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Key Points:
- Native Brazilian savannas and transitional ecotones are exhibiting widespread evidence of woody encroachment
- The main local factors found to be associated with woody encroachment were the recent fire suppression and land use abandonment

Supporting Information:
- Supporting Information S1

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Extensive 21st-Century Woody Encroachment in South America's Savanna

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Abstract Woody encroachment is occurring in all tropical savannas of the world. However, in the Brazilian savanna (the Cerrado), the extent of this phenomenon is still poorly documented. Here woody encroachment was quantified throughout the Cerrado biome and transitional ecotones using a trend analysis of the annual maximum of enhanced vegetation index obtained from the Moderate Resolution Imaging Spectroradiometer. The associations with potential local drivers, such as fire and land use regime, were assessed using satellite data of land cover and fire regime. We found that 19% of the remaining native vegetation showed significant evidence of woody encroachment in the last 15 years and 7% exhibited degradation processes. The local factors that favored woody expansion in 19% of the biome were a decrease of fire (34%) and land use abandonment (26%). Our study highlights that local human-associated drivers are playing a major role in woody encroachment and savanna degradation.

Plain Language Summary Increases in tree cover have been observed locally across the savannas of the globe, systems that are typically more dominated by grasses. Despite the increase in biomass, this process has the potential to decrease biodiversity. We used satellite data to identify where this woody encroachment is occurring in the Brazilian savanna biome, known as the Cerrado, and the potential local factors associated to this phenomenon. The results show that woody encroachment is widespread across the remaining areas of the Cerrado, with the absence of fire, decrease of fire incidence, and land use abandonment being associated with this process. These findings suggest the importance of land use management strategies and conservation policies focused on the Cerrado to conserve this unique biodiversity hotspot in the near future.

1. Introduction

Savannas cover around 20% of the Earth's surface and are considered critical in the global carbon cycle as they account for 30% of terrestrial net primary production (Grace et al., 2006). Tropical savannas are generally defined as having a continuous layer of C4 grasses and a discontinuous layer of C3 trees (Beerling & Osborne, 2006), encompassing a mosaic of vegetation, from sparsely treed grasslands to dense woody landscapes in which woody cover can vary spatially and temporally (Scholes & Archer, 1997). These ecosystems provide unique habitats and contribute to global biodiversity and ecosystem services (Bond & Parr, 2010).

Woody encroachment can be defined as a rapid increase in biomass, stem densities, or cover of woody plants, resulting in an open savanna ecosystem shifting toward a closed canopy system (Mitchard et al., 2009; Mitchard & Flintrop, 2013; Stevens et al., 2017). It is now well established that woody encroachment is occurring in most tropical savanna environments (Oliveras & Malhi, 2016; Stevens et al., 2017), and for the Cerrado it has important consequences for biodiversity (de Abreu & Durigan, 2011; Pellegrini et al., 2016; Veldman et al., 2015). For example, Abreu et al. (2017) reported a decline of 27% in plant species richness and a 67% loss of savanna endemics species in an area of Cerrado that has been experiencing woody encroachment over 30 years.

While there is no consensus yet about the causes of woody encroachment, it has been suggested that they vary among regions and ecosystems. Woody encroachment may be associated with global drivers, such as rising atmospheric CO_2 concentration (Buitenwerf et al., 2012; Franco et al., 2014; Moncrieff et al., 2014; Oliveras & Malhi, 2016; Phillips et al., 2009), and regional factors, such as changes in the precipitation and fire regimes, herbivory, and land use change (Devine et al., 2017; Wigley et al., 2010). Thus, understanding the drivers of this current trend of changing vegetation structure and composition is critical to predicting the long-term evolution of the savanna biome and the possible changes in its contribution to the planet's biogeochemical cycles and biodiversity.

Brazil hosts the most extensive tropical savanna biome of the world, the Cerrado, which is also the second largest biome in the country, after the Amazônian forest biome, covering around 22% of the national land area (2,036,448 km^2). Since the 1980s the Cerrado has undergone intense land use and land cover change associated with the expansion of agriculture and cattle ranching (Brannstrom et al., 2008), resulting in extensive fragmentation of the landscape. In recent years, the rates of conversion to agriculture in the Cerrado have surpassed those of the Amazon. For example, in 2015, the area of Cerrado vegetation cover loss was 9,483 km^2, which was about 50% higher than the total area lost across the Legal Amazon for the same year (INPE, 2018a, 2018b). Because of the high rates of vegetation cover loss and less restrictive environmental rules compared to the Amazon biome, the Cerrado is one of the most threatened Brazilian biomes (Bonanomi et al., 2018).

