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Review article: Fire emissions in the Brazilian Cerrado – dynamics, estimates, management, and their role in the global carbon budget

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Abstract. Estimating fire emissions in the Brazilian Cerrado requires integrating fire parameters, mitigation strategies, and policies. Despite the Cerrado's significant contribution to global fire emissions, research in this area is still overlooked when compared to other savanna ecosystems. Here, we provide a comprehensive understanding of the Cerrado's fire emissions within the global carbon budget by examining how fire dynamics, management, and policy shape emissions. We systematically reviewed 77 papers, of which 57 % address fire dynamics, management, and policy. While these are key to providing a holistic understanding of fire emissions, linking them to estimates is challenging, especially due to the difficulty in valuing the qualitative aspects of fire. This review only identified two papers that explicitly analyse fire emissions in the Cerrado and found that 17 % of papers are led by institutions located within the Cerrado biome area. These numbers reinforce the urgent need for further investigation into the topic. Most papers employ different methods to achieve their results. Evidence suggests growing interest in fire emissions in the Cerrado, reflected by the rising number of studies over the years. More research is required to provide a more comprehensive understanding of fire emissions in the Cerrado, to understand fire dynamics and emissions, and to identify potential mitigation measures that could help reduce the Cerrado's contribution to the global carbon budget. This could be achieved by better accounting for emission parameters across the Cerrado's vegetation types and fire regimes and by including fire management representation in land surface models and using observational data to constrain and assess their utility.

1 Introduction

The Brazilian Cerrado biome (hereafter referred to as "the Cerrado") covers approximately $2 \times 10^6\,km^2$ in central Brazil. It is the second-largest biome in Brazil, covering almost 24 % of the country (Brazilian Statistics Institute (IBGE), 2004). Around 49 % ($965\,783\,km^2$) of the Cerrado is covered by natural vegetation (MapBiomas, 2022), where anthropogenic land uses do not occur (e.g. pasture and agriculture). The Cerrado is one of the species-rich tropical savannas in the world (Klink and Machado, 2005; Schmidt and Eloy, 2020; Simon et al., 2009), and it is heavily influenced by fire (Fidelis, 2020; Pivello, 2011). Fire is the most critical factor in maintaining its health and biodiversity (Fidelis, 2020; Franke et al., 2018; Pivello, 2011) and the wide variety of ecosystems contained within it (Franke et al., 2018). Fire is also a major driver of carbon emissions, which influences the Cerrado's overall contribution to the global carbon budget.

In the Cerrado, the extensive range of vegetation assemblages influences fire through variations in fuel type and structure across the region, as well as microclimate conditions (Flannigan et al., 2009; Gomes et al., 2020a). The Cerrado comprises a mosaic of vegetation formations, or physiognomies, that range from grasslands (such as *Campo Limpo* and *Campo Sujo*) to savannas (such as *Cerrado Ralo*, *Cerrado Típico*, and *Cerrado Denso*) to forest formations (such as *Cerradão*) (Ribeiro and Walter, 2008). The open formations (grasslands and savannas) are dominated by grasses and herbs, or fine-fuel load, with few shrubs and trees (Ribeiro and Walter, 2008). Open formations have higher wind speed, higher air temperature, lower relative humidity, and lower fuel moisture than forests do (Hoffmann et al., 2012).

The Cerrado presents two distinct seasons: the rainy season (November–March), characterized by biomass accumulation and higher fuel moisture, and the dry season (April–October), when the accumulated biomass available for burning becomes highly flammable, and fire can rapidly spread (Gomes et al., 2020b; Hoffmann et al., 2012; Silva et al., 2021). Intense wildfires in the Cerrado tend to occur in the late dry season (LDS; August–October) (Moura et al., 2019; Silva et al., 2021), when fire emissions are expected to be higher.

In the Cerrado, higher temperatures and reduced precipitation are now more common due to climate change (Hofmann et al., 2021), which also change its fire regimes. Arruda et al. (2024) observed a shift in the peak of fire activity, with the highest concentration of fire events changing from September to October between 1985 and 2022. Fire events are also becoming more frequent and intense (Gomes et al., 2024; Oliveira et al., 2022; Pivello et al., 2021). Working groups I and II of the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR6 WGI/WGII; IPCC, 2021, 2022) and the United Nations Environment Programme "Spreading like Wildfire" report (UNEP, 2022) warn that climate change increases drought conditions, which can aggravate heatwaves, increasing the risk of fire occurrence and the intensity and frequency of extreme events such as wildfires. This happens because the combination of extreme-weather events that occur simultaneously, or compound events, can amplify their effects (dos Santos et al., 2024). Drought–heatwave episodes and extreme-fire events intensified by climate change also impact hydrological processes, including precipitation and evaporation trends, groundwater recharge, and soil infiltration capacity (Klink et al., 2020; Libonati et al., 2022). This is particularly important because the Cerrado region supports aquifers that supply major hydrographic basins in the whole country (Klink et al., 2020).

Fires in the Cerrado release substantial amounts of carbon into the atmosphere, primarily in the form of carbon dioxide (CO_2) but also as other greenhouse gases such as carbon monoxide (CO) and methane (CH_4) – CO_2 and CO combined account for 95 % of the carbon emitted during biomass burning (Ward and Hardy, 1991). CO_2 and CO are both involved in atmospheric chemistry and in the greenhouse effect in different ways. Savanna burning dominates the emission of CO through incomplete combustion due to limited oxygen (Ehhalt et al., 2001). Similarly, CO_2 is released during complete combustion of biomass burning (Prentice et al., 2001). CO_2 is a major greenhouse gas, and it is crucial in the absorption and trapping of infrared radiation in the atmosphere. The increased concentration of CO_2 in the atmosphere has warmed the Earth by alarming amounts (IPCC, 2022). Thus, understanding the contribution of each of these gases, especially CO_2, to fire emissions is essential, particularly in fire-prone locations such as the Cerrado.

Beyond emissions, fire interacts with several components of the carbon cycle, shaping complex processes over time (Bond et al., 2004). For example, post-fire recovery critically shapes the Cerrado's long-term carbon balance (Gomes et al., 2020b, 2024; Hamilton et al., 2024). If vegetation fully regenerates to its pre-fire state, there is no net effect on atmospheric CO_2 levels over time. Alternatively, if fire activity decreases and vegetation accumulates, the landscape may shift to a net carbon sink. Conversely, if fires reduce long-term vegetation cover, the Cerrado could become a sustained carbon source, as has been observed globally (Burton et al., 2024). In fact, Gomes et al. (2024) indicate that fires in the Cerrado have acted as a source of carbon emissions to the atmosphere over the past decades.

The Cerrado's fires are potentially responsible for more than 30 % (about $0.13\,\mathrm{Pg\,C\,yr^{-1}}$) of Brazil's total fire emissions (da Silva Junior et al., 2020). The Cerrado also accounts for about 14 % of Brazil's emissions from land use and land cover change (SEEG, 2023). Brazil is the highest emitter in the world in this category (Friedlingstein et al., 2023), contributing up to $0.4\,\mathrm{Pg\,C\,yr^{-1}}$ (Rosan et al., 2021). Thus, understanding the Cerrado's fire-driven carbon emissions is critical for accurately quantifying national greenhouse gas contributions; assessing Brazil's progress toward climate commitments, such as its nationally determined contributions (NDCs); and evaluating its role in the global carbon budget. Accurate quantification of these emissions helps evaluate carbon sources and sinks, greenhouse gas contributions, and the impact of land management and climate policies at both national and global scales.

In this context, understanding fire dynamics provides the means to assess fire emissions in the Cerrado, and the interaction between these is essential for uncovering the factors that influence the Cerrado's role in the global carbon budget and the broader implications for national and international policy. Linking fire dynamics to estimated emissions also guides mitigation by identifying aspects for potential intervention. For example, natural activities to avoid the release of greenhouse gases (GHGs) or to increase carbon storage by letting vegetation recover, termed natural climate solutions (NCSs), have emerged as a possibility for reducing emissions (Griscom et al., 2020). Tropical NCSs, like improved fire management, could mitigate $6.56\,\mathrm{Pg\,CO_2\,yr^{-1}}$ (petagrams of CO_2 annually) between 2030 and 2050 (Griscom et al., 2020). Management activities, which include fire management, have 26 % of NCS mitigation potential in Asia, Africa, and Latin America (Griscom et al., 2020). Lipsett-Moore et al. (2018) found that prescribed savanna burning, a typical fire management activity, could reduce 75 % of emissions from LDS fires in South America.

Thus, it is essential to account for fire emissions and recognize mitigation mechanisms worldwide. This is notably relevant for the Cerrado due to its intrinsic connection to fire. This review examines how fire carbon emissions in the Cerrado are estimated, and, in particular, what the parameters used to estimate emissions are, what fire carbon emissions estimates have been published, and their implications for fire management and policy. Since carbon is a major contributor to atmospheric greenhouse gas levels, this systematic review focuses on emissions in terms of carbon released by fire, including all the carbon components emitted during biomass burning or in terms of CO_2 alone due to its impact on the greenhouse effect.

This systematic literature review aims to gain a comprehensive understanding of the Cerrado's fire emissions within the global carbon budget by evaluating how fire parameters can inform emission estimates and mitigation strategies. In particular, we aim to (a) outline current emissions estimates, especially carbon, in regions that encompass the Cerrado or are limited to it; (b) describe fire parameters that support these estimates; (c) understand how these estimates fit the carbon budget; (d) identify mitigation strategies in the biome and their link to fire-driven carbon fluxes; and (e) identify research gaps. This will support improvements for future fire emission estimation, provide insights into the placement of the Cerrado in the global carbon balance, and assist with the creation of fire policies.

