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Research article

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ABSTRACT

Fire is one of the most powerful modifiers of the Amazonian landscape and knowledge about its drivers is needed for planning control and suppression. A plethora of factors may play a role in the annual dynamics of fire frequency, spanning the biophysical, climatic, socioeconomic and institutional dimensions. To uncover the main forces currently at play, we investigated the area burned in both forested and deforested areas in the outstanding case of Brazil's state of Acre, in southwestern Amazonia. We mapped burn scars in already-deforested areas and intact forest based on satellite images from the Landsat series analyzed between 2016 and 2019. The mapped burnings in already-deforested areas totalled 550,251 ha. In addition, we mapped three forest fires totaling 34,084 ha. Fire and deforestation were highly correlated, and the latter occurred mainly in federal government lands, with protected areas showing unprecedented forest fire levels in 2019. These results indicate that Acre state is under increased fire risk even during average rainfall years. The record fires of 2019 may continue if Brazil's ongoing softening of environmental regulations and enforcement is maintained. Acre and other Amazonian states must act quickly to avoid an upsurge of social and economic losses in the coming years.

1. Introduction

Amazon fires are associated almost exclusively with human activities (Barlow et al., 2019). These fires vary across space and time with changes in land use and cover. These changes are driven by complex interactions among factors such as governance (or lack thereof), international trade, the domestic land market and local climate (Barlow et al., 2019; Tasker and Arima, 2016). During unusually dry and hot years, accidental and illegal fires tend to escape from agricultural fields into standing old-growth, secondary and degraded forests. Although

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fires affect large areas of the Amazon, there is high variability in fire activity across the Basin (Aragão et al., 2007). This is partially explained by regional heterogeneity in the economic and biophysical factors that drive fires and in the regulatory measures that constrain fires. Understanding how fire activity has changed spatially and temporally across the Amazon is useful for improving fire policy effectiveness, including both prevention and suppression of forest fires.

Although periods of high precipitation seasonally dampen fire activity, droughts are becoming common in the region (Jiménez-Muñoz et al., 2016). Forest fires burn larger areas during droughts, especially when deforestation rates are high (Aragão et al., 2008). One study estimated that if deforestation continues to claim Amazon forests, up to 16% of southern Amazonian forests may burn in the near future (Brando et al., 2020). Projections for the end of the century in a land-use scenario with high forest fragmentation indicate that increase by up to 73.2%, mainly in the southern portion of the Amazon (Fonseca et al., 2019).

Fires are used as a tool for eliminating the felled trees in recently deforested areas, in clearing secondary forest or in renewing pasture (Barlow et al., 2019; Dias Filho, 2011). When these fires escape from control in years of extreme drought, such as 2005, 2007, 2010 and 2015/2016, they can cause large-scale forest fires (Alencar et al., 2015; Anderson et al., 2015; Morton et al., 2013; Silva et al., 2018). Even when there were reductions in deforestation fires, there was still enough burning activity to generate large-scale forest fires during drought years (Aragão et al., 2018). Recent informal statements by politicians at the federal and state levels attest to the reduction of enforcement investment, which appears to have led to a significant increase in deforestation and fires in the Amazon (Thomaz et al., 2020). This process culminated with the 2019 Amazon fire crisis (Barlow et al., 2019), leading to a presidential decree prohibiting fires and allowing the use of the army for law enforcement (Brazil, 2019). However, this did not reduce burning and contributed to further weakening of IBAMA, the federal environmental agency (Ferrante and Fearnside, 2020; OC, 2020). Weakening environmental regulations and agencies leads to an increase in the area burned in association with the return of high rates of deforestation in the Amazon, as was observed during the first 6-months of 2020 (INPE, 2020a).

Acre, which is in the 5th position in the deforestation ranking of Brazil's nine Amazonian states, has a solid history of forest conservation, for which it was granted the first jurisdictional REDD + program in the world (Acre, 2013). This important leadership is being threatened by a substantial increase in deforestation and fires since 2007 (INPE, 2020b), where the Action Plan for Prevention and Control of Deforestation in Amazonia has not prevented the resumption of deforestation in Acre in recent years (Fig. 1). The state is located in the southwestern Brazilian Amazon, and more than 84% of its ~164,000-km^2 area is under old-growth forests (INPE, 2020c), with 46% of the forest area protected by conservation units (Acre, 2010). In recent years, the advance of the agricultural frontier in the "arc of deforestation" (Fearnside, 2005), makes Acre a focus for land speculation, contributing to a significant increase in deforestation. Acre was the epicenter of two recent mega-droughts, in 2005 and 2010 (Lewis et al., 2011). The state is among the ten poorest of Brazil, with approximately 40% of its citizens below the poverty threshold (IBGE, 2019), but much of the deforestation is done by wealthy ranchers. This scenario of deforestation, droughts and the weakening of public policies, contributes to inefficient environmental management that leads to socio-economic and environmental conflicts with exacerbation of inequality and increases burning by rural actors.

To understand the dynamics of fire, it is essential to analyze its spatial and temporal distributions and also to disentangle forest fires from burning in already-deforested areas. The main type of near real-time satellite data available for this purpose is the so called "hot pixels," which indicate the location at which fires occur but do not allow estimation of the areal extent of the burns. Global remote-sensing products for burned areas are also available, but these underestimate fire-affected areas in dense tropical forests (Anderson et al., 2017; Pessôa et al., 2020), and detailed maps have only been produced for restricted spatial domains and/or time periods (Alencar et al., 2015; Anderson et al., 2015). Other estimates have spatial resolution that does not allow detecting the dynamics of small fires (INPE, 2020d; Morton et al., 2013).

In order to provide novel information on fire dynamics in the southwestern Amazon, which is a region that has recently been impacted by severe droughts and where there is a paucity of information on fire use, we investigated the interconnection between deforestation, agricultural burning and forest fires. We also explored the relationships of these phenomena with climate.

