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Agrosilvopastoral system as a potential model for increasing soil carbon stocks: a century model approach

Juliana Martins Ribeiro[(1)], Igor Costa de Freitas[(1)], Betânia Guedes Souza e Brito[(2)], Luiz Arnaldo Fernandes[(2)], Luiz Fernando Carvalho Leite[(3)], Demerson Luiz de Almeida Barbosa[(4)], Márcia Vitória Santos[(4)], Carlos Eduardo Pellegrino Cerri[(5)] and Leidivan Almeida Frazão[(1)*]

(1) Universidade Federal de Minas Gerais, Instituto de Ciências Agrárias, Montes Claros, Minas Gerais, Brasil.
(2) Universidade de Montes Claros, Centro de Ciências Biológicas e da Saúde, Montes Claros, Minas Gerais, Brasil.
(3) Empresa Brasileira de Pesquisa Agropecuária, Embrapa Meio-Norte, Terezina, Piauí, Brasil.
(4) Universidade Federal dos Vales do Jequitinhonha e Mucuri, Diamantina, Minas Gerais, Brasil.
(5) Universidade de São Paulo, Escola Superior de Agricultura "Luiz de Queiroz", Departamento de Ciência do Solo, Piracicaba, São Paulo, Brasil.

*** Corresponding author:**
E-mail: lafrazao@ica.ufmg.br

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ABSTRACT: Agrosilvopastoral systems have been used as sustainable production models that can promote soil organic carbon (SOC) storage. However, there are no simulation studies with the Century model to estimate the SOC accumulation capacity in the long term, analyzing the effects of management and climate change in integrated crop-livestock-forest (ICLF) systems. This study aimed to simulate soil C dynamics in two chronosequences of land-use composed of native vegetation (NV), degraded pasture (DPA) and ICLF system in the Cerrado of Minas Gerais, in addition to designing future scenarios to verify the potential of SOC accumulation through climate change. The results showed that the Century model reliably simulated the SOC stocks in the two chronosequences evaluated. The model predicted an increase in SOC stocks at two sites by converting the DPA system (46.04 and 42.38 Mg ha^{-1}) into ICLF systems (54.94 and 51.71 Mg ha^{-1}). The Century also predicted that a 20 mm decrease in rainfall and a 2 °C increase in temperature in the tropical regions studied could reduce the SOC stocks more expressively in degraded pastures, while agroforestry systems could show a smaller reduction in SOC stocks. In addition, the results showed that replacing degraded pastures into agrosilvopastoral systems, especially in clayey soils, contributes to increasing SOC stocks. Thus, agroforestry systems are potentially viable to maintain the sustainability of agriculture in the face of climate change.

Keywords: agroforestry, climate change, land-use change, soil organic matter.

INTRODUCTION

Increase of greenhouse gases (GHG) emissions in recent decades has been the subject of extensive studies on climate change and, in particular, the carbon dioxide (CO_2), which is emitted into the atmosphere when native vegetation areas are converted into agriculture, which are identified as one of the main factors in the agricultural sector, responsible for the GHG emissions (Carvalho et al., 2014; Fujisaki et al., 2015; Durigan et al., 2017; Cerri et al., 2018).

One of the strategies to mitigate climate change through soil carbon (C) accumulation is to identify soils that are low in C stocks, such as eroded soils and in stages of degradation, and convert them into sustainable agricultural systems (Lal, 2019; Lorenz et al., 2019). The conversion of degraded soils to sustainable production systems is an important management strategy to increase the potential for capture, storage, and sequestration of atmospheric C, mitigating GHG emissions (Minasny et al., 2017; Yang et al., 2019). Therefore, diversified and intensified systems, such as agroforestry systems, which integrate crop, livestock and forest in the same area, have the potential to promote CO_2 sequestration and to accumulate soil organic carbon (SOC) in depth with greater efficiency than conventional agricultural systems (Lorenz and Lal 2014; Coser et al., 2018; Ruiz et al., 2020).

As the potential for soil C accumulation is directly related to climatic conditions (temperature and rainfall), the type of soil (texture and mineralogy), and the type of vegetation cover (Brandani et al., 2015), the application of models that value the capacity of soils to accumulate C can complement studies about soil organic matter (SOM) dynamics. From this perspective, it is possible to compare modeled data from different edaphoclimatic conditions and management strategies with long-term experimental observations or chronosequence studies, aiming to adjust the model and make the data more reliable for scale applications.

The Century model has been used to evaluate the dynamics of SOM and nutrients in the long term, providing tools for analyzing the effects of management and climate change on productivity and sustainability in different agroecosystems (Parton et al., 1988). The model simulates the active (representing soil microbes and microbial products), slow (including resistant plant material derived from the structural pool and soil-stabilized microbial products arisen from the active pool), and passive (very resistant to decomposition and includes physically and chemically stabilized SOM) compartments that are directly affected by edaphoclimatic factors (for example, temperature, humidity and soil texture), litter chemical composition (lignin/N, C/N) and handling practices that control the decomposition rates and determine the flow of C between the compartments of the SOM (Metherell et al., 1993). In addition, the Century model simulates the microbial surface compartment related to litter decomposition on the soil surface. Plant residues above and below ground are subdivided into structural compartments related to the cell wall of plant residues, and metabolic, referring to the intracellular content of plant cells, depending on the lignin/N ratio in the residue. Increases in this proportion result in more residues, being added to the structural sets, which present slower decomposition rates (Parton et al., 1988). Thus, the Century model was created to simulate the dynamics of SOM in agroecosystems in temperate regions (Paustian et al., 1992; Parton and Rasmussen, 1994; Smith et al., 1997), but several studies show its applicability to tropical areas (Cerri et al., 2004, 2007; Bortolon et al., 2011; Brandani et al., 2015; Zani et al., 2018).

The objective of this study was to measure and to simulate the soil C dynamics in two chronosequences of land use intensification composed of native vegetation (NV), degraded pasture (DPA) and crop-livestock-forest integration systems (ICLF) in the Brazilian Cerrado, in addition to designing future scenarios to evaluate the SOC stocks in the face of climate change.

MATERIALS AND METHODS

Study areas

The first study area is located at Barra Farm (16° 38’ 44.02” S and 43° 42’ 43.77” W) in the municipality of Francisco Sá - MG, in the northern mesoregion of Minas Gerais State, and is located in an area between the Cerrado and Caatinga biomes (Figure 1). The predominant Cerrado phytophysiognomy is “Cerrado *sensu stricto*”.

The average altitude of the area is 590 m and the municipality’s annual rainfall for the past 30 years has been 1,003 mm. According to Köppen’s classification system, the climate is Aw (Tropical savannah climate) with a rainfall regime characterized by two well-defined seasons, with average temperature oscillating between 21 and 28 °C (Figure 2). The soil in the study area was classified as *Cambissolo Háplico eutrófico* (Santos et al., 2018) with medium texture (Table 1), which corresponds to a Cambisol (IUSS, 2015).

After converting the native Cerrado vegetation (NV1), the experimental area was first cultivated with *Urochloa brizantha* cv. Marandu (DPA1), and for about 13 years it remained without continuous management for maintenance of the plant stand homogeneity, fertilization, pest and disease management, and pre-defined stocking rate. The agrosilvopastoral system (ICLF1) was implemented in October 2012, where the genetic material of eucalyptus (*Eucalyptus urograndis*) was planted in double rows and forage sorghum (*Sorghum bicolor*) was grown between the lines. At the beginning of 2014, forage sorghum was planted along with the pasture, *Urochloa brizantha* cv. Marandu, and after its cultivation, the area was conducted as a silvopastoral system (eucalyptus and pasture). The arrangement of (3 × 2) + 14 m was adopted, and the figure 3 shows the chronosequence of the experimental area.

