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A meta-analysis of soil organic carbon dynamics under climate-smart agricultural systems in the Amazonian region

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ABSTRACT

Climate-smart agriculture (CSA) systems have been promoted as a nature-based solution to ameliorate carbon losses from cropland by increasing soil organic carbon (SOC) stocks. The scale to which CSA systems [i.e., integrated cropping (iC), integrated crop-livestock (iCL) and integrated crop-livestock-forest (iCLF)] can contribute to reversing SOC losses and promote C-storage is limited in knowledge. We used a meta-analysis to give a regional-level appraisal of SOC stock changes in relation to the adoption of CSA systems in Rondônia State, Brazil. The CSA systems (iC, iCL, and iCLF) accumulated SOC at mean rates of 0.37, 0.52, and 0.76 Mg C ha^{-1} yr^{-1}, respectively, which showed that iCLF had the highest SOC change rate, study span notwithstanding. On average, the rate of SOC (Mg C ha^{-1} yr^{-1}) change for short-term studies (< 11 years), 11–20 years, and above 20 years were 0.47, 0.93, and 0.55, respectively. Climate, altitude, and soil depth also have significant effects on the rates of SOC stock change. Oxisols and Ultisols promoted C sequestration, while Alfisols and other soil groups did not. The results from our meta-analysis established that CSA under the prevailing soil and environmental conditions can encourage more adoption of CSA by farmers, promote SOC accumulation, and consequently mitigate greenhouse gases (GHG) emissions, while guaranteeing food security. The study might support Brazil's Low-Carbon Agriculture Plan and help the country in achieving its Nationally Determined Contributions commitments on climate change mitigation through agriculture.

1. Introduction

Increase in demand for food, fiber, water, shelter, and energy due to rapid growth in human population has created severe threats on the global natural ecosystem, including global warming and climate change (Nwaogu and Cherubin, 2024). Soil is the core center and supports

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biodiversity, human survival, and most anthropogenic activities (Evangelista et al., 2023). Thus, soil has many burdens from these rising threats, causing imbalance in the global carbon (C) cycle (Lal, 2008). The soil organic carbon (SOC) contains the largest terrestrial carbon pool, comprising about 1550 petagrams (Pg) of C (Lal, 2011), which is more than twice the bulk of the C stockpile in either vegetation or the atmosphere (Anderson-Teixeira et al., 2009).

The Brazilian Amazon soils store approximately 47 Pg of C in the first 100 cm, and 44% of this C is in the superficial layer (0–30 cm) where many human disturbances occur (Moraes et al., 1995). This SOC is vulnerable to diverse activities and land use changes, which can either increase or decrease its stock, and an infinitesimal change in this C reservoir can substantially impact global C dynamics. Deforestation and agriculture are among the key land use and anthropogenic activities that can significantly affect the equilibrium between carbon inflows and outflows in the soil, which limits the sequestration and storage of SOC (Deng et al., 2016). Conversion of the Amazon forest to an agro-ecosystem (pasture or cropping) has either positive or negative effects on SOC, global C, climate, and biodiversity, depending on the prevailing management systems (Don et al., 2011). For instance, in the last century, agricultural expansion in Brazil displaced large areas of native vegetation with pasture and monocropping, which affected diverse soil functions and ecosystem services, including carbon sequestration, climate modification, food security, and others (Bossio et al., 2020; Eze et al., 2023; Lal, 2017; Padarian et al., 2022).

Poorly managed livestock production through extensive pasture is the primary agriculture in Brazil, which takes about 53% of the land area, and associated risks of degradation (Mapbiomas, 2021). Rondônia State is among the Brazilian States with large hectares of severely degraded pasture (Mapbiomas, 2021). Sustainable agricultural systems such as climate-smart agriculture (CSA) have been introduced in recent decades to recover the degraded pastures and increase SOC stock (de Souza Almeida et al., 2021).

The CSA, namely, integrated cropping systems (iC), integrated crop-livestock (iCL), and integrated crop-livestock-forestry (iCLF) are promising agricultural conservation practices for recovering the degraded pasture areas and increasing C sequestration (de Oliveira et al., 2016). The CSA systems are nature-based practices for SOC gain, especially in the degraded pasture lands, where there is the likelihood of enriching SOC stores from 0.82 to 2.58 Mg ha^{-1} yr^{-1} (da Oliveira et al., 2023). Like most States in Brazil, the Rondônia State has in recent decades, adopted these CSA systems (Carvalho et al., 2010; Maia et al., 2010). Though the CSA practices have proved to be beneficial in the State, they have been challenged by some factors, such as the dearth of qualified labor, scanty marketing options, lack of infrastructure, an unconducive regulatory setting, and, in some cases, poorly drained soils (Borges et al., 2025). These CSA practices have improved the degraded pasture areas, reduced livestock production impacts, promoted sustainable food productivity, and consequently decreased native vegetation conversion for agricultural expansion (Dumas et al., 2022; Pulina et al., 2021). The CSA systems, namely, soil fertilization with organic amendments, crop diversification, no-tillage, cover cropping, and crop-livestock and crop-livestock-forestry integration systems, have been implemented in Rondônia and other agricultural frontier States of Brazil (da Oliveira et al., 2023; Anghinoni et al., 2021). These practices are aimed at increasing soil C accumulation and enhancing soil health while promoting crop productivity (Anghinoni et al., 2021). The adoption of CSA in the region has been encouraged among farmers at various scales because crop residue retention and application of green manures from plants and animal wastes are widely adopted, which consequently reduces GHG emissions and increases SOC stocks (Nwaogu and Cherubin, 2024; da Oliveira et al., 2023).

Globally, the effect of CSA on SOC has been extensively studied, and some of these studies employed data from either field or secondary sources (e.g., institutional databases). Some of the previous studies failed to consider important information, such as study duration of over 2 years, CSA practices as the primary focus, with inclusion of at least two of the practices, soil texture, soil types, soil depth beyond 10 cm, as well as a reference or baseline land use. Similarly, other studies failed to include the climate or elevation in their investigations. These criteria were either totally omitted or poorly defined in some of the previous studies. To achieve a very reliable assessment of the impacts of CSA on SOC, these essential criteria and others need to be considered. Therefore, in our study, these vital criteria were well specified and followed during the data collection and analysis to effectively assess the roles of CSA on SOC.

Considering the critical role of C stocks in delivering soil functions, and as one of the novelties of the study, it was important to understand the effects of the specific drivers (e.g., climate, elevation, CSA system age, and soil) on SOC stocks in Rondônia State. Thus, the collation and analyzing of existing data at the State scale became critical in addressing the potential of CSA to ameliorate C footprints and SOC loss from the pastures in Rondônia State. We conducted a meta-analysis using peer-reviewed articles to evaluate the effects of three CSA management systems on SOC, and how SOC dynamics in these CSA systems were influenced by various environmental factors (e.g., soil, elevation, and climate) in Rondônia State. This work could be of significant benefit to the State, country, and globally by informing debates on carbon farming and low-carbon emission approaches for livestock. It could also offer a framework for implementing carbon farming systems that might support the soil research trajectory to increase C-stock, which will consequently enhance the realization of sustainable development goals. Further, the study might provide a quantitative basis for policy by supporting regional climate policies. These will help in the achievement of Brazil's food security and climate resilience targets, namely, the ‘ABC Plan’ towards meeting food security with a reduction in C loss and greenhouse gases (GHG) emission, as well as the ‘Nationally Determined Contributions (NDCs)’ to the 2015 Paris Summit Agreement on Climate.

