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Climate-smart agriculture and soil C sequestration in Brazilian Cerrado: a systematic review

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ABSTRACT: Climate-smart agriculture (CSA) practices, mainly no-tillage (NT), cover cropping (CC), soil fertilization with organic amendments (OA), and crop-livestock (CL) and crop-livestock-forestry (CLF) systems, has been widely adopted in areas from Brazilian Cerrado. The CSA may partly offset former soil C losses and contribute to climate change mitigation. However, contradictory findings brought uncertainties about the effect of CSA on soil C. Here, by a systematic review of 87 papers and using 621 data pairs, we provided a pervasive biome-scale analysis of soil C stock changes associated with the adoption of CSA across Brazilian Cerrado. All CSA practices evaluated showed average positive rates of C stock change, indicating a general tendency of soil C accretion after its adoption. In areas under NT, CC and CLF, greater rates were estimated for the deeper soil profile evaluated (0.00-1.00 m) (1.24 ± 0.85, 0.54 ± 0.54 and 1.00 ± 1.47 Mg ha^{-1} yr^{-1}, respectively), while OA and CL showed more soil C accretion when the assessment was limited down to 0.10 m depth (0.82 ± 0.60 and 0.59 ± 0.66 Mg ha^{-1} yr^{-1}, respectively). Unfortunately, the lack of basic information precluded any attempt to statically compare our estimations. In this sense, we must be cautious in stating that soil C sequestration occurs at those rates after the adoption of CSA practices. Despite these limitations, the results clearly show that the diversification and intensification of agricultural areas in the Cerrado by the adoption of CSA is a promising pathway to increase soil C stocks, and consequently, contribute to climate change mitigation and adaptation. Finally, our findings emphasize the importance of efforts that stimulate farmers to adopt these practices on large scale, such as Brazil's Low-Carbon Agriculture Plan, besides providing sound empirical evidence about the role of soil C sequestration in Brazil achieving its Nationally Determined Contributions commitments.

Keywords: soil organic matter, no-till, integrated agricultural systems, soil health, climate change mitigation.

INTRODUCTION

Globally, soils hold three times more carbon (C) than the atmosphere and about four times than the vegetation C pool (Lal, 2008; Le Quéré, 2018). The most current estimation data for global soil organic carbon (SOC) stocks are 1,400 ± 150 petagrams of carbon (Pg C) to 1 m in depth and 2,060 ± 220 Pg C to 2 m in depth (Batjes, 2016). Accordingly, any change in the soil C reservoir would significantly impact the global C budget. Global soil C losses due to the conversion of natural vegetation to agriculture amount to an accumulated 133 Pg C in the top 2 m soil layer (Ontl and Schulte, 2012; IPCC, 2022). The rate of C loss increased significantly over the past 200 years (Sanderman et al., 2017). According to the same authors, grazing and cropping lands contributed nearly equally to the loss of soil organic C (SOC). Such C losses notably affect both world food security and global climate change (Lal, 2020; Dasgupta and Robinson, 2022).

In Brazil, most soil C losses occurred in the Cerrado, one of the main hotspots of land-use change to agriculture expansion over the world in the last decades (Ramankutty et al., 2002). This biome occupies about 23.3 % of the Brazilian territory and 11 % of South America (2,045,000 km^2), with great importance for food, energy and fiber production, besides being one of the most biodiverse savannas globally (Bonanomi et al., 2019). Therefore, the expansion of agriculture across Cerrado has implications for the global C cycle. The substitution of natural vegetation is usually followed by soil C loss, especially when soil or crop management substantially reduces biomass input or increases SOC decomposition rate (e.g., monocropping systems and conventional tillage) (Guo and Gifford, 2002; Don et al., 2011).

Climate-smart agriculture (CSA) may partly offset former soil C losses and contribute to climate change mitigation, and eventually enhance the resilience and adaptation capacity of production systems (Paustian et al., 2016). The CSA practices, such as no-tillage, cover cropping, soil fertilization with organic amendments, and crop-livestock and crop-livestock-forestry systems have been widely adopted to enhance soil C accretion and to improve soil quality, while ensuring crop productivity (Anghinoni et al., 2021). The adoption of CSA in Brazil has been encouraged among farmers at different levels, including farmers' associations (e.g., FEBRADP[1]), public-private partnerships (e.g., Rede ILPF[2], RCGI[3]), private initiatives (e.g., PRO Carbono Bayer) and by public policies (e.g., Plano ABC[4] and ABC+[5], Brasil, 2021), and a lot of agricultural areas implemented these management practices across Brazilian Cerrado.

There is substantial new information on soil C change and C dynamics under CSA in the Brazilian Cerrado, however, this information has never been analyzed together. Moreover, contradictory findings generated by single-site experiments brought some uncertainties regarding the potential of the CSA to build-up soil C and mitigate climate change (e.g., Corbeels et al., 2016; Sant-Anna et al., 2017). Assembling the available data and estimating general responses at the biome level is essential to evaluate the role of CSA in recovering soil C stocks and for climate policy planning purposes.

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[1] FEBRADP: Federação Brasileira de Plantio Direto na Palha (Brazilian No-Till Farmers' Federation)

[2] Rede ILPF: Rede de Integração Lavoura-Pecuária-Floresta (Crop-Livestock-Forestry Systems Association)

[3] RCGI: Research Centre for Greenhouse Gas Innovation

[4] Plano ABC: Plano Setorial de Mitigação e de Adaptação às Mudanças Climáticas para a Consolidação de uma Economia de Baixa Emissão de Carbono na Agricultura (Agricultural Sector Plan for Mitigation and Adaptation to Climate Change and for the Consolidation of a Low Carbon Economy in Agriculture)

[5] Plano ABC+: Plano Setorial para Adaptação à Mudança do Clima e Baixa Emissão de Carbono na Agropecuária 2020-2030 (Brazilian Agricultural Policy for Climate Adaptation and Low Carbon Emission 2020-2030)

Accordingly, the main goal of this quantitative review is to provide a pervasive biome-scale analysis of soil C stock changes associated with the adoption of CSA in the Brazilian Cerrado. First, general data on soil C stocks under the main land-uses across the biome are presented to provide insights about baseline conditions. Thus, the effects of each CSA practice on overall soil C change rates are reported and discussed. Finally, we identified the main gaps (limitations) and opportunities for soil C research in Brazilian Cerrado. We believe that our review will provide sound empirical evidence about the role and impact of CSA on soil C accretion in Brazilian agricultural lands. The study also aims to contribute to the understanding of the role of CSA in achieving the country's Nationally Determined Contributions (NDC) to the Paris Agreement, which was recently updated 2022 (Brazil, 2022), as well as provide scientific evidence for further national climate policies and to the discussion about better scientific practices and the way forward on soil C research in Brazil.