2 Methods

According to Moher et al. (2009, p. 1), a systematic review is "a review of a clearly formulated question that uses systematic and explicit methods to identify, select, and critically appraise relevant research, and to collect and analyse data from the studies that are included in the review". It is based on rigorous criteria and a well-established and reproducible methodological approach to evaluate and synthesize the state of understanding of a specific topic (Cronin et al., 2008; Foo et al., 2021; Moher et al., 2015). We conducted this systematic review according to the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) statement (Moher et al., 2009) and the practical guide on conducting systematic searches by Foo et al. (2021). PRISMA was designed to guide authors in transparently reporting the review process (Moher et al., 2009).

We followed the four main steps outlined by Foo et al. (2021) to conduct this systematic review: (1) decide on a review question, (2) execute the search, (3) perform the initial literature screening, and (4) perform the full-text screening. We also combined the literature review steps outlined by Cronin et al. (2008), which include selecting a review topic; searching the literature; gathering, reading, and analysing the literature; and writing the review. After establishing our research question, "how can compiling published material on fire emissions in the Cerrado provide a holistic understanding of their role in the global carbon budget?", we combined keywords in English with the Boolean operators AND and OR in the Google Scholar database: fire AND emissions AND (Cerrado OR "Brazilian Savanna" OR (Savanna AND Brazil)). Keyword searches revealed a total of 3717 records.

We applied four inclusion criteria to identify the relevant literature: papers had to (1) be published in peer-reviewed journals with an impact factor greater than 1, (2) encompass the Cerrado biome, (3) be published after 2003, and (4) be conducted in areas that do not explicitly include anthropogenic land uses. Although we acknowledge the role of anthropogenic fires and the importance of further research to integrate these to fully assess fire emissions in the Cerrado, we focus on fires that are not explicitly used for anthropogenic land uses – as land clearing for agriculture implementation – to provide a clearer ecological perspective on fire emissions in the Cerrado and their implications for the global carbon budget. Thus, identifying the key drivers of fire emissions in the Cerrado's landscapes provide a strong basis for improving emissions estimates, understanding fire–climate feedback, and assessing long-term ecosystem resilience in the Cerrado.

To improve the assessment of our research question, we have also incorporated in our review papers that do not focus only on the Cerrado but rather include it as part of the analysis. Although we explicitly limited the region to the Cerrado in our keyword search, we often encountered papers that include the Cerrado but are not limited to it. Including these papers in our review allows for a complete analysis of fire emissions in the Cerrado from global to local scales.

Despite its constraints, the impact factor was included as an indicator of scientific quality (Andersen et al., 2006; Ketcham and Crawford, 2007). The search starts in 2003 because fire emissions estimation is highly dependent on satellite data, much of it from MODIS (Moderate-Resolution Imaging Spectroradiometer) satellite burn products, with full-year data available starting in 2003. The influence of MODIS data on our understanding of global fires can be seen in fire–vegetation modelling. There is broader disagreement between models on simulated burned area before the MODIS era and much higher agreement during the satellite period (Kloster and Lasslop, 2017; Hantson et al., 2020; Rabin et al., 2017). We evaluate the trend in the number of papers published over time using linear regression.

The criteria led to the initial screening of 109 papers. Although we used keywords to conduct our review, the searches still returned papers not in English or that did not mention fire emissions. 32 papers were excluded due to being duplicates, not in English, or not mentioning fire emissions. Review and perspective papers were included in this systematic literature review to contribute to a more complete analysis of fire emissions in the Cerrado. Review and perspective papers analyse previously published studies by evaluating the existing literature (review) or expressing opinions on a specific topic (perspective), while empirical studies provide new information based on observation or experiments. Although they do not focus on bringing original research, they supply the current knowledge of a specific topic and highlight the pertinent published literature (Cronin et al., 2008). We full-text screened the remaining 77 papers to confirm that they met all the eligibility criteria. Figure 1 demonstrates the systematic literature review process using the PRISMA diagram.

Once we had selected the papers, we adopted a systematic scheme to review, analyse, and synthesize them. We retrieved the following information from the 77 papers: title, year of publication, authors, journal, study design, area of study, what was measured, how it was measured, and institutions of the authors. The 77 papers selected for this literature review are available in the Supplement. After selecting the papers, we wrote a summary of each study to simplify the understanding of its content and to build a solid basis for writing the review (Cronin et al., 2008). From this, we framed the review by dividing the literature into themes. This approach has proven to be an efficient way to conduct and discuss the results from a systematic literature review in da Veiga and Nikolakis (2022).

We classified the reviewed papers based on (a) location range from global to local scales (global, tropical region, South America, Brazil, and the Cerrado), (b) topic of research, where we identified three topics in the literature: fire dynamics parameters, fire emission estimates, and fire management and policy; and (c) study design, divided into empirical, review, and perspective. These classifications allowed a deep understanding of the general scope of the published literature on fire emissions in the Cerrado, including the purpose of the studies. This, in turn, enabled the identification of key trends for future research, which are outlined in this review. We divide our results into four sections, first summarizing the overall trends in current publications and then highlighting the key findings from each of the three literature topics identified through our review process.

3 Results

3.1 Systematic literature review process

We reviewed 77 papers and incorporated them into the literature review process. The number of papers published has increased since 2003 (Fig. 2), indicating a rise in interest in understanding fire emissions in the Cerrado and a rise in papers on fire science being published.

There is a statistically significant increasing trend ($p \leq 0.005$) in the number of papers published throughout the time series, with a sharp drop in publications in the year 2022. 28 papers focused on the Cerrado, while 25 provide a global-scale analysis, 9 relate to Brazil, 9 to South America, and 6 to the tropical region. These numbers suggest that most papers are either restricted to the Cerrado or provide a broad global analysis, with fewer papers in between, as shown in Fig. 3.

Papers not restricted to the Cerrado provide a broader perspective on emissions, encompassing the biome instead of being limited to it. Often papers referring to one limited region were expanded to represent a broader area. For example, within the South American Biomass Burning Analysis (SAMBBA) project in 2012, Hodgson et al. (2018) used airborne flights in Tocantins, a Brazilian state dominated by the Cerrado, to represent fire emissions from smoke sampling for the whole Cerrado biome. Similarly, Mistry et al. (2019) use the examples of Brazil and Venezuela to illustrate how fire management can support emission reduction in South America.

As per the study design, we identified 60 empirical papers (78 %), 14 review papers (18 %), and 3 perspective papers (4 %). We further connect the study design with the coverage of the study area in Fig. 3.

We also observed that international (non-Brazilian) institutions drive most of the research captured by this literature review. We gathered the institution from the first author of each paper, of which 47 are international (61 %) and 30 are Brazilian (39 %). From the Brazilian-led papers, 13 (43.3 %) are from institutions located within the Cerrado biome area (Fig. 4). From the international-led studies, 16 papers (34 %) involve authors from Brazilian institutions, while 14 of the Brazilian-led studies (47 %) include authors from international institutions.

By reading the papers and through full-text screening of the content, we identified three topics of search from this systematic literature review process: (1) fire dynamics parameters, where the study aims to measure and evaluate parameters that can be further used to estimate emissions; (2) emission estimates, which include papers that focus on the quantification of fire emissions; and (3) fire management and policy, where papers discuss the importance of fire management and fire policy on influencing emission rates.

Of the 77 papers reviewed, 46 relate to fire dynamics parameters used to estimate emissions, 43 report the amounts of fire emissions, and 12 report fire management and policy. It is worth noting that 24 papers are related to more than one topic. These numbers indicate that most papers are not related to reporting emissions but provide information to support the understanding and estimation of fire emissions – 57 % (double counts included) of papers address fire dynamics, management, and policy.

Of the 43 papers that report fire emissions, 23 focus only on fire emissions, while 18 analyse fire emissions and fire dynamics parameters, 1 focuses on fire emissions and fire management, and 1 on the three topics. From the 23 papers exclusive to fire emissions, only 2 are restricted to the Cer-

