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Key Points:

- High-resolution data show fire dominance in land types other than deforested
- Fires escaping from managed pastures highly contribute to forest edge burning
- Fire-deforestation disconnection calls for fire control on managed lands

Supporting Information:

- Supporting Information S1

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Forest edge burning in the Brazilian Amazon promoted by escaping fires from managed pastures

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Abstract Understanding to what extent different land uses influence fire occurrence in the Amazonian forest is particularly relevant for its conservation. We evaluate the relationship between forest fires and different anthropogenic activities linked to a variety of land uses in the Brazilian states of Mato Grosso, Pará, and Rondônia. We combine the new high-resolution (30 m) TerraClass land use database with Moderate Resolution Imaging Spectroradiometer burned area data for 2008 and the extreme dry year of 2010. Excluding the non-forest class, most of the burned area was found in pastures, primary and secondary forests, and agricultural lands across all three states, while only around 1% of the total was located in deforested areas. The trend in burned area did not follow the declining deforestation rates from 2001 to 2010, and the spatial overlap between deforested and burned areas was only 8% on average. This supports the claim of deforestation being disconnected from burning since 2005. Forest degradation showed an even lower correlation with burned area. We found that fires used in managing pastoral and agricultural lands that escape into the neighboring forests largely contribute to forest fires. Such escaping fires are responsible for up to 52% of the burned forest edges adjacent to burned pastures and up to 22% of the burned forest edges adjacent to burned agricultural fields, respectively. Our findings call for the development of control and monitoring plans to prevent fires from escaping from managed lands into forests to support effective land use and ecosystem management.

1. Introduction

Over the past 30 years the Amazon has undergone an intensification of human activities in the forest, such as deforestation and logging [*Laurance et al.*, 2001; *Cochrane*, 2003; *Asner et al.*, 2005], and in particular at the forest edges due to the increasing expansion of agricultural and pasture lands [*Morton et al.*, 2006; *Armenteras and Retana*, 2012; *Davidson et al.*, 2012]. Amazonian fires have become much more frequent and widespread [*Barreto et al.*, 2006] due to the intensive use of fire to convert natural vegetation into agricultural and pasture fields and for the subsequent maintenance of deforested areas [*Cochrane et al.*, 1999; *Barona et al.*, 2010]. During extreme droughts occurring in El Niño–Southern Oscillation years or as a consequence of the warming of the tropical North Atlantic, the frequency of forest fires upsurges [*Aragão et al.*, 2007; *Alencar et al.*, 2011; *Chen et al.*, 2011], sometimes increasing the area burned by an order of magnitude, as in 1998 [*Alencar et al.*, 2006]. Such interactions between climate, land use change, and fire are of high relevance not only for understanding and predicting their environmental impact on the Amazon biome but also for regional and global climate feedbacks [*Cochrane and Laurance*, 2008; *Liu et al.*, 2013].

Advances in governance, through an increase in protected and indigenous areas and establishing the soy and beef moratoria, contributed to the reduction of deforestation since the mid-2000s [*Godar et al.*, 2014; *Nepstad et al.*, 2014], whereas fire activity seems to follow a different trend. Between 2000 and 2006, *Aragão and Shimabukuro* [2010] found increasing fire trends in 59% of the area that experienced reduced deforestation trends in the Brazilian Amazon, which they ascribed to slash-and-burn activities in secondary forests and to an increased fire risk with landscape fragmentation. Although only reported for 31% of the Brazilian Amazon, *Chen et al.* [2013] confirm the positive trend of annual active fires in areas where the deforestation rate concurrently decreased during 2001–2012. Specifically, the contribution of deforestation fires to the total number of detected fires has been declining since 2005 [*Ten Hoeve et al.*, 2012]. At the same time, fires set to maintain agricultural and pastoral lands in previously deforested areas that may escape into the forests have gained importance [*Achard et al.*, 2002; *Nepstad et al.*, 2008; *Bonaudo et al.*, 2013]. With droughts increasing in frequency and areal extent, fire leaking into fire-prone forests may be the main force

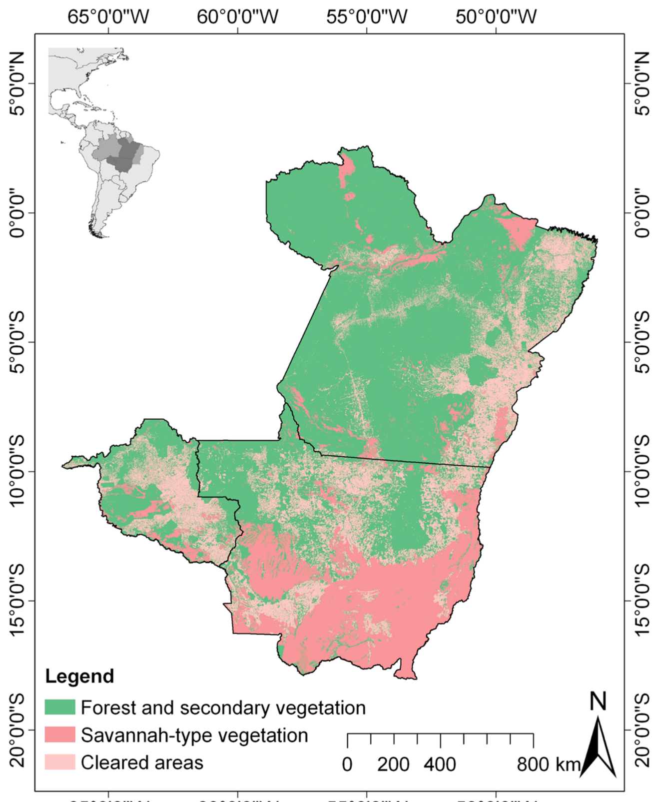

Figure 1. Map showing land cover in the states of Mato Grosso, Pará, and Rondônia (TerraClass 2008). Savannah-type vegetation includes *cerrado*, *campinas*, and *campinaranas*. Cleared areas include agricultural and pasture lands, urban areas, deforested areas, mines, and bare soil. The inserted map shows the location of the states of Mato Grosso, Pará, and Rondônia (in dark grey) within Brazilian Amazonia (in light grey).

of biome conversion [*Alencar et al.*, 2004; *Aragão et al.*, 2007]. The significance of understorey fires which escape from managed land into neighboring forests was noticed already in earlier studies [*Sorrensen*, 2000; *Nepstad et al.*, 2008]. Recent analysis has shown that understorey fires continue to occur unabated despite reduced deforestation calling for a fire-free land use management along the forest edges [*Morton et al.*, 2013].

