

DATASET ARTICLE

Organic Compounds in the Environment

The GrassSyn dataset: Soil organic carbon stocks in Brazilian grassy ecosystems

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Assigned to Associate Editor Shu Kee Lam.

Funding information

Centro de Síntese em Biodiversidade e Serviços Ecossistêmicos (SinBiose/CNPq), Grant/Award Number: 442348/2019-3;

Abstract

Although ecosystem management and restoration are known to enhance carbon storage, limited knowledge of ecosystem-specific soil organic carbon (SOC) stocks and processes hinders the development of climate-ready, biodiversity-focused policies. Baseline SOC stocks data for specific ecosystems is essential. This paper aims to: (i) examine SOC stock variability across major grassy ecosystems in Brazil and (ii) discuss data limitations and applications. We compiled the Grassland Synthesis Working Group dataset, which comprehensively aggregates SOC stocks data from published studies on main Brazil's grassy ecosystems. Our dataset results from systematic literature review and regional soil sampling datasets. The dataset provides spatially

Abbreviations: GrassSyn, Grassland Synthesis Working Group; NDVI, normalized difference vegetation index; SBD, soil bulk density; SiBCS, Brazilian soil classification system; SOC, soil organic carbon.

Bianca Ott Andrade and Cristhian Hernandez Gamboa contributed equally to this work.

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Research Centre for Greenhouse Gas
Innovation (FAPESP-SHELL Engineering
Research Centre), Grant/Award Number:
2020/15230-5

explicit SOC stocks, physical soil properties, and ancillary information from 182 studies (1996–2021) across 803 sites, spanning 35° latitude and 28° longitude. The dataset, structured in relational tables, reports soil C stocks and ancillary soil parameters at depths up to 100 cm. SOC stocks vary by grassy ecosystem types and sampling depth, with subtropical grasslands (Campos Gerais, South Brazilian highland grasslands, and Pampa) showing the highest SOC stocks across all depth layers (SOC 0–30 cm: 64.5–162.8 Mg C ha⁻¹; SOC 0–100 cm: 137.6–224.7 Mg C ha⁻¹). The tropical Cerrado and Amazon grassy ecosystems exhibit high SOC stocks, particularly in subsurface layers (SOC 0–30 cm: 53.6 and 38.3 Mg C ha⁻¹; SOC 0–100 cm: 109.8 and 121.4 Mg C ha⁻¹, respectively). Our data analysis shows high carbon stocks in natural/seminatural ecosystems, but some ecosystems are undersampled. The dataset on SOC stocks in grassy ecosystems could greatly aid Brazil's national greenhouse gas inventory.

Plain Language Summary

The Global South, including Brazil, faces challenges with data on soil carbon (C), hindering effective climate action. Improved soil sampling and consolidation of existing soil C data are essential for Brazil's contribution to global climate change mitigation strategies. This study looks at how much C is in the soil of natural grassy ecosystems in Brazil. This gives us a starting point to compare with areas where people manage the land. It shows how human actions affect C storage, guiding decisions on climate issues. Our results reveal high soil C levels in Brazil's grassy ecosystems, emphasizing the importance of protecting these areas to reduce greenhouse gas emissions. Key ecosystems, such as Highland grasslands, Savannas, Amazonian grasslands, and campo rupestre lack enough data and need focused studies. This research enhances Brazil's greenhouse gas inventory with C estimates for grassy ecosystems, demonstrating their role as important C sinks. More research is needed in subtropical and the Amazon grasslands, and standardizing soil C measurement methods remains critical.

1 | INTRODUCTION

Climate change, land degradation, and biodiversity loss are major challenges of the 21st century. Nature-based solutions—for example, conservation, restoration, and management—are emerging as promising strategies to mitigate these threats by protecting native ecosystems and enhancing carbon (C) storage (Reside et al., 2017). However, focusing exclusively on carbon may overlook the multifaceted value of biodiversity across terrestrial ecosystems. This narrow approach could potentially hinder the integration of comprehensive management strategies into effective policy frameworks, potentially impeding efforts to promote sustainability, resilience, and biodiversity conservation (Midgley et al., 2010). Accurate estimates of ecosystem-specific soil organic carbon (SOC) stocks are essential for developing

effective public policies and management strategies that effectively address both climate change and biodiversity loss.

Organic C stocks stored in undisturbed soils under native vegetation are a crucial component of the global C cycle. Information on these SOC stocks can provide a baseline for evaluating land-use change impacts as well as potential C sequestration by restoring degraded ecosystems. There is an ongoing concerted effort by the scientific community to expand and refine soil—including SOC—data availability (Arrouays et al., 2017; Peralta et al., 2022). Brazil ranks among the top five countries that hold >50% of the top-soil SOC stock (FAO & ITPS, 2020). The country is also recognized for its high potential to sequester substantial quantities of SOC in agricultural lands (Zomer et al., 2017) and its technical capability to do so (Wiese et al., 2021). Recently, Brazil established climate commitments under the

United Nations Framework Convention on Climate Change, targeting a substantial reduction in greenhouse gas emissions by 37% in 2025 and 50% in 2030, relative to 2005 levels, with a concurrent goal to achieve climate neutrality by 2050. Achieving these ambitious greenhouse gas emissions reduction targets requires science-based actions, encompassing both engineered and nature-based solutions, all of which depend on reliable SOC data. Previous initiatives to compile soil C data associated with native vegetation in the absence of significant disturbances (Batjes et al., 2004; Bernoux et al., 2002; Moraes et al., 1995) relied on publicly available data, especially World Data Centre for Soils (WDC-Soils) at ISRIC, the Netherlands (www.isric.org/explore/isric-soil-data-hub), and early Brazilian databases, now included in SISB (*Sistema de Informação de Solos Brasileiros*—Brazilian soil information system; www.bdsolos.cnptia.embrapa.br). These datasets contain large number of pedon data obtained from soil survey campaigns spanning several decades, which were not specifically targeted to SOC stock assessment. Therefore, they suffer from limitations such as data gaps, outdated and inconsistent analytical methods, and large temporal and spatial variations among soil sampling campaigns. These shortcomings can be resolved by field sampling campaigns using well-established protocols (notably IPCC, 2019; FAO, 2019), particularly for regions less represented in the above-mentioned SOC inventories. In fact, Brazil has launched a National Program for the Survey and Interpretation of Brazilian Soils (PronaSolos; Polidoro et al., 2016) to update and expand soil mapping in the country and include SOC stock assessment. However, these initiatives are time-consuming and demand consistent funding to yield palpable results. A less costly alternative approach is the meticulous collection and organization of legacy SOC data—data often dispersed throughout the peer-reviewed literature, thesis and dissertations, and targeted SOC sampling projects.