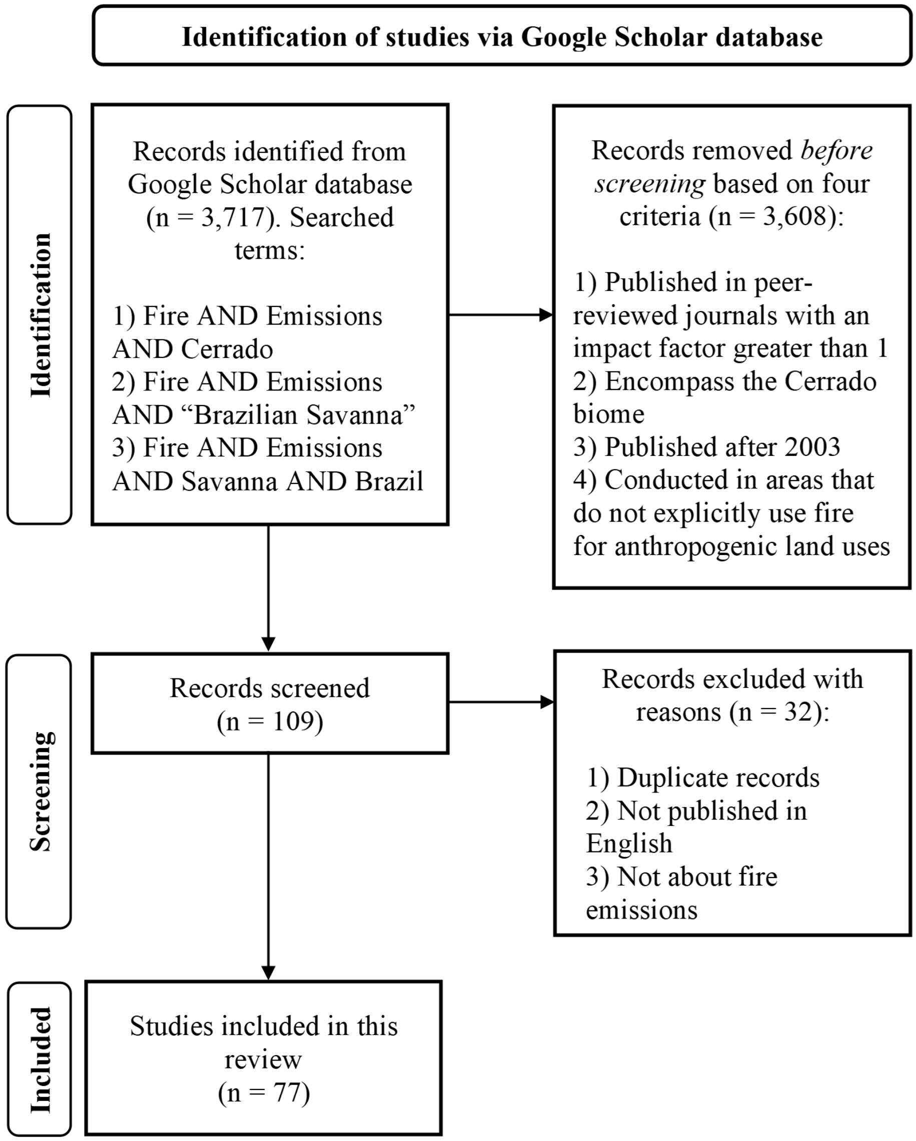


Figure 1. Adapted PRISMA flow diagram demonstrating the systematic literature review process divided into three steps: identification of potential papers through terms searched in the Google Scholar database and exclusion of papers based on the four criteria established for this research, screening of the papers selected and exclusion of papers with the reported reasons, and inclusion of papers in this literature review.

rado, 1 focusing on net CO_2 (Gomes et al., 2024) and the other on fine particulate matter (Mataveli et al., 2019). The remaining papers include the Cerrado region but are not limited to it (9 provide a global analysis, 5 relate to the tropical region, 4 to South America, and 3 to Brazil).

Most papers provide new information on the parameters used to estimate fire emissions and on emissions themselves rather than analysing the existing literature. These often handle modelling techniques, satellite observations, in situ observations, and even results found in previous studies, reflecting the importance of literature reviews in supporting the development of new data. In this study, we discuss "models" in terms of the qualitative and quantitative characterizations of components within a system and their interactions (IPBES, 2016). These tools are often combined to provide a more complete analysis. Modelling and satellite observation are frequently integrated, with satellite observations being data provided to models, models being evaluated by satellite observations, or even data assimilation between satellite data and modelling simulations. From our results, 22 empirical papers integrate modelling and satellite data; 4 integrate modelling and a literature review; 4 integrate satellite and in situ observations; and 1 integrates modelling, satellite data, a literature review, and in situ observations. Figure 5 shows the techniques used across the study areas in empirical papers.

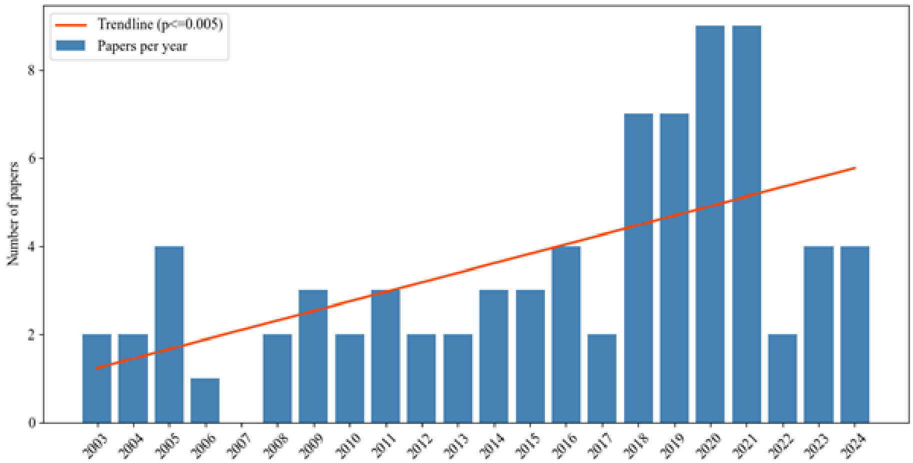
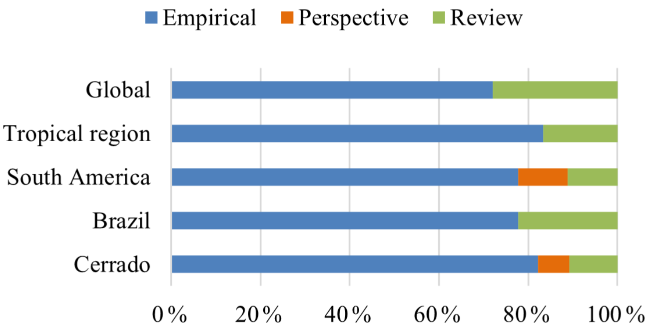


Figure 2. Number of papers published per year since 2003 that are included in the literature review (p value ≤ 0.005).



	Cerrado	Brazil	South America	Tropical region	Global
Empirical	23	7	7	5	18
Perspective	2	0	1	0	0
Review	3	2	1	1	7

Figure 3. Number of papers per study design and per coverage of study area in both percentages (chart) and absolute numbers (data table).

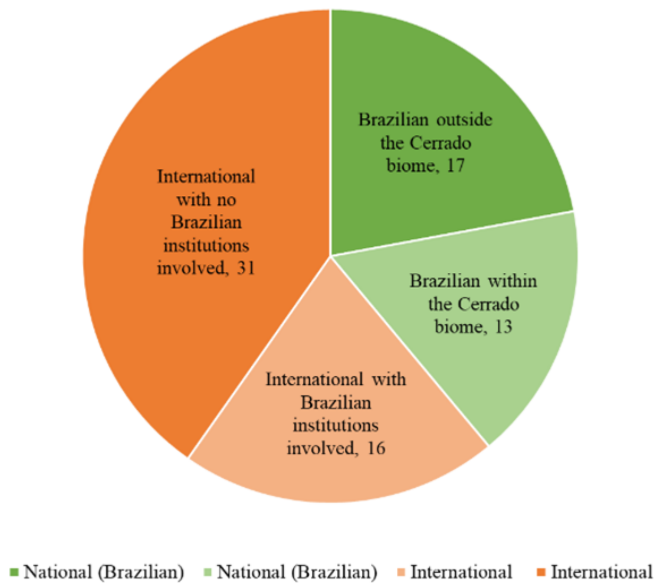


Figure 4. Institutions of the first authors from the papers reviewed. 47 papers involve first authors from international (non-Brazilian) institutions (oranges), while 30 come from Brazilian institutions (greens). From the international-led papers, 16 involve authors from Brazilian institutions, while 31 do not. From the Brazilian-led papers, 13 are from institutions located within the Cerrado biome, while 17 are not.

Of the 30 papers specific to the Cerrado, 4 were classified as review papers, and these are mostly related to the parameters associated with fire emissions, fire behaviour, and fire ecology (see Arruda et al., 2018; Bustamante et al., 2012; Gomes et al., 2018, 2020a). We further synthesize the main findings of the three topics from the systematic literature review process.

3.2 Fire dynamic parameters to estimate fire emissions

Papers under “fire dynamic parameters” encompass 46 % of the studies reviewed, underscoring the importance of variables like burned area, fuel characteristics, combustion completeness, combustion efficiency, and emission factors in fire emissions research. These parameters directly influence emission estimates, with their combination playing key roles in determining carbon emissions from fires. By examining these variables within the specific ecological and climatic context of the Cerrado, we gain insights into how fire behaviour and emissions in this biome interact.

