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Simulation of soil carbon and nitrogen stocks in conservation systems in Cerrado of Northeastern Brazil

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Abstract

Aim of study: Conservation management is an important alternative for the mitigation of environmental problems caused by conventional agriculture; however, information about long-term benefits of conservation systems is still incipient. Simulation modeling of soil organic matter dynamics has been applied using different types of land use and management. The models are essential tools for building scenarios for sustainable production systems. This study aims to use the Century model to simulate the effects of no-till and integrated crop-livestock system on soil carbon and nitrogen stocks and to establish scenarios in sandy soils at the Cerrado Brazil.

Area of study: Barbosa Farm in the municipality of Brejo, eastern Maranhão state, Northeastern Brazil.

Material and methods: An area that has been under no-till faming for fourteen years (NT), an area under both no-till and crop-livestock integration (NT-CLI), and an area under native Cerrado vegetation (reference) were selected. In each area, simulations of real scenarios and three future scenarios were carried out.

Main results: The simulated total organic carbon (TOC) stock values for the real scenarios were 41.15 Mg ha^{-1} and 44.91 Mg ha^{-1} with NT and NT-CLI systems, respectively; whilst for simulated total nitrogen (TN) stock were 2.29 Mg ha^{-1} with NT and 2.59 Mg ha^{-1} with NT-CLI systems. However, TOC values were more accurate compared to TN values. The complexity of TN dynamics may not be fully represented by the simulation.

Research highlights: Models show that future scenarios up to 2060, integrated crop-livestock system were more effective, storing up to 85.92 Mg ha^{-1} of TOC stock and 8.94 Mg ha^{-1} of TN stock.

Keywords: conservation agriculture; Century; integrated production systems; modelling; soil health.

Simulación de las reservas de carbono y nitrógeno del suelo en sistemas de conservación en el Cerrado del Nordeste de Brasil

Resumen

Objetivo del estudio: La gestión de conservación es una alternativa importante para mitigar los problemas ambientales causados por la agricultura convencional; sin embargo, la información sobre los beneficios a largo plazo de los sistemas de conservación es aún incipiente. Se han aplicado modelos de simulación de la dinámica de la materia orgánica del suelo utilizando distintos tipos de uso y gestión del suelo. Los modelos son herramientas esenciales para construir escenarios de sistemas de producción sostenibles. Este estudio busca utilizar el modelo Century para simular los efectos de la labranza cero y los sistemas integrados de cultivo-ganadería sobre las reservas de carbono y nitrógeno del suelo y establecer escenarios en suelos arenosos del Cerrado brasileño.

Área de estudio: Hacienda Barbosa en el municipio de Brejo, este del estado de Maranhão, nordeste de Brasil.

Materiales y métodos: Se seleccionaron un área con labranza cero (LC) durante catorce años, un área con labranza cero e integración de cultivos-ganadería (LC-ICG) y un área con vegetación nativa del Cerrado (referencia). En cada área se realizaron simulaciones de escenarios reales y de tres escenarios futuros.

Resultados principales: Los valores simulados de las reservas de carbono orgánico total (COT) simulados para los escenarios reales fueron de 41,15 Mg ha^{-1} y 44,91 Mg ha^{-1} con los sistemas LC y LC-ICG, respectivamente; mientras que para las reservas de nitrógeno total (NT) simuladas fueron de 2,29 Mg ha^{-1} con los sistemas LC y 2,59 Mg ha^{-1} con los sistemas LC-ICG. Sin embargo, los valores de COT fueron más precisos que los de NT. La complejidad de la dinámica del NT puede no estar plenamente representada por la simulación.

Conclusiones: Los modelos muestran que en los escenarios futuros hasta 2060, el sistema integrado de cultivo-ganadería fue más eficaz, almacenando hasta 85,92 Mg ha^{-1} de las reservas de COT y 8,94 Mg ha^{-1} de las reservas de NT.

Palabras clave: agricultura de conservación; Century; sistemas integrados de producción; modelización; salud del suelo.

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Introduction

Natural ecosystems are increasingly being transformed into areas dedicated to agricultural cultivation to meet for food, energy, and fiber production. Therefore, efforts are needed to conciliate agricultural production and sustainability, overall when considering the limited resources for future generations and the growing demand for food (Chabert & Sarthou, 2020). Conservation agriculture emerges as a strong ally to preserve resources and ensure food security (Page et al., 2020), being progressively adopted by farmers to the detriment of conventional agriculture (Silva et al., 2021). Conservation agriculture based on integrated production systems is a growing trend because it can improve soil quality, crop yields, and land use efficiency (Pooniya et al., 2022). Crop-livestock integrated systems have also resulted in improved efficiency in increasing organic matter, contributing to carbon (and nitrogen stocks in soil (Bieluczyk et al., 2020). And for this reason, there are national policies, such as the Low Carbon Emission Agriculture Program, that benefit and encourage the adoption of integrated systems by farmers and ranchers in Brazil (Brazil, 2021).

Carbon and nitrogen stocks are fundamental to determine the impact of agricultural systems on the maintenance of soil ecosystem services (Pellikka et al., 2023). Studies carried out in the Brazilian Cerrado biome (Savanna Biome) have showed that crop-livestock integrated can mitigate greenhouse gas emissions and sequester carbon in the soil (Oliveira et al., 2024). The average soil carbon stock is 60 Mg ha^{-1} in areas with crop-livestock integrated in the Brazilian Cerrado (Sant-Anna et al., 2017). Thus, although the deforestation of native vegetation contributes to implications for the global carbon cycle (Oliveira et al., 2023), crop-livestock integrated can partially compensate soil carbon losses to the atmosphere. Besides, the conversion of native vegetation to agriculture has also contributed to the increase in N_2O emissions, mainly attributed to the application of nitrogen fertilizers (Martins et al., 2015). However, the crop-livestock integrated system has demonstrated potential in reducing N_2O emissions when compared to conventional agriculture (Sato et al., 2017).

Despite that, increasing carbon and nitrogen stocks in crop-livestock integrated systems depends on how long the system is in place, intercropped crops, and soil cover use (Soares et al., 2019). Studies aiming at advancing the understanding of crop-livestock integrated systems as an option for long-term sustainable land use are necessary (Stieven et al., 2020). Such systems are complex and diverse because of the synergy between the integrated components (Farias-Neto et al., 2019). This complexity still constitutes a barrier for farmers in Brazil to adopt only the no-till system without the integration of crop and livestock components. A strategy used to understand the effects of conservation production systems is the use of simulation models focused on the dynamics of organic matter (Liang et al., 2023), mainly due to the model is ability to predict carbon and nitrogen over time. The model can be an essential factor in providing farmers with satisfactory results that boost the exploration and expansion of areas with crop-livestock integrated in Brazil.