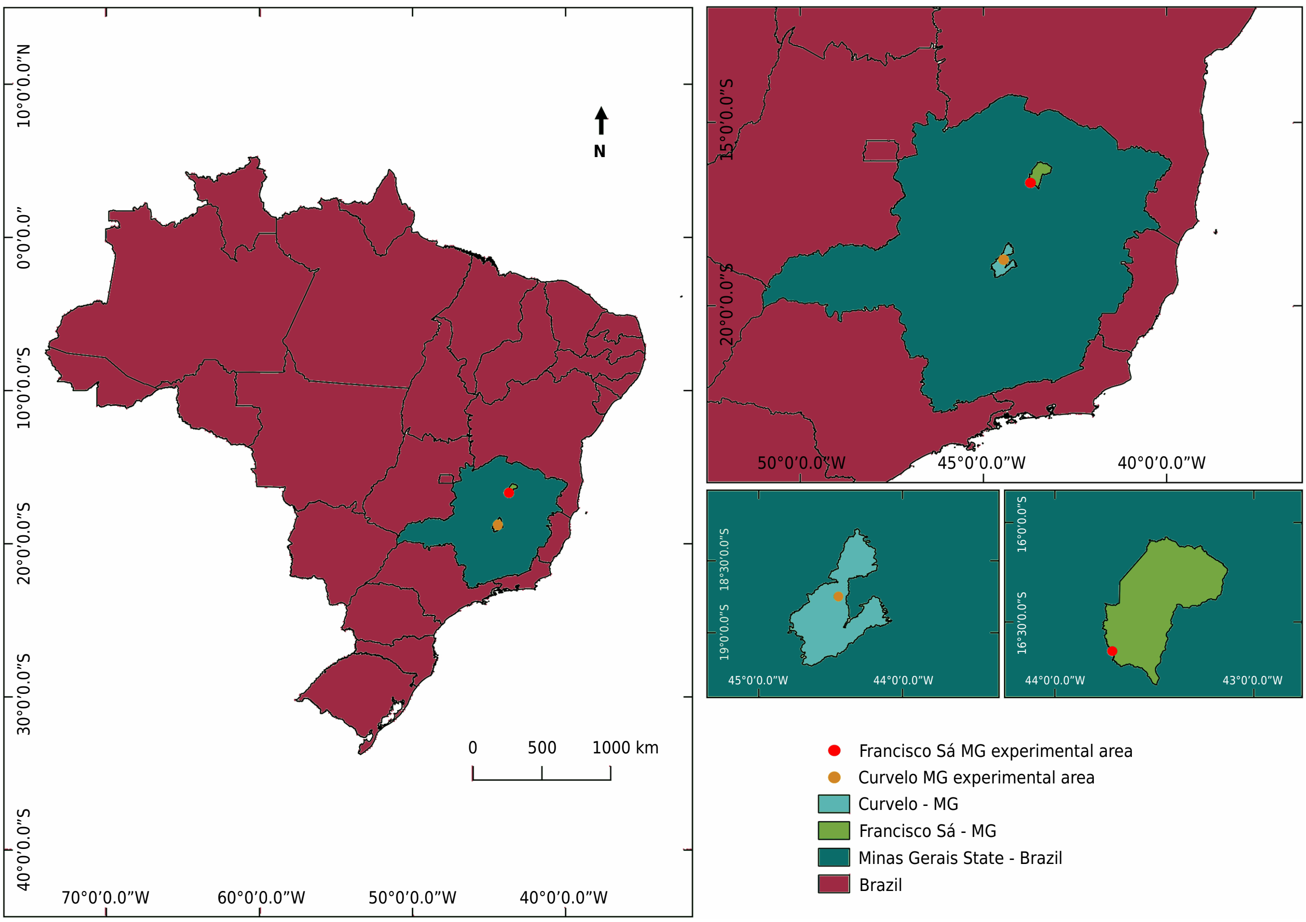

Figure 1. Location of the study areas in the municipalities of Francisco Sá and Curvelo, Minas Gerais State, Brazil.

Figure 2. Annual rainfall and average temperature for the last 30 years in the municipalities of Francisco Sá and Curvelo, Minas Gerais State, Brazil. Source: Inmet (2019).

Table 1. Soil properties at 0-20 cm in the two chronosequences of land use in the municipalities of Francisco Sá and Curvelo, Minas Gerais State, Brazil

Chronose-quence	Study area	Texture			Bulk density[1]	pH	C[1]		SOC stocks[1]	
		Clay	Silt	Sand		H_2O	2016	2018	2016	2018
		g kg⁻¹			g cm⁻³		%		Mg ha⁻¹	
Francisco Sá - MG	NV1[2]	280	300	420	1.29	5.40	2.63	2.39	66.17	60.16
	DPA1	240	240	520	1.38	5.90	1.60	1.81	43.72	47.31
	ICLF1	220	250	530	1.35	5.30	1.90	2.05	50.71	54.98
Curvelo - MG	NV2	524	322	154	1.10	6.11	4.00	4.40	80.21	88.66
	DPA2	686	241	73	1.22	5.33	1.87	1.80	39.45	43.04
	MAR	731	200	69	1.07	5.29	2.24	2.28	47.36	48.14
	ICLF2	684	233	83	1.15	5.84	2.47	2.43	51.62	53.71

[1] Determinated in the layer of 0.00-0.20 m. [2] NV1: Native vegetation; DPA1: Degraded pasture; ICLF1: Integrated Crop-Livestock-Forest systems; NV2: Native vegetation; DPA2: degraded pasture; ICLF2: Integrated Crop-Livestock-Forest system; MAR: Marandu Grass Monoculture. Physical characterization performed according to the methodology proposed by Claessen (1997).

The second area is located at the Moura Experimental Farm (18° 44’ 52.03” S and 44° 26’ 53.56” W) in the municipality of Curvelo - MG, central mesoregion of Minas Gerais State and is in a transition area between the Cerrado and Atlantic Forest biomes (Figure 1). The predominant Cerrado phytophysiognomy is “Cerradão”.

According to the Köppen classification system, the region’s climate is Aw, corresponding to a tropical savanna climate with concentrated rains in the summer (October to April) and high temperatures, while winter consists of a dry period (May to September) with lower temperatures. The annual rainfall rate in the municipality over the past 30 years was 1,064 mm, with an average temperature between 20 and 26 °C (Figure 2). The soil in the experimental area was classified as a *Latossolo Vermelho distrófico típico* (Santos et al., 2018) with clayey texture (Table 1), which corresponds to a Ferralsol (IUSS, 2015).

After converting the native Cerrado vegetation (NV2), the experimental area was initially cultivated with *Urochloa decumbens* Stapf pasture (DPA2), for about 20 years, and remained without continuous management for maintenance of the plant stand, fertilization, pest and diseases management, and pre-defined animals stocking rate. In 2014, the site was characterized by an area of exposed soil and the presence of invasive plants, when the agrosilvopastoral system (ICLF2) was installed. *Eucalyptus urograndis* (clone 144) was intercropped with corn (SHS hybrid 7920) and forage of marandu grass (*Urochloa brizantha* cv. Marandu). The arrangement of 12 × 3 m was adopted, with a 1.5 m separating the eucalyptus from the intercropped corn and forage.

The Marandu grass experimental unit (MAR) was installed in December 2014 using the same planting recommendations and cultivation described for *Urochloa brizantha* cv. Marandu in the ICLF2 system. The pasture area (DPA2) consisted of brachiaria grass (*Urochloa decumbens* Stapf) pasture and was previously used by dairy cattle and left without defined management and without maintenance fertilization for about 20 years, thus presenting a pasture characterized by low productivity, exposed soil and infestation of invasive plants. The area of native vegetation (NV2), classified as “Cerradão”, was located adjacent to the experimental units. The chronosequence and land-use are described in figure 3.

