Studies Related to Organic Carbon Stock in the Brazilian Cerrado: What have we Learned So Far?

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Authors' contributions

This work was carried out in collaboration between all authors. Author CDS designed the study, searched the data and wrote the manuscript. Authors PVE and ATOF revised its first draft and author MGCF revised its final version. All authors read and approved the final manuscript.

Review Article

ABSTRACT

Studies related to the impact of the climate changes in plants have increased in recent decades, especially those related to carbon flux in different ecosystems. Brazilian savanna (Cerrado) is the second largest biome in the country, and supports different types of vegetation such as fields, savannas and forests. The exclusive phytophysiognomies of this biome comprise of a forest (Woodland Cerrado), savannas (Typical, Dense, Sparse and Rupestrian), and fields (Dirty, Clean, Moist and Rupestrian) and also the Swampy Plains (Veredas), which provide ecosystems able to sink/stock/source different amounts of carbon. Looking forward to providing strategies to subsidize the conservation and management of the Brazilian Cerrado, we searched and synthetized the information on carbon storage in its different phytophysiognomies. Even though several data on carbon storage have been generated, the quantitative and estimated values differ in different aspects. We found substantial data to the managed ecosystems located in the savanna phytophysiognomies, contrastingly, there is a lack of information about the undisturbed and native

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areas. We herein suggest methods to be applied in future complementary studies on carbon storage of the already studied areas, and also of the undisturbed, but threatened native phytophysiognomies of the Brazilian Cerrado.

Keywords: Carbon storage; atmospheric carbon; above and belowground soil biomass; vegetation.

1. INTRODUCTION

The biodiversity conservation, the livelihoods support and the delivery of fresh water have been highlighted as important considerations in the selection of priority areas for conservation in tropics, but avoiding the increase of greenhouse gases (GHG) in the atmosphere is maybe one of the main arguments against deforestation in tropical regions currently [1-4]. Paradoxically, carbon emissions from changes in land-use are still an uncertain quantified component of the global carbon cycle [5]. To the tropics, it is discussed that the carbon quantification, almost entirely restricted to forest environments, are probably overestimated between 25% to 50% [1,5]. However, there is an increasing environmental awareness about the role of tropical savannas in the total atmospheric carbon balance [6]. Notably, the Brazilian savannas seem to play an important role in this scenery: while values of 111.4665 Mg ha^{-1} [7] and of 305.83 Mg ha^{-1} [8] for total stored carbon were found in this vegetation, an estimation to the total forest carbon stock in all Brazilian forests showed values between 102 and 123 Mg C ha^{-1}, varying according to canopy covering [9]. Brazil shelters the largest and most diverse neotropical savanna domain in the world, with several different phytophysiognomies, some of them, such as Seasonal and Gallery Forests, are shared with other Brazilian biomes [10-16]. There are six phytophysiognomies exclusive to the Biome (Cerrado *sensu lato*), found on well-drained and dystrophic soils: A- four different kinds of savanna: Dense Cerrado (Cerrado Denso), Typical Cerrado (Cerrado Típico), Sparse Cerrado (Cerrado Ralo) and Rupestrian Cerrado (Cerrado Rupestre), named as a whole as Cerrado *sensu stricto* vegetation; B- one forest type: The Woodland Cerrado (Cerradão); and C- three kinds of grassland: Clean Field (Campo Limpo), Dirty Field (Campo Sujo) and Rupestrian Field [16]. There are also other exclusive Cerrado phytophysiognomies that are related to seasonal flooded areas, e.g the Swampy Plains, named "Veredas" in Brazil and the Moist Field (Campo Úmido) [16,17]. Information about carbon cycling and storage in several and diverse phytophysiognomies that compose Cerrado domain are still scarce, except for those that present great interest in extraction for energy production, despite the crucial role of mass regulation and energy exchanges with the atmosphere played by the biome in all [2-3,8,18-20].

