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Carbon Soil Storage and Technologies to Increase Soil Carbon Stocks in the South American Savanna

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Abstract: The expansion of the agricultural frontiers that occurred in the last decades in the South American savanna (*Cerrado*), the second-largest biome in Brazil (covering an area of 204 million hectares), has accounted for a substantial portion of South America's CO_2 emissions. In this context, our research investigated the potential for soil carbon storage in the biome. The analysis of previous data (n = 197) shows a vertical distribution pattern of soil carbon stock: 26.17% for the upper 0–30 cm layer, 37.67% for the 30–100 cm layer, and 36.15% for the 100–200 cm layer. The total soil carbon storage for the biome is 13.5 $\pm$ 6.7 gigatons (n = 71) for the upper 0–30 cm layer, 30.5 $\pm$ 18.9 Gt (n = 64) for the 0–100 cm layer, and 47.8 $\pm$ 4.3 (n = 9) for the 0–200 cm layer. The results indicate that the soil carbon stock up to 1 m deep in the *Cerrado* ranges from 0.5% to 2.29% of the global soil organic carbon storage for this depth. Further research is necessary to investigate what happens at a depth of at least 2 m. The results also indicate that the soil under pasture lands constitutes the largest manageable pool for increasing soil carbon stocks via the restoration of degraded pastures.

Keywords: soil carbon stocks; south american savanna; cerrado; land-use change; landcover

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1. Introduction

Carbon dioxide (CO_2) is the anthropogenic greenhouse gas with the highest impact on climate change. The level of atmospheric CO_2 concentration has increased significantly since the pre-industrial era (>145%) [1,2]. Between 2007 and 2016, agriculture, forestry, and land-use change were responsible for 23% of total CO_2-equivalent emissions in the atmosphere worldwide [3]. Land-use and land-use change include several mechanisms (e.g., forest burning, deforestation, soil degradation, conversion of native vegetation for agricultural purposes) that lead to changes in soil carbon stock in both above and below-ground biomasses.

In this context, Brazil is an exemplary case of the impact of CO_2 emissions caused by land-use and land-use change. It is currently one of the world's largest greenhouse gas emitters (~2 gigatons of CO_2-eq per year). The expansion of the agricultural frontiers that has occurred in the Brazilian savanna and Amazon Forest accounts for a large portion of South America's CO_2 emissions. For instance, the South American savanna, also known as "*Cerrado*" used to cover an area of 204 million hectares (Mha) spanning across 12 Brazilian states. Due to having ideal conditions for high yield agricultural fields and pastures, it is now reduced to about 80 Mha (approximately 35% of its original coverage) [4,5].

The most recent Brazilian greenhouse gas emissions (GGE) inventory showed that the country emitted 1.47 Gt of CO_2-eq in 2016. Deforestation, degradation, or conversion of natural vegetation for agricultural use are responsible for 60% of total emissions. Although emissions due to land-use change decreased from 2.6 Gt of CO_2-eq in 2004 to 0.39 Gt of CO_2-eq in 2016, greenhouse gas emissions caused by agricultural activities have increased in Brazil in the recent past—from approximately 0.32 Gt of CO_2-eq in 1990 to 0.48 Gt of

CO_2-eq in 2016—primarily due to the growth in livestock production and agricultural management. The impact of land-use changes and agricultural activities in the last five years is unknown, as no official report has been published during this period [6].

In agricultural crops, soil emissions are partly offset by plants adding carbon to the soil. The best way to assess whether the soil is functioning as a carbon sink or source is to understand the dynamics of soil carbon stocks. The main questions regarding the capacity of soil carbon stocks [7] are: How much CO_2 can be sequestered by the soil in each of the world's ecosystems, and how long does it remain there? Does an increase in the net primary production of the system (due to higher atmospheric CO_2 concentrations and anthropic activities, e.g., nitrogen fertilization) lead to increased litter production and, consequently, carbon stock in soils?

As with other types of biomes, the *Cerrado* soils are impacted by a complex combination of several variables, e.g., organic carbon content, mineralogy, natural vegetation, climate, latitude and longitude, land-use, and agriculture management. In this light, this study aims to (i) characterize and discuss soil carbon stocks for different land-uses and land covers in the *Cerrado* region; (ii) summarize key questions and provide guidelines for future research in this field, and (iii) organize currently available data assessing the impact of agricultural management and land-use changes on soil carbon stocks at different soil layers. To this end, we have collected data on soil carbon stocks in the *Cerrado* from articles, academic theses, and technical reports. To the collected data the following specific questions were posed:

1. How much carbon can be sequestered by the soil in the *Cerrado* biome? What is its largest manageable carbon pool?
2. What current agriculture technologies and land management models are capable of increasing soil carbon stocks in the *Cerrado* biome?
3. What type of its native vegetation can store the most carbon in the soil?

2. Material and Methods

2.1. Study Area

The *Cerrado* is a mosaic of varied vegetation and gradients of wood coverage and height, ranging from forest to grassland [8,9]. Located at the geographic center of the South American continent, it is contiguous to different biomes, e.g., the Amazon Forest, *Caatinga* (sparse forest leafless in the dry season), Atlantic Forest, *Pantanal* (wetlands), and the Atlantic Ocean (by a thin strip of land in the north of the country). Mostly composed of woodland savanna, its vegetation is distributed among several different types (e.g., wet and dry grasslands, shrublands, and forests), which are home to the largest number and diversity of species among the world's savannas [10].

Different patterns of biomass accumulation and distribution occur in the *Cerrado* region, which can be divided into three categories and eleven phytophysiognomies [11]: grasslands (*campo limpo*, *campo sujo,* and *campo rupestre*), shrublands (*stricto-sensu cerrado*, park savanna, palm land, and *vereda*), and forestlands (riparian, gallery and dry forests, and *cerradão*). Carbon storage calculation in the *Cerrado* biome is based on carbon present in the soil and plants, which may be divided into four pools: aboveground biomass (living trees, shrubs, and grasses); necromass (fallen leaves and wood litter); belowground biomass (roots); and soil carbon [12,13].

As to the aboveground and belowground biomass throughout the *Cerrado* biome [14], the mean values found for each category of vegetation types are 113.36 Megagrams/hectare (Mg/ha) for forestlands (18% percent as belowground biomass), 60.71 Mg/ha for shrublands (58% percent as belowground biomass), and 26.39 Mg/ha for grasslands (70% as belowground biomass). However, these values should be analyzed with caution, as the above variation may reflect the natural environmental heterogeneity of these vegetation categories and their physiognomies as well as the use of different sampling methods [14].

Owing to its geographic extent, geology diversity, and proximity to other tropical biomes (Figure 1), the *Cerrado* exhibits a complex combination of edaphoclimatic and ecological determinants [15], which impact the carbon dynamics in its soil and biomass.

Another important factor is the ease with which some types of the *Cerrado* vegetation regularly and naturally burn during the dry period, resulting in seasonal changes in its carbon stocks.