While Brazil is renowned for its extensive tropical forests, it is important to recognize that a substantial portion of its territory, approximately one-third (Overbeck et al., 2022), consists of non-forest “open ecosystems” (*sensu* Bond, 2019). These ecosystems encompass grassy ecosystems (grasslands and savannas) that, despite being overlooked in terms of conservation (Overbeck et al., 2007), are remarkably diverse (Overbeck et al., 2015; Veldman et al., 2015) and hold immense ecological significance. Soils in these ecosystems store large amounts of C and could potentially sequester additional C through improved management (Conant & Paustian, 2002; Dondini et al., 2023; Terra et al., 2023). Unfortunately, in recent decades, these ecosystems have been systematically threatened by significant land use changes. The Brazilian Pampa—dominated by subtropical grasslands—and Cerrado—dominated by tropical savannas—have already lost 43.5% and 50% of their original distribution to the expansion of agriculture, respectively (MapBiomass, 2024). These

Core Ideas

- We quantified soil organic carbon (SOC) stocks across main Brazilian natural and semi-natural grassy ecosystems.
- SOC stocks average 74.3 Mg C ha⁻¹ (0–30 cm) and 125.6 Mg C ha⁻¹ (0–100 cm).
- Subtropical grassy ecosystems contribute the most to SOC stocks across all soil depths.
- Campos Gerais and tropical grassy ecosystems store more than half of total SOC stocks in the subsurface (30–100 cm).

land-use conversions compromise the provision of a wide range of ecosystem services, including biodiversity conservation, water availability, and SOC storage (Santos et al., 2021, 2022). In general, cultivation following conversion of natural land cover usually enhances soil organic matter (SOM) decomposition, leading to lower SOC stocks, while increasing greenhouse gas emissions (Chaplot & Smith, 2023; Lal et al., 2004).

The dynamics of SOC in grassy ecosystems have been widely debated (e.g., Conant & Paustian, 2002; Conant et al., 2017; Phukubye et al., 2022). Yet, a better understanding of SOC dynamics relies on the availability of baseline SOC data. In Brazil, comprehensive baseline data on SOC stocks in natural and seminatural grassy ecosystems is still limited and scattered across individual studies. Our goal is to enhance our understanding of soil C storage in Brazilian grassy ecosystems (as defined by Overbeck et al., 2022). Notably, there has been no previous initiative that specifically sought to compile SOC stock data in these ecosystems. Adhikari and Hartemink (2016) previously highlighted the challenges of working with existing soil data, which can be outdated, inconsistent, or incomplete. Brazilian grassy ecosystems are open ecosystems shaped, both today and historically, by disturbances such as fire and grazing, and they display substantial variability in terms of their ecological features due to factors like climate, soil properties, historical processes, and human activities (Overbeck et al., 2022). Consequently, there is a need for an SOC dataset that provides accurate, reliable, and standardized information on SOC stocks under native vegetation, which is publicly available and can be regularly updated. We provide such a novel dataset for Brazil's grassy ecosystems. We rescue and collate legacy soil data, organize it in a common structure, consolidate data from various sources, and make it accessible to researchers, policymakers, and land managers.

Our objectives were to (i) examine the variability of SOC stocks within and across Brazil's major grassy ecosystems,

supported by the newly compiled Grassland Synthesis Working Group (GrassSyn) datasets, and (ii) discuss the limitations and potential applications of the available data.

2 | MATERIALS AND METHODS

2.1 | Legacy soil data collection

We performed a systematic literature review using the Web of Science (including Scielo [Scientific Electronic Library Online], <https://webofscience.com/>), ScienceDirect (<https://www.sciencedirect.com/>), and the Brazilian Digital Library of Theses and Dissertations (<https://bdtd.ibict.br/vufind/>) to obtain data on SOC stocks. For that, we searched for keywords in Portuguese and English, in any part of the scientific study (title, abstract, keywords, and the main body of the manuscript), specifically focusing on research carried out in natural or semi-natural grassy ecosystems (i.e., sustainably managed grassy ecosystems composed of primarily of native species, thereby maintaining their characteristic biodiversity and ecosystem processes) in Brazil. For the Web of Science, our search strategy included using the following keywords: grass* OR savanna* OR savanna OR camp* OR “native pasture” OR rangeland* OR pampa* OR “campos sulinos” OR Cerrado AND soil NEAR/10 carbon AND (Brasil OR Brazil OR Brazilian). When using ScienceDirect, we utilized the following terms: grassland OR grassy, OR savanna, OR “native pasture”, OR rangeland, OR campo, OR pampa, OR Cerrado, combined with one of the following terms at a time: “soil carbon”, “carbon storage”, “carbon stocks”, and “carbon sequestration”. Lastly, for the Brazilian Digital Library of theses and dissertations, we used the following combination of words: “campo nativo” OR pampa OR pampas OR savanna OR “savana do Brasil” OR “savannah do Brasil” OR “pastagem nativa” OR “pastagens nativas” OR “pastagens naturais” OR “pastagem natural” OR “ecossistemas gramíneos” OR “savannas do Brasil” OR “biomas gramíneos” AND “carbono do solo” AND “estoque de carbono”. The searches were carried out in March 2021 and composed of scientific studies published from 1990 to 2021. This resulted in 1036 scientific papers and 54 theses and dissertations (Table S1). We skimmed all publications and selected for in-depth analysis those that were conducted in natural or semi-natural grassy ecosystems in Brazil and that assessed soil carbon stocks considering a depth of at least 20 cm. To be selected, study sites should not have undergone soil amendments (e.g., fertilizer and lime) or seeding/overseeding. If extensively grazed by livestock, they were managed without improvements to either the pasture or the soil. Specifically, our criteria included scientific studies that not only reported SOC stocks for distinct soil layers or horizons but also those that provided essential data for calculating SOC stocks when this information was absent,

such as total organic carbon (TOC) and/or SOM, soil bulk density (SBD), and coarse mineral fragments. A total of 178 scientific studies met the above criteria and had data incorporated into the datasets. Additionally, four datasets from soil sampling campaigns specifically targeting soil C were contributed (Assad et al., 2013; Dávila et al., 2019; Machado et al., 2024; Morais et al., 2020), bringing the total consulted scientific studies to 182.

In addition to “core” variables like SOM, SOC, SBD, and coarse mineral fragments, we examined the selected scientific studies for geographical information, soil textural data, and SOC-related ancillary information (e.g., climate classification, altitude, and grassy ecosystem cover type).