The Cerrado is characterized by a mosaic of vegetation types forming a structural gradient that encompasses grassland (*Campo limpo*), savanna (*cerrado tipico* or *Cerrado sensu stricto*), and cerrado woodland (*Cerradão*; Durigan & Ratter, 2016). Because of the heterogeneity of landscapes, this biome is considered a biodiversity "hotspot," with many endemic flora and fauna (Myers et al., 2000) but with plant diversity not necessarily correlated with biomass (Morandi et al., 2018).

Although a number of abiotic factors such as availability of soil nutrients and variations in soil water regime have an influence on Cerrado vegetation structure and composition (Franco et al., 2014), fire has been identified as the most important factor in maintaining the biomass gradient and biodiversity of Cerrado vegetation (Coutinho, 1990; Giselda Durigan & Ratter, 2016; Staver et al., 2011). Because of the importance of fire, changes in its dynamics can lead to changes in vegetation structure and composition. At high frequencies, fire facilitates the invasion of grasses and creates grass-dominated landscapes (Setterfield et al., 2010). On the other hand, fire suppression tends to favor the incursion of woody vegetation into grassland savannas, potentially causing a biome shift and biodiversity loss (Durigan & Ratter, 2016; Geiger et al., 2011; Moreira, 2000; Passos et al., 2018). Recent studies suggest that fire incidence in Cerrado is decreasing, with complete suppression in some areas due the mechanized agriculture expansion (Andela et al., 2017; Mataveli et al., 2018). These changes in fire dynamics have been identified as the main cause of woody encroachment in some Cerrado field sites (Durigan & Ratter, 2016).

While field studies have already assessed some drivers of changes in Cerrado vegetation structure, spatially explicit information sufficient to assess the process of woody encroachment and its likely causes has not been available at the biome scale. The main large-scale observation of woody encroachment has been made using the normalized vegetation index from the coarse spatial resolution (8 km × 8 km) orbital sensor Advanced Very High Resolution Radiometer and was focused on the African savannas (Mitchard et al., 2009; Mitchard & Flintrop, 2013). However, to the best of our knowledge, there are as yet no studies assessing where woody encroachment is occurring in the Cerrado biome and what the spatial drivers of this phenomenon might be. To investigate the woody encroachment, we used the enhanced vegetation index (EVI) computed from the multiangle implementation of atmospheric correction algorithm (MAIAC). The EVI maximum was used because this index has been shown to be strongly correlated with vegetation structure in the Cerrado (Abreu et al., 2017).

Unlike other savanna regions, Brazil has a highly accurate yearly classification of land cover available at spatial resolution of 30 m (MapBiomas, 2018), creating a unique opportunity to map the extent and driving factors of woody encroachment in the Cerrado. This information is crucial for understanding the dynamics of the Cerrado biome to support conservation policies and efforts to model the future of this biome. Therefore, the objectives of this study were (i) to identify where woody encroachment is occurring within the Brazilian Cerrado biome and in transitional savanna zones adjacent to the Amazônia, Caatinga, Atlantic forest, and Pantanal biomes and (ii) to assess the role of fire and land use change in controlling the process of woody encroachment. We used a buffer of 100 km to analyze the transitional areas between savanna and other vegetation types that are intertwined with successional processes operating (Morandi et al., 2015).

2. Materials and Methods

2.1. EVI From MODIS (MAIAC EVI)

We used the annual maximum EVI (EVI_{max}) as a proxy for woody encroachment. Abreu et al. (2017) demonstrated that EVI_{max} is strongly correlated with vegetation structure, such as tree basal area and leaf area index in the Cerrado. We extracted 16-day composite images at 1-km resolution between 2001 and 2015 from the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor (product MCD19A1_C6), on board the Terra and Aqua satellites. The MODIS EVI index was developed to optimize the vegetation signal in high biomass regions, decouple the canopy background signal, and reduce atmospheric influence (Huete et al., 2002; Huete et al., 2006). We used the data processed with the multiangle implementation of atmospheric correction algorithm (MAIAC; Lyapustin et al., 2012). MAIAC observations are based on MODIS Collection 6 Level 1B (calibrated and geometrically corrected) observations, which removed major sensor calibration degradation effects present in earlier collections. In addition, EVI data were corrected for bidirectional reflectance effects using the bidirectional reflectance distribution function, by normalizing all observations to a fixed sun sensor geometry (solar zenith angle of 45° and nadir view angle; Dalagnol et al., 2018).