Century model, among several existing models, has been widely used in different geographic and land use contexts. The model has been used in the United States (Nicoloso et al., 2020), Europe (Dimassi et al., 2018) and China (Zhang et al., 2021) to predict future scenarios conditions of carbon and nitrogen stocks in soil, thereby providing key information in decision-making regarding the management of agricultural activities. In Brazil, studies evaluating the use of the Century model have shown good accuracy in estimating carbon and nitrogen stocks in soil under subtropical conditions (Gonçalves et al., 2019), but also in tropical conditions dominated by biomes known as Caatinga (Althoff et al., 2018; Araújo-Neto et al., 2021; Primo et al., 2023) and Cerrado (Brazilian savanna) (Silva-Olaya et al., 2017). In the Cerrado region, Wendling et al. (2014) reported a difference of 1.88 Mg ha^{-1} for carbon and 0.4 Mg ha^{-1} for nitrogen between measured and simulated values in a no-till system.

However, there are few studies using the Century model in integrated systems, and even scarcer are those using the model in an integrated crop-livestock system under the Cerrado biome, where soils are dependent on organic matter content when aiming to improve physical and chemical properties of soil. Considering the need for information and use of conservation systems for increasing organic matter in soil, the present study aims to use the Century model to simulate carbon and nitrogen stocks in two conservation systems, no-till and no-till in a crop-livestock integration system. Furthermore, another approach will consist of predicting future scenarios of carbon and nitrogen stocks in the two conservation systems in comparison with native vegetation in sandy soil of the Cerrado biome of eastern Maranhão, Brazil.

Material and methods

Study area and soil sampling

The study was carried out at Barbosa Farm in the municipality of Brejo, eastern state of Maranhão, northeastern Brazil (03º42'0.93" S and 42º56'25.57" W, altitude of 98 m). Land relief ranges from undulating to smooth. According to the Koppen classification, the climate is tropical hot and wet (Aw). Average annual temperature is over 27 ºC and average annual rainfall is 1,835 mm. The study took place in a Cerrado biome with soil classified as *Argissolo Amarelo* (Brazilian classification, Santos et al., 2018), corresponding to a Ultisols, according to Soil Taxonomy (Soil Survey Staff, 2014).

Two agricultural areas were selected: an area that has been under no-till management for 14 years (NT) with soybean/millet rotation, and an area under both no-till and integrated crop-livestock (NT-CLI) systems with soybean/millet rotation for four consecutive years followed by rotation maize intercropped with *Brachiaria brizantha* (Hochst ex A. RICH) STAPF. cv. Marandu for a stocking rate of 2.5 animals ha^{-1} (cattle), that graze, on average, for a period of six months. In addition, an area of Cerrado with native vegetation (NV) land was used as a reference, which was under the same environmental conditions as the other two areas. Crops were managed using technical recommendations for liming, fertilizers, and pesticides, as well as other crop practices.

Soil sampling consisted of four composite samples collected at depths of 0.00 – 0.10 and four composite samples collected at depths of 0.10 – 0.20 m. The four composite samples were formed by nine subsamples distributed at equal distances on 2 ha plots in each area (no-till, no-till with integrated crop-livestock and native vegetation), when considering the homogeneity of the area under study. The Century model evaluates only the 0-0.20 m layer, therefore, values from each soil layer were averaged out to determine a single value. The argillic horizon begins after a depth of 0.50 m.

Analysis of soil chemical and physical attributes

Chemical and physical attributes of soil were determined to obtain input parameters for the Century model and to characterize the areas. Total organic carbon (TOC) was determined using wet digestion (Yeomans & Bremner, 1988), total nitrogen (TN) was quantified by sulfuric digestion in Kjedhal distillation (Bremner & Mulvaney, 1982), soil pH was determined in water (1:2.5), bulk density (BD) was determined using the volumetric ring method, and soil granulometry was determined using the pipette method (Teixeira et al., 2017).

Additionally, microbial biomass carbon (MBC), particulate organic carbon (POC), and organic carbon associated with minerals (OCAM) were determined. MBC was determined using microwave irradiation (Islam & Weil, 1998), POC was measured using physical carbon fractionation (Cambardella & Elliot, 1992), and OCAM was determined by the difference between TOC and the sum of MBC and POC. The determination of carbon fractions represented by MBC, POC and OCAM were used to verify possible similarities with observed active (som1 c(2)), slow (som2c) and passive (som3c) carbon values simulated by the Century model v4.5 in native vegetation area.

Total organic carbon and total nitrogen stock values were determined and corrected for mass considering soil layer depth and soil density, TOC and TN measured in the reference area (Carvalho et al., 2009).

Century v4.5 template initialization

The Century model simulates carbon (C) dynamics in plants and soils of natural or cultivated systems, using a monthly time step. In our work, we simulated only C and nitrogen (N) dynamics. The key Century inputs represent monthly climate variables, soil physicochemical properties, initial soil C and N levels, and plant information and management data. Plant production can be simulated using sub-models of pasture/crop, forest or savanna systems. Land use change can be represented by changing the type of community of the plant during the model runs; for example, start with forest, change to a cultivation system and then to the regeneration phase of the native vegetation. The residue production is divided into structural and metabolic residues with differing decomposition rates and initial lignin to N ratios. Soil texture and climate variables control the decomposition rate and organic N flows follow the C flows (Parton, 1987). The Century model version 4.5 was used for the calibration and validation procedures. The model developers (https://www.nrel.colostate.edu/projects/century/) provide pre-established parameters for several biomes and major crops around the world (Parton et al., 1994). The initialization of the Century model version 4.5 consisted of obtaining the necessary data for execution. At this step, input parameters related to soil attributes and climate data from 1990 to 2017 (Inmet, 2019) (Table 1) were inserted.

Table 1. Input variables used in parameterization and simulation of the Century v4.5 model. Brejo, Maranhão, Brazil.

Variables	Value											
Sand (g kg^{-1})	747											
Silt (g kg^{-1})	89											
Clay (g kg^{-1})	164											
BD (kg dcm^{-3}) [1]	1.6											
pH (H_2O)	5.7											
Months	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Rainfall (mm) [2]	208	268	348	319	202	66	35	11	06	15	37	79
Minimum temperature (°C)	22.8	22.7	22.7	22.8	22.5	21.7	21.3	21.5	21.9	22.3	22.7	22.7
Maximum temperature (°C)	32.5	31.7	31.4	31.3	31.4	31.4	32.1	33.8	35.2	35.8	35.5	34.5

[1]BD: Bulk density; [2]Climatic data from the scientific region, from 1990 to 2017.