2. Material and methods

2.1. Study area

The study covered Rondônia State in Brazil, which is in the Amazon biome, and is located between longitude 66°37′ and 60°44′ W, and latitude 7°59′ and 13°42′ S (Fig. 1). The total area of Rondônia State is 237,590 km^2 (Brasil et al., 2022). According to the Köppen Climate classification, Rondônia has a typical climate of the Amazonia region with specific classification as Aw (hot, humid, equatorial). Like most States in the Amazon biome, it has an average annual rainfall that ranges from 1990 to 2800 mm, with an annual average temperature ranging between 23 and 28 °C (Moreira et al., 2022). Rondônia State is on the trough of the Amazonian depression, with an elevation ranging from 100 to about 700 m (Alvares et al., 2013). The main soil group of the region, including the study area, is Oxisols (∼ 40%), which is classified as “Dystrophic Yellow Latosol” according to the Brazilian System of Soil Classification (Santos et al., 2018). The study also identified other soil groups, such as Ultisols (∼20%), Alfisols (∼8%), Quartzipsamments (∼12%), Inceptisols (∼6%), and Entisols (∼5%) (Maia et al., 2009; da Silva et al., 2022). As a typical Amazon forest zone, the vegetation structure is dense ombrophilous forests, consisting of thick and multi-stratified trees ranging from 25 to 30 m high, with pastures and fragments of croplands (Perigolo et al., 2017).

The State of Rondônia is one of Brazil's frontiers for crops and livestock production, among which the cattle production is remarkable, being the 5th largest producer State with about 13,871,863 bovine heads (Lima et al., 2022). Porto Velho, the Rondônia State capital, is famous for cattle products, ranking 7th among the municipalities with 968,778 heads (Associação Brasileira das Indústrias Exportadoras de Carnes—ABIEC, 2019).

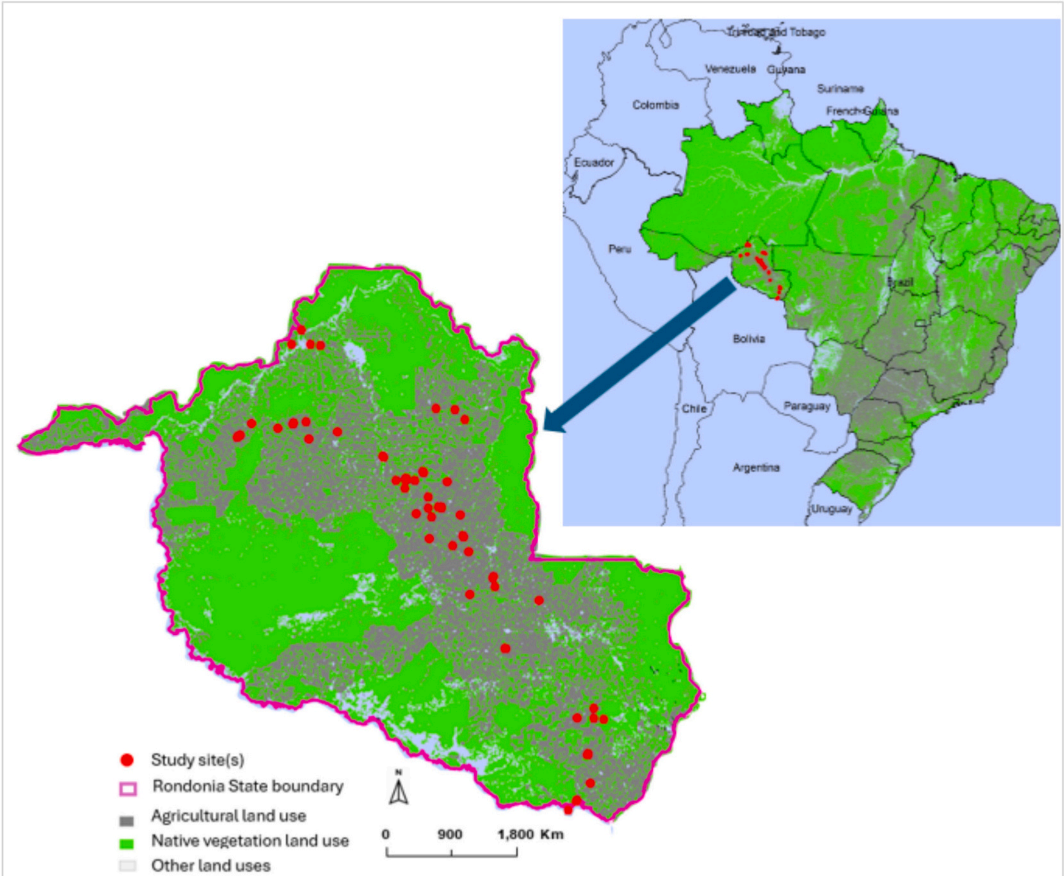

Fig. 1. Study observation data points on the SOC stocks in CSA areas in Rondônia State, Brazil. Rondônia State (*lower left map*), Brazil, in South America (*upper right map*).

2.2. Data extraction, processing, and analysis

A systematic literature review was conducted by applying PRISMA-Preferred Reporting Items for Systematic reviews and Meta-Analyses (see **Fig. S1 and Table S1**) to explore studies that appraised SOC stocks in CSA in Rondônia State, Brazil. The search was conducted in the Web of Science (WOS) database, exploring peer-reviewed scientific papers published before January 2024. The search approach considered terms available in the title, abstract, and keywords. The terms used were "Carbon" and "Climate-smart agriculture" and "Integrated agricultural production" OR "Carbon stocks" and "Integrated cropping system" and "Integrated Crop-Livestock" and "Integrated Crop-Livestock-Forestry" AND "Rondônia State" OR "Organic Matter" and "Integrated cropping system" and "Integrated Crop-Livestock" and "Integrated Crop-Livestock-Forestry" AND "Rondônia State". The Boolean 'OR' operator was used to include various or associated words of "soil carbon" and "Integrated cropping system" or "Integrated Crop-Livestock" or "Integrated Crop- Livestock-Forestry". On the other hand, the 'AND' operator included only studies that specifically examined SOC in Rondônia State.

Our search produced more than 200 publications, which were screened and reduced based on the following criteria:

(i) results must cover at least one of the below-mentioned CSA or integrated agricultural production systems in Rondônia State;
(ii) The study duration or timespan should be at least 3 years, and soil depth at least 15 cm to be included in the dataset. Though, only about 16% of our dataset was less than 5 years, and 4% is less than 20 cm in depth. And these were included because they met other selection criteria, and our dataset was not very robust thus, removing them might shrink the dataset and could distort valid results.
(iii) The study should report either SOC stocks or available bulk density and SOC concentration data to be used in estimating the SOC stocks if there is no data on SOC stocks;
(iv) There should be a reference or baseline which should be a previous land use or management such as native vegetation, degraded pasture or previous farming system before the adoption of the CSA. Note: In this study and in the study area, a degraded pasture is referred to as a pasture with poor soil health, low content of soil microbes, low production of biomass, low biodiversity, as well as low soil organic matter and soil organic carbon.

Considering the selected studies, we classified the CSA or integrated agricultural systems into three main types:

(1) integrated cropping system (iC), is an agricultural system which focuses mainly on annual and perennial crops cultivation with conservation farming practices such as mixed cropping, intercropping, crop rotation, no-till, cover cropping;
(2) integrated crop-livestock system (iCL), is an intensive farming practice that involves the integration of both crops and animals/pastures in time and space. It encompasses annual crops in rotation with pastures, thus promoting diversity, sustainable rotation and succession for efficient use of resources; and.
(3) integrated crop-livestock-forest system (iCLF) is a sustainable agricultural system which combines crops, animals/pastures, and forests at the same time on the same piece of land.