The prevalence of studies on fire dynamics parameters reflects the accessibility of these variables and indicates the importance of linking fire dynamics directly to emissions, with studies often highlighting the potential applicability of

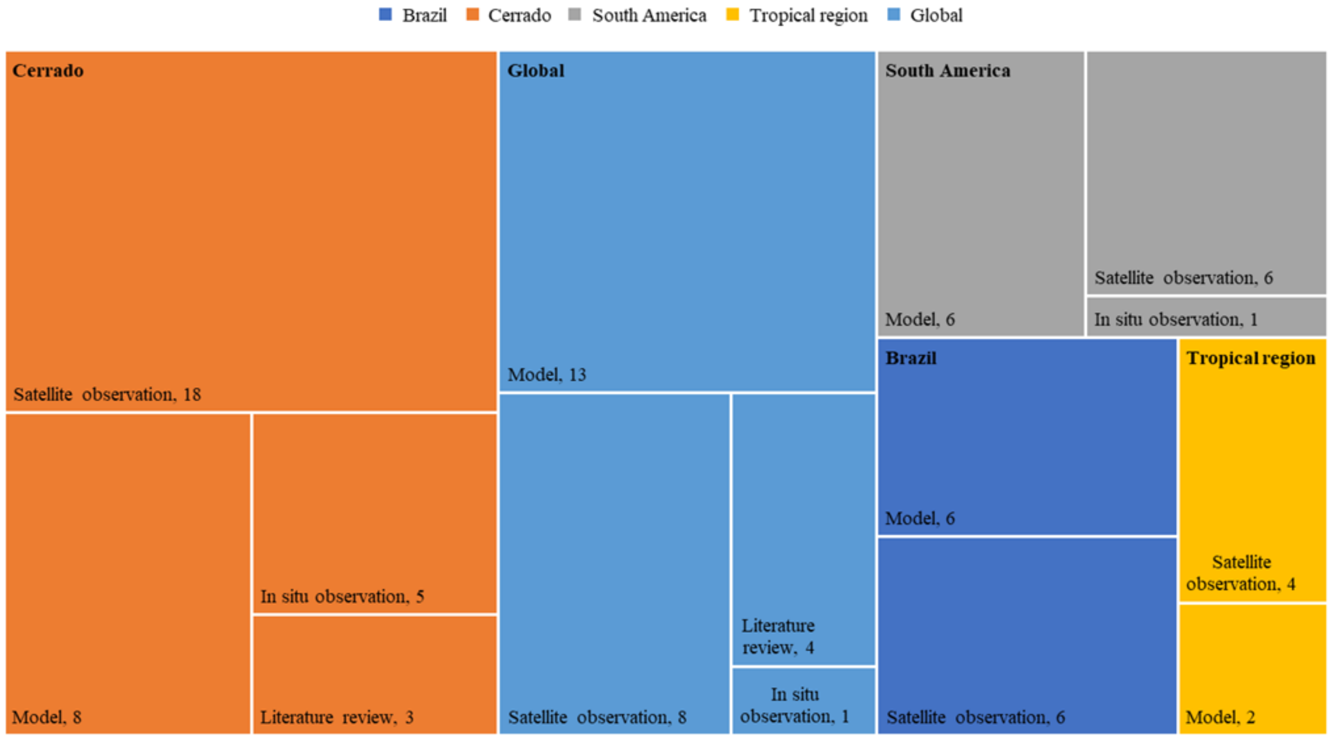


Figure 5. Tree map of the techniques used across study areas in empirical papers. The numbers represent the number of studies of each technique within each study area. The study areas, global, tropical region, South America, and Brazil, are regions that include results for the Cerrado. 26 papers combine different techniques and are double counted.

their research in fire emission estimation (e.g. Libonati et al., 2015; Pereira Júnior et al., 2014). This focus on fire dynamics provides some of the most current information available, yet it suggests a need for more research to correlate fire drivers to emissions. We further discuss the fire dynamics parameters found in the literature review process.

3.2.1 Burned area and fuel characteristics

Burned area detection in the Cerrado has mainly been measured via the satellites Aqua, Terra/MODIS, and Landsat/TM (see Libonati et al., 2015; Oliveira et al., 2021; Pereira et al., 2021) and is one of the primary parameters for estimating emissions. The Global Fire Emissions Database version 5 (GFED5) primarily relies on MODIS products to provide global burned area (Chen et al., 2023). GFED5 estimates 21.35 Mha yr^{-1} (2001–2020) for burned area in open savannas of the Southern Hemisphere of South America (SHSA), where the Cerrado is located. GFED5 burned area results are more aligned with data from higher-resolution satellite sensors (Chen et al., 2023), indicating enhancement compared to previous versions and the potential to improve fire emissions estimates derived from GFED5 (Chen et al., 2023).

Libonati et al. (2015) developed a regional algorithm using MODIS data to increase the accuracy of estimations of burned area in the Cerrado, demonstrating that regional products more accurately capture vegetation diversity. Also, to capture the variety of fire dynamics throughout the biome, Silva et al. (2021) map fire characteristics for the 19 ecoregions of the Cerrado, including the patterns and trends of burned area using MODIS data. Results show a great variation in the size of the burned area in the Cerrado, with large areas detected in the boundaries with other biomes (Silva et al., 2021). Using Aqua and Terra/MODIS data and the algorithm developed by Libonati et al. (2015), the National Institute for Space Research (INPE, in Portuguese) in Brazil has estimated that 16.2 % of the Cerrado was burned in 2007 (the equivalent of 329 138 km^2), a critical year in terms of wildfires in Brazil, and 3.6 % in 2009 (74 085 km^2), a year with low overall rates of burned area in the country.

The extent of the area burned is highly connected to the fuel characteristics, including fuel type (vegetation components), moisture (amount of water content), and load, and these are essential to determine the intensity and occurrence of fire, together with climatic conditions (Alvarado et al., 2017; Gomes et al., 2020b). Fuel type also influences the monthly peak in fire of each vegetation type due to climatic conditions. Grassy material tends to burn first because of its high flammability, with the fire peak from grassland happening in August (Arruda et al., 2024). In comparison, savannas tend to encounter more fires in September and October (Arruda et al., 2024). These impact the extent of area burned in each vegetation type. From 1985 to 2022, 85 % of burned area in the Cerrado affected native vegetation, with savannas accounting for 54 % and grasslands 11 % (Arruda et al., 2024).

Fuel load in the Cerrado is highly connected to the seasonal variation in precipitation (Oliveira et al., 2021). For example, drought was the strongest predictor of burned areas, made by Alvarado et al. (2017). Rainfall in the wet season allows fuel to build up, determining the fuel load available for burning. In contrast, rainfall in the dry season determines the moisture content of the accumulated fuel and, thus, the probability of burning (Alvarado et al., 2017). Fuel load increases with vegetation density (Oliveira et al., 2021), but grasslands have more biomass available for burning than forests due to the fine-fuel load in each physiognomy. Approximately 95 % of the biomass of the herb and grass layers is available for burning in the Cerrado. In comparison, only 0.01 % of the shrub and tree layers is available due to the high quantity of woody material and low quantity of grassy material (Gomes et al., 2020b).

The proportion of influence between climate and fuel on the resulting burned area and emissions varies and is still being discussed. In a global context, burned area is likely to increase worldwide due to climate change (Burton et al., 2024). In South America, an increase in temperature and a decrease in moisture availability is expected to drive an increase in burned area, including in the Cerrado (Burton et al., 2021). Similarly, Silva et al. (2019) predict increased burned area in the Cerrado under all IPCC Representative Concentration Pathway (RCP) scenarios. RCP 2.6, the scenario most closely aligned with the United Nations' 1.5 °C target, could lead to an increase in burned area up to 22 % by 2050 in the Cerrado.

3.2.2 Combustion efficiency, combustion completeness, and emission factors

Combustion efficiency, combustion completeness, and emission factors have been identified in the literature as important parameters to estimate fire emissions. Combustion completeness refers to the amount of biomass converted to gas, aerosols, and particulates during the combustion process and released into the atmosphere (Carvalho et al., 1998). Similarly, combustion efficiency identifies "the percentage of carbon released during combustion of biomass fuels in the chemical form of carbon dioxide" (Ward and Hardy, 1991, pp. 117–118). Combustion efficiency is often measured by the amount of CO_2 emitted divided by the amount of CO_2 and CO emissions combined, termed modified combustion efficiency (MCE; see Andreae, 2019; Hodgson et al., 2018; Vernooij et al., 2021). MCE tends to be higher in open savannas (Vernooij et al., 2023). Values above 0.9 tend to characterize fires in a flaming stage, and these are predominant in the Cerrado due to the dry fine fuel that is likely to rapidly burn (Hodgson et al., 2018).

Using airborne sensors, MCE has been reported to be 0.94 ± 0.02 in a flight above Tocantins in 2012 (Hodgson et al., 2018). Vernooij et al. (2021) used a UAV-based approach (uncrewed aerial vehicle) to sample smoke from grassland and savanna formations in 2017–2018 in a protected area also in Tocantins (*Estação Ecológica Serra Geral do Tocantins*, EESGT) in order to evaluate the seasonal burning differences. The authors concluded that LDS fires (after 1 July, more intense fires) have slightly higher MCE when compared to early-dry-season fires (EDS; before 1 July, milder fires): 0.963 and 0.957, respectively. In further studies, Vernooij et al. (2023) discuss that the MCE found in Vernooij et al. (2021) from measurements in EESGT may have underestimated the MCE in other parts of the Cerrado when analysing it on the biome scale. These values are consistent with other savannas in the world – the global MCE for savannas and grasslands averages 0.94 (Andreae, 2019), while MCE in the African and Australian savannas has been reported as 0.938 ± 0.019 and 0.86–0.99, respectively (Hodgson et al., 2018).

The emission factor (EF) is an essential component that contributes to estimating emission, and it refers to the ratio of a particular gas released divided by the fuel consumed, expressed in grams of that specific gas per kilogram of dry matter (Palacios-Orueta et al., 2005). EF depends on the type and moisture content of the fuel consumed, the amount of fuel burned, the amount and concentration of the gas emitted, and the meteorological conditions during the fire (Palacios-Orueta et al., 2005; Vernooij et al., 2023). Thus, EF is highly variable across studies and is often the source of uncertainty in fire emission estimates. In fact, Andreae (2019) argues that the emission factors of CO_2 and CO from forest fires are the main source of uncertainty in relation to the impact of vegetation fires on the global carbon cycle.

Andreae (2019) and Hodgson et al. (2018) argue that local values of EF can be used to improve estimates. Similarly, Vernooij et al. (2023) propose incorporating dynamic EF to improve representation of savanna's temporal and spatial variabilities, better capturing its fire regime and the resultant emissions. When comparing EDS and LDS fires in savannas worldwide, including the Cerrado, Vernooij et al. (2023) find that fuel moisture content and relative humidity were lower in the LDS compared to in the EDS, increasing fuel consumption and fire intensity over the dry season and resulting in higher EFs in the LDS. The values of EF found from recent studies are summarized in Table 1.