To understand why occurrence and interannual variability of fires remain high despite decreasing deforestation in the Amazon, potential drivers of land conversion need to be analyzed. This requires high-resolution land cover maps to specify in which land cover type fires occurred and where the new hot spots of fire activity are. Since most of burned forests are located 1 km or less from the forest boundary [*Armenteras et al.*, 2013; *Morton et al.*, 2013], it is important to specify from which land use type these fires originate if we are to improve our understanding of fire causes and to elaborate options for their control. If these fires indeed escape from neighboring managed land, it can only be evaluated by using high-resolution temporal information of fire occurrence to identify which of the neighboring burned areas burnt first. In the absence of on-ground monitoring of fire causes for the entire Amazon, an option for such attribution analysis is by combining fire events information with burned area and land cover data of the region from remote sensing.

In this study, we use high- and moderate-resolution satellite imagery for land cover and burned area, respectively, to evaluate how much area burned occurred in each land cover type in the Brazilian Amazon. We investigate how deforestation and degradation processes are related to fire occurrence and quantify the proportion of forest fires related to fires escaping from managed lands. We provide a comprehensive analysis on the relationship between fire occurrence, deforestation, degradation, and land use with a specific focus on fires occurring along the interface between forest and managed land. These analyses contribute important insights on fire regimes in recent years in the Amazon and support the assumption that most fires in the forest no longer originate from deforestation itself, but from fires that escape from managed lands under agropastoral activities, which have implications for management and monitoring of fires in the region.

2. Methodology

2.1. Area of Interest

We selected the Brazilian states of Mato Grosso (MT), Pará (PA), and Rondônia (RO) in Amazonia for our data analyses (Figure 1), as they share large-scale anthropogenic pressure patterns and characteristics. They concentrated 84% of all deforestation detected in the Brazilian Amazon between 2000 and 2012 [*Instituto Nacional de Pesquisas Espaciais* (*INPE*), 2015a]. Between 1999 and 2002, selective logging was concentrated in the states of MT and PA, where logged areas matched or exceeded deforested areas

[*Asner et al*., 2005]. In MT, tropical forest covers the northern part of the state, while the southern part features predominantly woodland savannah (*cerrado*) (Figure 1). The state has undergone a rapid expansion of mechanized agricultural production [*DeFries et al*., 2008], which has altered the dynamics of deforestation since the early 2000s [*Morton et al*., 2006]. MT is now an important producer of soybean, corn, and cotton [*Brown et al*., 2013]. According to TerraClass [*INPE and Empresa Brasileira de Pesquisa Agropecuária* (*EMBRAPA*), 2015], three quarters of PA were covered by forest and secondary vegetation in 2010. A smaller percentage of land was dedicated to agriculture compared to MT. However, ranching has shifted from northern MT to southern PA leading to greater cleared area [*Barona et al*., 2010], especially in southeastern PA (Figure 1). RO has a smaller proportion of its territory covered by forest and secondary vegetation than PA (60% in 2010 according to TerraClass). This is in part due to the rapid advance of soybean cultivation during the late 1990s in southeastern RO as part of a rapid northward expansion of soybeans in Brazilian Amazonia that started in the 1970s [*Fearnside*, 2001].

2.2. Data

2.2.1. Fire

The Moderate Resolution Imaging Spectroradiometer (MODIS) on board the polar-orbiting Terra and Aqua satellites maps fire-affected areas since 2000 [*NASA*, 2015]. We used the reprojected monthly Geotiff version available from the University of Maryland of MODIS collection 5 burned area product (MCD45A1) [*Roy et al*., 2002] from 2001 to 2010 (500 m resolution), of which Windows 5 and 6 cover the study area. The validation of the product [*Roy and Boschetti*, 2009] revealed some uncertainties associated with the detection, such as burned area underestimation owing to persistent cloud cover and overstorey vegetation, particularly in tropical closed-canopy forests where leaf area index and percent tree cover are high and obscure the surface. Other uncertainties arise from the difficulty in accurate mapping of burned areas that are small or spatially fragmented relative to the satellite's spatial resolution, as well as transient burned areas, for example, agricultural fields that are burned and then plowed [*Roy et al*., 2008; *Tulbure et al*., 2011].

We also employed the MODIS collection 5 global monthly fire location product (MCD14ML) developed by *Giglio et al*. [2003], which has been extensively validated [*Morisette et al*., 2005], for identifying the temporal sequence of burned area along the forest edges in the year 2010. Every 1 km spatial resolution active fire observation holds information about the location and time when it was detected by the sensors. Limitations in the detection are likely to be due to cloud cover, topographic shadows, or highly reflective surfaces. Patchy- and irregular-shaped fires or short-, small-, and low-intensity fires may be underestimated [*Klerk*, 2008; *Hawbaker et al*., 2008].

2.2.2. Land Use

Land cover maps of the Legal Amazon were produced by the TerraClass project showing a very detailed land use classification at 30 m resolution with data generated from the interpretation of Landsat Thematic Mapper 5 images [*Almeida et al*., 2009; *INPE and EMBRAPA*, 2015]. We employed the maps for 2008 and 2010 (see Text S1 in the supporting information for the description of land use classes). The non-forest class was excluded from all the analyses because we are interested in the influence of anthropogenic activities associated to land use changes on fire occurrence and extent within the forest biome, while the non-forest class covers natural vegetation with characteristics of savannah-type ecosystems with a different fire regime. Despite the high resolution of the land cover product, the information provided by TerraClass was reported to have commission errors from 8.3% (for annual agriculture) to 33.8% (for degraded pasture) and omission errors from 2.9% (for annual agriculture) to 57.8% (for areas in regeneration) during the mapping process [*Coutinho et al*., 2013]. This validation of the data set was done using high-resolution (2.5 m) SPOT satellite images and field observations in 535 locations.

