between the highest and the lowest eigenvalue of the matrix. As the set of possible independent variables showed severe multicollinearity ($CN > 1000$) according to the classification proposed by Montgomery et al. (2012), the constant $k = 0.05$ was added to the main diagonal of the X'X matrix, providing weak multicollinearity ($CN < 100$). Subsequently, the path analysis was performed, allowing the selection of the independent variables with a higher direct effect on the biomass. Those variables that presented a direct effect higher than the residual effect were considered adequate. Afterward, the multicollinearity diagnosis among these variables was also performed in order to ensure that the independent variables used for fitting the models did not present multicollinearity problems. All analyses were performed using the Genes (Cruz 2013) and Rbio (Bhering 2017) statistical programs.

Fitting, selecting, and validating biomass growth and production models Initially, aboveground biomass data and explanatory variables obtained from the 18 plots over the monitored period were divided into two subsets. Of the three plots of each management system, two were randomly selected for fitting the models and one for validating the estimates, totaling 12 plots for fit and 6 for validation. This criterion was adopted in order to ensure the representativeness of all management systems in the data used for fitting and validating the models. This strategy allows a single representative model to be obtained to estimate biomass in all management systems. To carry out the validation, the growth and production equations obtained with the adjustment of the models were applied to a set of data independent of those used in the adjustment (validation data). This allowed us to compare the aboveground biomass estimates, per unit area, generated by the equations with the observed values.

Since the intervals of the measurements in the experimental area varied (monitoring every two or three years), we decided to decompose the data of the plots of each monitored period into annual intervals. Thus, for a given year *i* in which there was no vegetation monitoring, the values of the variables used in the fitting of the models were obtained according to Eq. 1:

$$Y_{ij} = Y_{ij-1} + PAI_n \tag{1}$$

wherein: Y_{ji}= variable value obtained in the plot *j*, in the year *i*; Y_{ji}+1 = variable value obtained in the plot *j*, in the previous year (*i*-1);PAI_n = periodic annual increment obtained between two successive occasions.

The variables living aboveground biomass and total aboveground biomass at future ages (B_{L2} and B_{T2}, respectively) were associated with the explanatory plot-level variables, selected by path analysis ($X1_2$, $X2_2$, …, Xn_2) from linear and non-linear regression models. Thus, it was necessary to use a system, composed of equations that estimated both the aboveground biomass and each independent variable present in the model at a future age. Therefore, each explanatory variable at a future age ($X1_2$, $X2_2$, …, Xn_2) was related to its values at a current age ($X1_1$, $X2_1$, …, Xn_1) and with age after the implantation of the management systems (year 0), which allowed using the data of these variables in the current age to perform the prognosis of their values in future ages. The models to estimate B_{L2} and B_{T2} and to estimate their respective explanatory variables were adjusted separately. For all variables, several exponential and sigmoidal models available in the literature were fitted, in which the model chosen and presented here was the one with the best performance for the estimates. The fit of the models was performed by using the Excel and Curve Expert computational programs.

For all variables, the selection of the best equation was based on the following precision statistics: (a) correlation coefficient between observed in plots and estimated values by equations obtained with the adjustment of the models (r); (b) standard error of the estimate, in % (S_{xy}%); and (c) graphical distribution of residuals (Draper and Smith 1998). Residuals were obtained by the difference between observed and estimated values (Azevedo et al. 2020b). All these statistics were calculated considering the dependent variable in its original scale.

The validation of the system of equations was performed using the data not used in the fit of the models. Data obtained at each time, from 8 years after implementing the management systems, were used to estimate $B_{L\,2}$ and $B_{T\,2}$ at each future age up to 23 years after the deployment of management systems. The quality of the prognosis was evaluated by graphical analysis between the observed and estimated values considering the measurements at each age.

Application of the fitted models The system of equations obtained was applied to the data set (fit + validation) to perform the prognosis of B_L and B_T, for each management system, at annual time intervals. Thus, it was possible to obtain the mean annual increment (MAI) and current annual increment (CAI) curves. The MAI was obtained by the ratio between biomass predicted for each year and "age" at which this production was obtained. For this purpose, the year 1988, when the treatments were implanted, was considered the year zero for obtaining the "age" of the cerrado sensu stricto. The CAI was obtained from the accumulated prognostic biomass over one year.

The system of equations was also used to evaluate the possible impact of the fire that occurred 23 years after the implementation of the management systems on aboveground biomass accumulation in the area. Thus, the predictions of the aboveground biomass for 27 years, from the measurements performed for 23 years (before the fire) were compared with actual values recorded in 27 years measurement (after the fire), thus allowing to obtain the difference between observed and expected biomass if the fire had not occurred.