MATERIALS AND METHODS

Review scope and data compilation

A systematic literature review was performed to search for studies that evaluated the impacts of land-use and CSA practices on soil C across Brazilian Cerrado (edaphic savanna; Lopes and Cox, 1977). The search was conducted in the Scopus database, seeking peer-reviewed scientific papers published until September, 2021. Gray literature (technical papers, conference papers/abstracts, book chapters, dissertations and theses) was excluded. The search strategy was based on terms (in English) listed in the title, abstract and keywords, as described in the query string: (TITLE-ABS-KEY ("soil carbon" OR "soil organic carbon" OR "soil organic matter" OR "greenhouse gas*") AND (cerrado* OR savanna*) AND (braz*)). The Boolean operator OR was used to include variations or correlated words of "soil carbon" and "Cerrado"; while the operator AND was used to include only studies that obligatorily evaluated soil C in Brazilian Cerrado.

Our search resulted in more than 300 publications, which were screened based on the following criteria: (i) results must be based on field experiments in the Brazilian Cerrado, evaluating at least one of the below-mentioned CSA, (ii) the experimental design should include replications, and (iii) soil C stocks should be available or computable from SOC and soil density, (iv) a reference or baseline condition must be included in the study, ideally the previous land-use or management. Accordingly, a total of 1156 observations from 87 peer-reviewed publications were compiled. The distribution of the study sites included in this review is shown in figure 1.

Based on the evaluated CSA practices, the selected studies were categorized into five groups: a) no-tillage (NT) - tillage systems were investigated including NT; b) cover cropping (CC) - effects of cover crops during the off-season except pastures; c) integrated crop-livestock systems (CL) - annual crops in rotation with pastures; d) integrated crop-livestock-forestry (CLF) - CL in the presence of trees; and e) soil fertilization with organic amendments (OA). Most of the studies focused on the effects of a single CSA practice on soil C stocks, with very few research estimating the combined effects of integrated management options. Hence, possible synergistic effects on soil C stocks due to combined CSA practices were not assessed.

Soil C calculations

Soil C stocks (Mg ha^{-1}) were available for most of the studies, but for those assessments where C data was presented in concentrations, soil C stocks were calculated using the following equation:

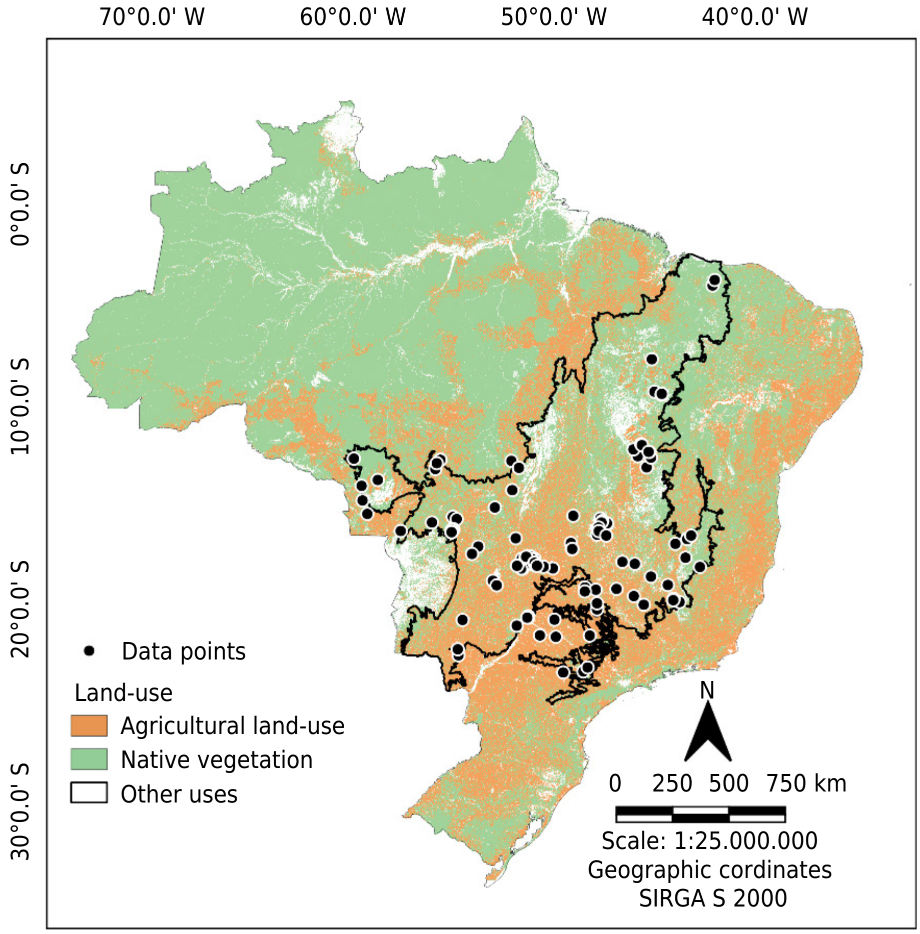

Figure 1. Study sites from peer-reviewed publications evaluating the rates of soil C stock change in agricultural areas under climate-smart soil management across Brazilian Cerrado.

$$C = (SOC \times Bd \times L)/10 \qquad \text{Eq. 1}$$

in which: C is the soil C stock (Mg ha^{-1}); SOC is the soil C content (g kg^{-1}); Bd is the bulk density (Mg m^{-3}); and L is the thickness of the soil layer (cm).

For a uniform comparison and upscaling approach regarding the adoption of the CSA practices, the data on soil C were converted to rates of soil C stock change (Mg ha^{-1} yr^{-1}). The annual rates were calculated considering the difference in C stocks between an area within the adoption of a given CSA practice and a reference (baseline), as described in equation 2:

$$\Delta C = (C_{CSA} - C_{REF})/t \qquad \text{Eq. 2}$$

in which: ΔC is the rate of soil C stock change (Mg ha^{-1} yr^{-1}); C_{CSA} is the soil C stock in an area under given CSA practice (Mg ha^{-1}); C_{REF} is the soil C stocks in the reference area (Mg ha^{-1}); and t is the time since the adoption of the CSA practice (years).

Assumptions and missing information

In a few studies, only soil organic matter contents were reported. In this case, SOC concentration was calculated using the conventional conversion factor (“van Bemmelen factor”) of 0.58 (Pribyl, 2010). Also, some authors reported SOC concentration, but not provided values for Bd. In these studies, we estimated Bd based on the negative correlation between this parameter and SOC (Cherubin et al., 2015; Poeplau and Don, 2015). From the collected dataset, an empirical relationship was established between

SOC and Bd for soils across Brazilian Cerrado (Figure 2), and missing data for Bd was calculated using the predicted values from the empirical function derived.

