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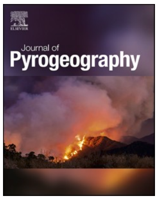

Including prescribed burning in fire modelling: A case study from the Brazilian Cerrado using the JULES-INFERNO model

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ABSTRACT

Prescribed burning (PB) is an important prevention activity under fire management. Similarly to other fire-prone settings, PB in the Cerrado is often implemented in protected areas to prevent intense wildfires in the drier months. We modelled burned area and fire carbon emissions in the Cerrado with the JULES-INFERNO model over a 30-year period (1990-2019), to evaluate the impacts of PB on a biome-scale. We first improve representation of the Cerrado in JULES-INFERNO, then simulate PB by setting an additional ignition to C4 grass during the early dry season. This is a counterfactual experiment where the PB additional set-up can be adapted to other regions worldwide. Over the 30 years, PB applied in the early dry season reduced burned area and fire emissions in the late dry season by 9.28% year^{-1} and 11.24% year^{-1}, respectively, when compared to the non-PB scenario. In years with increased fire activity, the reductions are higher than average. Our results are not effective on the annual balance. Our sensitivity experiment with increased EDS burnings suggests that shifting fire activity earlier in the season may reduce the impacts of uncontrolled fires in the Cerrado. To our knowledge, this is one of the few studies to explicitly include PB within a dynamic vegetation model, and to adjust a global model to better represent the Cerrado's fire predictions. Prospective studies are recommended to improve the understanding of the model's performance, including analysis of modelled parameters such as the C4 grass post-fire recovery, and the integration between observational and modelled data.

1. Introduction

The Brazilian Cerrado (hereafter “the Cerrado”) is heavily regulated by fire, and has likely evolved with fire for at least four million years (Simon et al., 2009). The Cerrado comprises a mosaic of vegetation formations, or physiognomies, that range from grasslands, to savannas, to forest formations (Ribeiro and Walter, 2008). These diverse vegetation types influence fire by providing a variety of fuel types and microclimatic conditions across its extent (Flannigan et al., 2009; Gomes et al., 2020b), with climatic drivers of fire in the Cerrado differing greatly across the biome (Silva et al., 2025).

As in other savanna environments, the dominance of fine fuel load is the main cause of the high flammability in the Cerrado (Hoffmann et al., 2012; Zanzarini et al., 2022). The open formations of the Cerrado (grasslands and savannas) are dominated by grasses and herbs with few shrubs and trees (Ribeiro and Walter, 2008). Open formations also have higher wind speed, higher air temperature, lower relative humidity, and lower fuel moisture than forest formations (Hoffmann et al., 2012). The combination of fuel and climate results in more intense fires in grasslands and savannas in the Cerrado (Hoffmann et al., 2012).

The Cerrado presents two distinct seasons: rainy or wet season (November-March), characterized by biomass accumulation and high fuel moisture, and 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). Natural fires are rare in the Cerrado, but occur due to lightning in

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the rainy season, producing low-intensity fires since the vegetation still holds high moisture content (Ramos-Neto and Pivello, 2000). Fires resulting from anthropogenic activities persist over a longer period and occur mainly in the dry season (Ramos-Neto and Pivello, 2000). As a result, 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 fuel load is higher and drier. Thus, fire occurrence and dynamics in the Cerrado are also seasonal and highly dependent on fuel characteristics, climatic conditions and ignition patterns (Da Veiga et al., 2025).

Due to climate change, higher temperatures and reduced precipitation are now more common in the Cerrado (Gomes et al., 2020b; Hofmann et al., 2021). According to the IPCC AR6 WGI/WGII (Intergovernmental Panel on Climate Change et al., 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 may result in increased burned area, progressively explained by climate change worldwide (Burton et al., 2024; Jones et al., 2022).

Fire and climate regulate one another – fire emissions contribute to the increase of greenhouse gases concentration in the atmosphere, which then creates warmer and drier conditions that facilitates the occurrence of more fires (Andela et al., 2017; Flannigan et al., 2009). Conversely, increased fire activity reduces carbon fuel, limiting fire occurrence in some ecosystems (Pausas and Keeley, 2014). Climate-carbon feedbacks are large in fire-prone settings such as the Cerrado, which are dry enough for flammability, but wet enough for fuel. These ecosystems are arguably more vulnerable to climate change and more important than most in determining global carbon cycle feedback. Managing fire in these ecosystems could therefore be an efficient climate mitigation strategy.

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). Actions to avoid the release of carbon or to increase carbon storage, termed natural climate solutions (NCS), have emerged as a possibility to reduce the effects of climate change (Griscom et al., 2020). Tropical NCS, like fire management, could mitigate 6.56 Pg CO_2 $year^{-1}$ between 2030 and 2050 (Griscom et al., 2020).

In Brazil, Federal Legislation explicitly allows fire management for conservation purposes since 2012 (Law 12,651/2012). Fire management and integrated fire management (IFM) encompass a set of activities, from fire prevention to fire suppression depending on the management goal. One common practice under IFM is prescribed burning (MYERS, 2006). From a national perspective, prescribed burning in Brazil is primarily conducted in the early dry season (EDS) by Federal environmental agencies within protected areas (PAs), meaning they are targeted to specific contexts that vary greatly from one PA to the other. Representing this diversity within fire management planning is difficult, hindering the understanding and the implementation of prescribed burning in the biome-scale.

From a cultural perspective, prescribed burning is conducted by Indigenous Peoples and Local Communities (IPLCs) for fuel load control and reducing risk of high-intensity LDS wildfires (Bilbao et al., 2025). Historically and still today, other cultural burns are conducted by IPLCs in their territories in the Cerrado for multiple purposes, including flowering and fruit production, control of invasive species, maintenance of ecological balance and biodiversity, hunting, enhancement of pasture regrowth for cattle raising, slash-and-burn agriculture, and ritual and ceremonial practices (Bilbao et al., 2025; Mistry et al., 2005). These burns are implemented at the landscape scale and at different periods throughout the dry season, with some being intentionally carried out during LDS, such as slash-and-burn practices (Bilbao et al., 2025; Mistry et al., 2005).

In 2024, Brazil approved the Integrated Fire Management National Policy (Law 14,944/2024), which aims to prevent wildfires and reduce their intensity and severity. The Policy also mentions greenhouse gas emission reductions, but it remains unclear whether these refer to annual, cumulative, or wildfire-specific emissions. In all cases, a central objective of the Policy is to improve understanding of the impacts of IFM activities, including prescribed burning.

Despite the increasing recognition of fire's importance to the Cerrado and the subsequent expansion of fire management operations, few studies have been published investigating the impacts in burned area and fire carbon emissions due to prescribed burning in a biome-scale, when compared to other savanna countries such as Australia (Da Veiga and Nikolakis, 2022).