2.2 | Datasets organization

Our datasets are structured as relational data and comprise five tables available in comma-separated (.csv) format, which contain the following information: (i) soil parameters for horizons and layers, (ii) general site information, (iii) SOC stocks, (iv) metadata information, (v) references (Figure 1).

Our datasets comprise information from a comprehensive set of 182 scientific studies or soil surveys, encompassing 803 sampling sites across Brazilian grassy ecosystems (as defined by Overbeck et al., 2022), except for those located in the Pantanal biome in Western Brazil, and coastal regions. We did not include the Pantanal region due to the limited availability of robust SOC stocks studies. Readers specifically interested in SOC stocks of this region should refer to Santos et al. (2012).

2.2.1 | Soil parameters for horizons and layers table

The table “soil parameters for horizons and layers” has 16 columns and 3437 rows, organizing information by sampling site and soil horizons and layers. The soil horizons/layers follow the range informed by the authors, with columns indicating the minimum, maximum, and total range. In some cases, there were discontinuities in the soil layer/horizons ranges, resulting in missing data for specific ranges when considering the entire soil profile. Soil parameters that capture changes in carbon stock and texture across the soil profile are as follows: coarse fragments (particle size >2 mm), TOC (%), SOM (%), SBD (g cm^{-3}), calculated SBD (g cm^{-3} ; calculated following Benites et al., 2007), SOC stock, SOC reported by the authors, as well as sand (g kg^{-1}) and clay (g kg^{-1}) content. All these information was reported by the authors in the scientific studies, with some exceptions explained below:

Approximately one percent of the sample sites did not report TOC, only SOM. These values were converted to TOC using the Van Bemmelen factor (Minasny et al., 2020).

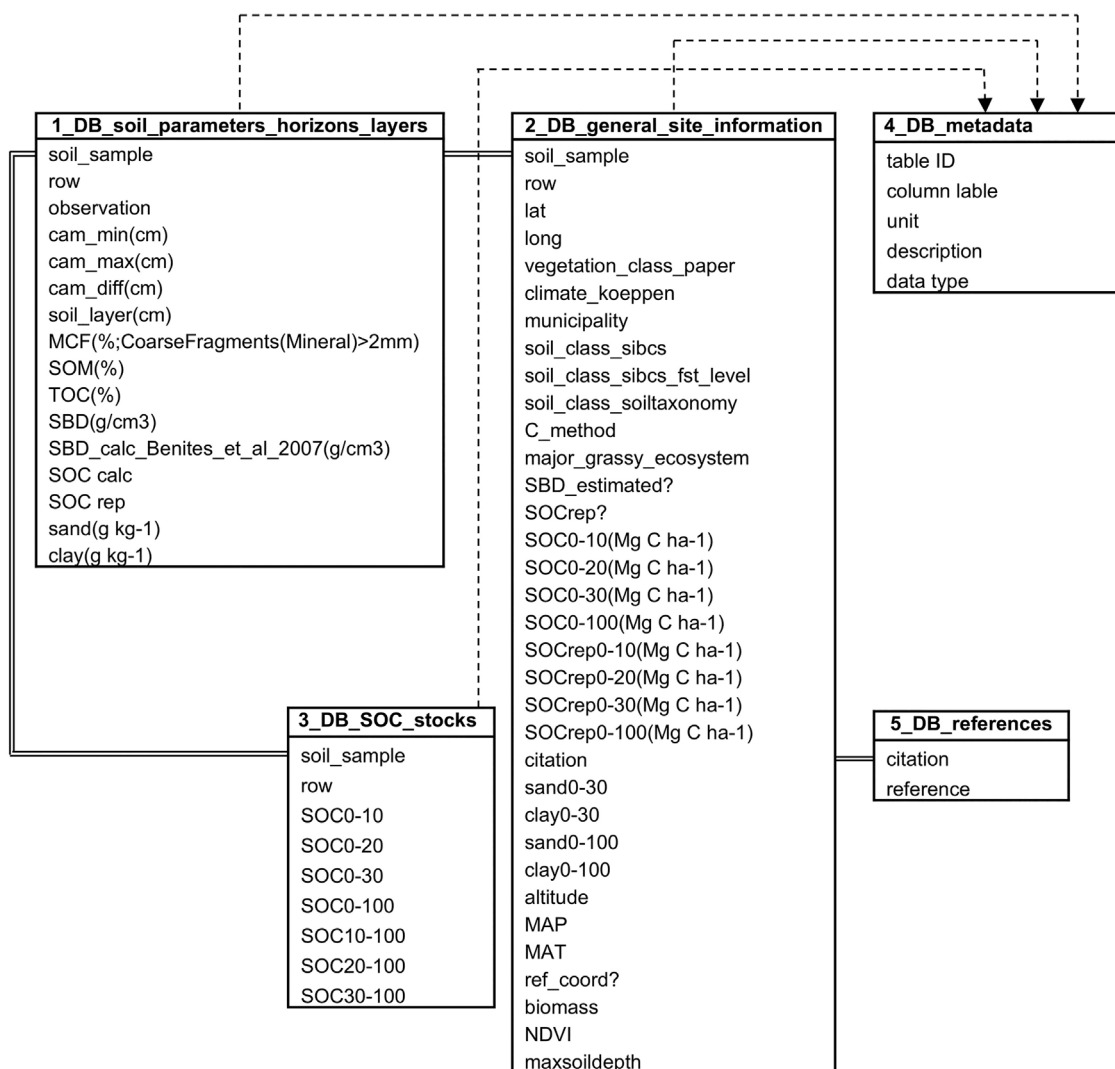


FIGURE 1 Dataset diagram. The boxes illustrate the five tables where the data are stored. Descriptions of abbreviations are found in the table named DB_metadata. MAP, mean annual precipitation; MAT, mean annual temperature; NDVI, normalized difference vegetation index; SBD, soil bulk density; SOC, soil organic carbon.

SBD was not available in 14% of the sample sites. To address these data gap, a pedotransfer function developed for Brazilian soils was applied to estimate SBD to overcome these data gap (Benites et al., 2007):

$$\text{calculated SBD (g cm}^{-3}\text{)} = 1.568 - 0.0005 \text{ clay (g kg}^{-1}\text{)} - 0.009 \text{ C (g kg}^{-1}\text{)} \quad (1)$$

SOC stocks were calculated per layer according to FAO (2019):

$$\begin{aligned} &\text{SOC stocks (Mg C ha}^{-1}\text{)} \\ &= \text{soil organic carbon of the layer (\%)} \\ &\times \text{soil bulk density (g cm}^{-3}\text{)} \times \text{layer thickness (cm)} \\ &\times (1 - \text{mineral coarse fragments (\% [decimal format])}) \end{aligned} \quad (2)$$

2.2.2 | General site information table

The “general site information” table comprises 34 columns and 803 rows and is organized by the soil sample site. It consolidates important data characterizing the sample site, including geographic location (latitude/longitude, municipality), environmental information (vegetation classification, grassy ecosystem type, Köppen–Geiger climate classification, and soil classification), sampling methods (carbon method used in the scientific study), soil properties (SOC stocks for specific layers, sand and clay content for specific layers, maximum soil depth sampled), SOC-related ancillary information (altitude, aboveground biomass carbon, normalized difference vegetation index [NDVI]), and bibliographical reference.