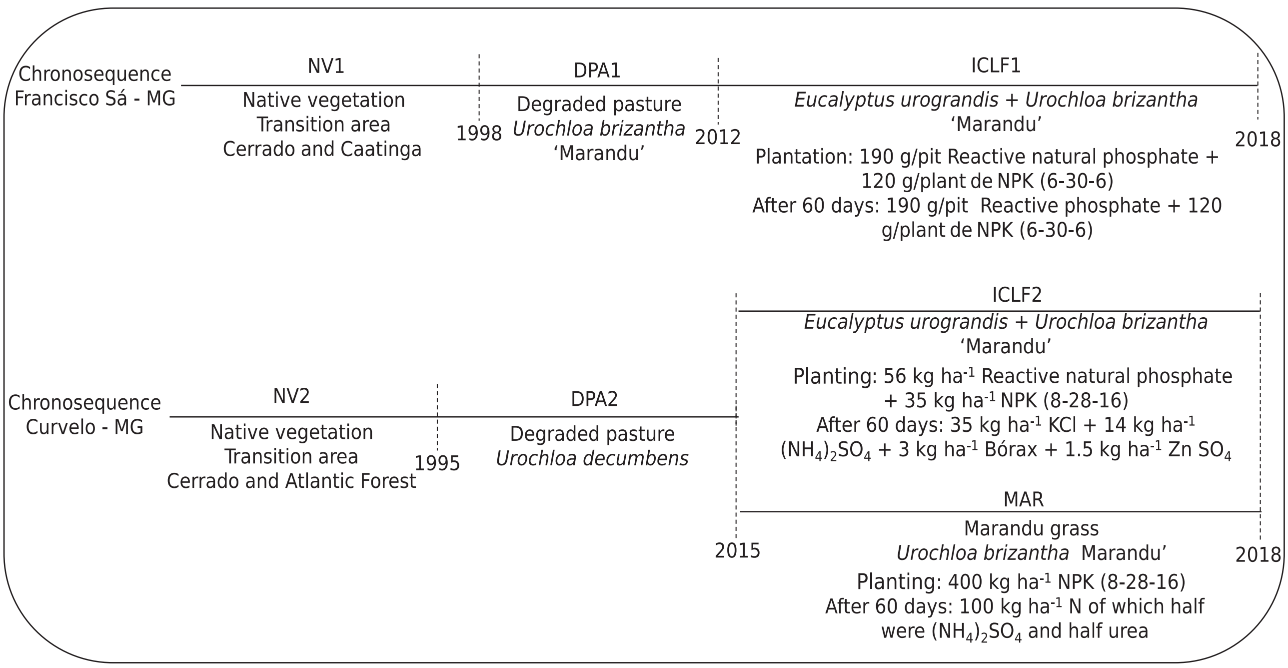

Figure 3. Chronosequence of land-use and brief description of the management practices used in the integrated systems located at the municipalities of Francisco Sá and Curvelo, Minas Gerais State, Brazil.

Soil physical and chemical analysis

Four soil trenches (1 × 1 × 0.5 m) were opened in different land-uses. Soil samplings were carried out in 2016 and 2018 at 0.00-0.20 m soil layer, and the samples were collected randomly in the tree lines (rows) and in the pasture (alleys). The samples were passed through 2 mm sieves, and the residues of plants, roots and seeds were removed manually. Determining bulk density, pH, clay content, silt and sand was carried out according to the methodology proposed by Claessen (1997).

To determine the total C content (Table 1), the soil samples were previously air-dried, homogenized, ground, and passed through 0.150 mm sieves and, later, analyzed by dry combustion in an elemental analyzer (Carlo Erba / CHN-1110) coupled to a mass spectrometer (Thermo Scientific/ Delta Plus). Soil C stocks in ICLF1, ICLF2, MAR, DPA1, and DPA2 systems were calculated for the same soil mass as their respective native vegetation (NV1 and NV2), according to the methodology proposed by Ellert and Bettany (1995) and Moraes et al. (1996).

Simulation of changes in soil carbon stocks

The Century model, version 4.0, was used to simulate changes in soil C stocks at 0.00-0.20 m soil layer in two chronosequences under different management practices, and the standard values of the fix.100 parameters were kept unchanged. Three compartments of soil organic matter (active, slow and passive) were evaluated, each representing fractions of soil organic matter with different potential decomposition rates. These compartments are directly related to edaphoclimatic factors, chemical litter composition such as lignin/N, C/N and management practices. These factors control the decomposition rates of organic material and determine the C and N flow between the SOM's compartments (Metherell et al., 1993).

Parameterizations for SOM evaluation were performed in the top 0.20 m, according to the Century model. The simulation yield variables evaluated were soil C stocks (somsc) and SOC compartments: active (som1c(2); which represents soil microbial biomass and microbial products, free light fraction), slow (som2c; resistant plant material to decomposition derived from structural compartment and microbial products stabilized in soil derived from active and surface microorganisms, soil occluded light fraction) and passive (som3c; very resistant to decomposition and includes physically and chemically stabilized SOM, soil humic substances, heavy fraction) (Metherell et al., 1993).

Initializing the Century model

To initialize the model, data on climate, soil texture, soil density, and pH and N input were inserted, as described by Parton et al. (1993). In this study, climatic data (average maximum and minimum monthly temperature and precipitation) for the period from 1988 to 2018 were used. The data sources were obtained by the National Institute of Meteorology (Inmet, 2019), whose weather stations, Montes Claros-A506 Station (16° 68' 63.16" S and 43° 84' 37.63" W) and Curvelo-A538 Station (18° 74' 77.11" S and 44° 45' 37.85" W), were close to the experimental farms, as well as historical information from the Meteorological Database for Teaching and Research - BDMEP, obtained by Inmet. The pluviometric index and average temperature of the last 30 years are shown in figure 2. The input data of soil texture, pH, and bulk density are described in table 1.

To initialize the compartments of the SOM model, Century was provided with the history of land-use and the management practices of the chronosequences of Francisco-Sá-MG and Curvelo-MG. An equilibrium condition (7000 years) was performed on the model for the Cerrado forest until 1995, (corresponding year 1), (*Chronosequence 2, Curvelo*) and 1998, (corresponding year 1), (*Chronosequence 1, Francisco Sá*), when the native vegetation was removed for the initial conversion to pastureland (Figure 3). After conducting pasture without management operations for 13 and 20 years in Francisco Sá and Curvelo, respectively, the areas were classified as degraded pasture. Then, in both places the degraded pasture was converted to an agrosilvopastoral system. In Curvelo, there was also a simulation of the conversion of degraded pasture into a well-managed pasture of Marandu grass.

The soil C data is derived from an initial several thousand-year "equilibrium" simulation using average precipitation and temperature data that was read from the site specific.100 file. The model was calibrated with SOC stocks measured under native vegetation of Cerrado *sensu stricto* (Chronosequence 1) and a second calibration was also performed for native vegetation of Cerrado "Cerradão" (Chronosequence 2). The output variable "somsc" was used because it most closely represents our measured soil C stocks. Calibration of the Century model was first performed for the chronosequence 1. After simulations, another calibration was performed for the chronosequence 2. The calibration process consisted of iteratively running the model, inspecting the output and changing the default biomass production parameters "prdx" for tropical trees or grasses until the "somsc" matched the measured soil C stocks. For *Eucalyptus urograndis* tree, above-ground biomass production in g m^{-2} was calculated from production data obtained by Santana et al. (2016) for this species in the northern region of Minas Gerais and parameterized in the crop.100 file to run the Century model.

