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Deforestation and land use and land cover changes in protected areas of the Brazilian Cerrado: impacts on the fire-driven emissions of fine particulate aerosols pollutants

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ABSTRACT

Although the current Amazon large-scale deforestation boom is not identified in other Brazilian biomes, local areas of the Cerrado are showing increasing deforestation. We have assessed the historical deforestation patterns focusing on the 2018–2019 biennium in two Protected Areas (PAs) of the Cerrado (Rio Preto and Bacia do Rio de Janeiro) where this process was identified, using the Brazilian official deforestation data. Both PAs are situated within an important Cerrado agricultural frontier, suffering intense pressure on Land Use and Land Cover (LULC). We have also estimated the impact of this increasing deforestation on fire emissions using the Brazilian Biomass Burning Emission Model with Fire Radiative Power (3BEM_FRP) model. In the Rio Preto PA the 2018 and 2019 deforestation rates were 73.5% and 188.0% higher than those observed in 2017, while at the Bacia do Rio de Janeiro PA this increase was 23.9% and 312.3%, suggesting that they are not currently effective at curbing deforestation. Most deforested polygons were converted into agriculture or pasturelands, and trends point to higher deforestation rates in 2020. Fire emissions and deforestation were not correlated, suggesting that non-deforestation fire drivers such as meteorological conditions and land management are important drivers of Cerrado biome fire emissions.

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1. Introduction

Deforestation is a major ongoing global anthropogenic disturbance (Wade et al. 2020; Seymour and Harris 2019), even while intact forests offer exceptionally valuable ecosystem services (Watson et al. 2018). Deforestation has broad detrimental impacts, e.g., atmospheric pollution (de Oliveira et al. 2020b), biodiversity loss (Paiva et al. 2019), and disease transmission and public health (Ellwanger et al. 2020). Deforestation also leads to regional climate

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changes (Alves et al. 2017) and alter the hydrological cycle (Vergopolan and Fisher 2016), among other possible impacts. Therefore, preserving dwindling natural forests should be a concern of utmost importance to the public, policy makers, and governments alike.

The establishment of Protected Areas (PAs) has been considered one of the most effective tools for reducing deforestation since forest loss in PAs occurs at lower rates than in non-protected forests (Wade et al. 2020; Johnson et al. 2017). While PAs are broadly crucial in protecting forest, many protected forests remain vulnerable to illegal deforestation and weak governance policies (and policy loopholes) that allow unsustainable wood extraction or agricultural conversion. These vulnerabilities are widespread in Brazil, leading this country to be the largest national contributor to forest loss in PAs over time (Wade et al. 2020). According to Nolte et al. (2013), the effectiveness of PAs depends mostly on government enforcement. The weakening of Brazilian environmental policy over time has been linked to the increased deforestation within PAs, even encouraging and legalizing deforestation and mining in PAs, relaxing environmental laws, reducing or suspending environmental fines, decreasing law enforcement actions targeting illegal logging, and discrediting environmental scientists and non-governmental organizations (Artaxo 2019; Rajão et al. 2020).

The Brazilian Amazon is suffering a deforestation boom in recent years (particularly 2018 and 2019) (Escobar 2019) with this increase not confined to unprotected forests. The large-scale Amazonian deforestation boom after 2017 has not been observed in other Brazilian biomes, but we have identified for the first time that local areas of the Cerrado are showing this deforestation pattern. As we present here, two examples of such Cerrado regions are the Rio Preto and Bacia do Rio de Janeiro PAs (Figure 1), located in the Extreme