2. Methods

2.1. Study area

Acre State has an area of 16,423,979 ha and is located in the southwestern part of the Brazilian Legal Amazon (Fig. 2a). According to the Köppen classification system, local climate is Af (without dry season) and Am (monsoon), with average annual temperatures between 22 °C and 26 °C and annual precipitation between 2200 mm and 2500 mm. By 2019, the state had 2,259,990 ha (14%) of its territory deforested (INPE, 2020c). Data from the TerraClass project show that deforested areas in Acre are normally occupied by cattle pasture (67%) and secondary forests (areas abandoned after use for agriculture or pasture) (EMBRAPA, 2017). Acre experienced extreme-drought events in 1998, 2005, 2010 and 2016, with maximum cumulative water deficits of up to 300 mm (Aragão et al., 2007; Silva et al., 2018).

2.2. Mapping of burning in already-deforested areas

In this study, burning in already-deforested areas was defined as fire scars in areas without native forest that are covered by pasture,

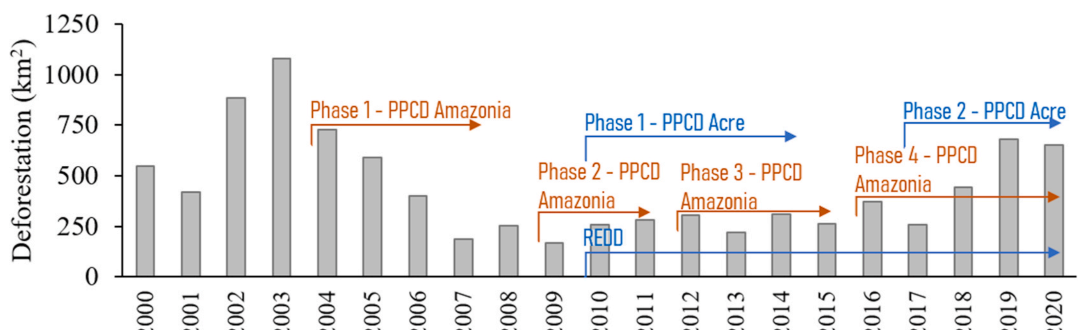

Fig. 1. Annual deforestation rates PRODES/INPE in the State of Acre, indicating years of the Action Plan for Prevention and Control of Deforestation in Amazonia (MMA, 2016) and in the State of Acre and jurisdictional REDD+ program (Acre, 2018).

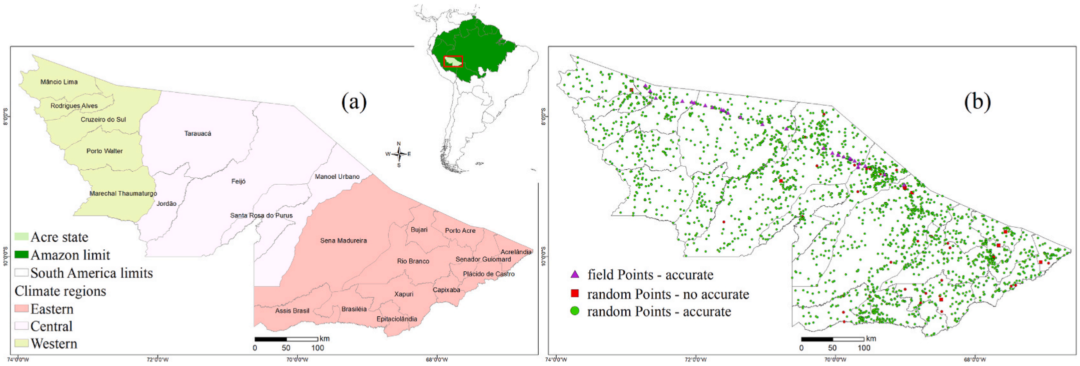

Fig. 2. Location of the study area showing the three climatic regions in Acre (a) and the distribution of burned mapping validation points (b).

agriculture or bare ground in areas of recently deforested native or secondary vegetation. The mapping of burned areas was based on supervised classification of Landsat 8 Operational Land Imager (OLI) satellite images from 2016 to 2019. Three images per year were used for the 14 scenes covering the state of Acre to encompass the entire burning season, from July to September (Supplementary Material, Table S1). The choice of several images to represent the year is due to the rapid disappearance of the scars from the fires, which occurs three to four weeks after the fire event.

We used the supervised minimum-distance classification method with cloud processing on the Google Earth Engine based on reflectance information from the Landsat 2, 3, 4, 5 and 6 spectral bands. This classifier calculates the spectral distance between the measurement vector for the candidate pixel and the average for each class signature. The classifier compares the Euclidean distance between the value for each pixel and the average for each cluster. Four classes were used: intact forest, water, deforestation and burn scar, with at least 20 samples per class.

After the supervised classification, the minimum mapped area was defined as 0.5 ha, representing five contiguous pixels. Areas smaller than this size were excluded from the analysis because they have less reliability due to the spatial resolution of the sensor. The burn-scar mapping was audited by manual adjustment or elimination of area that presented confusion with other targets, such as water bodies or deforestation. The audit was carried out by a team of four people, with the last stage being carried out by a specialist in the fire dynamics of Amazonian landscapes and in remote sensing.

The validation of the mapping of burn scars was based on field points and random points. Twenty nine field points were collected between August 2nd and 28th 2019 along federal highway BR 364. The random points were distributed between unburned and burned areas, totaling 1000 and 1500 points, respectively. These points were verified by experienced interpreters (Fig. 2b). Assessment of the overall accuracy of the classification and estimation of errors of omission and commission were performed using an error matrix as proposed by Anderson et al. (2017).

2.3. Mapping of forest fires

Forest fires were defined in this study as those in which the crowns of the trees were directly or indirectly affected by fire to the point that they cause a detectable impact on the optical satellite images, representing the scar left by the fire (Silva et al., 2018). These mapping procedures represent a continuity of the study performed by Silva et al. (2018) and are based on image processing of the Landsat series using the mixing model produced by CLASlite software. This software uses a spectral-mixing model associated with a robust spectral library to generate the following fractions: photosynthetically active vegetation, non-photosynthetic vegetation and soil. The dates of the images used for processing are from September to December (Supplementary Material, Table S2).

