Review article: Understanding the placement of fire emissions from the Brazilian Cerrado biome in the global carbon budget

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Abstract. Estimating fire emissions in the Brazilian Cerrado requires a comprehensive approach that integrates observational data, fire and vegetation modelling techniques, and policy. Although high quantities of global fire emissions come from the Cerrado, research in this area is still overlooked when compared to other savanna countries. This study systematically reviewed 69 papers on fire emissions from the Cerrado. The aim was to provide insights into the placement of the Cerrado in the global carbon budget and identify the research gaps that would support improved estimation of the biome's carbon balance. Our review finds that, in the Cerrado, studies often focus on quantifying fire dynamics parameters and emissions, and that a holistic approach is required to estimate fire emissions, which is hindered due to the difficulty in valuing the qualitative aspects of fire. Evidence suggests a rise in interest in understanding fire emissions in the Cerrado, reflected in the increased number of studies throughout the years. More research is required to understand the aspects of fire dynamics in the Cerrado, how these reflect fire emissions locally and globally and potential mitigation activities. This could be achieved 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 million km^2 in Central Brazil. It is the second largest biome in Brazil, covering almost 24% of the country (IBGE, 2004). 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). Its emissions and influence on vegetation growth, cover and structure make fire a major driver of the Cerrado's carbon balance. The Cerrado's fires are potentially responsible for more than 30% (about 0.13 PgC year^{-1}) of Brazil's total fire emissions (da Silva Junior et al., 2020). As a comparison, the Cerrado accounts for about 14% of Brazil's emission 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 with up to 0.4 PgC year^{-1} (Rosan et al., 2021). The Cerrado's role in Brazil's overall emissions profile is, therefore, critical, with fires contributing to a substantial share of the country's fire emissions, which has national implications for climate policies and international commitments (da Silva Junior et al., 2020; Pivello et al., 2021).

The Cerrado's extensive range of vegetation assemblages, in turn, 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 (Hoffmann et al., 2012). This combination of fuel and climate results in more intense and faster fires in grasslands and savannas than in forest areas in the Cerrado (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). Although natural fires ignited by lightning occur in the wet season (Batista et al., 2018; Ramos-Neto and Pivello, 2000), many fires result from anthropogenic activities during the dry season (Coutinho, 1990; Eloy et al., 2019; Pivello, 2011). 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. Therefore, fire occurrence in the Cerrado is also seasonal.

Fire participates in many complex interactions in the carbon cycle, from releasing carbon to benefiting ecosystems trajectories (Hamilton et al., 2024). Fire and climate regulate one another and can be in a positive feedback loop – climate and humans can influence fire patterns, and fire can influence climate by releasing carbon (Bowman et al., 2009). In the Cerrado, higher temperatures and reduced precipitation are now more common due to climate change, which also changes its fire regimes, with fire events becoming increasingly common (Gomes et al., 2020b; Hofmann et al., 2021).

The IPCC AR6 WGI/WGII (IPCC, 2021, 2022) and the UNEP “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). For example, the year 2020 was marked by compound drought-heatwave episodes, which favored fire activity and the increase in burned area in the Cerrado (Libonati et al., 2022; dos Santos et al., 2024).

Drought-heatwaves 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).

Beyond immediate emissions, fire also influences carbon balance over time. For example, post-fire recovery critically shapes the Cerrado's long-term carbon balance (Burton et al. 2024; Gomes et al., 2020b; 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. However, even in this scenario, fires can influence other greenhouse gases and aerosols. 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 observed globally (Burton et al., 2024).

During biomass burning, a large amount of carbon gases is released into the atmosphere. These emissions are mainly in the form of carbon dioxide (CO_2), 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 the greenhouse effect in different ways. CO is recognized as a major indirect greenhouse gas, meaning that it does not absorb enough terrestrial infrared radiation to be considered a direct greenhouse gas, but it influences the concentration of other direct greenhouse gases, such as CH_4 and tropospheric ozone, through atmospheric chemistry (Ehhalt et al., 2001).

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 absorbing and trapping infrared radiation in the atmosphere, causing the greenhouse effect. However, the increased concentration of CO_2 in the atmosphere has intensified the greenhouse effect and warmed the Earth in alarming amounts. Thus, understanding the emission of CO and CO_2 during the combustion process is important to recognize the impact of these gases in fire emissions, especially in fire-prone settings like the Cerrado. Due to their importance, the studies captured by this review often report 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.

From 1997-2016, savanna fires from Southern Hemisphere South America, which the Cerrado dominates, accounted for 6.36% of the global carbon from fires annually (Van Der Werf et al., 2017). This contribution is substantial, as it highlights the Cerrado's role as one of the world's major fire-emitting ecosystems. To put this into perspective, savanna fires from the Australia and New Zealand region, which refer to the Australian savanna, account for 4.55% of the global carbon from fire emissions emitted each year for the same period (Van Der Werf et al., 2017). Compared with the Cerrado, a relatively high number of fire studies were performed in Australia. Da Veiga and Nikolakis (2022) counted 64 papers from Australia and 29 from Brazil when documenting the interaction between fire management and carbon programs worldwide.

Fire studies in Australia have important benefits for understanding fire impacts in that region, and acts as an example to other savanna environments. Those include performing estimates of the release of GHG into the atmosphere and designing methods that can help reduce these emissions and providing insights into the interaction between actors in integrated fire management (IFM) practices (da Veiga and Nikolakis, 2022; Moura et al., 2019; Russell-Smith et al., 2009). The cultural, socio-economic and ecological aspects of fire are crucial to execute and evaluate IFM activities (Myers, 2006). IFM integrates traditional knowledge and its connection with fire, and Australia is a leader in documenting these (da Veiga and Nikolakis, 2022). Measuring the social and cultural dimensions of fire presents significant challenges, and often is excluded from fire emission estimates in the Cerrado.

Natural activities to avoid the release of GHG or to increase carbon storage by letting vegetation recover, termed natural climate solutions (NCS), have emerged as a possibility to reduce emissions (Griscom et al., 2020). Tropical NCS, like improved fire management, could mitigate 6.56 petagrams of CO_2 annually (Pg CO_2 $year^{-1}$) between 2030 and 2050 (Griscom et al., 2020). Management activities, which include fire management, hold 26% of NCS' mitigation potential in Asia, Africa and Latin America. 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. However, it is worth noting that some uncertainties may affect the estimates of fire management potential (Griscom et al., 2020). For example, limitations associated with spatial resolution and with expanding the details of local results to a broader scale.

It is essential to account for fire emissions and recognize mitigation mechanisms worldwide. This is particularly important for the Cerrado due to its intrinsic connection to fire. Thus, this systematic literature review synthesizes published material on fire emissions in areas of the Cerrado that do not explicitly include anthropogenic land uses, with aims to: (a) outline current emissions estimates, specifically CO_2, or fire dynamic factors that help support these estimates, in regions that encompass Cerrado or are limited to it; (b) understand how these estimates fit the carbon budget; (c) understand how measurements are done, how to use different, none-standardized measurement, and what observational products are available; (d) identify potential mitigation opportunities in the biome; and (e) identify research gaps. This will support improvements for future fire emission estimation and provide insights into the placement of the Cerrado in the global carbon balance.