This review aims at gathering and synthesizing the data produced so far for the Brazilian Cerrado, concerning either carbon or biomass stores and sequestration in its different phytophysiognomies and environmental strata. To this end, we searched the Periodical Portal Virtual Library of Coordination for the Improvement of Higher Education Personnel (CAPES) site (http://www.periodicos.capes.gov.br) for publications in specialized journals until June 2016, using the keywords: Cerrado carbon; Cerrado biomass; carbon stores; carbon stock; as well as the Federal University of Minas Gerais data bank (www.bibliotecadigital.ufmg.br) and other related data supporting the subject. We have found some studies that did not discriminate the exact phytophysiognomy in which they were developed, where authors referred to the vegetation as 'Cerrado *sensu stricto*', 'native vegetation of the Cerrado' or 'Cerrado typical vegetation'. Since the most representative vegetation of the biome is the Typical Cerrado, which is one of the Cerrado *sensu stricto* savannas, we believe that these studies were conducted in this phytophysiognomy, or at least, in one of the four kinds of savannas that represent the biome. Because of this, in the following text, we may refer to each of these non-discriminated phytophysiognomies simply as "savanna".

2. METHODOLOGY APPLIED TO BIOMASS AND CARBON MEASUREMENTS IN CERRADO PHYTOPHYSIOGNOMIES

We found 21 studies, with the theme of this section [3,8,13,17,21-37]. Ten of these studies stipulated in which phytophysiognomies they were conducted: Meirelles et al. [17] investigated a Moist Field, while Melo and Durigan [25] focused on Gallery Forests and Lopes and Miola

[27] investigated a Woodland Cerrado, a Dense Cerrado, a Typical Cerrado and a Gallery Forest. Rosolen et al. [30] studied a Dense Cerrado, and they did not distinguish this term from the "Woodland Cerrado". Wantzen et al. [31] investigated a Gallery Forest, a Swampy Plain and a savanna. Oliveras et al. [34] investigated a Dirty Field, Santana et al. [32] analyzed a Gallery Forest, a Woodland Cerrado, a savanna and a Dirty Field and Morais et al. [33] investigated a Woodland Cerrado. Rocha et al. [35] studied a savanna and a Gallery Forest. While Miranda et al. [37] did not name the studied pyhtopysionomy, they said that it is a savanna with no C4 photosynthetic vegetation, we refer to the vegetation of their study as Wooden Savanna. The other studies did not introduce the exact phytophysiognomy where they had been conducted, therefore the terms savanna or closed/open savanna, depending on the case, were applied

2.1 Soil Compartment

Different methods were used to quantify SOM/SOC in many studies. Abdala et al. [21] investigated SOM by the [38], in 620 cm below the surface of a gully. Corazza et al. [22] and Bayer et al. [24] used [39] method to measure SOC, down to 100 cm and 20 cm depth, respectively. Meirelles et al. [17], Resck et al. [13], Paiva and Faria [26], Rocha et al. [35] and Paiva et al. [36] measured SOC by the [40] method, the first two down to 60 cm, the third and fourth down to 40 cm and the last down to 20 cm. Rosendo and Rosa [29] investigated the first 40 cm, using a similar method, according to [41]. Neufeldt et al. [23], Wantzen et al. [31], Morais et al. [33] and Miranda et al. [37] measured SOC by chromatography after dry combustion, depths corresponding to 12 cm, 60 cm and 100 cm. All these studies resorted to soil density in order to convert data of C% to SOC stored in the respective depths, except for those developed by [30,36], in which this conversion has not been done. Rosolen et al. [30] evaluated SOC% down to 30 cm by an elemental analyzer attached to mass spectrometer.

Neufeldt et al. [23] investigated different SOM fractions (0-12 cm): Particulate organic matter (POM) was estimated on the basis of scanning electron microscopy micrographs of organic matter in particle-size separates according to [42]; non-cellulosic (NCP) and cellulosic polysaccharides (CP) were extracted with a two-step acid hydrolysis according to [43] and

determined colorimetrically with the MBTH reagent by [44] method; VSC-lignin was detected chromatographically after extraction with the alkaline oxidation according to [43,45]. Rosolen et al. [30,37] also investigated SOC nature (δ^{13}C) in their studies by the same method described above. These authors estimated soil carbon sequestration using linear regression analyses between cultivation time and SOC stock.

