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LETTER

Prescribed burning and integrated fire management in the Brazilian Cerrado: demonstrated impacts and scale-up potential for emission abatement

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Abstract

Fire management has proven successful in reducing deforestation, preserving biodiversity and mitigating greenhouse gas (GHG) emissions. After years of zero burning policies in fire-adapted ecosystems, and resulting increases in fire hazards and risks, countries are moving towards integrated fire management (IFM) including prescribed burning (PB). With a primary focus on biodiversity, Brazilian governmental organizations endorsed this paradigm shift in 2014, with the introduction of IFM in a number of protected areas (PA) of the Cerrado. Reducing high intensity mid/late dry season (M/LDS) fires through PB in the early dry season (EDS) has proven successful in other savanna ecosystems, with demonstrated mitigation potential as EDS fires are associated with lower GHG emissions. In the present study, Earth observation data were used to analyze the seasonality of active fires, burned areas and fuel loads. A dynamic performance benchmark (control-treatment paired sample test) was applied to assess the effectiveness of existing IFM activities in promoting emission abatement over the pre-covid period 2014–2019. Compared against the responses of PAs without IFM-PB, the PAs with IFM-PB showed significant increases in EDS fires (+137% hotspots) and EDS burned areas (from a share of 11.2% to 29.5% of the total yearly burned area). Fuel fragmentation through EDS-PB, tracked through calibrated fuel load maps, also led to a 62% reduction in burned areas in the IFM period 2014–2019. Combined M/LDS burned areas decreased from 85.1% of the total yearly burned area to a share of 67.7%. When applying the observed shift in fire seasonality and the effect of burned area reduction to all the PA of the Cerrado for the same period, we estimate an emission abatement potential of 1085 764 $tCO2e/y$. Given the fact that IFM followed a biodiversity-centred approach in the Cerrado, an emission abatement-centered approach could result in even higher abatement potentials.

1. Introduction

In the dry tropics, fire is a natural part of the landscape, shaping the flora and maintaining biodiversity. Seasonal droughts, high temperatures, and a co-evolving history with fire characterize these ecosystems, making them fire-dependent (Bowman *et al* 2009). Any changes in fire frequency and intensity can break these ecosystems' equilibrium. Integrated fire management (IFM) plays a pivotal role in sustaining the ecological health and resilience of dry tropical ecosystems. IFM is a framework for planning and operationalizing fire management that include social, economic, cultural and ecological aspects and with the objective of minimizing damage and maximizing benefits of fire (Goldammer 2010). IFM practices involve prescribed burning (PB), fire suppression, fire control, preparedness, as well as post-fire recovery and rehabilitation and community engagement to reduce the risks of uncontrolled wildfires (Goldammer 2010, Rego *et al* 2010, Croker *et al* 2023).

PB helps prevent large-scale wildfires by managing fuel loads and promoting a mosaic of vegetation structures (Minnich 2001, Bowman *et al* 2009). As such, PB supports ecosystems' capacity to recover and adapt to shifting environmental conditions, building up resilience against extreme events (Smith and Johnson 2021, Sample *et al* 2022). Another benefit of PB is the reduction of greenhouse gas (GHG) emissions, by shifting fire seasonality towards the early dry season (EDS) when fuel loads are lower and fuels more humid, resulting in smaller burned areas and more incomplete combustion processes (Price *et al* 2012, Lipsett-Moore *et al* 2018, Russel-Smith *et al* 2021). Emission abatement is therefore frequently estimated as the difference between EDS and late dry season (LDS) emissions (Lipsett-Moore *et al* 2018, Russell-Smith *et al* 2021). The West Arnhem Land Fire Abatement (WALFA) project in Australia has provided valuable insights into the role of PB in managing wildfires in dry savanna systems and its broader implications for environmental conservation, carbon abatement, and indigenous land management (Whitehead *et al* 2009, Russell-Smith *et al* 2015, Sangha *et al* 2021).

With ca. 2 million km^2, the Cerrado is the second largest biome in South America (Ratter *et al* 1997, IBGE 2019) and the most biodiverse savanna in the world (Myers *et al* 2000, Da Fonseca *et al* 2005). Fire has been driving evolutionary and environmental history in the Cerrado vegetation structure and composition (Simon *et al* 2009), also playing a crucial role in the livelihood of its rural communities (Mistry 1998). As other tropical savannas, the Cerrado landscape is heterogeneous, encompassing different ecoregions (Sano *et al* 2019) and covering different fire-dependent vegetation types, such as pure grassland, grassland with presence of shrubs, grass/shrub-dominated areas with scattered trees, tree dominated areas, closed forests and wetland areas. While grassy and savanna formations are more flammable and fire-tolerant, forest formations can be fire-sensitive when fire frequency becomes shorter than seedling establishment times (Hoffmann *et al* 2012). Regardless of the ecoregion, changes in fire regimes, due to either total fire exclusion or increasing fire frequencies, are threatening Cerrado's biodiversity, also affecting livelihoods (Durigan and Ratter 2016, Fidelis *at al* 2018, Durigan 2020).

A zero-burning policy prevailed in the protected areas (PA) of the Cerrado until the beginning of the 2010s, neglecting the specific ecological and cultural needs of each ecoregion (Durigan and Ratter 2016), a situation also observed in other protected savannas around the world (Barradas and Torres Ribeiro 2020). This uniform fire management approach in the Cerrado has proven to be ineffective to conserve ecosystems and biodiversity (Abreu *et al* 2017, Durigan 2020), since it promotes large-scale accumulation of fuels leading to vast uncontrolled LDS fires (Fidelis *et al* 2018, Barradas and Torres Ribeiro 2020). A paradigm shift in the official fire management position was initiated by Brazilian governmental and research institutions in 2012, when the concept of IFM was first discussed as a possible and desirable environmental management approach. Starting in 2014, numerous PA in the Cerrado have implemented the technical, ecological and socio-economic elements of IFM to manage and protect biodiversity and to enhance community livelihoods, including indigenous lands using traditional land management practices that rely on fire (Barradas and Torres Ribeiro 2020, Durigan *et al* 2020, Vernooij *et al* 2020). The generation of livelihood of local communities was previously hindered by the zero-burning policy of the government, under which also traditional fire practices were fought. With the introduction of IFM, an intercultural approach aimed at the co-management of fires in some PA (Barradas and Torres Ribeiro 2020).