2 Methods

According to Moher et al. (2009, 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 analyze 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 on 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 search; (3) initial literature screening; and (4) full-text screening. We also combined the literature review steps outlined by Cronin et al. (2008), which includes selecting a review topic, searching the literature, gathering, reading, analyzing the literature, and writing the review. After establishing our research question as "How compiling published material on fire emissions in areas of the Cerrado that do not explicitly include anthropogenic land uses can provide a better understanding of the placement of these emissions 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 3,617 records.

We applied four inclusionary criteria to identify relevant literature: papers had to be (1) published in peer-reviewed journals with an impact factor greater than 1; (2) encompass the Cerrado biome; (3) be published after 2003, for a two-decade period (2003-2022); and (4) be conducted in areas that do not explicitly include anthropogenic land uses, here referred to as "natural areas". We define natural areas as those covered by natural vegetation of the Cerrado, where anthropogenic land uses do not occur (e.g. pasture and agriculture). According to this criteria, 48.66% (965,783 km^2) of the Cerrado is covered by natural vegetation (MapBiomas, 2022). Because papers found by this review often do not specify the land use of their study area, we have not included papers that explicitly document fire occurring in anthropized areas, as a proxy for documenting existing literature on natural areas of the Cerrado.

To improve the assessment of our research question, we have also incorporated in our review papers that don't focus only on the Cerrado, but rather include it as part of the analysis. Despite its constraints, the impact factor was included as an indicator of scientific quality (Andersen et al., 2006; da Veiga and Nikolakis, 2022; 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, and there is greater certainty in these data from 2003 (see Andela et al., 2019; Silva et al., 2019). 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 then conducted the search for a two-decade period, covering research from 2003 to 2022.

The criteria led to the initial screening of 90 papers. Although we used keywords to conduct our review, the searches still returned papers not in English, or that did not mention fire emissions. 21 papers were excluded due to being duplicates, not in English, not mentioning fire emissions, or explicitly analyzing fire in anthropized lands. We full-text screened the remaining 69 papers to confirm they met all the eligibility criteria. Figure 1 demonstrates the systematic literature review process through the PRISMA diagram.

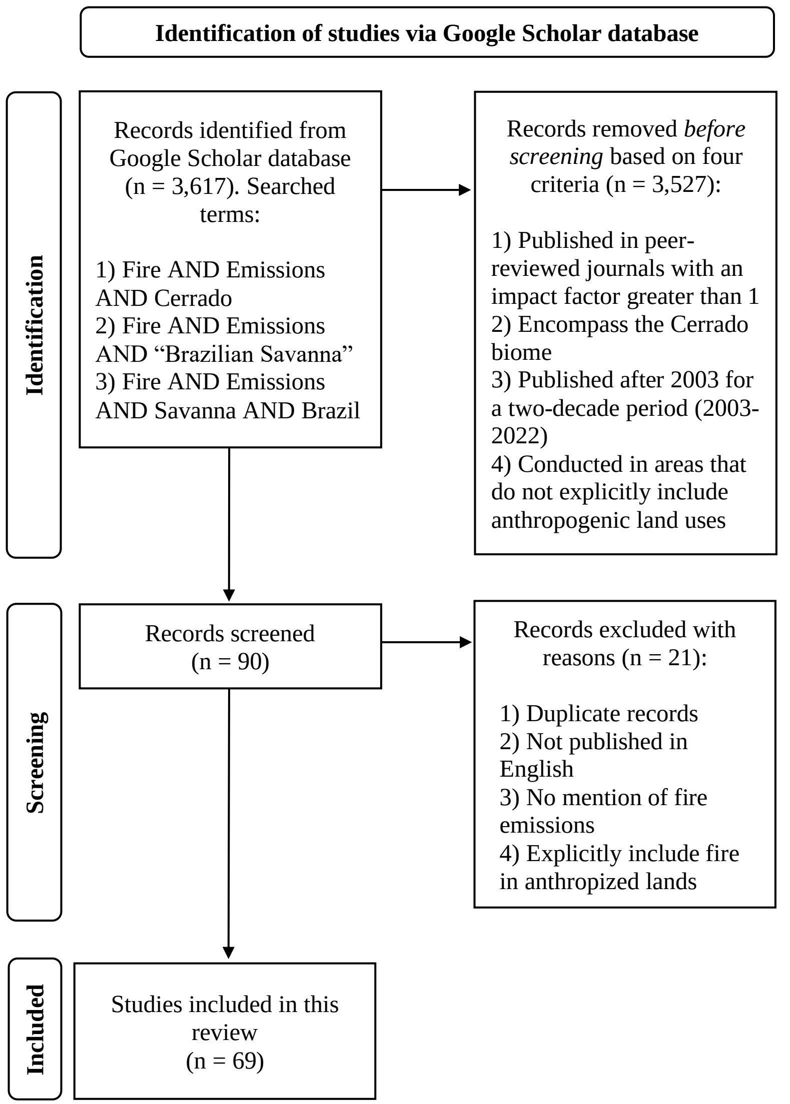


Figure 1: Adapted PRISMA flow diagram demonstrating the systematic literature review process divided into three steps: identification of potential papers through searched terms in the Google Scholar database, and exclusion of papers based on the four criteria established for this research; screening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

Once we had selected the papers, we adopted a systematic scheme to review, analyze, and synthesize them. We retrieved the following information from the 69 papers: title, year of publication, authors, journal, study design, area of study, what is measured, and how it is measured. The 69 papers selected for this literature review are available in the Supplement. We also wrote a summary of each paper to simplify the understanding of its content and 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 Cerrado; (b) topic of search, where we identified three topics in the literature: fire dynamics parameters, emission estimates, and fire management and policy; and (c) study design, divided into empirical, review, and perspective. This classification allowed a deep understanding of the general scope of current published literature on fire emissions in the Cerrado, including the purpose of the studies. This enabled us to identify 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 69 papers and incorporated them into the literature review process. From 2003-2022, the number of papers published has increased (Fig. 2), indicating a rise in interest in understanding fire emissions in the Cerrado and a rise in papers on fire sciences being published.