Results

The stocks of B_L and B_T accumulated by the natural regeneration of woody vegetation are positively correlated with the variables that express the structure (N and G) and the size of the vegetation (q, DD, HL, and HD) ($p < 0.0001$). The highest correlations were observed between the variables N and G ($r > 0.95$). The path analysis indicated that these two variables also present the highest direct effects on biomass, with values higher than those observed for the residual effect (Table 1). The high coefficient of determination ($R^2 > 0.96$)

Table 1 Estimates of direct and indirect effects of the analyzed variables on the stocks of living biomass (Bl) and total biomass (Bt) accumulated in the woody vegetation in a cerrado sensu stricto in Central Brazil after application of management systems

Effect	N_L	G_L	q_L	DD_L	HL_L	HD_L
Direct on B_L	0.257	0.518	0.037	0.131	-0.013	0.064
Indirect via N_L	–	0.254	0.180	0.232	0.195	0.222
Indirect via G_L	0.513	–	0.392	0.482	0.399	0.453
Indirect via q_L	0.026	0.028	–	0.033	0.029	0.029
Indirect via DD_L	0.118	0.121	0.116	–	0.114	0.122
Indirect via HL_L	−0.010	−0.010	−0.011	−0.012	–	−0.013
Indirect via HD_L	0.056	0.056	0.051	0.060	0.061	–
Total	0.972	0.993	0.768	0.932	0.783	0.881

Coefficient of determination: 0.9604; Residual effect: 0.1989

Effect	N_T	G_T	q_T	DD_T	HL_T	HD_T
Direct on B_T	0.217	0.474	0.096	0.135	-0.074	0.146
Indirect via N_T	–	0.213	0.158	0.193	0.158	0.184
Indirect via G_T	0.465	–	0.386	0.442	0.336	0.416
Indirect via q_T	0.070	0.078	–	0.088	0.061	0.078
Indirect via DD_T	0.120	0.126	0.124	–	0.101	0.125
Indirect via HL_T	−0.054	−0.052	−0.047	−0.055	–	−0.059
Indirect via HD_T	0.124	0.128	0.120	0.136	0.117	–
Total	0.952	0.990	0.840	0.944	0.696	0.898

Coefficient of determination: 0.9636; Residual effect: 0.1915

Where: N = density of individuals (ind. ha^{-1}); G = basal area ($m^2\ ha^{-1}$); q = mean squared Db (cm); DD = mean Db of the dominant tree (cm); HL = Lorey's height (m); and HD = mean height of the dominant trees (m). Variables accompanied by the letter "L" were obtained considering just living trees, and variables accompanied by the letter "T" considered living and dead trees and low residual effect values (RE < 0.20) indicated that the path analysis was suitable to express the cause-and-effect relationship between the analyzed variables, allowing the selection of explanatory variables for modeling the accumulated biomass along time.

The variables N and G (live and total) are highly correlated ($r > 0.98$) and have moderate to severe multicollinearity (live: CN = 174; total: CN = 102). Thus, because it presents a higher direct effect on biomass, the basal area was the only explanatory variable used to fit the models for biomass prognosis at future ages.

The best performance equations for estimating B_L and B_T as a function of living basal area (G_L) and total (G_T), respectively, provided a high correlation between observed and estimated values ($r > 0.99$) and low residual standard error ($S_{yx}\% < 10\%$) (Table 2). Similar fit statistics were also obtained for the best performance equations estimating G_L and G_T at future ages. These equations result from the fit of the sigmoidal Gompertz model, with future basal area (G_2) at future age (I_2) estimated from current basal area (G_1) at current age (I_1).

Although the systems of equations have presented favorable fit statistics for B_L and B_T modeling, the equations for G_2 prognosis tend to generate overestimation when the predictions are performed from G_1 values below five m^2 ha^{-1}, generally observed in a period less than 14 years after the cut (Fig. 2). However, from this value, the estimates obtained were not biased, with errors comprising around ± 10% for the basal area and ± 20% for biomass.

Similar behavior was verified in the validation of the system of equations that predicted B_L and B_T (Fig. 3). Predictions of these variables up to 23 years after cutting, from measurements taken at 14, 17, and 20 years, were distributed within the range of values observed in plots and without trends in the estimates over time. Maximum errors between observed and estimated values were around ± 20% for predictions from 14 years and ± 10% for 17 and 20 years. Therefore, the systems of equations were suitable for predicting basal area and aboveground biomass (living and total) at future ages.