All these CSA systems (iC, iCL, and iCLF), are nature-based production strategies that integrate either crop farming, herbivores, and/or forestry activities in the same place, designed to enhance the productivity and sustainability of agricultural systems by leveraging the synergies of different activities and resources. These systems are nature-based because most of the input resources used in their activities are organic and derived from nature; likewise, most of the practices. In this study, the common crops were soybeans, cowpea, peanuts, beans, maize, as well as other legume and grass cover crops (e.g., wheat, pigeon pea, millet, and oat). The *Eucalyptus spp* is the common tree type, but in some cases, common fruit tree species (e.g., guava, citrus spp., pawpaw, etc) were involved. The animals were mainly cattle and sheep. The common pasture type was rotational grazing, whereas the cropping system involved a continuous cropping system or an intercrop of legume and grass. These CSA systems were selected because (a) previous studies in the region have identified them as the key sustainable farming practices commonly adopted in the area (Dumas et al., 2022; Pulina et al., 2021; Anghinoni et al., 2021; Nwaogu et al., 2023a, 2023b); (b) they have proven to be the best systems to increase SOC stocks, increase food security, reduce GHG emission, and improve climate change resilience (Nwaogu and Cherubin, 2024;de Souza Almeida et al., 2021; de Oliveira et al., 2016; da Oliveira et al., 2023), and (c) some studies covered them in the study area (**Table S2**).

In this study, rearing of livestock in a forestry system (i.e., only livestock-forestry-LF) was excluded since there were not many studies on LF.

After the screening and elimination, 13 publications with 49 observation points (44.9% - iCL system; 34.7% iCLF system, 20.4%-iC system) match the criteria previously established, and the spatial distribution of the observation points (or site locations) in Rondônia State is included in this work (Fig. 1**,** and **Table S2**).

We collected the following response and explanatory variable data for each evaluated study: geographical location (latitude and longitude), climatic variable (precipitation and temperature), experiment duration, previous use, current use or system type, elevation, soil variables (types, texture, depth, bulk density, soil organic matter, SOC content, and stocks). The explanatory variables (e.g., climate, elevation, and soil properties) were selected because of (i) their applications in the selected dataset, and (ii) their significant roles in determining SOC stocks. For sites or studies where climatic variables were lacking, we used the WMO data (World Meteorological Organization; http://www.agteca.com/Projects/Climate/) and chose the data considering the nearest station from the site. The main soil types found in the studies were: Oxisols, American Taxonomy (Ferralsols, IUSS Classification), which is Latossolos or Latosols in Brazilian Taxonomy, and Ultisols (Acrisols), which are Argissolos in Brazilian Taxonomy. Others were Alfisols, Cambisols, Lixisols, and Alisols (IUSS Working Group WRB, 2022) (**Table S2**).

The data relating to SOC concentration and stocks were either extracted from the tables or figures provided with the support of GetData Graph Digitizer software v2.26 (http://getdata-graphdigitizer.com/download.php). The units of the data collected from the articles were converted when needed to match the standardized units in this work.

2.3. Data processing, analysis, and estimation

2.3.1. SOC stocks estimation

Soil organic C stocks (Mg ha^{-1}) were presented for most of the studies, but for those investigations where only SOC concentrations were shown, SOC stocks were determined using the following equation (Eq. (1)):

$$\text{SOC stock} = (\text{SOC x BD x L})/10 \tag{1}$$

Where: SOC stock = soil organic carbon stock (Mg C ha^{-1}), SOC = soil organic carbon concentration (g kg^{-1}), BD = bulk density (Mg m^{-3}), and L = thickness of the soil layer (or depth) (in cm).

For a homogeneous and systematic comparison and upscale strategy to the adoption of CSA, the SOC data were converted to rates of SOC stock change (Mg ha^{-1} yr^{-1}). The annual rates were computed considering the difference in SOC stocks between the adopted CSA practices (iC, iCL or iCLF) and a reference (baseline), as described in Eq. (2):

$$\Delta\text{SOC stock} = \left[C_{csa} - C_{ref}\right]/t \tag{2}$$

Where ΔSOC stock = rate of change of SOC stock (Mg ha^{-1} yr^{-1}), C_{csa} is the final SOC stock (Mg ha^{-1}) in the evaluated CSA systems; C_{ref} is the initial SOC stock (Mg ha^{-1}) in the previous land use or management system, and *t* is the time interval of each system or practice.

We also computed a response ratio (RR) for each pairwise comparison between SOC stocks in the SOC-CSA system treatment versus SOC-reference (or control), applying Eq. (3):

$$\text{RR} = [\text{SOC}_{csa}]/[\text{SOC}_{ref}] \tag{3}$$

Where, SOC_{csa} is the SOC (Mg ha^{-1}) stock estimated in the CSA systems, while SOC_{ref} is the SOC (Mg ha^{-1}) stock derived in the reference area that was considered our reference (or control or baseline) and represented the land use or management system before CSA adoption.

To report and explain the effect of the number of samples available in each study in our data set, more weight was assigned to work with larger samples (*N*-sample). Though meta-analysis ideally weighs the results considering the inverse variance of each study, this was not possible to do in our study as this information was unavailable in most of the extracted studies (Vicente-Vicente et al., 2016). Therefore, works in our research were weighted by sample size based on the approach proposed by (Adams et al., 1997) Eq. (4):

$$W_i = (N_{csa} \text{ x } N_{ref})/(N_{csa} + N_{ref}) \tag{4}$$

W_i represents the specific weight of the comparison, while the N_{csa} *and* N_{ref} represent sample sizes in the system (*CSA*) and control (*Ref*) treatments, respectively.

A Bootstrapping method (1000 iterations) using the "Boot" *package* of the RStudio (R core team), 95% confidence intervals (CIs) was computed for each weighted mean effect size. This resampling approach might be vital in ascertaining the significance of meta-analytical metrics because the data often have small sample sizes and could defy some basic distributional presumptions. Bootstrapping selects *N*-studies of a sample size of *N* and then calculates the statistic in a procedure that follows a reoccurring stream to create a distribution of feasible values (Aguilera et al., 2013).

2.3.2. Influence of timespan, climate, elevation, and soil parameters on SOC stock dynamics

For a qualitative and quantitative understanding of the effects of temperature, precipitation, elevation, soil depth, soil texture, and age of CSA on SOC stock rates, data obtained from the studies were grouped in subcategories within each of the following variables:

(i) temperature: < 25 °C, 25–27 °C, and > 27 °C;
(ii) precipitation: < 2000 mm, 2000–2500 mm, and > 2500 mm;
(iii) elevation: < 200 m, 200–300 m, and > 300 m;
(iv) soil depth: 0–20, 20–40, and 40–60 cm;
(v) soil texture (clay): varied across the CSA systems, and ranged from 125 to 700 g kg^{-1});
(vi) time since the adoption of the CSA systems: < 11 years (short term), 11–20 years (medium term), and > 20 years (long term) (Bai et al., 2019).

2.4. Additional features of the dataset, assumptions, limitations, and uncertainties

The studies used in our quantitative review applied different experimental designs, including randomized complete block design, chronosequence, paired sites, and pseudo-replication approaches. Furthermore, the studies employed distinct procedures to define the reference or baseline. For instance, some considered areas under native vegetation for reference, notwithstanding whether the land use preceding the one at the time of the assessment was different (Almeida et al., 2021; Bieluczyk et al., 2017). Typically, for a valid comparative analysis, SOC changes out to be estimated using the previous land-use (such as native vegetation, crop, pasture) or management (for example, traditional tillage, extensive pasture) as a baseline. Our study considered all soil carbon data reported as a baseline for SOC stock change rate calculations, because it is assumed that the exclusion of studies based on these criteria might impair reliable estimation, since the dataset would be decreased.

Some possible trade-offs were inevitable. For example, higher SOC stocks could lead to higher N_2O emissions, and the land use-SOC-N_2O nexus was neither measured nor covered in the dataset. Yet, this could serve as a possible uncertainty and might have a substantial effect on SOC, consequently hindering the gains of the CSA. Further, some studies failed to report soil vita data such as soil classification, climate, and elevation. These were extracted by visiting other relevant databases [(e. g., Köppen classification system for precipitation and temperature), and soil classification (Santos et al., 2018; Soil Survey Staff, 2014)]. Also, our analysis had a limitation as there was a smaller number of studies with the older age range, but we believed that this had no significant impact on the result since our findings agree with other reports in the area.