2.2.3. Deforestation

Annual deforestation maps for the period 2001–2010 were obtained from the PRODES project, which has been monitoring the deforestation of the Brazilian Amazon since 1988 [*INPE*, 2015a]. PRODES combines data from the Landsat Thematic Mapper, DMC (Disaster Monitoring Constellation Satellite), and CCD (China–Brazil Earth Resources Satellite (CBERS)) sensors (and their successors for recent years) and detects clearings of at least 6.25 ha where deforestation by clear-cutting has occurred. The spatial resolution is high (30 m, although it is aggregated to 60 m in the database), but the temporal frequency is low with one map each year. An important constraint in the selection of imagery for forest change detection when using a bitemporal approach is the lack of data due to the limitations imposed by cloud cover. Many areas of the Amazonia present an extremely persistent cloud cover, which prevents the satellites from obtaining cloud-free observations [*Giglio et al*., 2006, 2010]. When cloud-free images are not available for the desirable dates, methods exist to fill the gaps with data derived from other scenes or even other sensors, but this can introduce errors into the processing chain. The dynamic behavior of vegetation over time may introduce additional errors in the detection of forest changes. Besides, extensive deforestation monitoring in tropical forests by the PRODES project does not incorporate all the possible deforestation pathways because it is limited to deforestation associated to the original forest area, without taking into account degradation and deforestation of secondary forest. Once an area has been labeled as deforested by PRODES, it is not further revisited in subsequent years, which implies that forest regeneration is not assessed by the current method. In spite of all that, PRODES is the most advanced remote sensing-based forest monitoring system in tropical countries [*DeVries et al*., 2015].

2.2.4. Degradation

Areas in a deforestation process where the forest has not been totally removed (areas that are neither detected as forest nor as deforested) are classified as degraded by the DEGRAD project, which monitors the degradation of the Brazilian Amazon forest caused by wood extraction or by recurrent fires [*INPE*, 2015b]. DEGRAD employs data from the Landsat Thematic Mapper and CCD (CBERS) sensors to detect clearings of at least 6.25 ha. Annual maps for the period 2007–2011 at the same spatial resolution as PRODES (60 m) were employed for the analysis. Limitations of the degradation assessment in satellite imagery exist related to the interpretation of natural phenological change as actual land cover change and to the quick regeneration of the forest canopy that obscures changes in vegetation [*Barlow and Peres*, 2008; *Matricardi et al*., 2010]. Thus, significant forest degradation may remain undetected by satellite images and large-scale monitoring of forest cover. Additional limitations come from the fact that it neither makes a distinction between degradation by fire and by logging nor quantifies degradation in secondary forest. Nevertheless, it is the only data set that covers the entire study region at a relatively high spatial resolution.

2.3. Data Analysis

We worked with the geospatial processing program ArcMap 10.1 (Environmental Systems Research Institute) to conduct all spatial and temporal digital analyses. After preprocessing the data, the amount of burned area in the different land use types in 2008 and 2010 was quantified by intersecting burned area and land use maps. The same method was applied to the maps of deforested and burned areas detected in the same year to quantify the amount of deforested area that burned. To determine the amount of forest degradation following upon burnings, degradation maps were superimposed with burned area maps of the previous year (see Text S2 in the supporting information for additional details on data processing). Linear regression analysis was used to correlate the burned and deforested areas at monthly and annual time scale.

To estimate the proportion of burned forests adjacent to burned managed lands, we selected burned area polygons in forests which share boundaries with burned area polygons in agricultural fields and pastures, respectively. Adjacency in this context quantifies the amount of burned forests that may have been driven by escaping fires from managed lands, but only those adjacent fires that burned on managed land first can be included. We developed an algorithm that combines the information held in the burned area, active fires, and land use data sets. We selected burned areas larger than 2 km^2 which matched at least two active fire pixels to improve certainty in the active fires location in relation to burned areas at the forest edge [*Hawbaker et al*., 2008]. To identify if a forest burned area was driven by an escaping fire from neighboring managed lands, three requirements had to be fulfilled. First, burned areas in the forest had to be adjacent to burned areas in managed lands (fire perimeters must be spatially connected). Second, potential escaping fire events from managed lands must occur within a 1 km buffer zone created around fire events in the forest as the majority of forest burnings occurs within the first kilometer of the forest edge [*Armenteras et al*., 2013; *Morton et al*., 2013]. Third, the forest fire under study had to happen on the same day or up to 2 days later than the potential escaping fire in the managed lands (Figure 2). After examining if the first two conditions were met, forest fires with their corresponding burned area that also met the third requirement were selected and considered as forest fires driven by managed lands' fires. We tested the sensitivity of the temporal threshold being longer than 2 days and found that it did not change the proportion of burned forest caused by escaping fires from managed lands, indicating that most of the fires do not last more than 2 days.

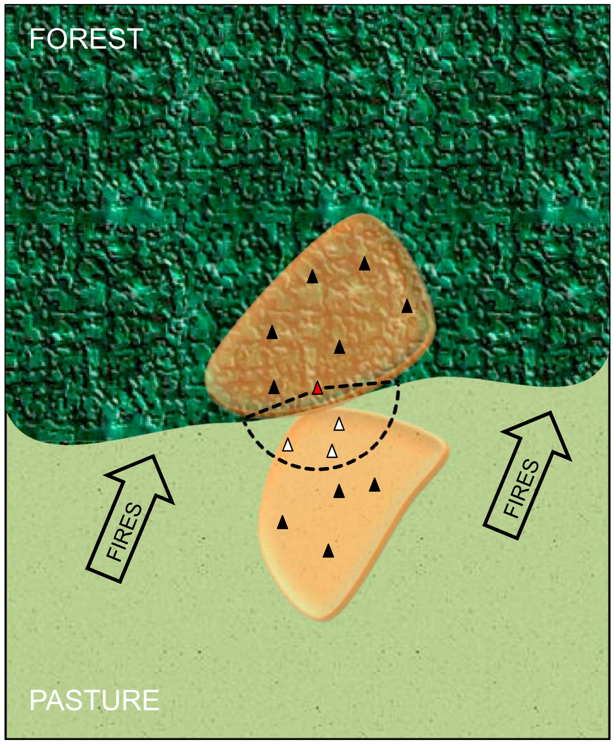

Figure 2. Schematic illustration of a burned area in the forest adjacent to a burned area in a managed land (in orange), which is a pasture in this case. Black triangles indicate active fires within the burned areas. The red triangle denotes the active fire in the forest currently under study. A 1 km buffer zone is created around it, and active fires in the pasture within the buffer are selected (white triangles). If the forest fire under study (red triangle) occurred up to 2 days later than any of the active fires in the pasture within the buffer (white triangles), the burned area in the forest can be attributed to escaping fires from the pasture.