Stabilization or equilibrium process

Stabilization is the initial stage of the modelling process, in which local climate and soil data are used as a basis. This procedure consists of preparing the model by considering as a reference the initial TOC stocks contained in the natural environment of native vegetation. After the stipulated period, it was assessed whether the levels of simulated TOC stocks corresponded to the observed TOC stocks. Carbon and nitrogen stabilization in soil was determined by simulating a period of 5,000 years for native Cerrado vegetation area. The purpose of the determined time was to seek the period in which the TOC stocks estimated by the model corresponded to the original TOC stocks observed in the 0,0-0,20 m layer. However, there is no definition of maximum or minimum time, just a projection or scheduling of time that is sufficient to verify whether the simulation of stocks generated by the model resembles the value observed in the field. The simulation has been performed because soil carbon and nitrogen data are derived from an initial simulation of a 1,000-year period (Metherel et al., 1993), minimum time to guarantee the stability of the simulated data.

Input data (Table 1) was used in stabilization/balancing process, and some necessary changes were made to the parameters of TREE.100 and CROP.100 files referring to the type and size of vegetation, as well as changes to parameters of the fixed file (FIX.100) of the Century v4.5 model. The changes aimed to adjust primary production, addition and decomposition rates of carbon and nitrogen in an area of native Cerrado vegetation (Wendling et al., 2014). These adjustments were also made because the model was developed for temperate climate regions. After making the necessary adjustments, native vegetation file was created by applying fire incidence, which occurs spontaneously in the period of low rainfall in the Cerrado of Maranhão (Silva-Junior et al., 2018), simulating vegetation burning events at 5-year intervals.

Simulated events in the areas

Initially, carbon and nitrogen simulations were carried out using real scenarios based on land use and management history in the areas. For each area, the model simulated the removal of native vegetation (year 2003) and conversion to agricultural purposes. Total organic carbon and total nitrogen stocks and compartments in soil were estimated over the years of cultivation from 2004 to 2018 (Table 2). After real data simulations, those of future scenarios were performed for TOC stocks, TN stocks, and soil compartments (active, slow, and passive) using the Century model. The smallest fraction is represented by active C (microbial biomass carbon), which consists of the most labile organic material, with an estimated time in soil of less than 5 years. Slow C (particulate organic carbon), represented by light organic matter, is an intermediate compartment in terms of content and decomposition rate between active C and passive C, with turnover times of between 10 and 50 years. Passive C represents the largest fraction of carbon in soil, contains physically and chemically stabilized C, with an estimated decomposition time rate between 200 and 500 years (Dimassi et al., 2018). Simulations consisted of three scenarios were created from 2019 to 2060 for no-till area and crop-livestock integration system (Table 3).

Table 2. History and sequence of use and management used in the carbon simulation of the areas by the Century v4.5 model. Brejo, Maranhão, Brazil.

Studied areas [1]	Simulated scenarios
NV	No-till farming (NT) for fourteen years up to the year 2002 and no-till integrated crop-livestock system (CLI).
NT	In 2004, conventional soybean cultivation began (plowing and harrowing). From 2005 to 2018, no-till soybean/millet rotation
NT-CLI	In 2004, conventional soybean cultivation began (plowing and harrowing). From 2005 to 2011, no-till soybean/millet rotation. In 2012, no-till integrated crop-livestock system (maize intercropped with *Brachiaria ruziziensis* (R. Germ. & Evrard) Crins] cv. Ruziziensis and input of animals – cattle in the off-season), preceded by plowing and harrowing before sowing. From 2013 to 2015 no-till soybean/millet rotation. In 2016, no-till with integrated crop-livestock system (maize intercropped with *Brachiaria ruziziensis* and input of animals – cattle in the off-season) preceded by subsoiling. In 2017 and 2018, no-till soybean/millet rotation.

[1]NV: native vegetation; NT: no-till; and NT-CLI: crop-livestock integration in a no-till system.

Table 3. Simulations of three scenarios for no-till area and crop-livestock integration system from 2019 to 2060. Brejo, Maranhão, Brazil.

No-till area	
First scenario	No-till soybean/millet cultivation
Second scenario	No-till soybean/millet cultivation in rotation every year with maize monoculture (NT rota M)
Third scenario	No-till soybean/millet cultivation in rotation every two years with maize intercropped with *Brachiaria. ruziziensi*s (NT rota M+B)
Crop-livestock integration system area	
First scenario	Crop-livestock integration system rotated with no-till soybean/millet cultivation and tillage every four years
Second scenario	Composed of the exclusive use of a crop-livestock integration system: maize + *B. ruziziensis* + input of animals, with subsoiling every five years
Third scenario	Crop-livestock-forest integrated (CLFI) system every six years

Statistical analysis

Laboratory-determined field data and simulated data in the Century model were compared to each other based on standard error of the mean, allowing testing calibration and validation of the model in MS ® EXCEL.

Results

Simulation of carbon and nitrogen stabilization

The simulation showed stabilization of TOC and TN stocks within 3,000 years (Fig. 1). Total organic carbon stock was stabilized at 42.97 Mg ha^{-1}, a value very close to that measured (42.96 Mg ha^{-1}) in the Cerrado native vegetation area.

Carbon compartments, except for the slow compartment, were also stabilized to values close to the real values (Table 4). In the present study, possible compartments (active, slow, and passive) of nitrogen were not determined. Real TN stocks was 2.53 Mg ha^{-1} while the simulated one was 2.36 Mg ha^{-1}. For the carbon/nitrogen ratio (C/N), a value of 18.0 was measured and a value 18.2 was simulated, representing an error of only 1%. Total organic carbon stocks in each compartment showed the following proportion: 0.3% of active C, 1.4% of slow C, and 98.3% of passive C.