2.2. Burned Area From MODIS (MCD64A1_C6)

The monthly MODIS Burned Area product (MCD64A1 Collection 6) was used for assessing: total area impacted by fire, fire trends, and fire frequency between 2001 and 2015. The MCD64A1 is generated using an improved version of the MCD64 burned area mapping algorithm, with reduced omission errors (Giglio et al., 2009). The algorithm uses as input data surface reflectance at 500-m spatial resolution coupled with 1-km MODIS active fires from the MODIS Collection 6 product. The MODIS data set was aggregated to a 1-km spatial resolution grid by calculating the burned area proportion of each year in each pixel.

2.3. Land Use and Land Cover Data Set

The annual Land Use and Land Cover (LULC) data set for the Cerrado and adjacent biomes was obtained from MapBiomas (Project of Annual Mapping of Land Cover and Land Use in Brazil, Collection 2.3) from 2001 to 2015. We used the LULC data set, first to compute the area of Cerrado vegetation for each vegetation class (forest, savanna, and natural grasslands) in the whole biome and second to calculate the time trends in land cover for the pixels with positive trends in EVI_{max}. The annual LULC map is based on an annual Landsat mosaic of Brazil with 30-m spatial resolution generated in the Google Earth Engine platform using the Random Forest classifier and with a general accuracy of 88.3% (MapBiomas, 2018). Because of the difference in spatial resolution between the LULC map and MODIS\MAIAC, the annual LULC map was resampled using information on the proportion of land cover classes in the pixels of 1-km spatial resolution. This processing was performed using IDL-ENVI 4.7 (Exelis).

In order to analyze only the changes occurring in the vegetation of the Cerrado biome and transitional areas, we produced a map of the 2015 vegetated areas. This map was based on the 2015 LULC map. To create this mask, we used the following MapBiomas classes: (i) forests, including seasonal semideciduous forest, thick woodland forests (*Cerradão*), and dry forests; (ii) savannas that include shrublands; and (iii) natural grasslands (*Campos*). Since our data consisted of the proportion of each land cover within a grid cell at MODIS spatial resolution (1 km), we only used pixels with the aggregated proportion of the targeted class >80%. We also used an agricultural land class, which includes areas of cropland and pastures, to analyze changes in land use regime.

2.4. Trend Analysis

To find the areas with woody encroachment, we performed a pixel-by-pixel linear regression of the EVI_{max} time series using the *raster* R package (Hijmans & van Etten, 2014). Changes through time were considered significant for pixels that presented a best fit line using an F test with a 90% confidence level (Anyamba & Tucker, 2005; Mitchard & Flintrop, 2013). Then, a mask was applied to analyze only pixels with >80% from Cerrado vegetation areas of in 2015 using MapBiomas (supporting information Figure S1). We only used the pixels where the EVI_{max} slope was >0.002 ($p < 0.1$) as a proxy of woody encroachment and <−0.002 for degradation, following Anyamba and Tucker (2005) and Mitchard and Flintrop (2013). With this threshold,