2.4. Analysis of the spatio-temporal patterns of burning in already-deforested areas

For the study period (2016–2019), the total burning in already-deforested areas was quantified by year and by recurrence. For each year, we quantified the size of the mapped areas of fire using seven classes: (0.5–2, 2–5, 5–10, 10–25, 25–50, 50–100, $\geq$100 ha). These analyses allow us to understand the magnitude and patterns of burning in already-deforested areas.

To uncover factors correlated with burnings, we categorized data according to land-tenure categories such as settlement projects, undesignated public land, private properties, conservation units and indigenous land (Acre, 2010). We applied analysis of variance with Levene's test and a post-hoc Tukey's test to evaluate the null-difference hypothesis between the means for burning in already-deforested areas and in new deforestation. This analysis helps clarify the use of fire to advance deforestation in areas in different land-tenure categories.

The relationship between deforestation and burning in already-deforested areas was assessed using data from the PRODES Project (INPE, 2020c). The "PRODES year" used for deforestation estimates refers to the period from August 1st of the previous year to July 31st of the nominal year (i.e., "2019" refers to August 1, 2018 to July 31, 2019). Based on these data, we performed three analyses: (I) quantification of the proportion of the total annual area of fires that came from the new annual deforestation, for example, we account for the burned area that occurred in the 2019 that was not detected as deforestation by PRODES 2018/2019, (II) quantification of the proportion of the total annual area of fires that came from the management of deforested areas consolidated in previous years, for example, burned in 2019 that had been detected as deforestation by PRODES 2018/2019, (III) analysis of the correlation between annual burning in already-deforested areas and annual deforestation for the same years using the municipal boundaries (IBGE, 2016) as the sample unit. The Spearman correlation test was used for this analysis.

The relationship between droughts and burning in already-deforested areas was assessed using monthly precipitation estimates based on satellite data from TRMM (Tropical Rainfall Measuring Mission v7, 3B43). For this study three climatic regions were defined based on the mean values of maximum cumulative water deficit (MCWD) - Aragão et al. (2007) for the 1998–2005 period: the eastern, central and western regions (Fig. 2a). Drought intensity was measured as the MCWD between the months of June and September. We applied the Spearman test for correlation significance. We tested the hypothesis of a null correlation between water deficit and fire extent in order to evaluate the evidence that drought acted as an influential factor on fires. This test addresses the fact that anthropogenic forces were not the exclusive source of the fires detected, and the significance of weather influence remains an open question for the period in the literature (Aragão et al., 2018; Barlow et al., 2019).

2.5. Analysis of the spatio-temporal patterns of forest fire

The definition used for forest-fire burn scars in this study was based on Silva et al. (2018), where trees were detected that were directly or indirectly affected by fire to the point that they cause an impact visible on the optical satellite images. We quantified the total area of forest fire per year and its recurrence. We used violin plots to analyze the distribution patterns of areas sizes, including the median, maximum and minimum for each year. We quantified forest fires by categorizing the data according to land-tenure categories such as federal government land, settlement projects, private properties, conservation units and indigenous lands (Acre, 2010).

We analyzed the relationship between droughts and forest fire based on the MCWD for the three climatic regions, as described in Section 2.4 and Fig. 2a. We calculated the Spearman correlation coefficient to test the relationship of the different predictor variables to fire occurrence.

3. Results

3.1. Spatio-temporal distribution of burning in already-deforested areas

We mapped 550,251 ha of burning in already-deforested areas in the state of Acre in four years (2016–2019) (Fig. 3a). Of this area, 64% occurred in 2016 and 2019 (Fig. 3b). The overall accuracy of estimates of burned area was 98.5% (97.9%–99.0%).

The year 2019 had the largest amount of burning in already-deforested areas among all of the years analyzed: 44% more than 2018, 46% more than 2017 and 4% more than the 2016 El Niño year. On the other hand, in 2017 and 2018, the area burned in already-deforested areas was 44% smaller than in 2016 and 2019. In the whole period analyzed, 67% (371,207 ha) of the burning occurred at least once in previously deforested areas and 33% (179,895 ha) occurred at least once in newly deforested areas. Of the total burning in already-deforested areas, 76% (323,284 ha) burned once, 19% (78,549 ha) burned twice, 4% (18,413 ha) burned three times and 1% (3868 ha) burned four times (Fig. 3b). Annually, 23%–46% of the burned area was associated with newly deforested areas.

The distribution pattern of areas revealed that between 52,000 and 69,000 ha were burned every year (Fig. 4, upper panel). These areas represent, respectively, 3 and 5% of the cumulative deforested area in Acre by the end of 2019 and are 17–55% greater than the 44,460 ha average area deforested annually in Acre over the 2016–2019 period (INPE, 2020c). The years 2016 and 2019 had the highest numbers of fires in already-deforested areas with more than 10 ha. These years also account for the largest percentages of the total burning in already-deforested areas (65 and 62%, respectively) (Fig. 4, lower panel). This difference becomes larger in areas > 50 ha, since in the years 2019 and 2016 the burning in already-deforested areas within this class was four times larger than in 2017 and 2018. Areas with up to 5 ha represented 22% (2019 and 2016) to 35% (2017 and 2018) of the total burning in already-deforested areas. These small areas represented 74% (2019 and 2016) to 81% (2017 and 2018) of the total number of areas affected by fires.

In regards to land-tenure categories, the years 2016 and 2019 had the largest amounts of burning in already-deforested areas when compared to 2017 and 2018 in all land-tenure categories (Fig. 5). Undesignated public land had the largest contribution to the total burned area (34% ± 1.9%), an average of 46,000 ha. On the other hand, Indigenous Lands had the smallest area burned in all years (1% ± 0.4%), an average of 1989 ha year^{-1}, with only 1% of the total area burned.

