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SOILS

Simulating soil carbon and nitrogen trends under an integrated system in the Brazilian Cerrado

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ABSTRACT. Management systems that include trees tend to provide higher amounts of plant biomass to the soil, contributing to the increase in carbon (C) and nitrogen (N) stocks. This study simulated C and N stocks and their compartments in a crop-livestock-forest integration system in the edafoclimatic conditions of the Maranhão Cerrado using the Century 4.5 model. The evaluated areas were native Cerrado vegetation (NV) and crop-livestock-forest integration (CLFI). The calibration process gradually modified the model parameters to better fit the simulated and observed soil C and N stocks. The best fit between the data was obtained after changes in the main parameters (DEC3(2), DEC4, and DEC5) that controlled the rate of decomposition of soil organic matter. C and N stocks increased by 14% and 15%, respectively, over 14 years after replacing NV with CLFI. The slow compartment of C presented greater sensitivity to changes in management, with an increase of 47% compared with that of NV. The active compartment increased by 31% and the passive compartment remained constant for over 14 years. Future scenarios, where pasture was maintained between the eucalyptus trees and the scenario that allowed the soybean, corn, and Brachiaria rotation between the trees, were more effective, accumulating approximately 37 Mg C ha^{-1}. The continuous contribution of residues from the trees and pasture increased C and N stocks in the long-term in the slow fraction, where the total organic carbon increased from 32 to 36 Mg ha^{-1} when NV was replaced with CLFI. The model predicted the C and N stocks with accuracies ranging from 1 to 11% of the observed values.

Keywords: soil organic matter; Century 4.5 model; carbon stocks; nitrogen stock.

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Introduction

The accumulation of carbon (C) in the soil of native forest areas is a result of the dynamic balance between the deposition of residue and its losses, controlled by decomposing microorganisms, position in the landscape, soil texture, and climate, which results in linearity in the values of C stocks in the soil over time. The deformation of this linearity occurs by anthropic action, particularly by the use of soil for agricultural purposes.

Agricultural activity can be paradoxical, from soil exploitation that results in increased greenhouse gas emissions to the search for maintaining soil organic C, which is seen as an opportunity to mitigate climate change. The adverse effects of land misuse result in a decrease in C stocks and the acceleration of soil degradation, which can compromise ecosystems that are essential to human welfare and the preservation of nature (Oelbermann et al., 2017; Althoff et al., 2018).

Some initiatives aim to increase C input in the soil, such as the ABC plan developed by the Ministry of Agriculture Livestock and Supply (MAPA), whose intention is to mitigate more than 140 Mg CO_2 eq. with the recovery of degraded pastures, increasing areas under the no-tillage system, and CLFI (MAPA, 2012). The 4p1000 initiative established the goal of increasing the global quantities of soil organic C at a depth of 0.0-0.4 m at the rate of 4% per year. This action could potentially stop the further increase of CO_2 in atmosphere (Sommer, Paul, Mukalama, & Kihara, 2018).

These initiatives share the common perspective that global warming is imminent and endangers the food and nutritional security of billions of people. Increasing C stocks maintains the proper functioning of the soil while conserving food production capacity for future generations. In this context, it is necessary to expand the use of conservationist management systems, such as CLFI, which can produce more food per area and increase the deposition of plant residues, consequently increasing C and nitrogen (N) stocks in the soil (Conceição, Matos, Bidone, Rodrigues, & Cordeiro, 2017).

Long-term experiments are required to verify the variations in C and N in the soil. However, this procedure is slow and expensive. Variations in C and N stocks over time can also be observed through models such as Century 4.5. Century can identify the factors that lead to the accumulation or losses of C and N (Weber, Mielniczuk, & Tornquist, 2016). However, there are few modeling studies on the dynamics of C in CLFI systems. For example, a study was conducted by Oelbermann and Voroney (2011) in Canada and Costa Rica for C and its fractions. Such studies are almost non-existent in the Cerrados of Brazil.

Thus, this study used Century 4.5 to simulate the carbon and nitrogen stocks of the soil and its compartments in a CLFI system in the edafoclimatic conditions of the Maranhão Cerrado.

Material and methods

Area description and sampling

The study was conducted at Fazenda Santa Luzia, in the municipality of São Raimundo das Mangabeiras, Maranhão State, Brazil (6°49'48" S and 45°23'52" W, 475 m altitude), located in the Cerrado biome. The region’s climate is of type Aw (tropical rainy), with dry winters and rainy summers (Koppen classification), an average annual temperature of 26.4°C, and annual precipitation of 1,154 mm, with rainy season from November to April. The soil has been classified as dystrophic red-yellow Oxisol (Latossolo) with a clayey texture (Jacomine et al., 1986).