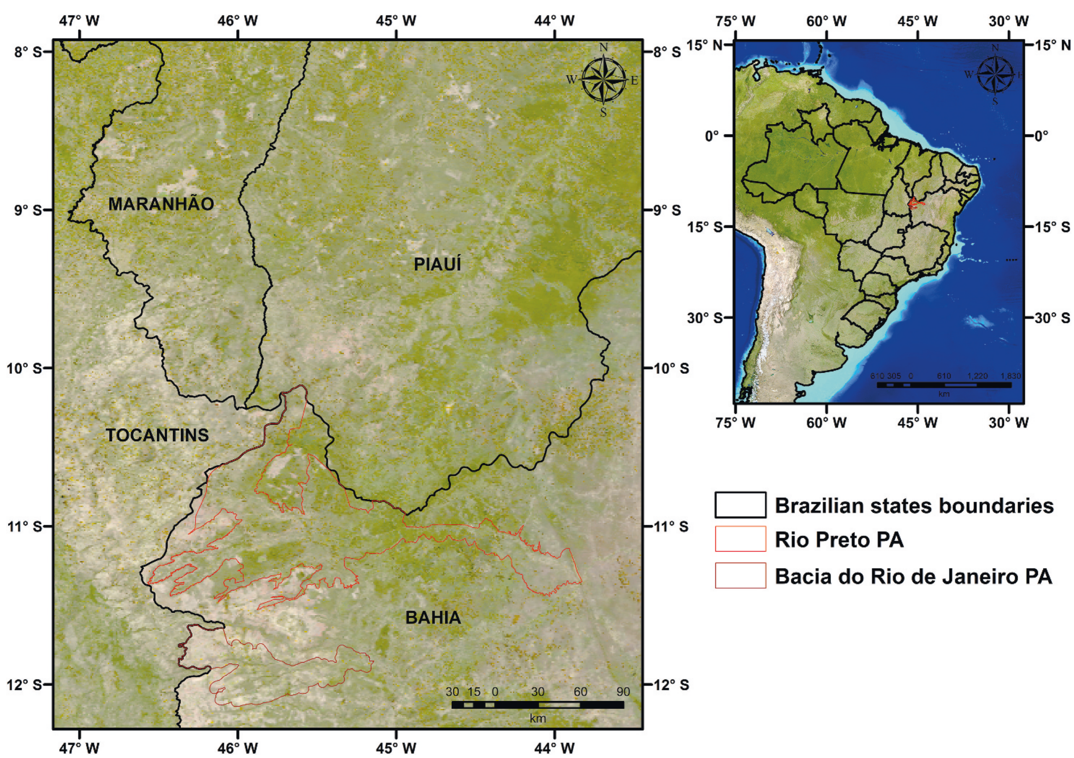

Figure 1. Location of the two PAs analyzed (Rio Preto and Bacia do Rio de Janeiro) within the MATOPIBA region and the Brazilian territory.

Western of the Bahia State. Similar to the Brazilian Amazon as a whole, deforestation has increased significantly since 2017 within these PAs (National Institute for Space Research (INPE) 2020). They are situated within a major Brazilian agricultural frontier, the border of the Maranhão (MA), Tocantins (TO), Piauí (PI), and Bahia (BA) states (named MATOPIBA), where Land Use and Land Cover Changes (LULCC) are a frequent threat to the natural vegetation (de Araújo et al. 2019). These PAs are classified as Environmental Protection Areas where occupation is possible with rural properties having to follow specific regulation, therefore a more frequent and accurate monitoring and law enforcement is needed for their effectiveness. This threat is even greater in the Rio Preto PA as it is part of the Jalapão Region Ecological Corridor (JREC), a biodiversity management mechanism that physically connects nine PAs aiming to allow the flow and free dispersal of species among them. JREC is composed not only of sustainable development PAs, but also from PAs classified as Permanent Protection Areas where no human induced LULCC is allowed. Therefore, the curbing-deforestation effectiveness of these distinct types of Cerrado PAs must be assessed.

Usually, especially in the Amazon biome, the process of deforestation employs fire as a final tool for land clearing and preparation (Pivello 2011) with deforestation and fire often positively correlated. Therefore, the emission of trace gases and aerosols from fires, which impacts climate change and endangers human health, are also expected to increase with the increasing deforestation. Such an increase and correlation was recently identified in a PA of the Brazilian Amazon when using the Brazilian official deforestation monitoring data and fire emissions derived from the Brazilian Biomass Burning Emission Model with Fire Radiative Power (3BEM_FRP) model (de Oliveira et al. 2020a). No similar study is available in a local-scale for the Cerrado. This is an important study as deforestation is not the only fire-driver of the Cerrado: climate conditions, since the Cerrado is a fire-prone biome, land management, especially considering that the study area is inserted within a major agricultural frontier, and the attempt to implement a zero-fire policy in a few PAs of the Cerrado also act as drivers of fire occurrence and, consequently, fire emissions in this biome (Schmidt and Eloy 2020). Therefore, the correlation between deforestation and fire emissions in the Cerrado may not be as clear as the one found in the local-scale study conducted in the Amazon by de Oliveira et al. (2020a). The above-mentioned model, 3BEM_FRP that enables the estimate of fire emissions with orbital remote sensing-based data used as inputs, has been proved effective in both large-scale and local-scale studies (Mataveli et al. 2019; Pereira et al. 2016; de Oliveira et al. 2020a; Cardozo et al. 2015) and, therefore, is suitable for the proposed study.

Based on the considerations above, this study aimed to assess deforestation, focusing on the 2018–2019 biennium, and its correlation with fire-driven emissions in the Rio Preto and Bacia do Rio de Janeiro PAs, located in the Brazilian Cerrado MATOPIBA region where recent increases in deforestation have been identified. To this end we have used the Brazilian official deforestation monitoring data and fire emissions estimates derived from the 3BEM_FRP model. Additionally, we have categorized Land Use and Land Cover (LULC) in deforested polygons identified by the Brazilian official deforestation monitoring data during the 2018–2019 biennium and compared the curbing-deforestation effectiveness of the sustainable development PAs Rio Preto and Bacia do Rio de Janeiro to the one of the permanent protection PAs inserted within the JREC.