3. Results

3.1. Fire Distribution by Land Use

The proportion of the different land cover types showed large variation between the states (Figure 3a). Forty-two percent of the territory of MT was covered by savannah-type vegetation, which is classified as non-forest in TerraClass, followed by forests (35%) and pastures (12%). Annual agriculture and secondary vegetation extended over 3% of the state each (Figure 3a). PA was mostly covered by forests (71% of the area) followed by pastures (9%). The large forested area in PA leads to a high cloud cover [*Asner*, 2001], preventing the satellite from observing the ground in some areas (1% was unclassified land). Unclassified land in combination with water bodies (5% of PA's territory) contributed to the others class being the third largest land use class in the state (see Text S1 in the supporting information for land use classes description). PA showed fewer non-forest (6%) and annual agriculture (0.2%) than MT. Around half of RO was covered by forests (54%) with pastures accounting for 22%. RO had 10% of its area occupied by non-forests, with smaller proportions of secondary and regenerating vegetation. Deforested areas made up 0.4% of the territory in each of the three states (Figure 3a).

Most of the burned area in all three states was found in pastures in 2008, when non-forest class was excluded (Table 1 and Figure 3b). According to MODIS, the annual burned area accounted for 5269 km^2, 2245 km^2, and 463 km^2 in MT, PA, and RO, respectively, for the year 2008 with burned area located in the non-forest class excluded. While the burned area in PA was concentrated in the southern half of the state, it did not show any distinctive spatial pattern in RO (Figure 4a). In MT, several clusters of burned areas were distributed in the central and eastern parts of the state in 2008. Fires occurred mostly in pastures (RO: 30%, MT: 31%, and PA: 34%) in the three states (Figure 3b). In MT, a major center of agricultural production, 28% of the burned area occurred in annual agriculture, compared to only 3% in RO and 0.1% in PA. A large proportion of PA could not be assigned to a specific land use due to cloud cover; thus, a considerable amount of burned area was connected to the others class, in which unclassified areas are included. A substantial amount of burned area was found in forests (RO: 25%, MT: 16%, and PA: 15%), while a smaller amount was located in secondary vegetation, degraded pastures, and regenerating areas. It is important to note that fire in deforestation made up only 7% (PA), 2% (RO), and 1% (MT) of the total burned area (Figure 3b). Our results show that the land use classes that contain the highest frequency of fires are pasture, forest, and agriculture, when the non-forest class is excluded (Figure 3b).

In all three states, land cover distribution remained widely unchanged in 2010 compared to 2008, indicating that differences in burned area distribution in 2010 were not a consequence of significant changes in land cover class proportions but likely of climate variations and/or changes in fire use as a management technique in specific land uses. In MT, secondary vegetation (+14%), pastures (+11%), and annual agriculture (+10%) increased at the expense of degraded pastures (−56%) and areas in regeneration (−29%) (Figure 5a). In PA we observed a different situation, where pastures (−6%) and forests (−1%) decreased, while areas in regeneration (+78%) and secondary vegetation (+14%) increased. RO experienced the smallest change