This study introduces the JULES-INFERNO Cerrado, which sets a counterfactual experiment where prescribed burning is applied at a biome-scale to assess its impact in terms of burned area and fire carbon emissions, using the JULES-INFERNO model. Joint UK Land Environment Simulator (JULES) represents the land surface component of the UK Earth System Model (UKESM), and the Interactive Fire and Emission Algorithm for Natural Environments (INFERNO) can act within JULES to simulate fire and to enhance its representation of vegetation disturbances (Burton et al., 2019; Clark et al., 2011; Mangeon et al., 2016). JULES-INFERNO has previously succeeded in evaluating current and future burned area and fire emissions in South America (Burton et al., 2021), but has not yet been adapted specifically to the Cerrado.

Few studies have explicitly represented prescribed burning within dynamic vegetation models. Here, we implement prescribed burning in JULES-INFERNO through a sensitivity experiment to evaluate its effects in the Cerrado. In doing so, we also adjust a global model to better represent burned area and fire emissions in the biome. This is especially relevant given the current climate change context, the need to move beyond global carbon cycle models towards region-specific ones that better capture key processes at the spatial scale of fire management strategies, and the recently approved IFM National Policy in Brazil and the potential outcomes it may generate.

This study comprises two key components. First, we include prescribed burning in JULES-INFERNO, and then we analyze its impact in burned area and fire carbon emissions in the Cerrado. This study is guided by two main questions: is prescribed burning an activity able to reduce burned area and fire carbon emissions in the Cerrado biome? If so, by how much and when? Based on the international examples and on the published studies undertaken in the Cerrado, the hypothesis is that prescribed burning applied in the early dry season reduces burned area and carbon fire emissions in the late dry season in the Cerrado.

2. Methods

2.1. Study area

The Cerrado biome is located in the Brazilian Central Plateau, occupying 24% of the Brazilian territory, or about 2 million km^2, and it is the second largest biome in Brazil (IBGE, 2004). The Cerrado covers a continuous area within twelve states and also includes isolated vegetation within four additional states mostly located in the Amazon (Ribeiro and Walter, 2008). These isolated patches, however, are not included in this analysis. The Cerrado has similar ecological and physiognomic characteristics as other savannas in Tropical America, Africa, Southeast Asia and Australia (Ribeiro and Walter, 2008). Thus, the Cerrado is a singular environment, but often referred to as the Brazilian savanna.

According to Köppen climate classification, the Cerrado is classified as Tropical savanna climate or tropical wet and dry climate (Aw) (Alvares et al., 2013). The Cerrado presents dry winters (April-October) and rainy summers (November-March), with an annual average precipitation of 1500 ± 500 mm (Empresa Brasileira de Pesquisa Agropecuária, 2005). Annual mean temperature ranges from 21.3 °C to 27.2 °C (Empresa Brasileira de Pesquisa Agropecuária, 2005).

Of the Cerrado area, 48.66% are under the natural vegetation classification (Mapbiomas, 2024). According to the MapBiomas 8.0 database, about 555,000 km^2 are under savanna formation, 250,000 km^2 under forest formation, and 78,500 km^2 under grassland formation. Thus, savannas are the predominant and the most representative vegetation formation of the Cerrado. In this study, we use C4 grass PFT to represent natural vegetation in the biome, as it is the dominant natural PFT in the Cerrado as simulated by JULES (Fig. S1 in the Supplementary Materials), being the vegetation type over which our PB simulations are performed.

2.2. Estimating burned area and fire emission with JULES-INFERNO and TRIFFID

The estimated burned area in JULES-INFERNO (Mangeon et al., 2016) is coupled to the Top-down Representation of Foliage and Flora Including Dynamics (TRIFFID) (Cox, 2001) to estimate fire emissions (Burton et al., 2019). TRIFFID calculates the amount of carbon released from vegetation due to fires ($\Lambda_{\mathrm{FIRE,veg}}$), along with the carbon emitted from fires from the decomposable plant material ($\Lambda_{\mathrm{FIRE,DPM}}$) and resistant plant material ($\Lambda_{\mathrm{FIRE,RPM}}$) pools (Harper et al., 2018). DPM and RPM soil carbon pools are used in this research to represent litter, as they are proxies of the litter carbon store due to their high turnover rates (Burton et al., 2019). Together, the amount of carbon released from vegetation and from the DPM and RPM pools due to fires represent total emitted carbon from fires (Λ_{FIRE}).

To better represent the Cerrado within JULES-INFERNO, we changed the $\Lambda_{\mathrm{FIRE,DPM}}$ equation (Burton et al., 2019, Equation (4)), as shown in Equation (1), and the regrowth rate of the C4 grass. Within TRIFFID, C4 grass tends to quickly recover, which can be addressed by increasing the mortality rate of grasses to prevent overgrowth (Burton et al., 2019). We address this issue by modifying the regrowth rate in C4 grass in JULES-INFERNO Cerrado.

$$\Lambda_{\mathrm{FIRE,DPM}} = \left(\mu_{\mathrm{min,DPM}} + \left(\mu_{\mathrm{max,DPM}} - \mu_{\mathrm{min,DPM}}\right)(1-\theta)\right) C_{\mathrm{DPM}} \sum_i \mathrm{BA}_i v_i \tag{1}$$

μ are the minimum and maximum completeness of combustion (CC) parameters of the DPM and RPM pools determined in INFERNO as $\mu_{\mathrm{min,DPM}} = 0.8$, $\mu_{\mathrm{max,DPM}} = 1.0$, $\mu_{\mathrm{min,RPM}} = 0.0$, $\mu_{\mathrm{max,RPM}} = 0.2$ (Burton et al., 2019); θ is the soil moisture content; C_{DPM} and C_{RPM} are the total available soil carbon in the respective soil pool (kgC m^{-2}) calculated in TRIFFID; BA_i is the burned area calculated in INFERNO to each PFT i; v_i is the fractional coverage per PFT estimated in TRIFFID.

First, the component 'carbon released from DPM pool due to fires ($\Lambda_{\mathrm{FIRE,DPM}}$)' was modified, since grasses provide a high fraction of DPM litter (Clark et al., 2011), and 41.00% of the Cerrado natural area is represented by C4 grass on average (1990-2019) (Fig. S1, Supplementary Materials). We decreased litter accumulation to provide more efficient burning in terms of accelerating DPM litter turnover rate, with the intention to avoid fuel building up. The Cerrado and other fire-prone environments naturally limit litter accumulation, as constant fires prevent organic material from accumulating over time. For this, we set the minimum combustion completeness of the DPM pool to maximum ($\mu_{\mathrm{min,DPM}}=\mu_{\mathrm{max,DPM}}$). This change led to the removal of soil moisture term (θ), so it does not limit the burning. The final $\Lambda_{\mathrm{FIRE,DPM}}$ equation used in this research is (Equation (2)):

$$\Lambda_{\mathrm{FIRE,DPM}=}\ \mu_{\mathrm{max,DPM}}\, C_{\mathrm{DPM}} \sum_i \mathrm{BA}_i v_i \tag{2}$$

Second, we reduced the regrowth rate of the C4 grass by altering C4 grass productivity, due to its fast recovery within TRIFFID (Burton et al., 2019). This was achieved by adjusting the quantum efficiency of the photosynthesis parameter of the C4 grass, which is an algorithm in TRIFFID to determine the efficiency in use of light of each PFT (Clark et al., 2011). This parameter is a pre-established algorithm, and it is set to 0.04 mol $\mathrm{CO_2}$ [mol PAR photons]$^{-1}$ to the C4 grass PFT. We halved this number to 0.02 mol $\mathrm{CO_2}$ [mol PAR photons]$^{-1}$ to evaluate its effect on post-fire regrowth.