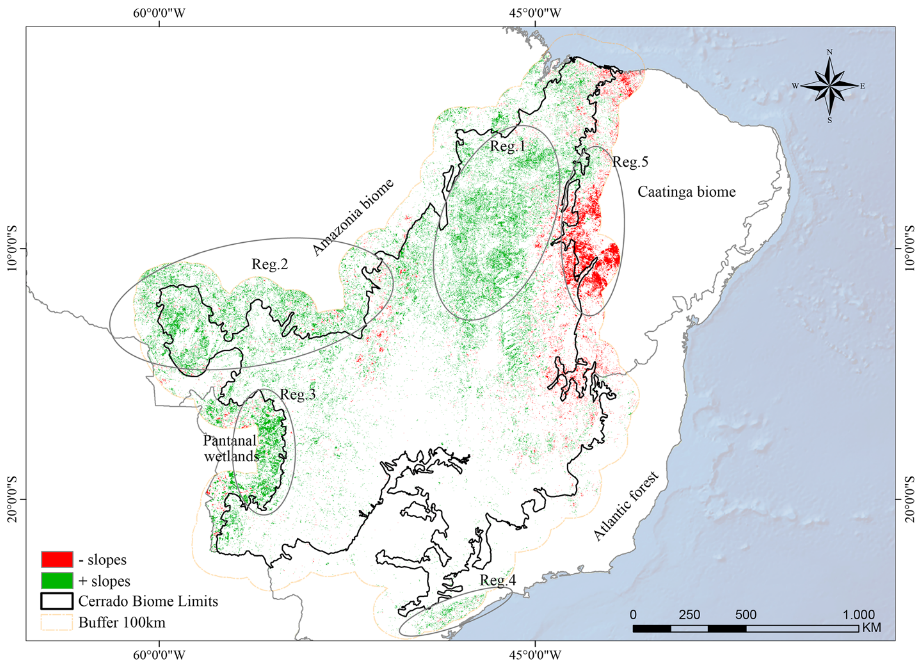

Figure 1. Trends of EVI_{max} between 2001 and 2015 for the Cerrado vegetation in 2015 and the main biomes of Brazil. Positive slopes indicate woody encroachment. All the pixels presented on the map was masked at a level of confidence $p < 0.1$. (More than 68% of the pixels presented $p < 0.05$.) See in Figure S2 and Table S1 the distribution of the confidence level and slopes. Boxes 1, 2, 3, and 4 indicate regions with the most concentration of increasing EVI_{max}. Box 5 is a region with high concentration of negative trends of EVI_{max}. EVI_{max} = maximum enhanced vegetation index.

only the pixels that presented a change of EVI_{max} of at least 0.03 in the EVI units over 15 years were included in the analysis.

To identify the potential drivers of woody encroachment, we used Boolean operators in ArcGIS® "select by attribute" tool to combine trends in land cover and fire incidence with pixels that exhibited increased EVI_{max}. We grouped the potential drivers into five classes: (i) no fire, pixels with no fire event in 15 years and no significant trend of agriculture lands; (ii) recent fire suppression, pixels with negative fire trend and no significant trend of agriculture lands; (iii) fire presence, pixels with more than two fire occurrences and no significant trend in agriculture lands; (iv) abandonment of agriculture lands, pixels with negative trend in agriculture lands and presence of fire (up to two fire events); and (v) increase of agriculture lands, pixels with a positive trend in agriculture lands. These last pixels contain signals from agriculture and cattle pastures and therefore are not associated with woody encroachment. Finally, we tested the association between these fire classes and woody encroachment.

3. Results

3.1. Spatial Characterization of Woody Encroachment With EVI_{max}

The trend analysis of EVI_{max} showed that both positive and negative trends occurred across the Cerrado as well as along the transitional zones within Amazônia, Caatinga, Atlantic forest, and Pantanal wetlands (Figure 1). Considering only areas of Cerrado vegetation, which were estimated to cover a total area of 911,047 km^2 of the study area (Figure S1), an area of 171,953 km^2 (19%) from the total vegetation cover showed a significant increase in EVI_{max} between 2001 and 2015 ($p < 0.1$), indicative of the occurrence of woody encroachment. Most of the increase (71%) is concentrated within the limits of the Cerrado biome and 29% within the buffer area (Table S3). In contrast, an area of 65,546 km^2 (7%) showed a decreasing trend in EVI_{max} (Figure 1). Spatially, most areas with an increasing EVI_{max} trend were located in the northern part of the Cerrado (Box 1, Figure 1) and within the transitional zone with the Amazon forest (Box 2, Figure 1) and the Pantanal wetlands (Box 3, Figure 1). We also detected small patches of EVI_{max} increasing