Authors provided geographic coordinates for the sampling sites in most cases (81%); otherwise, the centroid of the municipality was used as a proxy for location. The geographic

coordinates, when in degrees, minutes, and seconds, were converted to decimals. The coordinate system was based on the SIRGAS 2000 datum. We used the geographic location to obtain additional site information from external sources. These included grassy ecosystem type (based on the vegetation map provided by Overbeck et al., 2022), Köppen–Geiger climate classification (based on map provided by Alvares et al., 2013), altitude (obtained from SRTM 90 m Digital Elevation Model), aboveground biomass carbon (Englund et al., 2017), mean annual precipitation (MAP; Hijmans et al., 2005), mean annual temperature (MAT; Hijmans et al., 2005), and NDVI (based on Landsat 8 images from 2019 to 2023).

Soils were classified as reported in the selected studies, usually on the basis of the Brazilian soil classification system (SiBCS) (Santos et al., 2018). Additionally, we added USDA soil taxonomy (Soil Survey Staff, 2022) classification based on the relationship table from Santos et al. (2018).

We registered the SOC analytical method used in each paper as follows: D-C: dry combustion method (Nelson & Sommers, 1982); W-B: standard Walkley-Black (Skjemstad & Baldock, 2007); W-B-T: Walkley-Black with heating at -80°C (Tedesco et al., 1995); W-C-CO₂: W-B with CO₂ recirculation (Nelson & Sommers, 1982); W-C-Mmd: Mebius (Nelson & Sommers, 1982); W-C-Mbc: modified Mebius—heating to 150°C (Yeomans & Bremner, 1988). Studies that did not report the C determination method were assigned to the standard W-B method, as it is widely used for routine soil analysis in commercial laboratories in Brazil.

The “general site information” table also comprises both reported and calculated SOC stocks. Only 46% of the papers reported SOC stocks, frequently for different soil layer/horizon. We recalculated these stocks using TOC, SBD, and MCF as outlined in Equation 2 (for more details, see Section 2.1.1). For consistency, we adopted the reporting standards of 0–30 and 0–100 cm following the IPCC (2019) and FAO (2019) guidelines. Furthermore, we opted to calculate SOC stocks at depths of 0–10 and 0–20 cm, recognizing that these topsoil layers provide valuable insights due to their susceptibility to changes from land-use and management. It is important to highlight that SOC stocks at 0- to 10-cm, 0- to 20-cm, 0- to 30-cm, and 0- to 100-cm depths were only calculated when encompassing data were available for the layers chosen for this study, never obtained by extrapolation. In cases where the reported layers did not match the layers chosen in this study, we adjusted SOC stocks proportionally, assuming a simple linear relationship, similar to the method used by Bernoux et al. (2002). For example, when SOC data for 0–30 cm were not explicitly reported, but SOC stock for 0–45 cm layer was available, we assigned 30/45 (2/3) of the 0–45 cm SOC value to SOC 0–30 cm. While a more rigorous approach would fit depth distribution functions (such as equal areas splines) to estimate SOC stocks at specific depths, as described by Adhikari et al. (2014), these approaches ideally

require more data points per sample/soil profile, information that was in large part lacking in this study. The clay and sand content for 0–30 cm and 0–100 cm, on the other hand, were calculated as the depth-weighted average derived from the horizons/layers within these respective depth intervals.

2.2.3 | SOC stocks table

For the use in the boxplots and ordination analysis in this study, we created the table of SOC stocks by merging data from calculated SOC stocks and reported SOC reported columns from “General site information” table (see Section 2.1.2 for more detailed information) for the layers 0–10 cm, 0–20 cm, 0–30 cm, and 0–100 cm. If a soil sample site had both calculated and reported SOC information, we prioritized the calculated value for better dataset standardization. This resulting table of SOC stocks has nine columns and 803 rows, organizing information by soil sample site and soil horizons and layers.

Subsequently, we calculated sub-superficial SOC stocks (i.e., 10–100 cm, 20–100 cm, and 30–100 cm) by deducting the SOC data from 0–10 cm, 0–20 cm, and 0–30 cm layers from that in the 0–100 cm layer. This calculation was only possible when the sampling sites had SOC data for both superficial layers (i.e., 0–10 cm, 0–20 cm, 0–30 cm) and 0–100 cm.

2.2.4 | Metadata information table

The metadata information table has five columns and 61 rows, organized by table ID, column label, unit, description, and data type (Table S2). Each variable found in the “soil parameters for horizons and layers”, “general site information”, “SOC stocks”, and “references” tables is accompanied by a brief description, followed by its unit of measurement and data type (text, boolean, and numeric).

2.2.5 | References table

The reference table, with two columns and 182 rows, is organized by the soil sample site. One column includes the reference abbreviation as presented in the general site information table, while the other column contains the full reference.

2.3 | Data analysis

To explore patterns of SOC stocks in Brazilian grassy ecosystems, we conducted a principal component analysis (PCA)

for depth-specific SOC stocks. Because there is missing data in the table, we followed the approach proposed by Podani et al. (2021), which can handle missing data without data imputation by calculating correlations or covariances while accommodating varying numbers of observations for each pair of variables. The resulting eigenvalues and eigenvectors are utilized to compute component scores, bypassing missing values.