In summary, we changed litter accumulation to reduce fuel available for burning and limit fuel to build up. We also changed C4 grass productivity to reduce litter and allow litter to recover slower. We added an additional counterfactual experiment setup to enable the evaluation of changes of burned area and fire emissions in C4 grass PFT alone, not considering the land use changes made throughout the time series. For this, we held the fraction of agriculture and pasture constant at 1990's level over time (Fig. S2) by removing these two datasets from the dataset list setup.

2.3. Comparison of results with GFED5, GFED500m and INPE queimadas datasets

We used the Global Fire Emission Database version 5 (GFED5) (Chen et al., 2023) and the GFED500m data (van Wees et al., 2024) to compare with our burned area and fire emissions results, respectively. We additionally compare our burned area result with the *Banco de Dados Queimadas* from the Brazilian National Institute for Space Research (INPE), hereafter referred to as INPE Queimadas. GFED5 provides global monthly burned area at 0.25° spatial resolution from 2002 to 2022 (Chen et al., 2023). GFED5 burned area is mostly derived from the Moderate-Resolution Imaging Spectroradiometer (MODIS) MCD64A1 burned area product (Chen et al., 2023).

For fire emissions, we used the GFED500m data (van Wees et al., 2024) derived from burned area. We used the variable 'total biomass burning carbon emissions from aboveground' (C_AG_TOT; g C m^{-2} month^{-1}) to compare with our 'carbon released from vegetation due to fires' ($\Lambda_{\mathrm{FIRE,veg}}$) variable, and the variable 'total biomass burning carbon emissions from belowground' (C_BG_TOT; g C m^{-2} month^{-1}) to compare with our variable that estimates carbon released from litter due to fires ($\Lambda_{\mathrm{FIRE,DPM}} + \Lambda_{\mathrm{FIRE,RPM}}$). Total emissions from GFED500m are calculated as C_AG_TOT + C_BG_TOT, which is comparable to our Λ_{FIRE} variable. Data from GFED500m is freely available at https://zenodo.org/records/12670427.

INPE Queimadas provides datasets for active fire and burned area in Brazil, and we used the 1 km burned area product (AQ1km). AQ1km uses Aqua and Terra/MODIS collection 6 burned area product, and the regional algorithm developed by Libonati et al. (2015) to improve estimates. INPE's data is freely available at https://terrabrasilis.dpi.inpe.br/queimadas/portal/.

We regridded GFED5, GFED500m and INPE Queimadas data to 0.5°, using the linear regridding method, to be comparable with our results. For INPE Queimadas, the 1 km data was converted into percentage of the 0.5° grid cells covered by burned area, to make it comparable with GFED5 and JULES-INFERNO.

To evaluate our results, we present a comparison of the GFED5, GFED500m and INPE Queimadas datasets with the results from JULES-INFERNO Cerrado developed in this research. This includes the analysis of total burned area and total emissions for the whole time period, as well as for the EDS and LDS periods alone. We also evaluate the results spatially, where we compare the performance of our model based on the spatial distribution of burned area and fire emissions across the Cerrado.

Additionally, to evaluate how well the model reproduces the seasonal cycle of burned area in the Cerrado, we compare the JULES-INFERNO Cerrado (without prescribed burning) against GFED5 using two complementary metrics: Mean Phase Difference (MPD) and Mean Normalized Climatological Difference (MNCD).

We first quantify the timing (phase) of the burned area seasonal cycle following the approach of Kelley et al. (2013). Monthly climatological burned area in both GFED5 and our model is represented as a vector in the complex plane, where the vector length is proportional to the burned area and the direction corresponds to the calendar month. For example, a unit burned area in January is mapped to $1+0i$, April to $0+1i$, July to $-1+0i$, and October to $0-1i$, with intermediate months linearly interpolated around the unit circle.

For each dataset, the monthly complex vectors are summed, and the argument of the resultant vector gives the mean seasonal phase. The Mean Phase Difference (MPD) is then calculated as the absolute angular separation between the model and observational phase angles, normalized such that MPD = 0 indicates perfect phase agreement, and MPD = 1 indicates a six-month phase shift (i.e., complete opposition).

We also assess the seasonal concentration of burned area using a modified version of the concentration metric described in Kelley et al. (2013), adapted for regional scales. We define the MNCD as Equation (3):

$$MNCD = \frac{\sum_{m=1}^{12} \left| \frac{obs_m}{\overline{obs}} - \frac{mod_m}{\overline{mod}} \right|}{\sum_{m=1}^{12} \left| \frac{obs_m}{\overline{obs}} - \frac{1}{12} \right|} \tag{3}$$

Where *obs* and mod are the monthly climatological burned area totals for observations (GFED5) and the model (JULES-INFERNO Cerrado) respectively, and the over-bar denotes the annual mean. The denominator, therefore, represents the deviation of observations from a hypothetical case in which burned area is uniformly distributed throughout the year.

Under this definition, MNCD = 1 corresponds to a “null-model” case in which the model reproduces the *mean* seasonal concentration structure but no additional detail, MNCD <1 indicates skill in capturing the seasonal concentration pattern, and MNCD >1 indicates poorer-than-null performance.

2.4. Adding prescribed burning in the JULES-INFERNO model

We used JULES (Clark et al., 2011) version 6.3, and INFERNO (Mangeon et al., 2016), switch activated within JULES to simulate prescribed burning. The JULES-INFERNO simulations used are from the first component of the third simulation round of the Intersectoral Impacts Intercomparison Project (ISIMIP3a, https://www.isimip.org/), which provides historical simulations using GSWP3-W5E5 reanalysis climate up to 2019 (Frieler et al., 2024), at 0.5° spatial resolution. The JULES Earth System setup based on ISIMIP is detailed in Mathison et al. (2023).

JULES-INFERNO calculates burned area by combining ignition (natural and anthropic), flammability and average burned area per plant functional type (PFT) (Mangeon et al., 2016). We modified the total ignition equation (Mangeon et al., 2016, Equation (3)), which now includes a prescribed burning component (Equation (4)):

$$I_T = (I_N + I_A)\, f_{NS+}\, I_{PB} \;/\; \left(8.64 \times 10^{10}\right) \tag{4}$$

Where I_T is the total ignition; I_N is the natural ignition; I_A is the anthropic ignition; f_{NS} is the fraction of fires not suppressed; I_{PB} represents prescribed burning ignitions. The result is divided by $8{,}64 * 10^{10}$ to convert from ignition km^{-2} $month^{-1}$ to ignition m^{-2} s^{-1}.

f_{NS} is calculated as per Mangeon et al. (2016; Equation (2)), as shown in Equation (5):

$$f_{NS} = 7.7\left(0.05 + 0.9 \times e^{-0.05PD}\right) \tag{5}$$

Where PD is the population density (people km^{-2}).