3.2.3 Fire behaviour and intensity

Fire behaviour is limited by fuel characteristics and availability and by microclimate conditions. Fire behaviour is often analysed in terms of fire intensity (Gomes et al., 2020a; Silva et al., 2021), fire spread (Gomes et al., 2020a), heat released (Gomes et al., 2020a), fuel consumption (Andela et al., 2016), and fire return interval (Gomes et al., 2020b;

Table 1. Emission factors values from areas that include the Cerrado found by this review.

Study	Study area	Emission factor	Value ($g\,kg^{-1}$)
Van Der Werf et al. (2017)	Global – savannas	EF_{CO_2}	1686
		EF_{CO}	63
		EF_{CH_4}	1.94
Andreae (2019)	Global – savannas	EF_{CO_2}	1660
		EF_{CO}	69
		EF_{CH_4}	2.7
Vernooij et al. (2023)	Global – savannas	EF_{CO_2}	1685
		EF_{CO}	64
		EF_{CH_4}	1.85
Hodgson et al. (2018)	Cerrado	EF_{CO_2}	1711 ± 175
		EF_{CO}	74 ± 8
		EF_{CH_4}	2.23 ± 0.23
Vernooij et al. (2021)	Cerrado	EF_{CO_2}	1664
		EF_{CO}	48
		EF_{CH_4}	0.78

Pereira Júnior et al., 2014). Fire intensity here is defined as the rate at which fire releases heat energy (DeBano et al., 1998). For the Cerrado, this means that fire intensity follows a seasonal pattern, increasing in the dry months (Silva et al., 2021), and that it is also highly influenced by the vegetation type, increasing from forests to savannas and grasslands, where fine-fuel consumption is higher (Gomes et al., 2020a). Silva et al. (2021) indicate higher values of fire intensity at the end of the dry season in the Cerrado, when fuel moisture is lower and fuel availability for burning is higher.

Fire intensity can be measured through the fire radiative power (FRP). FRP is the instantaneous amount of energy released by fire in the combustion process (Wooster, 2002). FRP is often derived from MODIS data, and it relates to the intensity of fire and to the amount of biomass being consumed (Wooster, 2002). Although FRP has been used to provide estimates of fire intensity, Sperling et al. (2020) state that FRP from MODIS is underestimated for the Cerrado. Through FRP, Silva et al. (2021) estimate fire intensity in the Cerrado, with high values (FRP > 63.7 MW) found on the border with other biomes.

FRP data were combined by Andela et al. (2016) to derive fuel consumption estimates, which depend on combustion completeness and the amount of fuel available for burning. For the savannas in South America, where the Cerrado is included, high values of fuel consumption were estimated compared to from other savannas (Andela et al., 2016). For Andela et al. (2016), fuel consumption is partly driven by fire return periods, with grasses favouring a short return interval and thus resulting in low fuel build-up rates and lower fuel consumption. Pereira Júnior et al. (2014) modelled the fire return interval for a protected area in the Cerrado from 1997 to 2008, finding fire return intervals of 3 to 6 years depending on the vegetation type. Shorter fire return periods (biennial) have been reported for other areas of the Cerrado (see Batista et al., 2018; Gomes et al., 2020b), typically related to the fine-fuel load.

Fire spread in the Cerrado is connected to fuel load and moisture (Gomes et al., 2020a; Silva et al., 2021). Fires in the Cerrado spread from savannas and grasslands to forests due to the higher fine-fuel load available for burning, and the same pattern is observed for heat released (Gomes et al., 2020a). These reflect combustion completeness and carbon emission rates of the different physiognomies in the biome (Gomes et al., 2020a).

Together, these findings emphasize the critical role that specific fire dynamics parameters play in shaping fire emissions within the Cerrado. To estimate carbon emissions from fire, researchers utilize various methodologies and data sources to quantify the carbon released during combustion. By understanding how burned area, fuel load, combustion completeness, combustion efficiency, and emission factors vary across the landscape and seasons, researchers can better estimate fire emissions and their contribution to the global budget. The variables identified in this review as predominant factors associated with fire emissions in the Cerrado are summarized in Fig. 6. In the next sections, we discuss how current research brings this information together to estimate fire emission in the Cerrado.

3.3 Estimated fire carbon emissions in the Cerrado

Papers under "emission estimates" account for 43 % (43 papers due to papers being double counted) of the papers reviewed, with 23 papers focusing on estimating emissions alone, while the remaining papers include a combination of

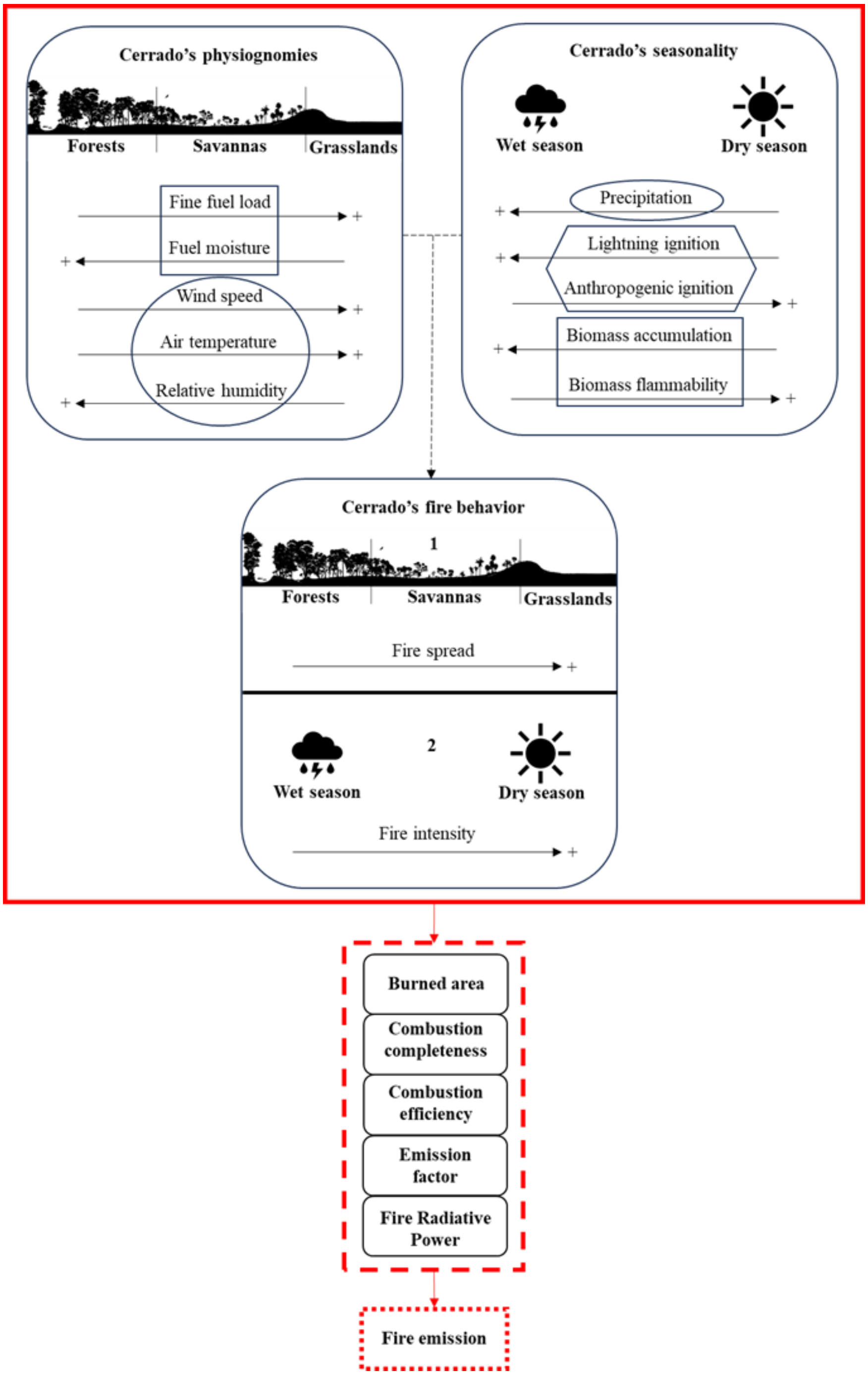


Figure 6. Variables associated with estimating fire emissions in the Cerrado that were found in the literature. The Cerrados's physiognomies, separated into forests, savannas, and grasslands, increase in fine-fuel load and decrease in fuel moisture from forests to grasslands. Microclimatic conditions also change across the physiognomies, with increasing wind speed and air temperature and decreasing relative humidity from forests to grasslands. The Cerrado's seasonality is divided into wet and dry seasons. The wet season is characterized by high precipitation, lightning ignitions, and accumulated biomass, whereas the dry season is characterized by low precipitation, anthropogenic ignitions, and flammable biomass. Fuel characteristics (square black boxes), climatic conditions (circular black boxes), and ignition (hexagonal black boxes) interact (dashed black lines) to determine the Cerrado's fire behaviour. Two aspects of fire behaviour are presented (numbers 1 and 2): (1) fire spread increases from forests to grasslands and (2) fire intensity increases in the dry season. The Cerrado's physiognomies, seasonality, and fire behaviour together (solid red square) interact to determine the size of burned area, combustion completeness, combustion efficiency, emission factors, and FRP. These (dashed red line) drive the resultant fire emissions (dotted red line). The image representing the Cerrado's physiognomies was adapted from the Brazilian Agricultural Research Corporation (Embrapa, 2024).

emissions estimates, fire dynamics parameters, and/or fire management and policy. Given the importance of the carbon gases released into the atmosphere during combustion to the global carbon budget, mainly in the form of carbon dioxide (CO_2) (Ward and Hardy, 1991), this section will synthesize the main findings related to fire carbon emissions from the Cerrado found in the literature review process, notwithstanding the impact of non-carbon gases emitted during biomass burning.