The areas evaluated were located in the native forest of Cerrado vegetation (NV) (Cerrado phytophysiognomy *stricto sensu*), which was used for the balance simulation. To implement the CLFI system, the NV was suppressed in 2002, followed by plow grid for ground preparation. Then, 5 Mg ha^{-1} of dolomitic limestone was applied and incorporated with a plow grid, followed by a leveling grid. In 2003, eucalyptus seedlings were planted and rice was cultivated among the rows. In 2004, soybeans were cultivated among the rows, and in 2005, corn was cultivated in consortium with the Brachiaria *Urochloa decumbens* cv. Basilisk among the rows, the corn was harvested, and the pasture was maintained. Between 2006 and 2017, pasture was maintained between the rows, and cattle were included with a stocking rate of four animal units per hectare. The total area covered was 24 ha.

Five soil samples were collected from each depth, 0.0-0.10 and 0.10-0.20 m. As Century 4.5 evaluates only the depth of 0.0-0.20 m, the sum of the values obtained at the depths was determined, thus obtaining a single value.

Analyses performed

The chemical and physical soil attributes were determined to obtain the input parameters of the Century model and characterize the studied areas. Total organic carbon (TOC) was determined using the wet method, as proposed by Yeomans and Bremner (1988), total nitrogen (TN) was quantified by sulfuric digestion in Kjedhal distillation as described by Bremner (1996), pH was determined using $CaCl_2$, soil density (SD) was determined by the volumetric ring method, and soil particle size was determined using the pipette method (Teixeira, Donagemma, Fontana, & Teixeira, 2017).

C and N stocks were determined using mass correction, considering soil layer thickness and density values, TOC, and TN observed in the reference area (Ellert & Bettany, 1995).

Century 4.5 model initialization

Model initialization involves obtaining the data necessary for execution. At this stage, the input variables for the local file concerning climatological and soil data were obtained. The model had the maximum and minimum average monthly temperatures (°C), monthly precipitation, soil density, particle size (sand, silt, and clay), and pH as the main input variables (Table 1). For the climatic data, the average values of 39 years (1977-2016) obtained at the weather station of Balsas, Maranhão, approximately 100 km from Santa Luzia farm, were used. The data were obtained from the National Institute of Meteorology (INMET, 2021).

Table 1. Main input variables used for simulations with the Century 4.5 model.

Variables	Values
Sand (g g^{-1})	0.451
Silt (g g^{-1})	0.097
Clay (g g^{-1})	0.452
Soil density (g cm^{-3})	1.22
pH ($CaCl_2$)	4.57
Monthly precipitation(1)	20.2, 17.1, 19.6, 11.7, 4.4, 0.5, 0.2, 0.3, 2.6, 8.3, 14.1, 17.3
Maximum monthly average T °C(2)	28.5, 26.3, 26.6, 32.5, 30, 31.9, 32.6, 34.1, 33.7, 31.7, 29.7, 30.2
Minimum monthly average T °C(2)	22, 19.7, 20.7, 22.3, 21.2, 20.5, 18.9, 20.2, 21.5, 21.1, 18.2, 19.8

(1)Precipitation (cm/month), (2)Temperature in degrees Celsius (T °C), maximum and minimum monthly average from January to December, for an average of 39 years (1977-2016). Fertility characteristics for the depth of 0.0–0.20 m for NV and CLFI, respectively: phosphorus - 9.3 and 6.9 mg dm^{-3}; potassium - 0.25 and 0.14 $cmol_c$ dm^{-3}; calcium - 3.7 and 3.8 $cmol_c$ dm^{-3}; magnesium - 1.0 and 1.0 $cmol_c$ dm^{-3}; and aluminum - 0.3 and 0.4 $cmol_c$ dm^{-3}.

Balance simulation

The stabilization of C and N in the soil was determined by simulating a period of 5,000 years for the area under NV. This simulation was performed because the soil C and N data were derived from an initial simulation of several thousand years (Metherall, Harding, Cole, & Parton, 1993).

Input data were used in the stabilization or balance processes (Table 1), and necessary changes were made to the parameters of the TREE.100 and CROP.100 files regarding the type and size of vegetation, and to the parameters of the fixed file (FIX.100) to adjust the primary production and rates of addition and decomposition of C and N in the NV area (Wendling, Jucksch, Mendonça, Almeida, & Alvarenga, 2014). After the adjustments, the native vegetation file was created by applying fire incidence, which occurs involuntarily during the period of low precipitation in the Maranhão Cerrado (Silva Junior, Anderson, Aragão, & Rodrigues, 2018), simulating vegetation burning events at 5 year intervals.

Parameterization of the Century for application in CLFI system

This stage was performed with some modifications to the original values of the model parameters such that the C and N stocks approached those observed in NV and CLFI. Physical-chemical (SITE.100), fixed (Fix.100), crop (CROP.100), forest (TREE.100), and pasture (GRAZ.100) parameters were varied in this study (Table 2).

Table 2. Century 4.5 parameters measured or modified during model calibration for CLFI.