2.2 Root Compartment

Root biomass was investigated in seven studies [7-8,21,26,28,33-34]. In order to measure biomass in the first investigation, [21] separated roots from soil (100 cm deep), washed, dried and weighed them. The authors also collected the root crowns and proposed a mathematical equation relating their dry weight (without roots) and the basal area of the trees (30 cm above ground). In the second study, fresh and dry root biomass were determined from soil samples down to 30 cm deep, from where roots were separated, weighed, dried and weighed again [26]. Authors considered carbon content as 48% of root dry biomass and, making use of proportions of root content as proposed by [46], they applied [47] equation to estimate carbon stored in this strata down to 2 m [26]. More recently, [8] using similar method to soil sampling and root biomass determination, clearly indicated that they considered the carbon mass stored to be 48% of dry biomass. Ribeiro et al. [7] investigated the biomass of roots separated by 1 cm sieve mesh from soil (100 cm deep). Durigan et al. [28] uprooted and weighed 102 trees (30 species among the highest density species in the community) of different sizes. In the field, roots were set apart from the soil, being their components separated according to [48] and then weighed. Oliveras et al. [34] separated the visible roots from air-dried soil (30 cm deep) with tweezers and then decahydrate pyrophosphate of sodium solution was added to disrupt soil aggregates, being the material washed in tap water, collected in a sieve and dried. Finally, [33] were the only ones to measure root carbon by an elemental analyzer.

2.3 Aboveground Compartment

There are mainly two distinct forms of carbon and biomass investigation (AGC, AGB) stored in live vegetation above ground: (1) by cutting and weighing the vegetation, named direct or destructive method [15], in which the carbon can be measured and then used as a constant part of

the dry biomass; or (2) the indirect or non-destructive method. It is possible to apply the destructive method to any vegetation strata with small methodological alterations in order to better to estimate the biomass in herbs, shrubs or trees. Even so, as its name suggests, this method is detrimental to the environment, being necessary for example, to remove many trees of different species to actually characterize a single arboreal community in the Cerrado [7]. For this reason, the application of the indirect method seems to be more suited to great extensions of vegetation, in which the field work is restricted to forest inventories [15]. The data produced in the inventories are then applied to mathematical models. The biomass is the dependent variable to these allometric equations, and those which are independent are easily measured, being the trunk diameter, at 30 cm (the base diameter, bD) or at 1.3 m above the soil (the breast height, BHD), the total height (H), or in the laboratory; the volume (V) and the wood density (WD). The use of the specific wood density as an extra independent variable, allows the application of these models to be done separately to different inventoried species, while its avoidance, even producing a bit less accurate results, permits the use of the equations to the community as a whole [7].

We found four studies of arboreal AGC quantification by the destructive method, three of them providing allometric equations for wooden vegetation. Abdala et al. [21] used their own unpublished data, obtained by cutting down 112 trees and shrubs, to estimate wooden AGB. They presented an allometric equation based on bD and H. The direct method was also used to quantify the carbon stored in the green and dry biomass of an arboreal community in a savanna from which 174 trees were felled in the same proportion as those represented in the community [3]. Several allometric equations, in which the predictor variables were bD and H, were produced and all of them presented a determination coefficient higher than 93% and standard error between 25.03 and 28.09%. In another study, five other ABG equations were also developed for an arboreal community of a savanna, to which 120 trees were selected according to the dominance of their species in the community [7]. The authors used CHD, H and WD as the predictor variables and the best models exhibited the determination coefficients around 89% and the standard error between 0.365 and 0.394. In order to determine the AGB, [28] used the same 102 trees separation criteria

and weighing, as mentioned above, but, then, they obtained the root/shoot ratio.