The goal of the new management strategy was to revitalize traditional fire uses and knowledge for sustainable natural resource management, to reduce late season fire hazards and their negative impacts on biodiversity of the Cerrado. Through prescribed low intensity EDS burning, with the goal of creating smaller scale patchy ecological fire regimes, the landscape becomes more resilient through the creation of a more diverse range of habitats and fuel-age classes (Penman *et al* 2011, Williamson *et al* 2012, Pereira Júnior *et al* 2014). In the long run, regular PB in the EDS is expected to shift the seasonality of fires from LDS to EDS fires, while also shifting fire severity from high to low intensity fires.

Even though the main goals of IFM in the Cerrado were to reduce large-scale high intensity fires, promote biodiversity and improve livelihoods, rather than to abate emissions, the existing activities offer a unique opportunity to assess the performance of PB for mitigation co-benefits, through seasonality shifts of fire and burned areas. Quantifying the emission abatement potential of IFM activities in the Cerrado would help promote IFM as a nature-based solution aligned with the 40 percent emission reduction goal for the Cerrado (a target defined in Brazil's Climate Change Law in 2009) and open the doors for potential future revenues in carbon markets (Tear *et al* 2021). Fundamental for the successful application of PB in fire-adapted ecosystems is the tracking of fuel loads and fuel continuity, in order to target critical areas for the planning of fuel fragmentation through PB. A satellite-driven approach to map fuel load was implemented by local institutions since 2018, due to its proven usefulness for PB planning (Franke *et al* 2018).

In this study, a paired-sample control-treatment impact assessment was conducted to investigate the potential of IFM PB operations in the Cerrado for abating GHG emissions. The impact over the first six years of PB implementation in the Cerrado (2014–2019) were assessed. The four PA in the Cerrado with the longest implementation of IFM activities were compared against four PA with similar landscape and protection characteristics that did not have IFM activities. The differences were assessed based on five fire-related indicators: number of active fires, seasonality of fire, burned areas, fuel loads and fuel fragmentation. Observed trends over the observation period were then scaled-up to all the PA of the Cerrado, to estimate GHG emission abatement potentials of IFM operations.

2. Methods

2.1. Study area

In 2014, a few PA first started to implement EDS PB as a tool to reduce the negative impacts from uncontrolled, high-intensity LDS fires. Over the years, PB was extended to several PA, and currently 36 are undergoing IFM operations (figure 1). Barradas and Torres Ribeiro (2020) and Barradas *et al* (2020) provide an overview of the history of fire management in the Cerrado. In order to assess the impact of IMF, the four PA with the longest history of IFM PB implementation (2014 and onward) were selected. In contrast to assessing the impact of IFM activities through a historical burned area baseline assessment (ex-ante) compared with a future with-project scenario (ex-post), this study uses the innovative approach of a dynamic performance benchmark. This novel methodology allows for a comparison of the variable of interest in areas with and without treatment, during the same years. In our case we are comparing the 'IFM PAs' against the 'control areas' (PAs without IFM activities) in the same observation period. The advantage of a dynamic performance benchmark (control-treatment paired sample test) is that the impact of IFM activities is compared against control areas over the same period, under the same climatic, political and socio-economic conditions. Such dynamic performance benchmark requires project area and control areas being in line with certain similarity criteria. While the PA cover different types of official legal protection (table 1), there is an equal share of strict PA and permissive PA, where, in practice, people are living and using natural resources in a sustainable way. Other similarity criteria such as vegetation types were also considered, and arable areas were masked out to solely focus on natural Cerrado vegetation. Using data from the Brazilian Annual Land Use and Land Cover Mapping Project (MapBiomas; https://plataforma.brasil.mapbiomas.org/) the vegetation types of all PAs were analyzed to prove the similarity in vegetation type. The four PA with IFM activities and the four control areas have a similar predominance of natural non-forest formation (Savanna Formation and Open Savanna) of 95.1% and 96.2% respectively. A pre-Covid pandemic period was chosen, to disregard any potential fire management-related influences caused by limited IFM operations.

2.2. Methodology

Various satellite data were used to analyze the effect of IFM and PB in the Cerrado. All Moderate Resolution Imaging Spectroradiometer (MODIS) collection 6 active fire detections MCD14ML data products from January 2013 to December 2019 for the Cerrado were used (available on-line via https://earthdata.nasa.gov/firms). In addition, the MODIS terra and aqua combined MCD64A1 version 6 burned area data product—a monthly, global gridded 500 m resolution product containing per-pixel burned area—was used for the same period (Giglio *et al* 2015). EDS and LDS fuel condition maps were derived from Landsat 8 Operational Land Imager (OLI) (Roy *et al* 2014) and Sentinel-2 data (ESA 2015) following the approach of Franke *et al* (2018). In this context, fuel condition represents the relative proportion of live to dead (or senescent) fuels and ground cover, where live fuels contain a higher percentage of water. Fuel condition is thus linked, but not equal, to fuel moisture (Franke *et al* 2018).

Field data from permanent plots (50 × 50 m) established by the Universidade de Brasília (Schmidt *et al* 2018) were linked to the fuel load maps. GPS-coded field data on pre- and post-fire biomass [kg m^{-2}] allow for an evaluation of relationships between sub-pixel estimations (dead fuel, live fuel, soil) and weighed biomass as input for a fuel load model (Franke *et al* 2018). The samples were taken in three of the four PA with IFM operations, namely PNCM, EESGT and PEJ in 2014 and 2015 (Schmidt *et al* 2018). In total, 99 samples from the sample locations were cloud-free and could be used.