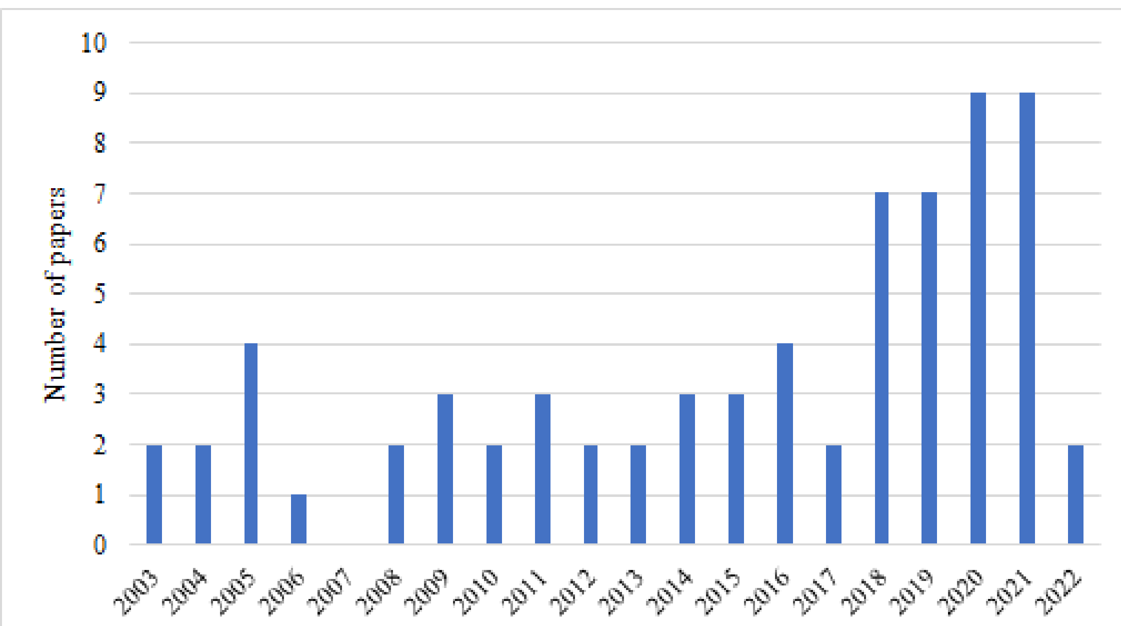


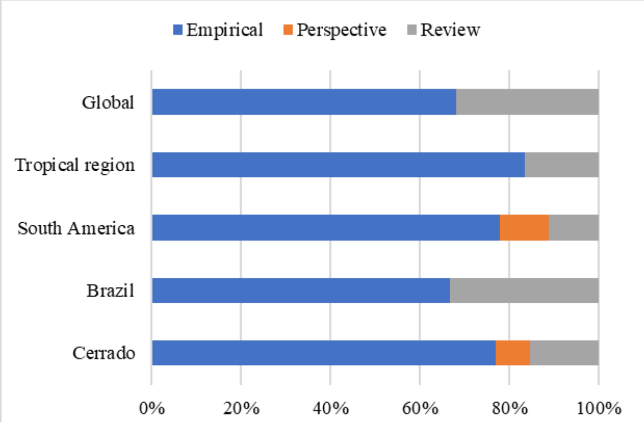
Figure 2: Number of papers published per year included in the literature review, Number of papers published per year from the 69 papers included in this literature review, from 2003 to 2022.

There is an increasing tendency in the number of papers published throughout the time series, but the year 2022 did not follow the growth trend shown in Fig. 2. This sharp drop in publications could indicate a gap in publications this year or a limitation of our research method that could not capture publications in 2022. It 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. For example, papers about fire dynamics and emissions in the Pantanal and in the Amazon rainforest were published in 2022 (see Barbosa et al., 2022; Dutra et al., 2022; Menezes et al., 2022; Silva et al, 2022; Walker et al., 2022). Papers published in 2022 related to fire dynamics and emissions in the Pantanal and in the Amazon show fire as a consequence of the compound impact of land use and climate in these regions (Barbosa et al., 2022; Silva et al., 2022; Walker et al., 2022).

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 emissions in the Cerrado, from global to local scales. 26 papers focused on the Cerrado, while 22 provide a global scale analysis, 6 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 of emissions, encompassing the biome instead of being limited to it. Often papers referred 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. Conversely, Mistry et al. (2019) use the example of Brazil and Venezuela to illustrate how fire management can support emission reduction in South America.

As per the study design, we identified 51 empirical papers (74%), 15 review papers (22%), and 3 perspective papers (4%). Empirical studies provide new information based on observation or experiments. Review and perspective papers analyze previously published studies by evaluating existing literature or expressing opinions on a specific topic. Although review and perspective papers do not focus on bringing original research, they supply the current knowledge of a specific topic and highlight pertinent published literature (Cronin et al., 2008). These were included in this systematic literature review to contribute to a more complete analysis of fire emissions in the Cerrado. We further connect the study design with the coverage of the study area in Fig. 3.



	Cerrado	Brazil	South America	Tropical region	Global
Empirical	20	4	7	5	15
Perspective	2	0	1	0	0
Review	4	2	1	1	7

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

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 43 are international (62.3%) and 26 are Brazilian (37.7%). From the Brazilian-led papers, 10 (38.5%) are from institutions located within the Cerrado area. 14 papers (32.6%) from the international-led studies involve authors from Brazilian institutions (Fig. 4), while half of the Brazilian-led studies (13 papers, 50%) include authors from international institutions. These numbers indicate that most studies in fire dynamics and emissions in the Cerrado are not led by institutions within the Cerrado region. In fact, most institutions are not even located within Brazil, with international institutions leading the studies and often not collaborating with Brazilian institutions.

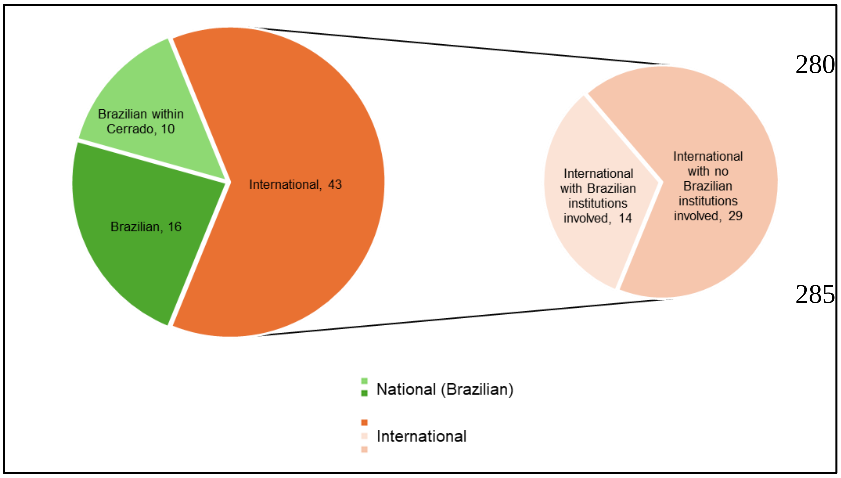


Figure 4: Institutions of the first authors from the papers reviewed. The chart on the left indicates that 43 papers involve first authors from international (non-Brazilian) institutions, while 26 come from Brazilian institutions, of which 10 are within the Cerrado region. The chart on the right indicates that, from the international-led papers, 14 involve authors from Brazilian institutions, while 29 do not.