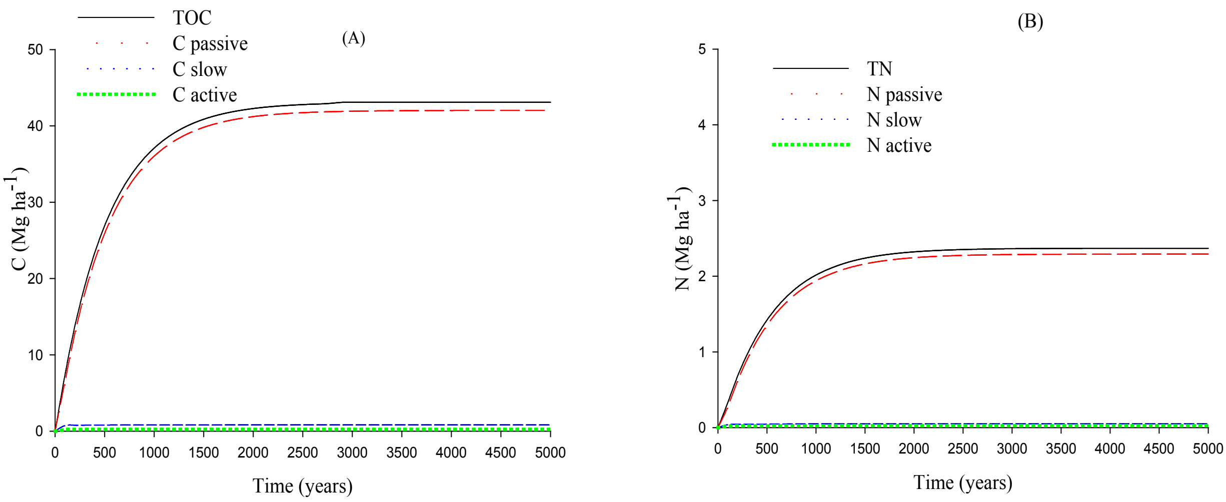

Figure 1. Carbon (A) and nitrogen (B) compartments observed in stabilization simulation of the Cerrado native vegetation area, estimated by the Century v4.5 model over a period of 5,000 years. TOC: total organic carbon; TN: total nitrogen.

Table 4. Values of measured and simulated stocks for total organic carbon and active, slow, and passive compartments in the Cerrado native vegetation area (equilibrium simulation), in Brejo, Maranhão state, Brazil.

Compartments	Carbon stock ------------------------ Mg ha^{-1} ------------------------		
	Measured	Simulated	Error (%) [1]
Active	0.16	0.17	6.25
Slow	0.60	0.70	16.66
Passive	42.20	42.10	0.23
Total	42.96	42.97	0.02

[1] ((Simulated value – Measured value)/Measured value)x100.

Simulation of C and N in real scenarios

Following stabilization simulation, real scenarios simulations were carried out for NT and NT-CLI where the model simulated changes in soil use and management. With the removal of native vegetation in 2003, there was an increase in TOC and TN stocks of 0.18 Mg ha^{-1} and 0.03 Mg ha^{-1}, respectively. In 2005, the no tillage practice started to be adopted and exclusive in NT area until 2011. In the 2013 season continued for consecutive five years no tillage practice and them was adopted NT-CLI areas.

During these years, the model simulated stock values of TOC, active, slow, and passive carbon above the values observed in NV area (Fig. 2). The use of conservation practices results in minimal soil disturbance and keeps constant soil cover, mitigating effects that could compromise organic matter dynamics.

For TN stocks and compartments (Fig. 3), the dynamics were similar to those observed for TOC. Both NT and NT-CLI areas, from 2005 onwards, revealed results superior to those of NV area. Until 2011, TOC and TN stocks were similar between NT and NT-CLI areas, but, in 2012, the model simulated values of 40.59 Mg ha^{-1} for TOC in NT area; 1.13; 5.28; and 34.18 Mg ha^{-1} for active, slow and passive TOC stocks, respectively. For TN, the simulated value was 2.15 Mg ha^{-1} and 0.29; 0.52 ;1.35 Mg ha^{-1} for active, slow and passive nitrogen, respectively. Conversely, stock values observed in NT-CLI in the same year were 38.44; 0.78; 3.57 and 34.12 Mg ha^{-1} for TOC, active, slow and passive C compartments, respectively, and 1.87; 0.20; 0.33 and 1.34 Mg ha^{-1} for TN, active, slow and passive nitrogen compartments, respectively.

However, from 2013 until the final year (2018), the model simulated higher C and N stock values in NT-CLI than those in NT area. In 2013 and 2017, five years after implementation of CLI, TOC stock values were 49.34 Mg ha^{-1} and 55.80 Mg ha^{-1}, respectively, and TN values were 3.39 and 3.85 Mg ha^{-1}, respectively, which represents an increase of 16% and 25% for TOC, and of 31% and 35% for TN, higher than the values observed in NT system for the same period.

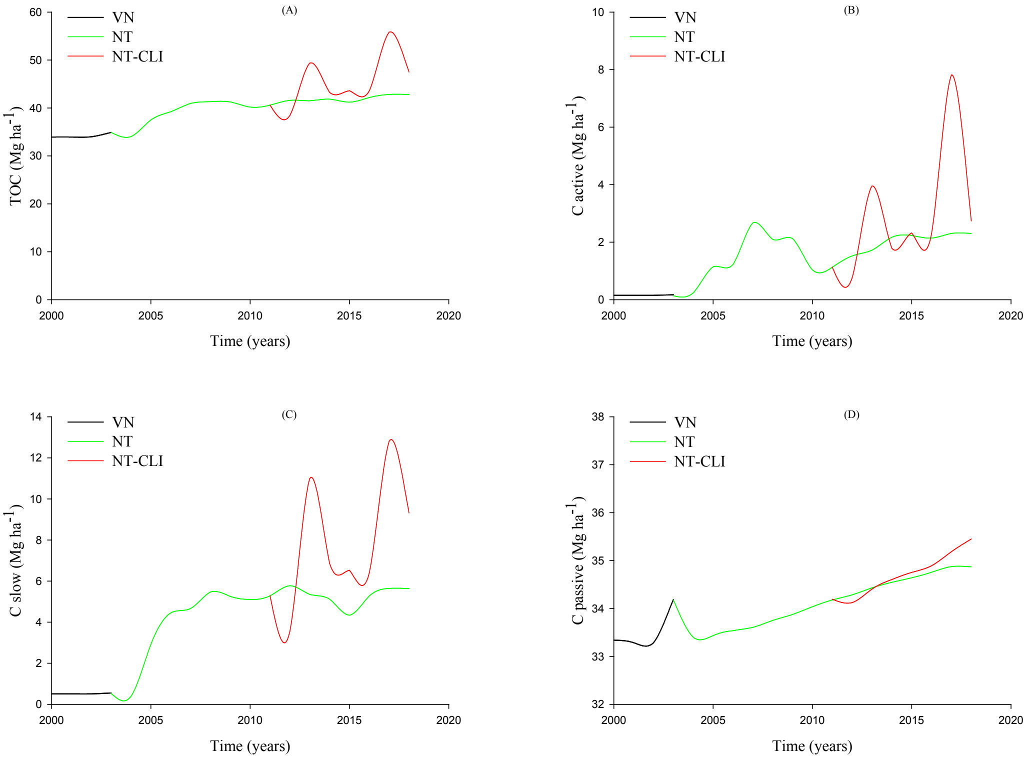

Figure 2. Simulations of total organic carbon (TOC) stocks (A) and, carbon active (B), carbon slow (C) and carbon passive (D) compartments estimated by the Century v4.5 model in areas of native vegetation (NV), no-till (NT) and no-till integrated crop-livestock (NT-CLI), in Brejo, Maranhão, Brazil.