Future scenarios

To simulate the impacts of different long-term management practices, for each of the evaluated chronosequence, the model Century runs were extended for 100 yrs after current scenarios were completed. Another "site.100" file was created for future scenarios. Scenarios were modeled for a 2 °C increase in temperature, according to IPCC scenarios (2018), and a decrease in monthly precipitation of 20 mm, in line with the downward trend in precipitation in the regions observed by Marengo (2007) and Cunha et al. (2019). Cunha et al. (2019) studied the Integrated Drought Index (IDI), which combines a meteorology-based drought index and an index based on remote sensing, to assess drought events from 2011 to 2019 in Brazil and verified the occurrence of droughts and droughts severe throughout Brazil and especially in semi-arid regions. Marengo (2007) pointed out that there may be a 20 % reduction in rainfall in the Southeast region. Thus, an annual reduction of 20 % was calculated for the climatic precipitation data of the last 30 years, and the average monthly reduction values were close to 20 mm. The data was altered in the "site.100" file to analyze the response of SOC stocks after the simulation of climate changes.

Statistical analysis

Statistical analyses of the observed and modeled quantitative data were performed according to the methodology proposed by Smith et al. (1997) to assess the adequacy of the Century model to SOC stocks measured as a function of management practices and the time released since land-use conversion. These metrics included were root mean square error (RMSE), Pearson correlation coefficient (r), coefficient of determination (R^2), mean difference between observed and simulated values (M), coefficient of residual mass (CRM) and modeling efficiency (EF).

RESULTS

The two chronosequences were chosen to represent different soil clay contents, climatic conditions and phytophysiognomies of the Brazilian Cerrado. As expected, SOC stocks were higher in areas of native vegetation.

Chronosequence 1 – Francisco Sá/MG

The Century model reliably simulated the SOC stocks of the chronosequence 1 as the values were very close to those determined in the laboratory (Figure 4a and figure 5a). After the native vegetation's removal and subsequent introduction of *Urochloa brizantha* cv. Marandu (DPA1), with 13 years without grazing management, SOC stocks decreased from 65.57 to 46.04 Mg ha^{-1} after ten years (Figure 5a). The SOC stocks will continue to decline if the DPA1 system remains without proper management since stocks will reach 32.27 Mg ha^{-1} at the end of the simulation after 100 years (2098 - Corresponding year).

However, the simulation was different when the DPA1 system was converted to ICLF1 in 2012, with the introduction and proper management of Marandu grass in 2014. Four years after the introduction of the integrated production system and with current management practices, Century simulated that SOC stocks would increase from 54.94 Mg ha^{-1} after 18 years to 76.10 Mg ha^{-1} after 100 years (2098 - Corresponding year), exceeding the equilibrium values of NV1, 65.57 Mg ha^{-1}, prior to 1998 (Figure 4 and figure 5a).

The future scenario of chronosequence 1 can be seen in figures 5b and 5c. We observed that the adoption of ICLF 1 system with good soil management practices can increase soil C stocks in levels close to that found in NV1 after 30 years (2027 - Corresponding year), to exceeding these values in later years. However, the DPA1 system will lead to a reduction in soil C stocks over time.

The future scenario with a decrease in rainfall of 20 mm per month showed a reduction in C stocks, when compared to the initial simulated SOC stocks without future scenarios (Figures 5a and 5b). In the ICLF1 system, soil C stocks ranged from 52.52 Mg ha^{-1} after 30 years (2027 - Corresponding year) to 60.57 Mg ha^{-1} after 100 years (2098 - Corresponding year). On the other hand, soil C stocks in DPA1 system ranged from 27.99 Mg ha^{-1} after 30 years to 20.50 Mg ha^{-1} after 100 years.

Likewise, in the future scenario increasing the average temperature in 2 °C (Figure 5c), there was a reduction in SOC stocks when compared to the initial simulated SOC stocks without future scenarios (Figures 5a and 5c). In the ICLF1 system, SOC stocks showed values from 57.35 Mg ha^{-1} after 30 years (2027 - Corresponding year) to 68.60 Mg ha^{-1} after 100 years. However, for the DPA1 system, the observed values ranged from 25.35 Mg ha^{-1} after 30 years to 19.64 Mg ha^{-1} after 100 years (2098 - Corresponding year).

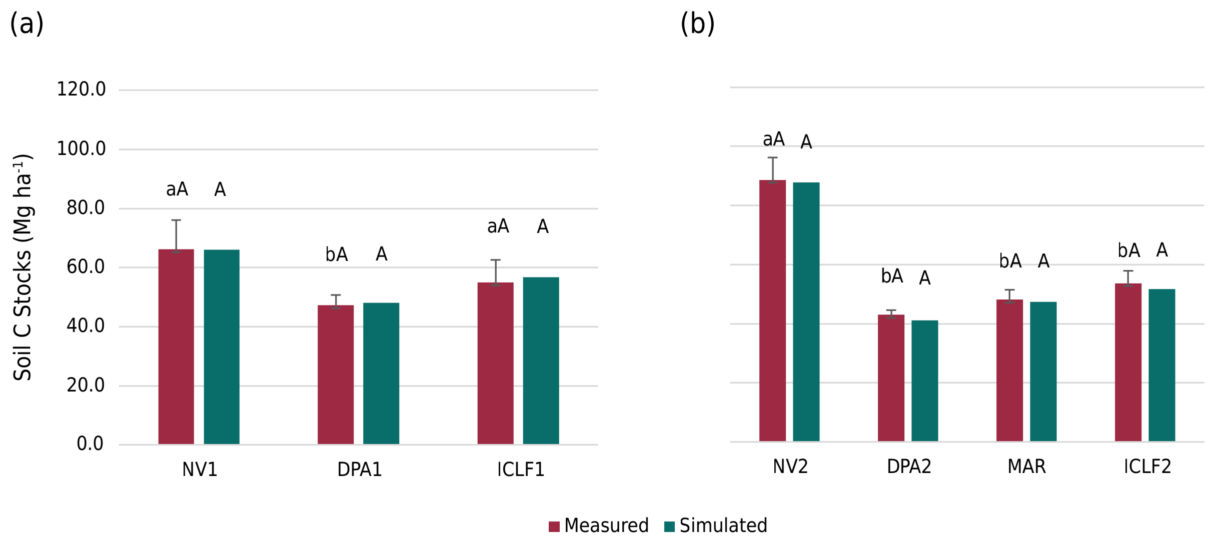

Figure 4. Measured and simulated values of soil C stocks at 0.00-0.20 m soil layer. Chronosequence evaluated in the municipality of Francisco Sá (a) and Curvelo (b), Minas Gerais State, Brazil. The averages followed by the same letter do not differ between land-uses "lower case" and between simulated vs measured "upper case" using the t test at 10 % probability. NV1 and NV2: Native vegetation, DPA1 and DPA2: Degraded pasture, ICLF1 and ICLF2: Integrated Crop-Livestock-Forest systems, MAR: Monoculture of Marandu grassd at the municipalities of Francisco Sá and Curvelo, Minas Gerais State, Brazil.