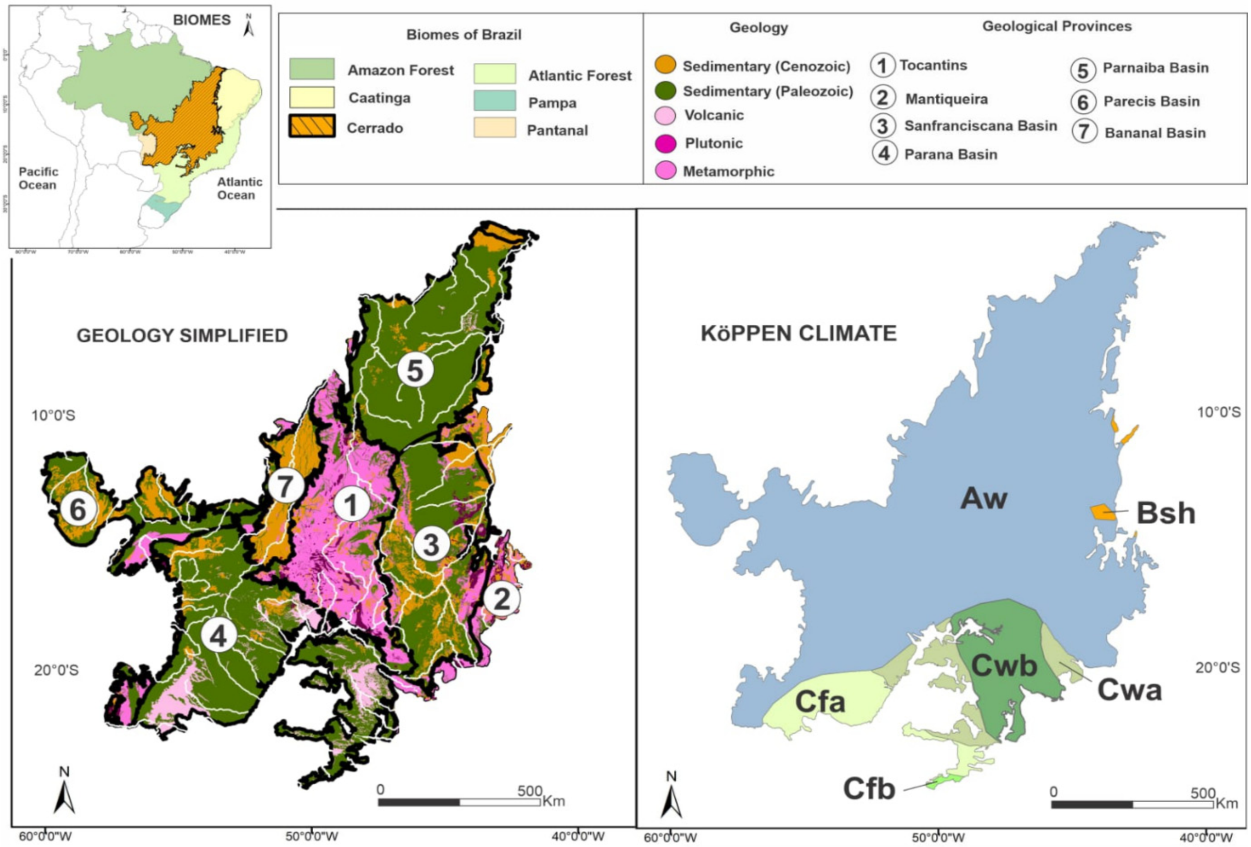

Figure 1. Map of the six Brazilian biomes [16], *Cerrado*'s geology and geological provinces [17], and Köppen [18] climate zones.

A tropical humid climate predominates in the *Cerrado* (Figure 1), with average temperature above 18 °C throughout the year, a dry season lasting from 3 to 6 months between April and September, and a rainy season with an average annual rainfall ranging from 700 to 1.400 mm yr^{-1} (*Aw* according to the Köppen climate classification). The climate in the southern area of the biome, where the temperature falls below 18 °C during the coldest month, is classified as *Cwa*, *Cwb*, *Cfa*, and *Cfb*. In small areas bordering the Caatinga biome, the average annual rainfall is under 500 mm yr^{-1}, with average temperatures above 18 °C throughout the year (*Bsh* according to the Köppen climate classification).

The regional geology (Figure 1) of the *Cerrado* biome comprises seven geological provinces and basins: Tocantins, Mantiqueira, Parnaíba, Sanfranciscana, Paraná, Parecis, and Bananal. These areas constitute a complex mosaic of different kinds of rocks of different geological ages (Figure 1). In its central area and eastern edge, crystalline rocks (metamorphic, igneous, and volcanic) from neoproterozoic shields prevail (Tocantins and Mantiqueira provinces). Four Paleozoic sedimentary basins occupy a vast area of the *Cerrado*, two of which are located in the E-NE (the Parnaíba and Sanfranciscana basins), and the remaining two in the W-SW (the Paraná and Parecis basins). Cenozoic sedimentary deposits are found in several provinces, with the most prominent being the Quaternary alluvial plain deposits that make up the Bananal Basin [19].

The *Cerrado* relief in the Paraná and Parecis Paleozoic basins is mainly composed of plateaus. The geomorphology in the Sanfranciscana and Parnaíba basins is predominantly characterized by the presence of plateaus and vast depression areas, whereas the relief in the Tocantins province (center) comprises mostly mountain ranges and plateaus (south) and depressions (north).

The main soil class in the *Cerrado* biome [20], according to the Brazilian Soil Classification System [21] and an approximated agreement between WRB [22] and USDA Soil Taxonomy [23,24], is *Latossolos* (Ferralsols [22]; Oxisols [23,24]), covering 45% of its area. It is followed by *Neossolos Quartzarênicos* (Arenosols [22]; Quartzipsamment [23,24]) and *Argissolos* (Acrisols, Lixisols, and Alisols [22]; Ultisols [23,24]) found in 15.2% and 15.1% of its area, respectively. Other minor occurrences are *Plintossolos* (Plinthosols [22]; Plinthic sub-group [23,24]), Lithic Neosols (Leptosols [22]; Lithic... Orthents and Lithic . . . Psamments [23,24]), and *Cambissolos* (Cambisols [22]; Inceptsols [23,24]), covering 9%, 7.3%, and 3.1% of its area, respectively. Rarer hydromorphic soils in the biome are *Gleissolos* (Gleysols [22]; Entisols [23,24]) and *Organossolos* (Histosols [22–24]), covering about 2.5% of the total area (Figure 2).

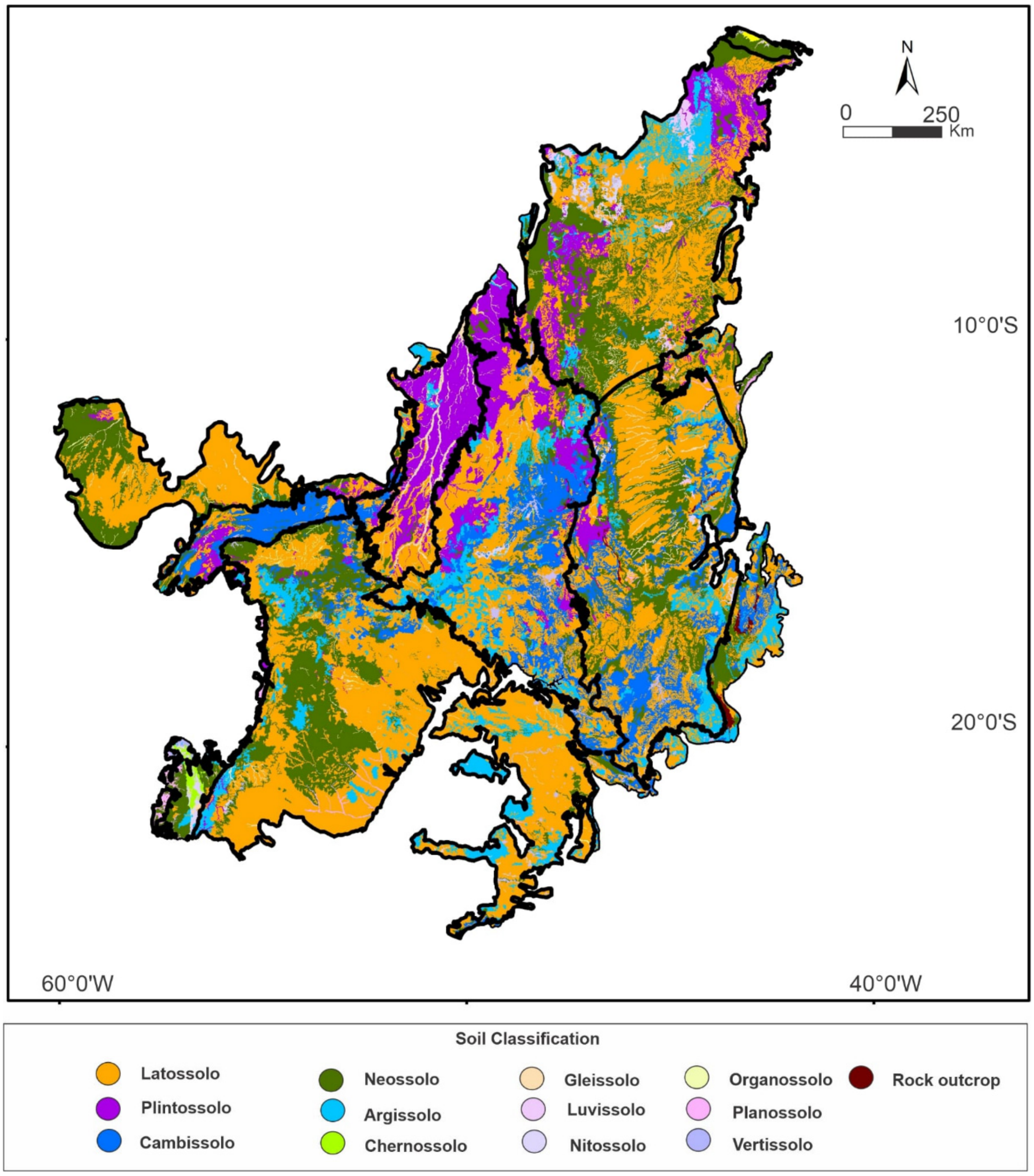

Figure 2. Soil map of the *Cerrado* region [25].