The first study cited in the previous paragraph [3] provided a mathematical model which was used in two subsequent investigations [8,32]. Paiva et al. [8] inventoried an area using the bD and H parameters to estimate the AGC of the same savanna to which this model was developed. Santana et al. [32] added a variable to this equation, being it the soil redness index (RI), arguing that this index has a positive and significant correlation to AGC in different phytophysiognomies. An equation which asks for bD and H as independent variables was used by [33] to calculate the AGC in a Woodland Cerrado and by [35] in both a savanna and a Gallery Forest in regeneration. Wooden AGB, in replanted Gallery Forests, was investigated by [25], in the model proposed by [48], in which BHD is the independent variable and the DBH dependent one. The authors extrapolated data to AGC using the 0.5 factor proposed by [49]. Lopes and Miola [27] estimated AGB according to [48], using measured DBH and estimated H as independent variables and AGC was considered 0.5 of AGB. Their investigation comprised a Woodland Cerrado, a Dense Cerrado, a Typical Cerrado and a Gallery Forest.

The ground later (herbs and shrubs) AGB/AGC was investigated in a destructive way, but the results were not used to provide allometric equations. Abdala et al. [21] quantified the AGB in the ground layer (wooden plants with less than 6 cm - bD, grasses, non-grasses and dead material) by removing all the material of 35 plots measuring 1m x 1m and drying at 70°C. As well, [17] measured AGB in grass vegetation by removing all the material of six 1 m^2 plots, but they separated live and dead material before drying (80°C). Ribeiro et al. [7] determined carbon stored in the shrub strata by removing all wooded vegetation with bD < 5.0 cm (30.0 cm from soil) from a plot, weighing and, subsequently taking a random sample of about 200 g to determine the fresh-to-dry weight relation. Oliveras et al. [34] clipped all the herbaceous individuals (grasses - Poaceae and Cyperaceae - and forbs/sub-shrubs) from plots, which were oven dried and grinded, and assumed to have an organic carbon proportion of 0.45 for herbaceous biomass.

Litter biomass deposition ratio was investigated by [36] by placing litter traps made of nylon mesh at 15 cm aboveground and, every 15 days for

one year, collecting the material, taking it to the laboratory, drying and weighing it. Litter biomass determination was done basically in the same way in the other studies: all the material was removed in the field from demarked squares (varying in size in each study), taken to the laboratory, dried and weighed (in different temperatures, according to the study) [21,23,33, 35-36]. Contrastingly, subsequent litter carbon content calculation procedures were more varied: [8] considered the proportion of 51% proposed by [46], while [33] used an elemental analyzer and [35] applied the [40] method.

3. CHARACTERISTIC OF BIOMASS AND CARBON STORES IN CERRADO

3.1 Total Biomass/Carbon

It is believed that the quantity of total organic matter (TOM) decreases along the Cerrado's wooded savanna/grassland phytophysiognomies gradient and increases in seasonal flooded areas [6,17]. There are a few studies reporting the total organic carbon (TOC) or TOM, which includes soil organic matter (SOM), root biomass and litter biomass in this biome. Abdala et al. [21] encountered the amount of 724.40 Mg ha^{-1} of TOM in a savanna, considering SOM and root biomass until a depth of 620 cm. An equivalent value (305.83 Mg C ha^{-1}) was also found in a savanna [8], considering TOC in soil down to 200 cm. Morais et al. [33] measured a medium value of 139.69 Mg ha^{-1} for TOC in a Woodland Cerrado, measuring a depth of 100 cm to SOC and carbon contained in roots.

3.2 Soil Compartment

Neufeldt et al. [23] showed a decline of POM, lignin and plant-derived polysaccharides from the sand to the clay fraction in the Cerrado soils, as well as an accumulation of microbial metabolized polysaccharides in the clay fraction and a SOM content twice as high in clayey soils than in loamy soils. This suggests that SOM humidification and mineralization in the Brazilian Savannas are similar to those of temperate soils, even though the role of the clay fraction is played by the silt in these environments. Although [37] found no correlation between clay and SOC contents, it is known that clay sorption sites ensure SOM physical retention and accumulation over the highly weathered soils of the Brazilian Cerrado, which is an important mechanism involved in their physical protection [2,6,23]. High proportions between these variables, such 89%

(620 cm deep) and 88% (200 cm), were encountered in well preserved savannas, while a value of 64.8% (100 cm) was found in a conserved Woodland Cerrado and the astonishing 97.8% and 95.7% (40 cm) were measured in a savanna and a in Gallery Forest, both in natural regeneration [8,21,33,35].

