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

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Abstract. Estimating fire emissions in the Brazilian Cerrado requires a comprehensive approach, combining 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 atmospheric carbon budget and 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 diversity 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 balances, with Cerrado fires potentially contributing more than 30% of Brazil's fire emissions (da Silva Junior et al., 2020).

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

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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). Intense wildfires in the Cerrado tend to occur in the late dry season (LDS; August-October) (Moura et al., 2019; Silva et al., 2021). Thus, fire occurrence in the Cerrado is also seasonal. 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).

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). Due to climate change, higher temperatures and reduced precipitation are now more common in the Cerrado, which also changes its fire regimes (Gomes et al., 2020b; Hofmann et al., 2021). According to the IPCC AR6 WGI/WGII (IPCC, 2021, 2022) and UNEP "Spreading like Wildfire" report (UNEP, 2022), climate change is increasing the risk of fire occurrence and the intensity and frequency of extreme events, such as wildfires. These result in more fire events in the Cerrado and, consequently, higher greenhouse gas (GHG) fire emissions in the Biome (Fidelis et al., 2018; Ramos-Neto and Pivello, 2000).

During biomass burning, a large amount of carbon gases is released to 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). 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). The 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 has important benefits for understanding fire impacts in that region, and acts as an example to other savanna environments. Those include, for example, performing estimates of the release of GHG into the atmosphere and designing methods that can help reduce these emissions (da Veiga and Nikolakis, 2022; Moura et al., 2019; Russell-Smith et al., 2009).

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Natural activities to avoid the release of GHG or to increase carbon storage, 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 CO2 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 natural areas of the Cerrado, with aims to: (a) outline current emissions estimates, specifically CO2, 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). Figure 1 demonstrates the systematic literature review process through the PRISMA diagram.

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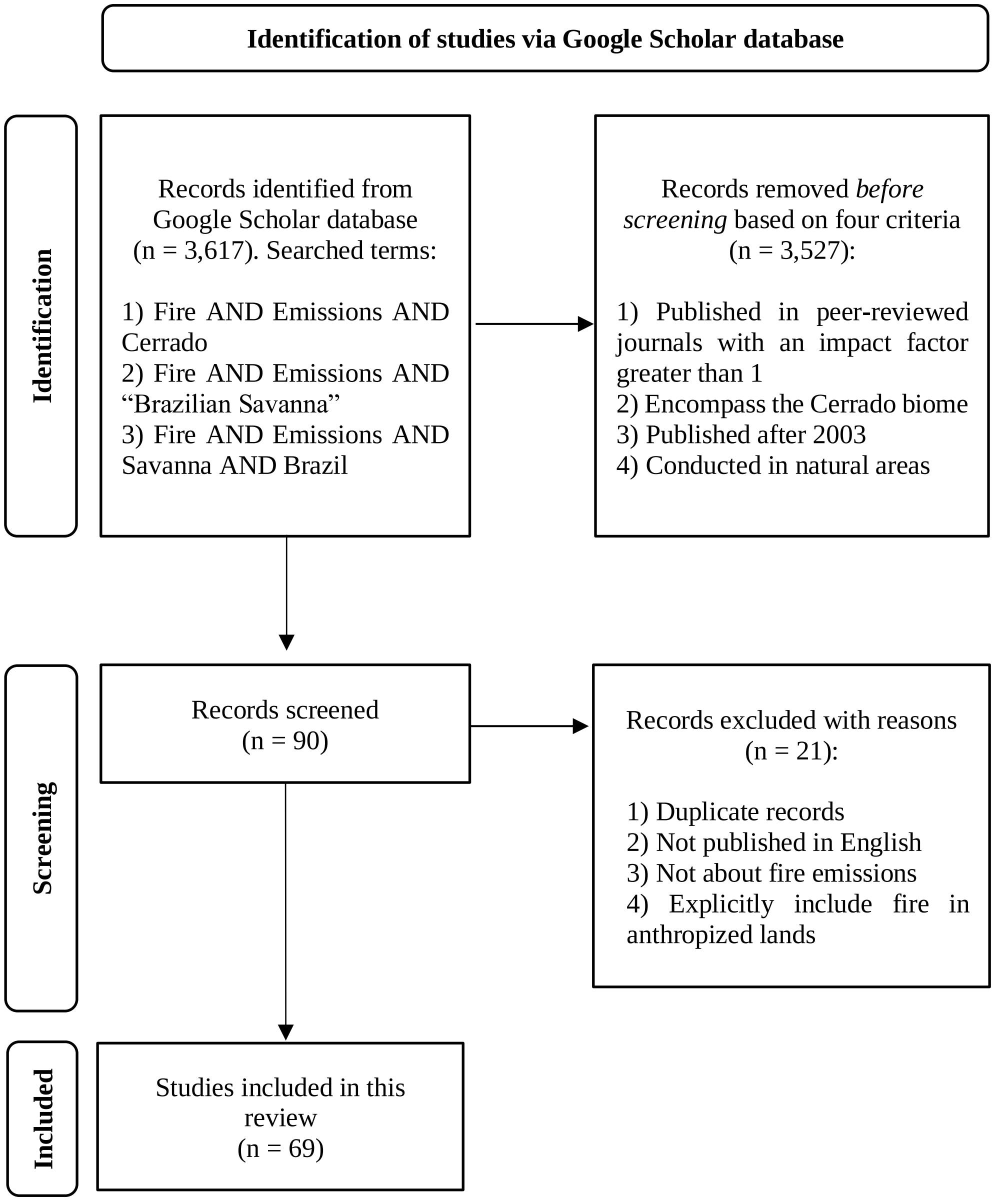