2. Materials and method

2.1. Deforestation data

Monitoring deforestation in the Cerrado is more challenging than in the Amazon due to higher vegetation heterogeneity. Brazilian official deforestation monitoring data provided by the National Institute for Space Research (INPE) were used to assess the historical deforestation patterns in the Rio Preto and Bacia do Rio de Janeiro PAs (Figure 1), focusing on the 2018 and 2019 deforestation data as this is the current deforestation boom in the PAs analysed.

There are two distinct official deforestation datasets made available by INPE: PRODES monitors clear-cut deforestation resulting in annually accurate deforestation rates, and the DETER monitoring system, which detects deforestation and provides monitoring and alerts on faster timescale to reveal emerging trends, facilitate inspection, and curb illegal deforestation (National Institute for Space Research (INPE) 2020). Both datasets have been developed to monitor the Amazon but are currently being expanded to the other Brazilian biomes. PRODES Cerrado is available since 2001, while DETER Cerrado started in May/2018. It should also be mentioned that from 2001 to 2012 PRODES Cerrado was provided biannually instead of annually, with half of the deforestation estimated in the biennium attributed to each year. The entire method of PRODES Cerrado is fully described in de Brito et al. (2020).

Regarding their accuracy, both Cerrado deforestation datasets were recently validated. PRODES Cerrado estimates were validated by three specialists in the phytophysiognomies of the Cerrado with the 2017, 2018, and 2019 deforestation estimates reaching an overall accuracy of 94%, 93%, and 93%, respectively. These estimates considered a sampling error of 3% and a 95% confidence interval. The validation of DETER Cerrado alerts consisted on field campaigns conducted in 2019 that inspected 367 polygons with 361 of them accurately showing areas that were deforested. These results are described in Cerrado DPAT (2020)

2.2. Detecting land use and land cover changes

The approach to categorize LULC in deforested polygons detected by PRODES during the 2018–2019 biennium (435 polygons, 365 of them located at the Rio Preto PA and 70 at the Bacia do Rio de Janeiro PA) was based on visual interpretation using the interpretation key developed by the TerraClass Project, responsible for categorizing LULC in deforested areas of the Brazilian biomes (Almeida et al. 2016). This process was performed by an analyst specialized in the phytophysiognomies of the Cerrado. Our LULC classification used the high spatial resolution Planet® images, considering all images available during the first semester of 2020. We disambiguated areas of unclear classification (6 polygons) by analysing time series of MODIS-based Normalized Difference Vegetation Index (NDVI) and Enhanced Vegetation Index (EVI) vegetation indices derived from the SATVeg web-based tool (Esquerdo et al. 2020), following the method adopted by Rudke et al. (2019). Three distinct LULC classes were identified in polygons deforested during the 2018–2019 biennium: agriculture, pasture, and urban allotments.

2.3. Estimating fire emissions

We selected a fire-emitted atmospheric pollutant species known to be a primary human health risk -Particulate Matter with diameter less than 2.5 µm ($PM_{2.5}$)- and hypothesized its increase from the deforestation and related fire. Annual estimates of $PM_{2.5}$ during the 2002–2019 period were obtained using the 3BEM_FRP model implemented on the PREP-CHEM-SRC emissions preprocessing tool version 1.8.3. Fires were the only activated source of emission in PREP-CHEM-SRC 1.8.3 and MODIS sensors active fires products (MOD14 and MYD14) (Giglio, Schroeder, and Justice 2016) were used as inputs in 3BEM_FRP. Model outputs were defined as the daily emission of $PM_{2.5}$ at the spatial resolution of 0.1°, subsequently aggregated into annual estimates and clipped to the delimitation of the Rio Preto and Bacia do Rio de Janeiro PAs. More details on the method applied are described in Mataveli et al. (2019).

This approach was successful in estimating fire emissions and correlating them with deforestation in the local-scale study of de Oliveira et al. (2020a). Regarding the accuracy of 3BEM_FRP estimates, Cardozo et al. (2015) validated the model outputs in a local-scale study with the model overestimating the reference data in 5%.

3. Results

We observed increasing annual deforestation in the Rio Preto and Bacia do Rio de Janeiro PAs after 2017 (Figure 2), following the Amazonian large-scale deforestation boom. In the Rio Preto PA, 1,868.14 km^2 were deforested from 2001 to 2019, corresponding to 16.3% of the total area of this PA (2,096.51 km^2 were deforested prior to 2001). The 2018 (87.8 km^2) and 2019 (145.7 km^2) deforestation rates were 73.5% and 188.0% higher than the 2017 rate (50.6 km^2), respectively. The 2019 deforestation rate was highest since the delimitation of this PA in 2006.