However, if native Cerrado vegetation is substituted by mismanaged pastures or crop systems, superficial SOC can decrease, or, otherwise, when no-till crops are implemented, it can raise, as a result of remnants of native vegetation, added calcareous or plantation residuals [13,22,24,31,50]. Rosendo and Rosa [29] showed a SOM increase in an improved pasture and a SOM decrease in a degraded pasture, when they were compared to a savanna (0-20 cm and 20-40 cm). Values of these depths were: 38.05 Mg C ha^{-1} and 26.80 Mg C ha^{-1}; 43.92 Mg C ha^{-1} and 33.5 Mg C ha^{-1}; 34.63 Mg C ha^{-1}, 27.51 Mg C ha^{-1}, respectively. The losses of carbon stock in degraded areas were also estimated to the upper 30 cm of different phytophysiognomies: savanna (47.6%), Gallery Forest (42.8%), Swampy Plain (14.3%) and Pasture (13.9%) [31]. In contrast, when a conventional tilled area in a savanna was changed to no-till, a carbon sequestration rate of 0.30 Mg ha^{-1} year^{-1} (20 cm) was measured [24]. It has been highlighted that this SOM increase, promoted by good farming practices, is possibly restricted to the soil surface, but some studies were conducted in deeper layers [13,22]. Resck et al. [13] found this benefit down to 60 cm: where the savanna control presented 44.6 Mg C ha^{-1}, against the more than 64 Mg C ha^{-1} of all the management systems studied (exotic pastures and tilled and no-till soybean or maize crops, with different time and history of exploration). In the top layer, the savanna had a significantly higher C stock than all the explored areas, while down to 100 cm C, the C stock was significantly greater in the long-term exploration area than in the savanna and in the area with short-term exploration. Likewise, no statistical difference was found on the average C% between the studied Wooden Savanna and the cultivated sites (several different soybean managements) [37], but for the top 0–5 cm layer, the authors encountered that the C% decreased with cultivation time, while for those at 75–100 cm deep, they found that C% increased with cultivation time. In this study, a clear trend of C increase with cultivation time, with a C accumulation rate of 1.1 Mg ha^{-1} C year^{-1}, was encountered.

Otherwise, a non-clear pattern in SOC loss or gain was observed in pastures and crops with different managements [30]. Authors found that the SOC% can rise or decrease either in non-managed or in managed pastures and the same effects can be promoted in no-till crops. Neufeldt et al. [23] explained SOM differences (0-12 cm), among the several different studied systems, on the basis of POM accumulation, which depends on litter amount and composition. So, in crop systems, with low litter input, SOM was smaller than in the savanna control, either in clay (22.9 Mg C ha^{-1} x 23.5 Mg C ha^{-1}) or in coarse-loamy soils (7.1 Mg C ha^{-1} x 9.8 Mg C ha^{-1}). The same effect was produced by the hard decay Pine litter, which provoked the reduction of SOM to 21.5 Mg C ha^{-1} in clay soil [23]. Indeed, SOC values encountered in areas in rehabilitation by agroforestry systems (AFS) or by natural regeneration (NR) followed the same trend of litter values in a savanna - AFS1, AFS2 and NR1- and in a Gallery Forest – AFS3 and NR2 [35]. Litter values were 5.31(±3.22) Mg C ha^{-1}, 4.80(±1.20) Mg C ha^{-1}, 5.29(±2.12) Mg C ha^{-1}, 3.38(±2.26) Mg C ha^{-1} and 4.97(±1.75) Mg C ha^{-1} to AFS1, AFS2, NR1, AFS3 and NR2, respectively. Meanwhile, to the same communities, SOC values were 46.29(±5.01), 57.83(±9.23), 45.33(±3.76), 42.87(±3.07) and 56.38(±9.72) in the surface (0-10 cm); 33.26(±6.11) Mg C ha^{-1}, 58.61(±5.13) Mg C ha^{-1}, 33.51(±7.06) Mg C ha^{-1}, 30.77(±0.11) Mg C ha^{-1} and 56.05(±4.73) Mg C ha^{-1} in 10-20 cm layer; and 49.26(±8.43) Mg C ha^{-1}, 74.14(±8.33) Mg C ha^{-1}, 52.11(±8.06) Mg C ha^{-1}; 29.40(±5.74) Mg C ha^{-1} and 46.50(±5.04) Mg C ha^{-1} in 20-40 cm layer [35].