Figure 1: Adapted PRISMA flow diagram demonstrating the systematic literature review process.

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 natural areas of the Cerrado can provide a better understanding of the placement of these emissions in the atmospheric 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, and (4) be conducted in natural areas. 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. 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). Therefore, this review does not include papers that explicitly document fire occurring in anthropized areas.

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 burnt 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).

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 not about fire emissions. 21 papers were excluded due to being duplicates, not in English, not about 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.

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. 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; (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 papers. 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.

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3 Results

160 ### 3.1 Systematic literature review process

We reviewed 69 papers and incorporated them into the literature review process. Since 2003, 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. The year 2022 did not follow the growth trend shown in Fig. 2, indicating a gap in publications in this year or a limitation of our research method that could not capture publications in 2022, or even a shifted focus away from the Cerrado studies due to, for example, political or financial constraints to encourage scientific studies in the region.

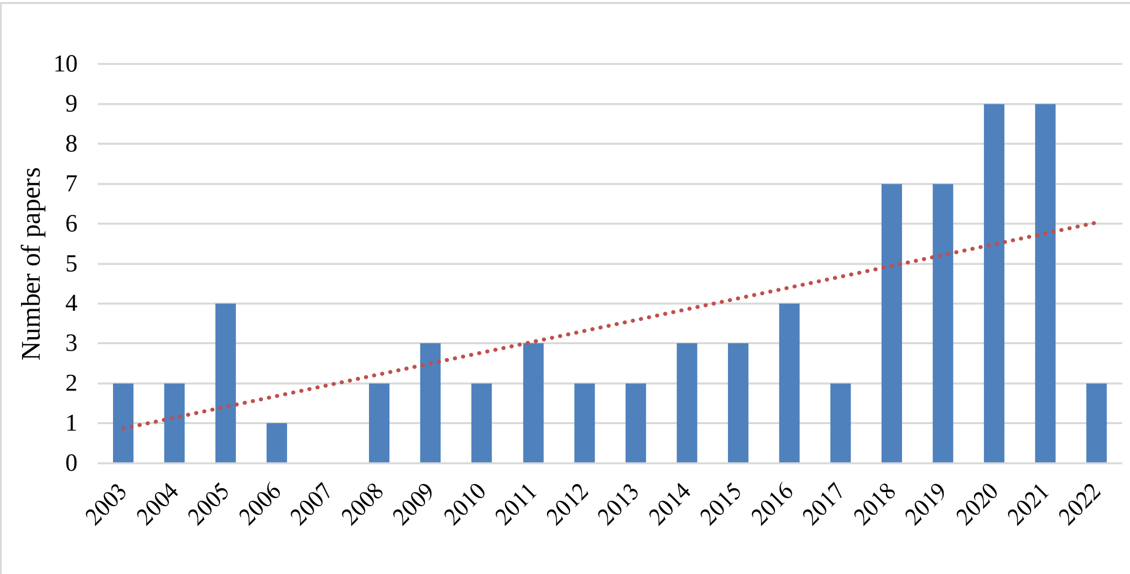

Figure 2: Number of papers published per year included in the literature review, with an increasing trendline (dotted orange line).