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 further be used to estimate emissions; (2) emission estimates, which include papers that focus on the quantification of fire emissions; (3) fire management and policy, where papers discuss the importance of fire management and fire policy to influence emission rates.

Of the 69 papers reviewed, 37 relate to fire dynamics parameters used to estimate emissions, 40 report the amounts of fire emissions, and 7 report fire management and policy - the total does not round up to 69 because 15 papers are related to more than one topic. These numbers indicate that many papers are not related to reporting emissions but provide information to support the understanding and estimation of fire emissions, demonstrating a potential to expand the study of GHG emissions from fire in the Cerrado. For example, Santos et al. (2021) use satellite imagery to estimate emissions and parameters, such as burned area and fire intensity, to support the application of prescribed burning in the Cerrado, but actual emissions estimates are not included.

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. Of the 26 papers specific to the Cerrado, 4 were classified as review papers, and these are mostly related to the parameters associated with fire emissions, fire behavior, and fire ecology (see Arruda et al., 2018; Bustamante et al., 2012; Gomes et al., 2018; Gomes et al., 2020a). We further synthesize the main findings of the three topics from the systematic literature review process.

3.2 Fire dynamics parameters to estimate fire emissions

Papers under ‘fire dynamic parameters’ encompass 44% of the studies reviewed, underscoring the importance of variables like burned area, fuel characteristics, combustion completeness, combustion efficiency and emission factor 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 behavior and emissions in this biome interact.

The area burned, typically measured via satellite or ground surveys, is one of the primary parameters for estimating emissions (Libonati et al., 2015; Mangeon et al., 2016; Silva et al. 2021). Coupled with the available biomass for burning and its characteristics — which depend on vegetation type, density, moisture and seasonal growth patterns — these elements 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 and produces pyrogenic carbon, 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.

The prevalence of studies on these fire dynamics parameters reflects both the accessibility of these variables and a gap in linking fire dynamics directly to emission. This focus on fire dynamics provides some of the most current information available, yet it suggests a need for more research to fill the gaps in understanding the chain from 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 and Terra/MODIS, and Landsat/TM (Libonati et al., 2015; Mataveli et al., 2019; Oliveira et al., 2021). To increase the accuracy of estimations of burned area in the Cerrado, Libonati et al. (2015) developed a regional algorithm to capture the local characteristics of the biome, considering the complexity of plant diversity and climate. Also, to capture the diversity of fire dynamics throughout the biome, Silva et al. (2021) propose dividing the Cerrado into 19 ecoregions based on the patterns and trends of fire intensity, seasonality, frequency, extent and scar size. Results show a great variation of fire intensity and size of 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 6.8% of the Cerrado was burned in 2020 (the equivalent of 139,644km^2), a critical year in terms of wildfires in Brazil, and 3.6% in 2009 (74,353km^2), a year with low overall rates of burned area in the country.

The year 2020 was a significant year in terms of burned area in the Cerrado due to a combination of factors (Pivello et al., 2021). 2020 was a drought year in the biome, intensified by prolonged dry season and heatwave (Hofmann et al., 2021; Libonati et al., 2022; dos Santos et al., 2024). This compound drought-heatwave episode aggravated fire activity in the Cerrado (Libonati et al., 2022; dos Santos et al., 2024). Although no estimates were found correlating the compound event of 2020 with fire emissions, it is expected that the drought-heatwave episode led to increased fire emissions due to the increased fire activity and burned area that occurred in that year. Also, 2020 was critical in terms of environmental policies and legislation in Brazil, which also reflected in the Cerrado (Schmidt and Eloy, 2020). The increase in deforestation, encouraged by political discourses, and the decline in environmental legislation enforcement created a favorable setting for fire occurrence in the Cerrado. The combination of climatic conditions and the intensification of an anti-environmental discourse by the Federal government favored the occurrence and spread of fires in the Cerrado in 2020, which was also observed in 2021, when INPE estimated 143,342 km^2 of burned area in the Cerrado.

The extent of 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; Haas et al., 2022). 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 herbs and grass layers is available for burning in the Cerrado. In comparison, only 0.01% of the shrubs and tree layers are 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 resultant burned area and emissions varies and is still being discussed. In a global context, studies suggest that burned area is more sensitive to climate than to fuel availability (Bistinas et al., 2014; Haas et al., 2022; Kelley et al., 2019). From the global analysis of Kelley et al. (2019), we can infer that this trend is also observed in the Cerrado, where moisture is a greater limiting factor to burned area predictions.

3.2.2 Combustion efficiency, combustion completeness and emission factor

Another important parameter identified in the literature to estimate fire emissions is termed combustion completeness, which refers to the amount of biomass converted to gas, aerosols and particulates during the combustion process and released into the atmosphere (Carvalho Jr. 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, 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 (see Andreae, 2019; Hodgson et al., 2018; Vernooij et al., 2021). 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, modified combustion efficiency 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, also in Tocantins, to evaluate the seasonal burning differences. The authors concluded that late dry season fires (LDS; after July 1; more intense fires) have slightly higher modified combustion efficiency when compared to early dry season fires (EDS; before July 1; more mild fires): 0.963 and 0.957, respectively. These values are considered high and are consistent with other savannas in the world – MCE in the African and in the Australian savannas have been reported as 0.938±0.019 and 0.86–0.99, respectively (Hodgson et al., 2018).

Gomes et al. (2020b) developed a model to simulate the relationship between fire frequency, plant biomass, and fire emissions in the Cerrado based on microclimate variables (wind speed, average air temperature, relative air humidity, and vapor pressure deficit) and aboveground biomass of grasses, herbs, shrubs, and trees. Burning of biomass has proven to be higher in open formations due to fuel characteristics; when analyzing the percentage of biomass burned about the total biomass, or the combustion factor, the BEFIRE model (Behavior and Effect of Fire) has estimated a combustion factor of 87% for grasslands, 86% for savannas, and 39% for forests in the Cerrado.

The emission factor (EF) is an essential component that contributes to estimating fire emission and is often documented in literature. EF is 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 amount of gas emitted, concentration of that same gas, and amount of fuel burned (Palacios-Orueta et al., 2005), and thus is highly variable across studies and often the source of uncertainty in fire emission estimates. Andreae (2019) and Hodgson et al. (2018) argue that local values of EF can be used to improve estimates. The values of EF found from recent studies are summarized in Table 1.

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

Study	Study area	Emission Factor	Value (g kg^{-1})
Hodgson et al. (2018)	Cerrado	EF_{CO2}	1,711 ± 175
		EF_{CO}	74 ± 8
		EF_{CH4}	2.23 ± 0.23
Van Der Werf et al. (2017)	Global - savannas	EF_{CO2}	1,686
		EF_{CO}	63
		EF_{CH4}	1.94
Vernooij et al. (2021)	Cerrado	EF_{CO2}	1,664
		EF_{CO}	48
		EF_{CH4}	0.78

3.2.3 Fire behavior and intensity

Fire behavior is limited by fuel characteristics, availability and microclimate conditions. For Cerrado, this means that fire intensity increases in the dry season, and that it also increases from forests to savannas and grasslands. Silva et al. (2021) indicates a larger fire intensity during the dry months in the Cerrado for 2001-2019, with more than 90% of burned area happening between June and October. Fire spread in Cerrado is connected to the amount of fine fuel load available for burning, which is also higher in savannas and grasslands than in forests. These reflect combustion completeness and the emission rates of the different physiognomies in the biome.