Although the calculation of soil C stocks based on an equivalent soil mass is desirable to compare changes in soil C stocks (Poeplau and Don, 2015), soil depth was not adjusted to account for changes in Bd within land-use unless the authors of the original data had already done it. Here, since the effects of native vegetation conversion on soil C changes were exhaustively evaluated on Brazilian Cerrado, our main focus was to assess the role of CSA practices in restoring the soil C stocks in agricultural lands. For such a scenario, not adjusting for an equivalent soil mass could only result in a slight bias in the estimation of soil C changes (Laganiére et al., 2010; Li et al., 2012). Moreover, as above mentioned, some studies did not report Bd data for the whole soil profile assessed, precluding any attempt to soil C stocks correction.

The publications used in our quantitative review presented various experimental designs such as paired-sites, pseudo-replication, chronosequence, and diachronic approaches. Additionally, the studies used different strategies to define the reference or baseline. For example, some considered areas under native vegetation as a baseline, even if the land-use immediately before the one at the time of the evaluation was different (e.g., Leite et al., 2014; Bieluczyk et al., 2017; Almeida et al., 2021). Ideally, for a sound comparison, soil C changes should be determined using the prior land-use (e.g., native vegetation, crop, pasture) or management (e.g., conventional tillage, extensive pasture) as a reference. We considered every soil C data provided as a baseline for soil C stock change rate calculations, because we believe that the exclusion of studies based on these criteria could result in less robust estimations as the dataset would be drastically reduced. This issue will be properly addressed in the section “Final remarks and the way forward for research”.

To evaluate the response of soil C at different depths, the dataset was divided into the following sampling depths: 0.00-0.10 m (also including soil C stocks down to 0.20 m), 0.00-0.30 m (also including soil C stocks between 0.00-0.20 and 0.00-0.40 m), 0.00-0.50 m (also including soil C stocks between 0.00-0.40 and 0.00-0.75 m) and 0.00-1.00 m (also including soil C stocks between 0.00-0.75 and below). Due to the variability of sampling approaches, we chose to keep studies that did not match the preestablished sampling depths of our assessment and assumed that these differences

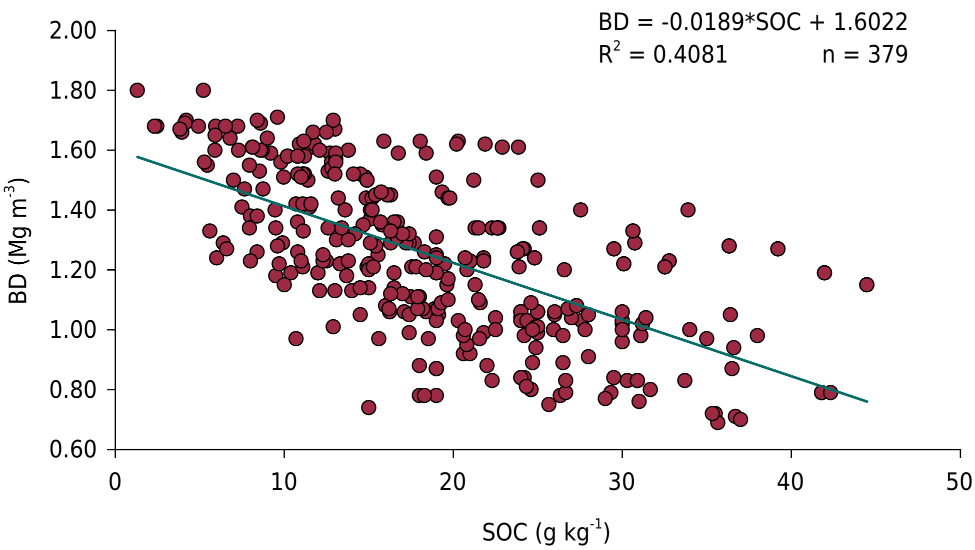

Figure 2. Correlation between soil organic C (SOC) (g kg^{-1}) and bulk density (Bd) (Mg m^{-3}) in soils from Brazilian Cerrado. r: Pearson’s correlation coefficient, statistically significant at 1 % level. n: number of samples.

did not affect the overall soil C trends significantly. Similar assumptions had been adopted in other important literature reviews and meta-analyses (e.g., Bárcena et al., 2014; De Stefano and Jacobson, 2018). Finally, studies reporting data for different sampling depths were included in more than one category.

Information on the location of the study site (municipality, state, latitude, longitude, altitude), climate (Köppen classification system, average rainfall and air temperature), soil classification (Soil Survey Staff, 2014; Santos et al., 2018), soil texture (textural class, clay, silt and sand content), land-use and management (previous use, main crop and cultivar/variety, off-season crop and cultivar/variety, cropping cycle, irrigation, mineral or organic fertilization, cropping system, tillage practice, crop residue management, crop rotation, livestock and/or forest integration) were also collected. In this sense, we considered as essential the (explanatory) variables which are important for soil C inventories or simulation of scenarios for decision-making or to support policymakers (i.e., SOC, Bd, time span, temperature, precipitation, and clay content). Finally, pooling every study plot which provided both data, we tested the linear correlation between SOC:clay and SOC:Bd for areas across Brazilian Cerrado using the Pearson coefficient (R Development Core Team, 2021).

RESULTS

Eighty-seven papers met the criteria for this systematic review, resulting in 1156 soil C stock data grouped into the four main land-uses in the Brazilian Cerrado and four sampling depths. Further, 621 data pairs were used to estimate the rates of soil C stock change in agricultural areas under CSA practices. Note that some of the studies reported data for multiple sites or more than one CSA practice. The soil depth assessed varied from 0.025 to 1.000 m, with an average of 0.408 m, and the time span of the studies ranged from 1 to 80 years, with an average of 11.9 years. The clay content varied between 10 and 762 g kg^{-1}, with an average of 421.12 g kg^{-1}.

Soil C stocks under the main land uses in the Brazilian Cerrado

Soil C stocks calculated at 0.00–0.10 m varied from an average of 37.51 ± 22.91 Mg C ha^{-1} in areas with native vegetation to 18.46 ± 9.97 Mg C ha^{-1} in areas under afforestation (Table 1). Pastures and croplands (under CSA) showed similar soil C stocks at this depth, with values ~22 % lower than those observed for native vegetation. For the 0.00-0.30 and 0.00-0.50 m soil layers, C stocks in areas under native vegetation were estimated at an average of 60.69 ± 26.56 and 86.87 ± 45.14 Mg C ha^{-1}, respectively (Table 1). For these soil layers, the differences among land-uses were smaller, with areas under afforestation and croplands featuring similar soil C stocks.

For the 0.00–1.00 m depth, native vegetation areas remain the largest soil C reservoirs of the biome. However, the average soil C stocks in croplands with CSA practices were similar to those observed in areas of native vegetation (Table 1). As discussed, areas of annual crops under CSA can potentially accumulate soil C and partly revert the C losses after native vegetation conversion. Finally, the soil with pastures resulted in a depletion of ~ 22 % in soil C stock when compared with that under native vegetation irrespective of the thickness of the soil layer used for calculations (Table 1).