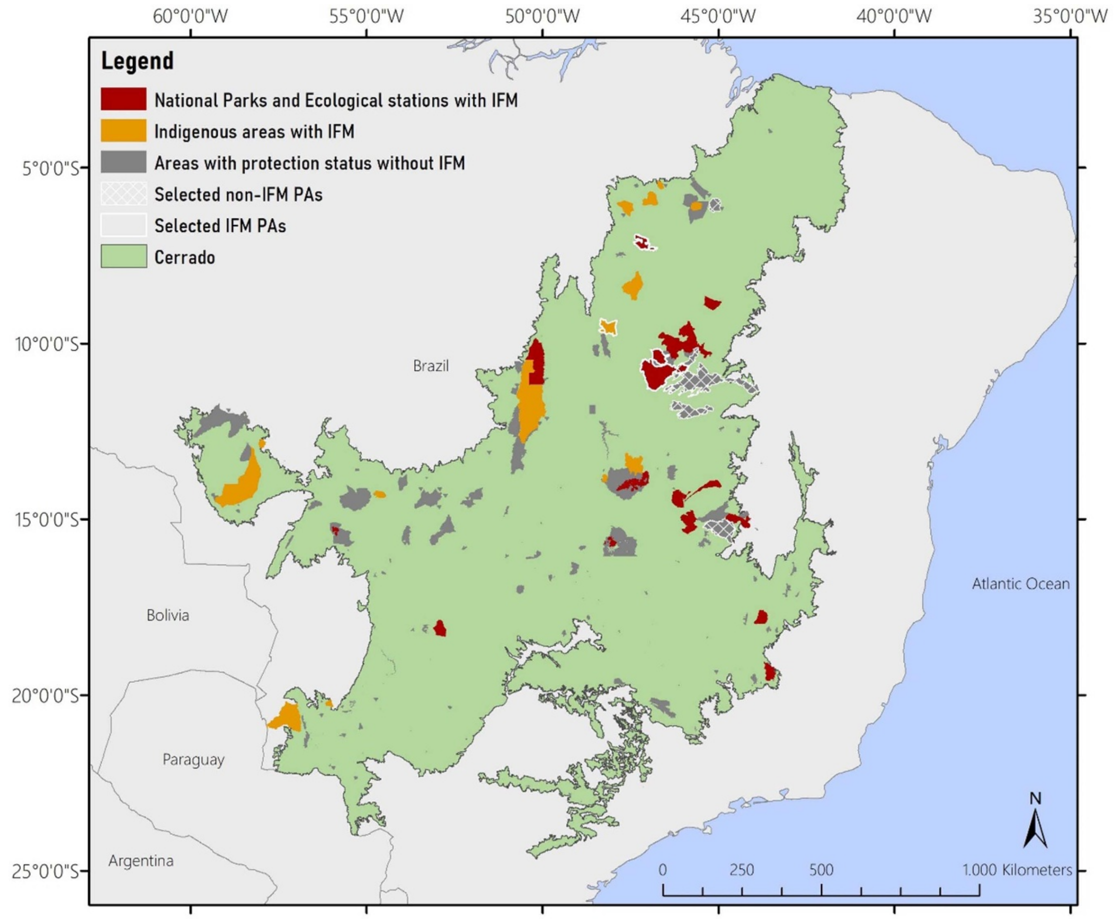

Figure 1. Location and extent of the Cerrado. Areas with protection status are shown with their corresponding status of PB implementation in 2020. To investigate the status of IFM operations in the protected areas, the institutions with the mandate of protected area and fire management conducted an inventory (PREVFOGO/IBAMA and ICMBio).

Table 1. Selected protected areas.

Protected area	Size	IFM operations
Parque Nacional da Chapada das Mesas (PNCM)	160 000 ha	Since 2014
Terra Indígena Xerente (TI Xerente)	187 000 ha	Since 2015
Estação Ecológica Serra Geral do Tocantins (EESGT)	712 000 ha	Since 2014
Parque Estadual do Jalapão (PEJ)	160 000 ha	Since 2014
Área de Proteção Ambiental do Rio Preto (Rio Preto)	1154 000 ha	none
Área de Proteção Ambiental Bacia do Rio Pandeiros (BDRP)	396 000 ha	none
Terra Indígena Kanela (TI Kanela)	126 000 ha	none
Área de Proteção Ambiental Bacia do Rio De Janeiro (BDRDJ)	355 000 ha	none

Different satellite data were used to assess the impact of PB on the seasonality of fire occurrence, burned area and fuel fragmentation and fuel loads. For the eight selected PA, monthly statistics of MODIS hotspots were generated for the years 2013–2019. The year 2013 is considered as the pre-IFM year, as the first PB for ecological purposes took place in 2014 (Barradas and Torres Ribeiro 2020). The hotspots from these eight areas were than combined in accordance to the IFM status, resulting in monthly hotspot statistics from four areas with IFM operations and from four areas without IFM. In addition, EDS (May and June), MDS (July and August) and LDS (September and October) hotspots were categorized for each year and linear trends in seasonality have been analyzed for explorative analysis of fire activity. Yearly statistics on burned area were generated using the MODIS burned area product for 2001–2019. For the burned area data, multiple years of the pre-IFM period (2001–2013) and the IFM period (2014–2019) were considered and linear trends for the different areas (with and without IFM) were analyzed.

To complement the linear trend analysis and to quantitatively test the significance of the IFM-PB activities, a generalized linear mixed model (GLMM) was applied, which tested fire responses as a function of management (IFM vs. non-IFM), with year as a co-variable and PAs as a random effect. It was applied to the IFM-treatment period (2014–2019) when the effect of the IFM activities can be best assessed. We applied the same model separately for each seasonality (EDS: May–Jun and M/LDS: Jul–Oct), and analyzed the responses of burned areas and number of fires (hotspots). To promote the comparability among PAs, the burned areas and the number of fires were divided by the respective areas of each PAs. When needed, log-transformed fire variables were used to promote normality of the data and homoscedasticity of the residues. We applied Poisson distribution for the number of fires, which were counts. Models were validated by means of graphical analysis of the model residuals. Our hypothesis for the IFM period is that the EDS shows higher burned area and hotspots in the IFM PA than in the non-IFM areas, and either less fire or no significant differences in burned area in the M/LDS in IFM compared to non-IFM areas.

For the fuel load mapping, the approach developed by Franke *et al* (2018) was modified and implemented in the Google Earth Engine (GEE), in order to scale the mapping up to the whole Cerrado. Therefore, the methodology had to be modified through mainly two aspects. First, a classical linear mixture model is used in GEE instead of the mixture tuned matched filtering. Second, the methodology implemented in GEE creates a 'quality mosaic' from Landsat 8 OLI (GEE asset: LANDSAT/LC08/C01/T1_SR surface reflectance) or Sentinel-2 images (GEE asset: COPERNICUS/S2_SR surface reflectance) within a period of up to 32 d (to ensure at least two Landsat images per composite). For the creation of the quality mosaics, the normalized difference vegetation index (NDVI) is first calculated for each individual image and the composite is then compiled pixel-by-pixel using the spectral reflectances of the highest NDVI value in the time series. The advantage of such composite is that data gaps caused by cloud cover are minimized. The spectral unmixing was then performed for EDS and LDS composites. The resulting values of the fuel condition map are sub-pixel fractions for live fuel (GV), dead fuel (NPV) and soil. In order to generate fuel load values, the sub-pixel fractions of soil (as a proxy of vegetation density) and NPV (as a proxy of main combustible biomass) were linked to the field data on pre- and post-fire biomass. A multiple regression model using these parameters was established to map fuel load in [kg m^{-2}] with an adjusted r^2 of 0.91 ($p < 0.001$, standard error = 0.059). A forest mask was finally applied, since the fuel load map have higher uncertainties in dense Cerrado types, where tree canopies cover surface fuels in the understory (Franke *et al* 2018). In addition, PB is not implemented in these dense forest areas, rather in the more open Cerrado types. Statistics of the fuel loads were generated for the EDS and LDS of the selected PA for each year (2013–2019) and linear trends of fuel loads in IFM areas were compared to trends in non-IFM areas.