Thus, the system of equations obtained were used for projecting the B_L and B_T stocks in the 18 experimental plots (adjustment + validation), from the inventory data taken 17 years after cutting. The projections made for each management system were consistent since both BL and BT estimates allowed obtaining MAI values similar to those observed until 23 years after cutting (before the occurrence of fire) (Fig. 4). The maximum CAI values ranged from 1.90 Mg ha^{-1} year^{-1} (S5) to 2.66 Mg ha^{-1} year^{-1} (S6) for B_L, and from 1.87 Mg ha^{-1} year^{-1} (S5) to 2.70 Mg ha^{-1} year^{-1} (S6) for B_T, and were recorded between 20 and 22 years after cutting. If the fire had not occurred at 23 years after cutting, projections indicate that in all management systems, the maximum MAI, identified when CAI and MAI curves meet, would occur between 23 and 27 years after cutting, with a tendency for this age to be closer to the lower limit of this range in management systems that provided higher MAI. The maximum expected MAI for B_L varied from 0.94 Mg ha^{-1} year^{-1} (S5) to 1.04 Mg ha^{-1} year^{-1} (S1), and for B_T ranged from 0.95 Mg ha^{-1} year^{-1} (S5) to 1.06 Mg ha^{-1} year^{-1} (S1).

The projections indicate that the maximum biomass production would occur at 28 years after implementing the S1, S2, and S6 systems and at 30 years in the other systems, with stocks of BL and BT up to 25.9 Mg ha-1 26.2 Mg ha^{-1}, respectively. The biomass of standing dead individuals (B_D), obtained by the difference between projected B_L and B_T, would represent from 0.03 to 4.27% of the total biomass in the different management systems over time, and therefore, close to those recorded in the period that the vegetation was protected from fires. However, after the fire recorded at 23 years after cutting, there was a reduction of B_L in all management systems (Fig. 5). This reduction ranged from 8.0% (S3) to 30.4% (S4) (mean = 19.3%) regarding the expected values at 27 years after cutting if the fire had not occurred. For B_T, this reduction was less marked and ranged from 0.1% (S2) to 24.4% (S4) (mean = 12.0%).

Table 2 Systems of equations selected for the prognosis of the production of living biomass and total woody vegetation of the cerrado sensu stricto in Central Brazil

System	Equation	Equation	r	$S_{yx}\%$
1 (Living biomass)	Equation 1	$B_{L2} = 1.36328G_{L2}^{1.10374}$	0.9929	9.08
	Equation 2	$G_{L2} = 17.37727e^{-e^{1.08284-0.18484G_{L1}\frac{I_2}{I_1}}}$	0.9948	7.27
2 (Total biomass)	Equation 1	$B_{T2} = 1.35037G_{T2}^{1.10606}$	0.9931	8.95
	Equation 2	$G_{T2} = 17.60095e^{-e^{1.08155-0.18239G_{T2}\frac{I_2}{I_1}}}$	0.9960	7.12

Wherein: B_{L2} and B_{T2} = living and total aboveground biomass at future age (Mg ha^{-1}), respectively; G_{L1} and G_{T1} = living and total basal area at current age (m^2 ha^{-1}), respectively; G_{L2} and G_{T2} = living and total basal area at future age (m^2 ha^{-1}), respectively; I_1 and I_2 = current and future ages in years, respectively; r = correlation between observed and estimated values; $S_{yx}\%$ = residual standard error, in %