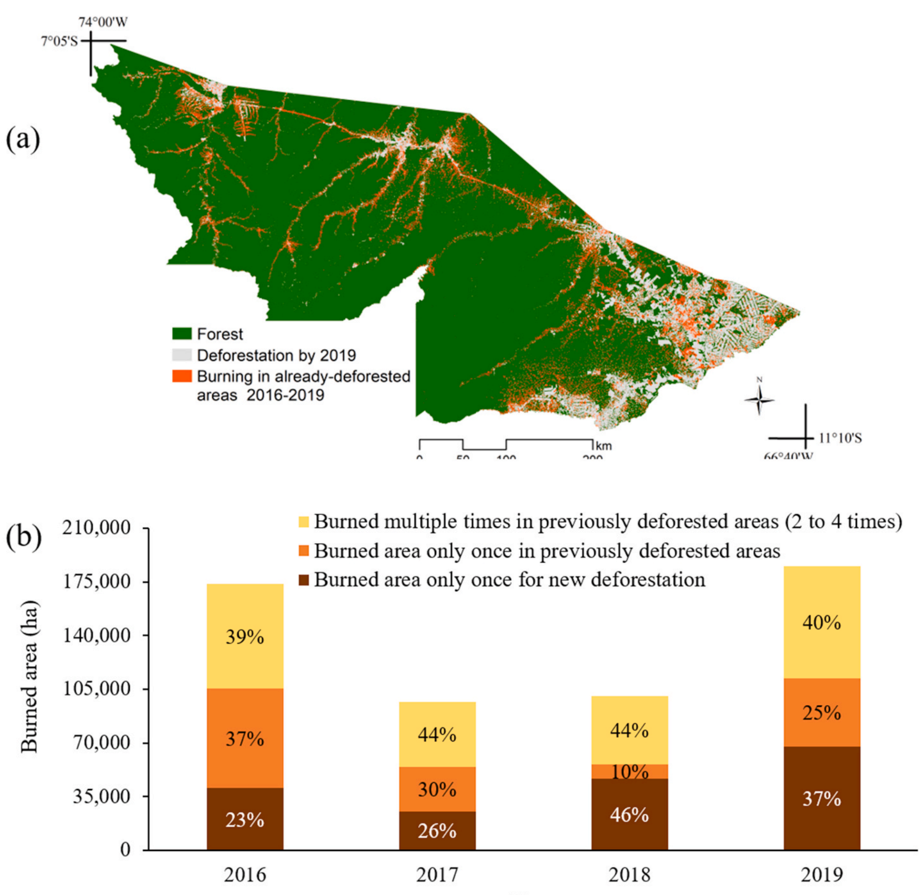

Fig. 3. Total burning in already-deforested areas in the state of Acre from 2016 to 2019 (a). Shown in brown are the burnings that occurred in freshly deforested areas in each year, in orange, the burnings that occurred only once in grid cells deforested in previous years (before the period analyzed), and in yellow, the grid cells in which burnings were detected multiple times during the period (b). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

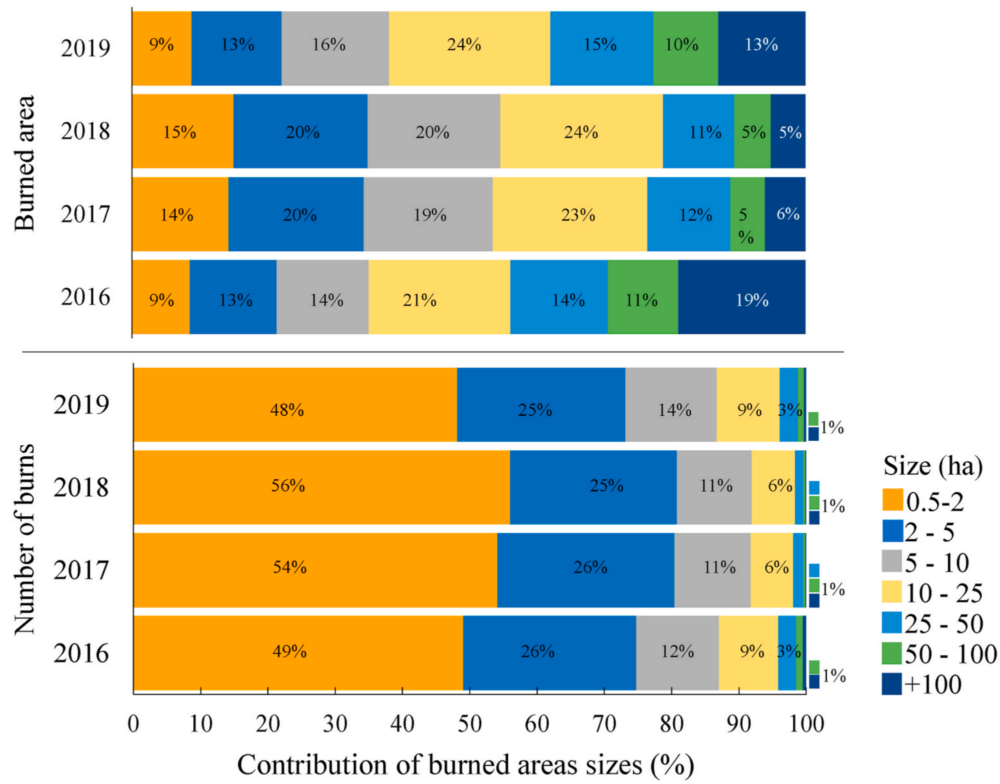

Fig. 4. Distribution of areas by size class for burning in already-deforested areas by burned area (upper panel) and number of burns (lower panel).

Together, all land-tenure categories except Indigenous Lands, totaled a burned area in 2019 and 2016 (349,134 ha) 80% larger than the area observed between 2017 and 2018 (193,870 ha).

In fact, incidence of fire in conservation units and federal government land was larger in 2019 than in all of the other years analyzed (burned areas in conservation units were 17% larger than in 2016, 53% larger than in 2017 and 55% larger than in 2018; burned areas in federal-government land were 12% larger than in 2016, 51% larger than in 2017 and 44% larger than in 2018). The percentage of burned areas in new deforestation (31%–42%) and in the already-deforested areas (58%–69%) were equivalent among all land-tenure categories with the exception of conservation units (ANOVA Levene's test and Tukey HSD test, $p < 0.001$), with more burning in new deforestation (51%) than in the already-deforested areas (49%), indicating the advance of new frontiers of deforestation (Fig. 5b).