3. Results and discussion

3.1. The impact of IFM and PB on fire seasonality

The first assessment of fire seasonality relied on monthly MODIS hotspots (2013–2019) and revealed differences between PA with and without IFM-PB operations over the considered observation period. The following aspects indicate the impact of PB on the seasonality of fire (figure 2):

(i) Pre-IFM year 2013 showed no difference in the onset and end of the fire season in the two area types; in the years that followed, more active fires were seen in PA with IFM compared against those with no IFM (indicative of the active implementation of IFM).
(ii) While the non-IFM areas constantly showed unimodal fire peaks in the LDS, there was a visible shift towards an earlier onset of fire occurrence through EDS ignitions in IFM-PB sites, with a more distinct shift from 2016 onwards, reflected as bimodal fire activity and quantitatively supported by a positive trend for EDS active fires (+137% compared to 2014 (figure 3)).
(iii) PA without IFM-PB showed more constant trends for all three seasonal categories (figure 4).
(iv) Sites with IFM-PB saw a more stabilized number of ignitions peaks per year and a buffering effect during years of extreme climate conditions such as 2015, where IFM-PB sites benefitted from more regulated fire responses (Fidelis *et al* 2018).
(v) In 2018, the fifth year of implementation, a shift of seasonal fire activities was recorded for the first time, with more EDS active fires than MDS or LDS active fires in the four PA with IFM activities. From the perspective of GHG emission abatement, shifts in fire seasonality towards EDS directly promotes emission reductions, since EDS fires have lower combustion and fuel load values than M/LDS fires, with higher values of accumulated dry fuel (IPCC 2006, 2019).

3.2. The impact of IFM and PB on burned area

For the pre-IFM period 2001–2013, the assessment of annually aggregated MODIS burned areas showed similar increasing trends for PAs that later received IFM treatment and for PAs without IFM activities (figure 5). This historical baseline reveals that PAs that later received IFM treatment clearly show higher totals of burned areas (average of 33.4% annual burned area) than those PAs in which no IFM activities were implemented (average of 19.0% annual burned area). In fact, the PAs were selected for IFM-PB because they were among the most

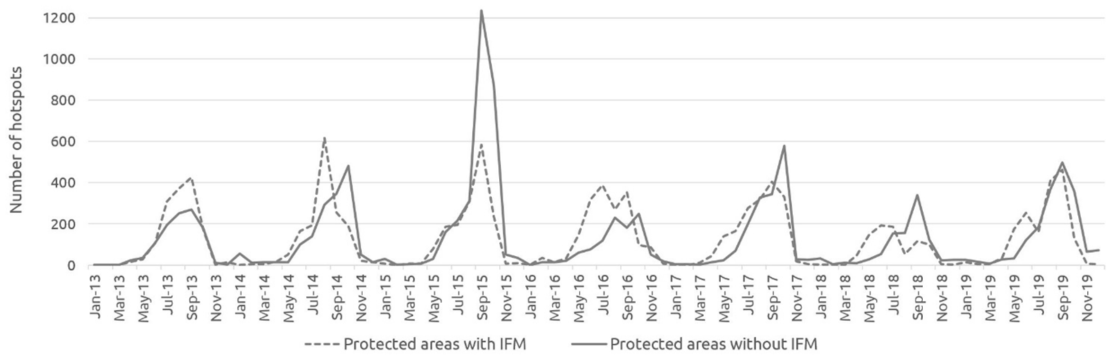

Figure 2. Monthly totals of MODIS hotspots for protected areas with IFM and for protected areas without IFM from January 2013 to December 2019.

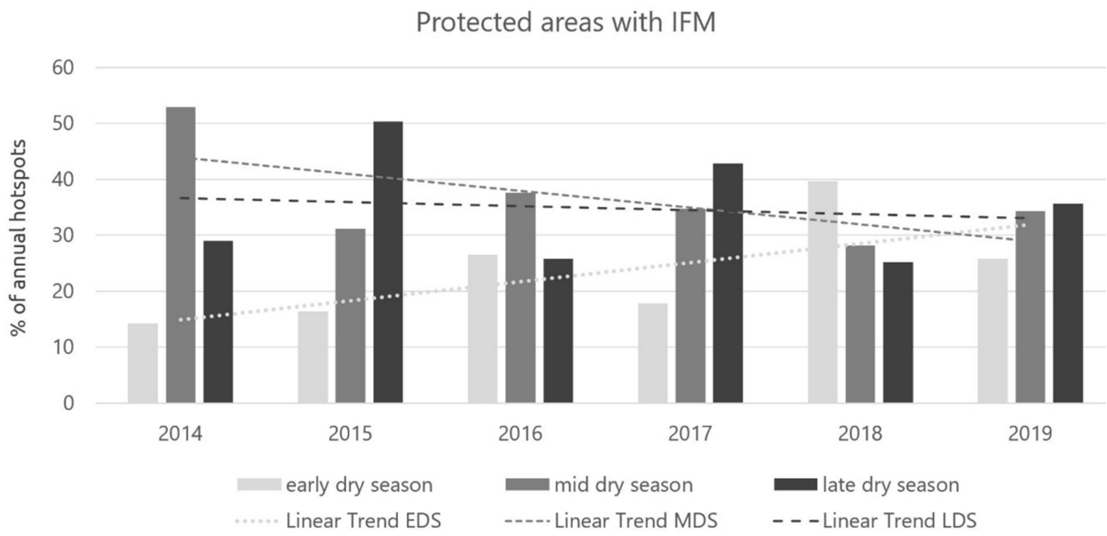

Figure 3. MODIS hotspots categorized into EDS fires (May and June), MDS fires (July and August) and LDS fires (September and October) with linear trends for protected areas with IFM from 2014 until 2019.