180 Although we explicitly limited the region to the Cerrado in our keyword search, we often encountered papers that include the Cerrado, but were 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.

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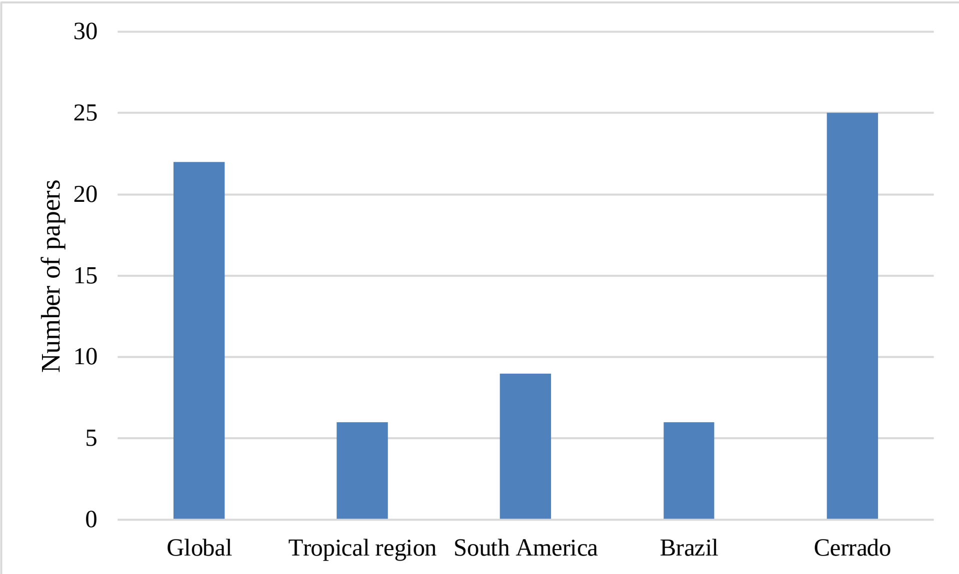

Figure 3: Number of papers per coverage of study area.

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 and 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 the state of fire emissions in the Cerrado. We further connect the study design with the coverage of the study area in Fig. 4.

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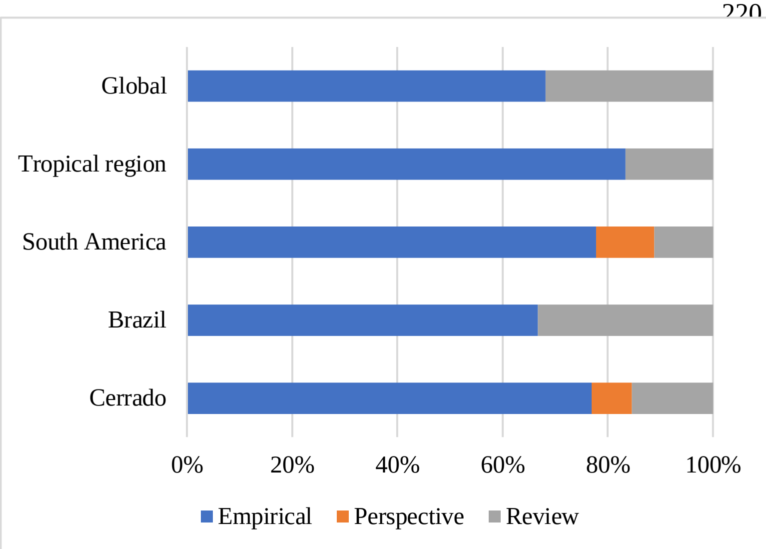

Figure 4: Percentage of papers per study design and per coverage of study area.

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 are further 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.