Rates of soil C stock change in croplands under climate-smart agriculture in areas from Brazilian Cerrado

Based on 57 data pairs, we calculated a rate of soil C stock change of +0.49 ± 0.45 Mg C ha^{-1} yr^{-1} in the 0.00-0.10 m soil layer when NT was compared to other tillage practices (Figure 3). In thicker soil layers (i.e., 0.00-0.30, 0.00-0.50 and 0.00-1.00 m), the rates of soil C stock change in areas under NT surprisingly increased (Figure 3), reaching 1.24 ± 0.85 Mg ha^{-1} yr^{-1} in the 0.00-1.00 m layer, the highest rate

Table 1. Carbon stocks at the 0.00–0.10, 0.00–0.30, 0.00–0.50 and 0.00–1.00 m soil layers in the main land uses of Brazilian Cerrado

Land-use	Soil C stock	SD (+/-)	n
	Mg ha^{-1}		
	0.00-0.10 m		
Native vegetation	37.51	22.91	82
Afforestation	18.46	9.97	23
Cropland + CSA	29.33	12.94	187
Pasture	29.53	11.23	42
	0.00-0.30 m		
Native vegetation	60.69	26.56	159
Afforestation	53.33	39.49	35
Cropland + CSA	54.59	21.91	242
Pasture	48.59	18.01	103
	0.00-0.50 m		
Native vegetation	86.87	45.15	58
Afforestation	81.10	43.64	24
Cropland + CSA	76.60	37.50	93
Pasture	69.35	30.66	21
	0.00-1.00 m		
Native vegetation	128.77	54.98	28
Afforestation	93.02	56.25	16
Cropland + CSA	130.68	39.24	28
Pasture	99.58	47.17	15

SD: standard deviation from the mean values; n: number of areas; CSA: climate-smart agriculture practices.

observed in our estimations. With the exception of the 0.00-0.30 m layer, negative rates of soil C stock change were observed in less than 10 % of the areas under NT, indicating the positive effect suitability of this practice on increasing soil C stocks in agricultural areas of Brazilian Cerrado.

Cover cropping is also associated with overall increases in soil C stocks in agricultural areas, irrespective of the thickness of the soil layer (Figure 3). Nevertheless, when compared to other CSA practices, lower mean rates of soil C accretion were observed in areas with cover crops. For the 0.00-0.10 m soil depth, data showed a rate of soil C accretion of 0.15 ± 0.58 Mg ha^{-1} yr^{-1}, while the average rate in the 0.00-0.30 and 0.00-0.50 m soil layers was at least twofold (Figure 3), despite half of the data pairs showing negative response ratios at 0.00-0.50 m. For the deepest soil layer (0.00-1.00 m), cover crop adoption resulted in a C accretion rate of 0.54 ± 0.54 Mg ha^{-1} yr^{-1}, however, unfortunately, the available database is limited for this depth (n = 9, from only two studies).

In integrated systems, positive C stock change rates were observed for all the evaluated soil layers. When comparing C stock change rates between CL and CLF, there is a trend of higher values in areas under CLF (Figure 3). For example, at the 0.00-0.30 m soil layer, the rates of soil C change for CLF were on average more than twofold than those calculated for CL. Moreover, in the 0.00-0.10 and 0.00-1.00 m layers, negative rates of soil C stock change were not found in any of the studies evaluating CLF. Indeed, at the 0.00-1.00 m depth, the average rate of soil C stock change in CLF was 1.00 ± 1.47 Mg ha^{-1} yr^{-1}, while no study matching our criteria was found to estimate the rates of CL at this depth (Figure 3). It is worth noting, however, that the results are derived from a lower number of CLF studies (n = 6).

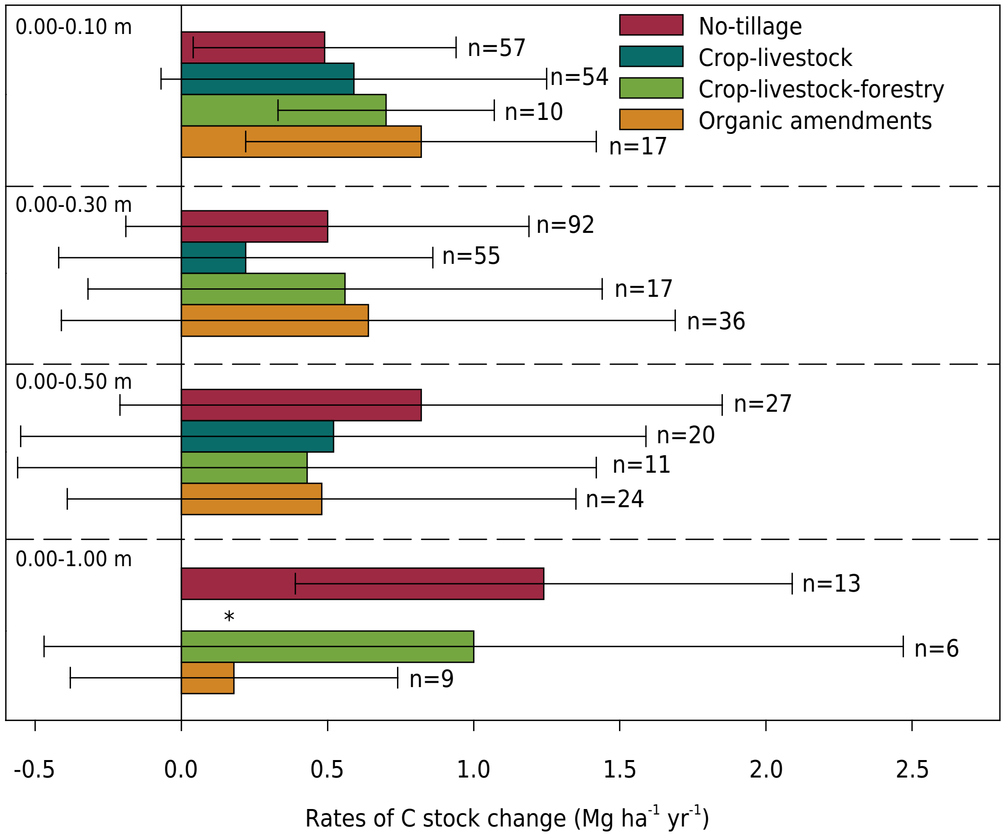

Figure 3. Rates of soil C stock change (Mg ha^{-1} yr^{-1}) in croplands under climate-smart agriculture in Brazilian Cerrado at different soil layers (0.00–0.10, 0.00–0.30, 0.00–0.50 and 0.00–1.00 m). Bars represent the standard deviation of the mean values, and "n" is the number of data pairs. *: There was no data for soil C changes in crop-livestock systems at 0.00-1.00 m depth.