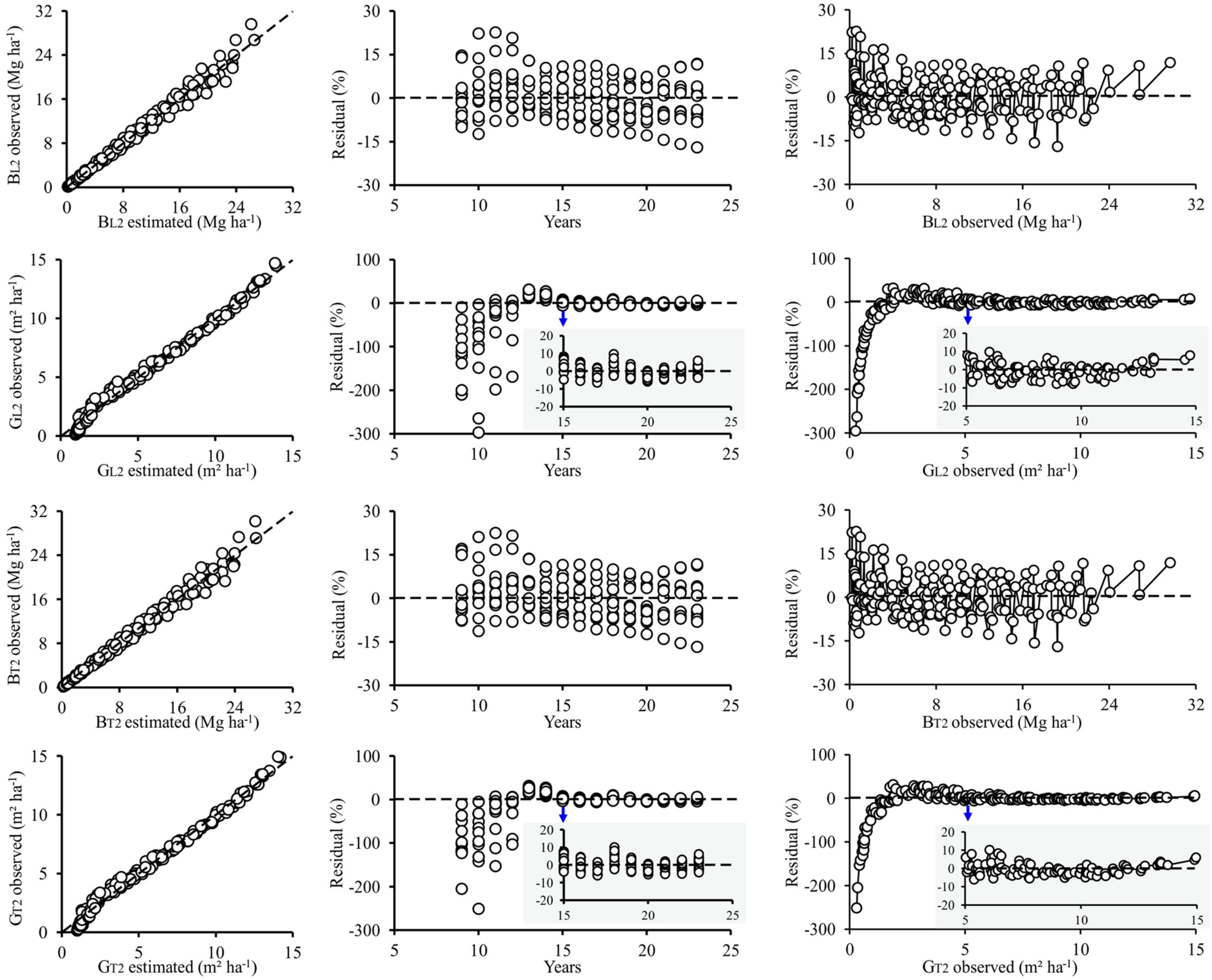


Fig. 2 Graphical distribution of residuals obtained from the prognosis of the living aboveground biomass (B_{L2}) and total (B_{T2}) and living basal area (G_{L2}) and total (G_{T2}) for future occasions in an area of cerrado sensu stricto in Central Brazil, after the implementation of management systems

Discussion

In our study, the accumulation of aboveground biomass along time was strongly related to the basal area recorded in the plots submitted to the different management systems, which was indicated by path analysis as the variable with the highest direct effect on biomass (Table 1). This correlation is expected since the basal area and biomass are related to the stem diameter (Torres and Lovett 2013; Wassihun et al. 2019). Furthermore, the basal area is easily obtained in forest surveys and integrates the effect of the number and size of trees (Torres and Lovett 2013; Wassihun et al. 2019; West 2009, 2006). Therefore, it is often used as an independent variable in estimating volume stocks, biomass, and carbon in different scenarios (Azevedo et al. 2016; Miguel et al. 2015; Oliveira et al. 2016; Roitman et al. 2018; Soares et al. 2016; Souza et al. 2014; Torres and Lovett 2013; Wassihun et al. 2019).

Thus, the use of the basal area as a predictor variable is suitable for modeling the growth and production of aboveground biomass in sites of cerrado sensu stricto at total stand level. From this information at current age, it becomes possible to project the biomass production by area for a future age. According to Cao (2014), models at the total stand-level provide consistent estimates, but they are low-resolution models that do not provide details on stand structure, such as individual tree models. In our study, the systems of equations obtained presented good fit statistics, with reliable estimates of biomass that could capture the existing variations among the biomass stocks in management systems, as verified by Azevedo et al. (2020a, b) in the same site studied here.