A similar pattern was observed in the Bacia do Rio de Janeiro PA. From 2001 to 2019, 866.3 km^2 were deforested, corresponding to 24.6% of the total area of the PA (2,392.15 km^2 were deforested prior to 2001). Following a period of decreasing deforestation from 2014 to 2017, deforestation rates in 2018 (20.2 km^2) and 2019 (67.4 km^2) were, respectively, 23.9% and 312.3% higher than the one observed in 2017 (16.3 km^2). The deforestation rate in 2019 was the fourth highest registered in the Bacia do Rio de Janeiro PA since 2001. The Rio Preto and Bacia do Rio de Janeiro PAs are the second and third most deforested PAs in the Cerrado since the beginning of PRODES Cerrado estimates in 2001. Furthermore, Rio Preto was the Cerrado biome PA with highest deforestation in 2019, and Bacia do Rio de Janeiro the third highest.

We observed distinct LULCC patterns in the 2018 and 2019 deforested polygons when comparing the two PAs analysed (Figure 3). Deforested areas in the Rio Preto PA were mostly converted into pasturelands (193.60 km^2, 82.97% of the deforested polygons), followed by agriculture (39.83 km^2, 17.00% of the deforested polygons). Urban allotments were also identified in 2018, corresponding to 0.03% of the deforested polygons during the 2018–2019 biennium. In the Bacia do Rio de Janeiro PA most of the deforested areas were converted to agriculture (52.89 km^2, 60.35% of the deforested areas during the 2018–2019 biennium). 39.15% of the polygons LULC was converted to pasturelands (34.31 km^2); urban allotments were found in 2019, accounting for 0.50% of the converted polygons.

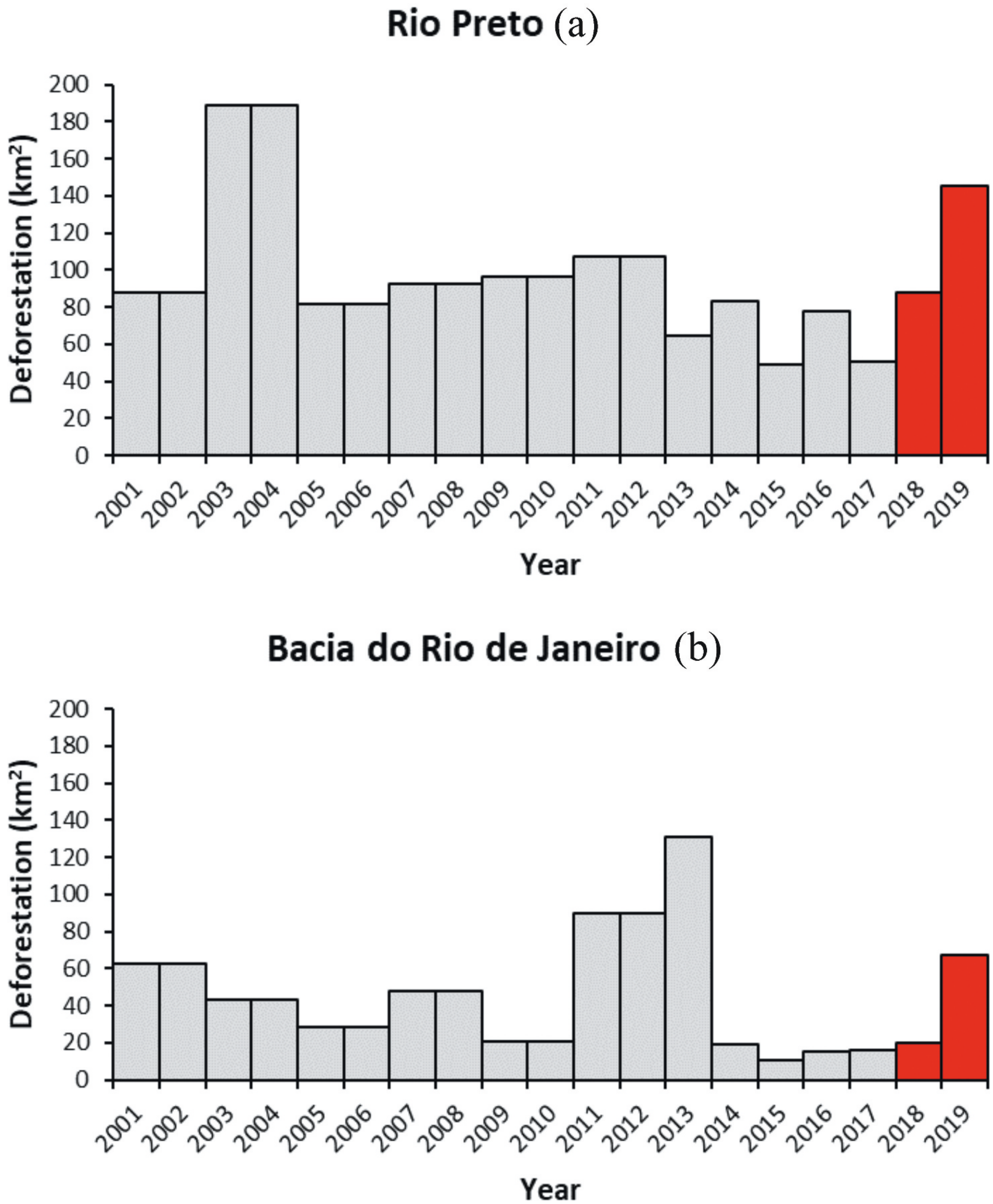

Figure 2. Annual deforestation rates in the Rio Preto (a) and Bacia do Rio de Janeiro (b) PAs, located in the MATOPIBA region, from 2001 to 2019.