Population density is also used to estimate I_A (Mangeon et al., 2016, Equation (1)) and was obtained from the ISIMIP3a protocol and was based on data from the History Database of the Global Environment (HYDE) v3.3 (Volkholz et al., 2024). Lightning used for I_N (Mangeon et al., 2016) was also obtained from the ISIMIP3a protocol, and based on LIS/OTD data (CECIL, 2006). LIS/OTD are gridded climatology datasets that record lightning flash rates detected by the Optical Transient Detector (OTD) and the Lightning Imaging Sensor (LIS), both aboard the Tropical Rainfall Measuring Mission (TRMM) satellite.

Anthropogenic ignition is calculated per Mangeon et al. (2016, Equation (1)), as shown in Equation (6):

$$I_A = k(PD)\; PD\alpha \tag{6}$$

Where k (PD) = 6,8 * $PD^{-0.6}$ and it is a function that represents the human influence on ignitions in rural and urban environments, and α = 0.03, which is a parameter that represents the number of potential ignition sources per person per month per km^2.

We acknowledge that the patterns of anthropogenic ignition for the global south, including the Cerrado, might act differently than what is proposed in Equation (6), meaning that population density might not act as a determining factor to ignition, as previously observed globally by Perkins et al. (2024, 2025) in WHAM! (the Wildfire Human Agency Model). Because there is not much research in this field specific for the Cerrado (the only study available is Ramos-Neto and Pivello, 2000), we guide our parameters based on Equation (6): applying the population density of 18.22 people km^{-2} derived from ISIMIP3a dataset, human ignition is 0.6386 km^{-2} $month^{-1}$.

I_{PB} is a four-dimensional dataset, meaning that it varies spatially (latitude and longitude), per time (month) and per PFT. Consequently, prescribed burning can be tested in and adapted to other regions of the world. Similar to the natural ignition component within JULES-INFERNO, I_{PB} is a counterfactual variable where ignition is uniformly distributed across the entire area. For this study, we set I_{PB} in the C4 grass PFT and in the early dry season (EDS) months (April, May and June) to analyze its effect on the LDS period (August, September, October).

I_{PB} is set to be equal to the sum of I_N and I_A in May, when natural ignitions are largest. Natural ignition according to ISIMIP3a is 0.07814 flashes km^{-2} $month^{-1}$ for May, adding the human ignition rate of 0.6386 km^{-2} $month^{-1}$, gives an I_{PB} value of 0.7168 fires km^{-2} $month^{-1}$. Thus, prescribed burning doubles the ignition rate for C4 grass fires in May, and the same value is applied to April and June. We choose to double ignition rates to provide a strong forcing to the model and a clearly detectable response, noting that burned area in the LDS is more than double that in the EDS and that the maximum anthropogenic ignition rate can be as high as 2.3 km^{-2} $month^{-1}$ (MANGEON et al., 2016).

3. Results

We first present the results from the comparison of the model before and after the changes in JULES-INFERNO and TRIFFID to represent the Cerrado, contrasting with GFED5, GFED500m and INPE Queimadas. We then analyze the effects of prescribed burning in the JULES-INFERNO Cerrado on burned area and fire emissions, with special attention to the years with highest burned area, according to our model.

3.1. Comparison of the model before and after the changes in JULES-INFERNO and TRIFFID to represent the cerrado

Although we ran the model from 1990 to 2019, the comparison process was carried out over the period 2003-2019, to keep the consistency with GFED5, GFED500m and INPE Queimadas, as these rely on MODIS satellite burn products, and there is greater certainty in these data from 2003 (see Andela et al., 2019; Silva et al., 2019).

JULES-INFERNO is known to overestimate burned area in several regions globally, including the Cerrado (Burton et al., 2019, 2021). When model adjustments were applied to better represent the Cerrado's fire dynamics, we observed a reduction in the overestimation of both burned area and fire emissions (Fig. 1). These results show that our model reduced 40.0% of average burned area per year, and 16.6% of averaged fire carbon emissions per year, compared to the original JULES-INFERNO model.

JULES-INFERNO returns an average burned area from 2003 to 2019

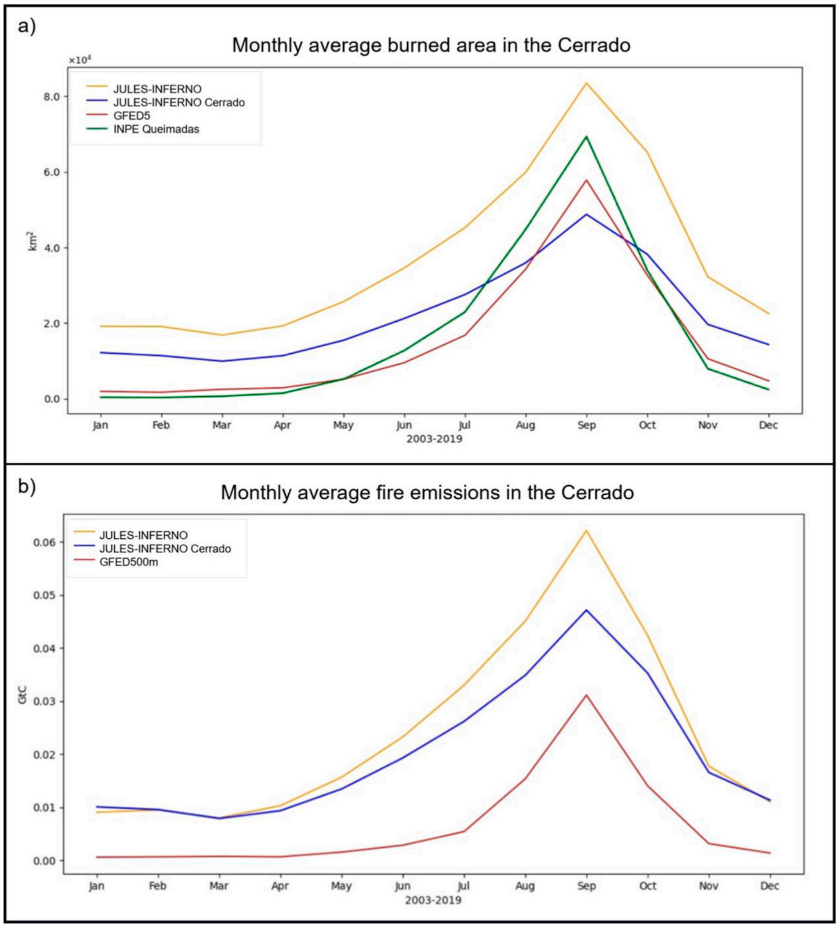

Fig. 1. Monthly average burned area (a) and fire emissions (b) in the Cerrado.

of 36,942.24 km^2 year^{-1}, ranging from 30,611.0 km^2 (2009) to 42,312.1 km^2 (2007). With the changes developed in this research, these numbers drop to 22,170.4 km^2 year^{-1}, from 16,005.9 km^2 (2013) to 29,342.4 km^2 (2015). GFED5 averages 15,051.4 km^2 year^{-1} for the same time period, ranging from 7978.9 km^2 in 2009 to 26,098.2 km^2 in 2007, while INPE Queimadas averages 15,675.5 km^2 year^{-1}, from 7532.6 km^2 (2009) to 23,272.2 km^2 (2012).