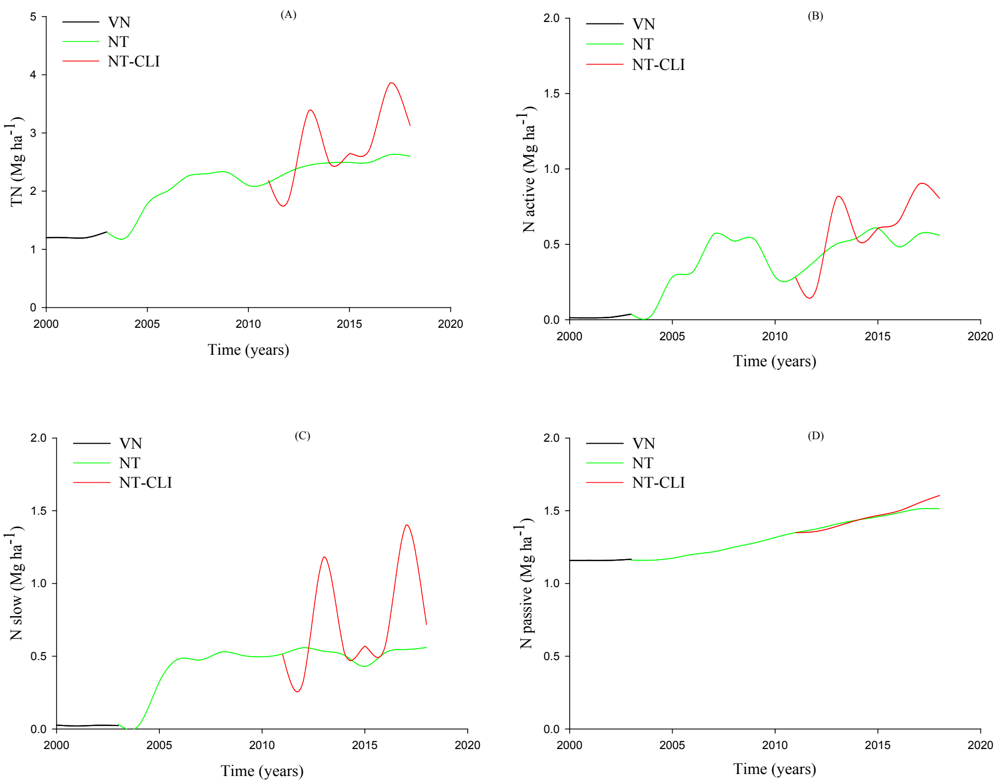

Figure 3. Simulations of total nitrogen (TN) stocks (A), and nitrogen active (B), nitrogen slow (C) and nitrogen passive (D) compartments estimated by the Century v4.5 model in no-till (NT) and no-till integrated crop-livestock (NT-CLI), in Brejo, Maranhão, Brazil.

Comparison between measured and simulated values

The differences for measured and simulated stocks correspond to an error of 9.81; 16.74 and 0.02% of carbon and 2.69; 12.60 and 6.71% of nitrogen for NT, NT-CLI and NV, respectively (Table 5). The model underestimated TOC stock in two conservation systems, while it overestimated it in NV. However, the TN stock showed an inverse response, where there was an overestimation of the model in conservation systems.

Table 5. Comparison between the values of total organic carbon and total nitrogen stocks, measured in the laboratory and simulated by the Century v4.5 model for the areas, in Brejo, Maranhão, Brazil.

	TOC stock (Mg ha^{-1}) [1]			TN stock (Mg ha^{-1}) [2]		
Area [3]	Measured	Simulated	Error (%)	Measured	Simulated	Error (%) [4]
NT	45.63	41.15	9.81	2.23	2.29	2.69
NT-CLI	53.94	44.91	16.74	2.30	2.59	12.60
NV	42.96	42.97	0.02	2.53	2.36	6.71

[1] TOC: total organic carbon. [2] TN – total nitrogen. [3] NT: no-till; NT-CLI: crop-livestock integration in a no-till system; NV: native vegetation. [4] Error = ((Simulated value – Measured value) / Measured value) 100.

Simulation of future scenarios

The three future scenarios proposed for each system were simulated, with the first scenario composed of a NT area maintained until the year 2060, which showed a slight increase in TOC stocks. Except for the passive compartment, the other compartments did not show significant changes in stock values over time. Among the scenarios, the model revealed that the second scenario (NT system soybean/millet with rotation every year with maize monoculture presented a greater capacity for carbon accumulation in the system (63.17 Mg ha^{-1} of TOC), compared to the third scenario (NT soybean/millet cultivation in rotation every two years with maize and *Brachiaria ruziziensis* (R. Germ. & Evrard) Crins] cv. Ruziziensis (Fig. 4).