Soil fertilization with organic amendments led to increases on soil C stocks in agricultural areas, regardless of the thickness of the evaluated soil layer (Figure 3). The greater average rate was calculated for the shallowest (0.00-0.10 m) soil layer (0.82 ± 0.60 Mg ha^{-1} yr^{-1}), with a clear trend of lower rates with increasing sampling depth. Despite the average positive response in studies evaluating the effects of OA on soil C accretion, 12, 39, 33 and 22 % of the data pairs assembled here showed negative rates of soil C stock change for the 0.00-0.10, 0.00-0.30, 0.00-0.50 and 0.00-1.00 m layers, respectively.

Main gaps and issues regarding soil C research in Brazilian Cerrado

Despite the satisfactory geographic distribution of study sites across the biome (Figure 1), the available data for soil C stocks were substantially fewer for some important agricultural regions. There is little information available on the effects of land-use and CSA practices on soil C stocks in MATOPIBA region (areas over the states of Maranhão, Tocantins, Piauí, and Bahia, collectively MATOPIBA), currently the main hotspot of agriculture expansion in the Brazilian Cerrado, and perhaps in the world. Moreover, there is a limited soil C database for integrated agricultural systems (mainly CLF; Figure 3), despite being one of the most encouraging strategies for the sustainable intensification of agriculture in Brazil and for achieving national greenhouse gases (GHG) emissions mitigation targets and adaptation (Brazil, 2022).

Most of the studies assembled here reported soil C stocks, but did not provide data on important ancillary/explanatory variables (Figure 4). About half of the studies did not provide the primary data on soil C concentration and bulk density, both used to calculate soil C stocks. Moreover, for more than 40 % of the areas, there is no information regarding the time of land-use change (Figure 4). Actually, a few studies provided detailed information about land-use history and management. On the other hand, most of the studies presented mean temperature and precipitation for the sites evaluated.

Surprisingly, clay content values were reported for every plot and soil depth in only 18 % of the studies (Figure 4). Pooling all available data, a significant linear correlation between organic C (g kg^{-1}) and clay content (g kg^{-1}) was observed (Figure 5). Despite being classified as a weak positive correlation (0.3< r <0.5), this observation is consistent with the general understanding that an increase in clay content is associated with greater soil C contents (e.g., Zinn et al., 2007, Singh et al., 2018). Accordingly, our assessment revealed an undesirable bias among the land-uses in studies evaluating soil C in Brazilian Cerrado. Areas under native vegetation, often used as a reference for soil C change estimations, presented, on average, lower clay contents when compared to other land-uses (Table 2). Specifically, for croplands, overall clay contents were 25 % greater than those observed in native vegetation.

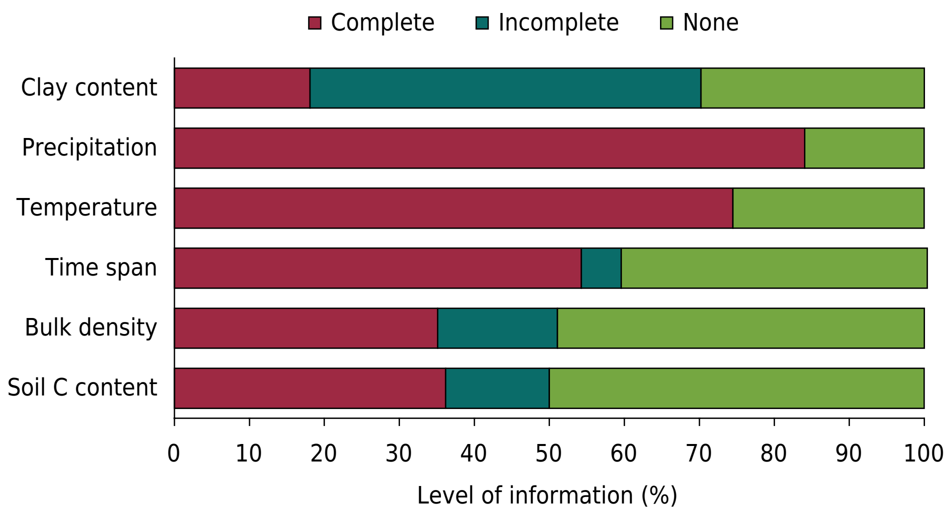

Figure 4. The lack of basic information in soil C studies across Brazilian Cerrado. Complete: available data for every evaluated plot and/or soil layer.

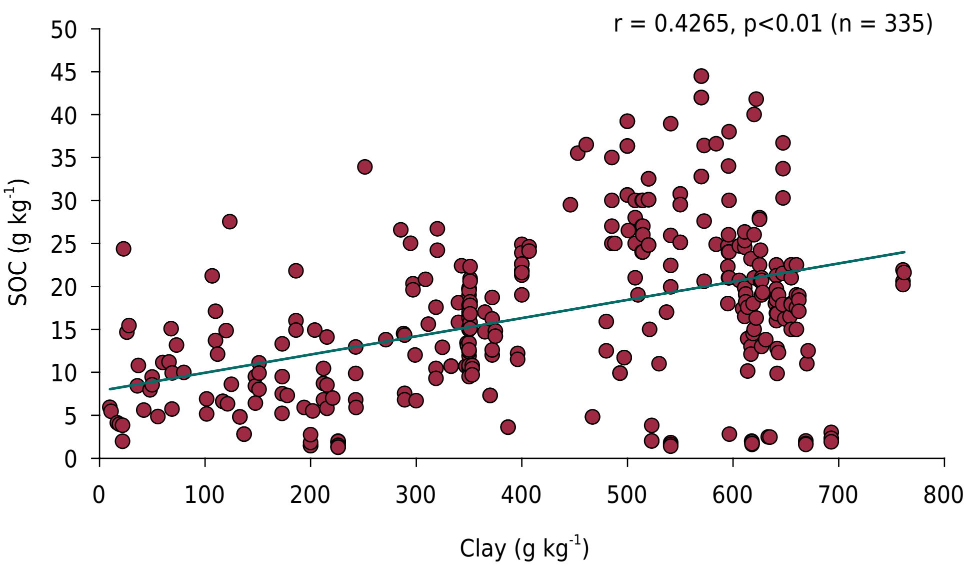

Figure 5. Correlation between clay content (g kg^{-1}) and organic C (g kg^{-1}) in soils from Brazilian Cerrado. r: Pearson's correlation coefficient, statistically significant at 1% level. n: number of samples.