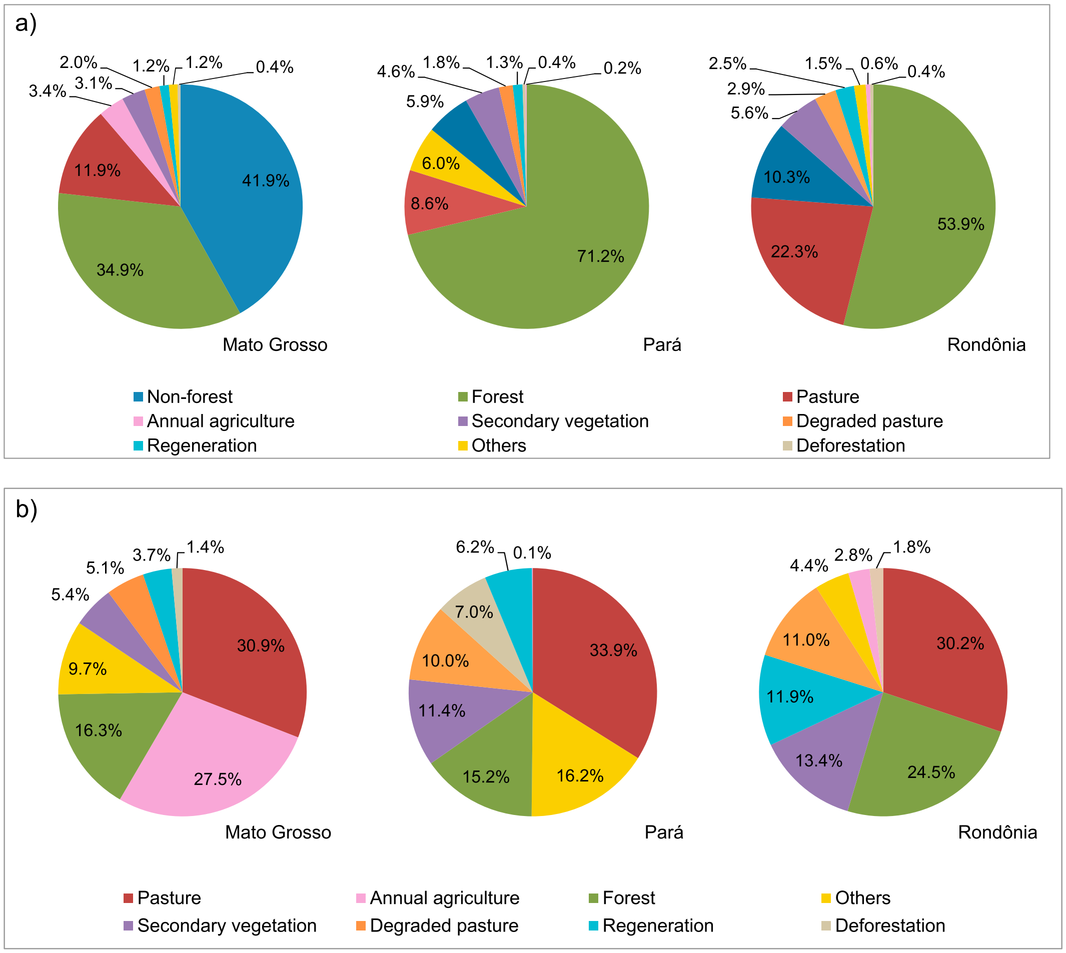

Figure 3. (a) Land use distribution and (b) burned area distribution in Mato Grosso, Pará, and Rondônia in 2008. The non-forest class has been excluded in Figure 3b.

compared to 2008, where areas in regeneration (−23%), pastures (−2%), and forests (−1%) decreased while annual agriculture (+38%) and secondary vegetation (+11%) increased. Deforestation decreased despite the relatively drier year of 2010 in all three states (between −74% and −28%) (Figure 5a).

In 2010, the burned area increased significantly to 13177 km^2, 16571 km^2, and 1636 km^2 in MT, PA, and RO, respectively, accounting for an increase of 638% in PA, 253% in RO, and 150% in MT in comparison to 2008. Burned area was concentrated in southeast PA, while no characteristic pattern was observed in RO. The northeast of MT showed a large concentration of burned area, although several clusters were also observed unevenly distributed across the state (Figure 4b). The amount of burned area increased in all land

Table 1. Burned Area Distribution in the Different Land Uses Excluding Non-forest (in Percentage)

	Mato Grosso		Pará		Rondônia	
	2008	2010	2008	2010	2008	2010
Annual agriculture	27.5	3.0	0.1	0.0	2.8	2.3
Deforestation	1.4	0.8	7.0	1.3	1.8	1.7
Degraded pasture	5.1	5.6	10.0	8.9	11.0	8.7
Forest	16.3	34.2	15.2	18.9	24.5	23.5
Others	9.7	10.4	16.2	12.6	4.4	23.6
Pasture	30.9	31.6	33.9	37.8	30.2	25.2
Regeneration	3.7	5.0	6.2	10.9	11.9	6.1
Secondary vegetation	5.4	9.4	11.4	9.6	13.4	8.9

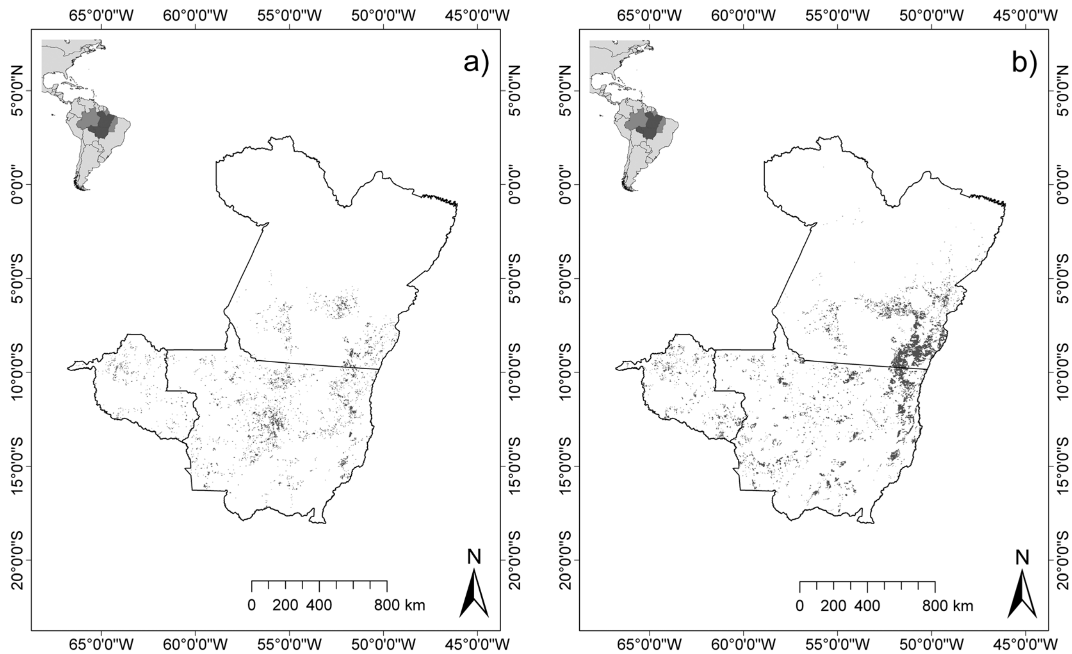

Figure 4. Spatial burned area distribution in (a) 2008 and (b) 2010 in Mato Grosso, Pará, and Rondônia (burned areas in the non-forest class have been excluded). The inserted map shows the location of the states of Mato Grosso, Pará, and Rondônia (in dark grey) within Brazilian Amazonia (in light grey).

use classes in 2010, except in annual agriculture in MT (−1051 km^2, which translates to −73% of decrease compared to 2008 values) (Figure 5b). The largest increase in burned area was found in forests in MT (+3645 km^2 or +424%) and in pastures in PA (+5478 km^2 or +719%) and RO (+272 km^2 or +195%) (Figure 5b). Burned area detected in deforested areas also increased in 2010 (PA: +63 km^2 or +40%, MT: +32 km^2 or +42%, and RO: +19 km^2 or +235%), but the increase was small in comparison to the changes in the rest of the land cover classes. These results provide important insights into the association between fires and anthropogenic activities, showing that most of the burned area is not associated with deforestation but rather with the use of fire for land management, especially in pastures.