2.2. Methods

A systematic survey for peer-reviewed articles and datasets on soil carbon stocks in the *Cerrado* region was conducted in technical reports, academic theses, and the relevant literature (Supplementary Material Table S1). These data were sorted and organized according to the depth of the soil carbon stocks (0–20 cm, 0–30 cm, 0–40 cm, 0–60 cm, 0–100 cm, 0–200 cm) as well the land-use and cover where they were measured. In addition, we analyzed the impact of agricultural management for every soil layer with carbon storage reported in the sources.

Although some authors opted for depths of 0–5 cm, 0–10 cm, and 0–50 cm, the above distribution of soil depths provides the largest amount of available data on carbon stocks. For this reason, information from those studies has been discarded. Each sample site was considered individually in the statistical analyses. In total, we analyzed 197 sampling points (41 sources with 1 to 12 sampling points each). In order to standardize the procedure, all the collected data on types of land cover vegetation have been categorized under forestland, shrubland, grassland, and wet grassland. In the *Cerrado*, wet grasslands have groundwater near or above the surface for most of the year (8 months or more). All information on land-use and agricultural land management was classified as tillage, no-tillage, planted forest, agroforest, pasture, and perennial crops.

As most sources (articles, reports, theses, and datasets) do not provide information or provide incomplete information on all the layers, we used a different amount of data for each soil depth, land cover or land-use. When providing an analysis of the evolution of carbon stocks over time (diachronic approach), we used only the most recent available data. Most of the sources make use of chronosequences (synchronic approach). When the analyzed data provided the means of several points, we used the mean values. The data used in this research was from eight Brazilian states: Goiás (GO), Bahia (BA), Minas Gerais (MG), Mato Grosso (MT), Mato Grosso do Sul (MS); São Paulo (SP), Maranhão (MA), and Distrito Federal (DF).

The fact that different methodologies have been used to determine soil carbon stocks in the *Cerrado* can hinder comparisons among data from different sources. Wet combustion methods, such as Walkley–Black and its modifications, while being more accessible, have the disadvantage of employing toxic reagents (such as Cr^{6+}) and measuring just organic carbon, thus underestimating the amount of carbon in the soil. For this reason, a correction factor of 1.32 is usually applied. Also, the estimate that only 60–85% of the organic carbon is oxidized depends on the mineralogy, aggregation, clay content, and quality of organic matter in the soil [26].

The wet combustion method employs a digestion mixture of soil, potassium dichromate ($K_2Cr_2O_7$), and sulfuric acid (H_2SO_4). Then, phosphoric acid (H_3PO_4) and diphenylamine are added; excess dichromate is titrated using ammonium ferrous sulfate [Fe $(NH_4)_2(SO_4)_2 6H_2O$)] (Mohr's salt). Modified methods, e.g., Melbius, use external heat to boost oxidation [26]. Sixteen sources use Walkley–Black or modifications of this method, but some of them do not have clear procedures. The standard formula for Walkley–Black is [27]:

$$\mathrm{OC} = \left[\left(1 - \frac{Va}{Vb}\right)(10)(0.003)(1.2987)(100)\right] / P_{sw} \tag{1}$$

where: OC (g kg^{-1}) = organic carbon; Vb = volume of ferrous sulfate used in blank titration (mL); Va = volume of ferrous sulfate used in sample titration (mL); 10 = volume of dichromate added; 0.003 = C equivalent (mg); 1.2987 = method recovery factor; P_{sw} = soil sample weight (mg).

In three sources (ten sites), the soil carbon stocks were measured using the Yeomans–Bremner method, a variation of Walkley–Black. Yeomans–Bremner assumes the reduced dichromate to be equivalent to the organic carbon in the sample. The difference between Melbius and Yeomans–Bremner is that the former uses an external heat of 100 °C and latter an external heat of 170 °C [26,27].

At all other sites, C contents were determined by dry combustion using an elemental analyzer (CNHS/O). The elemental analysis method is the standard method for determining soil carbon content as it enables fast measurement of soil carbon. However, it is costly when compared to the aforementioned methods. The soil is placed in a capsule and combusted at >900 °C, thus enabling the measurement of organic C, refractory C (e.g., charcoal), and inorganic carbon (carbonates) [27].

Accordingly, soil carbon stocks (SCS) were calculated using carbon content and bulk density as per the following formula [28]:

$$SCS = C * Bd * Lt \tag{2}$$

where: SCS = soil carbon stock (Mg ha^{-1}); C = C content (g kg^{-1}); Bd = bulk density (g cm^{-3}); Lt = soil layer thickness (cm)

3. Results and Discussion

3.1. Total Soil Carbon Stocks to Cerrado Area, Agricultural Land, and Native Vegetation

Considering all available data (Supplementary Material Table S1), the mean carbon stocks for the *Cerrado* biome are 49.5 Mg ha^{-1} (coefficient of variation = 43%) for the 0–20 cm depth, 68.1 Mg ha^{-1} (CV = 50%) at 0–30 cm, 84.5 Mg ha^{-1} (CV = 56%) at 0–40 cm, 134.6 Mg ha^{-1} (CV = 65%) at 0–60 cm, 166.1 Mg ha^{-1} (CV = 62%) at 0–100 cm, and 260.1 Mg ha^{-1}. (CV = 9%) at 0–200 cm. The lower coefficient of variation at 0–200 cm depth as compared to those at other depths can be explained by the lack of information on carbon stocks at this depth. The carbon stocks of the total sites, the agricultural land sites, and the native vegetation sites are shown in Figure 3.

Given the sum of urban areas, bare soils, mining areas, waterbodies, and non-observed sites being equal to 5.5506 Mha within a total of 203.9 Mha corresponding to the *Cerrado* [29], we assumed an area equal to 198.3 Mha for calculating total carbon stocks. The total soil carbon stocks (calculated by the means of the total data) for the *Cerrado* biome are 9.9 ± 4.2 Gt (n = 138) and 13.5 ± 6.7 Gt (n = 71) for the upper 0–20 cm and 0–30 cm depth layers, respectively. Subtracting 7.3% of the *Cerrado* land composed of *Neossolos litólicos* (no deeper than 0.3 m) results in a total area of 183.8 Mha for 31–200 cm depth; then, the total carbon storage is equal to 15.5 ± 8,7 Gt at 0–40 cm depth (n = 80), 24.7 ± 16 Gt at 0—60 cm (n = 40), 30.5 ± 18.9 Gt at 0–100 cm (n = 64), and 47.8 ± 4.3 at 0–200 cm (n = 9).

Global soil organic carbon at 0–1 m depth is estimated at 1462–1548 Gt plus 695–745 Gt of inorganic carbon [30]. In the *Cerrado*, the carbon stock at 1 m depth represents 0.5–2.29% of the global soil carbon storage at this depth. Refractory carbon (charcoal) may play an important role in the *Cerrado* because of the seasonal burns that naturally occur in the biome. Notwithstanding, the content of charcoal-derived carbon and how long it lasts in the soil are unknown because its resistant forms cannot be properly quantified with current methodologies. The carbon stocks of the total sites, the agricultural land sites, and the native vegetation sites are shown in Figure 3.

In most cases, it was possible to categorize each land-use using the adopted classification, except for one case [31] in which the land-use in two of its sites was classified as rainfed and irrigated crops. Only two sources present data from areas outside the main *Cerrado* region [32,33]. In these cases, the local vegetation is typical of the *Cerrado* biome, which can also occur in areas outside its legal boundary as isolated patches inside other biomes [14], as a result of local edaphoclimatic variability (e.g., soil, dry period, naturally occurring fires, etc.).