In terms of fire emissions and annual averages considering 2003-2019, JULES-INFERNO averaged 0.024 GtC year^{-1}, ranging from 0.019 GtC in 2009 to 0.028 GtC in 2007. JULES-INFERNO Cerrado averaged 0.020 GtC year^{-1}, from 0.012 GtC (2013) to 0.029 GtC (2015). GFED500m presents much lower values, averaging 0.0064 GtC year^{-1}, ranging from 0.002 GtC (2009) to 0.013 GtC (2007).

We hypothesize that more significant reductions are shown in burned area than in fire emissions (Table 1) because the changes made to JULES-INFERNO are related to the litter pool, which controls flammability (Harper et al., 2018). Thus, the woody biomass, which is responsible for most fire emissions (Bispo et al., 2020; Gomes et al., 2020a; Oliveira et al., 2021; Zimbres et al., 2020), has not changed.

Table 1
Comparison of the averaged burned area and fire emissions from 2003 to 2019 in the Cerrado from four datasets analyzed.

2003-2019	JULES-INFERNO	JULES-INFERNO Cerrado	GFED5/ GFED500m	INPE Queimadas
Burned area (km^2 year^{-1})	36,942.2	22,170.4	15,051.4	15,675.5
Fire emissions (GtC year^{-1})	0.024	0.020	0.0064	

When analyzing the dry months alone (April-October), we observe a less intense peak in the dry season for both burned area and fire emissions when compared to the JULES-INFERNO. Because fire emissions are calculated from burned area in all datasets, the peaks are consistent between the two variables (Fig. 2). The overall overestimation of JULES-INFERNO, and the reduced overestimation in JULES-INFERNO Cerrado in the dry season becomes evident in Fig. 2, along with an underestimation of burned area in JULES-INFERNO Cerrado during August and September when compared to GFED5 and INPE Queimadas (Fig. 2a).

The absolute monthly and yearly values from 2003 to 2019 for the 4 datasets for burned area and for the 3 datasets for fire emissions are available in the Supplementary Materials (Tables S1–S4), along with the difference (%) in values between our model and the other databases.

The overestimation of both JULES-INFERNO and JULES-INFERNO Cerrado can also be observed spatially (Fig. 3). For fire emissions (Fig. 3e–g) JULES-INFERNO Cerrado shows higher emissions over much of the region when compared to JULES-INFERNO, but this is offset by lower emissions in the southwest of the biome (black circles in Fig. 3), leading to a slight reduction in overall fire emissions across the time series.

The circled areas in Fig. 3 indicate fire activity that is detected in JULES-INFERNO, but not in the reference datasets. This is expected given the model inputs, and it could happen because JULES-INFERNO considers burned area in areas with crop and pasture (Fig. S2a) due to the presence of litter pool and high population density. By keeping it constant at 1990's level (Fig. S2b), we are able to decrease C4 crop and C4 pasture fractions, thus reducing overestimation. In reality, these are well-established large crop and pasture areas, and these tend to be

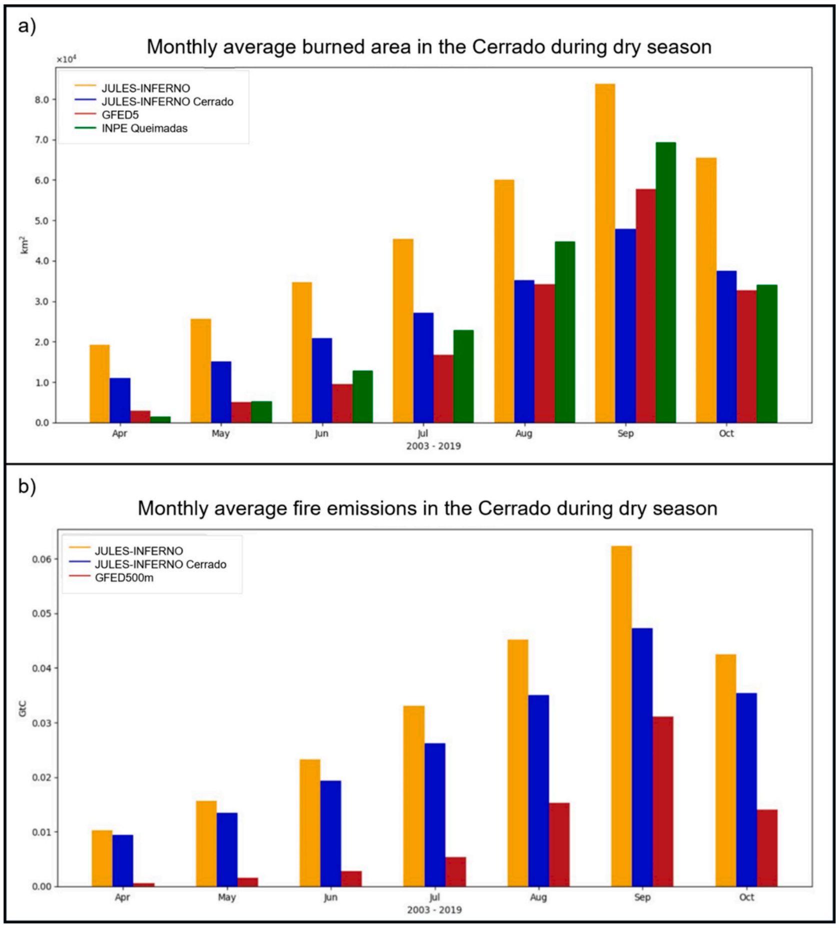

Fig. 2. Monthly average burned area (a) and fire emissions (b) in the Cerrado in the dry season months.