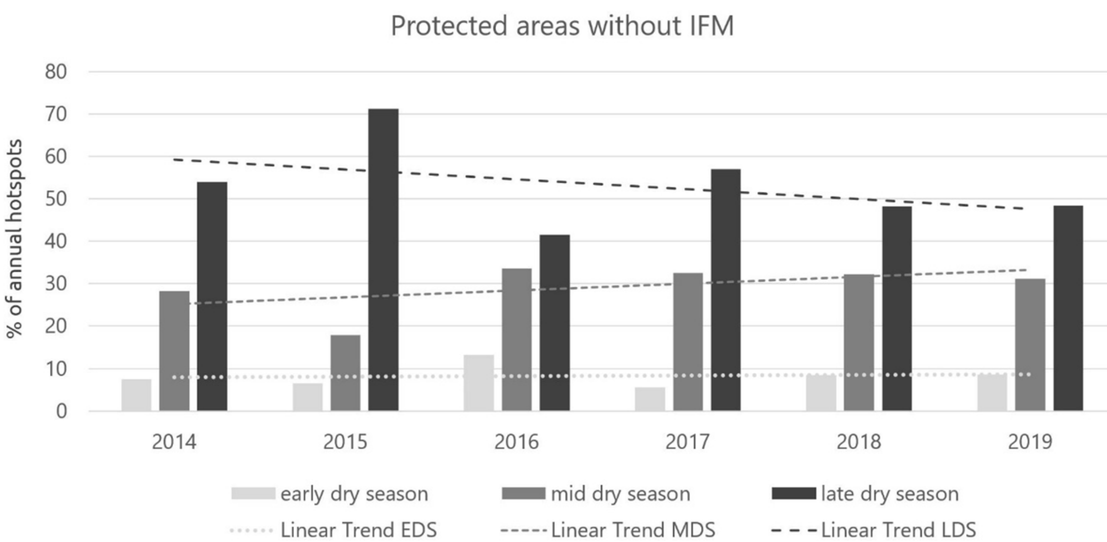

Figure 4. MODIS hotspots categorized into EDS fires (May and June), MDS fires (July and August) and LDS fires (September and October) with linear trends for protected areas without IFM from 2014 until 2019.

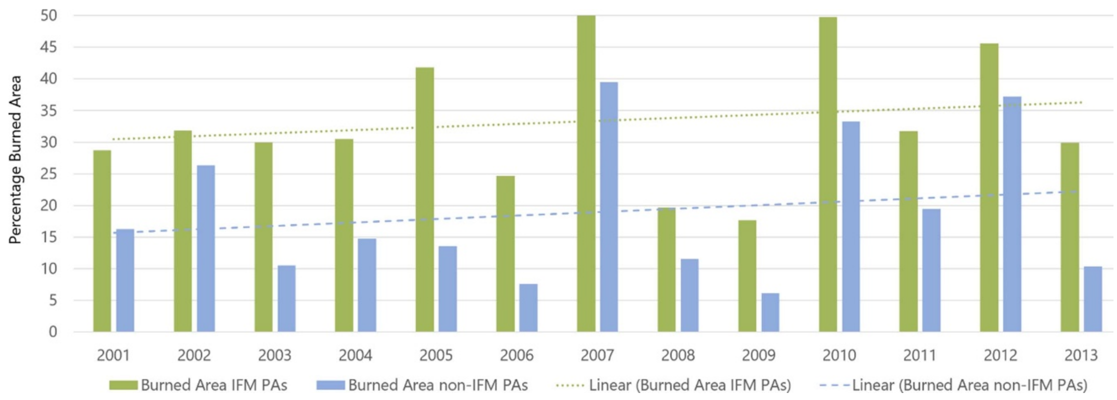

Figure 5. Percentage annual burned areas from 2001 to 2013 (pre-IFM period) in IFM PAs and non-IFM PAs.

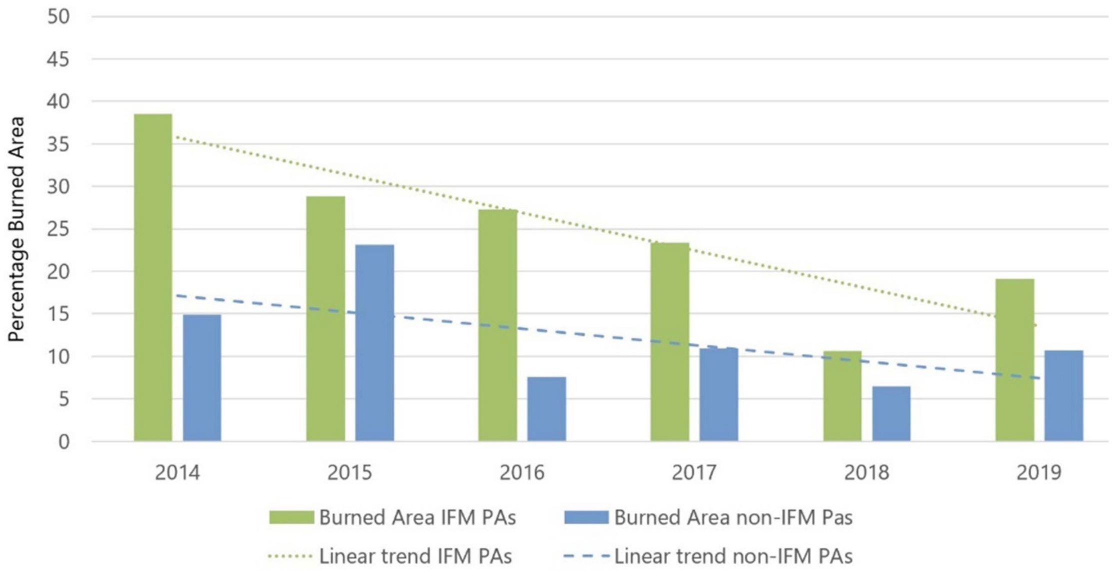

Figure 6. Percentage annual burned areas from 2014 to 2019 (IFM period) in IFM PAs and non-IFM PAs. Over that period, IFM PAs show an average of 24.6% burned areas (min. 10.6%, max. 38.5%), while non-IFM PAs show an average of 12.3% burned areas (min. 6.4%, max. 23.2%).

frequently burned areas in the Cerrado (Barradas and Torres Ribeiro 2020). In contrast, annual burned areas over the IFM period 2014–2019 revealed differences between PAs with and without IFM-PB. The following aspects indicate the impact of IFM-PB on the burned areas and seasonality: (i) the pre-IFM period (2001–2013) saw higher burned area extents in the PA that later underwent IFM-PB from 2014 onwards (figures 5 and 6). (ii) There was an annual reduction of burned area extent in PA with IFM-PB over the analyzed period (−62%, linear trend with $R^2 = 0.77$), while PA without IFM did not show a clear trend ($R^2 = 0.34$). (iii) As expected and desired, IFM-PB areas saw an increase in EDS burned area extents followed by a reduction of M/LDS burned areas (figure 7). According to the linear trend, M/LDS burned areas decreased from 85.1% of the total burned area to a share of 67.7%, while EDS burned areas significantly increased from 11.2% to 29.5% of the total burned area. Over the period 2014–2019, IFM PAs show an average of 20.4% EDS burned areas (min. 8.2%, max. 41.9%), while non-IFM PAs show and average of 4.7% EDS burned areas (min. 2.5%, max. 7.7%). In regard to M/LDS burned areas, IFM PAs show an average of 76.4% (min. 55.6%, max. 89.3%), while non-IFM PAs show and average of 87.1% M/LDS burned areas (min. 78.6%, max. 89.7%).