2.5. Statistical analysis

A meta-analysis approach was applied in this study to assess the influence of CSA systems on SOC stock changes based on independent studies. Considering the small number of studies and the high variability found between them (refer to Results), the random-effect model was applied. This random-effect model assumes that independent (i.e., explanatory) variables have fixed relationships with the dependent (i.e., response) variable throughout investigations, but that these fixed effects might differ from one study to another. For each variable (i.e., climate, elevation, soil texture, type, depth, and age of the CSA system), ΔSOC stock, the size of the effect (RR), and its 95% CI were computed using the "Meta" *package* in RStudio (R Core team). Our result considered changes in SOC stock rate and RR significant if the 95% CI did not overlap 0 (zero).

3. Results

3.1. Effects of CSA systems and adoption duration on SOC stocking rates

The SOC stock was positively influenced by the CSA (iC, iCL and iCLF) systems in Rondônia State (Fig. 2). The response ratio ranged from 0.15 to 1.64, and the iC had the lowest mean rate (0.37) while iCLF had the highest mean value (0.76). In terms of heterogeneity, data from all the CSA systems iC (20.4%), iCL (44.9%), iCLF (34.7%) revealed high heterogeneity (iC: $I^2 = 97.8\%$; Q = 815.73; d.f. = 8; $p < 0.001$; iCL: $I^2 = 98.5\%$; Q = 7369.54; d.f. = 26; $p < 0.001$; iCLF: $I^2 = 99.2\%$; Q = 4583.61; d.f. = 12; $p < 0.001$). The random effect model for the systems was non-significant (iC: MD = 2.641; z = 0.58; $p = 0.19$; iCL: MD = 3.813; z = 1.75; $p = 0.07$; iCLF: MD = 5.946; z = 3.05; $p = 0.34$).

In all the investigated CSA systems (iC, iCL, and iCLF), the rate of SOC stock changes for studies that were between 11 and 20 years of age were significant (Fig. 3). Similarly, studies for all the years under the iCLF showed that the rate of SOC stock changes was positive. In terms of average number of observed studies, the medium-term studies, that is, ages 11–20 years (52.2%) and below 11 years (27.7%) had the largest percentages. Also, on average, the rate of SOC stock change for 11–20 years was 0.93 Mg ha^{-1} yr^{-1} which is higher than the average value observed in either the short-term studies (3-10 years, i.e., <11 yrs) (0.47 Mg ha^{-1} yr^{-1}, or in the studies performed above 20 years (0.55 Mg ha^{-1} yr^{-1}).

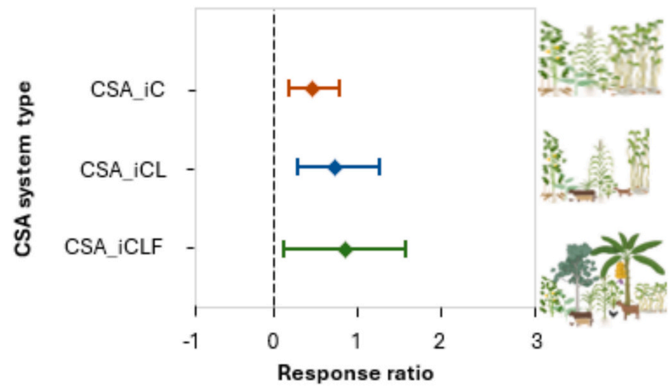

Fig. 2. Influence of CSA systems on the natural logarithm of the response ratio to rates of soil carbon change in Rondônia State, Brazil. The black broken line represents the boundary between a positive and negative response to the response ratio (RR). Effect sizes were considered significant if 95% Confidence intervals (CI) did not overlap zero. Definition of abbreviations: CSA represents Climate-Smart Agriculture, iC represents integrated cropping, iCL represents integrated crop-livestock, and iCLF represents integrated crop-livestock-forest.

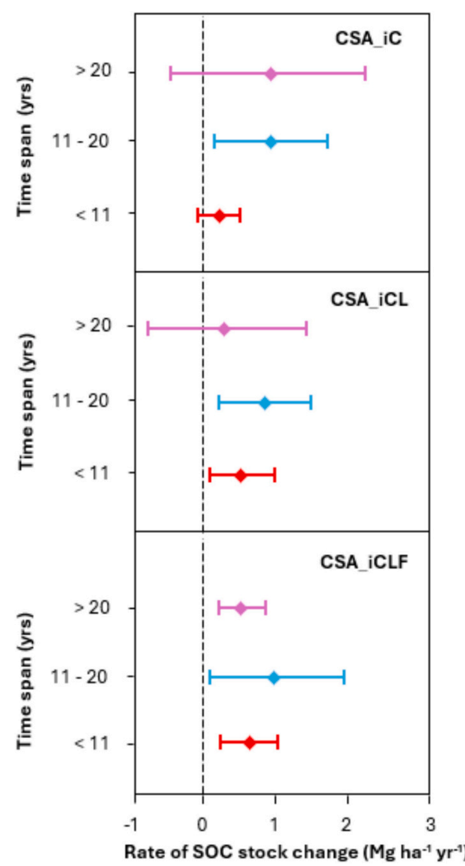

Fig. 3. Effects of time on SOC stock rate change in the CSA systems. The broken black line represents the boundary between a positive and negative response to the response ratio (RR). Effect sizes were considered significant if 95% Confidence intervals (CI) did not overlap zero. Definition of abbreviations: CSA represents Climate-Smart Agriculture, iC represents integrated cropping, iCL represents integrated crop-livestock, and iCLF represents integrated crop-livestock-forest.

3.2. Role of climate on SOC stocks in CSA systems

In all the CSA systems investigated, precipitation influenced the rate of SOC stock change. For the iCLF system, precipitation at every level had a significant effect on the SOC change rate, whereas for the iC and iCL systems, precipitation below 2000 mm did not have a significant effect on SOC stock change rate (Fig. 4a).

In all the studied CSA systems, precipitation amounts from 2000 to 2500 mm resulted in SOC stock change rates which were significant and greater than zero. On average, precipitation range between 2000 and 2500 mm (1.01 Mg ha^{-1} yr^{-1}) was greater than that for either below 2000 mm or above 2500 mm. The evaluated studies revealed that in all the CSA systems, temperature values below 25 °C had a significant effect on the rate of SOC stock change, while temperature above 27 °C did not have a significant influence on SOC change rate (Fig. 4b). Temperature below 25 °C for iCLF (0.73 Mg ha^{-1} yr^{-1}) recorded the highest mean rates for the SOC stock change.

3.3. Influence of soil depth and soil texture on SOC stocks in CSA systems

In all the CSA systems, the investigated studies observed a significant effect of soil depth on SOC stock change rate at the superficial depth (0–20 and 20 - 40 cm) (Fig. 5).

In contrast, there was no significant effect of depth on the rates of SOC stock change between 40 and 60 cm soil layers. The rates of SOC change in the iCLF system were 0.81 Mg ha^{-1} yr^{-1} at 0–20 cm, 0.65 Mg ha^{-1} yr^{-1} at 20–40 cm, and 0.52 Mg ha^{-1} yr^{-1} at 40–60 cm soil layers (Fig. 5-**iCLF**). In the iCL system (Fig. 5-**iCL**), the mean values of rates of soil SOC stock change at 0–20, 20–40 cm, and 40–60 cm were 0.69, 0.37, and 0.24 Mg ha^{-1} yr^{-1}, respectively. On the other hand, the iC system (Fig. 5-**iC**) had 0.25, 0.12, and − 0.02 Mg ha^{-1} yr^{-1} as the mean values of rates of soil SOC stock change at 0–20, 20–40 cm, and 40–60 cm, respectively.