The amount of carbon emitted to the atmosphere by fires is typically inferred by models implemented at different scales ranging from local to global analyses – of the 43 papers under emission estimates, 25 handle modelling techniques. Global and regional analyses tend to be less detailed, as they usually focus on capturing absolute emissions and on studying general aspects of large areas through a coarse resolution, and these are necessary to assess the impact of emissions on the global carbon balance (Palacios-Orueta et al., 2005; Rabin et al., 2018).

Two global emissions datasets were often used in the papers reviewed to develop and evaluate models of fire occurrence and effects, and these are GFED and the Global Fire Assimilation System (GFAS). Both rely on MODIS products to estimate emissions. GFED fire emissions estimates are based on MODIS burned area products and on the Carnegie–Ames–Stanford approach (CASA) model (Van Der Werf et al., 2017). GFAS estimates fire emissions globally using a conversion factor that links MODIS-derived FRP observations to combustion rates, resulting in the fuel consumption, which is then combined with emissions factors to estimate fire emissions (Kaiser et al., 2012).

For example, Burton et al. (2021) use the Interactive Fire and Emission Algorithm for Natural Environments (INFERNO) integrated into the Joint UK Land Environment Simulator (JULES) to evaluate current and future fire emissions in South America, and the results are compared to both GFED and GFAS. Pereira et al. (2016) estimate fire emissions also in South America using the Brazilian Biomass Burning Emission Model with FRP assimilation (3BEM_FRP), and the results are also compared to GFAS.

From 1997 to 2016, GFED fire emissions averaged $2.2\,\mathrm{Pg\,C\,yr^{-1}}$ globally (Van Der Werf et al., 2017). In the SHSA region, where the Cerrado is located, fire emissions averaged $0.291\,\mathrm{Pg\,C\,yr^{-1}}$, of which 49.3 % was from savanna fires ($0.14\,\mathrm{Pg\,C\,yr^{-1}}$). Considering these values, savanna fires from SHSA, which broadly includes the Cerrado, account for 6.36 % of annual global total carbon emissions from fires. GFAS does not provide subregional analysis, but carbon emissions for South America averaged $0.349\,\mathrm{Pg\,C\,yr^{-1}}$ (2003–2008), while GFED version 3.1 averaged $0.299\,\mathrm{Pg\,C\,yr^{-1}}$ (Kaiser et al., 2012).

This literature review identified 4 papers dedicated to estimating fire carbon emissions from the Cerrado fires, with 1 exclusively focused on estimating fire-related carbon emissions from the Cerrado (Gomes et al., 2024), while the other studies either include the Cerrado but are not restricted to it (da Silva Junior et al., 2020) or include emissions as well as fire dynamics parameters (Gomes et al., 2020a; Oliveira et al., 2021). However, some studies that estimate fire emissions in the Cerrado are not focused on carbon emissions but on aerosol (e.g. Hodgson et al., 2018; Pereira et al., 2009, 2022), fine particulate matter ($PM_{2.5}$) (e.g. Mataveli et al., 2019, 2023; Santos et al., 2021), and nitrogen compounds (e.g. Pope et al., 2020).

Gomes et al. (2024) uses satellite-derived burned area maps, surface fuel material maps, combustion factors, and emissions factors to estimate net CO_2 emissions from the Cerrado fires among other greenhouse gases. From 1985 to 2020, the Cerrado savanna emitted approximately 2 227 964 Gg of CO_2 ($0.018\,\mathrm{Pg\,C\,yr^{-1}}$) and removed approximately 1 495 725 Gg of CO_2 ($0.011\,\mathrm{Pg\,C\,yr^{-1}}$) due to biomass regrowth, resulting in a net CO_2 emission of 859 701 Gg ($0.007\,\mathrm{Pg\,C\,yr^{-1}}$) (Gomes et al., 2024). From GFED4s and MODIS data, da Silva Junior et al. (2020) estimated carbon emissions for the Brazilian biomes between 1999 and 2018. Brazilian biomes produced 8.09 Pg C of fire emissions (equivalent to $0.40\,\mathrm{Pg\,C\,yr^{-1}}$). By analysing all the Brazilian biomes, da Silva Junior et al. (2020) put fire emissions in the Cerrado into a national perspective, where it contributes 32.04 % of total fire emissions (about $0.13\,\mathrm{Pg\,C\,yr^{-1}}$), similar to the values found by Van Der Werf et al. (2017) for the savanna fire emissions in the SHSA region. According to da Silva Junior et al. (2020), the Cerrado is a major contributor to Brazil's fire emissions.

Gomes et al. (2020a) modelled carbon emissions associated with fine-fuel consumption, finding $0.230\,\mathrm{kg\,m^{-2}}$ for grassland, $0.210\,\mathrm{kg\,m^{-2}}$ for savanna, and $0.053\,\mathrm{kg\,m^{-2}}$ for forests, and concluding that the fine-fuel load was the main predictor of the amount of carbon released through fire. When considering different scenarios (moderate, medium, and extreme) for the fine fuel available for burning, the wind speed, and the vapour pressure deficit using the BEFIRE (Behaviour and Effect of Fire) model, Gomes et al. (2020b) showed that carbon emissions from fine-fuel consumption increased with the intensity of the scenario ($0.19\,\mathrm{kg\,m^{-2}}$ for moderate, $0.23\,\mathrm{kg\,m^{-2}}$ for medium, and $0.26\,\mathrm{kg\,m^{-2}}$ for extreme). Because the model only considers fine-fuel load, which is more abundant in grasslands due to the presence of grasses, carbon emissions decrease with the increase in woody biomass. These simulations confirm that fire-associated emissions depend on the vegetation type (Gomes et al., 2020a, b).

Oliveira et al. (2021) modelled fire emissions across the Cerrado by estimating fuel loads through remote sensing data over 4 years (2015–2018). Results averaged $0.066 \pm 0.013\,\mathrm{Pg\,CO_2\,yr^{-1}}$ ($0.018 \pm 0.00354\,\mathrm{Pg\,C\,yr^{-1}}$). When accounting for regrowth uptake, net emission was $0.015 \pm 0.004\,\mathrm{Pg\,CO_2\,yr^{-1}}$ ($0.00487 \pm 9.65 \times 10^{-4}\,\mathrm{Pg\,C\,yr^{-1}}$). Oliveira et al. (2021) consider these values low and suggest incorporating a more detailed vegetation map and the burning intensity of different fuel types to improve their estimates. The values of fire carbon emissions restricted to the Cerrado reported in this section are summarized in Table 2.

The difference in values (Table 2) indicates the complexity of estimating fire emissions, especially in a diverse region such as the Cerrado. The estimation of fire emissions relies on multiple variables, each quantified by different methodologies and databases. Also, the procedures used to extrapolate measurements and estimate emissions on broader scales differ among studies. When combined, these variabilities result in uncertainties associated with estimating fire emissions, which are often reported by the studies synthesized in this review (e.g. Andreae, 2019; Oliveira et al., 2021; Vernooij et al., 2023).

3.4 The influence of fire management and policy in estimating fire emissions in the Cerrado

In synthesizing the literature on fire emissions in the Cerrado, we identified 12 % (12 papers) of papers focused on fire management and policy, most (8) under the "review" and "perspective" categories. This indicates that fire management and policy are important in understanding fire dynamics in the Cerrado. Still, papers that address these do not usually bring new information based on observation or experiments but tend to synthesize or opine on the existing literature. For example, this review captured only one study that quantifies the amount of fire emissions mitigated by fire management in the Cerrado (Franke et al., 2024), probably due to the difficulty quantifying the social and cultural aspects of fire, which are intrinsic to fire management and policy.

Fire exclusion policies arose in Brazil as a reaction to the misuse of fire for pasture management and deforestation, especially in the 20th century (Durigan and Ratter, 2016). These policies dominated for decades in the Cerrado (Durigan and Ratter, 2016) also due to the misbelief that fire harms the biome, resulting in fuel accumulation and changes in the fire season and regime (Pivello, 2011; Pivello et al., 2021). Consequently, extensive LDS wildfires replaced small patchy burns (Moura et al., 2019; Pivello, 2011). A shift towards recognizing fire as essential to maintaining the Cerrado's diversity and ecosystem services led to a change in the federal legislation in 2012 (federal law no. 12,651/2012) to explicitly allow the use of fire for ecological purposes in fire-prone settings (Durigan, 2020; Pivello et al., 2021). Further, the acknowledgement of controlled fires as an essential socio-ecological component of fire-dependent ecosystems led to the Brazilian Integrated Fire Management (IFM) policy (Pivello et al., 2021), sanctioned in 2024 (federal law no. 14,944/2024).

The changes in policy to recognize the importance of fire to the Cerrado is also reflected in the increased numbers of protected areas (PAs) under fire management – the pilot IFM project, named the *Cerrado-Jalapão*, started in 2014 in three protected areas. The *Cerrado-Jalapão* project improved the understanding of fire dynamics in the biome (Durigan and Ratter, 2016). In 2024, Franke et al. (2024) identified 36 PAs undergoing IFM activities. Similarly, Santos et al. (2021) documented an increase in the number and spatial distribution of prescribed burns in PAs within the Cerrado from 2015 to 2018. Prescribed burning is a common activity in fire management used to reduce fuel load in fire-prone settings around the world (Santos et al., 2021).