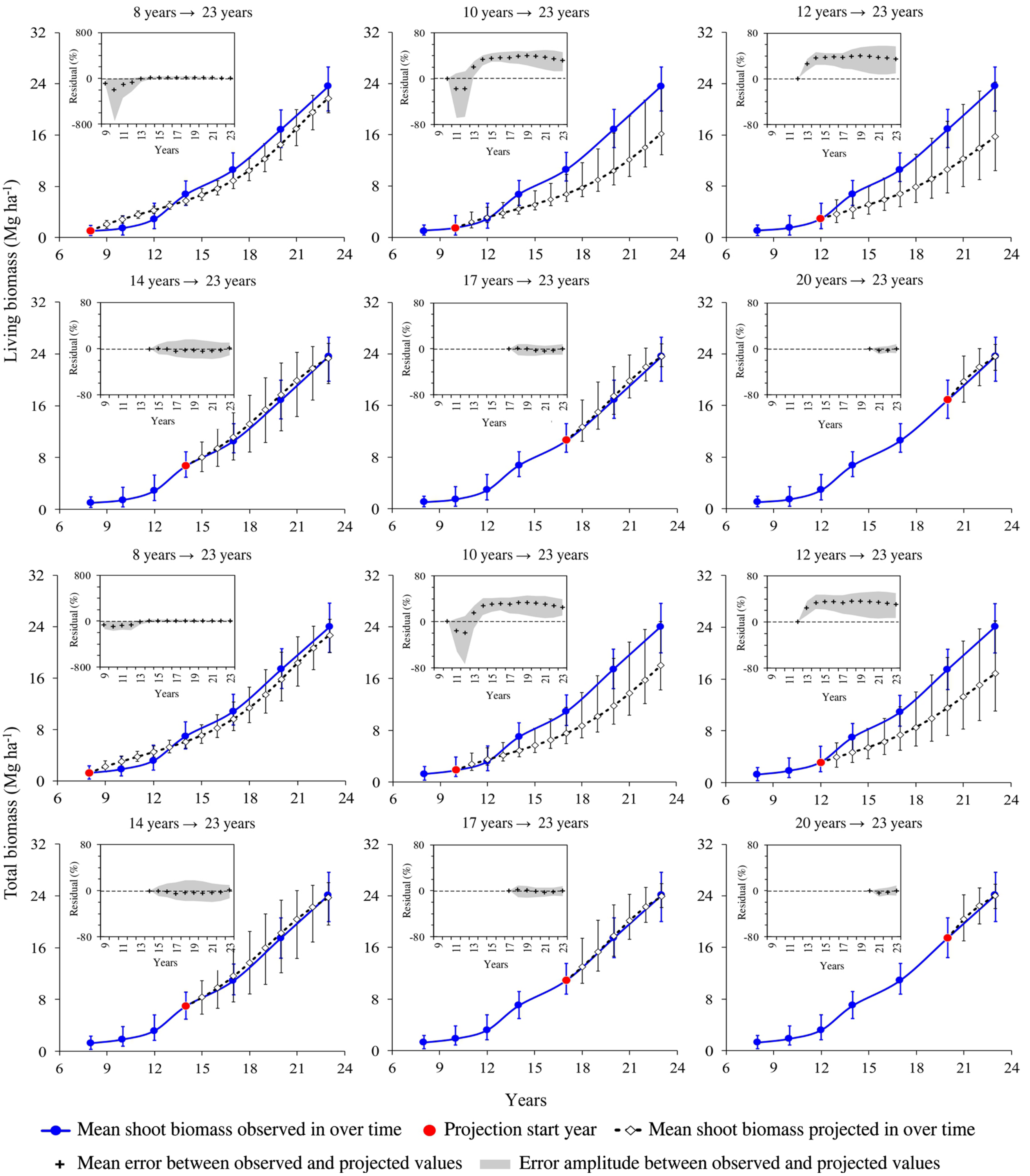


Fig. 3 Validation of systems of equations selected for the prognosis of the production of living and total aboveground biomass in a future time, considering the data of the inventories carried out from 8 to 20 years after the implementation of management systems and projected for the age of 23 years, in a cerrado sensu stricto in Central Brazil. Vertical bars represent the maximum and minimum values observed (blue color) and predicted (black color)

According to our results, estimates should be performed from a basal area at the current age of 5 m^2 ha^{-1}, since the graphical analysis of residuals (Fig. 2) and the validation of the equations (Fig. 3) did not reveal biases from this value. Other studies have indicated that the basal area in sites of cerrado sensu stricto in Central Brazil is usually in the range from 5.60 to 14.54 m^2 ha^{-1} (Almeida et al. 2014; Aquino et al. 2014, 2007; Assunção and Felfili 2004; Felfili et al. 2004, 2002, 2000; Fernandes et al. 2013; Lemos et al. 2013; Lima et al. 2010; Mews et al. 2011; Morandi et al. 2018; Oliveira et al. 2015; Roitman et al. 2008; Scolforo et al. 2000; Zimbres et al. 2020). In the literature, there were no studies projecting biomass production in sites of cerrado sensu stricto, as in the present study, with their stocks usually estimated only at current ages (Azevedo et al. 2020a; Miguel et al. 2015; Oliveira et al. 2016; Ribeiro et al. 2011; Roitman et al. 2018).

The maximum stocks of aboveground biomass projected by the systems of equations obtained here (~ 26 Mg ha^{-1}) would be achieved in a period from 28 to 30 years after implementing the management systems (Fig. 5). These stocks are close to the upper limit of the range from 9.9 to 24.5 Mg ha^{-1} reported in other sites of cerrado sensu stricto in Central Brazil (Abdala et al. 1998; Castro and Kauffman 1998; Miranda et al. 2017; Morandi et al. 2018; Rezende et al. 2006; Vale and Felfili 2005; Zimbres et al. 2020), which indicates that the estimates generated by the systems of equations are consistent.