DISCUSSION

Mean soil C stocks reported here ranged from 37.51 ± 22.91 Mg ha^{-1} (0.00–0.10 m) to 128.77 ± 54.98 Mg ha^{-1} (0.00–1.00 m) in areas under native vegetation in Brazilian Cerrado (Table 1). Even though Cerrado soils present, on average, smaller C stocks than other biomes in Brazil, such as Amazonia and Atlantic Forest (Gomes et al., 2019), areas under native vegetation across this biome storage large amounts of C. Our data are in line with overall estimations, in which soils of the Brazilian Cerrado contain about 24 Gt C down to 1 m depth, corresponding to an average soil C stock of 117 Mg ha^{-1} (Bustamante et al., 2006). In general, the conversion of areas under native vegetation to the evaluated land-uses in this study was associated with soil C losses (Table 1), mainly in the 0.00–0.10 m layer. This was expected since native vegetation usually stores most of the soil C in the upper layers, and generally, the conversion from native vegetation to another land-use drives soil C losses, especially in the tillage-affected upper layers (Oliveira et al., 2016; Minasny et al., 2017).

It was noteworthy that areas under afforestation had ~ 50 % less soil C in the 0.00-0.10 m layer when compared to areas under native vegetation (Table 1). In the Brazilian Cerrado, afforestation occurred mainly on degraded pastures or on marginal land with intrinsically low soil C stocks (Maquere et al., 2008; Tavanti et al., 2020). However, the deep and bulky root systems of the main tree species introduced in areas of afforestation (e.g., eucalyptus and pines) have great effects on C input and persistence at subsoil layers (Zinn et al., 2011). Accordingly, the differences between average soil C stocks in areas of native vegetation and afforestation notably reduced when assessments in deeper soil layers were included in our estimations (Table 1).

The effects on soil C stocks were fully assessed when native vegetation was converted to pasture (e.g., Assad et al., 2013; Oliveira et al., 2021), and will not be addressed in the following discussion. Despite the current efforts to recuperate pastures in Brazil (e.g., ABC and ABC+), most of the areas devoted to this land-use are currently in some level of degradation and its impacts on soil C stocks are well-known (e.g., Coser et al., 2018; Oliveira et al., 2021). Here, we found a C debt of ~ 22 % in pastures of Brazilian Cerrado when compared to our estimations for areas under native vegetation (Table 1). The climate-smart agriculture (CSA) practices discussed below are suitable options to restore soil C stocks including in land under pasture, as currently adopted in plenty of systems across the Biome.

Soil C changes in areas under no-tillage (NT) at greater depths (>0.3 m) are still a debatable topic, with studies showing positive rates only near the soil surface (e.g., Luo et al., 2010; Bai et al., 2019), others with soil C accretion in deeper soil profiles (e.g., Liu et al., 2014; Blanco-Canqui, 2021), and analysis with neutral balances or even soil C losses after adopting NT (e.g., Baker et al., 2007; Corbeels et al., 2016). In our study, the rates of soil C stock change in areas under NT increased when deeper soil layers were included in our estimations (Figure 3). Based on the currently available data, we are not able to determine the underlying mechanistic reasons for this result. However, we suggest that (i) the recent adoption of NT in areas with decades of conventional tillage, (ii) the

Table 2. Clay content under the main land-uses in Brazilian Cerrado

Land-use	Clay content	SD (+/-)	n
	g kg^{-1}		
Native vegetation	393.62	186.13	217
Afforestation	431.23	213.29	75
Cropland + CSA	493.03	176.74	458
Pasture	439.95	241.49	129

SD: standard deviation from the mean values; n: number of areas; CSA: Climate-smart agriculture.

widespread adoption of occasional tillage in NT areas and, (iii) the use of unsuitable baselines to estimate the rates of soil C changes may be associated with this pattern in areas under NT across Brazilian Cerrado.

Conventional tillage redistributes C deeper in the soil profile through the mixing action of tillage implements (Ogle et al., 2005). Moreover, NT may not necessarily add new-C (i.e., from current land-uses) into the soil, its contribution is primarily accomplished by protecting the old-C (i.e., from the previous land-uses) from decomposition (Six et al., 2000). In this sense, the greater rates of soil C accretion observed when deeper soil layers were assessed in our estimations could be associated with smaller losses of old-C, stored in subsoil because of the C redistribution during the decades of conventional tillage in most NT areas of Brazilian Cerrado.

The occasional tillage uses some method of soil preparation in NT areas aiming to reduce eventual problems associated with the absence of tillage (e.g., soil compaction, weed management and nutrient stratification) (Dang et al., 2015). In Brazil, some farmers have adopted the occasional tillage (Peixoto et al., 2020) and one of the main effects of this practice is reducing the vertical stratification of soil C (Blanco-Canqui and Wortmann, 2020). Accordingly, the occasional tillage also may be related to the increment in rates of soil C change when deeper soil layers were included in our estimations for NT areas across Brazilian Cerrado (Figure 3). Issues regarding the use of unsuitable baselines to estimate the rates of soil C changes will be properly addressed in the next topic.

Despite the lower values when compared to other CSA practices, the average rates of soil C change calculated here are in agreement with other efforts to estimate the potential of cover-crops (CC) to soil C accretion in agricultural areas. In a worldwide assessment, Jian et al. (2020) calculated a mean rate of 0.56 Mg ha^{-1} yr^{-1} with the adoption of CC. In this same study, it was observed that CC in temperate climates had greater soil C changes than those in tropical climates, in agreement with Bai et al (2019). In the Cerrado region, crop rotations are majorly composed of soybean or corn as main crops followed by a cover crop such as pearl millet or sorghum during the dry season. In this scenario, producing adequate amounts of plant residues, at least to keep the soil covered, is a very challenging goal. Accordingly, we believe that the adoption of CC by itself is not an effective option to recover the soil C stocks in agricultural areas of Cerrado. The integration with other practices, mainly NT, is mandatory to increase the rates of soil C accretion. However, few studies were carried out in areas under NT and with CC, precluding a data-based evaluation of the integration between both practices.

Available data also showed average positive rates of C change for both integrated crop-livestock (CL) and integrated crop-livestock-forestry (CLS) systems in all evaluated soil layers (Figure 3). Integrated systems are a suitable strategy for sustainable intensification of agriculture in Brazilian Cerrado, increasing food (and bioenergy) production while mitigating global warming by soil C sequestration. Moreover, CL and CLS are widely adopted practices for pasture recuperation in the Brazilian Cerrado and could contribute to partially recovering the soil C stocks in areas of extensive cattle raising under degradation. Currently, about 18.2 Mha of pastures are at some level degraded across Brazilian Cerrado (Pereira et al., 2018).

Regarding the overall higher rates of soil C stock change in areas under CLF when compared to CL (Figure 3), we believe that it is an effect of the intercropped trees, as pointed out by Le Bissonnais et al. (2017) and Shi et al. (2018). Besides the high amount of litter inputs provided by the natural senescence of leaves, the main tree species introduced in areas of CLF in Brazilian Cerrado have deeper and broader root systems, with positive effects on soil C accretion and stabilization (Zinn et al., 2011). Another possible reason for this positive effect of CLF is that trees require a minimum of six to seven years to be managed (e.g., eucalyptus for pulp production), and annual crops are usually restricted to the first two years followed by at least four to five years of pasture that are more tolerant to shade. In contrast, in CL systems annual crops are likely more frequent (50 % of time), reducing the influence of pasture on soil C inputs. Productive pastures generally promote higher soil C stocks than annual crops (Carvalho et al., 2014).