3.2. Fire in the Forest

3.2.1. Dissociation Between Deforestation and Fire

Burned and deforested area showed a remarkable variability between 2001 and 2010 (Figure 6). On the annual time scale, no significant relationship was found between the annual amount of burned area (excluding burned area located in the non-forest class) and deforested area (mapped by PRODES) over the 2001–2010 period in MT ($r^2 = 0.01$, $p > 0.05$), PA ($r^2 = 0.03$, $p > 0.05$), and RO ($r^2 = 0.06$, $p < 0.05$). Notably, deforestation fires were higher in the first half of the decade, when 73% of the total deforestation took place. Similar levels were only reached in the dry years of 2007 and 2010. The annual percentage of deforested area that burned across the three states remained below 13% (2776 km^2) in the period 2001–2010 (8% on average) (Figure 7). The disconnection found between burned area and deforestation would still be valid taking potentially burned areas within small deforested areas that may go unnoticed into account (see Text S3 in the supporting information).

Fires did not show a lagged effect after deforestation took place. One year after deforestation, fires occurred on average in only 4% of the deforested area across the three states between 2001 and 2010 (Figure S1 in the supporting information), which means that forests which were not burned in the dry season following deforestation were also not burned in the following year. After 10 years, 31% (PA), 27% (MT), and 13% (RO) of the deforested area accounted for in 2001 had burned. Most recurrent burns, linked to managed lands, are known to occur 3 to 4 years after the initial deforestation activity [*Lima et al.*, 2012]. We divided deforested area into two categories: old deforestation (deforested area detected between 2001 and 2006) and recent deforestation (deforested area detected between 2007 and 2010), in order to recognize fires connected to

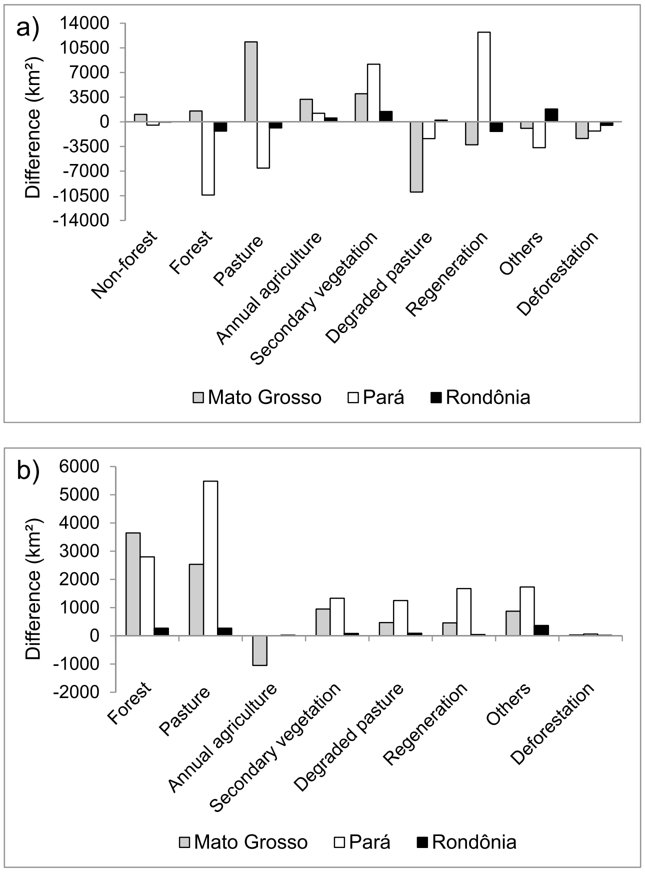

Figure 5. Differences in the areal extent distribution of the (a) land cover classes and (b) burned area between 2010 and 2008 (in km^2, based on 2008 values) in Mato Grosso (grey bars), Pará (white bars), and Rondônia (black bars). The non-forest class has been excluded in Figure 6b. Note the different scales on the vertical axis.

management of cropland and pastures (old deforestation) or the conversion processes of deforestation (new deforestation). Of the burned area mapped in 2010, 7684 km^2 (74% on average of the total) occurred in areas that were deforested between 2001 and 2006 (old deforestation) (Figure S2 in the supporting information). The evidence shows that the processes of deforesting per se lead to only a slight increase in burned forest area, whereas fires used for land management in previously deforested areas have the largest effect on forest burning.

Considering the low correlation found between deforestation and fire, we also explored the relationship between forest degradation and fire in order to explain the high proportion of burning occurring in the forests. However, we found low values of degraded area in areas mapped as burned during the previous year, making up 3186 km^2 across the three states between 2007 and 2011 (4% on average of the total degraded area in the period) (Figure 7). The highest percentages of burned degraded area were found in 2008 and 2011, following dry years, respectively. The results suggest a small influence of forest degradation in forest fires, but given the limitations of the MODIS sensor in mapping small burnings or detecting burned areas below the canopy, the amount of forest degradation driven by fire may be larger. Therefore, these results present a lower bound estimation of burned degraded area.

3.2.2. Strong Influence of Fires Escaping From Managed Pastures

Considering the low temporal and spatial correlation between deforestation and fire in the forest (Figures 6 and 7, respectively), other processes must strongly influence forest fire occurrence. The large amount of burned area found not only in pastures and agricultural lands but also in forests (Figure 3b) suggests that