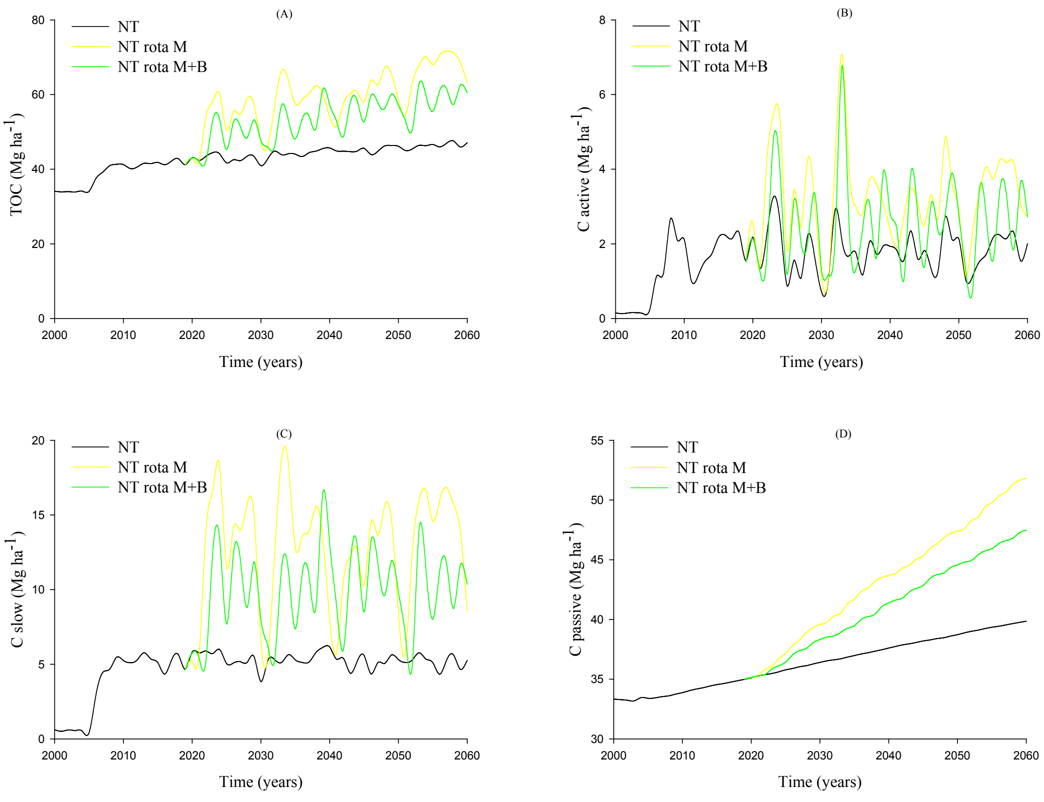

Figure 4. Simulation of total organic carbon (TOC) stocks (A), and carbon active (B), carbon slow (C) and carbon passive (D) compartments estimated by the Century v4.5 model for future no-till soybean/millet (NT) area, no-till soybean/millet rotated with maize monoculture (NT rota M) and no-till soybean/millet rotation intercropped with maize + B. ruziziensis (NT rota M+B) in Brejo, Maranhão, Brazil.

For NT, the model simulated a value of 6.17 Mg ha^{-1}. Nitrogen compartment, as well as the TN value, showed similar behaviour to the carbon compartment and TOC value, that is, according to the simulated scenarios, higher values were found in NT rota M area (Fig. 5).

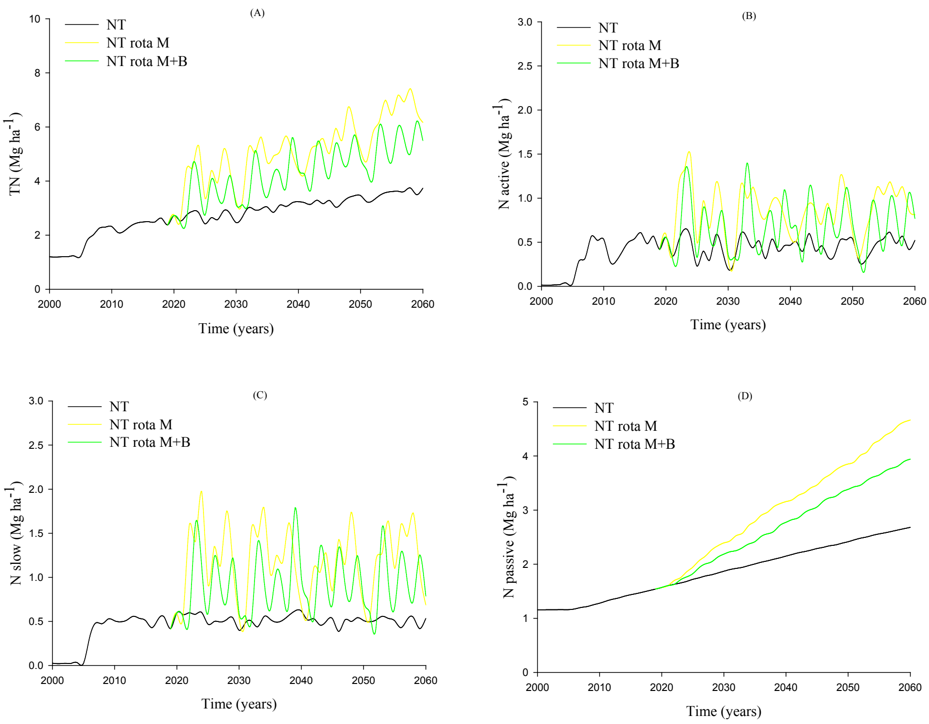

Figure 5. Simulation of total nitrogen stocks (TN) (A), and nitrogen active (B), nitrogen slow (C) and nitrogen passive (D) compartments estimated by the Century v4.5 model for future no-till soybean/millet areas (NT), no-till soybean/millet rotated with maize monoculture (NT rota M) and no-till soybean/millet maize + B. ruziziensis rotation (NT rota M+B) in Brejo, Maranhão, Brazil.

In NT-CLI area of the three future scenarios, the maintenance of a no-till system, every four years, a crop/livestock system until the year 2060 was the one with the lowest potential for TOC stocks and compartments (slow and passive), compared to other future scenarios. On the other hand, the exclusive use of integrated crop-livestock system (continuous CLI) proved to be more efficient in terms of TOC (85.92 Mg ha^{-1}) and TN (8.94 Mg ha^{-1}) storage capacity in soil over time (Fig. 6 and Fig. 7).