Despite the increasing recognition of fire's importance to the Cerrado and the subsequent expansion of fire management operations, as well as the global relevance of fire management in reducing emissions (Moura et al., 2019), this review identified only one study that quantifies the reduction in fire carbon emissions achieved through fire management in the Cerrado. Franke et al. (2024) show an emission abatement of 26 677 $tCO_2e\,yr^{-1}$ (equivalent) (2014–2019) in specific protected areas and a reduction potential of more than 1085 $tCO_2e\,yr^{-1}$ (2014–2019) when the result is scaled-up to all protected areas in the Cerrado. The reduction in emissions from prescribed burning is due to lower fuel consumption and combustion factors of early-dry-season fires when compared to middle-/late-dry-season fires (Franke et al., 2024). These values are considered conservative due to analysing mainly fine fuels, and Franke et al. (2024) argue that estimations could be improved using high-resolution data that would allow the identification of small-scale fires.

This literature review also documents studies that estimate activities associated with fire management, such as prescribed burning, important for further emission estimates. Mistry et al. (2019) suggest reduced burned area and late-dry-season emissions from IFM in the Cerrado. Batista et al. (2018) compare two areas within the Canastra National Park, one under fire suppression and the other under fire management. The area under fire management presented less burned area annually (2000–2015), with a higher proportion of areas burned in the EDS. Similarly, Franke et al. (2024) identified increased EDS and decreased LDS burned area extents as a result of fire management. Over 2014–2019, Franke et al. (2024) estimated an average of 20.4 % EDS burned area in PAs under IFM vs. 4.7 % in PAs that do not apply IFM. Conversely, middle- to late-dry-season burned area averaged 76.5 % in IFM PAs, while that average reaches 87.1 % in non-IFM PAs. Santos et al. (2021) also document reduced burned area in the late dry season due to fire management in two indigenous territories in the Cerrado, which led to reduced fire intensity and reduced extreme wildfires, indicating a reduction in further fire emissions.

The literature review shows that assessing fire emissions in the Cerrado is particularly complex due to the region's ecological diversity and the interplay of fire dynamics, policy, and cultural practices. Fire management remains challenged by the lack of understanding of fire dynamics parameters from early- and late-dry-season burning (Mistry et al., 2019; Pivello et al., 2021), as estimated biomass, combustion com-

Table 2. Values found in the literature for fire carbon emissions in the Cerrado. Units are petagrams of carbon per year ($Pg\,C\,yr^{1}$) and kilograms per square metre ($kg\,m^{-2}$).

Study	Study area	Value	Units	Observation
da Silva Junior et al. (2020)	Cerrado	0.13	$Pg\,C\,yr^{-1}$	Based on MODIS data and on GFED4s.
Gomes et al. (2020a)	Cerrado – grassland	0.23	$kg\,m^{-2}$	The study estimates the amount of carbon released in combustion, which is used as a proxy for estimates of fire-associated emissions.
	Cerrado – savanna	0.21	$kg\,m^{-2}$	
	Cerrado – forest	0.053	$kg\,m^{-2}$	
Oliveira et al. (2021)	Cerrado	0.018 ± 0.00354	$Pg\,C\,yr^{-1}$	Includes results from a Bayesian model developed by the authors based on remote sensing imagery, as in Franke et al. (2018).
Gomes et al. (2024)	Cerrado – savanna	0.018	$Pg\,C\,yr^{-1}$	Focuses only on the savanna formation of the Cerrado.

pleteness, and burned area affect fire emissions (Mistry et al., 2019). Understanding the role of these aspects in estimating fire emissions contributes to the development of consistent fire policies in Brazil (Durigan, 2020; Durigan and Ratter, 2016; Moura et al., 2019), which influence Brazil's national and international commitments to carbon emission reductions (Pivello et al., 2021).

4 Discussion

To our knowledge and according to our search criteria, this is the first systematic literature review to provide an overview of fire emissions in the Cerrado. By analysing the existing literature on fire emissions in the Cerrado, we identified key topics that contribute to a broad and holistic understanding of the role of these emissions in the carbon budget on regional, national, and global scales. This understanding includes not only direct fire-related carbon emission but also the underlying fire dynamic parameters, fire management practices, and fire policies, along with the various methodological approaches used to estimate these.

In synthesizing the literature, we observed a growing interest in fire science in the Cerrado from multiple perspectives, as shown by the number of papers published annually. Pivello et al. (2021) also observe an increase in studies on fire. This is probably due to an increased recognition of fire's importance in the global carbon balance and the increased number of alarming fire events reported in recent years due to climate change (Burton et al., 2024; Hofmann et al., 2021; Oliveira et al., 2022). The year 2022 did not follow the growth trend, which could indicate a gap in publications this year or a limitation of our research method (i.e. not capturing publications in 2022). In the following years, publications tend to increase compared to in 2022. The decrease in 2022 could also indicate a shifted focus away from the Cerrado studies due to political or financial constraints, to encourage scientific studies in the region, or due to a shifted focus towards other regions of Brazil. Pereira et al. (2024) indicate an increase in papers published about fires in the Pantanal after the 2020 mega-fire in the biome. Papers related to fire dynamics and emissions in the Pantanal published in 2022 show fire as a consequence of the compound impact of land use and climate in these regions, and similar findings were reported for the Amazon rainforest in papers also published in 2022 (see Barbosa et al., 2022; Dutra et al., 2022; Menezes et al., 2022; Silva et al., 2022; Walker et al., 2022).

We saw that papers often encompass a global and regional emissions analysis, with local (Cerrado) analysis accounting for about 36 % of papers included in this review. The remaining 64 % of papers represent global and regional (Brazil, South America, tropical region) analysis, often understanding the role of emissions from a holistic perspective and providing insights into the influence of local emissions on the global carbon balance. Additionally, many papers in this systematic literature review are led by non-Brazilian institutions or lack authors from Brazilian institutions. In fact, fire emissions studies in the Cerrado are rarely led by institutions from within the region. This highlights opportunities to enhance collaboration between Brazilian and non-Brazilian institutions and to make stronger partnerships between different regions within Brazil.

The papers reviewed have shown that input data uncertainty affects output accuracy. In the Cerrado studies, for example, uncertainties regarding the accuracy of spatial patterns of physiognomies and climatic seasonality throughout the biome (i.e. length of dry and wet seasons and rainfall amount) impact the absolute estimates of fire emissions and future projections. While global-scale studies often generalize such patterns, local studies include the complexity and diversity of a limited region, which is essential to capture changes in fire dynamics and to assess the components that influence emissions at smaller scales (Palacios-Orueta et al., 2005). They could be extrapolated to represent more extensive areas. Although there are uncertainties at both global and local scales, the use of remote sensing techniques contributes to the accuracy of emission estimations, and it is the core of much recent research regarding fire occurrence and emissions worldwide (Lasslop et al., 2019). However, it is important to acknowledge that some uncertainties, such as limitations associated with spatial resolution and with expanding the details of local results to a broader scale, may also limit the accuracy of results, as observed in fire management potential assessments (Griscom et al., 2020).

Some changes that can be made to improve carbon accounting from fire in the Cerrado include acknowledging the heterogeneity of the biome, especially regarding climatic seasonality and fuel characteristics (Gomes et al., 2018; Oliveira et al., 2021); incorporating location-specific algorithms and datasets that improve the representation of the Cerrado (Libonati et al., 2015; Mataveli et al., 2023; Oliveira et al., 2021); and accounting for other carbon pools, such as soils and belowground, which are large components of the carbon in the Cerrado's physiognomies (Bustamante et al., 2012).

Examining fire carbon emissions reveals that local emissions reflect the global carbon budget. A key factor in carbon balance analysis is vegetation regrowth since a significant portion of the CO_2 emitted by fire is sequestered during post-fire biomass recovery (Andreae, 2019; Van Der Werf et al., 2017; Gomes et al., 2024). This literature review identified one study that includes the removal of CO_2 by regrowth in the Cerrado, quantifying the net CO_2 emissions from the Cerrado fires from 1985 to 2020 (Gomes et al., 2024). Vegetation regrowth removed 63.5 % of the CO_2 emitted, indicating that fire in the Cerrado has been a source of carbon to the atmosphere in recent decades (Gomes et al., 2024). For a shorter time series (2015–2018), Oliveira et al. (2021) also found the Cerrado fires to be a net emitter of CO_2. Further research is needed to enhance the understanding of the long-term carbon balance of Cerrado fires. This literature review contributes by providing an overview of published studies on fire emissions in the region.

Compiling the literature on fire emissions in the Cerrado has revealed several studies that focus on fire dynamics, management, and policy rather than on estimating emissions, with studies often stating their relevance for providing insights into emission estimates and the importance of the Cerrado's fire emissions to the global carbon balance. This indicates that estimating fire emissions requires a holistic approach. For example, including the perspectives of fire culture, ecology, and policy within emissions is essential, given the importance of fire to the biome. Fire culture refers to the interaction between humans and fire, encompassing the factors that drive societies to use it (see Pivello et al., 2021). The use of fire, shaped by cultural traditions and socioeconomic conditions, can influence the extent of burned areas and the resulting fire emissions. Traditional communities, for instance, may occasionally use fire on a small scale (Pivello et al., 2021).