3 | DATASET DESCRIPTION

3.1 | Geographic extent and environmental attributes

Brazilian grassy ecosystems have historically been overlooked in terms of conservation, restoration, and management. Their ecological importance and carbon sequestration potential are undervalued, partly due to limited availability of data on SOC stocks. The GrassSyn project, titled “Biodiversity of Brazilian grasslands and savannas: patterns and drivers, ecosystem services, and strategies for conservation and restoration”, aims to address this gap by enhancing our understanding of vegetation patterns and the ecosystem services, including carbon stocks, that these ecosystems provide. Our study, part of the GrassSyn project, is the first to quantitatively assess and compare SOC stocks within grassy ecosystems at a national level in Brazil, spanning approximately 35 degrees of latitude (2.88° N–32.38° S) and 28 degrees of longitude (35.14° W–63.82° W). The distribution density is conveyed visually by the points on the grassy ecosystem map (Figure 2). Among the grassy ecosystem types, savannas in the Cerrado have the highest number of soil sampling sites (464 sites; 57.8% of total sites), followed by South Brazilian highland grasslands (144; 17.9%), Pampa grasslands (130; 16.2%), Campos Gerais (21; 2.6%), and savannas in the Amazon (17; 2.1%). The remaining grassy ecosystem types each contribute <2% to the total number of samples (Table 1). Samples in savannas in the Cerrado, Pampa grasslands, South Brazilian highland grasslands were collected from 96, 36, and 18 municipalities, respectively, while the remaining samples were taken from five or less municipalities.

Throughout this large geographic area, our datasets cover great environmental diversity, befitting a country with continental proportions. Sampling sites span tropical (A), dry (B), and humid subtropical (C) climates, with the savannas in the Cerrado being the grassy ecosystem type with the greatest diversity of climate types, including Am (tropical monsoon), Aw (tropical with dry winter), Bsh (dry semi-arid with low latitude and altitude), Cfa (humid subtropical with oceanic climate and hot summer), and Cwa (humid subtropical with dry winter and hot summer). Sampling sites in the South Brazilian

highland grasslands (Cfa and Cfb humid subtropical with temperate summer), the Pampa grasslands (Cfa and Cfb), and the savanna in the Amazon (Am and Aw) are distributed over two different climate types. Conversely, the campo rupestre, Campos Gerais, Highland grasslands, and savannas in the Caatinga are restricted to a single climate type, namely, Cwb (humid subtropical with dry winter and temperate summer), Cfb, Aw, and Bsh, respectively.

The textural triangles in Figure 2 illustrate considerable variations in soil texture, showing soils from diverse geological origins and highlighting the comprehensive representation of soil types in this study. Pampa grasslands exhibit the highest diversity of soil types, totaling 11 classes (sensu SiBCS) and 12 classes (sensu soil taxonomy). Savannas in the Cerrado come next with seven classes for both SiBCS and Soil Taxonomy classifications. South Brazilian highland grasslands have a total of seven classes (sensu soil taxonomy) and six classes (sensu SiBCS). The other grassy ecosystem types encompass up to five distinct soil types, considering one of the abovementioned classifications (Table 1). In the savannas of the Cerrado, Campos Gerais, and Highland grasslands, the predominant soil type is Oxisol. Campo rupestre, savannas in the Caatinga, and Amazonian white sand grasslands and shrublands have Entisols, Aridisols, and Quartzipsamments as primary soil classes, respectively. South Brazilian highland grasslands and savannas in the Amazon predominantly develop over Inceptisols and Entisols, while Ultisols dominate in the Pampa grasslands (Table 1).

3.2 | C methods

We observed a lack of standardization of SOC analytical method and maximum soil sampled depth across the dataset. Only a few grassy ecosystems, generally with limited sampling sizes—savannas in the Caatinga ($n = 3$), highland grasslands ($n = 1$), and Amazonian white sand grasslands and shrublands ($n = 11$)—employed a unique SOC analytical method (in all cases it was W-C-Mbc). In contrast, Pampa grasslands ($n = 130$), savannas in the Amazon ($n = 17$), savannas in the Cerrado ($n = 464$), and South Brazilian Highland grasslands ($n = 144$) use five to seven different methods, while the remaining have less than three. Regarding the maximum sample depth adopted by the authors, the Amazonian white sand grasslands and shrublands was the only type of grassy ecosystem where all sampled sites were at least 100 cm deep. Other noteworthy tropical grassy ecosystems include campo rupestre ($n = 12$), savannas in the Amazon, and savannas in the Cerrado, which had maximum depth sampled with an average of >75 cm. All the others had maximum depth sampled averaging 30 cm or more, except for Highland grasslands.

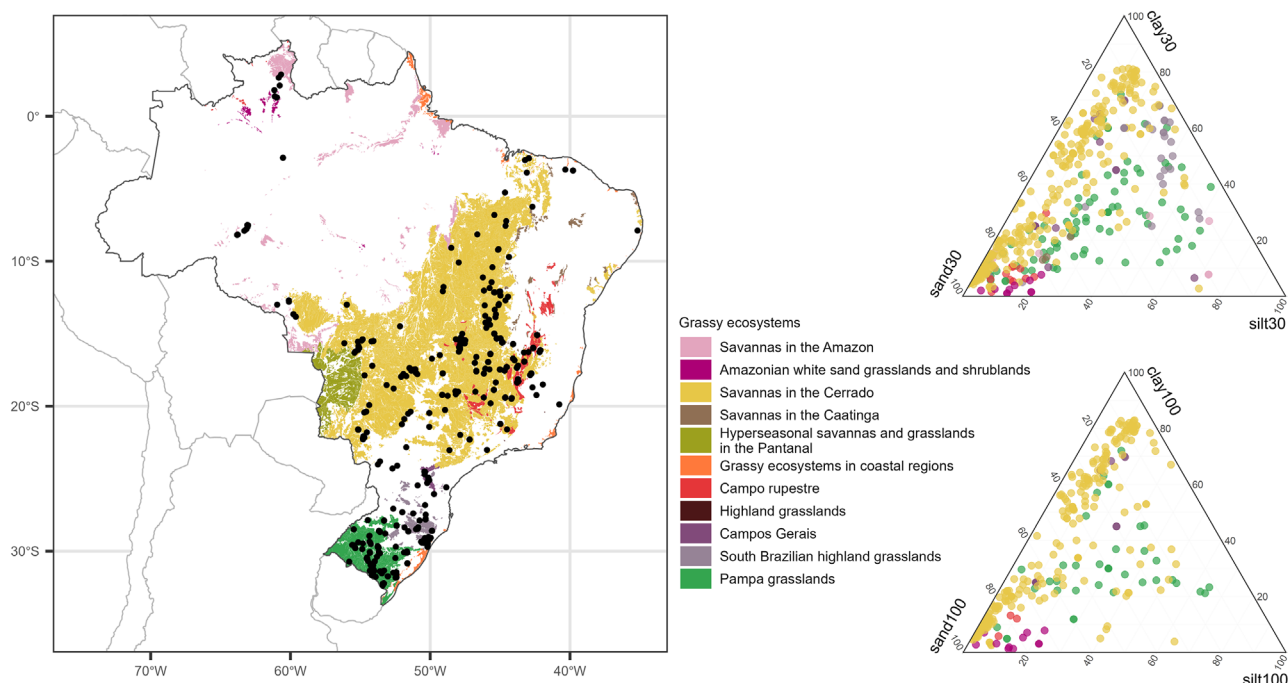


FIGURE 2 Distribution of soil organic carbon (SOC) data across Brazilian grassy ecosystems (sensu Overbeck et al., 2022) and distribution of soil texture among study sites. The colors used in the figures correspond to different grassy ecosystem types. Textural concentrations were calculated at soil depths of 0–30 ($n = 508$) and 0–100 cm ($n = 353$) to facilitate comparisons within and among grassy ecosystems and are represented by the top and bottom textural diagram, respectively. The map represents all 803 sample points, with the top and bottom textural diagram representing samples from 490 and 345 sample points, respectively.