The highest CAIs for aboveground biomass (~ 1.9 to 2.7 Mg ha^{-1} $year^{-1}$) occurred from 20 to 22 years after implementing the management systems, while the maximum MAIs (~ 0.9 to 1.1 Mg ha^{-1} $year^{-1}$) occurred from 23 to 27 years. Such increments varied according to the management systems assessed (Fig. 4). If the aboveground biomass values were converted to CO_2 sequestration, the cerrado sensu stricto would absorb from 3.5 to 5.0 Mg CO_2 ha^{-1} $year^{-1}$, with MAI ranging from 1.7 to 2.0 Mg CO_2 ha^{-1} $year^{-1}$. It is important to note that about 70% of the total biomass accumulated in the vegetation of cerrado sensu stricto is partitioned below ground (Abdala et al. 1998; Castro and Kauffman 1998; Paiva et al. 2011), which indicates that the biomass stocks of the *cerrado* sensu stricto exceed that recorded in our study, in which only aboveground biomass was assessed.

The contribution of Cerrado vegetation to climate change mitigation is conditioned to the occurrence of fires (Azevedo et al. 2020a; Kauffman et al. 2019; Miranda et al. 2004). We observed that the B_D fraction tends to be higher in the period immediately after the fire occurrence. On the other hand, longer protection of vegetation against fires increases B_T stocks, with a decreased B_D fraction (Fig. 5). The occurrence of fires contributes to a reduction in the density and basal area of individuals in the community (Almeida et al. 2014; Azevedo et al. 2020a; Felfili et al. 2000), hence resulting in decreased aboveground biomass (Fig. 5).

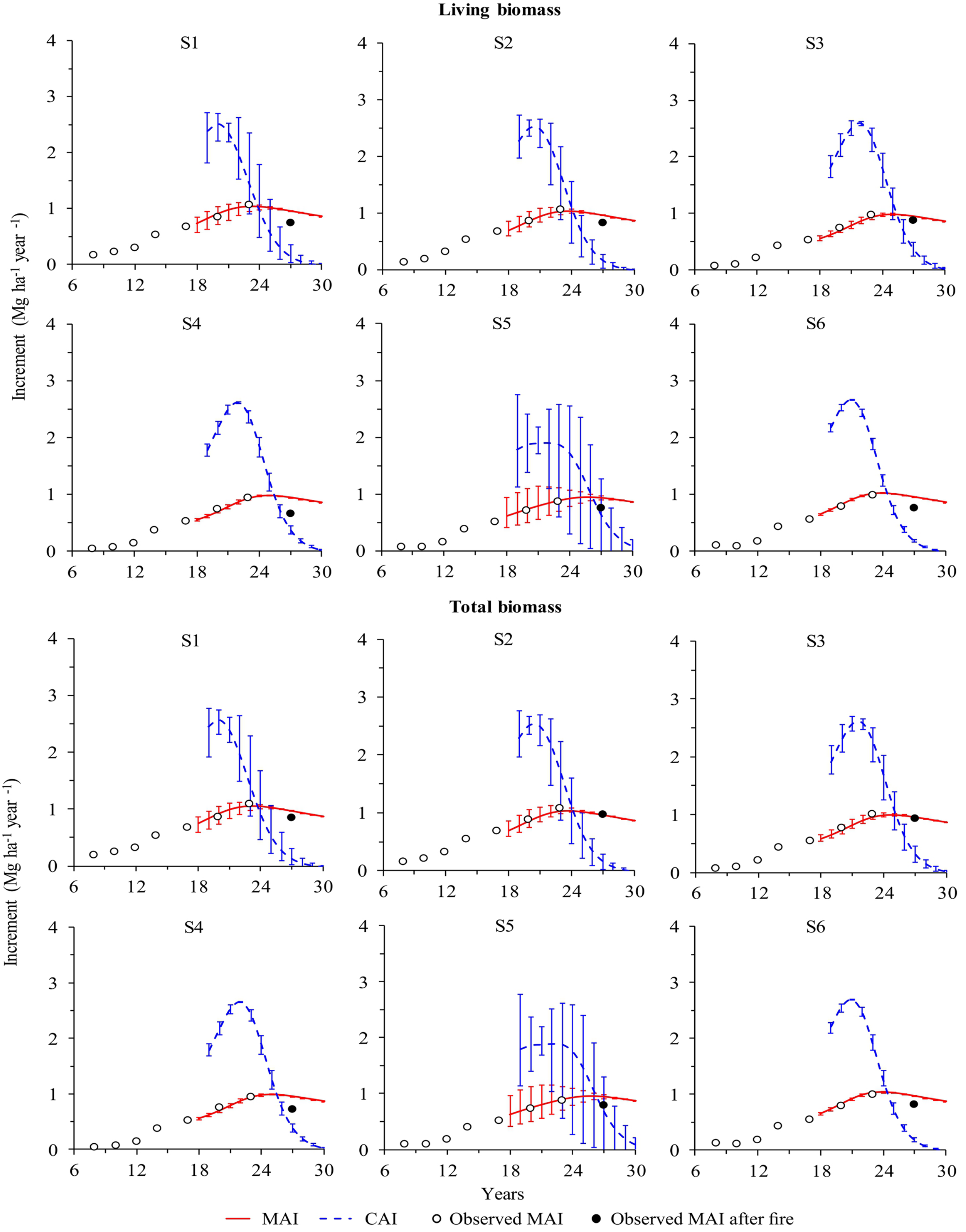
Although the fire has decreased the basal area and aboveground biomass (living and total) of the woody community in the sites subjected to all management systems, the relationship between these variables remained similar to that observed in the period before the fire (Fig. 6). Four years after the fire occurrence, the living and total aboveground biomass were 19.3% and 12.0%, respectively, lower than the values projected for that year if the fire had not occurred (Fig. 5). These values correspond to an emission of 9.1 Mg CO_2 ha^{-1} considering only living trees, and 5.7 Mg CO_2 ha^{-1} considering the total trees (living + dead). If our monitoring had been carried out immediately after the fire, it would certainly reveal an even more accentuated emission. Thus, the fire transformed the cerrado sensu stricto into a source of CO_2 emissions to the atmosphere and should be one of the major elements to consider when considering the management and conservation of this ecosystem.