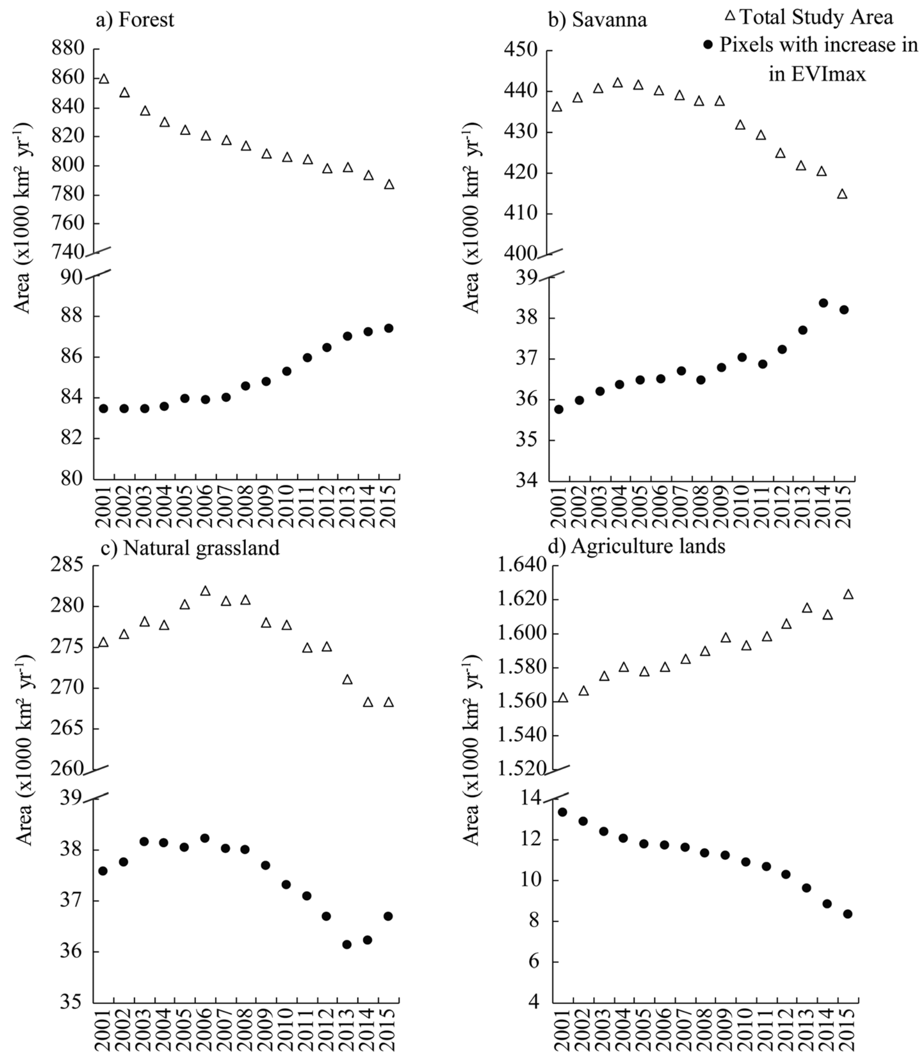

Figure 2. Total area (km^2) per year for each land cover class taken from MapBiomas for the following classes: (a) forest, (b) savanna, (c) natural grasslands, and (d) agriculture lands. The open triangles are the entire study area. The filled circles represent a fraction of the study area that is exhibiting increase in EVI_{max}. EVI_{max} = maximum enhanced vegetation index.

in the southern end of the Atlantic forest biome (Box 4, Figure 1). Negative trends were mostly concentrated in the northeast (Box 5, Figure 1), along with the border with the Caatinga biome (seasonally dry forest).

3.2. Land Cover Changes

In the whole study area, there was a linear decrease of forest cover between 2001 and 2015, with a total loss of 72,465 km^2 (Figure 2a). Savanna cover increased by 5,420 km^2 from 2001 to 2005, followed by decrease of 26,876 km^2 from 2006 to 2015 (Figure 2b). The change in area of natural grasslands oscillated with an increase of 2,339 km^2 between 2001 and 2009 and a decrease of 9,673 km^2 by 2015 (Figure 2c). In summary for the entire study area, Cerrado vegetation had been decreasing since 2009, with a total loss of 101,255 km^2. On the other hand, there had been a steady increase (in total 60,217 km^2) of agriculture land cover for the 2001–2015 period (Figure 2d). More details on the spatial distribution of land cover changes are given in Figure S3.

While vegetation cover decreased over the whole study area, the analysis of changes in land cover only inside the pixels with positive trends in EVI_{max} exhibited a different pattern. In those pixels, we found