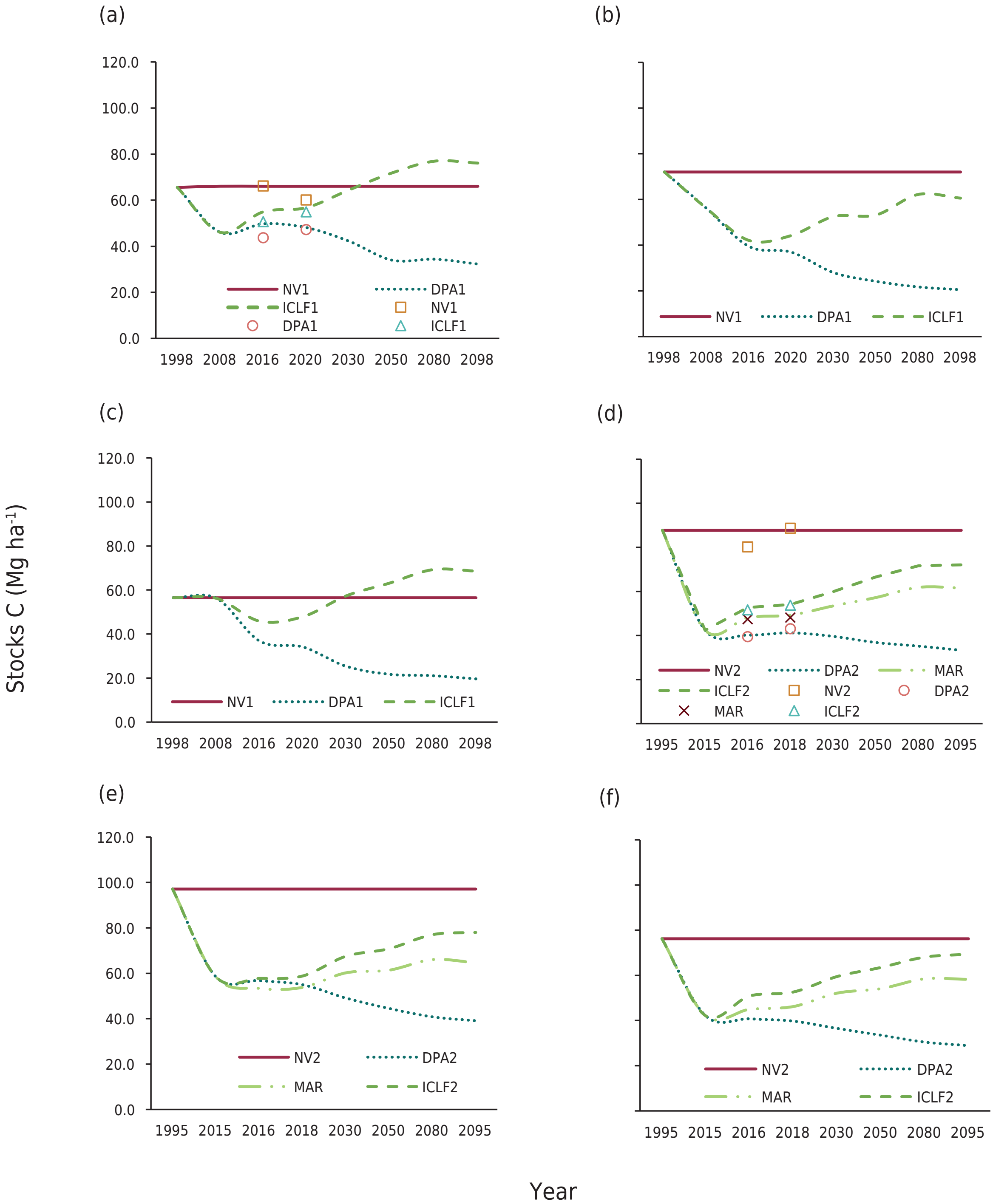

Figure 5. Soil C stocks measured (symbols) and modeled (lines) at 0.00-0.20 m soil layer using the Century model for simulation up to 100 years. (a) 26 % clay content; (d) 52 % clay contend; (b) and (e), rainfall less than 20 mm per month; (c) and (f), temperature increase in 2 °C. Chronosequences evaluated in the municipalities of Francisco Sá (a), (b) (c) and Curvelo (d), (e), (f), Minas Gerais State, Brazil. NV1 and NV2: native vegetation; DPA1 and DPA2: degraded pasture; ICLF1 and ICLF2: integrated crop-livestock-forest systems; MAR: monoculture of Marandu grass.

The simulations of the active, slow and passive compartments modeled by Century showed differences between the systems. In chronosequence 1 (Figure 6a), the active and slow compartments of the DPA1 system decreased over time. However, when converting it to the ICLF1 system (Figure 6b), its values increased considerably. For example, in the DPA1 system, the active and slow fractions reduced from 0.79 Mg ha^{-1} and 39.08 Mg ha^{-1} after 10 years to 0.41 Mg ha^{-1}, and 8.55 Mg ha^{-1} at the end of the simulation, after 100 years (2098 - corresponding year), respectively. Different pattern was observed for the passive fraction, which remained stable over time. However, in the ICLF1 system, there was an increase in the same fractions (active and slow) that ranged from 1.72 and 30.22 Mg ha^{-1} after 18 years to 1.67 Mg ha^{-1} and 49.49 Mg ha^{-1} at the end of the simulation, after 100 years, respectively.

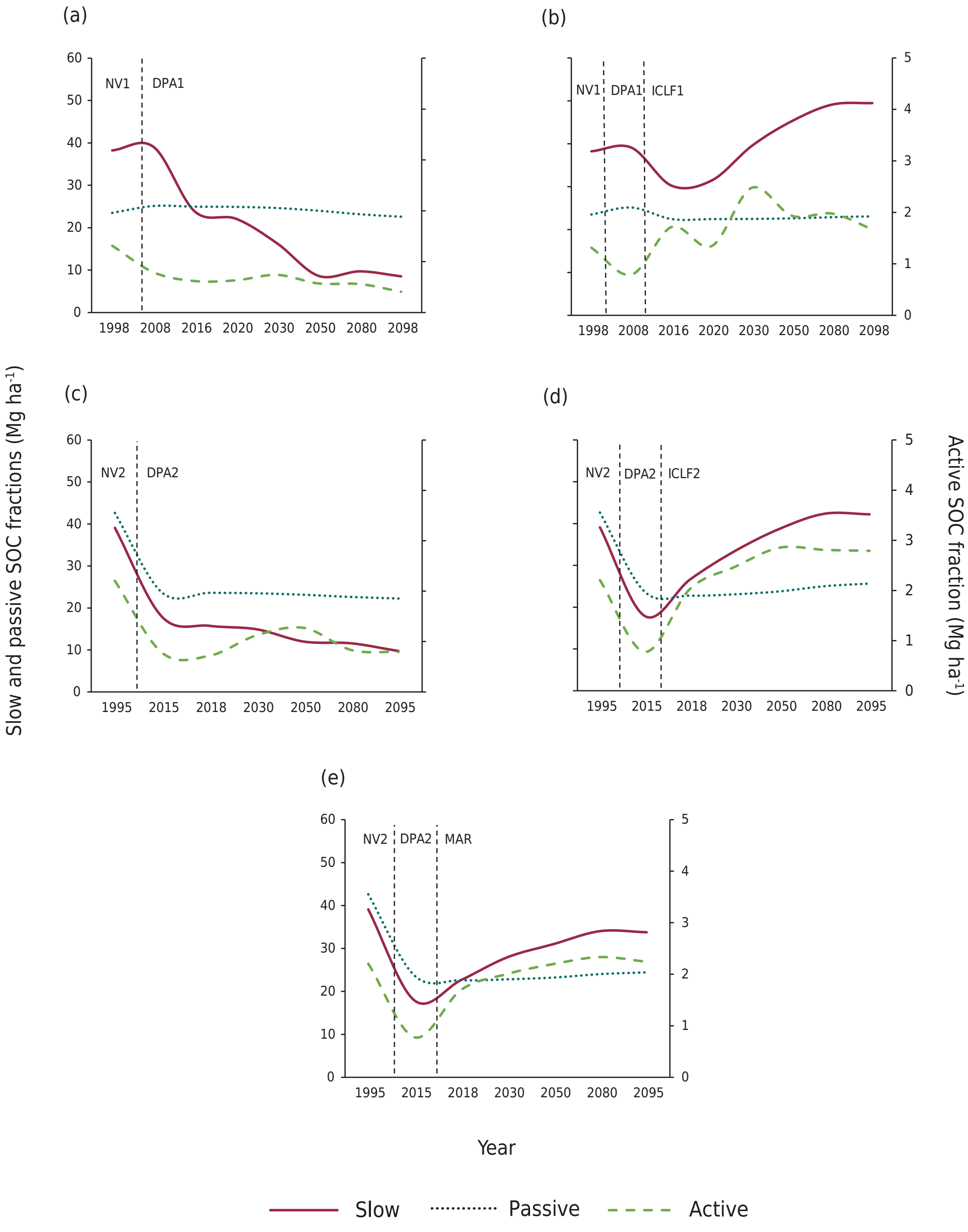

Figure 6. Carbon stocks in the Slow, Passive and Active compartments of soil organic matter. Chronosequence evaluated in the municipalities of Francisco Sá (a, b) and Curvelo (c, d, e), Minas Gerais State, Brazil. NV1 and NV2: native vegetation; DPA1 and DPA2: degraded pasture; ICLF1 and ICLF2: Integrated Crop-Livestock-Forest systems; MAR: Monoculture of Marandu grass.