In the same litter dependence, SOC proportions grew significantly in preserved vegetation across a gradient savanna/Gallery Forest [36]. While at the part of the savanna that was further from Gallery Forest SOC it was about 2%, in the boundary area between them it was about 3% and inside Gallery Forest it was about 4-5%. These values were presented in the first 10 cm, while from 10 cm to 20 cm SOC presented the same behavior, but with lower values. Indeed, [31] showed that SOC variation among phytophysiognomies, due to accumulated organic matter and strongly influenced by the amount of litter and environmental humidity. They found the greatest SOC values, at 0-30 and 0-60 cm deep respectively: Gallery Forests (242.6 and 360 Mg C ha^{-1}), Swampy Plain (184.8 and 201.9 Mg C ha^{-1}), savanna (42.9 and 57.7 Mg C ha^{-1}), Pasture (37.3 and 62.3 Mg C ha^{-1}).

Other values to preserved vegetation were: 0.241257 Mg C ha^{-1} (60 deep) in Moist Field; 642.00 Mg ha^{-1} (620 cm depth) and 133.59 Mg C ha^{-1} (100 cm depth) in two different savannas; 90.26 Mg C ha^{-1} (100 cm depth) in a Woodland Cerrado [17,21-22,33]. In the same studies a trend in the decrease of SOM/SOC in the direction of lower layers (100 cm) was encountered among phytophysiognomies: about 5% of the SOM content were found in the first top 10 cm in two studies made in savannas (620 cm and 100 cm), while more than 40% of SOC was found in the first 10 cm of a Woodland Cerrado (100 cm deep) [21-22,33].

The SOC δ^{13}C signature permits inference on the balance between C3 and C4 sources of SOC by vegetal community, being the lowest values correspondent to the presence of C3 vegetation [30,37]. Miranda et al. [37] showed that δ^{13}C values increase with depth, being lower in cropped areas, exceptionally at the surface (0–5 cm), where it is possible to find no C4 signature. However, recently cultivated areas can demonstrate high C3 signature (27.6‰), similar to the Wooden Savanna. Rosolen et al. [30] could not find a clear pattern to the SOC δ^{13}C signature among soybean cultivated areas in comparison to a Wooden Savanna, but they verified a C3 substitution pattern in all pastures studied, being them improved or degraded.

3.3 Roots Compartment

The greatest part of living biomass in Cerrado fields is contained in the roots, which represents an efficient strategy for conservation of nutrients because of fire factors in savannas [8,51]. Oliveras et al. [34] showed that fire regime, however, had no influence in total root biomass (30 cm deep) in a Dirty Field. Contrastingly, it was correlated to variation of total root distribution in depth, relatively homogeneous in fire absence (37.1% at 0–10 cm; 32.1% at 10–20 cm; 30.9% at 20–30 cm), but with more pronounced decrease in fire occurrence (49.0–57.9% in the first 10 cm; ~28% at 10–20 cm; and 13.4–22.2% at 20–30 cm) [34]. Decrease on OC percentages, according to increase in depth, was also found in a Woodland Cerrado in which the medium values for total carbon in roots were: 59.73% (0-30 cm), 23.01% (30-50cm) and 17.27% (50-100 cm) [33]. Abdala et al. [21] found a great Coefficient of variation (from up to 22% to almost 32%) around the medium value of root biomass (43100 kg ha^{-1}, 620 cm deep) in the studied savanna, especially due to variation in

the amount of the thick roots, but a constant pattern of root distribution in depth was encountered among samples, decreasing with depth. The pattern of root distribution, according to diameter classes, was also measured (90 cm deep): medium sized roots always responded to 10-20% of the total root biomass; fine and very fine roots showed a decrease from about 60% to 40% of the total root biomass in the first 40 cm deep, increasing again to 70% in the deepest portion; and thick roots have exhibited an opposite behavior, increasing from 20% to 40% of the total root biomass in the first 40 cm and decreasing to about 20% in the 90 cm layer [21].