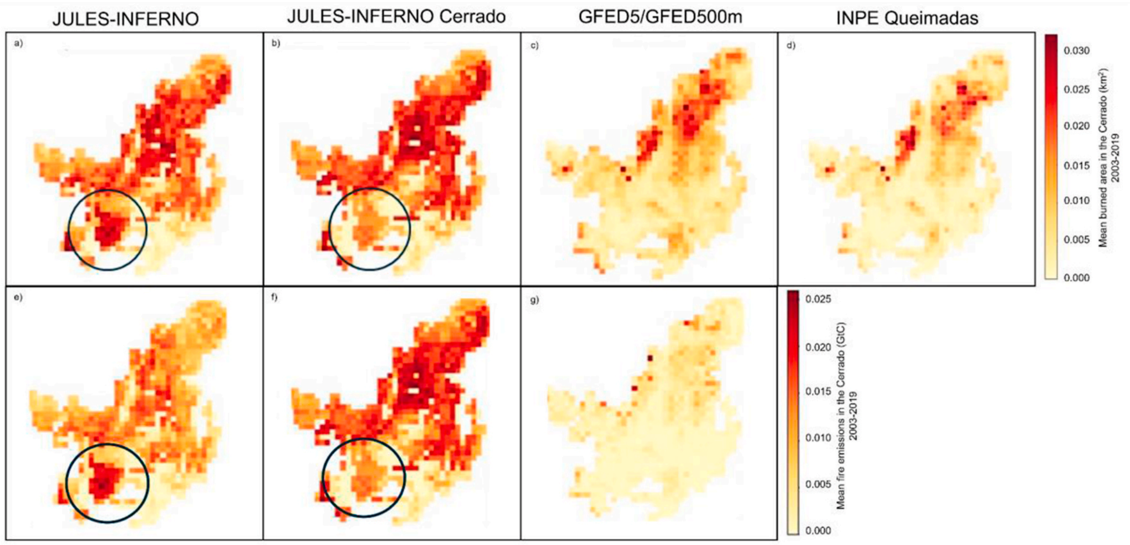

Fig. 3. Spatial distribution of burned area (a-d) and fire emissions (e-g) in the Cerrado.

highly mechanized and not use fire. Thus, fire tends to decrease in these areas, because the consolidated agriculture and pasture lands do not require the use of fire, leading to the southern portion of the Cerrado not burning for at least 30 years (Arruda et al., 2024; Gomes et al., 2024). However, in our counterfactual set-ups, JULES-INFERNO does not consider this local characteristic in land use and thus predicts burning in that region.

Additionally, when evaluating the seasonal cycle of burned area in JULES-INFERNO Cerrado (without prescribed burning) against GFED5 using diagnostics of phase and concentration adapted from Kelley et al. (2013), we estimate that the Mean Phase Difference (MPD) over the Cerrado is 0.23, corresponding to a mean timing mismatch of about 40 days. This indicates that the phase of the seasonal fire cycle is reproduced reasonably well, with only modest mismatch in burned area timing. We further assessed the seasonal concentration of burned area using a Mean Normalized Climatological Difference (MNCD) metric. The model yields MNCD = 0.97 compared with a regional mean null model of 1.0 and a median null-model (as suggested in Burton et al., 2019) value of 1.03, indicating some skill in capturing the observed seasonal concentration pattern.

3.2. *Analysis of prescribed burning results on burned area and fire carbon emissions in the cerrado*

For the prescribed burning *versus* non-prescribed burning comparison, we analyzed the three decades of data, from 1990 to 2019. We added the prescribed burning component to JULES-INFERNO Cerrado and compared the results from the baseline simulations from JULES-INFERNO Cerrado.

For the 30 years of analysis, we observe an average reduction in the LDS months in both burned area and fire emissions when prescribed burning is applied. For burned area, the reduction averages 9.28% (10,684.2 km^2), while fire emissions reduce on average 11.34% (0.0126 GtC) when compared to the non-prescribed burning scenario (Fig. 4). The reduction in burned area and fire emission during the LDS is due to the reduced fuel resultant from the increase in burned area during the EDS months (April, May, June).

The spatial distribution of burned area and fire emissions with and without prescribed burning are shown in Fig. S3 (Supplementary Materials). If we consider the annual balance, then we do not see a reduction in either burned area or fire emissions. This is possibly a consequence of doubling ignitions in the EDS, and uniform fire size applied to prescribed and non-prescribed burning. Given that intense and devastating wildfires tend to occur in the LDS in the Cerrado (Da Veiga and Nikolakis, 2022; Silva et al., 2021), and that these are increasingly common due to climate change (Intergovernmental Panel on Climate Change et al., 2021; 2022), prescribed burning in the EDS becomes an important activity to reduce the impacts of LDS burns. These prescribed burns are controlled and carefully managed, in contrast to the often uncontrolled and severe LDS fires. Thus, this study provides results that suggest increased overall burned area and fire emissions (Table S5), but a decrease in destructive fires.

The spatial distribution of the difference between burned area (Fig. 5a) and fire emissions (Fig. 5b) with and without prescribed during the LDS months show where in the Cerrado prescribed burning can be more effective. Our results indicate this happens in the northern part of the Cerrado, which coincides with the region with higher fraction of C4 grass. This was expected since prescribed burning was applied to the C4 grass PFT in our simulations.

3.2.1. *Prescribed burning in the cerrado in years with increased fire activity*

We evaluate the three years that had the highest burned area (2015, 2004, 2010), according to our model JULES-INFERNO Cerrado, to demonstrate that prescribed burning provides higher than average reductions in burned area and fire emissions in years with increased fire activity.

For 2015, burned area in the LDS months was reduced by 10.45% (17,736.4 km^2) and fire emissions were reduced by 11.81% (0.021 GtC), compared with the 9.28% (10,684.2 km^2) reduction in burned area and 11.34% (0.0126 GtC) in fire emissions for the whole time series average. For 2004, burned area was reduced by 10.97% (16.625,0 km^2) and fire emissions were reduced by 13.42% (0.020GtC) in the LDS. For 2010, burned area in the LDS months was reduced by 10.87% (15.233,7 km^2) and fire emissions were reduced by 12.41% (0.017GtC). Fig. S4 (Supplementary Materials) shows the reductions for the three years mentioned.

Thus, according to our model in counterfactual experiments, prescribed burning reduces burned area and fire emissions during LDS, and higher reductions are observed in years with higher fire activities. Prescribed burning has not shown effectiveness in the annual analysis, given the increase in burned area and fire emissions in the EDS: for the average reductions of 9.28% in burned area and 11.34% in fire emissions in the LDS months, these increased in the EDS by 259.07% and 166.89% respectively. Although these numbers may not be realistic, they impose a significant forcing on the model and a distinctly detectable response.

4. Discussion

When analyzing the impact of prescribed burning, especially in years with high fire activity, it becomes evident that climate plays a key role in fire emissions predictions, and we suggest that climate might have a greater impact than fuel in JULES-INFERNO fire emissions prediction. This corroborates to Kelley et al. (2019) findings, which suggest that the Cerrado region is more limited by moisture than fuel.

As for the C4 grass productivity, Burton et al. (2019) observed that grasses recover quickly within TRIFFID, and that this could be addressed by increasing the mortality rate of grasses to prevent overgrowth. To address this issue in our simulations, we reduced the recovery rate of C4 grass by halving the efficiency use of light, and we were able to provide closer values of burned area and fire emissions contrasted with the comparison datasets. This suggests that the success of prescribed burning in reducing burned area and emissions depends on the recovery rate of C4 grasses.