Parameter	Description	Code	Value
SITE.100	Number of soil layers	nlayer	8
	Number of soil layers in the top-level	nlaypg	8
	Soil sand	sand	0.451
	Soil silt	silt	0.097
	Soil clay	clay	0.452
	Soil pH	pH	4.54
	Effect of annual precipitation on atmospheric N fixation	epnfa	0.00445
	Effect of annual precipitation on non-symbiotic soil N fixation	epnfs	0.01080
FIX.100	Maximum decomposition rate of soil organic matter with active turnover	dec3(2)	15
	Maximum decomposition rate of soil organic matter with slow turnover	dec4	0.009
	Maximum decomposition rate of soil organic matter with intermediate turnover	dec5	0.8
	Minimum C/N ratio for material entering active pool	varat1(2,1)	8
	Minimum C/N ratio for material entering slow pool	varat2(2,1)	15
TREE.100	C allocation fraction of new production for mature forest leaves	fcfrac(1,2)	0.02
	C allocation fraction of new production for mature forest fine roots	fcfrac(2,2)	0.09
	C allocation fraction of new production for mature forest fine branches	fcfrac(3,2)	0.06
	C allocation fraction of new production for mature forest coarse roots	fcfrac(5,2)	0.08
CROP.100	Potential aboveground monthly production for crops	prdx(1)	1.8 (soy); 1.7 (rice); 0.5 (pasture)
	Plant growth type: 1 - perennial plant (grass, dynamic carbon allocation); 2 - annual plant (crop, dynamic carbon allocation)	frtcindx	2.0 (soy); 2.0 (rice); 1 (pasture)
	Fraction of C allocated to roots at planting, with no water or nutrient stress.	frtc(1)	0.65 (soy); 0.45 (rice); 0 (pasture)
	Final fraction of C allocated to roots	frtc(2)	1 (rice); 0 (pasture)
	Time after planting (months with soil temperature greater than rtdtmp) at which the final value is reached	frtc(3)	3 (soy); 3 (rice)
	Maximum fraction of C allocated to roots under maximum nutrient stress	cfrtcn(1)	0 (soy); 0 (rice); 3 (pasture)

	Minimum fraction of C allocated to roots with no nutrient stress	cfrtcn(2)	0 (soy); 0 (rice)
	Maximum fraction of C allocated to roots under maximum water stress	cfrtcw(1)	0 (soy); 0 (rice); 0.4 (pasture)
	Minimum fraction of C allocated to roots with no water stress	cfrtcw(2)	0 (soy); 0 (rice); 1 (pasture)
	Harvest index maximum (fraction of aboveground live C in grain)	himax	0.45 (soy); 0.4 (rice); 0.5 (pasture)
	Symbiotic N fixation maximum for grass/crop	snfxmx(1)	0.05 (soy); 0.005 (rice)
	Number of soil layers used to determine water and mineral N, P, and S that are available for grass/crop growth	claypg	8 (soy); 8 (rice); 8 (pasture)
GRAZ.100	Fraction of live shoots removed by a grazing event	flgrem	0.15
	Fraction of standing dead removed by a grazing event	fdgrem	0.01

Results and discussion

A few changes in the fixed variable files (FIX.100) were necessary to adjust the decomposition rates of the organic matter compartments to those observed in the native forest of the Cerrado (NV). These adjustments are required if Century 4.5 is to be used for tropical conditions as the model is designed for temperate regions. The model parameterization for each region comes from the contrasting edafoclimatic conditions between biomes, and decomposing organisms varying their response regarding the temperature and humidity, which, in turn, affect the dynamics of soil organic matter (Weber et al., 2016).

In Brazil, C modeling studies have been conducted in regions such as the Amazon (Cerri et al., 2007), Pampas of Rio Grande do Sul (Weber et al., 2016), Atlantic Forest (Leite et al., 2004), Caatinga (Althoff et al., 2018), and Cerrado (Wendling et al., 2014). Several studies, mainly from the Cerrado region, have observed the acceleration of the decomposition of the active, slow, and passive compartments. The original values of DEC3(2), DEC4, and DEC5 present in the Century 4.5 model cannot adequately emulate the decomposition of organic matter in the Brazilian Savanna soil.

Changes in fixed parameters are not only key for regions with tropical climates, but also for those with temperate climates. Oelbermann et al. (2017) suggested that the climate in southern Argentine Pampa is temperate, and classified as mesothermal sub-humid-humid (Thornthwaite classification) with an annual precipitation of 860 mm and an average temperature of 14.3°C. The changes in the DEC(2), DEC4, and DEC5 parameters decreased from the original values and were readjusted to 4.000, 0.0013, and 0.0500, respectively (Oelbermann et al., 2017).

A period of 5,000 years was simulated for stabilization. In this context, the C and N stocks were consolidated approximately 2,000 years after the initialization of the model. TOC stabilized at 32.3 Mg ha^{-1}, C in the passive compartment at 25 Mg ha^{-1}, C in the slow compartment at 5.7 Mg ha^{-1}, and C in the active compartment at 1.3 Mg ha^{-1}. TN stabilized at 1.9 Mg ha^{-1} and its passive, slow, and active compartments at 1.6, 0.2, and 0.1 Mg ha^{-1}, respectively. The sum of the compartments reached 100% for both C and N.