It is argued that subterranean biomass corresponds to the greatest part of the total biomass in Cerrado phytophysiognomies, as well as the proportion between subterranean and aerial biomass (ratio root/shoot) can vary greatly, depending on the age or succession stage of the vegetation, the species' functional group and abiotic characteristics of the area [2,6]. Durigan et al. [28] found that the degree of openness of savannas is also related to this index, encountering lower values in the closed savanna (0.21±0.10) than in the open one (0.76±0.73). Meanwhile, a higher root/shoot ratio (1.0) was encountered in a savanna [21].

3.4 Aboveground Compartment

Some studies of AGB/AGC have been conducted in savannas, most of them restricted to arboreal community, to which values of 4.93(±0.54) Mg. C ha^{-1}, 8.60 Mg ha^{-1}, and 62.9655(±14.6%) Mg. ha^{-1} were found [3,7-8]. Not only the savanna overstory community, but also its ground layer was investigated by [21], who found 26.020 Mg. ha^{-1} to wooden AGB, of which 12% was correspondent to shrubs, and 0.005580(+2.240) Mg. ha^{-1} to the lower stratus, with grasses representing 0.004130 (+0.500) Mg. ha^{-1}. Lopes and Miola [27] highlighted that AGB values in the Typical Cerrado (3.85 Mg ha^{-1}), and the Dense Cerrado (3.3 Mg ha^{-1}) were lower than in the Woodland Cerrado (9.90 Mg ha^{-1}) and higher than in the Gallery Forest (2.10 Mg ha^{-1}). Much lower values of live AGB of 0.2616 Mg ha^{-1} (±0.0371) and of dead standing AGB of 0.7996 Mg ha^{-1} (±0.03483) were measured to the Moist Field by [17]. In contrast, a great AGC value of 12.287 Mg C ha^{-1} was encountered to the Gallery Forest, higher than the 11.831 Mg C ha^{-1} obtained to the Woodland Cerrado, the 8.013 Mg C ha^{-1} found in the savanna and the 4.223 Mg C ha^{-1} of the Dirty Field [32]. These authors also

highlighted that all of AGC values were significantly and directly related to the RI of the respective soils (20 cm) [32]. Besides soil quality, fire is an important factor in vegetal modulation in the Cerrado domain. In spite of this, [34] didn't find a clear relationship between fire regimes and AGC in herbaceous (grasses and forbs/sub-shrubs) vegetation. While unburnt and low frequency fire (each 4 years) areas exhibited lower values of grasses, when compared to areas submitted to high fire frequency (every 2 years), forbs/sub-shrubs biomass was low in unburnt plots and the highest in 4-year frequency burnt areas. However, these authors could verify in all treatments a correlation between seasonal hydric variation and AGC in both strata, higher in the wet than in the dry season. Melo and Durigan [25] investigated if planted Gallery Forests serve as sinks for atmospheric carbon dioxide. They found that, in Cerrado domain, AGB can increase from 2.1(±0.9) Mg ha^{-1} year-1, when native species are grown by human intervention, to 18.9 Mg ha^{-1} year-1, when the exotic *Pinus* is cultivated.

Paiva and Faria [26] argued that the probable reason for the lower SOC (20cm deep) in the savanna studied by them in relation to a Dense Cerrado previously investigated was the thicker litter layer in this second phytophysiognomy. Litter biomass averages were measured to several phytophysiognomies, in different areas: Woodland Cerrado - 5.36(±4.92) Mg ha^{-1} [33]; savannas - 5.29(±2.12) [35], 5.19(±0.19) Mg ha^{-1} [21], and 3.62 Mg ha^{-1} [8]; Gallery Forest - 4.97(±1.75) Mg C ha^{-1} [35]. In another study, the total annual litterfall production in an adjacent Gallery Forest (6.3 Mg ha^{-1} year^{-1}) and savanna (3.5 Mg ha^{-1} year^{-1}) was also measured, where highly significant differences were encountered [8].