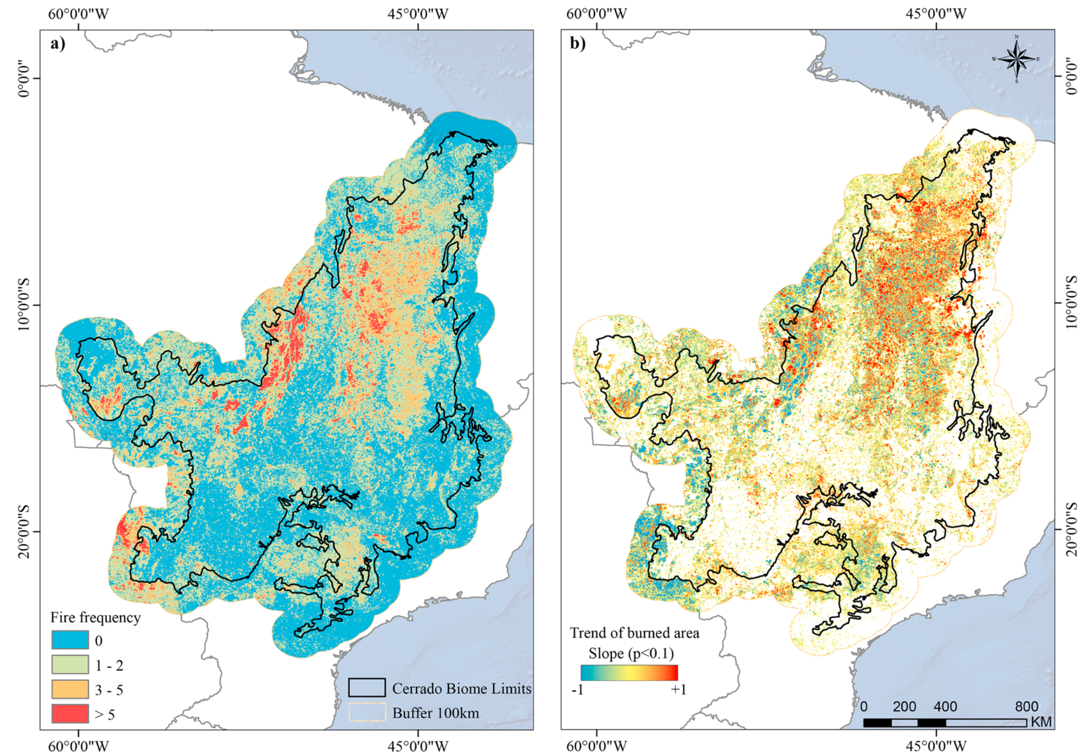

Figure 3. Spatial distribution of (a) fire frequency in the Cerrado biome between 2001 and 2015 from the product MODIS MCD64A1_C6 and (b) pixel-by-pixel trend of burned area proportion through time ($p < 0.1$); the nonsignificant pixels appear in white color.

a total increase of the forest class of 3,954 km^2 (5%) from 2001 to 2015 (Figure 2a, closed circles). Savannas increased by 2,457 km^2 in the same period (7%, Figure 2b), natural grassland areas (Figure 2c) increased between 2001 and 2006 but decreased thereafter losing 883 km^2 (2%). Agricultural lands declined by 4,973 km^2 (34%) from 2001 to 2015 (Figure 2d), indicating land use abandonment. Therefore, besides the whole studied area is experiencing high rates of vegetation loss and increase in agriculture areas, in the pixels with increase in the EVI_{max} the forest and savannas classes are increasing; on the other hand natural grasslands and agriculture lands are decreasing, indicating evidences of woody encroachment.

3.3. Fire Dynamics

Considering the cumulative burned areas, which include areas that have more than one fire per year, we estimated an average burned area of 161,620 km^2/year (SD = 74,348) between 2001 and 2015 (Figure S2). We found that 52% of the study area had no fire occurrence during the study period, 35%, 10%, and 3% had up to 2, 5, and >5 fire occurrences over 15 years, respectively. The highest frequency of fires occurs in spatially structured patches in the central part of the Cerrado and near to the border with the Amazônia biome (Figure 3a). Among the pixels with at least one fire occurrence, 19% (581,479 km^2) showed an increase in the proportion of burned area, while 20% (623,444 km^2) showed a decrease (Figure 3b). The decreasing trend of burned area was observed most consistently in regions of the Cerrado biome along the transitional zones with Amazônia biome and Pantanal Wetlands (Figure 3b).

Analyzing the extent of burned area for the fraction of pixels experiencing an increase of EVI_{max} from 2001 to 2015, we found a mean burned area of 15,125 (±7,301) km^2/year or 9% per year of the total area (Figure S4 and Table S3). In these burned pixels where increase of the EVI_{max} is occurring, the average fire frequency was of 3 (SD = 2) events over 15 years. Considering the total cumulative burned area within pixels experiencing woody encroachment and also over the whole study area, we found a pattern that varied year to year, peaking in 2007, 2010, and 2012 (Figure S4) when burned area increased by more than 100%; however, there is nonsignificant trend through time for the total burned area.