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3.2 Fire dynamics parameters to estimate fire emissions

Papers under 'fire dynamic parameters' encompass 43% of papers reviewed, suggesting that measuring and evaluating variables used to estimate emissions are crucial to developing fire emission research. The most common variables involved in fire emission documented in the literature are burned area, fuel characteristics, biomass burned, combustion factor, combustion efficiency and emission factor.

Burned area detection in the Cerrado has mainly been done with 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 6.9% of the Cerrado was burnt in 2020 (the equivalent of 139,644 km^2), a critical year in terms of wildfires in Brazil, and 3.7% in 2009 (74,353 km^2), a year with low overall rates of burned area in the country.

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). Drought was the strongest predictor of burned areas made by Alvarado et al. (2017). 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.

Fuel load in the Cerrado is highly connected to the seasonal variation in precipitation (Oliveira et al., 2021). 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). This means 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).

Thus, fire behavior is limited by both fuel characteristics and 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. 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 the emission rates of the different physiognomies in the Biome. The variables associated with fire emissions in the Cerrado estimates are summarized in Fig. 5.

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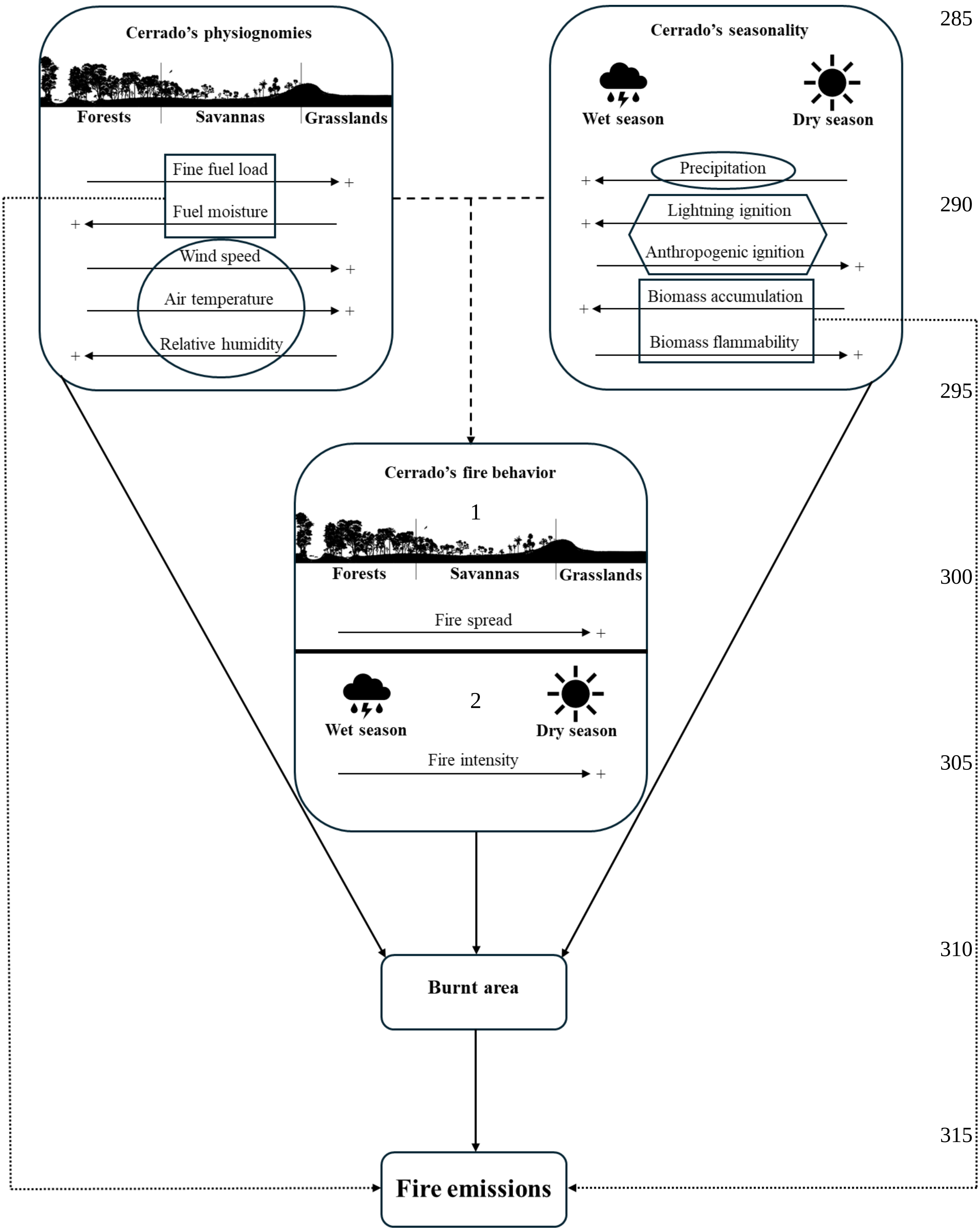