4. GAPS IN RESEARCH

Half of 22 presented studies did not provide a proper nomenclature to the vegetal community investigated, which is an obstructor to result comparisons, because of the great variation in TOC among the Cerrado phytophysiognomies. Some of them have not been investigated yet, such as the Clean Field, the Rupestrian Field and the Rupestrian Cerrado. Besides that, the most well studied phytophysiognomy, the Gallery Forest, was investigated in only five studies - followed by the Wooden Cerrado (four), the Dense Cerrado and the Dirty Field (two) and the Moist Field and the Swampy Plain (one),

indicating that we know almost nothing about carbon stock variation in the biome.

Soils, the most relevant carbon compartment in the world [52], were contemplated in 14 of these studies. We already know that rehabilitation of degraded areas of Wooden Cerrado, Gallery Forest and savanna may improve SOC amounts, turning these areas into important sinks of this element in the global cycle. However, we know nothing about endangered Brazilian Cerrado phytophysiognomies, such as those very biodiverse vegetations that grow on rock environments. Besides this, few studies were really conducted to deep layers in the soil and almost no one investigated either the nature of SOC in Cerrado or this level of accumulation.

Little information of the root compartment and AGB is available and this data almost always relates to arboreal-wooded communities, being litter compartment poorly studied, as well as herbaceous and shrubby strata. Over savanna, these strata were investigated in only six studies, which brought information about seven different vegetal formations. The application of the already developed AGB allometric equations, despite their restriction to arboreal communities of the Cerrado *sensu stricto*, is still infrequent. Also, only four studies on carbon sequestration were found, two of them about soils and the others about AGB. Only in one of these studies the phytophysiognomy was specified. Furthermore, TOM was very poorly investigated, with only three studies, two in savannas and one in a Woodland Cerrado.

5. FINAL CONSIDERATIONS

The great potential of 70% the Brazilian Cerrado lands for the agricultural and pasture expansion has conferred a high level of fragmentation and degradation to its vegetation, ensuring the status of a hotspot to the biome [6,24,53-54]. Together with these, other disturbances such as fire occurrences and climatic events, beyond modifying its physical and chemical soil properties, are negatively correlated to carbon storage, influencing the net annual flux of carbon into the atmosphere, which increases the emission of GEG and aggravates the effects of climate change on the planet [1,6,20,51,55]. Different phytophysiognomy types in the biome, with compartments with different characteristics, are expected to be correlated to varied carbon storages. Knowing this relation is fundamental to the conservation and management of these

ecosystems, especially because protected areas within the biome are rare [32,56]. An important approach in this kind of study is evaluating the change in TOC over time, looking toward providing data to Brazilian Cerrado conservation and Greenhouse effect mitigation, principally to those phytophysiognomies that are supported on rocks that since disturbed are hard to be recovered [56].

Non-destructive methods to the quantification of the AGC are available and should be used in new studies and also applied to forest inventories that had already been done. For example, the increment in the number of trees in a savanna in a decade could have been easily extrapolated for AGC by the use of a mathematical equation [8]. It would still be better if this equation included specific data for each species, to a more precise and reliable biomass estimation [57].

Some actions are then necessary to reach these purposes in future works: Expand research to all phytophysiognomies of the biome, investigate all their carbon compartments, considering also herbaceous plants and shrubs of aboveground biomass, improve soil data to greater depths and make use of specific wood density data in mathematical models used to AGC quantification.

6. CONCLUSION

The aim of this review was to synthetize the studies conducted until now which are related to carbon storage in the Brazilian Cerrado. No standard methodology was detected in the available literature and several of the studies do not specify the exact phytophysiognomy in which they were conducted. Also, the carbon quantities estimated in the same phytophysiognomy, and among different ones, varied greatly. Little information has been generated in areas not considered appropriate for agrosilvopastoral activities, being most of the data restricted to the remaining native savannas and to managed systems in their domain. The unknown scenario of the other phytophysiognomies hinders strategies for the conservation of the endangered megadiverse biome whose vegetation is of difficult recovery.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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