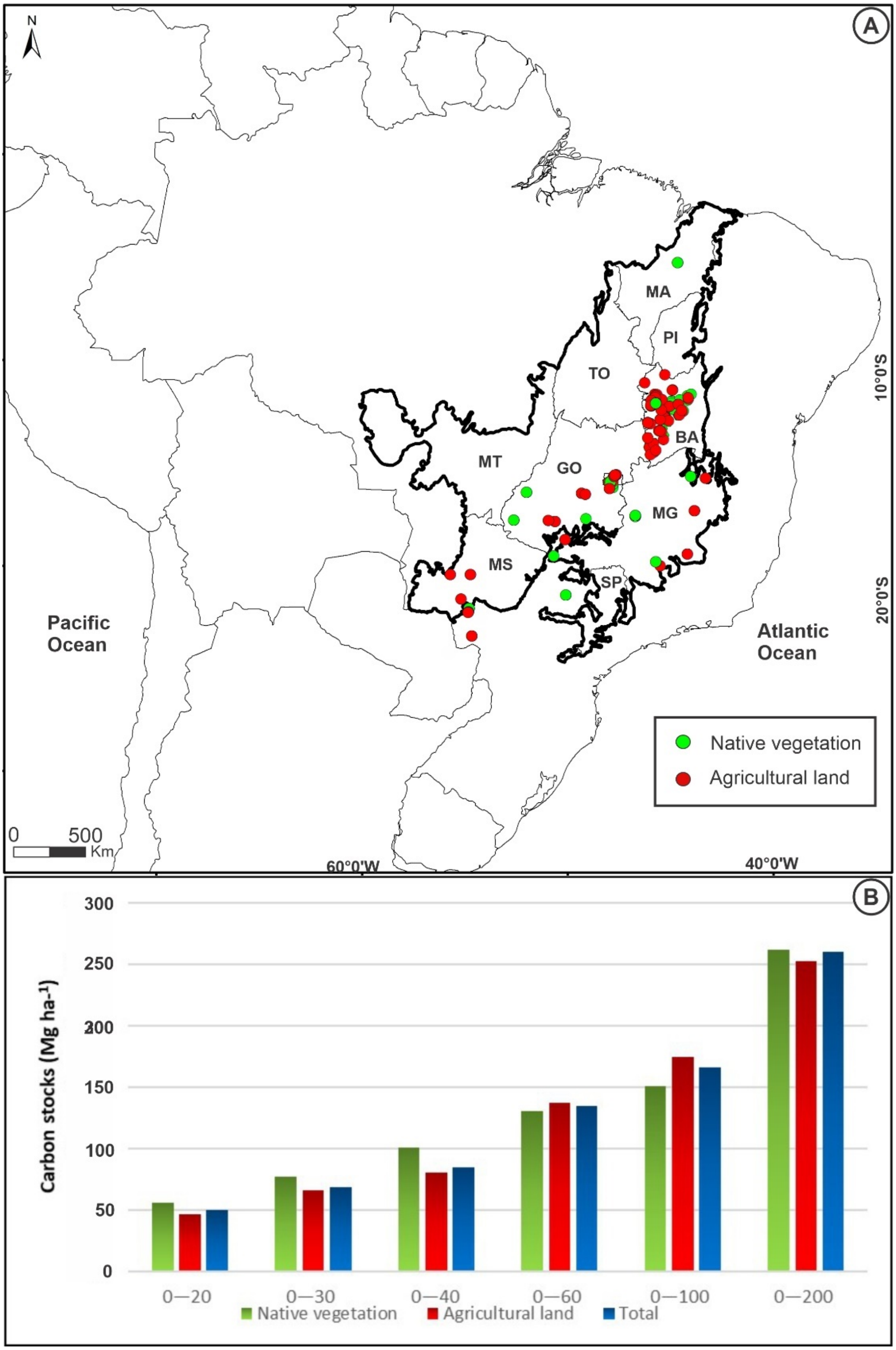

Figure 3. (**A**) Locations of the sampling sites; (**B**) mean values of soil carbon stocks for total sample points, agricultural land, and native vegetation.

The largest number of sources used in this research provide data on agricultural lands and superficial layers. The few studies that focus on native vegetation usually provide data for deeper layers of soil. Since information on soil carbon stocks in agricultural lands below 100 cm depth is lacking, further research on the dynamics of carbon stocks in the deepest layers in response to soil management, land-use change, or even climatic change is necessary. Table 1 shows the number of sites for each depth and land-use.

Table 1. Soil carbon stocks in *Cerrado* biome.

Land-Use	Soil Layer	Number of Sites	Min	Mean	Max	CV (%)
Native vegetation				Mg ha^{-1}		
	0–20	44	16.2	55.7	123.8	49.4
	0–30	17	21.7	77.0 a	178.2	60.3
	0–40	18	28.9	100.7 a	208.9	54.4
	0–60	16	50.4	130.3 a	278.1	60.6
	0–100	22	54.6	150.4 a	414.4	124
	0–200	8	230.0	261.2 a	297.0	9.3
Agricultural land						
	0–20	94	16.1	46.7	112.2	43.7
	0–30	54	23.5	65.5 a	162.5	45.5
	0–40	62	29.6	79.9 a	212.8	115.7
	0–60	24	36.8	137.3 a	303.7	82.4
	0–100	42	51.7	174.0 a	466.1	118.7
	0–200	1	252.0	252.0 a	252.0	

CV: coefficient of variation. Means for the same soil depths followed by the letter a are not significantly different at $p < 0.01$ (Mann–Whitney test).

The lowest value (Table 1) for soil carbon stocks at both 0–20 cm and 0–40 cm depths in agricultural lands (tillage system) and shrubland (native vegetation) was found in western Bahia State. The site is on *Neossolos Quartzarênicos* (i.e., maximum 15% clay content) and *Aw* (Köppen climate classification) with 1.100 mm annual precipitation [34]. The lowest value (Table 1) for native vegetation at 0–30 cm depth is in São Paulo State shrublands on sandy *Latossolos* (Ferralsols [22]; Oxisols [23,24]) with 16% clay content [32].

The lowest carbon stock value (Table 1) for native vegetation at 0–60 cm depth was found in Minas Gerais State shrublands on 16% clay content soil [35]. Additionally, low values for shrublands were found in western Bahia at 0–60 cm depth at several sites under sandy soils (mean value of 51.4 Mg ha^{-1}) [31]. This source also shows the lowest value (Table 1) for agricultural lands (pastures) at 0–60 cm and 0–100 cm depths [31]. The lowest and highest values (Table 1) for native vegetation at 0–200 depth were found at sites with clayey soils in Distrito Federal shrublands and grasslands, respectively [36].

The highest value of soil carbon stocks for native vegetation at 0–20 cm, 0–30 cm, and 0–40 cm depths was found in *Organossolos* (Histosols [22–24]) in Distrito Federal wet grasslands [37], where groundwater level varies seasonally, i.e., rising during the rainy season. The local vegetation is mostly composed of herbaceous plants of the *Poaceae* family, with plants of the *Cyperaceae*, *Asteraceae*, and *Lamiaceae* families also present.

3.2. Vertical Distribution of Soil Carbon Stocks in the Cerrado Biome

The vertical distribution pattern of soil carbon stocks in the *Cerrado* biome is as follows: 26.17% (0–30 cm depth), 37.67% (30–100 cm depth), and 36.15% (100–200 cm depth). The distribution of the soil carbon stocks for agricultural land is 25.97% (0–30 cm depth), 43.05% (30–100 cm depth), and 30.96% (100–200 cm depth), whereas for native vegetation it is 29.49% (0–30 cm depth), 28.10% (30–100 cm depth), and 42.40% (100–200 cm depth).

Using the 0–200 cm layer as reference, some data show [36] that 60–70% of the carbon stocks are located in the first meter of soil. This proportion is significantly higher in grasslands (±70.5%) and lower in forestlands (66.5%) and shrublands (61.9–64.3%). Between 16% to 25% of the carbon stocks are located at 0–20 cm soil depth.

3.3. Soil Carbon Stocks in Native Vegetation

At two other wet grassland sites [38], the mean carbon storage at 0–60 cm depth for *Plintossolos* (Plinthosols [22]; Plinthic sub-group [23,24]) and *Gleissolos* (Gleysols [22]; Entisols [23,24]) was 211.3 Mg ha^{-1} and 278 Mg ha^{-1}, respectively. The total area for these three types of soil, where wet areas are common, make up almost 12% of the *Cerrado* region [20]. While *Gleissolos* and *Organossolos* occur only in flooded areas, some sub-types of *Plintossolos* occur in dry areas as well. Considering all variations and possibilities, the area of hydromorphic soil in the *Cerrado* region is estimated at 2.1% [20] of its total area.

Even in the case of wet grasslands with few sample points (Table 2), no distinction between gallery forest and *Cerradão*, and no data for layers deeper than 60 cm, the data suggest that this type of vegetation cover can store more carbon in the soil than other types in the *Cerrado* biome. For example, carbon stocks for wet grasslands are 51% (0–20 cm depth), 44.4% (0–30 cm), 74.5% (0–40 cm), and 96.3% (0–60 cm) higher than those for forestlands, as shown in Table 2.

Table 2. Soil carbon stocks in native vegetation in the *Cerrado* biome.