Chronosequence 2 – Curvelo/MG

The Century model estimates were consistent with the changes observed in the field in the SOC stocks of the chronosequence 2 (Figure 4b and figure 5d). After removing the native vegetation (NV2) and introducing the *Brachiaria decumbens* pasture (DPA2), maintained for 20 years without management and with low-productivity, the SOC stocks decreased from 87.74 Mg ha^{-1} in year 1 (1995 - Corresponding year) to 42.38 Mg ha^{-1} after 23 years (2018 - Corresponding year). The model predicted a decline in SOC stocks over time, with values of 33.28 Mg ha^{-1} at the end of the simulation, after 100 years (2095 - Corresponding year). However, in 2015, part of this system was converted into an area with ICLF2, combining *Urochloa brizantha* 'Marandu' with *Eucalyptus urograndis*, and another part in monoculture of *Urochloa brizantha* 'Marandu' (MAR). According to the results of the simulation, the conversion to these systems with maintenance of current management practices would promote an increase in SOC stocks in ICLF2 and MAR, ranging from 51.71 and 48.11 Mg ha^{-1} after 23 years to 72.07 and 61.57 Mg ha^{-1} after 100 years, respectively (Figure 5d).

The introduction of good soil management practices promoted an increase in SOC stocks in the ICLF2 system in greater proportions compared to the other systems evaluated, and this increase is gradual over time. However, the simulation showed that the DPA2 system reduced C stocks over time.

Future scenarios for the chronosequence 2 can be seen in figures 5e and 5f. Firstly, with a decrease in rainfall of 20 mm per month, we found an increase in SOC stocks (Figure 5e) in ICLF2 and MAR systems, ranging from 67.48 and 60.20 Mg ha^{-1} after 30 years to 78.00 and 64.64 Mg ha^{-1} after 100 years, respectively. However, for DPA2 system, there was a decline over time, with values of 39.09 Mg ha^{-1} after 100 years. Secondly, in the future scenario, increasing the average temperature by 2 °C, there was a reduction in SOC stocks, compared to the initial simulated values in the evaluated systems (Figures 5d and 5f). For ICLF2 and MAR, values ranged from 59.48 and 52.13 Mg ha^{-1} after 30 years to 69.37 and 58.22 Mg ha^{-1} after 100 years, respectively. However, for t DPA2 system, there was a decline in SOC stocks over time, with values of 28.90 Mg ha^{-1} after 100 years.

The simulations of the active, slow and passive compartments of Curvelo/MG chronosequence are shown in figures 6c, 6d and 6e. In the DPA2 system (Figure 6c), the active and slow fractions decreased from 0.78 and 17.87 Mg ha^{-1} after 20 years to 0.79 and 9.74 Mg ha^{-1} at the end of the simulation, after 100 years, respectively. When the conversion of the DPA2 system to ICLF2 occurred, the values of the active and slow fractions increased from 2.03 and 26.56 Mg ha^{-1} after 22 years to 2.79 and 42.21 Mg ha^{-1} after 100 years, respectively (Figure 6d).

Increased values in the active and slow compartments were also evident in the conversion of DPA2 system to MAR, which ranged from 1.70 and 22.64 Mg ha^{-1} after 22 years to 2.24 and 33.77 Mg ha^{-1} after 100 years (Figure 6e). It is noted that the values of these fractions were higher in the ICLF2 system than in MAR. In addition, we observed that the passive fraction values were reduced when NV2 system was changed to DPA2, varying from 42.63 Mg ha^{-1} in year 1 to 23.65 Mg ha^{-1} after 20 years of simulation and a slight increase with the introduction of the ICLF2 and MAR systems.

Statistical results

The results of the statistical tests used to evaluate the simulations in the two chronosequences are described in table 2. The measured and simulated SOC stocks, respectively, showed a high correlation ($r = 0.95$; $p<0.05$) for chronosequence 1 and ($r = 0.97$; $p<0.05$) and chronosequence 2 (Figure 7). The result of the simulations produced values of $R^2<1.0$, meaning that the deviation from the average of the simulations of the simulated values is less than that observed in the measurements. The CRM values ranging from -0.03 and -0.06 allowed us to infer about the success of the simulation process. The results for RMSE (ranging from 5.66 and 7.28) indicated that we found a small difference between the measured and simulated values. The modeling efficiency (EF) ranging from 0.75 and 0.97 provides a comparison of the efficiency of the chosen model with the efficiency in describing the data as the average of the observations. Its positive value indicates that the simulated values describe the trend in the measured data better than the average of the observations. The M values calculated close to zero (-1.64 and -3.08) between observations and simulated scenarios showed that the consistent error was small.

DISCUSSION

The Century model accurately simulated the SOC changes influenced by the history of land-use of the two chronosequences evaluated in the Brazilian Cerrado. Our results confirmed that the model was efficient and capable of assertively simulating variations in soil C stocks in the chronosequences of land-use evaluated. Our findings agree with several studies that used the Century model to assess the impacts on SOC stocks in different chronosequences and soil management practices. Using the Century model, Cerri et al. (2004, 2007), Tornquist et al. (2009), Bortolon et al. (2011), Brandani et al. (2015), Silva-Olaya et al. (2017) and Zani et al. (2018) reliably reflected SOC trends in studies of agricultural chronosequences and changes in soil management in Brazil.

The management history influenced the SOC stocks of the two studied chronosequences, when the soil under DPA was converted into a more conservationist-integrated farming system such as ICLF1 and ICLF2 (Figure 4). The litter, originating from the natural deforestation of the eucalyptus and the influence of the root system of the pastures, deposited on the soil by these systems, contributes to the inputs of SOM and increase of the SOC stocks over time.

Table 2. Statistical tests applied for comparison between simulated and observed values of soil C stocks in the two chronosequences located at Francisco Sá (n = 5) and Curvelo – MG (n = 7), in the Cerrado of Minas Gerais State, Brazil

Chronosequence	r[(1)]	R^2	CRM	RMSE	EF	M
						Mg ha^{-1}
Francisco Sá - MG	0.95	0.98	-0.06	7.28	0.75	-3.08
Curvelo - MG	0.99	0.90	-0.03	5.66	0.97	-1.64
Ideal values	1.00	1.00	0.00	0.00	1.00	0.00

[(1)] r: sample correlation coefficient; R^2: coefficient of determination; CRM: coefficient of residual mass; RMSE: root mean square error; EF: modeling efficiency; M: mean difference between observed and simulated values.