The comparison between the data for measured (32 Mg ha^{-1}) and simulated C stock (32.3 Mg ha^{-1}) demonstrated that Century 4.5 accurately simulated the dynamic balance conditions of NV, had a discrepancy of only 0.3 Mg ha^{-1}, and an error of 1% (Table 3). There was a difference between measured (2.2 Mg ha^{-1}) and simulated N stock (1.9 Mg ha^{-1}), which corresponded to an absolute value of 0.3 Mg ha^{-1} and an error of 11% (Table 3).

Table 3. C and N stock values obtained through chemical analysis and simulation by the Century 4.5 model in the 0.0-0.20 m layer of a Oxisol in São Raimundo das Mangabeiras, Maranhão State, Brazil.

Management system	C Stock (Mg ha^{-1})		Error C (%)	N Stock (Mg ha^{-1})		Error N (%)	C/N Ratio		Error C/N (%)
	Obs.[1]	Sim.[2]		Obs.[1]	Sim.[2]		Obs.	Sim.	
NV	32.00	32.32	1.00	2.20	1.95	11.40	14.54	16.60	14.17
CLFI	36.38	37.43	2.90	2.53	2.42	4.35	14.38	15.47	7.58

[1]Observed - data obtained in the laboratory; [2]Simulated - values simulated by Century 4.5.

Simulation of real scenarios for CLFI

Eucalyptus was introduced after the fall of NV in 2002, and rice was cultivated among the rows in the 2003/2004 crop. Soybeans and corn were cultivated in the following period, establishing Brachiaria in the area between 2006 and 2017. Passive C stocks have remained constant for over 14 years (Figure 1a). Passive C represented 79% of the TOC under NV, decreasing to 67% under CLFI. Passive N decreased in proportion from 82 to 69%, despite a slight increase of 6% in values with the conversion of NV (1.6 Mg ha^{-1}) to CLFI (1.7 Mg ha^{-1}).

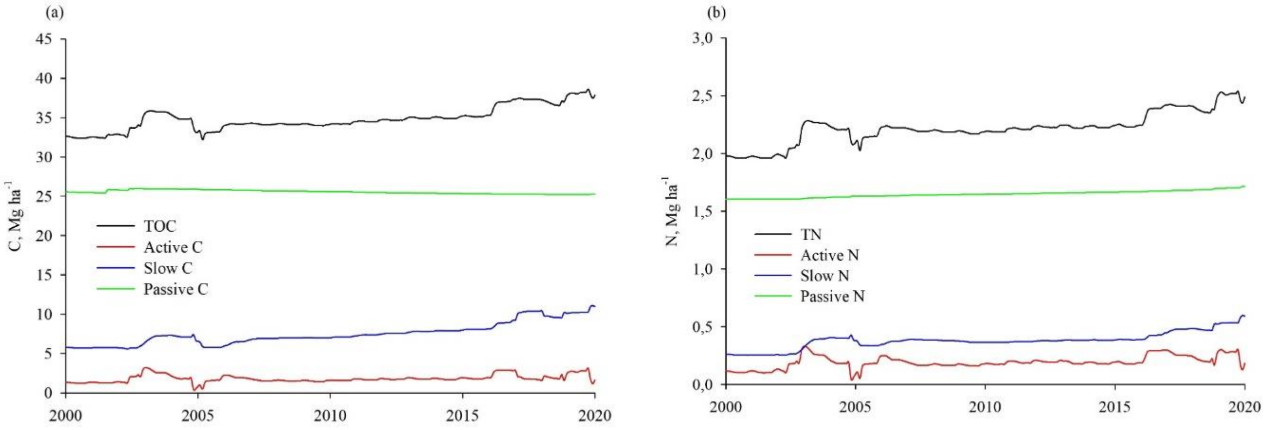

Figure 1. Temporal dynamics of the C (a) and N (b) compartments in the simulation of the 14-year period for the CLFI system by the Century 4.5 model.

This model demonstrates that slow C is decisive for the elevation of C stocks in the CLFI system. In 2002, under NV, the model estimated 5.7 Mg ha^{-1} for slow C (Figure 1a). After deforestation, there was a rapid transfer of C from the forest residue to the slow compartment, which reached 7.3 Mg C ha^{-1} between 2003 and 2005 (Figure 1a). This increase was also noticeable for slow N, which increased from 0.3 to 0.4 Mg ha^{-1} (Figure 1b). After this period, there was a decrease in the slow compartments of the C and N stocks, which may be due to the inability of young Eucalyptus to maintain the input of plant biomass. Competition between trees and annual crops has also been reported (Moreira et al., 2018).

When competition occurs between species, plants undergo morphological changes that directly affect the absorption of radiation and the accumulation of photoassimilates, resulting in dry matter production (Mendes, Lacerda, Cavalcante, Fernandes, & Oliveira, 2013). The diffusion of solar radiation by trees in time and space (effect of the age of the trees and the position of the tree lines) on the morphological characteristics of corn in CLFI systems results in a decrease in the production of plant biomass, as reported by Bertomeu (2012), who found a reduction of 19 to 66% in corn biomass in a CLFI system compared to that in a corn monocrop.