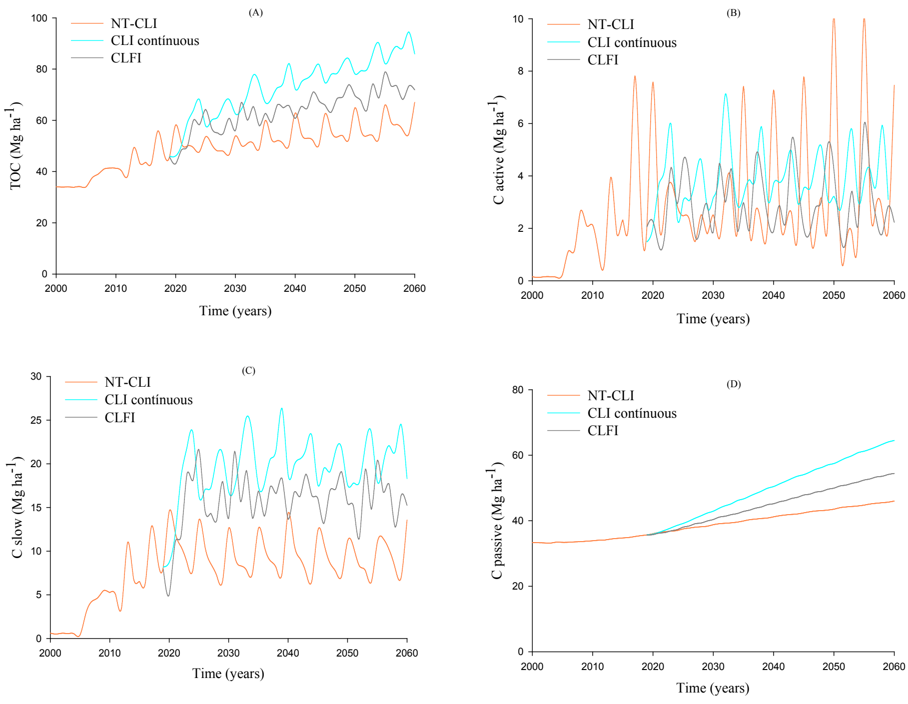

Figure 6.Simulation of total organic carbon (TOC) stocks (A), and carbon active (B), carbon slow (C) and carbon passive (D) compartments estimated by the Century v4.5 model for future no-till areas with crop-livestock integration (NT-CLI), continuous integrated crop-livestock (CLI) and integrated crop-livestock-forest (CLFI) systems in Brejo, Maranhão state, Brazil.

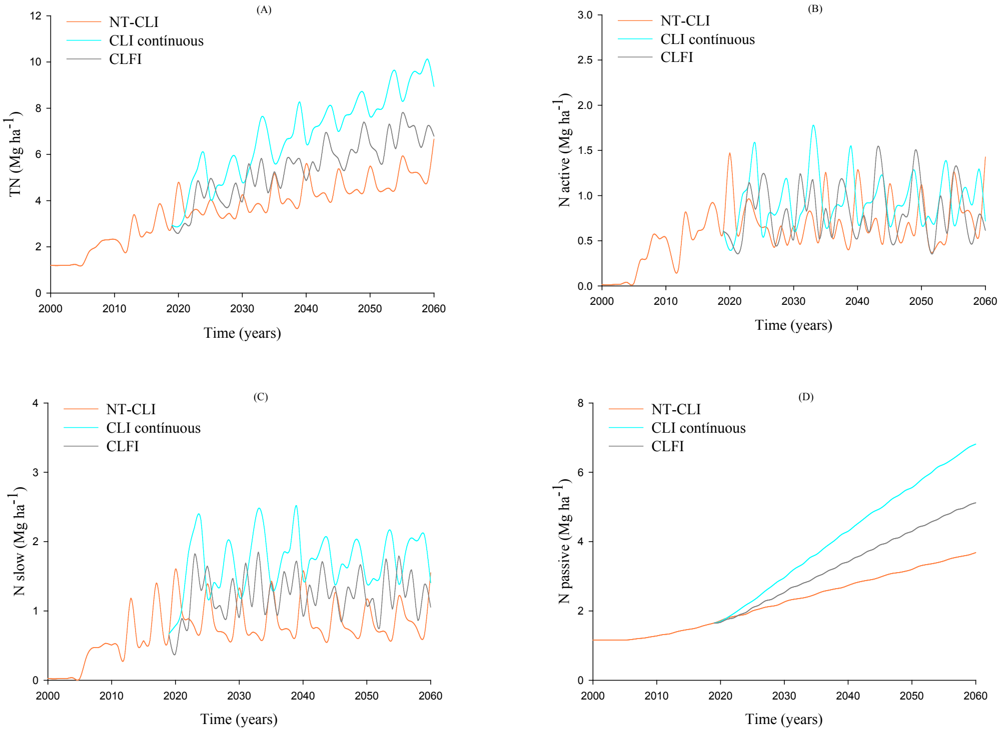

Figure 7. Simulation of total nitrogen stocks (TN) (A), and nitrogen active (B), nitrogen slow (C) and nitrogen passive (D) compartments estimated by the Century v4.5 model for future no-till areas with integrated crop-livestock (NT-CLI), continuous integrated crop-livestock (CLI) and integrated crop-livestock-forest (CLFI) in Brejo, Maranhão state, Brazil.

Discussion

The accuracy observed for TOC and TN stocks was achieved due to adjustments made to the model. The adjustments were necessary because the Century model was designed and validated to simulate the dynamics of soil organic matter under temperate climate conditions, in the North American Plains region (PARTON et al., 1987). In this case, the adjustments considered the parameters from the TREE.100 and CROP files. 100 regarding vegetation, as well as changes to the parameters of the fixed file (FIX.100) of the Century v4.5 model. The equilibrium simulation was less accurate for TN stock than that for total TOC stock. This result may be due to the complexity of the nitrogen cycle, besides there are several factors that influence the dynamics of this nutrient (Wang et al., 2021) that may not be fully represented by the model. Oliveira et al. (2017) found a discrepancy between measured and modeled N stock; however, they considered the possible and rapid transformations of N in a hot and humid environment during sampling, transport and processing of soil samples.

To establish similarities between values measured in laboratory and those simulated by the model, carbon and nitrogen modeling studies carried out in Brazil have implemented changes in fixed parameters, which can be observed in several works developed under Brazilian tropical, subtropical, and semi-arid climate conditions (Wendling et al., 2014; Althoff et al., 2018). Each Brazilian region has different edaphoclimatic conditions that influence the dynamics of soil organic matter (Gomes et al., 2019). Even so, greater errors associated with the NT-CLI scenario were recorded, and more when considering the complexity of the system that correlates the dynamics of organic matter in the integration of agricultural culture with pasture in a tropical climate.

In the Cerrado region, Wendling et al. (2014) reported 1.85% of active C, 7.27% of slow C, and 90.86% of passive C from stabilization simulation. This result differs from the data obtained in the present study. Although both correspond to simulations originating from the same biome, they may present different phytophysiognomies and edaphoclimatic conditions (Ribeiro et al., 2023). Despite this, it was observed that the largest fraction of C is found in the passive compartment, that is, chemically protected from the action of microorganisms (Ribeiro et al., 2023), being considered mainly organic material associated with minerals (MAOM) (Schimell, 2023).