When compared to CLF, tillage operations, even occasionally, are more frequent in areas of CL and its effects on the rates of soil C changes have been discussed earlier. Finally, in the 0.00-1.00 m layer, the average rate of soil C changes in CLF areas was 1.00 ± 1.47 Mg ha^{-1} yr^{-1} (Figure 3). Such a high rate should be considered with caution, since substantially fewer data were available to CLF areas at this depth (n = 6). Clearly, for Brazilian Cerrado, more studies on the impact of integrated systems in the soil C balance are required, and these should include deeper soil layers (at least down to 1.0 m).

Despite some negative soil C stock change rates, soil fertilization with organic amendments (OA) led to overall increases in soil C stocks in agricultural areas of Brazilian Cerrado (Figure 3). This effect was also observed by other studies worldwide (e.g., Maillard and Angers, 2014). The higher soil C stocks in these areas are associated with the direct C input by the OA itself and the indirect C input through increasing crop production (Bhattacharyya et al., 2010). The effects of OA on crop yield are well-established, being related to the high amounts of nutrients they introduce into the system, mainly N (Oliveira et al., 2017). Farms dedicated to the production of poultry, swine and beef feedlot are common in the Cerrado region owing to the abundance of grains for feeding. Accordingly, integrating these sectors would be a win-win strategy by accumulating C into the soil, saving possible GHG emissions associated with the use of synthetic N fertilizers, and decreasing the C footprint of Brazilian meat as well.

Unfortunately, most of the studies assembled here focused on the effects of a single CSA practice on soil C stocks, with very few research estimating the combined effects of the integrated management options on soil C accretion, limiting any analysis regarding the interactions between the CSA. However, we believe that combining CSA might potentially enhance C accumulation in agricultural areas of Cerrado. To mention but a few, we suggest the adoption of NT in areas with CC and/or CL as a strategy for a more positive soil C balance in these systems, as well the diversification (e.g., CL or CLF) of areas under OA application to deal with the lower effect of this practice on the rates of C change at deeper soil layers. Nevertheless, more field experiments are still needed to support these possible synergistic effects.

The rates of soil C change from figure 3 were calculated using a simplistic approach, which is an arithmetic average among the studies. It did not take into account the temporal or spatial variation of the dataset; different studies were given the same weight and the plot size or the number of repetitions was not considered. The lack of required data in the studies (raw values for each replication, number of replications, standard deviation, etc.) does not allow us to do so. Accordingly, unfortunately, we cannot state whether the mean values are statistically significant and this is beyond the scope of this research. The data presented in figure 3 aim to show the likely direction and relative magnitudes of soil C changes after the adoption of CSA practices. Such data must be viewed with discretion. Our results are promising; however, we must be cautious in stating that soil C sequestration occurs at those rates after the adoption of CSA practices across Brazilian Cerrado.

Another possible limitation of our assessment is the fewer data available for some important regions, mainly MATOPIBA (Figure 1). MATOPIBA is an area of ~73 million hectares where large extensions of native vegetation have been converted to agriculture in the last decades (Zalles et al., 2019). Besides higher temperatures and lower precipitation, most of the soils in MATOPIBA have low clay content and consequently low C stocks (Donagemma et al., 2016). Accordingly, soil C dynamics following the land-use change and management are supposed to be quite different when compared to other regions of Brazilian Cerrado. In this sense, new efforts are needed to quantify and elucidate the effects of CSA practices on the low soil C stocks of MATOPIBA.

The great diversity of soil types, land-uses, and management practices in agricultural areas of Cerrado call for as many studies as possible to be included in any overall estimation, even though not all studies provide the full set of parameters, as observed in our assessment (Figure 4). In this sense, we advocate that the exclusion of studies without some basic information could result in less reliable and robust estimations, besides drastically reducing the dataset assembled here. However, it is mandatory to provide some important ancillary/explanatory variables in studies evaluating the effects of land use and soil management on C balance. Most of the conclusions and extrapolations based on these data, very useful for, for example, C inventories and climate policy, will depend on the provision of the primary data as those from figure 4.

Only half of the studies reported soil organic C (SOC) and bulk density (Bd) for every plot and depth evaluated (Figure 4). Moreover, some authors reported SOC but not provided values for Bd. Since Bd is required to calculate soil C stocks, we had to estimate Bd from a function based on correlations between SOC and Bd using reported values (Figure 2). Despite being widely used in similar efforts (e.g., Poeplau and Don, 2015; Jian et al., 2020), we are sure that this process includes additional uncertainty in our results. In this sense, we strongly recommend that SOC and Bd should be reported for every plot and depth evaluated in future studies.

We recognize the convenience of presenting only the C stocks for the whole soil profile, but most inventories and modeling studies need SOC and Bd data for every sampled soil layer. Recognizing the importance of these efforts to draw overall conclusions about the effects of land use or management practice on the soil C balance, and also on climate policy, we ask colleagues to include the primary dataset at least in the supplementary material (data for every site, plot, and replication). Likewise, it is important that studies report the time span since the adoption of a practice whenever possible. This information is crucial to estimate the rates of soil C change associated with land use. Finally, we also encourage the authors to provide detailed information on land use history and management practices.

A significant linear correlation between SOC (g kg^{-1}) and clay content (g kg^{-1}) was observed in soils across Cerrado (Figure 5). Correlations between clay content and soil C are expected, at least in soils of similar mineralogy (e.g., Zinn et al., 2007, Singh et al., 2018). The adsorption of C on the clay surface makes it less available for microbial decomposition (Zinn et al., 2007). Moreover, by binding soil C into soil aggregates, a physical barrier is formed between decomposers and soil C, which decreases water and oxygen availability for decomposition (Six et al., 2000).

Clay content is an important explanatory environmental parameter for soil C dynamics. In this sense, we found very concerning the fact that areas under native vegetation, often used as a reference for soil C change estimations, presented, on average, lower clay contents when compared to other land uses (Table 2). In this scenario, differences among land-uses and CSA could be influenced by variations in clay content, which would affect the magnitude of responses on the effect of agricultural practices on soil C.

Most studies evaluating soil C dynamics across Cerrado adopted a chronosequence or synchronic approach, where soil C stocks were measured in areas under different land uses or CSA, including a reference, often areas under native vegetation. In this approach, areas sampled are supposed to be located adjacent to each other, minimizing differences in climatic, topographic, and soil properties. However, as observed in our assessment (Table 2), fine-scale spatial variability of clay content could bias the rates of soil C changes in studies that adopted a chronosequence approach (Fearnside and Barbosa, 1998). As rule of thumb, areas less suitable to agriculture (i.e., low clay content and nutrient availability, sloppy or of high soil acidity) are usually spared as legal reserves of native vegetation to comply with the Brazilian Forest Code. In this sense, in chronosequence studies, soil properties under native vegetation and under other land uses could be slightly different, thus increasing the uncertainty associated with estimations of soil C stock changes.