Coupled with the available biomass for burning and its characteristics – which depend on vegetation type, density, moisture, and seasonal growth patterns – burned area, fuel characteristics, combustion completeness, combustion efficiency, and emission factors set the stage for potential emissions. Fire intensity, driven by conditions such as dry weather, strong winds, and fuel accumulation, influences combustion efficiency. High-intensity fires tend to consume more fuel, resulting in higher combustion efficiency and more complete combustion. This reduces emissions of pollutants such as carbon monoxide and particulate matter but increases emissions of carbon dioxide. In contrast, incomplete combustion results in higher emissions of pollutants such as particulate matter and carbon monoxide, which may persist in soils over long periods. Combustion completeness further influences the amount of biomass converted to carbon and released into the atmosphere. Together, these parameters allow for the estimation of emissions based on the combination of burned area, fuel load, and combustion completeness.

Thus, this review indicates a critical need to develop interdisciplinary studies to bridge fire policies and fire emissions in the Cerrado. Understanding fire dynamics, including the opportunities to mitigate emissions from fire activities, is essential for recognizing fire's role in achieving global environmental and climate targets. For instance, Martin (2019) identifies United Nations Sustainable Development Goals that are related to fire and land management: goals 3 (good health and well-being), 13 (climate action), and 15 (life on land). These impact the 2015 Paris Agreement target to limit warming to 1.5 °C by 2100. In fact, da Silva Junior et al. (2020) find that fire activities undermine Brazil's emission reduction targets under the Paris Agreement. The Paris Agreement outlines commitments for climate actions and acknowledges the importance of mitigation and removal actions, where fire management can play an important role. If great effort is put into mitigating emissions and removing carbon, 1.5 °C, although ambitious, could be achieved, with Brazil holding the highest mitigation potential in the land sector (Roe et al., 2019). Together with other countries, improved forest management in Brazil, which includes fire management, could help to increase carbon removal by 40 Gt CO_2 by 2050 (Roe et al., 2019).

Studies that discuss the cultural and socioeconomic aspects of fire often do not discuss them from the emissions' perspective. Estimating the influence of humans on fire emissions is a complex task, which is also reflected in the lack of equations and algorithms to reproduce fire management strategies in land surface models. This complexity emphasizes all factors that need to be considered beyond quantifying the amount of carbon emitted to the atmosphere. Despite the difficulty in measuring these, the lack of inclusion of these aspects in fire emission estimates could also be due to the shift towards recognizing fire as essential to the Cerrado being recent, especially when compared to other fire-prone settings. For example, the WALFA (West Arnhem

Land Fire Abatement) project in northern Australia became entirely active in 2005 (Russell-Smith et al., 2013), where traditional people, scientists, and governmental institutions collaborate to reduce fire emissions through fire management activities (Russell-Smith et al., 2013). Meanwhile, the pilot IFM project in the Cerrado started in 2014 (Schmidt et al., 2018).

Compared with the Cerrado, a relatively high number of fire studies were performed in Australia, which demonstrates the potential to expand the study of emissions from fire in the Cerrado. Da Veiga and Nikolakis (2022) counted 64 papers from Australia and 29 from Brazil when documenting the interaction between fire management and carbon programmes worldwide. The Australian studies, especially in the WALFA region, act as an example to other savanna environments, including to the Cerrado's pilot IFM project (Schmidt et al., 2018). The WALFA project reaffirms the potential of management activities to reduce emissions in savanna countries. EDS burns in the region emit 48 % of what is emitted in the LDS (Russell-Smith et al., 2009). Similarly, Khatun et al. (2017) suggest that, in the Tanzanian miombo, EDS burns could avoid carbon emissions and enhance carbon uptake. Studies in Mozambique and Botswana explore the potential of EDS burns to reduce emissions in southern African savannas (Russell-Smith et al., 2021).

Climate change increasingly affects fires, and adaptation and mitigation activities are essential to limit these effects (Burton et al., 2024). Direct human impacts may offset the effects of climate change on fire worldwide (Burton et al., 2024), especially in fire-prone environments. In fact, Andela et al. (2017) found a decreasing trend in fire activity driven by human activities worldwide. These indicate an opportunity to investigate the potential of fire management to mitigate emissions in the Cerrado and to understand fire emissions in the biome. The lack of available data and accessibility has been acknowledged in the literature as a gap in research regarding fire dynamics in the Cerrado, primarily due to its heterogeneity (Bustamante et al., 2018; Gomes et al., 2018; Oliveira et al., 2021). Developing more specific algorithms able to capture the climatic seasonality and fuel diversity of the Cerrado, understanding the above- and belowground carbon pools of each physiognomy using in situ evaluations and satellite-derived approaches, and incorporating these into fire emissions estimates in the Cerrado could improve carbon measurements in the biome.

Consequently, this would improve fire emission estimates in the Cerrado. Pathways towards this improvement include connecting observational information with modelling and a better assessment and quantification of the impact of the qualitative aspects of fire estimates. Examples of how these can be achieved are by better accounting for emission parameters across the Cerrado's vegetation types and fire regimes; valuing prescribed burning emissions and including these in fire modelling; representing fire management in land surface models; using in situ observations to assess models' utility and as input data to modelling; and incorporating the ecological, social, and cultural aspects of fire in fire emission estimates. These could address uncertainty and improve models' accuracy, thus providing better accounting for fire emissions in the Cerrado and worldwide.

Table 3. Parameters included in current studies and parameters to be considered for future studies to estimate the fire emissions in the Cerrado captured by this review.

Parameters included in current studies in the Cerrado	Parameters to be considered for future fire emission estimates in the Cerrado
Biomass burned	Belowground and soil carbon pools
Burned area	Fire culture
Combustion efficiency	Fire ecology
Combustion factors	Fire policy
Emission factors	Location-specific algorithms
Fire intensity	Socioeconomic aspects of fire
Fuel characteristics	

Our research question was "how can compiling published material on fire emissions in the Cerrado provide a holistic understanding of their role in the global carbon budget?" Analysing published papers on fire emissions in the Cerrado provides valuable insights into its role in the carbon balance. These include understanding the parameters used to estimate emissions, quantifying the amount of carbon released into the atmosphere by fires, and identifying important aspects of fire dynamics that are sources of uncertainty or are not considered in fire emission estimates. These are summarized in Table 3.

This systematic literature review presents an overall assessment of the published literature on fire emissions in the Cerrado to understand its placement in the carbon budget, considering the criteria used to narrow our search. Including Portuguese as a research language and consulting other search database platforms, such as Web of Science, could have resulted in more papers being included. "Grey literature" was not within the scope of our research method but could potentially result in more findings. Grey literature is defined as "unpublished research (e.g., dissertations, conference abstracts, preprints or unpublished datasets), or those published outside of traditional academic publishing (e.g., governmental reports)" (Foo et al., 2021, 1711).

Finally, the challenges in estimating fire emissions worldwide lie in not only measuring carbon directly released but also capturing the nuanced effects of fire on ecosystems and the broader Earth system (Hamilton et al., 2024). Continued and diversified research is needed to improve the understanding of fire dynamics in the Cerrado and to understand how these reflect fire emissions locally and globally. These will assess current knowledge gaps regarding fire emission estimates in the Cerrado by enhancing the understanding of the role of emissions from the biome in the global carbon budget and potential mitigation activities to achieve global environmental and climatic goals and by providing a better foundation for future projections.

5 Conclusion

This systematic literature review synthesized 77 peer-reviewed papers, from local to global scales, according to a set of criteria to understand fire emissions in the Cerrado and their place in the global carbon budget from a holistic perspective. From our literature review process, we found that research on fire emissions in the Cerrado is still overlooked when compared to other savanna ecosystems. Based on our knowledge and search criteria, this is the first systematic literature review to provide an integrated understanding of fire emissions in the Cerrado, where fire dynamics, management, and policy emerge as crucial for estimating fire emissions. By providing the necessary context for the drivers of emissions, their variability, and potential mitigation strategies, we highlight how insights from fire behaviour and fire regimes are essential for estimating emissions.

Although our research question and keyword search focus on fire emissions, the literature review process often revealed papers on fire dynamic parameters that are drivers of emissions estimates, indicating a gap in connecting fire dynamics and emissions research in the Cerrado. Thus, we examine how fire dynamics shape emissions and identify where further integration of these fields could improve our holistic understanding of fire emissions in the Cerrado. This is possible due to a clearer understanding of the variables considered when estimating emissions, a deeper comprehension of the published values estimated, and the identification of important aspects of fire regimes that influence fire policy and mitigation strategies.

Fire management and policy emerged as key themes in our literature search because they play a crucial role in shaping fire regimes and, consequently, fire emissions in the Cerrado. While there is limited empirical research quantifying the direct impact of fire management on emissions in this region, discussing management strategies is essential to fully assessing the factors that influence fire-driven carbon fluxes. Understanding how management affects fire regimes provides a pathway to improving emissions estimates and identifying potential mitigation strategies.

Thus, this review demonstrates that understanding the placement of fire emissions in the global carbon budget requires a holistic approach that draws together disciplines across fire science, especially in a distinct environment such as the Cerrado, while reinforcing the urgent need for further investigation into the topic. The complexity of estimating fire emissions outreaches that of measuring carbon, and this review highlights the urgent need for interdisciplinary studies to connect fire parameters with fire emissions, which then influence fire policies and the achievement of climate commitments. Continued research is needed to fully understand and quantify the influence of fire dynamics and mitigation strategies on fire emissions in the Cerrado.

Data availability. The list of papers reviewed is available in the Supplement.

Supplement. The supplement related to this article is available online at https://doi.org/10.5194/nhess-25-3581-2025-supplement.

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