Undesignated public lands (*terras devolutas*), settlement projects and private properties represent 93%–95% of the area larger than 50 ha of burning in already-deforested areas (Table 1). In 2016 and 2018, private properties represented the largest contribution to large areas. In 2018 and 2019, undesignated public land was the main contributor to large burned areas, reaching 46% of the total.

3.2. Deforestation and burning in already-deforested areas

At the municipal level, burning in already-deforested areas is significantly related to the annual rate of deforestation recorded by INPE ($p < 0.001$, $r = 0.74$, Spearman; Fig. 6). The year 2019 had the largest area affected by fire (180,000 ha) and the highest annual deforestation rate in the last 14 years (68,800 ha) ($p < 0.001$, $r = 0.74$) and the lowest correlation was for the year 2017 ($p = 0.023$, $r = 0.49$). Burning in already-deforested areas was more intense in 2019, representing 41% of the mapped area (34% - 56,783 ha - in 2016, 37% - 35,387 ha - in 2017, 39% - 39,312 ha - in 2018 and 41% -71,344 ha - in 2019).

The total burning in already-deforested areas represented 4%–8% of the deforested area for the entire state of Acre (Supplementary Material, Table S2). In the central region of Acre, the municipality (county) of Santa Rosa do Purus burned 30% of the cumulative deforested area detected by PRODES, Manoel Urbano, Feijó, Manoel Urbano, Jordão, Sena Madureira and Porto Walter burned from 10 to 22%. The municipality of Assis Brasil, in the Alto Acre region, is an extreme case where, in 2016 and 2019, 20%–24% of the deforested area was affected by fire, respectively. These processes confirm the fact that fire is used not only to burn areas that are being deforested, but also in previously deforested land such as pasture or secondary vegetation ("*capoeiras*"), with the objective of managing these already-deforested areas. It should be remembered that many recently deforested areas are not burned in the same year as the forest felling, a detail that is not captured by this analysis.

3.3. Spatio-temporal distribution of forest fires

Forest fires in the period analyzed reached 34,084 ha, with the year 2016 accounting for 91.3% of the total fire-affected area (31,117 ha), followed by 2019, with 5.6% of the total (1920 ha) (Fig. 7). The average overall accuracy of forest-fire identification by this method is 98.8% (98.1%–99.4%). In 2016, there were areas of up to 3927 ha, followed by 2019 with a maximum area of 350 ha, 2017 with 143 ha and 2018 with 33 ha.

Forest fires were clustered in the eastern region of the state of Acre in all years: 97% in 2016, 84% in 2017, 94% in 2018 and 100% in 2019. The land-tenure categories that contributed most to forest fires were settlement projects and private properties in all of the years analyzed, with the exception of 2019, where 78% of the fire occurred in conservation units, Indigenous Lands and undesignated public land in the extreme southeastern portion of Acre (Table 2; Supplementary Material, Figure S2).

3.4. Droughts, burnings in already-deforested areas and forest fires

We identified a gradient in the maximum cumulative water deficit

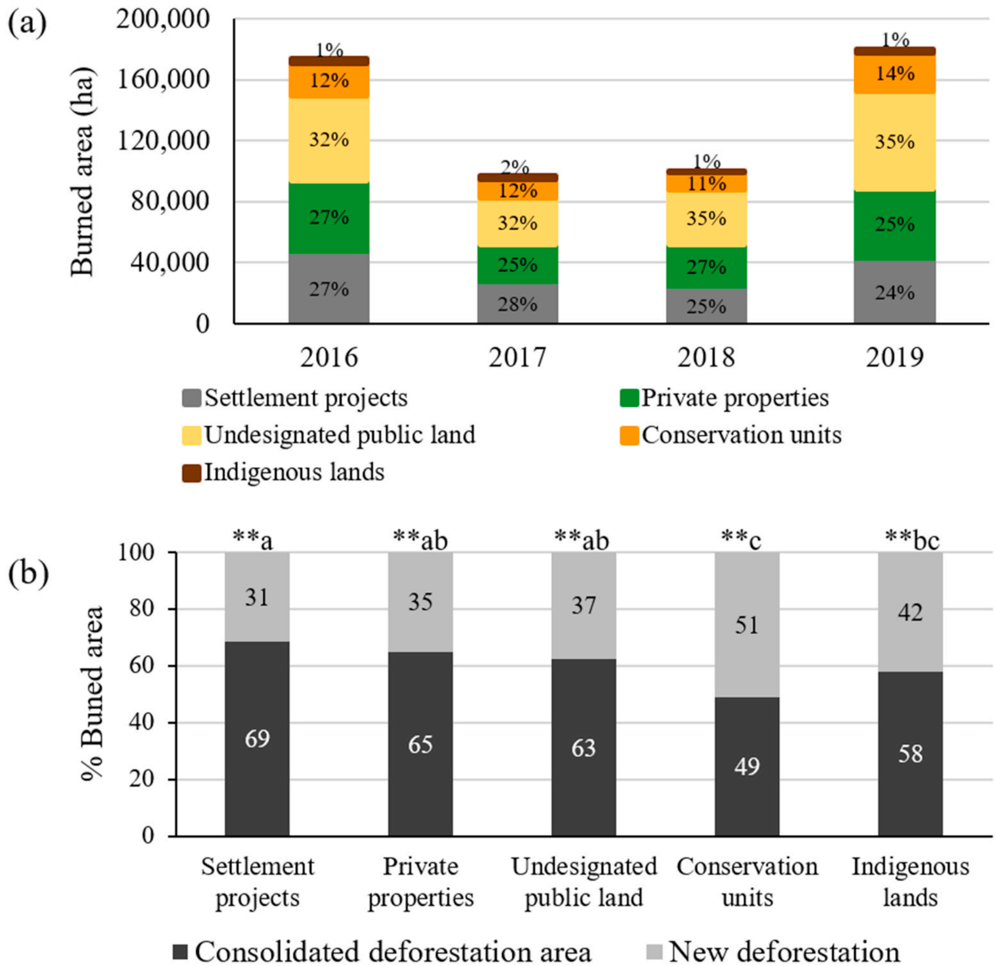

Fig. 5. Burning in already-deforested areas by land-tenure category in the 2016–2019 period: (a) area burned per year by land-tenure category, and (b) percentages of area burned in new deforestation and in the burning in already-deforested area. The values in the bars indicate the percentage contribution of each class. Different letters indicate significantly different means (ANOVA and Tukey HSD test, $p < 0.001$).