In all the CSA systems, the rates of SOC stock changes were significantly affected by the clay contents except for the sandy-clay, which were below 250 g kg^{-1} of clay (Fig. 6). Irrespective of the CSA systems, soils with clay content in the range of 400–700 g kg^{-1} were more efficient in SOC accumulation.

3.4. Effect of elevation and soil types on SOC stocking rates

The rate of change of carbon stocks in all the CSA systems studied was significantly affected by elevation above 300 m (Fig. 7). At all elevation in the iCLF system (Fig. 7-**iCLF**), the rate of change of carbon stock was greater than zero. The values of SOC change for elevation above 300 m were 0.89, 0.50, and 0.41 Mg ha^{-1} yr^{-1} for iCLF, iCL, and iC systems, respectively. Across all the CSA systems, the average rate of change of carbon stocks for studies above 300 m was 0.59 Mg ha^{-1} yr^{-1}, which is twice higher than the average values for 200–300 m, and five times higher than the average values for studies below 200 m.

Oxisols and Ultisols covered more than 50% of the studies in our dataset, and these soil types have positive effects on the rate of SOC change when compared with Alfisols and other soil types (Fig. 8). Oxisols had 0.71 Mg ha^{-1} yr^{-1} of SOC change rate, Ultisols had 0.56 Mg ha^{-1} yr^{-1}, while Alfisols and others recorded 0.19 Mg ha^{-1} yr^{-1}.

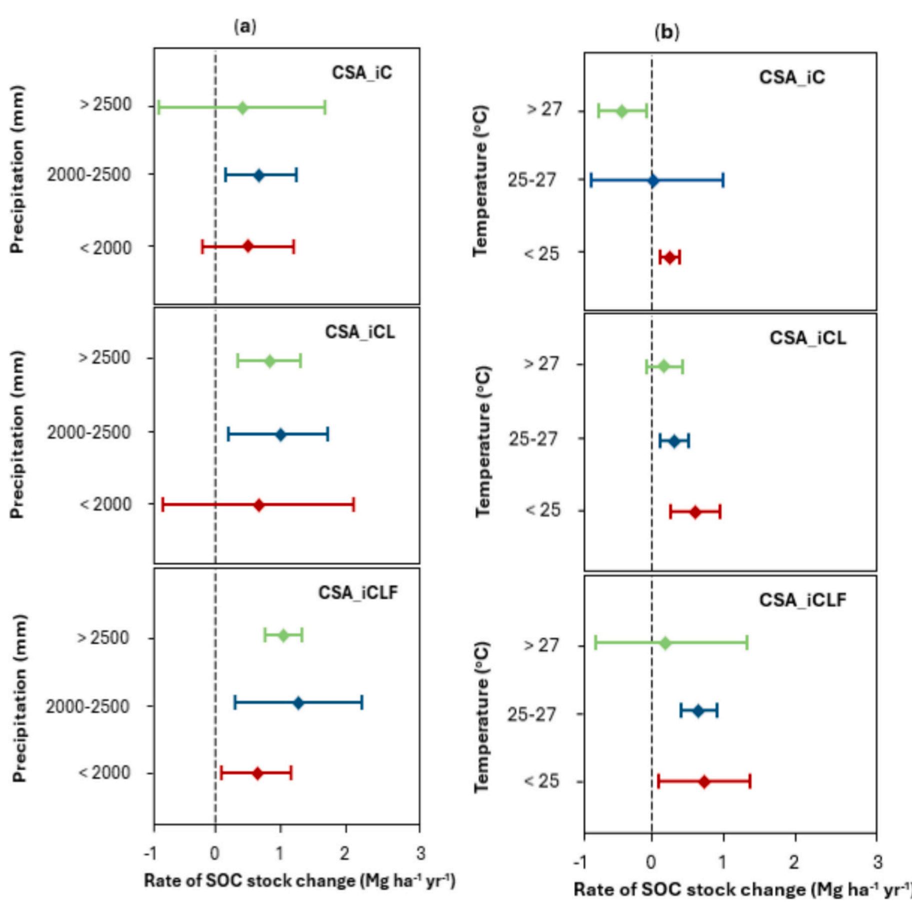

Fig. 4. Influence of climate on the rate of change of carbon stocks in CSA systems. Precipitation (Fig. 4a), and temperature (Fig. 4b). The broken black line represents the boundary between a positive and negative response to the response ratio. Effect sizes were considered significant if 95% Confidence interval (CI) did not overlap zero. Definition of abbreviations: CSA represents Climate-Smart Agriculture, iC represents integrated cropping, iCL represents integrated crop-livestock, and iCLF represents integrated crop-livestock-forest.

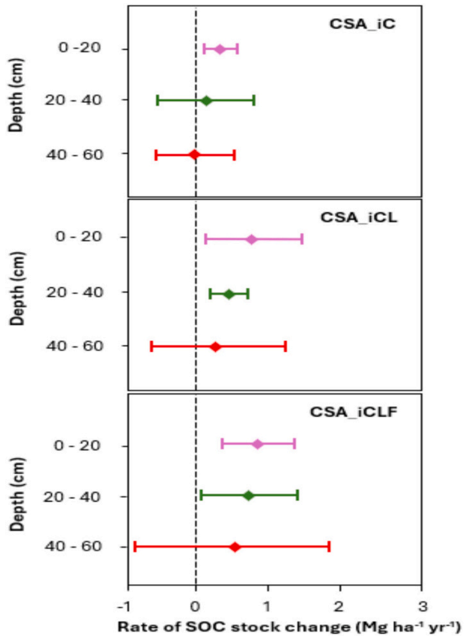

Fig. 5. Influence of depth on the rate of change of carbon stocks in CSA systems. The broken black line represents the boundary between a positive and a negative response to the response ratio. Effect sizes were considered significant if 95% Confidence intervals (CI) did not overlap zero. Definition of abbreviations: CSA represents Climate-Smart Agriculture, iC represents integrated cropping, iCL represents integrated crop-livestock, and iCLF represents integrated crop-livestock-forest.

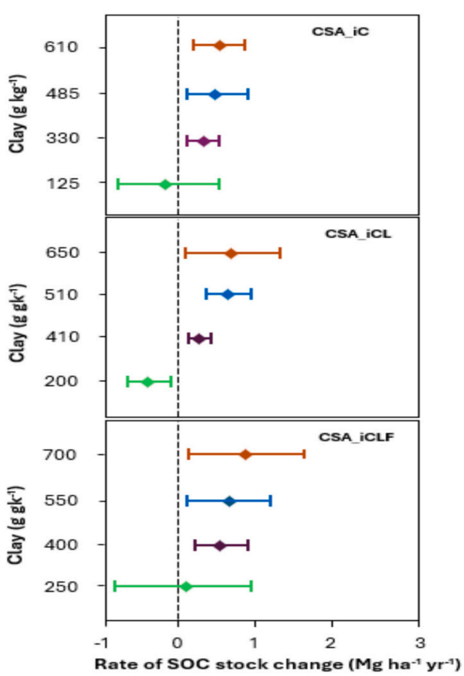

Fig. 6. Influence of clay (soil texture) on the rate of change of carbon stocks in CSA systems. The broken black line represents the boundary between a positive and negative response to the response ratio. Effect sizes were considered significant if 95% Confidence intervals (CI) did not overlap zero. Definition of abbreviations: CSA represents Climate-Smart Agriculture, iC represents integrated cropping, iCL represents integrated crop-livestock, and iCLF represents integrated crop-livestock-forest.