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Figure 5: Variables associated with estimating fire emissions in the Cerrado found in the literature. The Cerrados's physiognomies, separated into forests, savannas and grasslands, increase in fine fuel load and decrease in fuel moisture from forests 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 increase 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 burnt area, resulting in fire emissions (solid lines). The dotted lines represent the influence of fuel characteristics directly on emission: large burnt areas with low fuel moisture and low flammable biomass emits less than smaller burnt areas with low fuel moisture. The image representing the Cerrado's physiognomies was adapted from the Brazilian Agricultural Research Corporation (Embrapa n.d.).

The proportion of influence between climate and fuel on the resultant burnt area and emissions varies and is still being discussed. In a global context, studies suggest that burnt 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 burnt area predictions.

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.

Another important parameter identified in the literature to estimate fire emissions is termed combustion efficiency, or "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 CO2 emitted divided by the amount of CO2 and CO emissions combined, termed modified combustion efficiency (see Andreae, 2019; Hodgson et al., 2018; Vernooij et al., 2021).

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.

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 burnt (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.

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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

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

Satellite observations not only assist the estimation of fire emissions by providing supporting data to estimate parameters but also provide direct measurements of 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.

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 relies on the study done by Van Der Werf et al. (2017) to quantify fire emissions globally, and estimations are based on MODIS burned area products, on small burned areas detection derived from MODIS (GFED version GFED4s), and on the Carnegie–Ames–Stanford Approach (CASA) model. 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

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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) also 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 per year, 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 per year (0.018 ± 0.00354 PgC year^{-1}). When accounting for regrowth uptake, net emission was 0.015 ± 0.004 Pg CO_2 per year (0.00487 ± 9.65 10^{-4} PgC year^{-1}). Oliveira et

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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.

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).

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}).

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 a 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. 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 (da Veiga and Nikolakis, 2022; Durigan and Ratter, 2016; Schmidt and Eloy, 2020).

Despite the relevance of fire management to fire emissions, 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. However, we found studies that estimate the 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 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.

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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 burnt in areas of the Cerrado during the first three years (2014-2016) of implementation of *Cerrado-Jalapão* by 40-57% (Schmidt et al., 2018). In Canastra National Park in Brazil, areas under fire management also presented less annual area burnt (Batista et al., 2018). These reaffirm the potential of management activities to reduce emissions, as shown in other savanna countries, such as Australia, South Africa, and Venezuela (Mistry et al., 2019; Moura et al., 2019).

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, not only in the region but also on national and global scales. For example, we 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 (Van Der Werf et al., 2017). Similarly, and from a national perspective, da Silva Junior et al. (2020) have shown Cerrado fires to contribute more than 32% of the Brazilian total fire emissions (about 0.13 PgC year^{-1} over the 20 years).

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).

Most papers provide new information on the parameters used to estimate 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.