In the agricultural year 2006/2007, pasture was introduced between rows, followed by the inclusion of cattle. From this period onwards, stocks of slow C increased from 5.8 Mg ha^{-1} in 2006 to 8.4 Mg ha^{-1} in 2016 (47% increase compared to NV) (Figure 1a). The slow N increased by 15% during the same period (Figure 1b). The inclusion of forage plants in the CLFI system, with moderate grazing intensity, increased the contribution of residue in the system and increased C stocks in the soil (Salton et al., 2011; Calil et al., 2019). In 2017, there was a noticeable increase in the slow compartment of C (10 Mg ha^{-1}) and N stocks (0.5 Mg ha^{-1}). The model interpreted this increase as an additional contribution of plant biomass that occurred at the beginning of Eucalyptus removal (cutting).

The active compartment is composed of microbial biomass, exudates and by-products, degraded plant residues, organic acids, starches, and proteins. Active carbon represented 4% of the TOC of NV (Figure 1a), i.e., 1.3 Mg C ha^{-1}. Active C increased to 1.9 Mg ha^{-1} with the removal of NV between 2003 and 2005 (Figure 1a), corresponding to 5.5% of the TOC. From 2006 to 2016, it stabilized at 5%, decreasing to 1.7 Mg ha^{-1} (31% increase compared to NV). The largest discrepancy in the CLFI system was active N, which represented 5% of TN in NV and increased to 11% after conversion to CLFI.

The results presented above indicate greater sensitivity of the active and slow compartments to changes in the management system, and at the same time, greater stability of the passive compartment. However, simulated soil organic matter compartments (active, slow, and passive) are abstract (conceptual) and cannot be directly confronted with physical particle size fractions, although some links can be performed effectively after adjusting the decomposition parameters of the model (Parton, Schimel, Cole, & Ojima, 1987; Metherall et al., 1993).

Comparison between simulated and observed values

The increase in C stocks of 32 Mg C ha^{-1} observed in the field in NV to 36 Mg C ha^{-1} in CLFI (14% increase) is more easily obtained using trees as they increase in size over the years and, consequently, increase the deposition of plant biomass (Wink, Reinert, Müller, Reichert, & Jacomet, 2013), as compared to using only annual crops. However, information on CLFI modelling is scarce (Oelbermann & Voroney, 2011).

Simulated C stocks for CLFI were 37 Mg ha^{-1}, whereas those observed in the field were 36 Mg C ha^{-1}, with an error of 2.9% (Table 3). There was an increase in TOC from 32 to 35 Mg C ha^{-1} with the removal of NV for the establishment of Eucalyptus between 2002 and 2004 (Figure 2a), which resulted in annual C gains of 1.3 Mg ha^{-1}. This increase is consistent with that reported by Tsukamoto Filho, Couto, Neves, Passos, and Silva (2004), who verified the participation of rice in the formation of a TOC of 36% in CLFI systems in year 1. The participation of soybeans was 6.4% in year 2, and that of pasture decreased from 12% in year 3 to 4.4% in year 11.

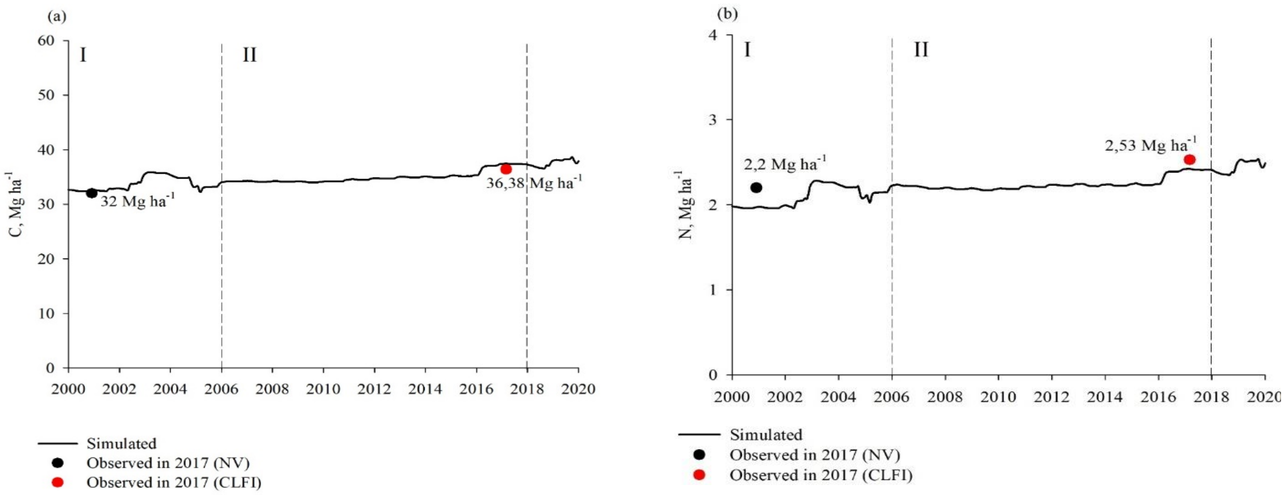

Figure 2. Evolution of C (a) and N (b) stocks at different times that comprised the CLFI simulated by the Century 4.5 model and observed in the field. I - Eucalyptus, among the rows: rice (2003), soybean (2004), corn (2005); II – Eucalyptus, among the rows: pasture.