3.3. Statistical analyses of the IFM-PB impacts on hotspots and burned areas

Based on the GLMM results, the IFM period (2014–2019) shows the expected effects of the IFM activities in burned area and hotspots (table 2): significantly higher fire activity during the EDS in the IFM PAs, compared to the non-IFM PAs, with no significant differences between IFM and non-IFM areas in the M/LDS. The lack of significance of burned areas

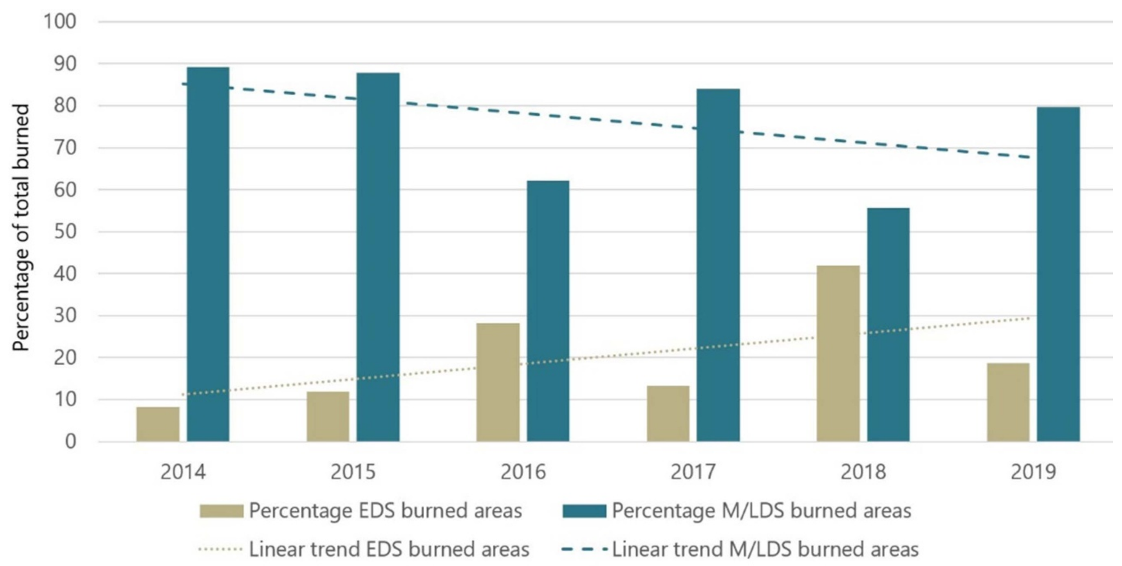

Figure 7. Percentage of EDS and M/LDS burned area of total burned areas per year in IFM PAs with linear trends from 2014 to 2019.

Table 2. Statistics of the generalized linear mixed model for the IFM period 2014–2019, for burned area and hotspots. Seasonality includes EDS and M/LDS in PAs with IFM-PB (EESGT, PNCM, TI Xerente, PEJ) and without IFM-PB (BDRDJ, Rio Preto, BDRP, Kanela). Variables are log-transformed, with the correspondent exponential estimates also shown. Threshold of significance is $p \leqslant 0.1$ *, $p \leqslant 0.05$ **, $p \leqslant 0.01$***.

	EDS				M/LDS			
	Estimate	Standard error	Exponential estimate	$Pr > t$	Estimate	Standard error	Exponential estimate	$Pr > t$
Burned area in IFM vs. non-IFM	2.8071	0.7250	16.6	***	1.3189	0.9764	3.7	ns
Hotspots in IFM vs. non-IFM	0.0200	0.0068	1.3	***	0.0145	0.0459	1.0	ns

in the M/LDS is actually a validation of the success of the IFM activities in the IFM period. Thus, the average burned area in the pre-IFM period (2001–2013) was far higher in IFM areas than in non-IFM areas and, therefore, IFM activities have achieved a reduction in burned areas in the IFM period that is now not significantly different between IFM treatments. GLMM does not look for trends, it rather assesses the differences among groups, but the decreasing burned area trends can be seen in figure 7 for the M/LDS and in figure 6 for the annual decrease.

3.4. The impact of IFM and PB on fuel loads

Fuel types, fuel loads, fuel availability and fuel arrangement (continuity/fragmentation) greatly influence fire ignition and total burned areas (Scott and Burgen 2005, Cochrane and Ryan 2009). One of the major successes for the effective planning and evaluation of EDS PB in Cerrado, was the implementation of an approach for satellite-based mapping of fuel loads and fuel arrangements (Franke et al 2018). The produced geo-information product helped fire managers to plan EDS PB to achieve a small-scale and patchy fire regime in areas where the former zero-fire policy led to large-scale and continuous fuel loads. The result is a landscape of smaller-scale, multi-fire-regime mosaics, driven by a diversity of fuel types and ages, which can be tracked in the fuel load maps in the observation period (figure 8).

The pre-IFM short fire return intervals and high-intensity LDS fires were changing the Cerrado to a more open, grass-dominated landscape, since they increased the mortality of small woody plants following burns or scorches. This fire-driven savannization of the Cerrado has long been reported (Moreira 2000, Miranda et al 2002, 2009, Oliveras et al 2013, Pereira Júnior et al 2014). An analysis of fuel load trends (2014–2020) in the PAs with IFM-PB revealed generally lower average fuel load levels in comparison to non-IFM areas, due to the previous short fire intervals in the PAs that later received IFM operations (figure 9). After IFM implementation in 2014, fuel loads increased with average accumulations of 0.29 t/ha over a period of six years. IFM-PB is not only an excellent tool for reducing high intensity LDS fires through fuel fragmentation, but also seems promising for ecosystem restoration, by promoting longer recovery times for vegetation and thus a relevant