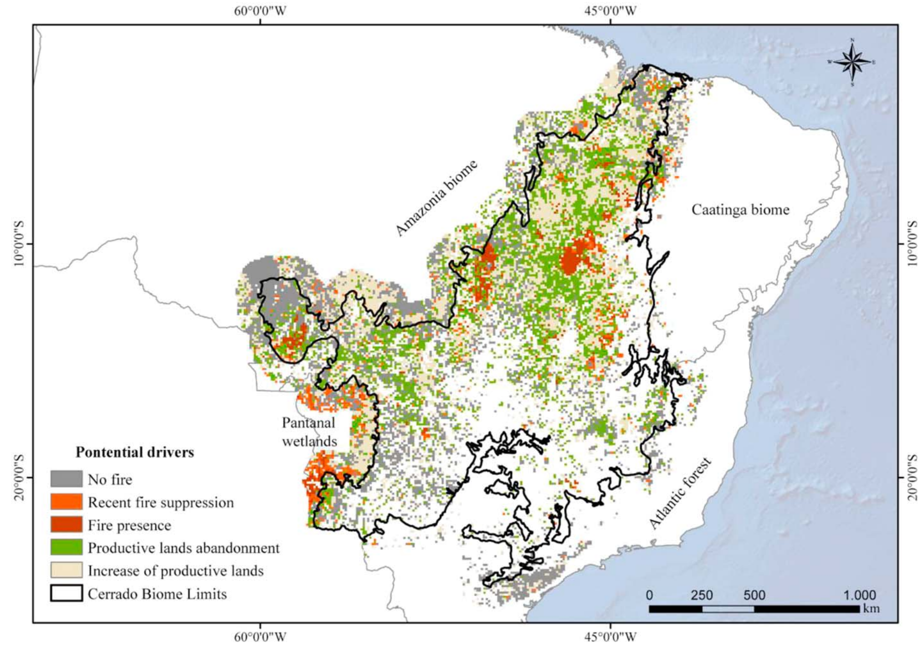

Figure 4. Spatial distribution of the most frequent potential local drivers for the pixels with woody encroachment evidence. To facilitate the representation, the pixels were aggregate in a 10-km grid. For the clarification of the classes see section 2.3.

3.4. Drivers of Woody Encroachment

Regarding the potential drivers of woody encroachment, our results show that 25% (43,499 km^2) of pixels with evidence of woody encroachment showed no fire presence over the studied period and were more concentrated in the southwestern region of the Cerrado biome, within the transitional zones with the Amazônia biome (Figure 4). Small patches without fire occurrence were also found in the southeast, within the Atlantic forest. We found 9% (15,464 km^2) of pixels with recent fire suppression, and they were located mostly within the Pantanal wetlands. Areas with increased fire frequency occurred in small patches in the central region of Cerrado, in about 7% (12,889 km^2) of the pixels. They experienced a mean fire frequency of four events between 2001 and 2015. Abandonment of agriculture lands was concentrated in the central north region totaling 26% (44,776 km^2) of pixels exhibiting woody encroachment. In 32% (55,324 km^2) of pixels with positive EVI_{max} trend, in the western and northern borders of the biome, we found increase in the agriculture lands.

4. Discussion

We report for the first time the extent of woody encroachment and degradation for the Cerrado biome. We show that 19% (171,953 km^2) of Cerrado vegetation is experiencing woody encroachment, mainly in northern part of the Cerrado and within the Amazon and Pantanal wetlands transition. This area is almost three times larger than the area experiencing degradation, as indicated by a decrease in EVI_{max}, and 14 times larger than the total area being deforested across the Cerrado biome in 2015 (INPE, 2018b). The areas with a decreasing trend in EVI_{max} were mostly on the border with the Caatinga biome, characterized by the overexploitation of woody resources and an ongoing severe drought that has affected this region since 2011 (Tomasella et al., 2018). Our findings are in agreement with a recent field study, which reported increases in biomass and changes in the Cerrado vegetation composition in different types of savanna vegetation close to the transition with Amazon (Passos et al., 2018).

The increases in EVI_{max} that indicate positive woody encroachment were associated with changes in the fire regime and agricultural land abandonment. The absence of fire occurrence and a decrease in burned area in the Cerrado is consistent with previous global (Andela et al., 2017) and regional studies (Mataveli et al.,

2018) that have reported a decreasing trend in the burned area for some regions of Cerrado. This decrease of fire occurrence is mostly related to the expansion of intensive and mechanized agriculture in the Cerrado (Andela et al., 2017). Studies have demonstrated that the suppression of fire in protected areas (Durigan & Ratter, 2006; Durigan & Ratter, 2016) was the main cause of the advance of forest-like formations into savannas. Our results support this hypothesis, as about a quarter of the remaining areas with evidence of woody encroachment had not experienced fire events over 15 years and 9% a decrease of fire occurrence. Human intervention is likely the main driver of changing fire regimes and reduction in the contiguity of Cerrado, which has been severe, causing large-scale landscape fragmentation (Durigan & Ratter, 2016; Klink & Machado, 2005). This fragmentation can influence the accuracy of the burned area data from MCD64 product mainly in the southern part of Cerrado where vegetation has been converted into other types of land use (e.g., croplands and pastures), leading to small fire patches that difficult the detection of the burned area at the spatial resolution of MODIS (Rodrigues et al., 2019).