Fire emissions, however, did not clearly track the deforestation pattern in the PAs analysed (Figure 4), suggesting that deforestation is not the predominant fire driver in the study area during this observational period. Despite increasing deforestation of 2018–2019, $PM_{2.5}$ emissions in the Rio Preto PA were higher in 2019 (5,614 tonnes) and 2017 (5,523 tonnes), and relatively low in 2018 (2,119 tonnes). In the Bacia do Rio de Janeiro PA total $PM_{2.5}$ emission in 2017 (1,736 tonnes) was higher than emissions observed in 2018 (615 tonnes) and 2019 (1,129 tonnes). MODIS active fires have followed the same pattern of fire emissions. In the Rio Preto PA, MODIS sensors have detected 973

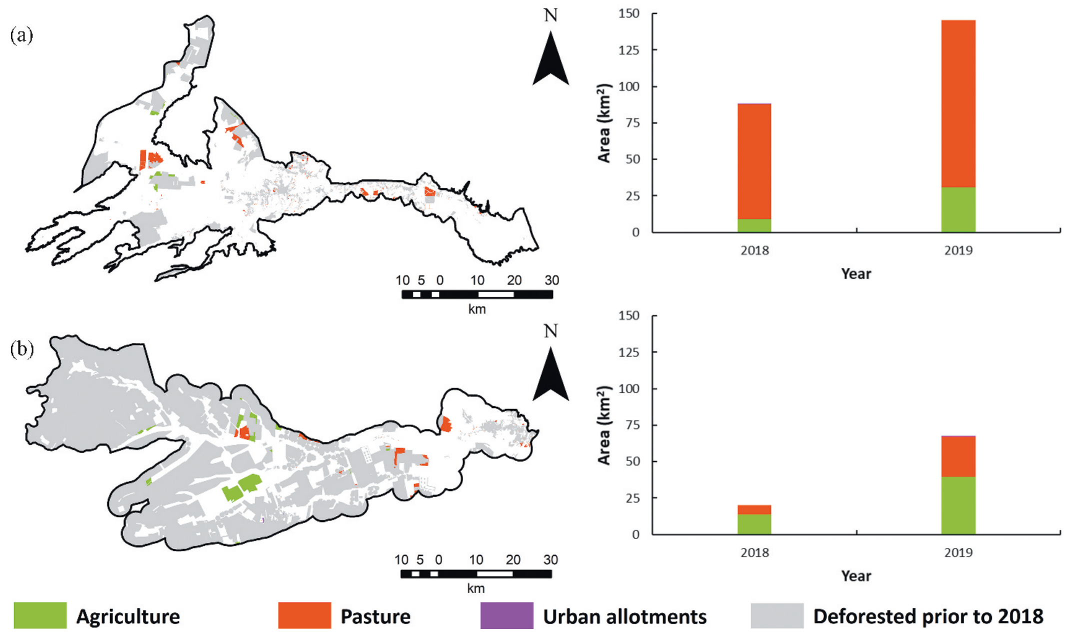

Figure 3. Land-use in deforested polygons detected during the 2018–2019 biennium in the Rio Preto (a) and Bacia do Rio de Janeiro (b) PAs.

active fires in 2017, 583 in 2018, and 1,143 in 2019. In the Bacia do Rio de Janeiro PA, 302 active fires were detected in 2017, 144 in 2018, and 173 in 2019.

4. Discussion

4.1. Deforestation in the Rio Preto and Bacia do Rio de Janeiro PAs

The current Brazilian conservation units organizational structure established by the Law 9,985/2000 defines several different types of PAs. The Rio Preto and Bacia do Rio de Janeiro PAs are considered Environmental Protection Areas where occupation is allowed and specific regulation governs the management of rural properties. Nevertheless, the significant increase in deforestation after 2017 found in both PAs suggests that this type of PA is not effective for reducing deforestation in the MATOPIBA region. This is in agreement with Eloy et al. (2015), who concluded that Environmental Protection Areas do not prevent the expansion of soybean plantation in the Cerrado since landowners can deforest up to 80% of their properties for planting crops. This difficulty in curbing deforestation in the Cerrado is also observed in other initiatives such as the Brazilian online Rural Environmental Registry (CAR) system, designed to curb deforestation since 2012 that is non-effective in soybean frontiers (Rajão et al. 2020). Nunes de Oliveira et al. (2017) have also highlighted the need for a stronger role of environmental agencies in monitoring and enforcement to slow land conversion in the MATOPIBA region.