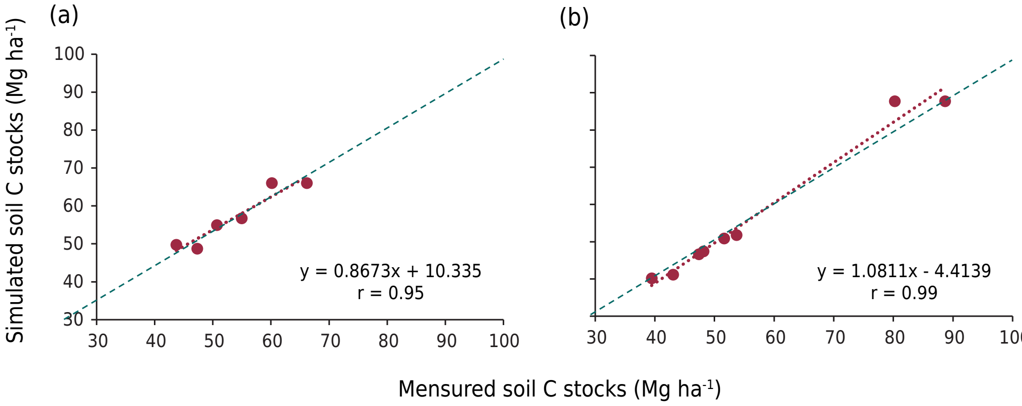

Figure 7. Measured versus simulated soil C (a,b) in the municipality of Francisco Sá and Curvelo, respectively, in areas under native vegetation, degraded pastures, crop-livestock-forest integration systems and pasture monoculture in the Brazilian Cerrado, n=4.

Studying a chronosequence with sugarcane, Zani et al. (2018) simulated the SOC stocks and found that the addition of vinasse (sugarcane residue) to the soil increased the SOC stocks at the expense of the system without vinasse application, confirming the importance of the entry of residues for the increment of SOC stocks in agricultural management systems. Similarly, Brandani et al. (2015), used the Century model to evaluate the SOC dynamics in conventional sugarcane systems, with waste burning, and the use of conservationist management without burning waste. These authors observed that, at the end of the simulation, the conservationist system maintained SOC stocks at levels equal to or higher than native Cerrado vegetation, while conventional practices, such as burning residues, would cause SOC stocks reduction to levels below 60 % of native vegetation levels.

The model simulated that the deforestation of native Cerrado and the implementation of pastures, which due to the lack of adequate management practices, were in a degradation stage, culminating in a decline in SOC stocks (Figure 5). When converting the DPA1 and DPA2 pasture into the ICLF1 and ICLF2 system, respectively, there was an increase in SOC stocks, the same was verified for the MAR system, but with lower values. In the chronosequence 1, at the end of the simulation, the SOC of the ICLF1 system (showed higher values than the native Cerrado (NV1; Figure 5a). This also occurred in the active, slow, and passive SOM compartments. As the active compartment has a very fast turnover rate, its monitoring can be useful as an alert to changes in soil quality. Similar results were found by Cerri et al. (2007) who, assessing the accuracy of the Century model in estimating SOC changes in 11 chronosequences in forest condition for pastures in the Brazilian Amazon, predicted that deforestation and conversion to well-managed pastures would cause an initial decline in SOC stocks (0.00-0.20 m) followed by a slow rise to levels higher than the native forest.

In another study by Oelbermann and Voroney (2011), the Century model was adequate to simulate SOC stock changes in tropical and temperate monoculture and agroforestry systems. The model predicted, over time, a decline in SOC stocks for the monoculture system and an increase in SOC in agroforestry systems. According to the authors, this result was associated with a higher input of SOM from tree pruning and litter. In our evaluations modelled by Century, an increase in SOC stocks was observed for the active, slow, and passive compartments, when DPA system was converted into ICLF1, ICLF2 and MAR (Figure 6). This is related to the conservationist soil management practices that increase the content of SOM, due to greater floristic diversity, litter input, and presence of roots in the soil, mainly by forage grass, contributing to an increase in SOC stocks over time.

The active, slow and passive compartments of NV1 and NV2 are different since they present different phytophysiognomies and edaphoclimatic conditions (Figure 2). The floristic composition of native vegetation is quite different, which may contribute to the differences in the carbon fractions of the active, slow and passive compartments. Furthermore, these NVs are an example of the interference of climate in the decomposition dynamics of SOM. The NV1 rainfall is distributed over a few months of the year, with several months with dry period. This can cause stress in the microbiota community and increase the mineralization rates of SOM when the soil has moisture again, and even the consumption of the most protected organic matter in the soil, such as the slow and passive compartments, may occur.

Under these conditions, easily decomposable compounds are consumed (active soil compartment) and small populations of k-strategist microorganisms survive and slowly consume the most resistant and stable organic matter in the soil. Microbial activity continues to decrease, part of the carbon is physically protected in the micropores, while another part, which is chemically protected, such as humic substances (passive compartment), can be acted upon by k-strategist microorganisms, releasing carbon into the atmosphere. In stable systems like NVs, this is compensated during the annual cycle by slow and continuous decomposition by k-strategists, resulting in a small net change in SOM over time. However, in conventional agricultural systems, soil tillage contributes to the reduction of slow and passive soil compartments (Brady and Weil, 2013; Vries and Shade, 2013; Jansson and Hofmockel, 2020).

In the scenarios of future precipitation reduction (Figures 5b and 5e), we found that the permanence of the DPA1 and DPA2 systems would cause a reduction in SOC stocks, while the introduction of the ICLF1, ICLF2 and MAR systems would promote increases in SOC stocks. According to Roe et al. (2019), the introduction of trees in agricultural systems promotes benefits for increasing water flow in the system. For example, the presence of deep roots increases the water's infiltration capacity and the litter deposition increases the levels of organic matter in the soil, which together improve the soil structure and the stability of the aggregates, preventing water loss through the evaporation process.

The presence of trees in agricultural systems has an important role in the production and regulation of temperatures and freshwater flows on a regional and even global scale (Ellison et al., 2017). Our simulations with future scenarios for increasing regional temperature (Figures 5c and 5f) showed that the permanence of the DPA1 and DPA2 systems would cause a reduction in SOC stocks, decreasing the soil carbon reservoir over time, while the change of land use to ICLF1 systems, ICLF2 and MAR would promote increases in COS stocks. Strategy for land-use change from degraded areas to agricultural systems containing trees and reforestation associated with strategies to reduce forest deforestation are important for adaptation and mitigation strategies in the face of climate change. In addition, Brazil is among the ten countries with the greatest potential for GHG mitigation in the land use sector, which can help achieve the 1.5 °C temperature target proposed in the Paris Agreement (Roe et al., 2019).

According to Houghton et al. (2015), adopting sustainable strategies, such as reforestation, using degraded lands with the introduction of forest species, and containing deforestation, has great potential to prevent global warming above 2 °C. According to these authors, the management of tropical forests becomes important, since they maintain large carbon stocks in their plant biomass and in the soil. The scenarios of reduced rainfall and increased average temperature in the regions of Francisco Sá and Curvelo/MG corroborate with the data obtained in the two weather stations (Figure 2), where there was a tendency to decrease precipitation and increase the region's average temperature over the past 30 years. This global trend is in line with projections made by the IPCC (2018) and by several studies (Schewe et al., 2014; Sedláček and Knutti, 2014; Schleussner et al., 2016a,b; Rogelj et al., 2018).

Agricultural systems with a greater diversity of floristic species stimulate the growth of a more abundant and diversified heterotrophic decomposing community with the capacity to increase SOC stocks and contribute to the mitigation of climate change (Buzhdygan et al., 2020). A similar idea is expressed by Oelbermann and Voroney (2011), considering that the systems with greater diversity of floristic species show a high input of SOM, contributing to the increase of SOC stocks in the long term and, consequently, of the active, slow and passive C compartments of the soil.

A study performed by Oelbermann et al. (2017) also obtained reliable results when applying the Century model to analyze long-term SOC in monoculture and intercropped systems with corn and soybean crops. The authors observed that SOC stocks declined when production was under monoculture with conventional soil management, after which there was an increase in SOC when implementing the intercropped system. In addition, an increase in SOC stocks was observed in the active and slow fractions of the intercropped systems to the detriment of monocultures. According to Lal (2018), the adoption of sustainable soil management practices, with the introduction of trees to the agricultural system, implies increasing of SOM and promoting the C sequestration from the atmosphere for fractions that are physically and chemically protected in the soil, contributing to the mitigation of GHG emissions.