When comparing our results to other studies previously published, we observe that prescribed burning has potential to reduce even more burned area and fire emissions than documented in this research. From observational studies, Schmidt et al. (2018) estimated 40%–57% reduction in burned area affected by LDS wildfires when prescribed

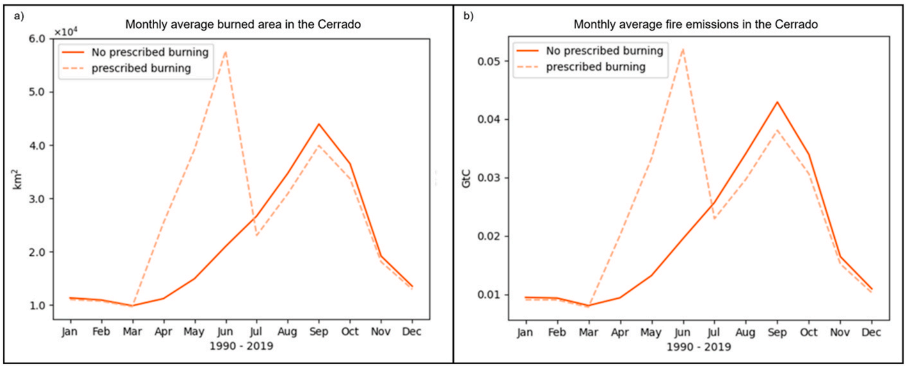

Fig. 4. Monthly average burned area (a) and fire emissions (b) with (dashed line) and without (solid line) prescribed burning in the Cerrado, from 1990 to 2019.

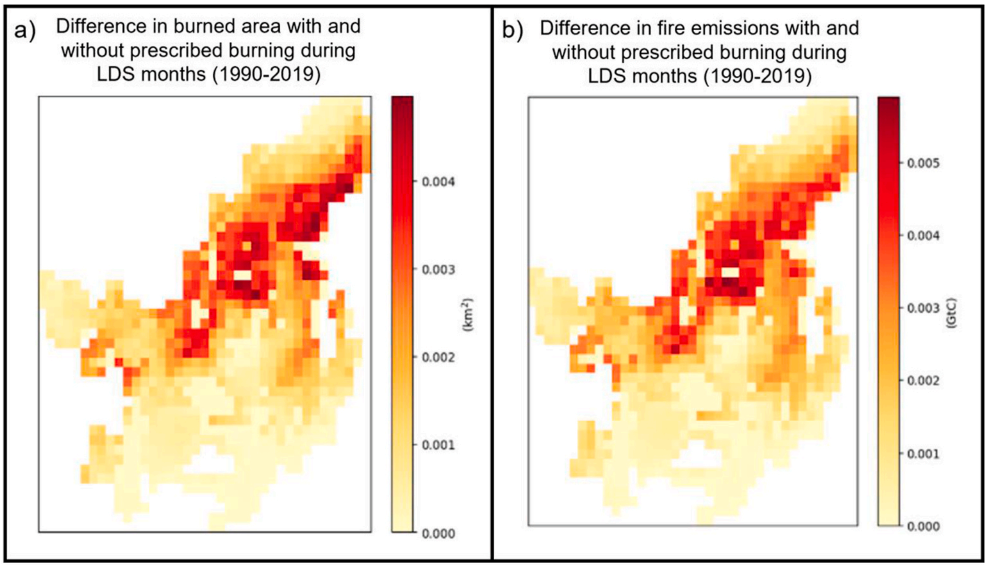

Fig. 5. Spatial distribution of the difference in burned area (a) and fire emissions (b) with and without prescribed burning in the Cerrado, during the LDS months (August, September, October).

burning was applied in three PAs in the Cerrado, from 2014 to 2016, within the scope of the Pilot Integrated Fire Management program. Yearly, that averages 13.3%–19%, which is higher than the reduction found in our research, where LDS burned area reduced 9.28% yearly with the application of EDS prescribed burning. However, Schmidt et al. (2018) found that the total burned area did not significantly reduce, which is a similar outcome of our research, where the annual balance of burned area is not reduced with the inclusion of prescribed burning.

Different from our results, Franke et al. (2024) document a potential annual emission abatement of 1085.64 tCO_2e year^{-1} (2014–2019) when applying EDS prescribed burning to all PAs in the Cerrado, equivalent to 2.96×10^{-7} GtC year^{-1}. Franke et al. (2024) use satellite and field data from a few PAs and then extrapolate the results to all PAs in the Cerrado, where burned area is also linked to fire emission estimates. Their results indicate a potential to improve our results in terms of mitigating emissions by integrating different methodological techniques.

To compare our results with the Australian example, which is a leader in publishing studies on prescribed burning in their savanna environment (Da Veiga and Nikolakis, 2022) and provided the basis for the Pilot Integrated Fire Management program in the Cerrado, Russell-Smith et al. (2013) found CO_2 emission reductions of 37.7% annually and burned area reductions of 7.9% annually (2005–2012) when compared to the baseline, against the 11.37% reduction in carbon fire emissions and 9.28% reduction in burned area found in our research for the Cerrado. These mean that our results are similar to those found by Russell-Smith et al. (2013) for burned area, but not for emissions. This could be due to the Australian study being based in a different environment and in observational data.

Our study examines counterfactual scenarios, where the ignition rate for C4 grass fires in May doubles, and the same value is applied to April and June, fire size of prescribed and non-prescribed burning are the same, and the values for C4 crop and C4 agriculture are constant. These leave scope for future improvements, such as applying different prescribed burning values and fire sizes, and testing the complete removal of different PFTs to investigate the impacts on results. Thus, we do not propose immediate management implementation actions, but rather provide a modelling framework that includes prescribed burning, explore its outcomes in terms of burned area and fire emissions, and support fire management decision-making perspectives.

Future improvements for modelling prescribed burning in the Cerrado include: incorporating local algorithms and datasets that improve regional representation (Barbosa et al., 2025; Libonati et al., 2015; Oliveira et al., 2021); splitting the Cerrado into subregions and evaluating the changes in burned area and fire emissions within them, as this would consider local biodiversity, different prescribed burning values for each subregion, and shifts in the prescribed burning window, as observed globally due to climate change by Hsu et al. (2025); including fire spread in the JULES-INFERNO model, since most of the fire emissions avoided with prescribed burning is due to fire not spreading to forested areas (Oliveira et al., 2023); analyzing different fire uses and sizes for prescribed and non-prescribed burnings; and adapting the population density algorithm when estimating ignitions, since high population density does not necessarily translate into high fire activity (Knorr et al., 2014), given the limited wildland-fire-interface in the Cerrado and other Brazilian biomes.

Splitting the Cerrado into subregions would enhance the model representation at more detailed scales. Global models are often too coarse to capture the heterogeneity found at the landscape scale, which can obscure local processes that should be accounted for at a regional scale. This limitation underscores the need for methodological improvements that can better represent fine-scale ecological processes and regional dynamics. Through refinements, it becomes possible to enhance simulation of fire parameters, better predict fire behavior, assess carbon emission and burned area, and support evidence-based decisions in the Cerrado or in other regions where similar model adaptations are implemented.

Currently, MPD and MNCD show that the model reproduces the large-scale seasonal structure of fire activity in the Cerrado, supporting its use for evaluating regional scale prescribed burning effects. Our analysis provides evidence for the overall effectiveness of seasonal prescribed burning strategies across the region, but not precise location-specific recommendations.