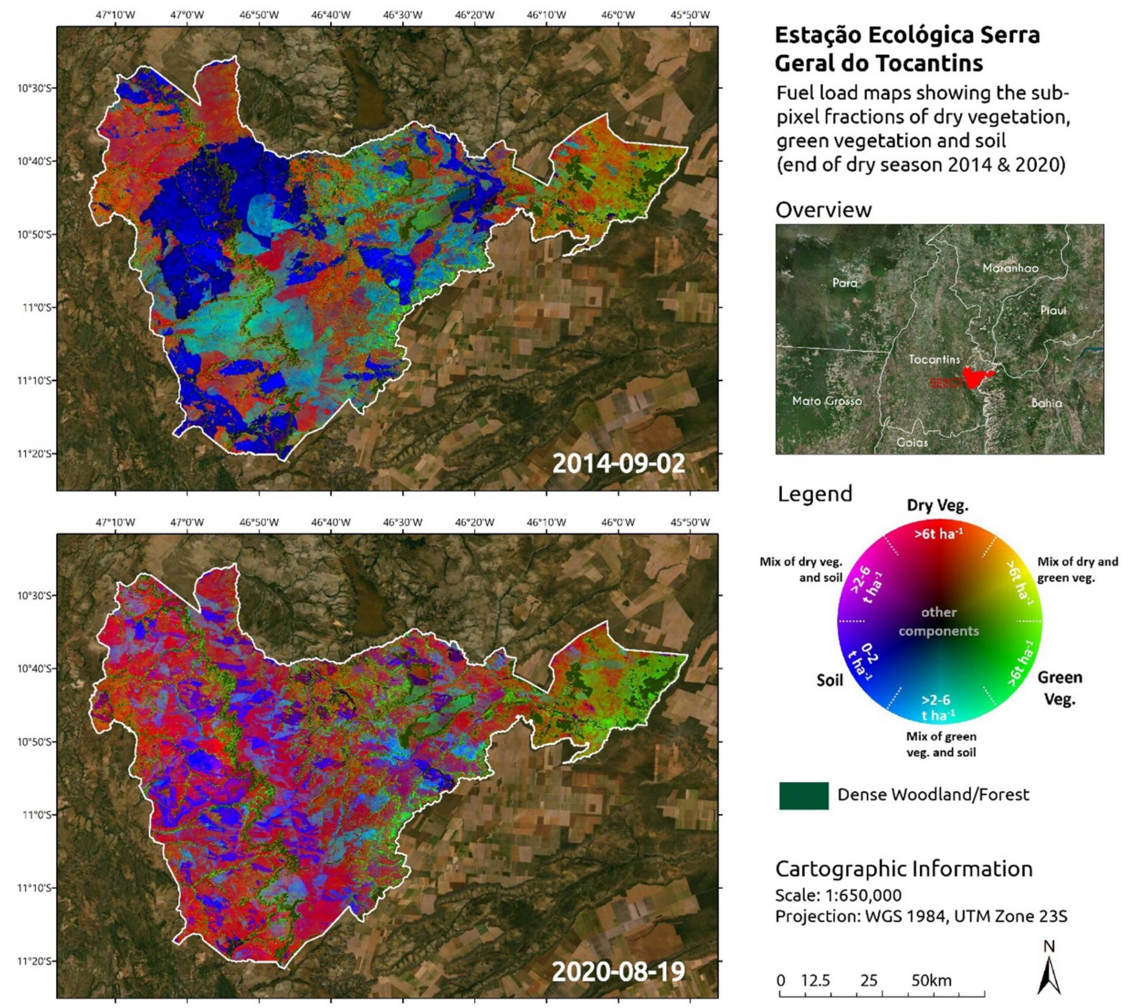

Figure 8. Comparison of the pre-IFM fuel load map of 2014 (top) with the with-IFM fuel load map of 2020 (bottom) for the ecological station of Serra Geral do Tocantins (ESEGT), one of the protected areas with most fire under former 'zero fire' policies. In 2014, PB was implemented to promote small-scale mosaics with different fire regimes (pyrodiversity), using satellite-derived fuel load maps as a planning basis. Comparing these fuel load maps, the modification of the previous large-scale fires (blue areas) and high fuel areas (red areas) (top image) to a small-scale fragmented fire regime with high pyrodiversity (bottom image) becomes obvious. In the fuel load maps, red colours indicate a high amount of dead fuel and blue colours indicate a high soil fraction following fire events, with a continuous mixture of both in purple. Green areas mainly represent dense Cerrado, gallery forests and moist grass areas in wetlands.

carbon sink in highly fire-degraded areas of the Cerrado. The carbon sequestration effects in living biomass through fire management and its potential to be included in emission reduction schemes, as well as related challenges, have already been discussed in previous studies (Lipsett-Moore *et al* 2018, Russell-Smith *et al* 2021). Well-designed IFM-PB planning, implementation and monitoring, with the right amount of fire, at the right time and place, can successfully restore ecosystem diversity, increase carbon storage, and support mitigation action.

3.5. The impact of IFM and PB on biomass burning emissions and emission abatement

The size of annual burned areas largely drive biomass burning emissions (equation (1), IPCC 2019). Independently of their seasonality, less burned areas will lead to lower emissions. However, for emission abatement, shifts in burned area towards EDS lower GHG emissions, due to lower fuel consumption and lower combustion factors of EDS fires (IPCC 2019).

$$L = A{*}M_B{*}C_f{*}G_{\mathrm{ef}}{*}10^{-3}\,(tCO2_e) \qquad (1)$$

where L is the amount of GHG emissions from fire in tonnes of $CO2_e$ and includes all the relevant GHGs per ecosystem type. A are burned areas in hectares, M_B are fuel loads ($\mathrm{t\,ha^{-1}}$), C_f is the combustion factor (dimensionless) and depends on ecosystem type and season, and G_{ef} is the emission factor ($\mathrm{g\,kg^{-1}}$ of dry matter) for each ecosystem type and GHG.