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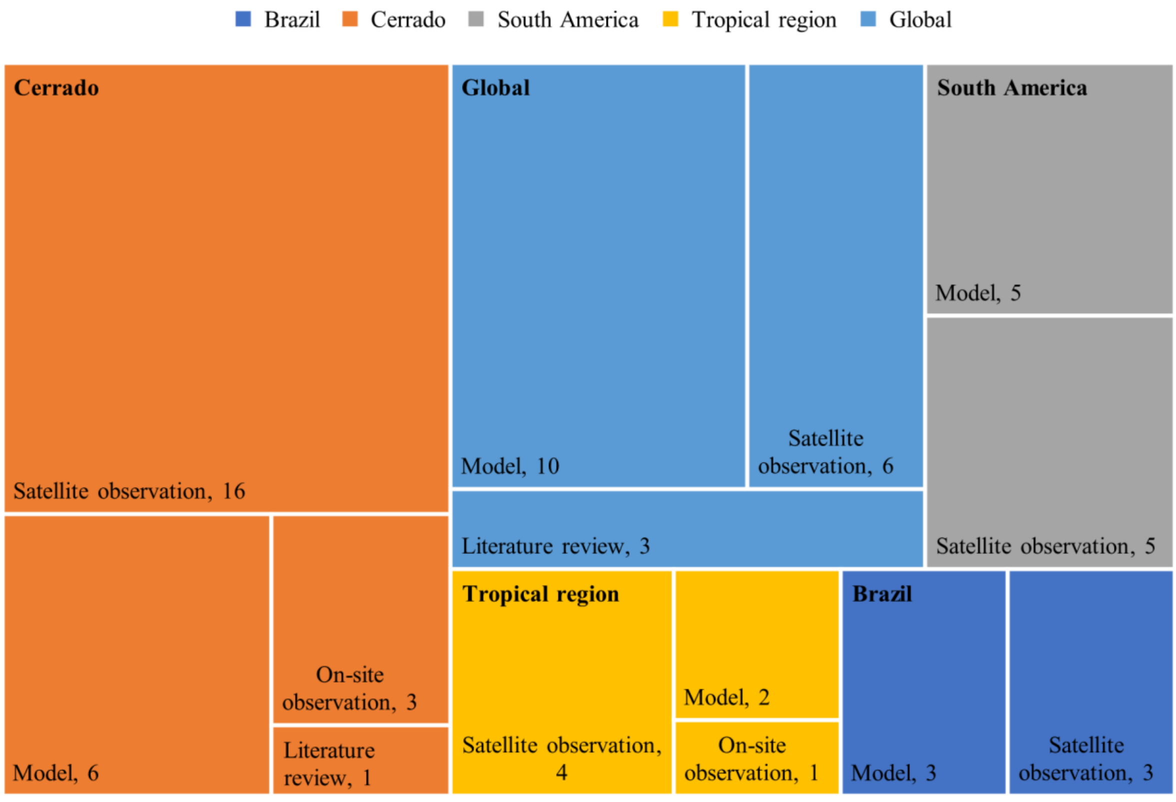

Figure 6: Treemap of the methodological techniques used across study areas in empirical papers. The numbers present the number of studies of each methodological technique within each study area. The study areas Global, Tropical region, South America and Brazil are regions that include results for the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

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.

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 example, the Paris Agreement of 2015, of which Brazil is a signatory country, has established GHG reduction targets and recognizes the importance of voluntary activities to reduce emissions, reassured at the Conference of the Parties 27 (COP 27). Fire management could be a critical way to meet these targets (Lipsett-Moore et al., 2018; Martin, 2019). The United Nations 2030 Agenda for Sustainable Development Goals also includes goals that are intrinsically related to fire, such as goals 3 (good health and well-being), 13 (climate action), and 15 (life on land) (Martin, 2019).

Therefore, estimating local fire emissions is reflected in the atmospheric 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

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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 emissions 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.

Compiling published material on fire emissions in the natural areas of 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, 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. Pathways towards improving fire emissions in the Cerrado include connecting observational information with modelling and a better assessment and quantification of the impact of qualitative aspects in fire estimates. Examples of how this can be achieved is by valuing prescribed burning emissions and including these in fire modelling, representing fire management in land surface models, using on-site observations to assess models' utility and as input data to modelling, 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.

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

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.

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 included more papers. 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.

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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 in 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 atmospheric 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. This demonstrates 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. This complexity is reflected in the divergence of values and units of carbon emissions estimates and in the multiple parameters used to estimate emissions.

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 atmospheric carbon budget. This is possible due to a clearer understanding of the variables considered when estimating emissions and of the published values estimated, and due to 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 can be made available upon request to the corresponding author.

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

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