Land Cover	Soil Layer	Number of Sites	Min	Mean	Max	CV (%)
				Mg ha^{-1}		
Forestland						
	0–20	7	33.1	65.2 bc	112.8	51.0
	0–30	2	51.0	100.4 bc	149.7	69.5
	0–40	6	45.6	104.6 a	189.7	54.0
	0–60	5	61.5	124.0 bc	266.6	67.6
	0–100	5	82.5	182.4 a	414.4	74.1
	0–200	2	248.0	251.2 a	254.3	2
Shrubland						
	0–20	27	16.2	48.9 b *	79.0	29.1
	0–30	11	21.7	54.3 b	96.6	40.4
	0–40	7	28.9	71.4 a	119.9	38.2
	0–60	7	50.4	86.3 b	154.4	45.6
	0–100	12	54.6	130.5 a	203.1	42.0
	0–200	3	230.0	169.0 a	271.2	13.9
Grassland						
	0–20	7	31.1	54.2 b	72.0	28.3
	0–40	2	54.7	68.3 a	81.9	28.2
	0–100	3	99.7	170.2 a	209.0	28.9
	0–200	4	277.0	285.0 a	297.0	3.7
Wet grassland						
	0–20	3	76.0	98.5 c *	123.8	24.4
	0–30	3	113.3	145.0 c	178.2	22.4
	0–40	3	148.8	182.6 a	208.9	16.8
	0–60	3	211.4	243.5 c	278.1	13.7

CV: coefficient of variation. Means for the same soil depths followed by a (not significantly different at $p < 0.05$; Kruskal–Wallis test), b,c (not significantly different at $p < 0.05$; Pairwise Main–Whitney exact test), and * (significantly different at $p < 0.001$; Pairwise MW exact test).

Forestlands [31,36,39–44] can occur under hydromorphic soil conditions as gallery forests and in dry areas in a formation known as *Cerradão* (type of savanna forest). Their canopy covers 70–90% of the area, with trees usually 8 m high, occasionally reaching 15 m. Shrublands [31–36,44–63] consist of an open formation with scattered trees and shrubs with a 20–70% canopy. Grasslands [36,62,64,65], which include some shrubs less than 3 m high, exhibit a 20% canopy maximum. Wet grasslands [37,38] extend across a narrow region of flooded plains along main rivers and lowlands. While this mosaic of different vegetation types can be found throughout the *Cerrado*, most of it is composed of shrublands associated with well-drained soils.

Because of strong anthropogenic pressure, grasslands in the *Cerrado* (*campo limpo*, *campo sujo*, and *campo rupestre*) are its most threatened type of vegetation. The *Cerrado* grasslands occur on sandy, dystrophic, or lithic soils, with a pronounced dry season. Their open formation is maintained by naturally occurring fires [66], which impact their soil carbon stocks. Contrary to the grasslands in the south (*pampas*) or in the country's highlands, the *Cerrado* grasslands exhibit lower percentages of carbon stocks. For example, the carbon stock values for grasslands are 12.8% (0–20 cm) and 34.7% (0–40 cm) lower than those for forestlands (Table 2).

The *Cerrado* grasslands are now almost restricted to national/state conservation parks. Their preservation is critical because of threats posed by livestock production, which changes their makeup by replacing native species with fast-growing exotic grasses. Grassland areas are also affected by fragmentation, which changes their natural pattern of fires. The absence of naturally occurring fires turns their vegetation into shrublands.

Wet grasslands (*campo limpo úmido*), characterized by the absence of trees and bushes [38], occur as belts along valleys enclosing gallery forests. The occurrence of wet grasslands instead of gallery forests may be attributed to the fact that the groundwater remains close or above the ground surface in these areas during some periods of the year [37]. The landscape in these regions is marked by abrupt vegetation transitions. The *Cerrado* wet grasslands are usually located at shallow water tables in riverbed areas and valley bottoms, often between shrublands and gallery forests [38].

These environments exhibit significantly higher soil carbon stocks than those of shrublands and grasslands at 0–20, 0–30, and 0–60 cm depths. Hydromorphic soils, which remain under anaerobic conditions during part of the year, are important carbon storage sinks not only in wet grasslands but also under gallery forests. However, due to some physical characteristics of these soils, hydrological changes—which usually happen when the water table is drained prior to the land being used for agriculture or pasture—will result in high emissions of carbon dioxide and, consequently, the loss of soil carbon stocks. Soil saturation leads to low microbial activity and, as a result, low organic matter decomposition and limited oxygen diffusivity, which impact CO_2 emissions and soil carbon stocks.

Gallery forests, which can store 400–1000 Mg ha^{-1} of carbon in the top one-meter layer of soil [49], also occur in the response to the same edaphic characteristics. Located near riverbanks, wet grasslands, and shrublands, these environments should be protected because they provide a haven for wildlife and act as carbon sinks

3.4. Soil Carbon Stocks for the Planted Forest, Agroforest, Pasture, and Perennial Crops

Table 3 shows data for ten different planted-forest sample sites. These sample points represent the most common economic use for planted forests in the *Cerrado*, covering 3.06 Mha of it [29]. Nine of these sites are used to grow *Eucalyptus* spp.: two sites were established in 1984 and 2004 and measured in 2008 [40]; one site characterized as a 13-year-old unmanaged forest [48]; four sites with *Eucalyptus urophylla* × *Eucalyptus grandis* plantations under seven years of establishment [46]; two sites with *Eucalyptus camaldulensis* plantations less than seven years old; and one site with a 20-year-old *Pinus caribaea* (var. hondurensis) plantation [35]. The hybrid *Eucalyptus* plantation [46] is used to produce pulp and paper. In its 7th year (harvest year), this site exhibited soil carbon stocks ranging from 267 to 325 Mg ha^{-1} [46] (Table 3).

Fast-growing forests such as *Eucalyptus* plantations are efficient systems for the accumulation of aboveground and belowground biomass [67]. Their leaves and other residues (e.g., litter and dead roots after a cycle of production) contribute to increasing carbon storage in the soil [68]. The forest canopy also protects the soil from erosion, due to direct impact of rainfall, and from solar irradiance, which results in lower air and topsoil temperatures. Under these environmental conditions, it is easier for clayey soils to stabilize the carbon present in or added to the soil [69].

Table 3. Soil Carbon Stocks in planted forests, agroforests, and pastures in the *Cerrado* biome.

Land Cover	Soil Layer	Number of Sites	Min	Mean	Max	CV (%)
Planted Forest				Mg ha^{-1}		
	0–20	7	44.9	86.2 b *	102.5	23
	0–30	2	135.4	138.8 bc	142.1	3
	0–40	7	78.4	150.8 b *	183.3	24
	0–60	9	41.6	169.7 a	262.4	52
	0–100	7	148.2	303.7 b *	414.0	29
Agroforest						
	0–20	7	25.0	48.9 bc	98.2	69.4
	0–30	3	71.2	118.7 b	144.1	34.7
	0–40	7	41.1	89.0 bc	208.0	82.6
	0–60	3	65.3	209.8 a	301.0	60.3
	0–100	2	407.8	430.4 b	453.0	7.4
Pasture						
	0–20	24	24.4	42.8 c *	112.2	40
	0–30	14	23.5	54.2 c	162.5	65
	0–40	14	39.0	74.3 c *	212.8	55
	0–60	3	36.8	129.8 a	303.7	116
	0–100	18	51.7	122.3 *	466.1	199
	0–200	1	252.0	252.0	252.0	

CV: coefficient of variation. Means for the same soil depths followed by a (not significantly different at $p < 0.05$; Kruskal–Wallis test), b,c (not significantly different at $p < 0.05$; Pairwise Main–Whitney exact test), and * (significantly different at $p < 0.001$; Pairwise MW exact test).

E. camaldulensis is used to produce wood charcoal. When it is grown in coppice systems, it can contribute to stabilizing soil carbon. However, these systems are usually established in areas with poor sandy soils, as is the case of the site used in this research [35]. This site, which is in its last year of production, presented carbon storage values ranging from 41.6 to 59.8 Mg ha^{-1} at 0–60 cm depth [35] (Table 3). It should be noted that there are also unmanaged forests of this species, usually found in the southern boundary of the *Cerrado* region.

Besides *Eucalyptus*, *Pinus* is also planted in the *Cerrado* and is commonly used for timber (with a 20-year production cycle). *Pinus* plantations exhibit carbon storage values of approximately 65.75 Mg ha^{-1} at 0–60 cm depth [35].

Eight sample sites represent agroforests in the *Cerrado* (Table 3): two silvopastures established in 1994 and 2004 and measured in 2008 [40]; one intercrop of *Acrocomia* palm and pasture [45]; one recently established intercrop of *Eucalyptus* and rice; one 1-year-old intercrop of *Eucalyptus* and soybean; two *Eucalyptus* plantations in a livestock-forest system, both measured in 2001 after 2–3 years of establishment [44]; and one integrated crop-livestock-forest system established in 2011 in a region of transition between the *Cerrado* and the Amazon Forest, measured in 2013 [70].