Chronosequences will continue to be used because there are no long-term field experiments for most land use change and CSA scenarios in Cerrado. This clearly emphasizes the importance of documenting the ancillary/explanatory variables as those from figure 4 for every plot and depth evaluated in studies about soil C dynamics. Such information could be very useful to validate the chronosequences. Finally, we suggest a maximum difference of 5 % in the clay contents among land uses to minimize the influence of texture on the estimations of soil C changes in agricultural areas using the chronosequence approach. However, field experiments are still needed to support this claim.

FINAL REMARKS AND THE WAY FORWARD FOR RESEARCH

All CSA practices evaluated in our estimations for Brazilian Cerrado (no-tillage, cover cropping, crop-livestock systems, crop-livestock-forestry systems, and soil fertilization with organic amendments), showed average positive rates of C stock change, indicating a general tendency of soil C accretion after the adoption of these practices in agricultural areas, irrespective of the soil depth evaluated (Figure 3).

Unfortunately, most of the studies assembled here reported soil C stocks without presenting some very important information. We suggest the colleagues provide all data available (e.g., soil C content, bulk density, clay content) for every site, plot, replication, and depth evaluated as supplementary material. Detailed information would represent a major improvement in inventories, meta-analysis or simulation (modeling) efforts to draw general conclusions and support policy makers, for example. Also, for a sound comparison, soil C changes after CSA adoption should be determined using the prior land-use or management as baseline, such as the suggestions from table 3. Several studies adopted the native vegetation as baseline and we believe this is not a realistic reference for evaluating the effects of CSA practices on soil C recovery in scenarios with several land use and management changes.

Despite the limitations discussed above, diversification and intensification of agricultural areas in the Cerrado by the adoption of CSA is a promising pathway to increase soil C stocks, and consequently, contribute to climate change mitigation and adaptation (Figure 6). Furthermore, soil C sequestration enhances soil health, as well as the provision of other soil-related ecosystem services (Paustian et al., 2016; Smith et al., 2019), with indisputable effects on crop yield, increasing or stabilizing the production of food, feed, fiber and energy. The rates of soil C change could be greater or less than estimated here, but our findings emphasize the importance of efforts that stimulate farmers to adopt these practices on large scale, such as ABC and ABC+ Plan, besides providing sound empirical evidence about the role of soil C sequestration to Brazil achieving its NDC commitments (Brazil, 2022).

Although the positive effects on soil C accretion, we are aware that CSA practices assembled here may alter nitrous oxide and/or methane emissions (e.g., Guenet et al., 2021; Lugato et al., 2018), which, to some extent, would offset its benefit on climate change mitigation. For a comprehensive assessment of soil C sequestration, net C

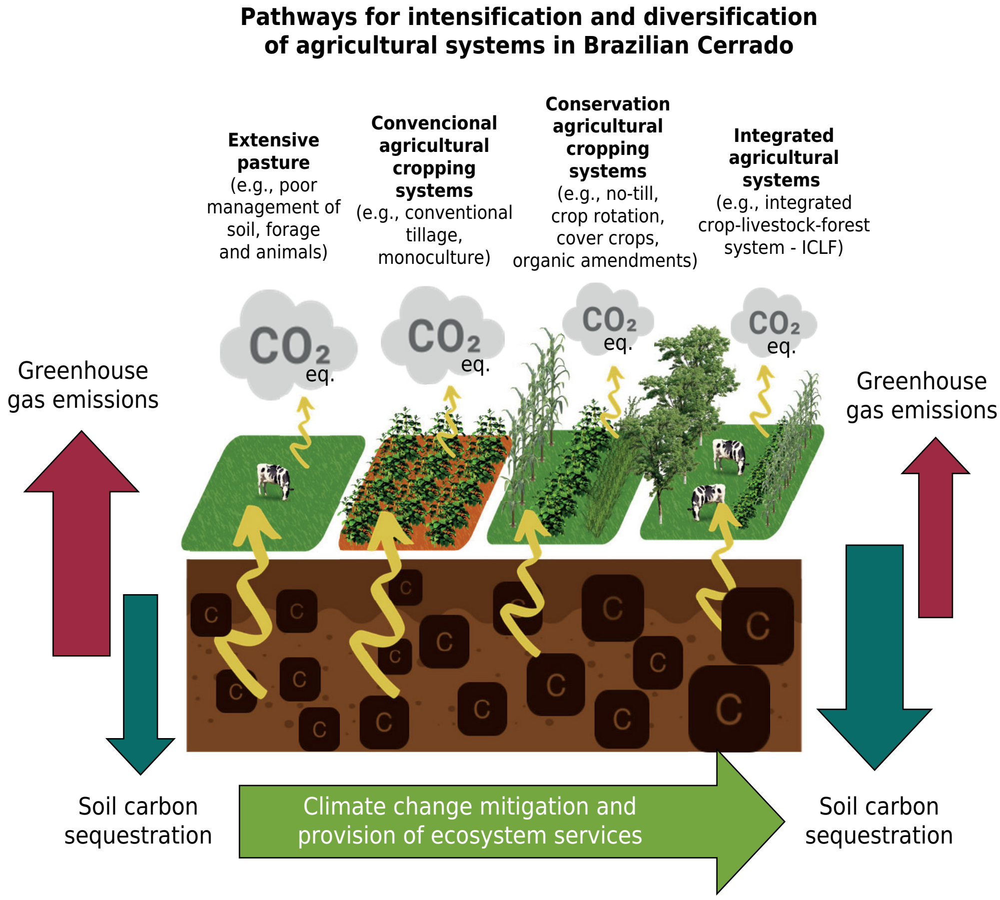

Figure 6. Conceptual framework of soil C sequestration and some of its additional benefits in areas of Brazilian Cerrado under climate-smart agriculture practices.

Table 3. Suggested baselines for soil C sequestration assessment after the adoption of climate-smart agriculture practices

Climate-smart agriculture practice	Suggested baseline for soil C sequestration assessment
• No-tillage	• Area under conventional tillage
• Cover cropping	• Monocropping area and/or fallow
• Crop-livestock systems	• Monocropping area or degraded pasture
• Crop-livestock-forestry systems	• Monocropping area or degraded pasture
• Organic amendments	• Non-fertilized area or mineral fertilization

accounting is needed, which also considers the GHG emissions associated with a CSA practice. In our assessment, only 11 studies evaluated the net C accounting. More research evaluating the effects of CSA practices on GHG emissions is crucial. Finally, we also suggest future investigations regarding mechanisms of C stabilization and possible C gaps and saturation in areas of Brazilian Cerrado, including deeper soil layers.

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