TABLE 1 Overview of the Grassland Synthesis Working Group (GrassSyn) soil organic carbon (SOC) stocks database according to grassy ecosystem types.

Grassy ecosystem types	No. of sampling sites	Number of climate zones (Köppen–Geiger)	Number of soil classes		Predominant soil class	
			SiBCS	Soil taxonomy	SiBCS	Soil taxonomy
Savannas in the Cerrado	464	5	7	7	Latossolo	Oxisol
South Brazilian highland grasslands	144	2	6	7	Cambissolo	Inceptisol
Pampa grasslands	130	2	11	12	Argissolo	Ultisol
Savannas in the Amazon	17	2	5	4	Cambissolo	Entisol
Campos Gerais	21	1	5	5	Latossolo	Oxisol
Amazonian white sand grasslands and shrublands	11	1	3	3	Neossolo	Quartzipsamment
Campo rupestre	12	1	1	1	Neossolo	Entisol
Savannas in the Caatinga	3	1	1	1	Neossolo	Aridisol
Highland grasslands	1	1	1	1	Latossolo	Oxisol
Total	803		13	19		

Abbreviation: SiBCS, Brazilian soil classification system.

3.3 | SOC stocks

The number of soil sampling sites varies greatly among different grassy ecosystem types (Table 1) and across sample depths. The central (tropical) and southern (subtropical)

regions of Brazil have the highest concentration of soil sampling sites in the dataset. Regarding soil depth, the number of soil samples with available data on SOC stocks decreases as we consider greater soil depths: 0–10 cm ($n = 803$), 0–20 cm ($n = 777$), 0–30 cm ($n = 636$), 0–100 cm ($n = 368$), 10–100 cm

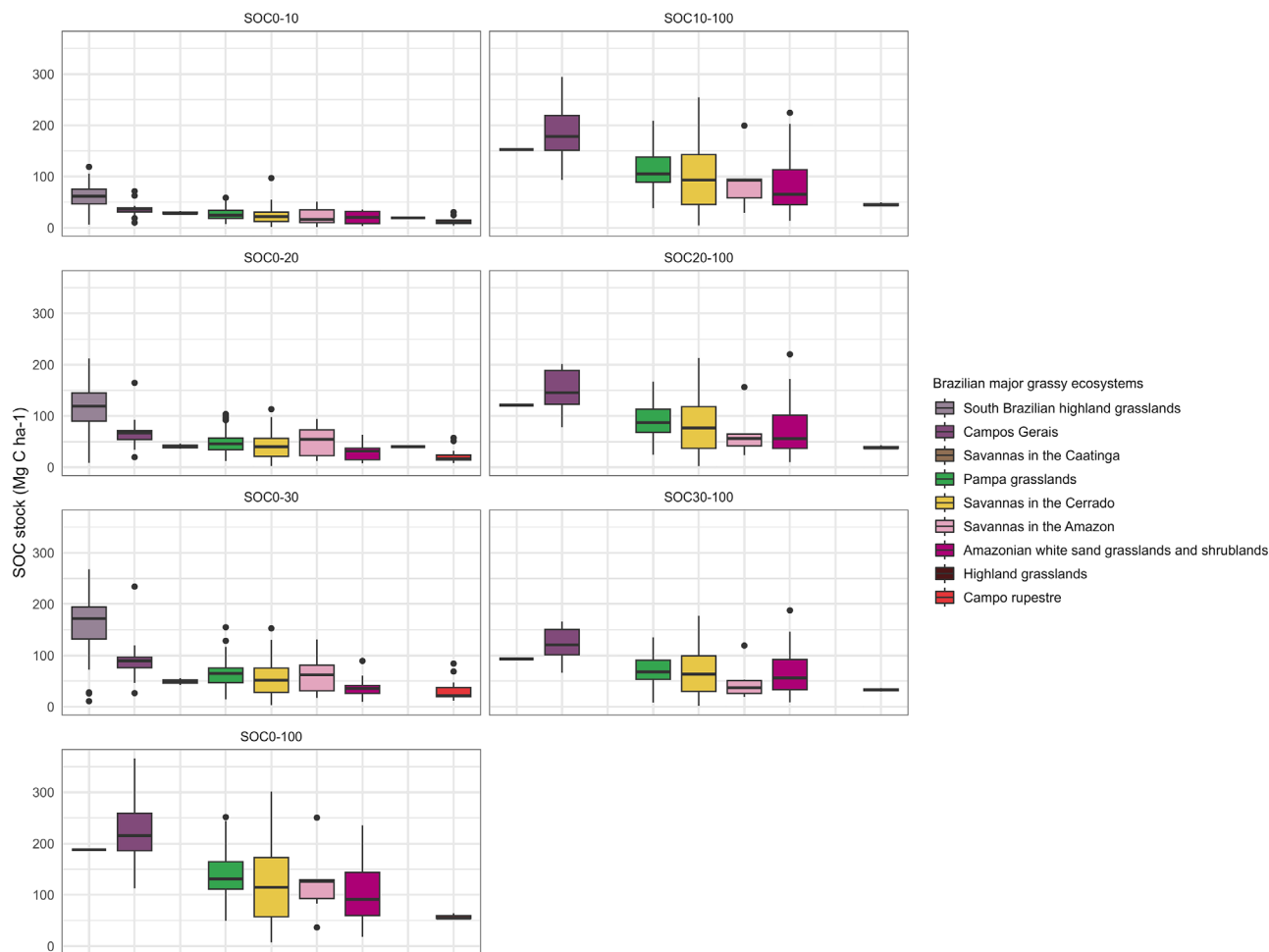


FIGURE 3 Box plots of soil organic carbon (SOC) stocks (SOCS) at 0–10 cm ($n = 803$), 0–20 cm ($n = 777$), 0–30 cm ($n = 636$), 0–100 cm ($n = 368$), 10–100 cm ($n = 368$), 20–100 cm ($n = 368$), and 30–100 cm ($n = 364$) depth per grassy ecosystem type. The majority of SOC stocks (88%–94%) were calculated using specified methods depending on the soil layer considered; otherwise, author-reported SOC values were used. Outliers are represented by dots above or below the boxplot. The colors used in the figures correspond to different grassy ecosystem types.