After the initial period of C intake in the soil, C stocks decreased to 33 Mg ha^{-1}. In 2006, Brachiaria replaced annual crops and was maintained in the following years. During this period, the accumulation rate was 0.4 Mg C ha^{-1} year^{-1}. According to Isernhagen, Rodrigues, Diel, Matos, and Conceição (2017), the conversion of NV into CLFI contributed to the reduction of C stocks in the soil by 20%, which represented a loss of 17 Mg ha^{-1}. Conceição et al. (2017) compared the evolution of C stocks between 2011 and 2014 and found that the CLFI system delivered the largest gains in three years, with an increase of 7.8% as against the values of 3.6, 0.6, and −0.3% for pasture, no-tillage system, and Eucalyptus, respectively.

The N stocks observed in the NV of 2.2 Mg ha^{-1} increased by 15% in the CLFI. The model was effective in comparing the simulated and observed results in the field for TN in CLFI, with an error of 4.3%, simulated N stocks of 2.4 Mg N ha^{-1}, and observed N stocks of 2.5 Mg N ha^{-1} (Figure 2b). However, a discrepancy between the simulated and observed values of TN has been observed in other studies involving tree cultivation. Wink, Reinert, Tornquist, and Silva (2015), who employed the Century 4.5 model to compare different Eucalyptus forests, found that the younger the Eucalyptus forest, the smaller the TN error. Eucalyptus at 20, 44, 120, 156, 180, and 240 months resulted in errors of 6, 16, 54, 70, 22, and 32%, respectively. Wendling et al. (2014) found an error of 29% for TN when evaluating planting of *Pinus* at 372 months.

Simulation of future scenarios

Three future scenarios have been proposed for the CLFI, as shown in Figures 3 (TOC) and 4 (TN). The first scenario, which maintains the characteristics of the CLFI already underway, showed no gains in C stocks at the end of the last simulation year. However, with the cutting of Eucalyptus, soil turnover, and subsequent reestablishment of CLFI with Eucalyptus planting every 14 years, there was a noticeable decrease in the stocks of C to approximately 35 Mg C ha^{-1}, which persisted for five years. With the growth of Eucalyptus and increased deposition of plant biomass, C stocks were re-established to 37 Mg C ha^{-1} (Figure 3a).

In the second scenario, the CLFI_ROTA was similar to the first scenario only in the cutting time of the Eucalyptus (14 years), which presented a cycle of six years of cultivation of soybeans in year 1, corn in year 2, soybeans in year 3, corn in year 4, and Brachiaria in years 5 and 6 among the rows. This rotation between legumes and grasses resulted in a faster response time for the recovery of C stocks when Eucalyptus was cut. More precisely, in the slow C (Figure 3c) between 2018 and 2050, Eucalyptus was cut twice, with the soil later revolved. CLFI_ROTA presented average C stocks in the slow fraction of 11 Mg C ha^{-1}, CLFI of 10 Mg C ha^{-1}, and EUCA of 8 Mg C ha^{-1} (Figure 3c).