Globally, the population density and the fire use limitations have been previously observed in WHAM! a global model designed to capture human behavioral and land-use drivers of fire use and management (Perkins et al., 2024). WHAM! advances on population density approaches by replacing uniform anthropogenic ignition with representation of managed fire uses, unmanaged fires and natural ignition (Perkins et al., 2015, 2024). While JULES-INFERNO Cerrado adapts JULES-INFERNO to improve representation of the Cerrado, and adds prescribed burning to the ignition component, WHAM! is a separate model that couples with existent dynamic global vegetation models, as demonstrated in WHAM-INFERNO (Perkins et al., 2025).

As previously stated, few studies have explicitly included PB within a dynamic vegetation model. Besides JULES-INFERNO Cerrado and WHAM! Rabin et al. (2022) introduce PB to the dynamic global vegetation model LPJ-GUESS, coupled to the fire model SIMFIRE-BLAZE (Knorr et al., 2014; Rabin et al., 2017), to evaluate the effectiveness of PB in terms of fire intensity, burn severity, and ecosystem carbon balance under future climate change scenarios in two European regions (Rabin et al., 2022).

In our study, we do not differentiate between types of fire in the LDS. Instead, we analyze counterfactual scenarios to assess how EDS interventions influence LDS wildfires. In the current JULES-INFERNO framework, anthropogenic ignition is uniformly represented. A key direction for future model development would be to explicitly differentiate among fire uses. We address this limitation by introducing prescribed burning as a separate ignition component, and future improvements to the model would be to differentiate between fire uses. Other modelling approaches, such as WHAM! (Perkins et al., 2024, 2025), address this issue by replacing uniform anthropogenic ignition with behavior- and land-use-based representations of fire use.

Our counterfactual experiment evaluates a scenario in which EDS burning is widely spread across the Cerrado, leading to reduced LDS burned area and fire emissions, especially in years of intense fire, according to our model, as 2004, 2010 and 2015. From our results, prescribed burning increases overall burned area and fire emissions, but reduces destructive wildfire (Table S5). The overall increase can be explained by the doubling of ignitions in the EDS, and by the assumption of uniform fire size in prescribed burning and non-prescribed burning scenarios. We choose to double ignition rates to provide strong forcing to the model and a clear detectable response. Although counterfactual, the modified ignition represents important steps towards explicitly representing prescribed burning within a dynamic vegetation model, and leaves scope for future improvements in terms of fire size and ignition calibration.

This is particularly important because the peak of the fire season in the Cerrado is in the LDS months, and in this period the biomass available for burning is accumulated and highly flammable, resulting in large wildfires and ecological damages (Gomes et al., 2020b; Hoffmann et al., 2012; Silva et al., 2021). Added to this, climate change is increasing the risk of fire occurrence and the intensity and frequency of extreme events, such as wildfires (Intergovernmental Panel on Climate Change et al., 2021; 2022). For the Cerrado, it might be that the biome may not be resilient to projected increases of frequency and intensity of extreme fire years. For example, Gomes et al. (2020b) compared different fire frequency intervals and showed that increasing fire frequency leads to a decline in tree and shrub biomass recovery, thereby affecting atmospheric carbon dynamics by reducing the amount of carbon absorbed through vegetation regrowth. Thus, fire management is important to prevent ecosystem shift and destructive wildfire activity.

Our results support fire management activities by assessing a sensitivity experiment where EDS widely applied to the Cerrado would reduce burned area and fire emissions in the LDS period. This is crucial given the domination of fire exclusion policies in the Cerrado, which arose in Brazil as a reaction to the misuse of fire for pasture management and deforestation, especially in the 20th century, and due to the misbelief that fire harms the biome (Durigan and Ratter, 2016; Fidelis, 2020). These policies dismantled the fire management practices applied by traditional and Indigenous peoples, and disregard the ecological roles of fire in fire-prone settings (Barradas et al., 2020). As a result, extensive LDS wildfires have replaced small patchy burns (Fidelis, 2020; Moura et al., 2019; Pivello, 2011). By demonstrating consequences of prescribed burning, we are able to emphasize the value of integrating traditional knowledge and academic actors, and the need to enhance dialogue between traditional and academic sciences.

An example of the growing recognition of fire as an important aspect of the Cerrado is the Integrated Fire Management National Policy (PNMIF; Law 14,944/2024), sanctioned in July 2024. In this context, the results from this study provide insights into the objectives of the PNMIF, which aims, among other goals, to reduce the intensity and severity of wildfires, especially under the impacts of climate change. PNMIF also indicates that IFM activities, which include prescribed burning, should be applied to prevent the occurrence and reduce the impacts of wildfires, which often occur in the LDS.

5. Conclusion

To our knowledge, few studies have explicitly represented prescribed burning within dynamic vegetation models. As part of our approach, we also refine a global model configuration to better represent burned area and fire emissions in the Cerrado, aiming to examine the impacts of prescribed burning in a biome-sale. This was achieved by adding a prescribed burning element to the ignition component in the JULES-INFERNO model. This element varies by month and by PFT, making it adaptable to other regions of the world. This is a great achievement given the increased risk of wildfires worldwide, reassuring the relevance of prevention mechanisms in mitigating the impacts of climate change.

In our counterfactual experiment, we find reductions in the late dry season in both burned area and fire carbon emissions by 9.28% and 11.34% per year, respectively, from 1990 to 2019, when prescribed burning is applied in the early dry season. In years with high fire activity, the reduction in burned area and fire emissions is higher than the average when prescribed burning is included. Our sensitivity set-ups resulted in increased overall burned area and fire emissions, due to the increased fire activity during EDS, but reduced destructive wildfire.

The results from this research raise new perspectives for studies in the future, which could potentially improve our model and address the Cerrado's prescribed fires in more suitable ways. We identify five major improvements that could be made to enhance our results: splitting the Cerrado into subregions to better address the diversity of the biome; better integrating modelling techniques with on-site observations and local datasets; including fire spread in the JULES-INFERNO model; improving population density algorithm when estimating ignition; and identifying parameters in the model that can be modified to represent post-fire recovery rates.

Finally, our experiment supports fire management activities in the Cerrado by evaluating the potential impacts of biome-scale prescribed burning on reducing LDS wildfires. This is particularly relevant given projected increases in fire frequency and intensity under climate change, ongoing policy and governance changes in Brazilian fire management strategies, and the intrinsic relationship between fire and the Cerrado biome.

CRediT authorship contribution statement

Renata Moura da Veiga: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Chantelle Burton:** Writing – review & editing, Visualization, Validation, Supervision, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Douglas I. Kelley:** Writing – review & editing, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation. **Eddy Robertson:** Writing – review & editing, Validation, Supervision, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Eleanor Burke:** Software, Methodology, Data curation. **Manoel Cardoso:** Writing – review & editing, Methodology, Investigation, Formal analysis. **Maria L.F. Barbosa:** Writing – review & editing, Visualization, Investigation, Formal analysis, Data curation. **Fabiano Morelli:** Writing – review & editing, Validation, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Celso von Randow:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Investigation, Funding acquisition,

Formal analysis, Data curation, Conceptualization.

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Declaration of competing interest

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.pyro.2026.100006.

Data availability

Data will be made available on request.

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