Satellite observations also play a pivotal role in measuring fire intensity, and this includes providing direct measurements of fire intensity by quantifying the radiative energy emitted during the carbon oxidation of combustion. This instantaneous measure is termed Fire Radiative Power (FRP) (Van Der Werf et al., 2017). FRP considers temperature, area affected by fire, and emissivity rates and often uses MODIS active fires data as inputs (Ichoku et al., 2008; Mataveli et al., 2019; Vermote et al., 2009). When multiple FRP observations are available, it is possible to estimate the quantity of energy radiated during the combustion process, termed Fire Radiative Energy (FRE) (Vermote et al., 2009). The parameters combined are used to estimate fire emissions worldwide, including the Cerrado. The variables identified in this review as predominant factors associated with fire emissions estimates in the Cerrado are summarized in Fig. 5.

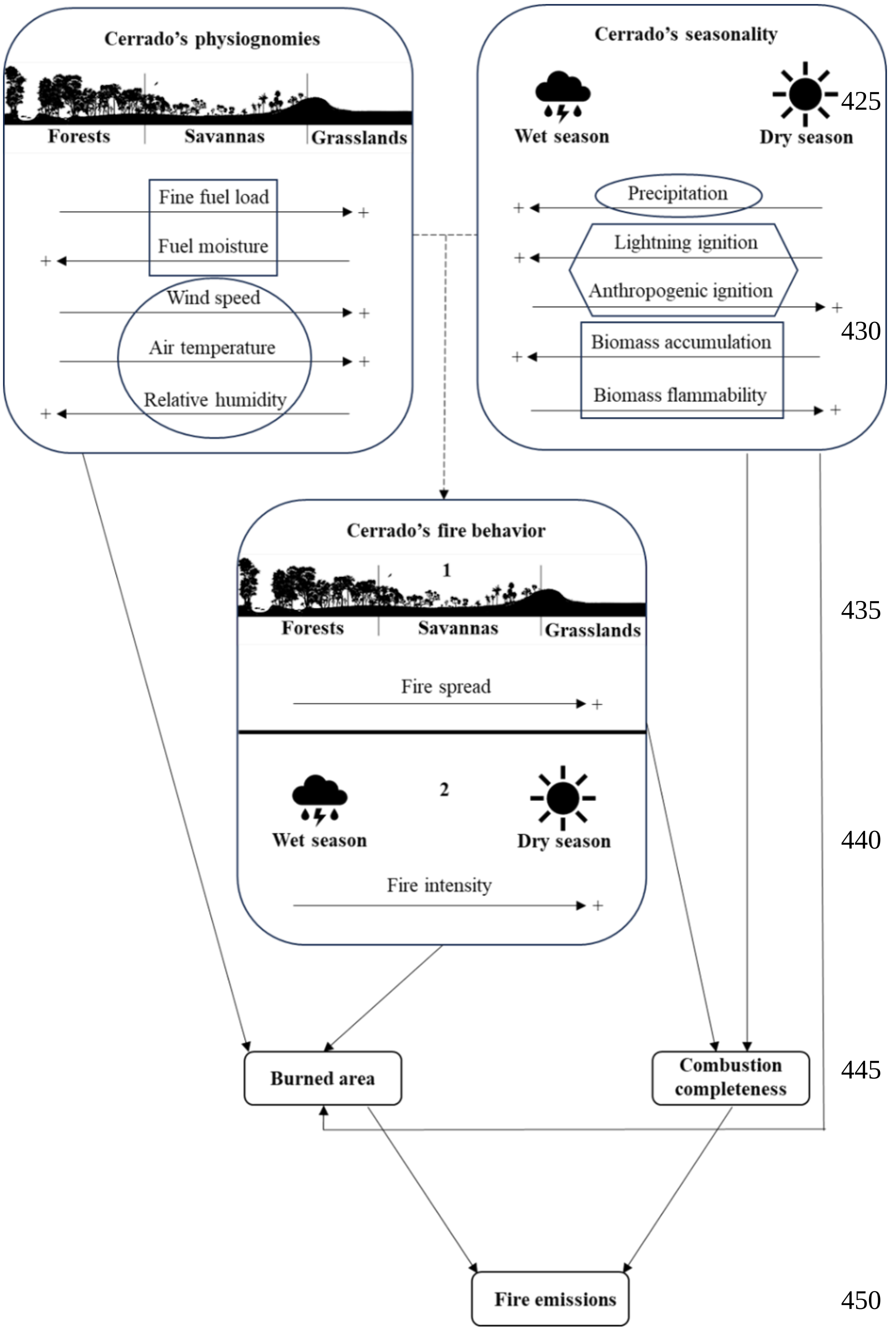


Figure 5: Variables associated with estimating fire emissions in the Cerrado found in the literature. The Cerrados's physiognomies, separated into forests, savannas and grasslands, increase in fine fuel load and decrease in fuel moisture from forests to grasslands. Microclimatic conditions also change 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 boxes), climatic conditions (circle boxes)

and ignition (hexagon boxes) interact (dashed lines) to determine the Cerrado's fire behavior. Two aspects of fire behavior are presented (numbers 1 and 2): 1) fire spreads from forests to grasslands; 2) fire intensity increases in the dry season. The Cerrado's physiognomies, seasonality and fire behavior together drive the size of burned area, resulting in fire emissions (solid lines). High-intensity fires typically consume more fuel, leading to higher combustion efficiency and more complete combustion. Combustion completeness then affects the proportion of biomass converted into carbon and released into the atmosphere, also resulting in fire emissions (solid lines). The image representing the Cerrado's physiognomies was adapted from the Brazilian Agricultural Research Corporation (Embrapa, 2024).

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 factor vary across the landscape and seasons, researchers can better estimate fire emissions and their contribution to global greenhouse gas levels. These insights lay the foundation for targeted fire management strategies that consider both ecological and climatic factors unique to the Cerrado. In the next sections, we discuss how current research brings this information together to estimate fire emission in the Cerrado.

3.3 Estimated fire emissions in the Cerrado

Papers under 'emission estimates' account for 48% of the papers reviewed. The amount of GHG emitted to the atmosphere by fires is typically inferred by models implemented at different scales ranging from local to global analyses. 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). Pan et al. (2020) compare global datasets of biomass burning emissions, including the Global Fire Emission Dataset (GFED). GFED quantifies fire emissions globally, and estimations are based on MODIS burned area products and on the Carnegie–Ames–Stanford Approach (CASA) model (Van Der Werf et al., 2017). Version 4s of GFED also includes small burned area detection to improve its results, and small burned area detection in GFED4s relies on MODIS burned area product, on active fire from MODIS, and on surface reflectance observations (Van Der Werf et al., 2017). According to Van Der Werf et al. (2017), GFED values could be improved using FRP and FRE to reduce uncertainty from small burning area detection.