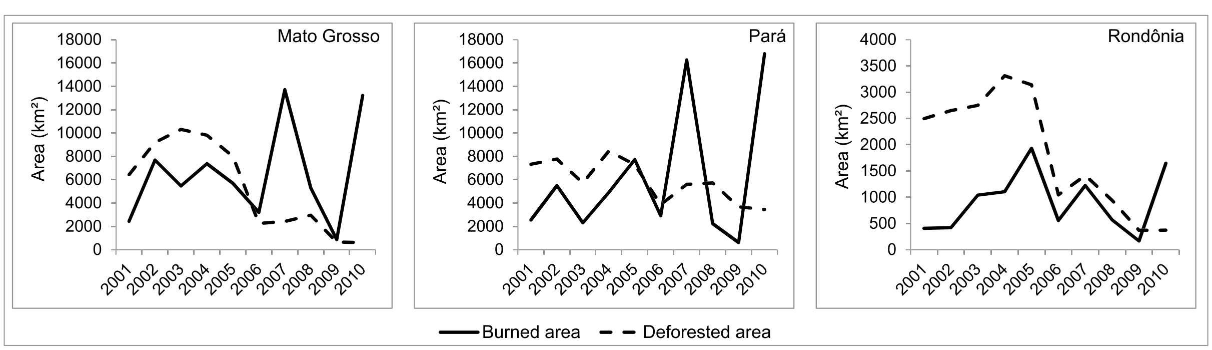

Figure 6. Annual area burned (solid line, with burned areas in the non-forest class excluded) and deforested area (dashed line) in km^2 over the period 2001–2010 in Mato Grosso, Pará, and Rondônia. Note the different scales on the vertical axis for Rondônia.

forest fire occurrence is linked to fires set on pastoral or agricultural lands in the vicinity of the forests as a cheap, labor-saving way of clearing and managing land. Fires used for nutrient mobilization, pest control, and removal of brush and litter accumulation may go out of control and escape from managed lands into forests; therefore, the majority of burned forests are located along the forest boundaries.

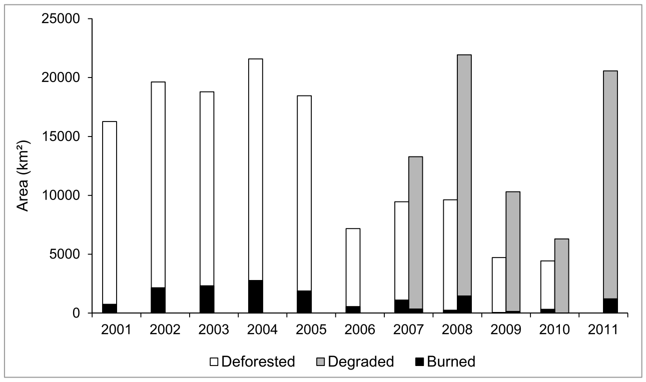

Figure 7. Annual deforested area (in white), degraded area (in grey), and the proportion burned each year (in black) in km^2 over the period 2001–2010 for deforestation data and 2007–2011 for degradation data. Annual values are summed over Mato Grosso, Pará, and Rondônia. Deforestation was superimposed with burned area detected in the same year, while forest degradation was superimposed with burned area detected in the previous year.

We found that in 2010, the year with the highest amount of burned area in the study period, 1571 km^2 (MT), 1289 km^2 (PA), and 212 km^2 (RO) of the burned area in the forests, was touching the boundaries of burned areas in pastures (Figure 8a), making up 69%, 87%, and 68% of all the burned forests, respectively. Smaller amounts of burned forests were located adjacent to burned agricultural fields: 168 km^2 (MT), 39 km^2 (RO), and 21 km^2 (PA), making up 7%, 12%, and 1% of all the burned forests, respectively (Figure 8b). These values indicate not only that most of the forest fires concentrate along the forest edges but also that their majority is found in close vicinity to pastoral lands. RO showed the largest proportion of the total burned forests spatially connected to burned agricultural lands, whereas PA showed the greater amount of burned forests spatially connected to burned pastures.

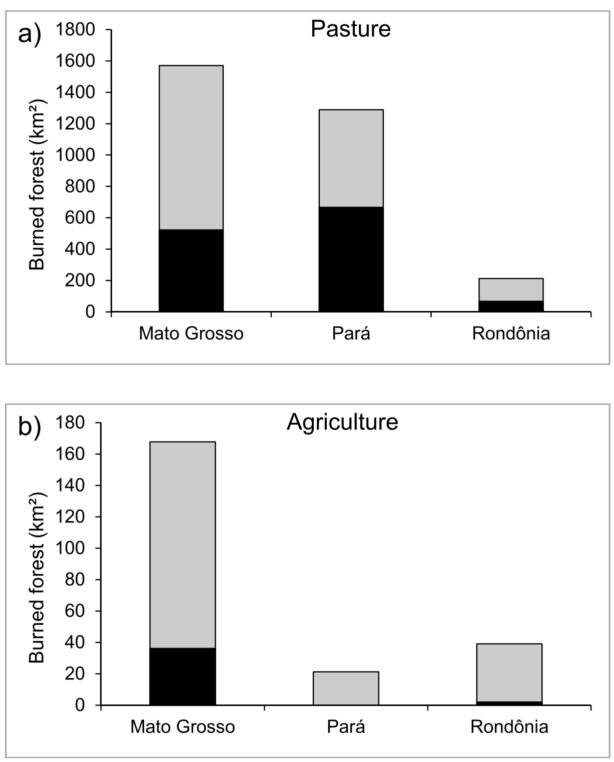

Figure 8. Annual burned forest which is located along the forest edge adjacent to burned (a) pastoral and (b) agricultural fields (grey bars, in km^2) in Mato Grosso, Pará, and Rondônia in 2010. The amount of burned forest edges attributed to escaping fires from these managed lands is shown in black.

To prove that burned areas in forests are the continuation of burned areas in managed lands, it is required to check the dates of the fire events that originated the burned areas. Investigating the temporal sequence of the fire events along the forest-managed land interface (see section 2.3 and Figure 2), we found that 666 km^2 (PA), 523 km^2 (MT), and 68 km^2 (RO) of the burned forest edge adjacent to burned pastures (shown in grey in Figure 8a) originated from fires that escape from those adjacent pastures (shown in black in Figure 8a). That translates to 52% (PA), 33% (MT), and 32% (RO) of the burned forest edge adjacent to burned pastures. The proportion of burned forest driven by fires which escaped from agricultural lands was smaller with 36 km^2 for MT and 2 km^2 for RO, which translates to 22% and 5% of the burned forest edge adjacent to burned agricultural fields, respectively (Figure 8b). The amount of burned forest connected to escaping fires from agricultural lands is negligible in PA because only 0.1% of the territory is covered by that land use (Figure 3a). These results provide the first estimate of the contribution of managed lands to forest edge burning showing the substantial amount of burned forests driven by fires that escape from pastures. This demands escaping fires to be included in the plans and policies aiming forest fires reduction in the region.