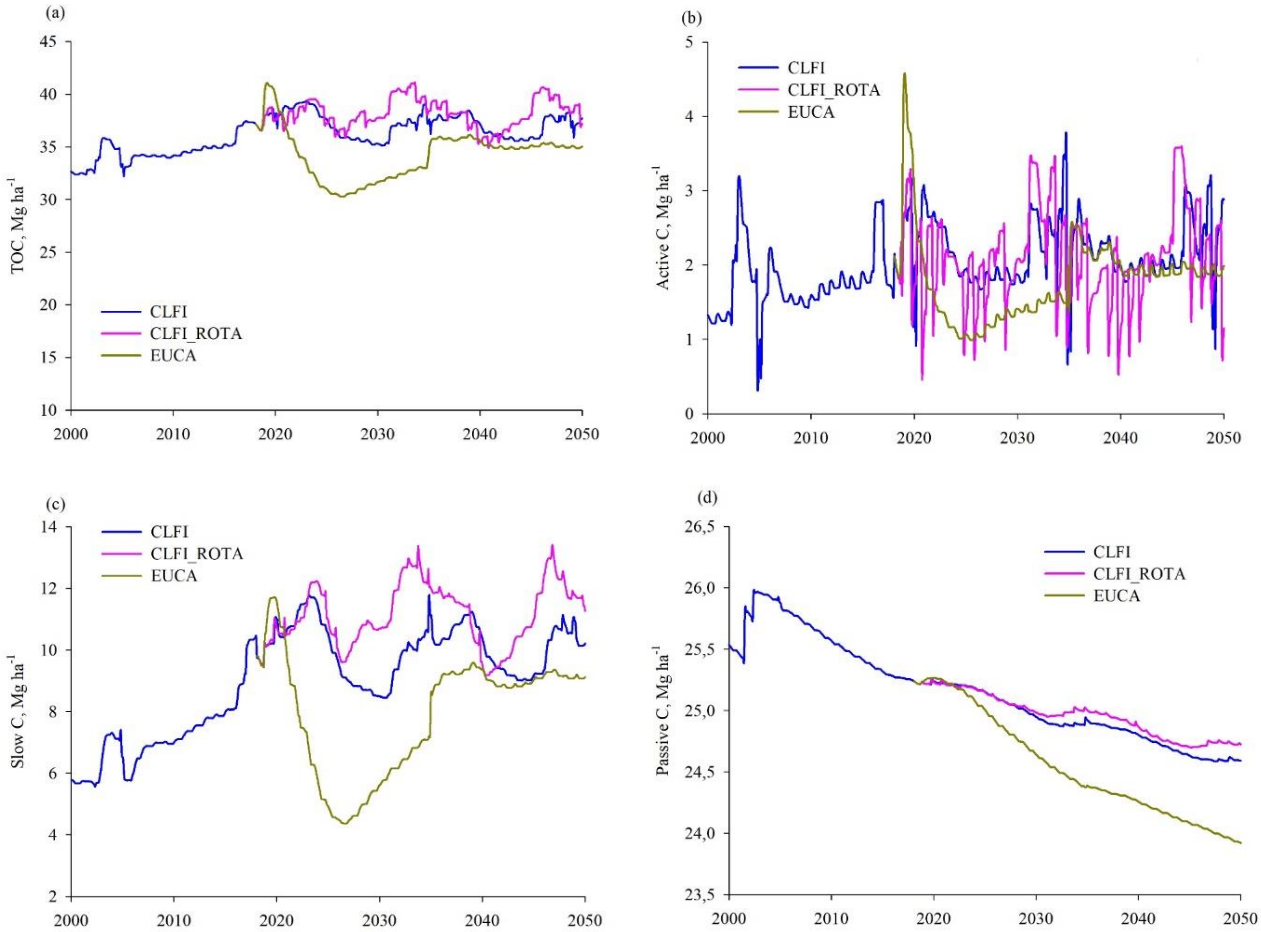

Figure 3. Variation of TOC stocks (a), active compartment (b), slow compartment (c), and passive compartment (d) estimated by the Century 4.5 model for CLFI, crop-livestock-forest integration with soybean, corn, and Brachiaria rotation (CLFI_ROTA), and Eucalyptus cultivation (EUCA).

In the third scenario, EUCA, which consisted only of the Eucalyptus forest, with a cycle of 14 years between planting and cutting, presented the longest response time for recovering C stocks, as shown in Figure 3c, between 2020 and 2035. In 2050, EUCA contributed 34 Mg C ha^{-1} to the soil, whereas CLFI_ROTA contributed 38 Mg C ha^{-1} (Figure 3a). The EUCA scenario was responsible for the largest drop in passive C. In 2018, it was 25 Mg C $ha^{-1,}$ and in 2050, it was 24 Mg C ha^{-1}, a decrease of 4%. The arboreal component is an important C sink because of its high capacity to accumulate C in woody biomass and provide more recalcitrant residues (Cecagno et al., 2018).

The C stock of the active fraction behaved irregularly in the CLFI_ROTA scenario, with peaks and decreases in C, which were mainly due to crop alternation, given that the climatic conditions were the same for the three scenarios, thus distinguishing them from CLFI, which presented irregularity only in the periods of Eucalyptus cutting and soil turnover. EUCA presented the most irregular line in the graph, with a large peak of active C only between 2018 and 2020, the transition period from CLFI to Eucalyptus forests (Figure 3b).

The best scenario found for both TN and its compartments was the CLFI_ROTA with soybean/corn rotation and subsequent Brachiaria cultivation, demonstrating the need to avoid soil turnover and monocrop among Eucalyptus rows. Unlike C stocks in the passive compartment, N showed improvements in its stocks in the three scenarios, particularly in CLFI_ROTA, which was 12 and 22% higher (Figure 4d) than in the future CLFI and EUCA scenarios, respectively.

The largest N oscillations were observed in the active and slow compartments (Figure 4b and c). The active nitrogen in the three proposed scenarios was always above 5% of the TN, with 10% CLFI, 8% CLFI_ROTA, and 10% EUCA. The changes in N stocks up to 2050 were mainly due to the slow and passive compartments, as they presented significant gains in N (Figure 4c and d). The N submodel adds a differentiated routine for N input into the soil: fertilization. The contribution of N through fertilization was explored more in the CLFI_ROTA scenario than in the other two scenarios. Thus, the N resulting from fertilization, after losses by volatilization and leaching, is moved to the active, slow, and passive fractions (Parton et al., 1987; Metherall et al., 1993), which certainly contributed to the greater contributions of N in the CLFI_ROTA scenario.