Despite the lack of information about soil carbon stocks in the *Cerrado* agroforests, it is known that the soil carbon storage worldwide in these systems may reach 300 Mg ha^{-1} at 1 m depth [71]. The integrated crop-livestock-forest system is implemented to intensify land-use, but it is not widely adopted in the *Cerrado* because of its complex management and the lack of information on crop and livestock production and forestry performance under these conditions. Usually, these systems are designed according to the type of forest to be planted. It is usually implemented by dividing the area into rows, 15 to 30 m apart. In the first year, the trees (forest) are planted intercropped with the first crop (usually soybeans). Then, in the 2nd or 3rd year, the pasture is established intercropping the forest.

Anthropic grazing lands in the *Cerrado* region make up a total of 60 Mha [29]. In order to measure their impact on carbon storage, several researchers studied soil carbon stocks in pastures (Table 4). One of them assessed a mean of twenty sample points (Supplementary Material Table S2) in western Bahia [31]. Most of the sample points are in areas covered by *Brachiaria decumbens* or *B. brizantha* [32,36,40,48,51,58,60,64,65,72]. Both *Brachiaria decumbens* and *B. brizantha* take up 80% of the pastures in the *Cerrado* region [32].

Table 4. Soil carbon stock for tillage and no-tillage systems.

Land Cover	Soil Layer	Number of Sites	Min	Mean	Max	CV (%)
Tillage				Mg ha^{-1}		
	0–20	22	16.1	39.7	84.9	37
	0–30	19	45.4	63.3 a	81.5	18
	0–40	14	29.6	61.2 a	116.3	39
	0–60	2	85.7	91.5 a	97.2	9
	0–100	8	125.3	147.8	176.4	14
No-tillage						
	0–20	28	20.7	46.0	87.1	30
	0–30	10	40.2	63.5 a	85.9	24
	0–40	19	37.5	70.3 a	124.3	28
	0–60	4	92.9	102.4 a	116.1	10
	0–100	3	135.8	160.0 a	186.3	13

CV: coefficient of variation. Means at the same soil depth; those followed by the letter a are not significantly different at $p < 0.05$ (Mann-Whitney test).

Other species present in these pastures are *Panicum maximum* [58,64], *Paspalum atratum* [64], *Andropogon gayanus* [58], and *Pennisetum glaucum* [47]. Some points were measured in areas with mixed species, such as *Brachiaria brizantha* + *Stylosanthes guianensis* [64] and *Andropogon gayanus* + *Neonotonia wightii* + *Centrosema brasilianum* [64]. No information on the variety of species was found for four of the sample points [54,57,59,73].

Agricultural lands with perennial crops, e.g., coffee, citrus, sugarcane, and palm trees, take up 6.42 Mha of the *Cerrado* region [29]. The data available on croplands derive from six sample points: one from *Acrocomia* palms in Maranhão State; one from *Coffea arabica* in Minas Gerais State; and four from jatropha trees in Distrito Federal.

3.5. Soil Carbon Stocks for Tillage, and No-Tillage Systems

Nowadays, the total area of no-till farming in the *Cerrado* is estimated at 11 Mha [54] of a total annual cropping land estimated at 17.4 Mha [29]. Table 4 shows values for soil carbon stocks in tillage and no-tillage systems and sheds light on the difference between these farming techniques in regards to carbon storage, namely, carbon stocks are higher in no-tillage systems: 15.8% at 0–20 cm, 14.8% at 0–40 cm, 11.9% at 0–60 cm, and 8.2% at a 0–100 cm depth.

The 37 tillage sample points in question are divided into different management techniques: cotton in monoculture and in annual and biannual rotation with soybean and maize [72]; soybean [61,62], cotton, and maize monocultures [34] or in rotation [33]; annual soybean and maize rotation (one crop per year) [50]; sorghum in succession with maize [43]; soybean in rotation with maize succeeded by cover crop plants [74]; soybean-based crop rotation [52]; soybean as first crop and maize as second crop (same year) [54] in succession with forage grasses during the autumn–winter season [58,75]; rice and soybean-based crop rotated with cover crop plants [55]; rotation of maize and common bean varieties [63,65]; and no information found [48,60].

There are forty-two no-tillage sample points under different land managements: forage grasses or sorghum in succession with soybean [39]; cover crop plants in succession with maize [76] and soybean [74]; different rotations crops designed for using cotton, maize, and soybean [33] in succession with forage grasses [34,72]; annual soybean and maize rotation (one crop per year) [50]; sorghum in succession with maize [43]; soybean-based crop rotation [52,62], soybean as first crop and maize as second crop [54] succeeded by forage grasses [75]; rice and soybean-based crop rotation succeeded by cover crop plants [55]; rotation of maize, common bean varieties [63,65], and rice or tomatoes [60]; soybean monoculture [61,62]; and no information found [48].

The highest value for tillage and no-tillage systems at 0–20 and 0–40 cm depths was found in Minas Gerais State, in a 30% clay *Latossolo Vermelho-Amarelo eutrófico* (Ferralsol [22], Typic Eutrustox [23,24]) [43]. At 0–30 cm depth, the highest values for tillage and no-tillage systems were found in Minas Gerais State in a 42% clay *Latossolo Vermelho distrófico*

(Ferralsol [22], Typic Haplustrox [23,24]) [75], and in Distrito Federal in a 50% clay *Latossolo Vermelho distrófico* (Ferralsol [22], Typic Haplustrox [23,24]) [52], respectively.

The highest value of carbon stock in tillage systems at 0–60 cm depth was found at *Empresa Brasileira de Pesquisa Agropecuária* (EMBRAPA) *Cerrado* research center in Distrito Federal [50]. The highest value for no-tillage systems at 0–60 cm depth was found in Goiás State, in a *Latossolo Vermelho distrófico* (Ferralsol [22], Typic Haplustrox [23,24]) [39].

The lowest value for agricultural land (pasture) at 0–60 cm and 0–100 cm depth was found at several sites in sandy soils in western Bahia (Supplementary Material Table S2). This source describes the agricultural land under investigation as rainfed agriculture and irrigated agriculture. For this reason, its values were not considered in Table 4, only in Table 1. The sample analysis in rainfed agriculture [31] showed mean values of 42.6 Mg ha^{-1} at 0–60 cm depth and 57.4 Mg ha^{-1} at 0–100 cm depth. Irrigated agriculture presented a mean of 78.1 Mg ha^{-1} at 0–100 cm depth.

3.6. Causes of the Decline of Soil Carbon Stocks in Pastures

Usually, pastures are established right after the replacement of native plant species. In the *Cerrado*, most pastures are classified as degraded [32]. A productive pasture is capable of storing equal or higher values of soil carbon than those of native vegetation [32,36,48,54,64], depending on the type of the latter (Table 2). It should also be noted that undisturbed fragments of native vegetation are unlikely to be found in the *Cerrado* nowadays. Lower pasture productivity and, consequently, declining soil carbon stocks are due to years of bad management (e.g., no fertilization, overgrazing, and weed infestation).

Moreover, in areas dominated by croplands, it should be taken into consideration that livestock is produced in areas with nutrient-poor sandy soils or lithic soils and in marginal land areas where mechanization or irrigation are unviable. For this reason, lower mean values of carbon stocks are more commonly found in pastures as compared to those found in agricultural lands and native vegetation areas [31]. The extensive livestock farming in Brazil's central region is widely known for poor land management practices; thus, restoring degraded pastures is one of the best ways to increase soil carbon stocks in the *Cerrado* region.

A survey carried out at four sites in different states evaluated the impact of soil management on carbon stocks under pastures. The highest value of soil carbon stocks (164.7 Mg ha^{-1}) at 0–100 cm depth was found in a site in Minas Gerais State (67% clay content soil). At other sites, with clay content between 11% and 42%, soil carbon stocks ranged from 53 to 95 Mg ha^{-1} at the same depth [32]. The difference in carbon stocks between well-managed productive pastures and degraded pastures ranged from 9.3 to 26.6 Mg ha^{-1} at 0–100 cm depth [32]. Considering 60 Mha pastures [29] of which 30 Mha are degraded, the restoration of these pastures can result in 0.27–0.79 Gt of carbon stored in the soil at 0–100 cm depth [32]. In addition, considering the mean value of 54.2 Mg ha^{-1} (Table 3) for the upper 0–30 cm layer, restoration can increase soil carbon stocks by 15% at 0–30 cm depth [73], i.e., 0.23 Gt. Therefore, these data indicate that pastures constitute the largest manageable soil carbon pool in agricultural land in the *Cerrado* biome.