Approximately 10% of the total area of the Rio Preto PA was deforested after its creation in 2006, with 2% occurring during the 2018–2019 biennium. At the Bacia do Rio de Janeiro PA, 22.8% of the natural vegetation was deforested after its expansion in 2001, with 2.5% occurring during the 2018–2019 biennium. This increasing deforestation

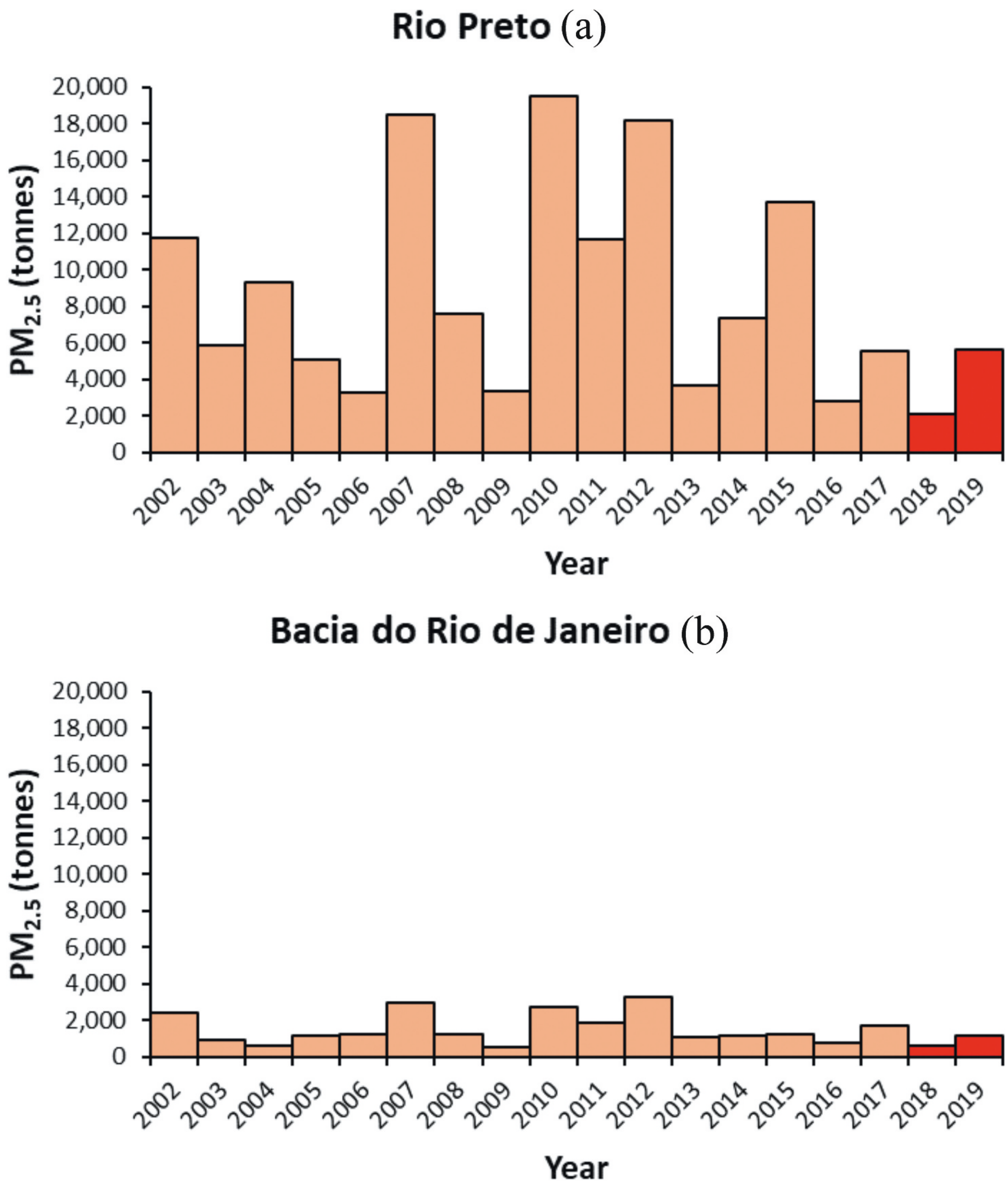

Figure 4. Annual total estimated emission of $PM_{2.5}$ associated with fires in the Rio Preto (a) and Bacia do Rio de Janeiro (b) PAs during the 2002–2019 period.

was, in contrast, not found in any of the Permanent Protected Areas of the JREC, suggesting that this type of PA is effective at reducing/curbing deforestation in the MATOPIBA region. The exception within the JREC was the Serra da Tabatinga PA, where the 2018 (25.17 km^2) and 2019 (11.15 km^2) rates were, respectively, 483% and 158% higher than the one estimated in 2017 (4.32 km^2) but this is an Environmental Protection Area type allowing human occupation and land management. Moreover, the fact that Permanent Protected Areas of the MATOPIBA are often located in areas that are not suitable for soybean cultivation contributes to the curbing-deforestation effectiveness of these PAs (Eloy et al. 2015).