Our study is the first one to model the growth and production of biomass (living and total) of woody vegetation in sites of cerrado sensu stricto. As previously discussed, the prognosis generated from the developed systems of equations has shown to be consistent with the biomass stocks present in the studied site and other cerrado sites in Central Brazil with similar phytophysiognomy. Furthermore, as the aboveground biomass estimates accumulated over time are obtained from the basal area of the stand, we believe that the effect of fire and other events causing biomass reduction can be evaluated from simulations using the equations obtained here. For this purpose, it will be necessary to consider a certain percentage of basal area removed from these events. Therefore, our study is relevant to support decision-making and develop public policies and strategies for managing and conserving natural resources in the Cerrado biome.

Conclusions

The basal area allows obtaining accurate and consistent estimates of aboveground biomass stocks, living, and total, per area unit, accumulated over time in the regenerated woody vegetation in cerrado sensu stricto after implementing management systems.

After implementing management systems, the maximum mean annual increase of aboveground woody biomass (living and total) in the cerrado sensu stricto occurs between 23 and 27 years after the cutting of vegetation. Maximum stocks of living (25.9 Mg ha^{-1}) and total (26.2 Mg ha^{-1}) aboveground biomass are expected for a period between 28 and 30 years after cutting.


Living biomass
S1
S2
S3
S4
S5
S6
Total biomass
S1
S2
S3
S4
S5
S6
Increment (Mg ha^{-1} year^{-1})
0
1
2
3
4
6
12
18
24
30
Years
MAI
CAI
○ Observed MAI
● Observed MAI after fire

◂**Fig. 4** Projections of mean annual increment (MAI) and current annual increment (CAI) of woody biomass for each management systems applied in 1988 in a cerrado sensu stricto in Central Brazil. The management systems S1 to S6 are described in Fig. 1. Vertical bars represent the maximum and minimum values of MAI (red color) and CAI (blue color)

The occurrence of forest fires decreases the accumulation of biomass in the site, and its effect can be simulated from the systems of equations developed in this study.