($n = 368$), 20–100 cm ($n = 368$), and 30–100 cm ($n = 364$) (Figure 3).

SOC stocks at 0–10 cm, 0–20 cm, 0–30 cm, and 0–100 cm average 30.3, 54.5, 74.3, and 125.6 Mg C ha⁻¹, respectively. SOC stocks at 0- to 10-cm depth range from 1.3 up to 119 Mg C ha⁻¹, while SOC stocks at 0- to 20-cm depth range from 2.3 up to 212 Mg C ha⁻¹, and SOC stocks at 0- to 30-cm depth range from 3.2 up to 268 Mg C ha⁻¹. Considering 0- to 100-cm depth SOC stocks range from 7.6 up to 366 Mg C ha⁻¹ (Figure 3). At all sampling depths mentioned above, South Brazilian highland grasslands and Campos Gerais stand out with the highest SOC stocks.

SOC stocks at 10–100 cm, 20–100 cm, and 30–100 cm average 69.3, 84.4, and 102.5 Mg C ha⁻¹, respectively. SOC stocks at 10- to 100-cm depth range from 4.7 up to 294.5 Mg C ha⁻¹, while SOC stocks at 20- to 100-cm depth range from 2.2 up to 220.3 Mg C ha⁻¹, and SOC stocks at 30- to 100-cm depth range from 1.75 up to 187.9 Mg C ha⁻¹ (Figure 3). In all sampling depths mentioned above, we can observe a much

greater variation in terms of SOC in subsurface compared to surface values for Campos Gerais, Pampa grasslands, savannas in the Cerrado, and Amazonian white sand grasslands and shrublands.

The first two principal components (PCs) of the PCA ordination analysis describe 87% of the total variation of the dataset (Figure 4). PC1 is mainly influenced by the negative correlation between SOC 30–100 cm and SBD (Table S3), which are negatively correlated. In contrast, PC2 is influenced by SOC 0–30 cm, along with sand and clay content. South Brazilian highland grasslands stand out for their high levels of SOC 0–30 cm, strongly influenced by higher altitudes, high rainfall, and lower temperatures. Across the range of grassy ecosystem types found in Brazil, a distinct gradient, guided by soil physical properties, is evident in the northwest-southeast direction. Amazonian white sand grasslands and shrublands, savannas in the Caatinga, and campo rupestre are restricted at one extreme of this gradient, characterized by high sand concentrations, higher SBD, and lower SOC stocks. Savannas in

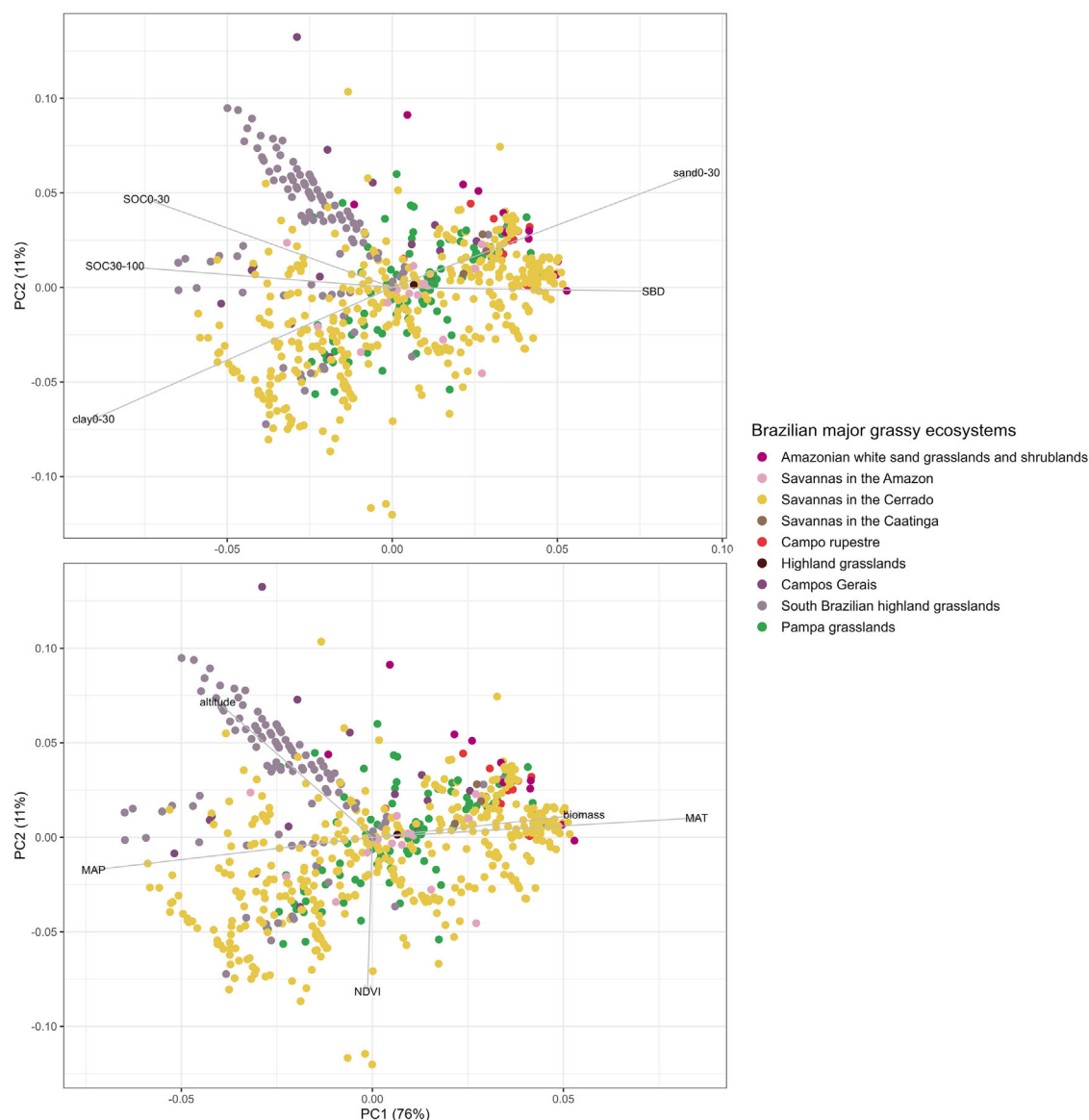


FIGURE 4 Principal Component Analysis ordination plot summarizing soil data containing soil organic carbon (SOC) 0–30 cm (soil carbon stock at 0- to 30-cm depth), SOC 30–100 cm (soil carbon stock at 30- to 100-cm depth), SBD (soil bulk density), sand 0–30 cm (sand content at 0- to 30-cm depth), and clay 0–30 cm (clay content at 0- to 30-cm depth). The bottom plot presents environmental data—which include MAT (mean annual temperature), MAP (mean annual precipitation), altitude, normalized difference vegetation index (NDVI), and aboveground biomass carbon—were plotted as arrow vectors on unconstrained ordination to better interpret gradients.

the Cerrado, Pampa grasslands, and savannas in the Amazon are more evenly distributed across this gradient. They encompass a broader range of variation in terms of temperature and rainfall, directly impacting SOC stocks and carbon fixed in the plant biomass.