Table 1
Area occupied by the class of areas greater than 50 ha of burning in already-deforested areas by land-tenure category and year.

	2016		2017		2018		2019	
	ha	%	ha	%	ha	%	ha	%
Undesignated public land	16,341	32	3595	33	4306	41	18,892	46
Settlement projects	13,295	26	2588	24	1977	19	8074	20
Private properties	18,975	37	4191	39	3573	34	11,775	29
Indigenous lands	167	0	117	1	72	1	0	0
Conservation units	2126	4	274	3	672	6	1945	5
Total	50,904	100	10,765	100	10,600	100	40,686	100

(MCWD) in the three climatic regions of Acre in the period analyzed. The eastern region had the greatest water deficit during the dry season every year, followed by the central and western regions (Supplementary Material, Figure S2). Furthermore, the correlation between MCWD and occurrence of burnings in already-deforested areas was positive for all years ($p = 0.03$, $r = -0.62$, Spearman; Fig. 8a), except for 2019. Similarly, MCWD had a negative correlation with occurrence of fires in the climatic regions of Acre, with the eastern and central regions exhibiting the strongest relation, especially for 2016, when there was an El Niño event ($p = 0.0016$, $r = -0.80$, Spearman; Fig. 8b). The burning in already-deforested areas was a record in 2019, the year in which there was weak El Niño, with water deficits equivalent to the years 2017 and 2018 (visible in Figure S3 in the Supplementary Material).

4. Discussion

4.1. *Impact of burning in already-deforested areas*

This study retrieved georeferenced and time-varying data on burning in already-deforested areas. This provides an important complement to the widely used PRODES deforested-area product from the Brazil's National Institute for Space Research (INPE) (INPE, 2020c). The main addition to the already-available fire products from INPE, namely active-fire point detections ("hot pixels") and the new burned-area product (INPE, 2020d), is the greater accuracy of our data due the higher spatial resolution with which the extent of burned areas is measured (70 m in the new product *versus* 1 km in the INPE products). The information presented by this study allows visualization of burned

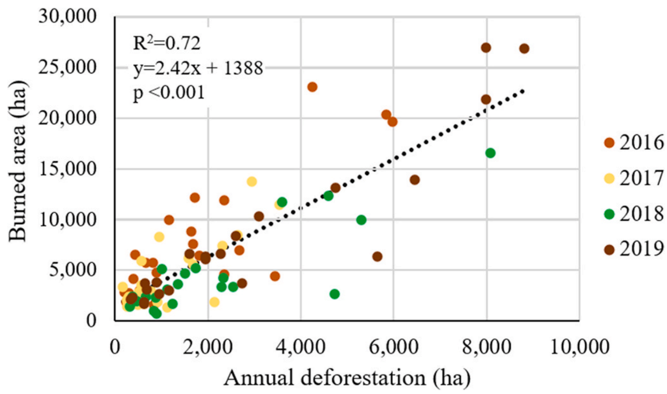

Fig. 6. Relationship between annual increase in deforestation and burning in already-deforested areas for the state of Acre from 2016 to 2019.

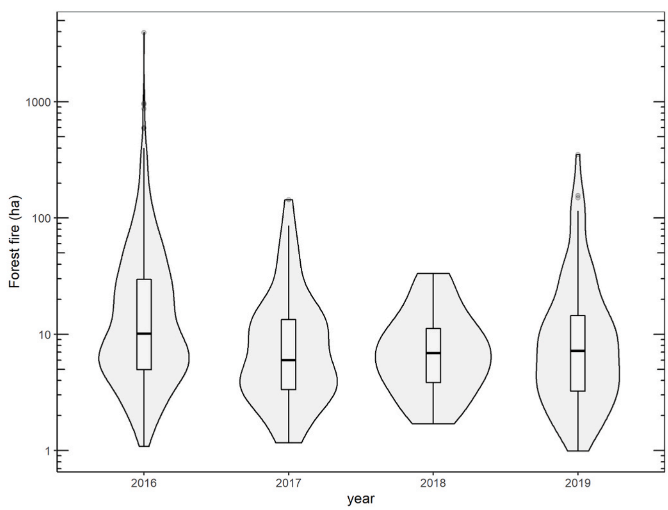

Fig. 7. Areas of forest fire (inner boxplot) and the empirical distribution of area by sizes (outer curves of the violin plots).

areas as small as 0.5 ha in area, allowing assessment of the annual burning rate for 2016–2019, in which fire frequency and extent achieved record-breaking levels in the Amazon. The data presented here provide a valuable expansion of the information available for policymakers.

Our results indicate that 2019 had the largest area of burning in already-deforested areas in Acre, 80% greater than 2018 and even 4% greater than the area burned during the El Niño in 2016. The proportion of fires in recently deforested land was higher in 2018 and 2019. In 2019, the contribution was 41%, following the trend of increasing deforestation in Acre (INPE, 2020c).

The contribution of areas larger than 10 ha to the total area of burning in already-deforested areas was greater in 2019 than in 2017 and 2018, representing 32% of the total area mapped. Fire in areas larger than 50 ha represented an average of 18% of the total burned area we mapped over the whole period, with peaks reaching 26% in the 2016 and 2019. These areas are usually associated with extensive cattle ranching (EMBRAPA, 2017); they amount to 66% of the deforested area in Acre. These areas are in medium and large landholdings and represent the main source of ignition for forest fires in Amazonia (Cano-Crespo et al., 2015; Dias Filho, 2011).