4. Discussion

Our study supports the assumption that fire incidence responds strongly to anthropogenic land use changes and introduces new information about the contribution of specific land use types to forest edge burning. We can now specify the land use type from where the fires originated and escaped into the forests filling the data gap by combining diverse remote sensing data sets in the absence of extensive on-ground data. A large proportion of burned forests was adjacent to burned pastures (76% on average across the three states). Of this amount, 41% (1257 km^2) on average of the burned forests can be attributed to escaping fires from pasture fields (Figure 8a). This highlights the high risk of fires escaping from these sites into contiguous forests. Since most of forest conversion is destined for cattle pasture [*Morton et al*., 2006] and the conversion process has accelerated over the last four decades [*Nepstad et al*., 2006], management plans to reduce the accidental spread of fires into neighboring forests should come into focus. In Amazonia, the use of fire for land management is one of the major sources of carbon emissions, being involved in the vegetation-atmosphere interactions [*Morton et al*., 2008]. For this reason, we need to have a good understanding of the dynamics of fires occurring in pastures to develop initiatives to minimize edge-driven fire processes and for policy development targeting reduced carbon emissions. Additional studies are required to quantify the effect of changes in burned area in the respective land uses on total fire-related emissions, as small fires burning in high-biomass forests can release as much carbon as large-scale fires burning in low-biomass land cover types.

The largest proportion of burned area was found in pastures (30%–34%, depending on the state), while only a small amount was found in deforested areas in 2008 (Figure 3b). The situation changed in 2010 when the amount of burned area located in most of the land uses strongly increased, especially in forests and pastures (Figure 5b), while the proportion of the different land use types in the states showed only small variations in 2010 compared to 2008 (Figure 5a). This indicates that differences in the amount of burned area between the two years can be a consequence of the widely reported severe drought of 2010 which increased fire risk [*Lewis et al*., 2011; *Marengo et al*., 2011]. In particular, the large increment in burned area in pastures in 2010 may be due to a more extensive use of fire for clearing and managing pastoral lands taking advantage of the drier conditions. As a result, fires escaping from pastures into the forests may have increased in that year inducing a larger amount of burned forests.

The small amount of burned area encountered in deforested areas (Figure 3b) supports the claim that from 2005 onward, most of the burned area is not associated with new deforestation [*Aragão and Shimabukuro*, 2010; *Chen et al*., 2013] but instead with the use of fire to clean and renew pastures, to convert secondary forests, and to burn crop residues. It explains why annual burned area did not follow the same trend as deforestation (Figure 6), which declined from 2005 onward, possibly as a consequence of policy changes such as the implementation of the action plan to prevent and control deforestation in 2004 [*Ministério do Meio Ambiente*, 2013]. Even though *Lima et al*. [2012] reported values of 32% on average for annual deforested area burned between 2001 and 2005 at local scale in a deforestation hot spot, we found lower values at the state scale (10% on average for the same period). These results provide evidence that anthropogenic pressure is very heterogeneous in the region due to the large ecological, socioeconomic, political, and institutional differences.

Burned areas in deforestation spots are not obscured by the canopy; thus, in the absence of clouds the potential underestimation of burned areas in deforested areas lies in the spatial resolution of the MODIS sensor (see section 2.2.1 and Text S3 in the supporting information). Including potentially undetected burned areas from small-scale fires incorporated in the Global Fire Emissions Database (GFED4) [*Randerson et al*., 2012] would increase the total annual amount of burned area. However, there is no information about the location of the burned polygons within each grid cell, which prevented us from directly comparing between the amount of annual deforested area that burned using the MCD45A1 and GFED4 burned area products (see Text S3 in the supporting information). High spatial resolution burned area products with spatially explicit information at global scale would allow to perform finer analyses on forest edge processes as well as on the environmental impact of fires.

The low proportion of annual degraded area that was detected as burned area in the previous year suggests that fire would play a minor role in forest degradation (Figure 7). As the only drivers contemplated by the DEGRAD product are fires and logging, forest degradation would be mainly controlled by logging. However, more effective remote sensing techniques to improve the detection of burned areas inside the forests would be desirable in order to account for all the burnings occurring below the canopy (see Text S3 in the supporting information). Despite the difficulties in mapping forest degradation due to the quick regeneration of the forest canopy [*Barlow and Peres*, 2008; *Matricardi et al.*, 2010], targeting forest degradation in addition to deforestation is crucial because degraded area often exceeds deforested area in the Brazilian Amazon [*Peres et al.*, 2006; *Souza et al.*, 2013]. Finer temporal resolution of the large-scale degradation products would advance the degradation assessment through satellite imagery.

5. Conclusions

The high-resolution land cover data allowed us to ascribe detected burned area to specific land use classes (excluding wildfires in savannah-type areas). We found that most of the burned area occurred in pastures in the three states, followed by forests, secondary vegetation, and annual agriculture. In addition, only a small amount of the burned area occurred in deforestation, which supports the claim that fires are used predominantly as a land management tool and less in deforestation processes nowadays. This is supported by the high interannual variability in burned area despite the declining deforestation trend during the study period and the low spatial overlap between burned and deforested areas. Spatial correlation between burned and degraded areas was even lower. On the contrary, our study confirms that fires that escape from managed lands largely contribute to forest fires, especially those originating in pastures. Considering the large amount of burned area found in those managed lands and the notable number of fires escaping from there into the forest, more research is required on the role of policy, management practices, and human behavior. To prevent fires from escaping into neighboring forests, an effective fire management and monitoring system becomes crucial. Better training in management techniques should also be promoted. Also, this poses a new challenge for fire models, sometimes embedded in dynamic vegetation models, to consider the human factor in fire ignition and spread in order to reduce uncertainty in fire regime projections and their interaction with socioeconomic drivers.

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