Given the importance of *Brachiaria* for increasing soil carbon stocks, it is usually used in rotation with soybean- or maize-based crops during autumn–winter as well as in livestock-forest and integrated crop-livestock-forestry systems and intercropping perennial crops. This system improves the physical and biological quality of soils, protects them from erosion, and assists in the control of weeds, with the roots of the perennial crop growing deeper due to competition. In addition, it increases water and nutrient availability, thereby helping maintain the perennial crops during the dry season [77].

Integrated crop-livestock systems have been in use in the *Cerrado* region since the 1980s and their main objective is to ensure optimal productivity throughout the year by interspersing the system with a third grazing cover crop (usually *Brachiaria/Panicum*) in autumn–winter. These seeds are planted and mixed with fertilizers between the rows of maize. Once the seedlings are established, they remain suppressed under the canopy of maize. After the crop is harvested, they begin to grow and provide soil cover [78]. These systems are key to carbon storage in no-tillage systems by diversifying carbon input and protecting the soil. Nowadays, it is common to make use of forage grasses even where livestock grazing is not intended.

The roots of *Brachiaria (Ulochoa)* spp. reach great depths [77] and improve the physical quality of soils by increasing the complexity and connectivity of the soil pore networks [79]. Its capacity to provide aboveground biomass of resistant straw with high carbon/nitrogen ratio and lignin content [80] ranges between 7.4 and 18.8 Mg ha^{-1} [81]. This straw protects the soil from erosion and reduces soil water loss by evaporation. Also, by maintaining optimal topsoil temperature at high air temperatures and incidental solar radiation [82], common in the *Cerrado* region, the straw can reduce weed infestation [81], increase the phosphorus availability to plants [83], and improve nitrogen use efficiency [79].

3.7. Potential and Limitations of Soil Carbon Storage in No-Till

Worldwide, carbon storage in croplands is estimated at more than 140 Gt for the upper 0–30 cm layer of soil (i.e., about 10% of global storage at this depth). In South America and Brazil, it is estimated at about 9.42 Gt and 5.063 Gt for the same depth, respectively [84]. The *Cerrado* croplands store 0.4 ± 0.07 Gt and 0.68 ± 0.16 Gt for tillage (n = 8; 6.4 Mha) and no-tillage (n = 19; 11 Mha) soils, respectively, at 0–30 cm depth. Therefore, the *Cerrado* croplands are responsible for 9.02–13.9% of the total soil carbon stocks in South American croplands and 16.78–25.87% of the total soil carbon storage in Brazilian croplands for the upper 0–30 cm layer.

Differences between tillage and no-tillage systems, as indicated by the mean values in Table 4, are in accordance with the literature. In rainfed cotton crops in Goiás State using the same rotation after nine years, soil carbon stocks in no-tillage systems at 0–40 cm depth were 20% higher than those in tillage systems [72]. A study in the state of Minas Gerais shows values of soil carbon stocks for the top 0–20 cm layer around 9% higher for no-tillage systems than those for tillage systems [74].

A survey in western Bahia measured high carbon sequestration stocks per year. The initial soil carbon stock at 0–40 cm depth was 17.63 Mg ha^{-1}. After six years, the mean value of soil carbon stocks for the tillage areas in a monoculture system was 30.26 Mg ha^{-1}, resulting in an increase of 2.105 Mg ha^{-1} per year. During the same period, the soil carbon stocks in a rotation and no-tillage system increased by 3.47 Mg ha^{-1} per year at a 0–40 cm depth [34]. Western Bahia has one of the lowest potentials for carbon storage in the upper layers due to its sandy, acidic, and nutrient-poor soils [31,34]. Under these edaphoclimatic conditions, agricultural management techniques for correcting the soil acidity, e.g., limestone application, fertilization, and crop rotation, are key to achieving higher values of soil carbon.

This increases in western Bahia surpasses that for the 0–40 cm layer (between 0.32 and 1.46 Mg ha^{-1}) found in 9- to 21-year-old no-tillage crops with soybean as first crop and maize, sorghum, or millet as second crop in the State of Goiás [54]. It also surpasses that of 1.2 Mg ha^{-1} per year found in a 9-year-old no-tillage system of cotton rotated with soybean, corn, and forage grasses after nine years on clayey soil in the same state [72]. These results indicate that crops under no-tillage systems constitute an important tool to increase soil carbon stocks. However, the amount of increase depends on the type of soil, climate conditions, clay content, rotation crops, and the initial soil carbon content [54].

Carbon sequestration in degraded soils is higher during the years immediately after crop implementation. Therefore, given the low initial carbon stocks at the experimental site and the low potential of western Bahia [34], its yearly accumulation rates are likely to decrease in the future [31]. Carbon sequestration under these conditions is limited and is likely to decrease as soon as the soil carbon sink is saturated, which could happen in about twenty years under edaphoclimatic conditions in the *Cerrado* [54].

Nowadays, soil compaction, acidification, and herbicide resistance pose important challenges to no-tillage systems. Dependent on soil moisture, compaction occurs as a result of many years of heavy machinery traffic. This problem can be solved in many cases by chiseling and subsoiling, as these land management techniques do not invert the layers and, as a result, do not disturb the soil as much as plowing and arrowing do [85]. Therefore, in light of preserving soil carbon stocks, minimal-disturbance management is recommended when strategic tillage is employed to solve soil compaction problems. In the case of acidification, it is usually solved by applying limestone to the soil. However, while the effectiveness of applying limestone without plowing and/or arrowing is controversial, there is no current technology to address soil acidification without strategic tillage.

Finally, increased weed resistance to herbicides in the *Cerrado* region has become the main concern for crop growers as the implementation of herbicide-resistant transgenic crops has increased in the last decades. It is estimated that 95% of soybeans, 89% of maize crops, and 95% of cotton crops are glyphosate-resistant [86]. Weed management in no-tillage systems is highly dependent on herbicides. Weed resistance to glyphosate increased in the region as it was previously used only in foliage desiccation but is now used as a post-emergent herbicide during the entire crop cycle of the aforementioned species. The way no-tillage management is currently carried out, i.e., by applying the same active ingredient on crops several times a year during many consecutive years, results in an environment with a high selection pressure [85,87].

Strategic tillage does not have to be recommended for controlling weeds, as many types of agricultural management can be employed to reduce or control herbicide-resistant weeds, such as selecting fast-growing crop varieties in order to decrease spacing between rows and increase plant density, rotating herbicides (different action mechanisms), rotating crops (crop diversification), and using species that can produce resistant straw and cover the soil during winter [85,87].

3.8. Relation of Soil Type and Roots Depth in the Soil Carbon Stocks

The *Cerrado* soils are usually weathered and depleted of nutrients. Most sites (170) reported by the sources used in this study are on *Latossolos* (Figure 4), which is the main class of soil in the *Cerrado* region. *Latossolos* exhibits greater depth (>2 m) and clay content variability (>16% to 70%), which results in biological and pedogenic activity at more than 2 m depth [21]. About 10 sites are on *Neossolos Quartzarênicos,* which also exhibits great depth (>2 m) but less than 16% of clay. Only a few sample points with high values of soil carbon storage were found at a 0–60 cm depth in native vegetation (wet grassland) areas on *Gleissolos* (i.e., with a gray horizon indicating iron reduction), *Organossolos* (i.e., with a histic horizon), and *Plintossolos* (i.e., with horizons of continuous petroplinthite). However, there is no information or evidence about its soil carbon storage below 60 cm deep in wet grasslands.

For each type of soil, the potential to store carbon depends on its depth and aggregate size fraction [88]. Available data indicate that high carbon storage in the *Cerrado* is usually found in high clay-content soils of metamorphic/volcanic origin and at subtropical climates. Also, this potential is contingent on the net primary productivity of each ecosystem, i.e., litter in topsoil and root biomass in deep soil.

Shrubland roots reach 9 m deep [89] or more; thus, even though about 70% of below-ground biomass occurs in the upper 0–30 cm layer [9], carbon storage is likely to be found below 2 m deep in the *Cerrado* soil. In agricultural lands, soybean and maize monocultures cannot reach similar values of soil carbon stocks as compared to those found in the native vegetation areas because roots in these crops measure 0.7–0.9 m maximum, with most of them located in the upper 0–30 cm layer [90].

The roots of the most common pasture species established in the *Cerrado* can reach a depth of about 5 m [77]. The fact that the majority of the *Cerrado* area (>60%) is covered by *Latosssolos*, a type of soil that has the potential to store carbon at depths greater than 2 m—something that cannot be fully confirmed because there is no available data for depths greater than 2 m—suggests the importance of using grass in rotation or intercropping agricultural systems in the *Cerrado*.