GFED was extensively used to develop and evaluate models of fire occurrence and effects (e.g. Hantson et al., 2020; Kelley et al., 2013; Lasslop et al., 2020; Rabin et al., 2018). In one application for South America, for example, the Interactive Fire and Emission Algorithm for Natural Environments (INFERNO) (Mangeon et al., 2016; Burton et al., 2019) was integrated into the Joint UK Land Environment Simulator (JULES) (Clark et al., 2011) and used to evaluate current and future fire emissions in that region (Burton et al., 2021). Other models developed for South America are based on FRP to estimate emissions, such as the Global Fire Assimilation System (GFAS) (Kaiser et al., 2012) and the 3BEM with FRP (3BEM-FRP) (Pereira et al., 2016).

Conversely, 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 might be extrapolated to represent more extensive areas. For example, Santos et al. (2021) used satellite-derived products to analyze the influence of prescribed burning in the dynamics of fire in two Indigenous Territories in the Cerrado, from which attributes for the whole biome can be inferred. Although there are uncertainties with 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).

From 1997 to 2016, GFED fire emissions averaged 2.2 PgC year^{-1} globally (Van Der Werf et al., 2017). In the SHSA region (Southern Hemisphere South America), where the Cerrado is located, fire emissions averaged 0.291 PgC year^{-1}, of which 49.3% were from savanna fires (0.14 PgC year^{-1}). Considering these values, savanna fires from SHSA, which broadly include the Cerrado, account for 6.36% of annual global total carbon emissions from fires. As a comparison, the Australian savanna encompassed in the AUST region (Australia and New Zealand) is the region's largest source of fire emissions, accounting for 86.3% of the 0.116 PgC year^{-1} emitted in AUST. This means that AUST savanna fires contribute 4.55% of annual global carbon emissions from fires.

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 PgC of fire emissions (equivalent to 0.40 PgC year^{-1}). By analyzing 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 PgC year^{-1}), similar to the values found by Van Der Werf et al. (2017) for the savanna fire emissions in the SHSA region. The Cerrado presented significant emissions in the dry season (da Silva Junior et al., 2020). According to da Silva Junior et al. (2020), the Cerrado is a major contributor to Brazil’s fire emissions.

Using the BEFIRE model, Gomes et al. (2020a) estimated carbon emissions from fine fuel consumption of 0.230 kg m^{-2} for grassland, 0.210 kg m^{-2} for savanna, and 0.053 kg m^{-2} for forests. When considering different scenarios (moderate, medium, and extreme) for fine fuel available for burning, wind speed, and vapor pressure deficit, the study showed that carbon emissions increased with the intensity of the scenario (0.19 kg m^{-2} for moderate, 0.23 kg m^{-2} for medium, and 0.26 kg m^{-2} for extreme), with herbs and grasses accounting for 80% of the total emissions, and trees and shrubs for the other 20% (Gomes et al., 2020b). Because the model only considers fine fuel, which is more abundant in grasslands, followed by savannas and forests (Ribeiro and Walter, 2008), carbon emissions decrease with the increase of woody biomass.

Oliveira et al. (2021) modelled fire emissions across the Cerrado by estimating fuel loads through remote sensing data over four years (2015-2018). Results averaged 0.066 ± 0.013 Pg CO_2 year^{-1} (0.018 ± 0.00354 PgC year^{-1}). When accounting for regrowth uptake, net emission was 0.015 ± 0.004 Pg CO_2 year^{-1} (0.00487 ± 9.65 10^{-4} PgC year^{-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 reported in this section are summarized in Table 2.

Table 2: Values found in the literature for fire emissions in the Cerrado. Units are: petagrams of carbon per year (PgC year^{-1}) and kilogram per square meter (kg m^{-2}).

Study	Study area	Value	Units	Observation
Van Der Werf et al. (2017)	Southern Hemisphere South America (SHSA)	0.291	Pg C year^{-1}	GFED is based on the CASA model and on MODIS data.
	SHSA savanna fires	0.143463	Pg C year^{-1}	
da Silva Junior et al. (2020)	Brazil	0.4	Pg C year^{-1}	Based on MODIS data and on GFED4s.
	Cerrado	0.13	Pg C year^{-1}	
Gomes, Miranda, Soares-Filho, et al. (2020)	Cerrado – Grassland	0.23	Kg m^{-2}	The study only considers fine fuel, and it is based on eight experimental burn studies across Cerrado.
	Cerrrado - Savanna	0.21	Kg m^{-2}	
	Cerrado - Forest	0.053	Kg m^{-2}	
Oliveira et al. (2021)	Cerrado	0.018 ± 0.00354	Pg C year^{-1}	Includes results from a bayesian model developed by the authors based on remote sensing imagery, as in Franke et al. (2018).

The difference in values, and even in the units used to report results (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 procedure used to extrapolate measurements and estimate emissions on broader scales differs among studies. When combined, these variabilities result in uncertainties associated with estimating fire emissions, often reported by the studies synthesized in this review. For this reason, Houghton (2003) states that comparing results from contrasting approaches can be misleading if the processes behind them are poorly understood.

Reducing uncertainties is also critical to generating more accurate estimates of fire emissions. Within the REgional Carbon Cycle Assessment and Processes (RECCAP) scope, the Global Carbon Project explains that contrasting results can help evaluate the models' strengths, weaknesses, and uncertainties. This could lead to a more holistic understanding of the processes involved in fire emissions, further improving estimates and providing better grounding for future projections.

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. 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 (Bustamante et al., 2018; Gomes et al., 2018; Oliveira et al., 2021); incorporating location-specific algorithms that capture the diversity of the biome (Libonati et al., 2015; Oliveira et al., 2021); better accounting of carbon stocks existent in the biome (Bustamante et al., 2018); and accounting for other carbon pools, such as soils and belowground, which are large components of carbon in the Cerrado's physiognomies (Bustamante et al., 2012). These will improve understanding of fire emissions in the Cerrado and their placement in the global carbon balance.

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

In synthesizing the literature on fire emission in the Cerrado, we identified 8% of papers focused on fire management and policy, all 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 existing literature. For example, this review captured no studies quantifying the amount of fire emissions mitigated by fire management in the Cerrado, probably due to the difficulty in quantifying the social and cultural aspects of fire, which are intrinsic to fire management and policy. 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. That makes sense, given all factors that need to be considered beyond quantifying the amount of GHG emitted to the atmosphere.