Agricultural exploration in the study areas began in 2004, that is, during this period there was a conversion of native vegetation to conventional soybean cultivation. Coincidentally, this same year corresponds to the year in which reductions in soil TOC and TN stocks were observed. This result is associated with the decomposition of organic matter accelerated by the effect of soil disturbance from conventional preparation (plowing and harrowing) for soybean cultivation. Damião et al. (2021) also observed a decrease in C and N stocks soon after the conversion of native vegetation to pasture and attributed this result to physical disturbance of the soil. As mentioned by Chen et al. (2016), there is greater stability of soil structure in areas of native vegetation that provide protection from destruction processes of soil organic matter.

However, starting in 2005, the N stocks and compartments were similar to those observed for TOC stocks and compartments, that is, both the NT area and the NT-CLI, presented results superior to those of the NV area. No-till system has the capacity to add and maintain organic matter, contributing to soil quality (Krauss et al., 2020). In addition to the benefits of no-till farming, increased accumulation of carbon and nitrogen in soil under CLI is due to the addition of organic residues under soil surface and in the form of humic substances released by forage crops in soil (Araújo et al., 2017). Even more when considering the Cerrado biome, where temperature and humidity do not favor the maintenance and coverage of residues on the soil, but favoring the decomposition of organic matter (Oliveira et al., 2022).

There was no discrepant difference in passive C values in the systems, demonstrating that they are less sensitive; on the other hand, active and slow C respond more quickly to agricultural management, being driven by the entry and decomposition of organic matter (Dangal et al., 2022). The lowest values of TOC and TN observed in NT-CLI area are due to tillage consisting of plowing and harrowing, when the conversion to native vegetation (2004) for an agricultural system occurred. It is also worth noting that the Century model is not coupled to any plant productivity model, so the results obtained here only infer the processes that occur in the soil and ignore possible increases in TOC and TN due to increases in biomass productivity of plants in NT-CLI (Abramoff et al., 2018).

Between 2013 and 2018, the model simulated higher values of TOC and TN stocks in the NT-CLI area than in the NT area, probably because the frequent supply of organic residues and the synergism between crops, pastures and livestock in integrated systems influences soil microbial activity, which plays an important role in maintaining cycling and C and N contents in the soil (Sousa et al., 2020). Mainly related to the light fraction of organic matter, which is more active, therefore, more sensitive to short-term management and more susceptible to the action of microorganisms (Ferreira et al., 2024). Thus, compared to the NT area, which does not have forage species in rotation or intercropped with annual crops and without animal input, the use of the CLI system has shown a greater potential for accumulation of C and N in the soil (Soares et al., 2019).

The differences between the results for measured and simulated TOC and TN stocks demonstrate the potential of the Century model to simulate TOC and TN stocks in soil for a tropical environment, corroborating the results found in other studies (Wendling et al., 2014; Althoff et al., 2018). However, regarding the accuracy of the model in simulating C and N stocks under tropical conditions in integrated systems, a greater discrepancy between measured and simulated values was observed in integrated crop-livestock system (NT-CLI), which probably owes to the complexity resulted from a synergism that the model was not developed to assess properly. Cerri et al. (2014) and Vogado et al. (2024) have also observed greater differences between measured and Century-simulated TOC and TN stocks in CLI system, probably attributed to the mechanisms of addition and loss of organic matter in soil under tropical climate conditions, which still needs further adjustments.

Higher C and N values observed in no-till area with maize monoculture were not expected because the organic material input is governed only by one crop (maize) compared to NT rota M+B area, where there is a greater number of cultivated species – maize intercropped with *B. ruziziensis*. However, the result may be linked to the annual maize monoculture rotation (NT rota M) being a more intense approach than every two years maize + *B. ruziziensis* rotation. Damião et al. (2021) concluded that maize monoculture is sufficient to significantly increase the stock of C and N in the soil in long-term forecasts. Similarly, Bieluczyk et al. (2020), based on a study with stable isotopes of ^{13}C, stated that the root biomass of corn contributes more effectively to the stock of C compared to the biomass of *B. ruziziensis* roots. Therefore, another hypothesis is that the consortium maize + *B. ruziziensis* favors competition between both cultures that culminates in the reduction of TOC and TN.

As shown by the simulation, CLI was superior to CLFI in terms of TOC and TN storage capacity in the soil over time. It is possible that the reduction in C and N stocks in the CLFI is a response to *Brachiaria* (tropical forage) shading by the tree component, which culminates in the reduction of above and below ground biomass (Damião et al., 2021). This result agrees with Bieluczyk et al. (2020), who although recognizing the importance of the forest component for adding residues, the authors confirmed that the CLI system promotes greater accumulation of organic matter when compared to the CLFI system. Furthermore, it is possible that the model simulates how the presence of trees in periods of water scarcity can negatively affect crop productivity through competition for water (Pezzopane et al., 2019), especially between June and November, a dry winter period. Thus, the model can simulate that the increase in crops in the same area can increase competition for available water in the soil and, eventually, reduce biomass production.

The highest values for TOC and TN stocks observed in simulated continuous CLI system may be explained by the more diverse annually input of organic material compared to NT-CLI system. The superiority of continuous CLI over CLFI may be linked to subsoiling every five years. In other words, although the CLFI system has greater potential for C and N accumulation, the management carried out causes a decline in the TOC and TN stock in the CLFI system, as there is greater vulnerability with anthropogenic disturbances (Zhang et al., 2020). Furthermore, although the forest component (eucalyptus) presents C allocation in the soil (Sarto et al., 2020), there is a limitation of the Century model. This occurs because, unlike annual crops and pastures, the model does not consider the input of C by the forest component in the surface layer of the soil, but it also does not consider the input of C in depth as a consequence of the roots of trees that are deeper. Another factor is that the model can consider the inhibitory or competitive effect of the forest component on other plant species that make up the system. There is a clear need for mathematical models that more accurately simulate soil C and N changes in more complex farming systems such as integrated systems (Damião et al., 2021).

Conclusions

Century model proved to be efficient in simulating total organic carbon stocks, but less accurate for total nitrogen stocks in sandy, cohesive soils of the Cerrado region under conservation systems. No-till crop-livestock integration system provided higher increments in carbon and nitrogen. For future gains in carbon and nitrogen, no-till farming rotated annually with maize monoculture and continuous integrated crop-livestock system are preferable because these systems stood out for storing carbon and nitrogen in soil. Therefore, the two systems are indicated as best forms of exploitation in the Cerrado region of eastern Maranhão, Brazil. The Century model should undergo more calibration studies, especially for integrated systems under different edaphoclimatic conditions.

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