Deforestation rates have been increasing throughout Brazilian Amazonia since 2012 (INPE, 2020c) and our results show that the increasing trend in fires associated with this was maintained and that it accelerated with an upward surge in the 2019. A likely future trend of increased deforestation would be associated with still more fires. Aragão et al. (2018) divided Brazilian Amazonia into one-degree grid cells and showed that, although fire increases in grid cells where deforestation increases, there is also a very large amount of forest burned in grid cells without increased deforestation, and that in the 2015 drought fires burned large areas of forest throughout the region independent of the amount of deforestation.

4.2. *Impact of forest fire*

The fact that major forest fires occurred in Acre in 2019 despite this not being a year of extreme drought, when all other years without extreme droughts had almost no forest fires, reflects the virulently anti-environmental rhetoric and policies currently in place. Among the years analyzed, it was only in 2016 that an extreme drought event was recorded, when the El Niño was very strong (NOAA, 2020).

The size of the largest mapped areas of forest fires reflect the magnitude of the fires, showing the size of the spread of the fire. In 2016, we had a maximum area with size of 3900 ha (mean = 38 ha, median = 10 ha). In 2019, we mapped a maximum area of 350 ha (mean = 17 ha, median = 5 ha), which was greater than in any year without extreme droughts recorded by Silva et al. (2018).

The relationship between droughts and forest fires is different from the relationship with burned areas in the pastures and new clearings. In these deforested areas the occurrence of fires observed in this study coincided with rainfall deficit below −180 mm. Burning after deforestation was shown to occur throughout Acre. The concentration of forest fires in the analyzed period (2016–2019) was in the eastern region of Acre, which is a historically drier region compared to the other regions of Acre (Aragão et al., 2007). In 2019, forest fires occurred only in this region, where the largest areas were located near the triple national boundary where Brazil, Peru and Bolivia meet and where a drought was recorded with MCWD of −240 mm (Supplementary Material Figure S3). The concentration of large fires in specific regions may be a reflection of the fact that the climate in the southwestern portion of Amazonia is getting progressively drier, as reported by Aragão et al. (2008), Fu et al. (2013) and Staal et al. (2018).

Projections for the future indicate that Acre is among the areas with the greatest risk of prolonged drought periods and major forest fires (Faria et al., 2017; Fu et al., 2013). These scenarios cause ecological concerns regarding the degradation of forests and loss of biodiversity (Barlow et al., 2016). This also has implications for the state's economy (Campanharo et al., 2019; Mendonça et al., 2004) and public health

Table 2
Contribution of land-tenure categories to the area of forest fires in the state of Acre between 2016 and 2019.

Land-tenure category	2016		2017		2018		2019	
	ha	%	ha	%	ha	%	ha	%
Settlement projects	9543	31	487	65	108	36	228	12
Private properties	12,525	40	148	20	85	29	195	10
Undesignated public land	7364	24	114	15	69	23	466	24
Conservation units	1657	5	0	–	36	12	476	25
Indigenous Lands	28	0	0	–	0	–	555	29
Total	31,117	100	749	100	298	100	1920	100

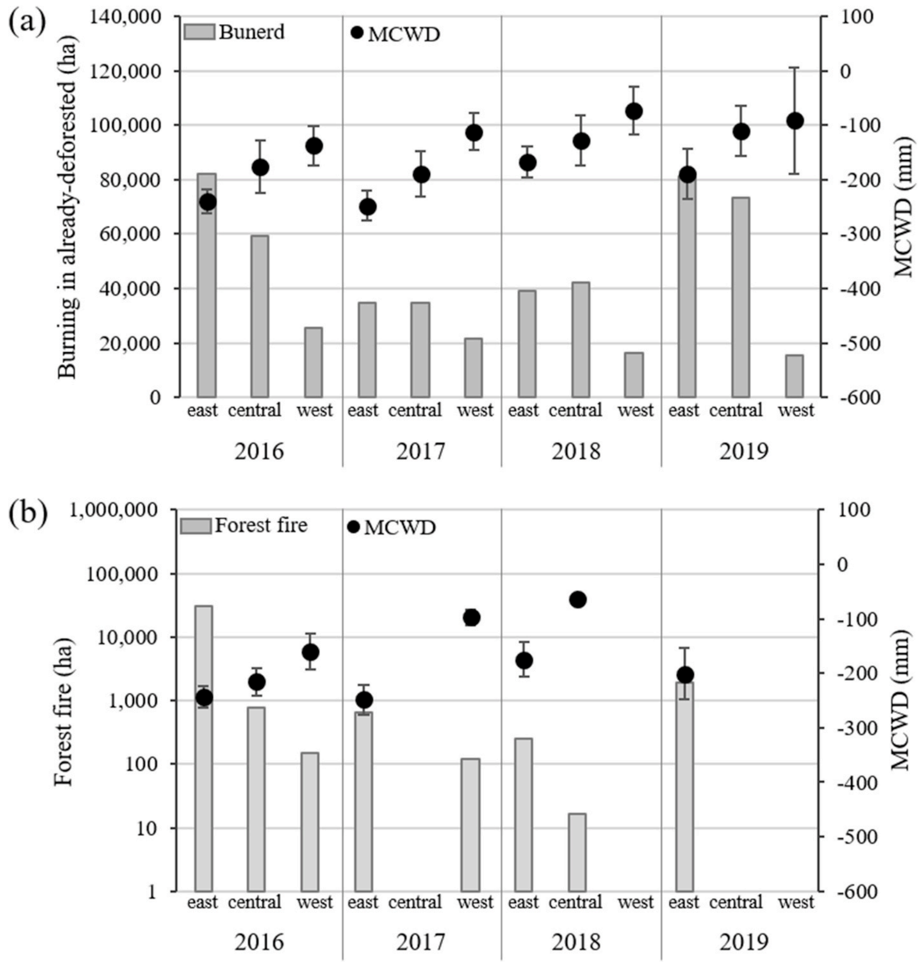

Fig. 8. Temporal relationship between (a) maximum cumulative water deficit (MCWD) and burning in already-deforested areas and (b) MCWD and forest-fire area in the state of Acre from 2016 to 2019 in the three regions analyzed (east, central and west regions).

(Machado-Silva et al., 2020; Morello et al., 2019). Policy concerns include loss of the benefits from REDD (reducing emissions from deforestation and forest degradation), which is under implementation in Acre through the Acre-California agreement (Acre, 2013).