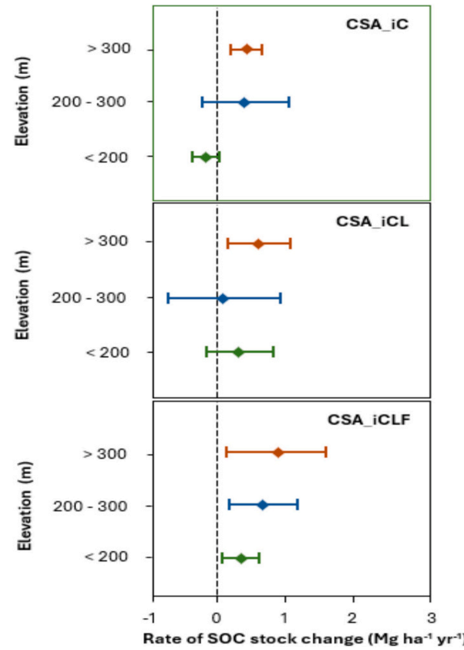

Fig. 7. Influence of elevation on the rate of change of carbon stocks in CSA systems. The broken black line represents the boundary between a positive and negative response to the response ratio. Effect sizes were considered significant if 95% Confidence intervals (CI) did not overlap zero. Definitions of abbreviations: CSA represents Climate-Smart Agriculture, iC represents integrated cropping, iCL represents integrated crop-livestock, and iCLF represents integrated crop-livestock-forest.

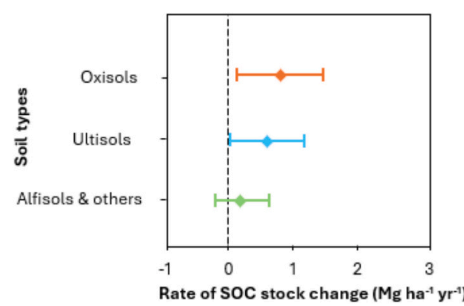

Fig. 8. Effect of soil types on SOC stock rate change in the CSA systems. The broken black line represents the boundary between a positive and negative response to the response ratio. Effect sizes were considered significant if 95% Confidence intervals (CI) did not overlap zero. Not all the study locations reported the main soil types ($n = 44$). Oxisols, that is Ferralsols in the American Taxonomy, and Latossolos or Latosols in the Brazilian Taxonomy. Ultisols or Acrisols in the American taxonomy, and Argissolos in the Brazilian taxonomy.

4. Discussion

4.1. *Effects of CSA systems on SOC*

The findings from our study revealed that CSA systems (viz., iC, iCL, and iCLF) are good options for soil carbon stock, especially in the State of Rondônia, where there are large pastures with degraded features, and severe deforestation caused by high demands associated with population growth (da Silva et al., 2022). In comparison with the conventional farming system, the CSA system offers more environmental and socio-economic benefits, including food security, climate change mitigation and adaptation by increasing carbon stores and decreasing CO_2 emissions from agricultural soils (Fig. 9).

The significant role of these CSA systems in enhancing SOC has been

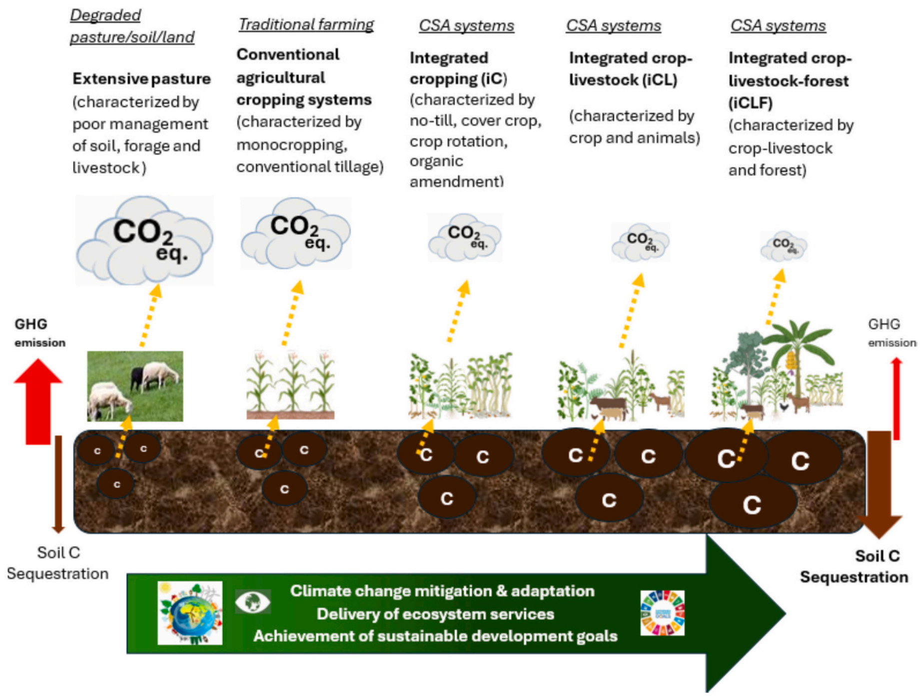

Fig. 9. Conceptual framework of soil carbon sequestration and related benefits in areas of Rondônia State under extensive pasture, conventional farming, and CSA systems.

reported within Brazil (Cheng, 2024; de Freitas et al., 2020; Gama-Rodrigues, 2020; Marchão et al., 2024; de Oliveira et al., 2024; Sato et al., 2019; Zaro et al., 2020), and outside Brazil (Chen et al., 2017; Ologunde et al., 2024; Valenzuela et al., 2022). Other potential of these CSA systems includes promoting soil microbial activities, nutrient cycling, decreasing the intensity and density of soil compaction and erosion, enhancing soil aeration, total porosity, aggregation, and moisture content (Pezarico et al., 2013). The CSA systems support soil functional services, ecosystem services, and sustainable development goals (Evangelista et al., 2024; Nwaogu and Cherubin, 2024). In contrast to our findings, some other studies have reported that the potential of CSA to increase SOC does not apply to all the related practices. It was revealed that conservation tillage (or no till) can increase soil respiration (Chen et al., 2021) but the practice has not been beneficial for increasing SOC stocks on its own except in combination of other practices (Christopher et al., 2009). For instance, in a global meta-analysis, an insignificant rate, below 6% increase in SOC was found under a conservational or no-till system (Bai et al., 2019). These discrepancies might be attributed to the fact that tillage systems do not directly promote SOC but encourage the build-up of carbon by positively influencing soil properties. Similarly, cover crops can enhance SOC stocks (McClelland et al., 2021), but do not globally increase SOC content over the long term (Blanco-Canqui, 2022). This could be explained by the differences in cover crop species, management (e.g., choice of species intercropping, planting time and termination), and prevailing environmental conditions (such as climate) at different locations.

However, other studies agreed with our findings about the potential of CSA in increasing SOC storage relative to conventional systems (Abril, 2013; Cheng, 2024). According to (Cheng, 2024) who reported that though iC or iCL might show substantial soil improvements, iCLF can stock more carbon because it has forest combinations, thus retaining more soil carbon than iC, iCL, or pasture soils. Though iC or iCL systems sequester SOC, they lack the deep rooting capacity of trees, which supports higher levels of microbial activities and provides recalcitrant carbon that slows carbon decomposition (Abril, 2013).

Furthermore, in a 7-year experiment, Moreira et al. (2022) observed 194 Mg ha^{-1} of total soil carbon stock in a CSA-iCL which was 44.8% higher than that obtained in either native vegetation or conventional cropping system in Brazil. Meanwhile, the role of the litter and decayed roots from the forest trees might have supported a positive accumulation of SOC under the iCLF system over time (Marchão et al., 2024). In addition to improving soil conditions, CSA especially iCLF has potential to offset GHG emissions within agricultural activities. It has been reported in Brazil, that iCLF system on just 15% of the area of a farm (with a stand of 417 trees ha^{-1}) could compensate GHG emissions from livestock and the C loss from the initial crop establishment phase (Souza et al., 2020).

Contrary to our findings, a study across 23 sites in South African countries (Malawi, Mozambique, Zambia, and Zimbabwe) revealed no significant difference in SOC between CSA and traditional farming systems. This inconsistent might be because of poor and inadequate management, such as adoption of only a single CSA practice in the South African region, as well as time.