In Brazil, approximately 60 % of pasturelands are in some stage of degradation (Andrade et al., 2014; Oliveira et al., 2017). The replacement of these degraded areas, with low SOC stocks, by more sustainable management systems, such as the ICLF, presents itself as an alternative to monoculture systems in promoting improvements in soil quality and increasing SOC stocks in the short, medium and long-term (Conceição et al., 2017). Our simulations showed that the replacement of DPA1 by the ICLF1 system (Figure 5a) showed an increase in SOC stocks that can compensate, in the long run, the losses of C that occurred by converting native vegetation to pasture. In addition, the simulation revealed a greater contribution by SOC in the conversion of DPA2 into the ICLF2 system than in the MAR system, at the end of the simulation (Figure 5d). This can be explained by the greater input of litter and tree roots and greater biomass production by the root systems of the Marandu grass in the soil, which provides, according to Lal (2018), accumulation of SOM for a good performance of the system productivity, allowing improvements in the physical, chemical and biological properties of the soil to reduce the inputs of agricultural products.

The entry of organic waste, with a low C:N ratio, such as litter, root senescence, and crop residues, can reduce the priming effect of native SOM in agroforestry systems, contributing to the increase in SOC stocks (Cardinael et al., 2018). When organic waste with a high C:N ratio is added to the soil, microorganisms, in search of energy and nutrients, decompose the native SOM, releasing stabilized C in the passive compartment of the atmosphere.

According to Pezzopane et al. (2021), integrated systems with the presence of trees have a high productive potential and capacity to remove atmospheric C and mitigate GHG emissions, where *E. urograndis* with eight years and density of 167 trees per hectare showed a total biomass of 9.175 Mg ha^{-1} yr^{-1} and C stocks in the stem of 4.125 Mg ha^{-1} yr^{-1}. Müller et al. (2009), using different species in silvopastoral system with 10 years and population density of 105 plants hectare, estimated the stem biomass of 2.481 Mg ha^{-1} yr^{-1} and C stocks of 1.117 Mg ha^{-1} yr^{-1} for *E. grandis*, and biomass accumulation of 1.28 Mg ha^{-1} yr^{-1} and C stocks of 0.58 Mg ha^{-1} yr^{-1} for *U. brizantha*. In the same way, Pezzopane et al. (2020) found biomass accumulation data for the species of *Urochloa brizantha* cv. BRS Piatã in integrated systems with *Eucalyptus urograndis*, containing 333 trees per hectare, ranging from 0.79 to 1.14 Mg ha^{-1} $cycle^{-1}$ of forage dry mass. According to the authors, forage accumulation in integrated systems was similar to the intensive monoculture system. This denotes that the entry of light into the integrated system, with the presence of trees, is crucial for the proper management of these systems and for obtaining forage with adequate productivity.

According to previous studies, the potential of C accumulation in the trees of integrated systems is related, among other factors, to the species, the population density and the entry of light into the system. In addition, integrated systems, as reported by Pezzopane et al. (2021), have the potential to sequester C, which, depending on the destination of wood, can store the C in the biomass for long periods. Santana et al. (2016), evaluating the productivity of *E. urograndis* in silvopastoral system and monoculture, found the highest average volume of wood per tree, around 0.2228 m^3 (111.4 m^3 ha^{-1}) when compared to monoculture (0.1895 m^3 per tree). The authors also argue that well-managed integrated systems have a high potential for recovering degraded pastures, as they are an indicator of soil quality recovery.

Regarding the simulation results for SOC stocks (Figures 5 and 6), they also can be related to C and N inputs in the soil, as well as turnover rates of SOM. Thus, considering the difference in the clay content (Table 1), the more clayey soil in chronosequence 2 showed less SOC losses than chronosequence 1, associated with sustainable agricultural practices that can contribute to greater accumulation in SOC stocks, as well as in the probable dynamics of the formation and stabilization of new soil aggregates. In clayey soils, the organic material is better protected from decomposition by microorganisms because it is linked to humo-clayey complexes or sequestered inside the aggregates (Six et al., 2000). Therefore, the results of this simulation indicate that clayey soils for these land uses are priority situations for allocating resources to increase carbon fixation in the soil.

CONCLUSION

Century model can be applied to evaluate the chronosequences of the land-use intensification with agrosilvopastoral systems in the Cerrado region. The SOC stocks increased over time in the conservationists' systems, including well-managed pastures. However, the integrated farming systems were the best alternatives for SOC accumulation in relation to pasture in monoculture. So, the land-use change from degraded pasture to agroforestry systems would not only recover SOC stocks, but their stocks can reach higher values than native Cerrado areas after 100 years of simulation. The model also predicted that the decrease in rainfall and an increase in temperature by 2 °C in the studied region could cause a decline in SOC stocks, especially in degraded systems, while agrosilvopastoral systems can be more resistant to reducing SOC stocks over time.

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SUPPLEMENTARY DATA

Supplementary data to this article can be found online at https://www.rbcsjournal.org/wp-content/uploads/articles_xml/1806-9657-rbcs-47-e0220136/1806-9657-rbcs-47-e0220136-suppl01.pdf.

AUTHOR CONTRIBUTIONS

Conceptualization: Carlos Eduardo Pellegrino Cerri (equal), Juliana Martins Ribeiro (equal), Leidivan Almeida Frazão (equal) and Márcia Vitória Santos (supporting).

Data curation: Betânia Guedes Souza e Brito (supporting), Carlos Eduardo Pellegrino Cerri (equal), Demerson Luiz de Almeida Barbosa (supporting) and Luiz Fernando Carvalho Leite (supporting).

Formal analysis: Carlos Eduardo Pellegrino Cerri (equal), Demerson Luiz de Almeida Barbosa (supporting), Igor Costa de Freitas (supporting), Juliana Martins Ribeiro (equal), Leidivan Almeida Frazão (equal), Luiz Arnaldo Fernandes (equal) and Luiz Fernando Carvalho Leite (supporting).

Funding acquisition: Leidivan Almeida Frazão (lead).

Investigation: Juliana Martins Ribeiro (lead), Luiz Arnaldo Fernandes (equal), Leidivan Almeida Frazão (equal), Luiz Fernando Carvalho Leite (supporting) and Márcia Vitória Santos (supporting).

Methodology: Betânia Guedes Souza e Brito (supporting), Carlos Eduardo Pellegrino Cerri (equal), Igor Costa de Freitas (supporting), Juliana Martins Ribeiro (equal), Leidivan Almeida Frazão (equal), Luiz Arnaldo Fernandes (supporting) and Luiz Fernando Carvalho Leite (supporting).

Project administration: Leidivan Almeida Frazão (lead).

Resources: Leidivan Almeida Frazão (equal) and Márcia Vitória Santos (supporting).

Supervision: Carlos Eduardo Pellegrino Cerri (equal), Leidivan Almeida Frazão (lead), Luiz Arnaldo Fernandes (supporting), Luiz Fernando Carvalho Leite (supporting) and Márcia Vitória Santos (supporting).

Writing – original draft: Betânia Guedes Souza e Brito (supporting), Carlos Eduardo Pellegrino Cerri (equal), Demerson Luiz de Almeida Barbosa (supporting), Igor Costa de Freitas (supporting), Juliana Martins Ribeiro (equal), Leidivan Almeida Frazão (equal), Luiz Arnaldo Fernandes (supporting), Luiz Fernando Carvalho Leite (supporting) and Márcia Vitória Santos (supporting).

Writing – review & editing: Betânia Guedes Souza e Brito (supporting), Carlos Eduardo Pellegrino Cerri (equal), Demerson Luiz de Almeida Barbosa (supporting), Igor Costa de Freitas (supporting), Juliana Martins Ribeiro (equal), Leidivan Almeida Frazão (equal) and Luiz Arnaldo Fernandes (supporting).

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