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). As a result, 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 fire regime. Consequently, extensive LDS wildfires replaced small patchy burns (Fidelis, 2020; 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 to explicitly allow fire management for conservation purposes in fire-prone settings (Federal Law 12,651/2012). In 2014, the Pilot Integrated Fire Management project emerged in protected areas of the Cerrado with conservation purposes based on the Australian model (Schmidt et al., 2018), named the *Cerrado-Jalapão* project. *Cerrado-Jalapão* encouraged a further shift away from fire suppression policies, allowed scientific experiments to report the ecological benefits of fire in the Cerrado, and improved the understanding of fire dynamics in the biome (Durigan and Ratter, 2016; Schmidt and Eloy, 2020).

Despite the relevance of fire management to fire emissions, this review did not identify studies quantifying the reduction in fire emissions achieved through fire management in the Cerrado. However, we found studies that estimate parameters of prescribed burning. Prescribed burning is a common activity under fire management, where fire under controlled conditions is seen as a technical and ecological tool to control fuel load, provide vegetation patchiness, and avoid late dry season intense wildfires while maintaining the ecosystem integrity (Myers, 2006; Schmidt et al., 2018). Prescribed burning is usually done at the end of the wet season or early dry season, and it reduces fire intensity and can result in less fire spread (dos Santos et al., 2021; Schmidt et al., 2018), suggesting a reduction in emissions from fire management activities.

Dos Santos et al. (2021) have shown that LDS burns have higher combustion factor, heat released, and fire intensity when compared to EDS burns. Fire management has reduced LDS area burned by 40-57% in the three PAs encompassed in the *Cerrado-Jalapão* project during the first three years (2014-2016) of implementation (Schmidt et al., 2018). In the Canastra

National Park in Brazil, areas under fire management also presented less annual area burned (Batista et al., 2018). These reaffirm the potential of management activities to reduce emissions, as shown in other savanna countries. In northern Australia, more specifically in the WALFA (West Arnhem Land Fire Abatement) area, a region recognized as a reference for integrating fire studies with traditional knowledge, EDS burns emit 48% of what is emitted in the LDS (Russell-Smith et al., 2009). The WALFA project applies EDS burns to reduce LDS burns, and during its first 7 years of implementation, GHG emissions have reduced more than 37% when compared to the pre-project 10-year emissions baseline (Russell-Smith et al., 2013). Similarly, Khatun, Corbera, and Ball (2017) suggest that, in the Tanzanian miombo, EDS burns could avoid carbon emissions and enhance carbon uptake by approximately 10 tC ha^{-1} in a 20-year period. Studies in Mozambique and Botswana explore the potential of EDS burns to reduce emissions in southern African savannas (Russell-Smith et al., 2021).

Assessing fire becomes even more challenging when dealing with a diverse region such as the Cerrado. From reviewing the literature, essential aspects that influence the estimation of emissions emerged, such as fire dynamics, ecology, policy, and culture (see Arruda et al., 2018; Durigan and Ratter, 2016; Pivello et al., 2021). Understanding the role of these aspects in estimating fire emissions contributes to the development of consistent fire policies in Brazil (Arruda et al., 2018; Bustamante et al., 2018; Durigan and Ratter, 2016; Gomes et al., 2018), which influence Brazil's national and international commitments to carbon emission reductions (da Silva Junior et al., 2020; Pivello et al., 2021).

4 Discussion

This systematic review allows for a better understanding of Cerrado's placement in the carbon budget on regional, national and global scales. In synthesizing literature, we identified a growing interest in understanding fire dynamics in the Cerrado from multiple perspectives, as shown in the number of papers published annually. 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 because of climate change and intense human activities (Hofmann et al. 2021; Loehman et al. 2014). We identified that papers often encompass a global and regional emissions analysis, with local analysis accounting for 38% of papers included in this review. The remaining 62% of papers represent global and regional analysis, often understanding the role of emissions on a broad scale and providing insights into the influence of local emissions on the global carbon balance. Additionally, we found that many of the papers covered in this systematic literature review is driven by non-Brazilian institutions and/or do not include authors associated with Brazilian institutions. Of all the papers included, only 10 involve first authors from institutions located within the Cerrado region. This indicates an opportunity to enhance collaboration between Brazilian and non-Brazilian institutions, and even a potential to increase partnership between different regions within Brazil.

Most papers provide new information on the parameters used to estimate fire emissions and on emissions themselves rather than analyzing existing literature. These often handle modelling techniques, satellite observations, on-site observations and even results found in previous studies, reflecting the importance of literature reviews in supporting the development of new data. These tools are often combined to provide a more complete analysis. Modelling and satellite observation are frequently integrated, with satellite observations being data providers to models, or models being evaluated by satellite observations, or even through data assimilation between satellite data and modelling simulations. From our results, 13 empirical papers integrate modelling and satellite data, 2 integrate modelling and literature review, 1 integrates satellite and on-site observations, and none directly integrate modelling and on-site observations. Figure 6 shows the methodological techniques used across study areas in empirical papers.