4.2. Age of CSA systems versus SOC

Regarding the age of the experiments in Rondônia State, it was observed that a larger percentage of the studies or observed study points were between 5 and 20 years, and this had significant rates of SOC stock changes across the CSA systems. This trajectory in SOC stocks over time was also reported in other studies within and outside Brazil (Han et al., 2016; Poeplau and Don, 2015; da Silva et al., 2024). Our findings indicated that in all time span, the iCLF system showed a significant effect on the rates of SOC stocks. Also, study time span 11–20 years did not only reveal a positive effect on SOC but also accounted for the highest rates of SOC sequestration. On the contrary, the longer time span (or older in years) had a negative trend in SOC storage rates. Although our analysis had a smaller number of studies with older age range, and this might have influenced the results from the old age of the CSA systems. A study by Cheesman et al. (2016), showed that CSA has a limited potential to significantly increase SOC stocks beyond seven years of practice in South Africa. Also, a study by Nyamangara et al. (2013) observed no significant difference in SOC content (0–20 cm depth) between CSA (up to nine years) and conventional practices across 15 study areas in Zimbabwe. A reason for these inconsistencies in the results might be due to the differences in study time, management, soil type, and climate (Cheesman et al., 2016). For example, in another study, an increase in SOC stocks under CSA as compared with conventional practices was observed after only four years of CSA practice (Thierfelder et al., 2013).

It is important to emphasize that dynamics in SOC driven by land use age could be attributed to many factors. (1) current land use reaching its equilibrium. It has been reported that the older system could have lower SOC because they had reached an equilibrium (Perez-Flores et al., 2018; Poeplau et al., 2011); (2) It could be that the older systems would regain their SOC stocks over longer time of cropping with increase in farm litters decomposition on the soil (Deng et al., 2014). Studies have presented different views on the 'SOC-land use age nexus'. For example, SOC sequestration rate was found to have increased in the early years of land use establishment (Barre et al. (2010). On the other hand, Poeplau et al. (2011) reported that a decrease would be anticipated once a new SOC equilibrium is reached after many years. Whereas Deng et al., 2016 affirmed that a decrease might be experienced but not permanent, an increase could be regained later, after longer years of sustainable management. However, this fluctuation in SOC in time depends largely on other factors such as land use conversion types, and land use history and management. In a case where a system (e.g., farmland) tends to decrease in SOC stocks, it is advisable to continue with sustainable practices as it might regain over time. For instance, a global metadata analysis found that with afforestation on grassland, SOC stocks indicated the trend of declined–increased–declined–increased following time (Deng et al. (2016). On the other hand, in a conversion from grassland to farmland, SOC accumulation showed no significant difference among different system age groups but decreased in the first 30 years and began to increase after 30 years (Deng et al., 2016).

4.3. Role of climate on SOC under the CSA systems

The precipitation trend in Rondônia State is relatively high with a mean annual value above 1800 mm. Our study observed that precipitation affected the rate of SOC stock change in all the CSA systems investigated. This effect was most significant in the iCLF system where every precipitation level showed a positive SOC value. Precipitation promotes photosynthetic processes enhancing above and belowground fauna and flora, which result in a surge of respiration rate with accelerated abundance of species and elevated biodiversity (Xue et al., 2024; Yu et al., 2019). Several studies have reported the effects of precipitation on soil functions and ecosystem services, including the above and belowground components (Cao et al., 2024; Li et al., 2022; Shi et al., 2018; Xu et al., 2020; Yang et al., 2024). High precipitation intensity was found to have increased the functional diversity and biodiversity of soil nematodes (Cao et al., 2024). Yang et al. (2024) established that elevated precipitation enhanced the positive impact of soil fungi and regulated the impact on bacteria from negative to positive with an increased soil microbial community. Precipitation has also been known as a regulator of microbial activities responsible for litter decomposition by resolving water stress and promoting nutrients diffusion for microbial growth (Li et al., 2022) and SOC sequestration (Xu et al., 2020; Xue et al., 2024). In disagreement to our findings, increased precipitation might also decrease nutrient availability by affecting exchangeable cations, thus limiting specific soil microbial growth (Shi et al., 2018), which consequently reduced SOC concentration (Szili-Kovács and Takács, 2024). However, the effects of precipitation on SOC could be positive or negative depending on multiple interacting factors, including flooding and its duration, plant species, management, as well as soil types and properties.

The average annual temperature in Rondônia State ranges between 23 and 28 °C. Our study observed that the rate of change of SOC in the temperature range between 23 and 25 °C was positive in all the investigated CSA, while higher temperature values did not support the accumulation of SOC. This might be explained by the reason that high temperatures induce higher decomposition process, leading to a loss of SOC when compared to optimal temperature (Chen et al., 2024; Zhang et al., 2024). The iCLF system had the highest carbon sequestration, temperature level notwithstanding. Therefore, tropical climate regions (including the Rondônia State) could gain from the adoption of iCLF system because the existence of the forest trees and associated elements modifies local climate and improves microclimatic comfort (de Freitas et al., 2020; Nwaogu and Cherubin, 2024), which consequently normalizes the decomposition process (Sun et al., 2024).

In sum, both temperature and precipitation could have either negative or positive impacts on SOC depending on other related environmental factors such as biomass characteristics and microbial decomposition rate, and soil type (Erhagen, 2013). It has been reported that as the temperature increases, it affects the transpiration rate, reduces plant productivity, and consequently reduces the carbon input to the soil (Moore et al., 2021). Further, an increase in temperature, could lead to enhanced soil microbial activity is enhanced which in turn caused a higher mineralization of SOC (Mao et al., 2015). On one hand, it has been established that with every 10 °C rise in temperature, the decomposition rate doubles thereby decreasing the SOC (Kirschbaum, 1995). While, on the other hand, it has been revealed that microbial activity declines with the decrease in temperature thereby decreasing the decomposition rate of biomass litter and SOC. Similarly, higher precipitation could provide a positive effect on SOC accrual by promoting biomass growth and increasing microbial biomass carbon, while, on the contrary, might also promote the leaching and erosion of SOC (Rizinjirabake et al., 2019).

4.4. Influence of soil depth, types and properties on SOC in CSA systems

We found a significant effect of soil depth on SOC stock change rate at superficial depth for all the CSA systems. Previous studies within and outside our study region have reported more SOC stocks in the top-soil layers than in the sub/deeper soil layers, and in CSA than in conventional systems (Mantovani et al., 2024; Valenciano et al., 2024; Wiesmeier et al., 2012). This might be attributed to the addition of crop residues, litter, and livestock manure at the surface soil depth (Mantovani et al., 2024). Contrary to our findings, a study in France reported that SOC content was either significantly higher in subsoil than in topsoil layer or there was no significant difference between the two layers. Also, a study in Minas Gerais state, Brazil reported that SOC accumulated in the subsoil layer (20–40 cm depth) than in topsoil layers (0–20 cm) (Vicente-Vicente et al., 2016). This could be caused by any of the following reasons: (i) the decomposability of the organic matter available to the resident communities did not decrease with depth; (ii) the accumulation of SOC in the vegetable cover is still derived from the previous vegetation at a deeper depth, or (iii) C storage in subsoils is driven by microbially-processed C being translocated down the soil profile as DOC and consequently became chemically protected in the subsoils (Matus et al., 2014).