4.3. *The prominence of the 2019 fires may hide a worrying trend*

Aside from the anomalous 2016 El Niño year, 2019 was outstanding in terms of total burned area and also in terms of forest area burned. Since this was also true for the annual deforestation rate, which increased to a level 50% above the average for 2016–2019, it may be the case that a new trend of greater forest suppression and degradation was started in 2019. Additional evidence comes from the significant negative correlation of 62% between burned area and water deficit. This shows that climate was not behind the record fires in 2019 (Barlow et al., 2019), suggesting these fires were intentional and were not unintended accidental fires (Stabile et al., 2020).

Institutional change favoring deforestation and fires is another new trend. Barlow et al. (2019) argued that the deforestation policy under the presidential administration that began in January 2019 deviated from the successful approach of 2004–2012, a reference to the Action Plan for Prevention and Control of Amazon Deforestation (PPCDAM), which, together with macroeconomic factors, helped reduce the annual deforestation in Brazilian Amazonia by 84% in the decline that ended in 2012 (West et al., 2019; West and Fearnside, 2021). The current federal administration has weakened institutional enforcement capacity, resorting to an emergency approach to environmental policy (Ferrante and Fearnside, 2019; Pereira et al., 2019). The administration's discourse has led deforesters to believe that violations of environmental laws will be forgiven and that regulations will be further relaxed (Klingler and Mack, 2020). The combination of concrete institutional changes and anti-environmental discourse encourages both deforestation and burning, even when the government attempts to reverse this effect.

The government decreed a moratorium on fires for 60 days in August 2019, and a 120-day ban was decreed in 2020 (Brazil, 2019). Military enforcement of these bans did not prevent large amounts of deforestation and burning (Finer et al., 2020; Moutinho et al., 2020; OC, 2020), and the federal environmental agencies that the presidential administration has largely dismantled have not had their surveillance and enforcement capacities restored. Another controversial aspect was the claim by Brazil's president that the country's Amazonian fire crisis was caused by indigenous people and subsistence farming by traditional communities (Ferrante et al., 2020). However, our results show that in all years evaluated in Acre only 1–2% of the total burning was in Indigenous Lands and 11–14% was in conservation units (which include extractive reserves inhabited by traditional communities) (Fig. 5a); in contrast, 32–35% was in undesignated public land, which is the primary target of large land grabbers (*grileiros*).

4.4. *Protected areas are under increased pressure*

Despite 2019 not having the largest area of forest burned, the year stood out in the share of the burning that was in conservation units and

Indigenous Lands (hereafter, "protected areas"). The conjecture that at least part of the burning envisaged illegal occupation of protected areas is supported by recent studies (Keles et al., 2020). These use remote sensing to show the routine transgression of the legal constraints on land use that involve deforestation and fires, in addition to land-grabbing (*grilagem*). They also demonstrate that forest suppression and degradation are used as a strategy for pressuring institutions to dismember protected areas or withdraw their protected status.

Among the protected areas, the Chico Mendes Extractive Reserve is under the most social, political and economic pressure (Hoelle, 2011; Mascarenhas et al., 2018; Vadjunec et al., 2009). This protected area represented 43–66% of the total burning in already-deforested portions of protected areas. Between 2018 and 2019, burning in already-deforested areas in this extractive reserve increased by 340%. According to Fearnside et al. (2018), the Chico Mendes Extractive Reserve had the fourth largest loss of forest by 2014 of the 73 extractive reserves of the Brazilian Amazon. This protected area is under strong pressure from deforestation, driven by the increase of livestock, invasion of land and by the devaluation of forest productive chains such as rubber and Brazil nuts (Hoelle, 2011; Vadjunec et al., 2009). Even though conservation units are identified as a barriers to deforestation and burning (Pfaff et al., 2014), the results presented here must be taken as an important warning sign with regard to their preservation.

4.5. Stricter land and environmental policies could bring great gains

The fact that the greatest share of the area burned (65%) was in areas owned by the government demonstrates that the bulk of Brazil's Amazon burning is due to weak enforcement, as has also been the case for deforestation (Araujo et al., 2009). In addition, the share of burned areas above 50 ha in area, which peaked in 2019, suggests that medium to large landholders play a relevant role in fire-assisted land-cover change, which is another parallel with deforestation (Cano-Crespo et al., 2015; Dias Filho, 2011; Godar et al., 2014). Therefore, there are two reasons why more rigorous policy would bring great gains. First, avoiding deforestation in government-owned land is saving economically valuable resources for current and future generations of Brazilians, which is a duty of the government (Stabile et al., 2020). Second, large areas and landholdings are detected with less error than smaller ones, and targeting them is more cost-effective (Godar et al., 2014). This means that there is a clear opportunity for more rigorous policy to deliver significant outcomes.

5. Conclusions

A novel high-resolution measurement of the areal extent of fires was developed as part of this study and was applied to the case of Brazil's state of Acre, whose leadership in sustainability has been challenged by rising amounts of fire and deforestation. Two classes of fire were investigated: burning in already-deforested areas and forest fires. The spatial and temporal patterns showed the prominence of 2019 fires in both classes and the propensity of a given location to burn more than once. Significant correlations that were positive with deforestation and negative with water deficit were also found, as well as the dominance of federal lands, including protected areas, among the land classes with large areas burned. The importance of burns above 50 ha in area shows the role of large actors. Importantly, it was shown that climate was not a driver of the 2019 fire season. This adds evidence to attributing the upsurge to the discourse and policies of Brazil's presidential administration that began in January 2019.

Our arguments arrive at a moment when the needed changes to preserve Acre's regional leadership in sustainability are still possible. Authorities should undertake strong action and target budgetary resources for surveillance and enforcement of environmental restrictions. Authorities must also alter their discourse to emit signals consistent with sustainability.

One important limitation of the analysis, and also a task for future study, is the lack of precise investigation of which, among relevant biophysical, climatic, socioeconomic and institutional factors, are the main predictors of burned area. This would improve the usefulness of the data generated here for policy planning, including the positioning of fire brigades.

Credit author statement

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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