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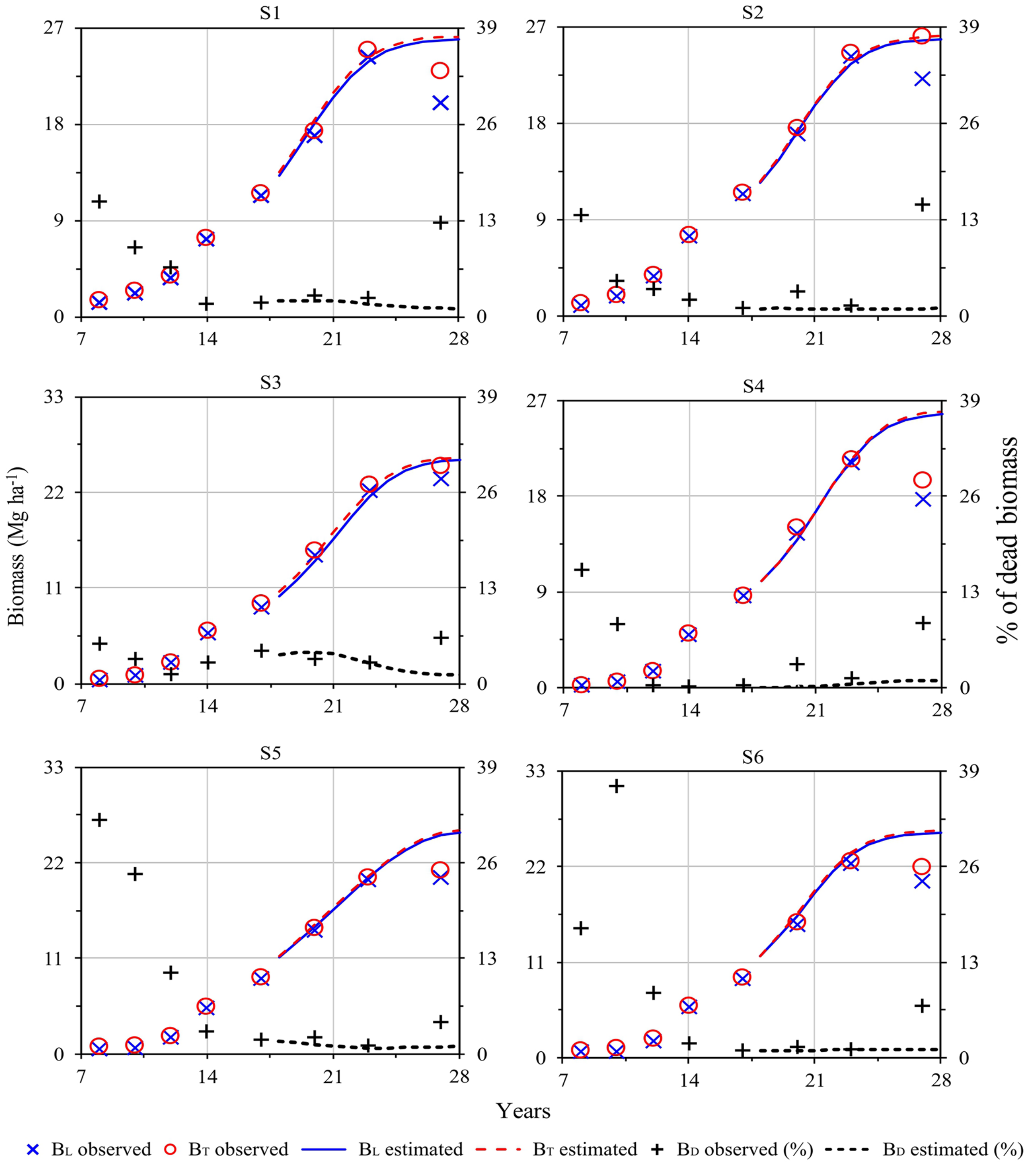

Fig. 5 Living and total aboveground biomass and fraction of dead biomass observed in the monitoring period and projected from data observed at 17 years after cutting the woody vegetation in a cerrado sensu stricto in Central Brazil, under different management systems in 1988. Management systems S1 to S6 are described in Fig. 1

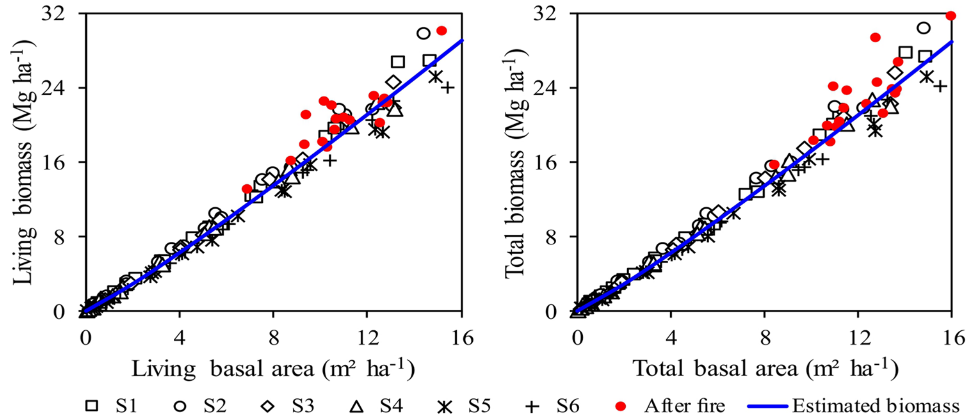

Fig. 6 Relationship between aboveground biomass and the basal area of a cerrado sensu stricto in Central Brazil, before and after the fire in 2011. The management systems S1 to S6 are described in Fig. 1

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Authors' contributions GBA, AVR, and GTOSA designed the field trials and collected the data. GBA and GTOSA performed all statistical analyses and produced a draft of the manuscript. EPM, FGA, LPRT, and PET contributed to a critical review of the manuscript. All authors read and approved the final manuscript.

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Data availability The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflicts of interest The authors declare that they have no competing interests.

Consent for publication All authors of the manuscript have read and agreed to its content and are accountable for all aspects of the accuracy and integrity of the manuscript.

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