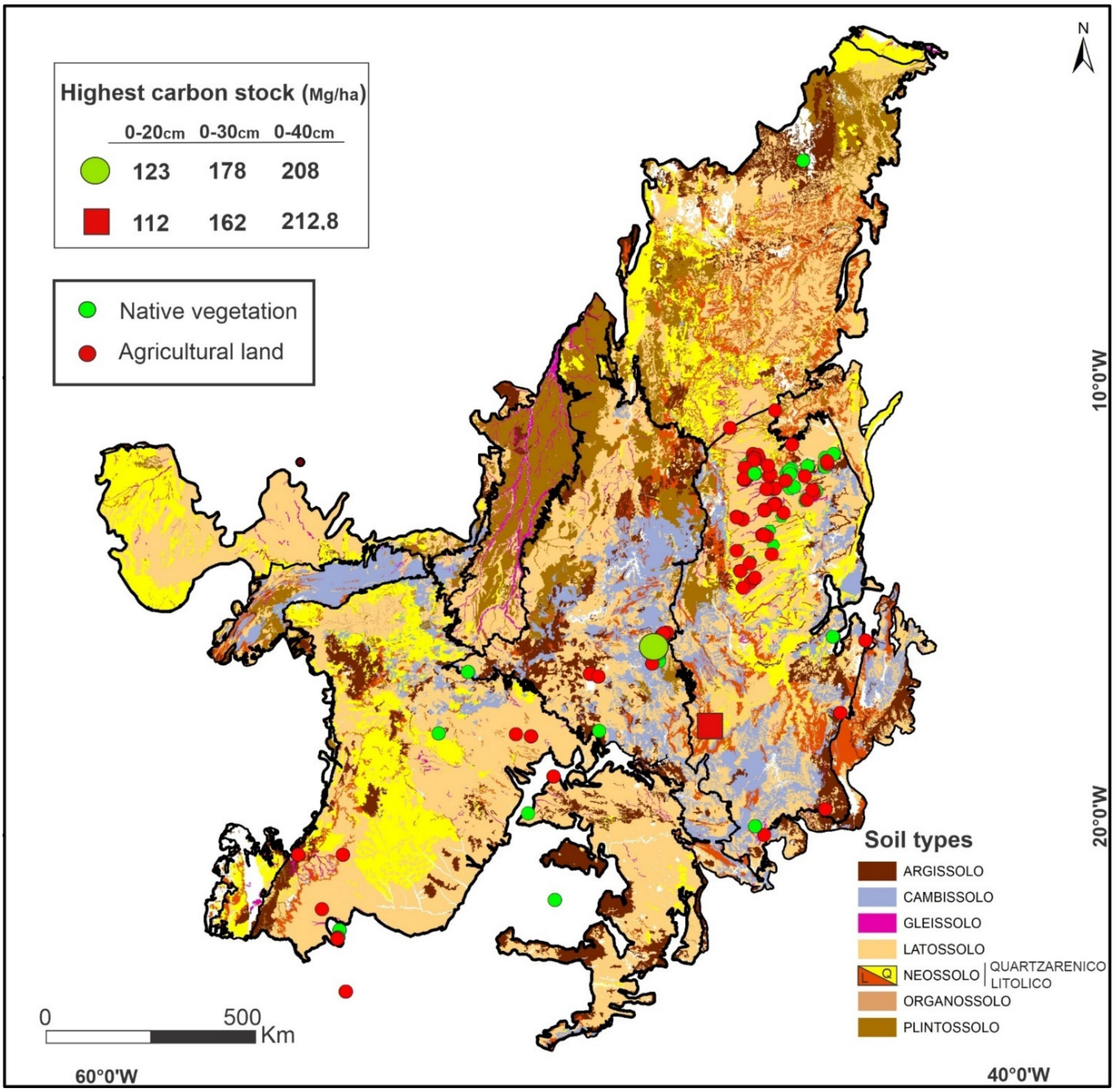

Figure 4. The position of the sample plots in the *Cerrado*, and the location of the highest carbon stocks data throughout the biome.

On the other hand, *Neossolos Litólicos* (Leptosols [22]; soils of the Lithic sub-group [23,24]), which make up about 7% of the biome, are 0.3 m deep or less. In addition, some types of *Cambissolos* (Cambisols [22]; Inceptsols [23,24]), which together cover about 3% of the *Cerrado,* have lithic contact at a depth between 50 and 100 cm from the soil surface [21].

3.9. Role of Charcoal and the Variability among Soil Carbon Stocks Data

Soils in the *Cerrado* region often exhibit large amounts of refractory carbon (charcoal) as a result of wildfires, which play an important role in shaping its native vegetation [11,52], and due to an increasing number of anthropogenic fires, which are carried out to clear the native vegetation and open new areas for agricultural purposes. A few studies have attempted to develop conceptual models for carbon pools in soils. These models classify soil carbon pools under three types: *active* (soluble organic carbon and biomass; 5-year turnover); *intermediate* (>53 µm particulate organic matter; 20-to-40-year turnover); and *passive* (200-to-1500-year turnover) [91–93].

When native vegetation is converted into agricultural land, the existing charcoal may remain in the soil for a long period of time. Existing variability among data on soil carbon stocks [94] is due to several factors, such as different measuring methods [26], changes in soil bulk density due to land-use conversions [50], and use of either diachronic or synchronic approaches [95]. Therefore, any comparison among values found in different studies should be conducted with caution. The same goes when analyzing outlying values that lack logical explanation or are uncorroborated by data from similar studies.

Hence, comparing data on soil carbon stocks from different areas of native vegetation in agricultural lands or comparing data from no-till systems to those of tillage systems may lead to the overestimated of soil carbon storage values. For instance, the overestimation of soil carbon stocks in the upper layer may occur when comparing tillage systems to no-tillage systems, agricultural land to native vegetation, and degraded pastures to well-managed pastures due to the high soil bulk density. In order to correct differences in soil bulk density values for different land-use and land cover data, soil carbon stocks must be calculated on an equivalent soil mass basis [96,97].

Some of the sources used in this study provided no information about correcting values of soil carbon stocks on an equivalent mass basis. Given that six of them assessed differences in soil carbon stocks in tillage and no-tillage systems [34,43,55,72,74,76], one assessed carbon stocks in well-managed and degraded pastures at 1 m depth [40], and another also assessed carbon stocks in well-managed and degraded pastures but at 0–30 cm depth [73], their carbon stock values may be overestimated for tillage in comparison with no-tillage systems (Table 4) and for degraded pastures in comparison with well-managed pastures [40,73].

4. Conclusions

Our study investigated and analyzed data (n = 197) on total soil carbon stocks in the *Cerrado* biome. The results indicate gaps that need to be further explored. This study shows the distribution pattern of soil carbon stocks in the *Cerrado* biome and indicates evidence of existing carbon stocks below 2 m depth, especially in native vegetation and pastures, which needs to be further investigated. The lack of data on soil carbon stocks in agricultural lands below 100 cm depth should also be the focus of future research.

One of the limitations on our analysis derives from the uncertainty associated with the small number of sampling points and the variability among the available data due to differences in methodological procedures. It is important that future studies adhere to international research standards, as some soil researchers in the *Cerrado* have adopted intervals (0–20 and 0–40 cm depth) different to those prescribed in international standards (0–30 and 0–60 cm).

As regards the planning of research on soil carbon stocks, the *Cerrado* areas under investigation should be divided according to soil type and land-use/cover, taking into consideration their different geological/geomorphological provinces. For example, in spite of the Bananal basin province (Figure 1), where *Plintossolos* predominates (Figure 2), having a high potential for carbon storage, no data are available on soil carbon stocks for this type of soil in this province. Another example can be found in the Tocantins basin province (Figure 1), where *Cambissolos* are common; this type of soil presents low carbon stocks due to its shallowness (0.5 to 1 m depth).

Assessing the carbon storage potential for different soils under different land-uses/covers at different depths is important not only to characterize the total soil carbon storage in the *Cerrado* biome, but also to assess the impact of land-use change on carbon storage. Restoring degraded pastures as well as intercropping them with perennial crops or forests or rotating them with soybean and maize are also important measures to increase soil carbon stocks in the *Cerrado* region. Implementing no-tillage systems remains an effective way of increasing soil carbon stocks, in spite of demands for the use of the strategic tillage in the long run. By promoting lasting carbon storage in these different types of soil under different land-uses and covers, these measures can contribute to lowering CO_2 emissions and, as a result, mitigating the impact of climate change.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su14095571/s1, Table S1: Soil Carbon Stocks Data in *Cerrado* biome; Table S2: Georeferenced points of Soil Carbon Stocks Data from MATOPIBA.

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