4.2. Drivers of LULCC in the MATOPIBA region

The primary drivers of LULCC in the MATOPIBA are related to crop expansion. This region is located at the centre of Brazil's recent agricultural boom, and encompasses a quarter of the Cerrado's soybean production (Soterroni et al. 2019). As double-cropping practice is not usual in this region, producers expand the agropastoral areas using land clearings to increase profits (Nunes de Oliveira et al. 2017). In the Extreme Western of the Bahia State landscape changes are driven by agropastoral advance into natural vegetation areas to meet agribusiness demands, particularly from the global market (de Araújo et al. 2019). Management practices are characterized by either (i) pastureland for non-commercial crop cultivation and small-scale cattle ranching, which is the primary land-use after deforestation or (ii) large-scale high-yield single crop agriculture, particularly soybeans, cotton, maize, and coffee (Spera 2017). These agropastoral activities are favoured by the local edaphoclimatic conditions, ideal for implementing highly mechanized large-scale agriculture (Nunes de Oliveira et al. 2017).

The pattern of deforestation within both PAs follows a cycle of primary conversion from natural vegetation to pasture, and then to mechanized crop agriculture (Nunes de Oliveira et al. 2017). In the Bacia do Rio de Janeiro PA, agriculture was the predominant LULC after deforestation because it is located at the centre of the large-scale crop production of the Extreme Western of the Bahia State (Spera 2017). In the Rio Preto PA, pasturelands predominated in the deforested polygons likely due to a less consolidated, though increasing, large-scale crop practice. If the LULCC pattern continues, most of these pastureland polygons will be converted into agriculture in the near future. The presence of urban allotments in both PAs highlight also increasing pressure on natural vegetation since urbanization can drive LULCC to meet local demands for food crops.

According to Spera (2017), supporting initiatives to spare land by intensifying agriculture from single to double crop practices could reduce land conversion even more than the creation of Environmental Protection Areas since the MATOPIBA region does have the natural conditions needed for intensification. However, the recent reduction of control against illegal deforestation and the increased profitability that pushes farmers to convert more land (Angelsen and Kaimowitz 2011), together with the long-term impacts of agricultural intensification (e.g. pollution, erosion, and increased pressure on water resources), reduce the real possibilities of this practice for the Cerrado conservation.

4.3. Future trends in deforestation

By comparing the alerts derived from DETER monitoring system from January to June of 2020 with those from the same period of 2019 we observe that the increasing deforestation trend of the 2018–2019 biennium is ongoing in both PAs. DETER alerts increased from 67.90 km^2 to 85.19 km^2 (~25%) at the Rio Preto PA, while at the Bacia do Rio de Janeiro PA this increase was close to 15% (from 32.70 km^2 to 37.48 km^2).

4.4. Fire emissions and deforestation

The absence of correlation between the annual total deforested area and annual total $PM_{2.5}$ emitted from fires from 2002 to 2019 in both PAs analysed (Figure 5) suggests that non-deforestation fire drivers are the most important source of fire emissions in the study area