Most fires in the Cerrado are surface fires that spread through fine, highly flammable, non-woody fuel (Miranda *et al* 2002). In grass-driven fires, non-CO_2 gases (CH_4 and N_2O) are the main source of emissions (IPCC 2019). In the IPCC guidelines on fire emission calculation (2006, 2019), CO_2 emissions

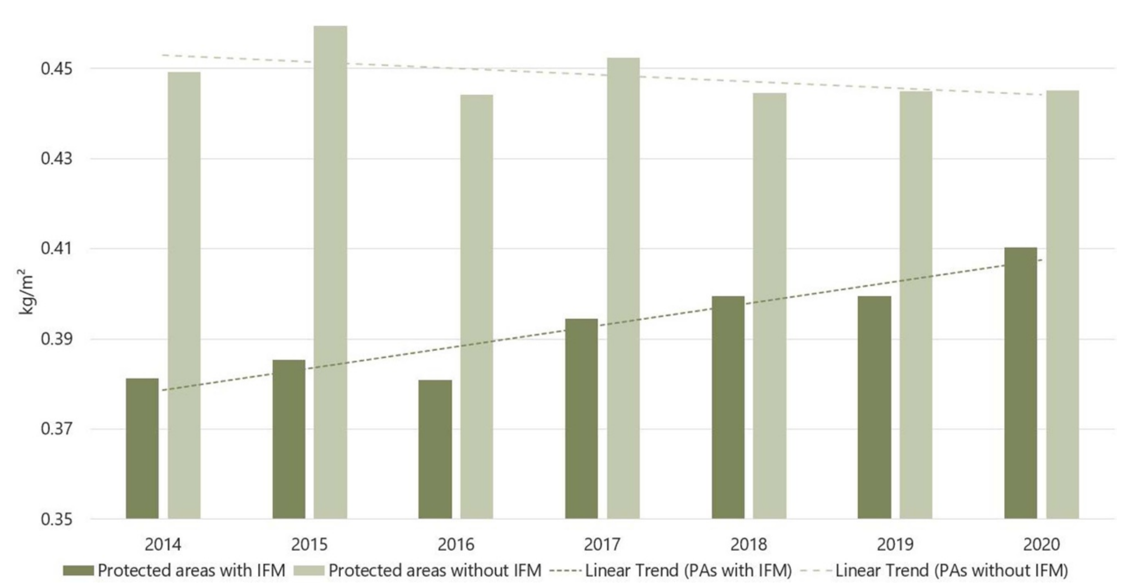

Figure 9. Mean LDS fuel loads [kg m^{-2}] per year with linear trends for protected areas with IFM ($r^2 = 0.88$) and without IFM ($r^2 = 0.31$) from 2014 to 2020.

are excluded and considered carbon-neutral, since next year's regrowth is assumed to compensate this year's emissions. Additional CO_2 sinks due to IFM-PB restorative processes remain unaccounted for in the IPCC guidelines.

Our results showed that non-CO_2 emissions (CH_4 and N_2O) in the PA with IFM activities were influenced by significant increases in EDS burned area and decreases in M/LDS burned areas, but also by the reduction of the total burned area. By applying equation (1) together with conservative estimates of fuel loads derived from Sentinel-2 data (0.385 and 0.464 kg m^{-2} in EDS and M/LDS, respectively), an emission abatement of 26 677 tCO2*e*/*y* results for the assessed PAwith IFM-PB activities in the IFM period 2014–2019 and a theoretical emission abatement potential for all PA in the Cerrado are estimated at 1085 764 tCO2*e*/*y*, for the same period. Emission abatement estimates increase by ca. 67% when applying the IPCC Tier 1 default fuel consumption values for savanna grasslands. Our IPPC approach-based estimates are conservative compared to other emission mitigation estimates for the Cerrado (e.g. 9.2 M tCO2*e*/*y*; Lipsett-Moore *et al* 2018), also since our approach considers mainly the fine surface fuels, which are the most common fire-consumed fuel compartment in the Cerrado. This is also reflected in the comparison with the much larger emission estimate from the national forest reference emission level (FREL) for the Cerrado (32 001 633 tCO2*e*/*y*; average for the period 2016–2021; Cerrado FREL), that focuses exclusively on forested land. While MODIS burned area data are suitable for estimating the savanna fire emission abatement potential at large scale, higher resolution satellite data will significantly improve emission estimates at IFM project level, since smaller fires can be detected. In a study in sub-Saharan Africa, where small fires constitute a large share of total fires, 80% more burned areas were mapped with Sentinel-2 images than with the 500 m MODIS product, which also led to higher GHG emission estimates (Ramo *et al* 2021). Especially for the scenarios with IMF, in which EDS PB led to a very small-scale fuel fragmentation, fire emission calculations would benefit from high resolution data through an improved identification of small-scale fires. This would be particularly relevant for digital monitoring, reporting and verification (dMRV) tools for fire-related carbon projects.

4. Conclusion

PB, as one pillar of IFM in the fire-adapted ecosystems of the Cerrado, was implemented as the first of such initiatives in Latin American dry ecosystems. After its implementation in a few PA, where measurable positive impacts were achieved in a short term, involved Brazilian authorities collaboratively institutionalized IFM and implemented it in other PA, creating their own IFM success story. Political will was supported by technical and scientific guidance, including properly calibrated remote sensing data supplying valuable information on fuel loads and fragmentation for IFM-PB implementation in the PA. The present study demonstrates the effectiveness of PB for emission abatement through several remarkable achievements. PA with IFM-PB showed a clearly buffered fire response compared to those without IFM-PB, both looking at the number of fires and the extent of burned areas, particularly in extreme years such as 2015. Promoted by successful fuel fragmentation through PB, first shifts in fire seasonality from M/LDS to EDS were achieved after four years of IFM operations, accompanied by reductions in burned areas in the M/LDS and significant increases in EDS burned areas. Since GHG emissions are largely driven by total burned area and seasonal combustion effectiveness (with lower values in EDS), emission abatement was a direct consequence of IFM operations in the study areas. Scaling up IFM operations across all PA in the Cerrado represents a substantial theoretical emission abatement potential. Since emission abatement was only considered as a co-benefit during IFM operations so far, the here estimated emission abatement potential remains a conservative estimate. Promoting longer recovery times for woody vegetation can additionally provide carbon sequestration potentials. This study not only proves the effectiveness of previous IFM operations, but also reflects the unique governance setting in the Brazilian Cerrado that allowed the testing of PB to promote low intensity fire regimes. For the first time, this study confirms the usefulness of Earth observation (EO) data to support the planning, implementation and monitoring of IFM policies in the PA of the Cerrado.

Following the ecological, economic and social success of PB initiatives in other savanna ecosystems of the world, such as the WALFA Project in Australia, emission abatement through IFM-PB in the Cerrado could aim at accessing payments for emission reduction approaches. Certified carbon offsets could be pursued in fire-adapted dry ecosystems in South America through PB, as a way to support local communities and to protect biodiversity. Science-based transparent certification standards, policy frameworks for carbon schemes as well as accurate dMRV tools using EO data are needed to ensure the quality of offsets. In a post-Glasgow net-zero-by-2050 mitigation-committed world, the paradigm shift initiated by the Brazilian government and national research institutions from a zero-burning policy towards IFM and PB in the Cerrado is a promising path to follow.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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