The role of soil texture on the sequestration of carbon was established in our study. Irrespective of the CSA systems, soils with clay content in the range of 400–700 g kg^{-1} were more efficient in SOC accumulation than the clay-sandy soils, which had lower clay contents (< 300 g kg^{-1}). Our study dataset from Rondônia revealed that clay had more than 25% of the soil texture, while sand had a relatively very low rate. Soils with substantial clay content have been identified with significant rates of change in SOC stocks (Dexter et al., 2008; Oliveira et al., 2024; Pulley et al., 2023; Tang et al., 2022). SOC bound to clay in aggregates within a soil became protected from mineralization, consequently building longer-term stocks (Dexter et al., 2008). The iCLF system had the highest clay content, and this might be attributed to the management system and a decrease in the rates of soil erosion, which improved the soil structure (Jinger et al., 2022). Higher clay content in the iCLF enhances the effectiveness of the system by increasing the soil health. This could be because clay-rich soils have been known to sequester more carbon due to their ability to shield carbon particles into mineral and organic agglomerates (Kleber et al., 2021). It was also reported that trees slow carbon decomposition, thereby contributing to better chemical stabilization of SOC through its adsorption on soil clay minerals (Six et al., 2002). In contrast, a study in Mt. Cameroon found that clay content had a significant negative correlation with soil OM and soil C accumulation (Tsozué et al., 2019). The influence of environmental variables such as altitude on clay content could be the reason for this negative correlation or disparity with our result (Tsozué et al., 2019). Mt. Cameroon is over 5 times higher than our study area, and it has been revealed that as the organic matter increases along the topographic gradient, the clay content and bulk density decrease (Tsozué et al., 2019).

Oxisols followed by Ultisols dominated the studies in Rondônia State, and they had more than 200% SOC stock when compared to Alfisols. This agrees with other studies in the area which stated that Oxisols predominated Rondônia State by encompassing about 40% of the area, while Ultisols (~20%), Quartzipsamments (~12%), Entisols (~8%), Inceptisols (~6%), and Aquent Entisols (~5%) followed (Maia et al., 2009; da Silva et al., 2022). However, prior to CSA adoption, Oxisols in Rondônia State has been characterized with low SOC sock caused by degraded pasture which on average ranges from −0.03 to +0.72 Mg ha^{-1} yr^{-1} (da Silva et al., 2022), the introduction of CSA systems has helped to improve SOC stock with average ranging from 0.37 to 0.76 Mg ha^{-1} yr^{-1} as shown in our study. CSA systems, especially with the integration of forests have enormous potential to increase SOC stores (Cheng, 2024; de Freitas et al., 2020; Fronza et al., 2024; Mantovani et al., 2024; Marchão et al., 2024; Monteiro et al., 2024; Mosier et al., 2021; Nwaogu and Cherubin, 2024; de Oliveira et al., 2024; Ologunde et al., 2024; Sato et al., 2019; Seó et al., 2017; Silva et al., 2024; Stanley et al., 2018; Zaro et al., 2020).

4.5. *Effect of elevation on SOC stocking rates*

Further, findings from our study revealed that higher elevations above 300 m tend to sequester more carbon than the lower altitudes. SOC stock has been identified to be higher in soils with relatively high elevation due to low temperature which optimizes and reduces the rates of decomposition (Chen et al., 2024; Zhu et al., 2019). However, as the elevation increases in its magnitude up to a certain height, the SOC is likely to decrease because of the limited ecosystem productivity that becomes associated with much harsher climatic conditions (Chen et al., 2016; Zhu et al., 2019). Our dataset showed that Rondônia State has a moderate elevation that was not above 700 m, thereby supporting the sequestration of SOC rather than emitting carbon. Elevations below 300 m impede SOC stock, especially in the iC and iCL systems. This could be because in most tropical regions (e.g., Rondônia State) lower elevations have relatively elevated temperatures, which induces carbon loss due to accelerated decomposition (Tsozué et al., 2019; Wu et al., 2024). Moreover, the absence of trees to regulate the elevated temperature in the iC and iCL systems relative to iCLF might also be a factor.

However, it has been widely reported that SOC increases with an increase in elevation, but this holds true to a certain height. For example, contrary to our findings, at very high or extreme elevations, SOC has been reported to have decreased. For example, in the Qilian Mountains, SOC density increased with increasing elevation from 2650 to 3400 m on the shady slopes, but a decreasing trend in SOC was recorded above 3400 m, where the vegetation began to change from the forests to the alpine shrublands (Chen et al., 2016). Also, at the Himalayan Mt., SOC was found to decrease with an increase in elevation (Bangroo et al., 2017). This decrease in SOC at extreme elevations could be because of the insufficient ecosystem productivity due to harsher climatic conditions.

4.6. *The soil potential (or saturation capacity) to accumulate soil organic carbon*

While the study of SOC stocks is important for determining the carbon balance at different scales, the soil's capacity to accumulate SOC is crucial. Many soils in Brazil, including those in Rondônia State, are managed (Matos et al., 2023; Araújo et al., 2023; Silva et al., 2025; Junior et al., 2024), and it has been established that most “managed” soils exhibit a high carbon saturation deficit (Six et al., 2024). For instance, the MAOC level of most soils in our study region is below the MAOC contents of 84–86 mg Cg − 1 (for 2:1-mineral-dominated soils), and 43–46 mg Cg − 1 (For 1:1-mineral-dominated soils) based on the reported results and benchmarks (Feng et al., 2013; Georgiou et al., 2022; Matus, 2021; Araújo et al., 2023; Matos et al., 2023; Silva et al., 2025; Junior et al., 2024). Though managed soils have been reported with lower SOC, including MAOC contents, yet they could get increased over time through improved management (Junior et al., 2024; Prairie et al., 2023). By introducing sustainable land use and agroecological management systems such as CSA practices, the total SOC (including POC and MAOC) was observed to have increased within and outside our study region (Araújo et al., 2023; Silva et al., 2025; Junior et al., 2024; Prairie et al., 2023).

5. Conclusion

The study found that though all the CSA systems enhanced SOC stock, iCLF showed the highest potential to increase SOC in the degraded soils of Rondônia State. Environmental variables (e.g., climate, system age, and soil attributes) have significant influences on the SOC stock dynamics. We found that studies that covered between 11 and 20 years revealed significant positive effects on SOC. On the other hand, the shorter studies (< 11 years) and the longer/older studies (> 20 years) had negative effects on SOC storage rates. Though our analysis had a smaller number of studies with an older age range, this might have influenced the results from the older age of the CSA systems. Also, it was found that precipitation amounts ranging between 2000 and 2500 mm promoted SOC stock when compared with either lower or very high precipitation levels. Further, soil depth, soil texture, and elevation also have a reasonable influence on SOC accumulation, but their effects depend on the specific CSA management type. While iCLF supported SOC stock irrespective of the elevation, only the higher elevations promoted C-concentrations under iC and iCL.

This meta-analysis therefore emphasizes that the practice of CSA could successfully stabilize as well as elevate SOC levels across soils in the Amazonian region. By this ecological benefit, climate change mitigation is achieved while the degradation caused by agricultural expansion is reduced. Besides being the first time a similar study has been performed in Rondônia State, this study differs from previous meta-analyses on the CSA-SOC nexus because it provides synergy between agricultural productivity, carbon management, and climate change resilience in an agricultural frontier Amazonian region, where pasture degradation is a common challenge. These will help achieve Brazil's food security and climate change mitigation and adaptation targets, namely the ‘ABC Plan’ to meet sustainable development goals by increasing food production, reducing carbon loss, and greenhouse gas (GHG) emissions. It will also support the achievement of the country's ‘Nationally Determined Contributions (NDCs)’ to the 2015 Paris Summit Agreement on Climate.

Meanwhile, the significant role of CSA in SOC accumulation should not give the total impression that there are no trade-offs. For instance, if not sustainably managed, the CSA system might induce GHGs (NO_3, CH_4) emissions, thereby limiting the benefits of the system. Further studies need to be conducted to evaluate the relationships between the CSA systems and GHG emissions in Rondônia State.

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Declaration of competing interest

No potential conflict of interest was reported by the author(s).

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No acknowledgement to be reported by the author(s).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.crsust.2026.100336.

Data availability

The authors confirm that the data supporting the findings of this study are available within the article [and/or] its supplementary materials.

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