3.4 | Limitations and potential application of these datasets

Any accounting of soil C data from different sources carries inherent uncertainties deriving from the original data. The

studies retrieved were conducted across several decades, and we assumed that the natural and semi-natural grassy ecosystems sampled were at a steady state with regard to soil C. Where these areas were grazed, care was taken to reject studies reporting intensive cattle management practices that could undermine this assumption. One key aspect is the C analytical method: many earlier studies utilized the W-B wet combustion for determining C concentration of soils, which can be less accurate than the standard dry combustion method that predominates today. In addition, using the WB may not fully oxidize and quantify pyrogenic C, which can be an important and intrinsic C pool of grassy ecosystems soils that have

historically evolved and managed with fire. As discussed in Batjes (2011) and Smernik et al. (2000), we should expect an underestimation of C stocks with W-B wet combustion.

The dataset comes with inherent limitation regarding the reported SOC stocks. Note that 37% of the collected data are derived from shallow sampling (up to 30-cm depth), with some exceptions, such as the IFMG dataset (Moraes et al., 2020), that included soil sampling to 100-cm depth. To enhance the accuracy of regional SOC assessments, it is advisable to expand sampling to greater soil depths, aligned with international recommendations (0–30 and 0–100 cm) (IPCC, 2019; FAO & ITPS, 2020). A study by Boddey et al. (2010) demonstrated a remarkable threefold increase in SOC storage when examining depths of up to 100 cm in Brazilian Oxisols. This underscores the importance of comprehensive soil sampling practices for a more robust understanding of SOC dynamics.

The GrassSyn SOC datasets are the most comprehensive available for soils in Brazilian grassy ecosystems with no history of land-use change. The datasets developed in this study can serve as baseline data for monitoring the impact of land-use changes on soil C. They also enhance the accounting of ecosystem carbon stored in preserved vegetation in Brazil, particularly by refining estimates in the Brazilian National Inventory of Greenhouse Gases, thereby supporting the development of effective policies. Refining these estimates would require new soil sampling campaigns in the remnants of grassy ecosystem.

4 | SUMMARY

We expect that this systematic review and the accompanying dataset of SOC stocks in grassy ecosystems will significantly contribute to the Brazilian National Greenhouse Gases Inventory. Robust estimates of SOC stocks in natural grassy ecosystems are crucial, providing a baseline for comparison with managed grassy ecosystems and allowing an assessment of SOC stocks changes due to land-use change and management. In this context, these data offer valuable insights into the performance of the agricultural sector. Furthermore, our efforts in retrieving and compiling these data align with the call to rescue legacy soil data, including unpublished data from theses, dissertations, field reports, and project databases, as emphasized by Arrouays et al. (2017). Our results show that Brazil's grassy ecosystems store substantial SOC stocks, and their conservation is critical to avoiding additional greenhouse gas emissions. However, some of Brazil's grassy ecosystems, such as the Highland grasslands, savannas in the Caatinga and Amazonian grasslands, and campo rupestre, are underrepresented and require coordinated sampling efforts. We emphasize the importance of standardized sampling protocols

for a better understanding of SOC dynamics and accurate C stocks estimation.

AUTHOR CONTRIBUTIONS

Bianca Ott Andrade: Data curation; formal analysis; visualization; writing—original draft; writing—review and editing. **Cristhian Hernandez Gamboa:** Conceptualization; data curation; methodology; project administration; writing—review and editing. **Gabriel William Dias Ferreira:** Conceptualization; investigation; writing—review and editing. **Martin Wiesmeier:** Methodology; writing—review and editing. **Eduardo Delgado Assad:** Resources; writing—review and editing. **Carlos Eduardo Pellegrino Cerri:** Funding acquisition; project administration; writing—review and editing. **José Márcio Mello:** Resources; writing—review and editing. **Vinícius Augusto Moraes:** Resources. **Gerhard E. Overbeck:** Project administration; writing—review and editing. **Herval Vieira Pinto-Junior:** Resources; writing—review and editing. **José Roberto Soares Scolforo:** Resources. **Carlos Gustavo Tornquist:** Conceptualization; data curation; funding acquisition; project administration; supervision; writing—review and editing.

ACKNOWLEDGMENTS

This paper is an outcome of the project 'GrassSyn - Biodiversity of Brazilian grasslands and savannas: patterns and drivers, ecosystem services, and strategies for conservation and restoration' conducted within the Brazilian Synthesis Center of Biodiversity and Ecosystem Services (SinBiose - Centro de Síntese em Biodiversidade e Serviços Ecos-sistêmicos, Brazil; grant 442348/2019-3 to GEO), funded by MCTI/ CNPq, as well as by the Research Centre for Greenhouse Gas Innovation (RCGGI), jointly sponsored by FAPESP-SHELL Engineering Research Centre (Project 2020/15230-5). GWDF acknowledges the research grant from CAPES (process number 88887.144594/2017-00), while BOA and CHG acknowledge research grant from FUSP. HVP-J and GEO acknowledge support by CNPq (150021/2022-4, 304852/2022-8, respectively). CGT acknowledges a RCGGI-FUSP fellowship.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

All data are available in the FigShare repository (<https://doi.org/10.6084/m9.figshare.24919629.v1>). The dataset meta-data is given in the Supporting information.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Andrade, B. O., Gamboa, C. H., Ferreira, G. W. D., Wiesmeier, M., Assad, E. D., Cerri, C. E. P., Mello, J. M., Morais, V. A., Overbeck, G. E., Pinto-Junior, H. V., Scolforo, J. R. S., & Tornquist, C. G. (2024). The GrassSyn dataset: Soil organic carbon stocks in Brazilian grassy ecosystems. *Journal of Environmental Quality*, 1–14. <https://doi.org/10.1002/jeq2.20665>