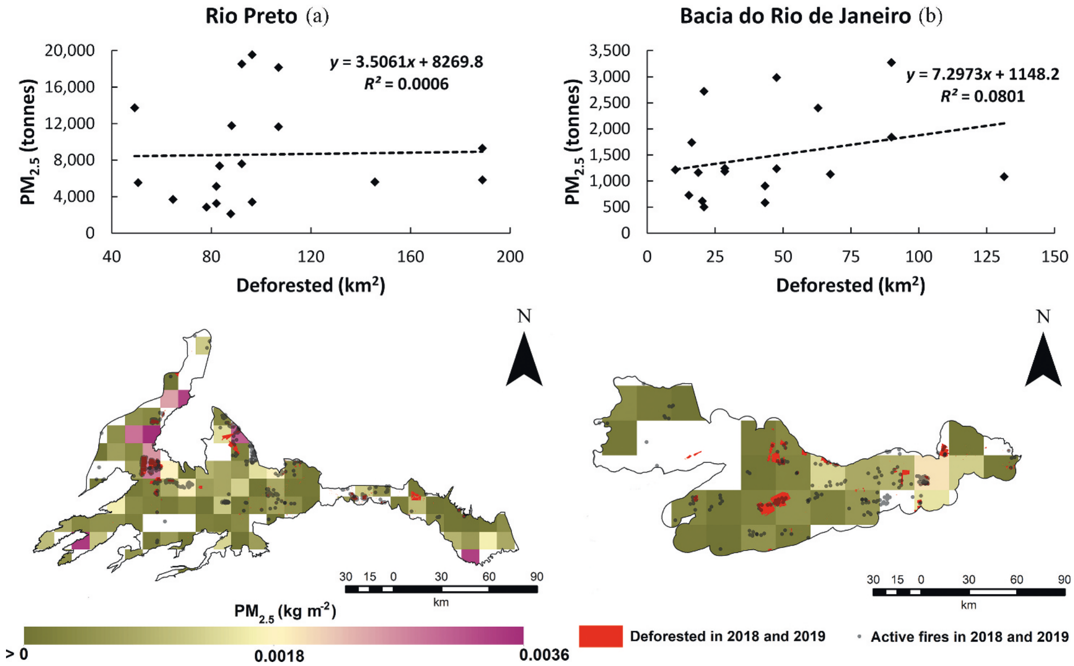

Figure 5. Correlation between annual total deforestation and annual total PM2.5 emitted from fires in the Rio Preto (a) and Bacia do Rio de Janeiro (b) PAs during the 2002-2019 period, spatial distribution of estimated PM2.5 emissions from fires and spatial distribution of active fires detected by MODIS during the 2018–2019 biennium.

during this observational period. Accordingly, several grid cells displayed $PM_{2.5}$ emissions in the absence of deforestation during the 2018–2019 biennium.

The analysis of MODIS active fires corroborates this result (Figure 5). In the Rio Preto PA, MODIS detected 1,726 active fires during the 2018–2019 biennium with only 485 active fires occurring in areas deforested in this time period. In the Bacia do Rio Preto PA, 317 active fires were detected in this time period with 196 of them occurring in areas deforested. Instead, active fires and associated emissions occurred in areas deforested prior to 2018, probably related to land management (shifting cultivation, burning residues, or to stimulate the regrowth of pastures), or in natural vegetation areas that were not deforested. The lack of a fire management policy may also cause wildfires in remaining native vegetation areas during late dry season due to the accumulation of dry fuel loads, especially in areas neighbouring crop plantations (Schmidt and Eloy 2020). Both PAs analysed do not have an established fire management policy. Flores et al. (2020) also highlight the need for the Cerrado fire management since long fire-free periods in a PA close to the study area allowed grass fuels to build-up and caused wildfires to become more intense and uncontrolled, endangering riparian forests that may shift into an alternative ecosystem state.

Apart from anthropogenic disturbances, climate conditions must also be considered a major driver of fire emissions in this fire-prone biome and help to explain fire-emissions patterns. Drier conditions are favourable for fire creation and spread, and enhance the role of fire in land conversion, land management, and increase the number and area impacted by wildfires in natural Cerrado vegetation. When analysing the role of drivers in fire activity of the MATOPIBA region, Silva et al. (2020) found that climate individually explains 52% of fire activity in this region. Accordingly, the two years we estimated the highest emission in both PAs (2007 and 2010) were the driest ones in the Cerrado from 2002 to 2015.

Finally, despite the good agreement of 3BEM_FRP with reference data (Cardozo et al. 2015), we should mention a few difficulties that potentially impacted the final estimate of fire emissions derived from this model: smaller size fires, less intense fires, or fires covered by clouds or thick smoke may not be detected by MODIS sensors, the accurate determination of fire location, and the less sensitivity of MODIS to detect fires at off-nadir viewing angles (Mataveli et al. 2019).

5. Conclusions

In this study we evaluated an increasing deforestation trend and its impacts on the emission of $PM_{2.5}$ associated with fires in two Protected Areas (PAs) classified as Environmental Protection ones located in the Brazilian Cerrado MATOPIBA region. We found a remarkable advance of deforestation during the 2018–2019 biennium and evidence that this pattern is set to increase in 2020. On the other hand, we did not find an increase of deforestation in Permanent Protection Areas of the JREC, suggesting that this type of PAs is in fact effective in the MATOPIBA region. Agricultural frontiers are advancing within both PAs, with a LULCC pattern of primary conversion from natural vegetation to pasture and then to crops. The presence of urban allotments within both PAs is expected to enhance the anthropogenic pressure on natural vegetation due to local agricultural demands.

We observed a decoupling of deforestation and fire emissions in the study area during this observational period. This shows the importance of other fire-emissions drivers in the Cerrado, a fire-prone biome where meteorological conditions, the traditional use of fire for land management, and fires in natural vegetation areas that were not deforested are very important and drive fire emissions. We also highlight that this correlation may exist on long-term analysis or in large-scale Cerrado studies. Therefore, further evaluation is necessary in future studies, especially considering the impacts of the recently applied fire management policies in a few PAs of the Cerrado. Such techniques will eligibly decrease fire occurrence and, consequently, fire emissions but their potential to this end is still being investigated.

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Data availability

All data used in the current study are available from the corresponding author on request.

Conflicts of Interest

The authors declare that there is no conflict of interest that could be perceived as prejudicing the impartiality of the research reported.

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