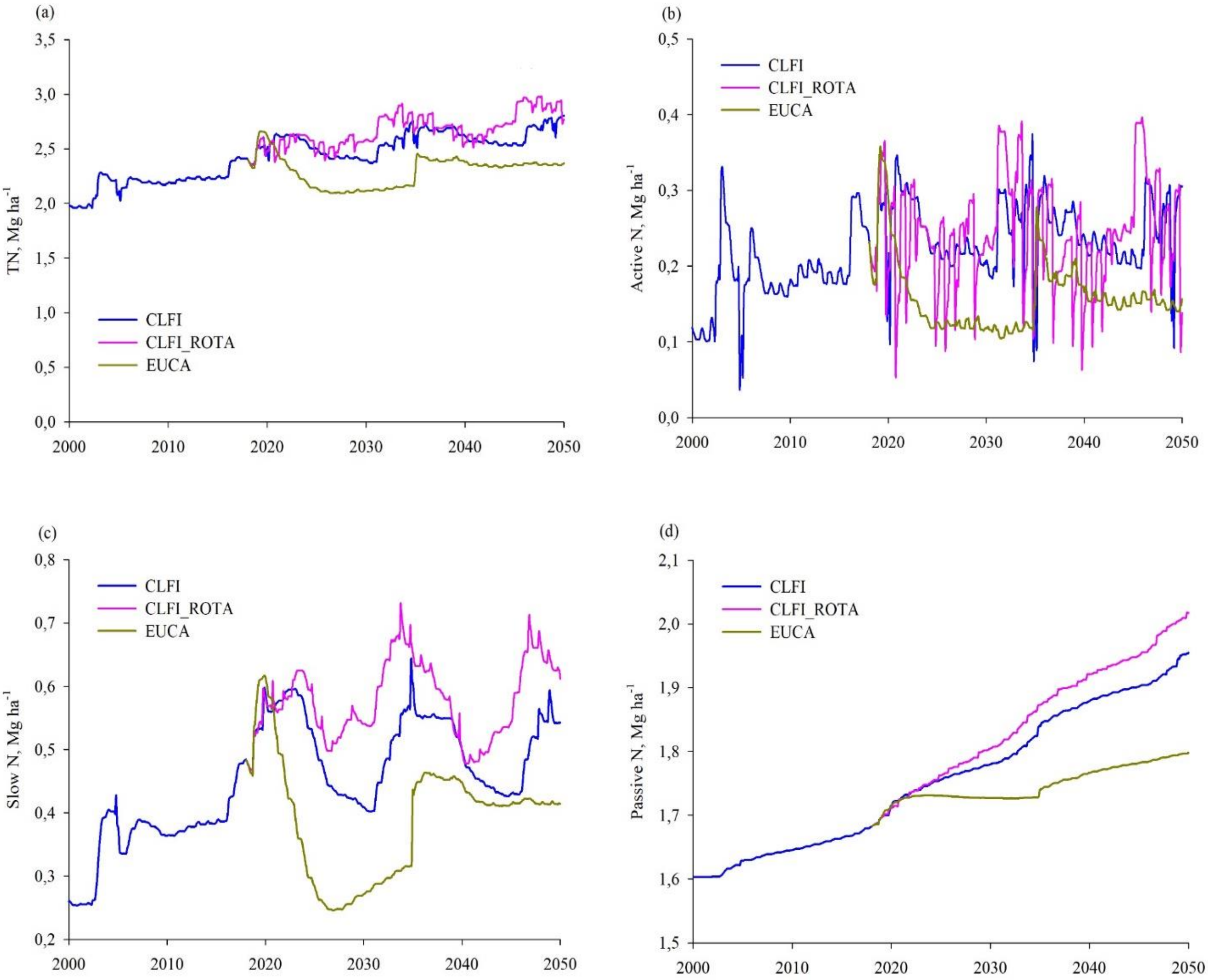

Figure 4. Variation of TN stocks (a), active compartment (b), slow compartment (c), and passive compartment (d) estimated by the Century 4.5 model for CLFI, CLFI_ROTA, and EUCA.

Legumes such as soybean, which comprise integrated systems, can be a significant source of N for subsequent crops, contributing to an increase in TN in the soil. Additionally, the CLFI system is the target of public policies that aim to promote sustainable and resilient agriculture to climate change in Brazil as it improves the chemical, physical, and biological conditions of the soil and promotes the removal of CO_2 from the atmosphere through the growth of trees and accumulation of C in the soil (Conceição et al., 2017).

Conclusion

Century 4.5 demonstrated that replacing native Cerrado forest with CLFI increased soil carbon and nitrogen stocks, primarily in the slow fraction. The model illustrated the potential effects of the consortium of trees, annual crops, and pastures on soil organic matter dynamics, with prediction accuracy of C and N stocks ranging from 1 to 11% compared to observed values. Future scenarios promoting higher C and N stocks involved maintaining CLFI with pasture and CLFI with crop rotation between rows of eucalyptus.

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