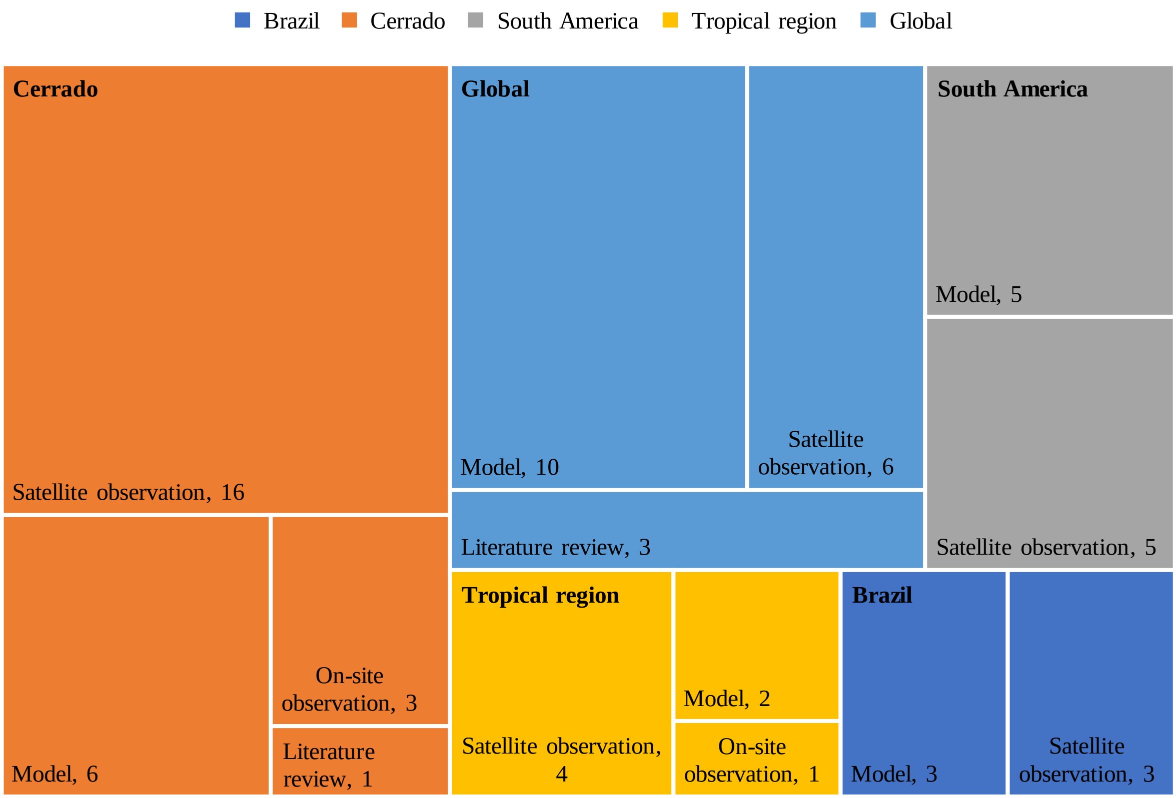


Figure 6: Treemap of the methodological techniques used across study areas in empirical papers. The numbers present the number of studies of each methodological technique within each study area. The study areas Global, Tropical region, South America and Brazil are regions that include results for the Cerrado. Some papers combine different techniques and are double-counted.

Therefore, estimating local fire emissions is reflected in the global carbon budget. A vital factor to consider when analyzing fire emissions is vegetation regrowth since much of the emitted CO_2 is sequestered during the recovery of the post-fire ecosystem (Andreae, 2019; Van Der Werf et al., 2017). In savanna environments such as the Cerrado, fine fuel load, responsible for 95% of fuel available for burning in the biome, can regain its initial biomass 15 months after a fire event (Gomes et al., 2020b). However, it is uncertain if biomass recovery in the Cerrado fully offsets fire emissions, especially under changing fire regimes, and better accounting for vegetation regrowth is needed to understand if fire dynamics are a net CO_2 source or sink to the atmosphere in the long term and what are the mitigation opportunities to assess this issue.

Our research question is "How compiling published material on fire emissions in areas of the Cerrado that do not explicitly include anthropogenic land uses can provide a better understanding of the placement of these emissions in the global carbon budget?". Analyzing published papers on fire emissions in these areas in the Cerrado provides valuable insights into its role in the carbon balance. This includes understanding the parameters used to estimate emissions, quantifying the amount of carbon, especially CO_2, 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.

Table 3. Parameters included in current studies and parameters to be considered for future studies to estimate 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 factor	Fire policy
Emission factor	Location-specific algorithms
Fuel characteristics	Socioeconomic aspects of fire

Aiming at compiling literature on fire emissions in the Cerrado has led to several papers that do not explicitly estimate fire emissions themselves, but rather discuss fire dynamics and parameters used to estimate emissions. This indicates that there is a gap in the literature regarding fire emissions estimates in the Cerrado. However, studies have indicated that fires in the Cerrado play an important role in the global carbon balance. For example, Van Der Werf et al. (2017) found that savanna fire emissions from the Southern Hemisphere South America region, which includes the Cerrado, averaged 0.14 PgC year^{-1} over 20 years, accounting for more than 6% of global fire emissions per year. Similarly, and from a national perspective, da Silva Junior et al. (2020) have shown Cerrado fires contribute more than 32% of the Brazilian total fire emissions (about 0.13 PgC year^{-1} over the 20 years).

Our review also indicates that published literature fails to analyze fire emissions from a holistic approach in the Cerrado. Including the perspectives of fire culture, ecology and policy within emissions is essential given the importance of fire to the biome. However, studies that discuss these aspects often do not discuss them from the emissions' perspective. Despite the difficulty in quantifying the social and cultural aspects of fire, the lack of inclusion of these 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 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 Integrated Fire Management project in the Cerrado started in 2014 (Schmidt et al., 2018).

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 for mitigating 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, as 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. 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. The 1.5 °C target is ambitious, yet achievable if great effort is put into mitigating emissions and removing carbon, with Brazil holding the highest mitigation potential in the land sector (Roe et al., 2019). Together with other countries, improved forest management – which includes fire management – in Brazil could be able to increase carbon removal by 40 $GtCO_2$ by 2050 (Roe et al., 2019).

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 in fire worldwide (Burton et al., 2024), especially in fire-prone environments, and this is an opportunity to investigate the potential of fire management to mitigate emissions in the Cerrado, and to understand fire emissions in the biome. Pathways towards improving fire emissions in the Cerrado include connecting observational information with modeling and a better assessment and quantification of the impact of qualitative aspects in fire estimates. Examples of how these can be achieved are by valuing prescribed burning emissions and including these in fire modeling, representing fire management in land surface models, using on-site observations to assess models' utility and as input data to modeling, and incorporating non-carbon aspects of fire in fire emission estimates, such as the ecological, social and cultural aspects. These could address uncertainty and improve models' accuracy, thus providing better accounting of fire emissions in the Cerrado and worldwide.

This systematic literature review presents an overall assessment of 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 included. The "grey literature" was not in 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). However, to our knowledge, this is the first systematic literature review to present a general scope of fire emissions in the Cerrado.

Finally, the challenges in estimating fire emissions worldwide lie not only in measuring the carbon directly released, but also in 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 how these reflect fire emissions locally and globally. The lack of data availability 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 by on-ground evaluations and satellite-derived approaches, and incorporating these into fire emissions estimates in the Cerrado could improve carbon measurements in the biome. 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 in achieving global environmental and climatic goals, and by providing a better grounding for future projections.

5 Conclusion

This systematic literature review synthesized 69 peer-reviewed papers, from local to global scales, according to a set of criteria to understand the placement of fire emissions in the Cerrado in the global carbon budget. Most of the papers reviewed are designed as empirical. Based on our knowledge and search criteria, this is the first systematic literature review to provide an overview of fire emissions in the Cerrado.

In assessing documented literature, we identified three prominent topics when searching about fire emissions in the Cerrado: fire dynamics parameters, emission estimates, and fire management and policy. These demonstrate that estimating fire emissions is complex and requires a holistic approach that draws together disciplines across fire science, especially in a distinct environment such as the Cerrado, and estimating emission outreach measuring carbon. Thus, 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 climatic commitments. This complexity is reflected in the divergence of values and units of carbon emissions estimates and in the multiple parameters used to estimate emissions.

This review demonstrates that papers fail to report on fire emissions themselves, with fire dynamics and parameters used to estimate emissions in the Cerrado often being the focus of published literature. However, we found that reviewing literature on fire emissions from the Brazilian Cerrado biome contributes to the understanding of the placement of these emissions in the global carbon budget. 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 dynamics that still need to be considered. These are typically of qualitative nature. Continued research is needed to fully understand fire dynamics and emissions in the Cerrado, and we suggest pathways to achieving improvements.

Code availability: No codes were used in this literature review.

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

Authors' contribution: RMV conceptualized the study and prepared the original draft. RMV, CvR, CB, DIK, MC and FM interpreted and analyzed data. RMV, CvR, CB, DIK and MC substantially revised and edited the study.

Competing interests: The authors declare that they have no conflict of interest.

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