Besides the changes in fire dynamics in most of the areas experiencing woody encroachment, we found a significant percentage of pixels (26%) undergoing land use abandonment, showing that the increase of the EVI_{max} over time could also be associated with vegetation regrowth. Furthermore, we found evidence that forests are also expanding into grasslands and abandoned agriculture lands (Figure 2). Changes in vegetation composition during the process of woody encroachment have been reported in several studies performed at the plot level (Durigan & Ratter, 2006; Geiger et al., 2011; Morandi et al., 2015; Passos et al., 2018). However, the results presented here have some intrinsic uncertainties associated with the nature of land cover maps and relying on a relatively coarse spatial resolution (1-km^2 pixel) and need be interpreted with caution. For example, we found that 32% of the pixels with positive trends in EVI_{max} had an increasing proportion associated to increase in agriculture land, even if that proportion was very small (a mean coverage of 5% [$SD = 4\%$] of the 1-km pixels), they could have had a small effect on EVI_{max} values over those pixels since the overall agriculture proportion decreased (Figure 2d, filled circles). Moreover, we hypothesize that the EVI_{max} increase in the west and south boundaries of the study area can be regrowth of secondary vegetation or regrowth due the recent abandonment of agricultural areas. For instance, comparing our results with the Project for Monitoring Deforestation in the Legal Amazon mask, we found that about 17% (29,864 km^2) of the EVI_{max} increase is occurring in areas of transitional forests within the Amazônia buffer area and only 0.1% (181 km^2) was classified as deforested prior 2015 and can be areas of secondary vegetation. To tackle these issues future studies will be needed at a finer-scale resolution (thus avoiding land cover mixtures per pixel) with better land use and land cover map combined with extensive ground-truth field data.

A trend of increasing woody encroachment in other tropical savannas, such as Australia and Africa, has been observed in several studies (Buitenwerf et al., 2012; Cuni-Sanchez et al., 2016; Janssen et al., 2018; Mitchard & Flintrop, 2013). A recent meta-analysis based on field data suggests that in African savannas, the vegetation encroachment rate was higher than that observed in Australia, and rising atmospheric CO_2, changes in land management, fire occurrence, and rainfall were likely drivers (Stevens et al., 2017). Likewise, the same study suggests that the woody encroachment rate in the remaining savannas of South America is increasing more rapidly than both African and Australian savannas. They hypothesized that the fire suppression and land fragmentation were likely the main causes of this encroachment in South American savannas, which is supported by this study. Nevertheless, we hypothesize that this woody growth also might be synergistic with the increased atmospheric CO_2 concentrations, which stimulates carbon uptake in plants (Buitenwerf et al., 2012; Hoffmann et al., 2000; Leakey et al., 2009). We suggest future research lines combining Earth observation data and ground studies to try to parse out what the impact of increased atmospheric CO_2 in this phenomenon due different land use practices over time.

The rapid and widespread increase in woody encroachment is clearly associated with above-ground carbon accumulation (Pellegrini et al., 2016) and consequently could result in significant afforestation over time, increasing the ecosystem carbon. Therefore, since Cerrado is one of the 25 biodiversity hotspots of the world due to its high number of endemic species (Durigan & Ratter, 2016; Myers et al., 2000), this could lead to a loss of biodiversity, for example, because the outcompeting of light-demanding species (Abreu et al., 2017; Pellegrini et al., 2016). The resulted increase of the ecosystem carbon will be at the expense of reduction in species diversity on the Cerrado (Abreu et al., 2017). The fact that the phenomenon of woody encroachment appears to be affecting almost one fifth of the remaining area of the Cerrado strongly suggests that this is a major threat to the future of the Cerrado biome conservation and its affiliated transitional ecotones. In addition, the woody encroachment also can impact the availability of water resources due the increase of water uptake by plants (Honda & Durigan, 2016). This could impact more than 30 million Cerrado inhabitants (IBGE, 2018), the agriculture production, hydroelectricity generation, and other regions that are dependent on the water resources originating in the Cerrado, such as the Northeast of Brazil.

5. Conclusion

This study reports for the first time a remarkably widespread process of woody encroachment in the Cerrado, which is also occurring in the transitional areas with other biomes (Amazon, Atlantic forest, and Pantanal wetlands). Woody encroachment was primarily driven by the recent fire suppression and land use abandonment. Future research needs to address the role of global drivers (climate change and increasing atmospheric CO_2) as well as other local drivers on woody encroachment (e.g., rainfall). Our results highlight the urgency of adopting management strategies and conservation-oriented policies for the Cerrado, especially if we intend to conserve its unique biodiversity and set of ecosystem functions into the future.

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