Forest Policy and Economics 127 (2021) 102447

Contents lists available at ScienceDirect

Forest Policy and Economics

journal homepage: www.elsevier.com/locate/forpol

Costs and effectiveness of public and private fire management programs in the Brazilian Amazon and Cerrado

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ARTICLE INFO

Keywords:
Budget expenditure
Integrated fire management
Aliança da Terra
ICMBio

ABSTRACT

There is a noted lack of information on the effectiveness of investments in forest fire management in Brazil. Here, we quantify the budget expenditures of one private and one public fire-management program. We then compare burned areas within conservation units (CUs) and private rural properties (PPs) with and without investments in fire management in the Brazilian Amazon and Cerrado biomes. Investments in fire management in CUs total US$ 0.51 ha^{-1} yr^{-1} in the Amazon and US$ 5.32 ha^{-1} yr^{-1} in the Cerrado. Roughly, 94% of the public investment in fire management in CUs is only assigned to suppression activities, although seven CUs in Cerrado have undertaken innovative Integrated Fire Management (IFM) that includes prevention practices. Cerrado CUs with brigades for fire suppression have reduced burned area by 12%, on average, compared with CUs without brigades. Further, CUs that also included prevention practices as part of IFM reduced burned areas by an additional 6% from CUs with only fire suppression practices. Investments in both fire prevention and suppression on private lands amounted to US$ 15.89 ha^{-1} yr^{-1}. We identify a reduction of 50%, on average, in burned areas after PPs joined the fire mitigation program of Aliança da Terra. In face of increasingly disruptive wildfires alongside finite financial resources, we call for the need of a mix of cost-effective private and public fire management programs with strong emphasis on prevention practices.

1. Introduction

Managing forest fire requires understanding its role in ecosystem functioning (CIFFC, 2017). Fire occurs naturally in various ecosystems around the world, from boreal forests to tropical savannas. In some environments (e.g. Mediterranean and tropical savannas), fire stimulates regrowth and thus contributes to the ecosystem health, whereas in other regions (e.g. tropical rainforests), fire is exogenous and generally disruptive (Marquis, 2002; Barlow et al., 2012; Brando et al., 2014). Such aspects indicate that the adaptation of management techniques to different types of landscape is paramount. Here, we consider fire management as any activity that either prevents or suppresses fires. We also adopt the term Integrated Fire management (IFM) mainly as a comprehensive planning process for managing fires to protect people, their assets and forest resources (Schmidt et al., 2018). In general, fire management in various regions of the world faces the same problem: increasingly disturbing forest fires alongside finite financial resources, thus requiring ever more cost-effective fire management programs. However, a common response to the increasing threat of fire is to ask for more governmental budgets for emergency firefighting (Mendes, 2010; Topik, 2015). In the United States, for example, annual fire suppression costs as of 2017 have surpassed US$ 2.4 billion (NIFC, 2019) and are expected to increase by 67% over the next 10 years (Topik, 2015). Other countries also invest heavily in firefighting. For instance, annual expenditures amount to € 600 million in Spain (MAPA, 2019) and € 78.1 million in Portugal (CTI, 2017), while Australia has disbursed US$ 553 million for firefighting in 2019 (NSW, 2019).

Although governments have generally channeled much larger budget shares to firefighting (Mendes, 2010; Topik, 2015), there is increasing evidence supporting that the cost-effectiveness of fire

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https://doi.org/10.1016/j.forpol.2021.102447
Received 26 November 2019; Received in revised form 28 January 2021; Accepted 8 March 2021

management is higher when investments in fire prevention, including fuel management (e.g. prescribed burning, opening of fire breaks), are balanced with those of firefighting. In this respect, Thompson et al. (2016, 2017) and Heines et al. (2018) provided evidence that a balanced combination between prevention and suppression activities has reduced wildfires in the United States. Snider et al. (2006) estimated that this combination could save up to US$ 240 per hectare. Similarly, Nepstad et al. (2001), Oliveira et al. (2018) and Strand et al. (2018) argue that a combination of prevention and suppression, if associated with improved agricultural practices, can reduce forest fires, particularly in regions of intense land-use change.

There have been few studies that adequately investigate whether major fire management programs have been effective in reducing burned areas and which practices should be prioritized by governmental and private investments. The few studies that quantify the budget costs of fire management have been mostly carried out in the Global North (Lankoande, 2005; Gebert et al., 2007; Ashe et al., 2009; Zybach et al., 2009; Topik, 2015), while estimates of these costs remain largely unquantified in tropical forests (Gebert et al., 2008; Mendes, 2010; Minas et al., 2012). Specifically in Brazil, such studies remain absent. Therefore, there is a pressing need for quantitative analyses that relate investments in fire management practices (i.e. prevention and suppression budget costs) to their benefits in terms of reduced fire and hence burned areas. To fill this gap, we quantify the budget expenditures and measure the effectiveness of two fire management programs in the Brazilian Amazon and Cerrado biomes: one public and one private. More specifically, our analysis quantifies budget costs of fire management in both private rural properties (PPs) and public federal conservation units (CUs) between 2012 and 2016. In addition, we analyze the effectiveness of prevention and suppression activities in reducing burned areas on both types of land ownership. Our research contributes to advancing fire management in the Amazon and Cerrado biomes (Myers et al., 2000; Pivello, 2006) and provides insights into the country's complex fire management decision-making processes aimed at a more effective allocation of resources.

Table 1
Mean annual budget expenditures for fire management between 2012 and 2016. Values refer to public investments for 6 months of fire management as well as private investments for the same period (see Tables S1 and S2—Supplementary Information—for more detailed data).

N°	Item*	ICMBIO Program		AT program	
		Value	Standard Deviation	Value	Standard Deviation
1	Number of firefighters (person/year)	844	116	9	0
2	Annual salary of brigade chief (US $/person/year)	5262	429	7745	2217
3	Annual salary of firefighter (US $/person/year)	3914	507	3442	985
4	Equipment for individual use (US $/person/year)	1458	138	1872	380
5	Travel Expenditures[1] (US $/person/year)	2022	685	3717	1066
6	Food Expenditures (US$/person/year)	990	245	515	166
7	Equipment maintenance (US $/year)	not informed	–	150	0
8	Vehicle maintenance[2] (US $/year)	not informed	–	14,500	988
9	Communication costs (US$/year)	not informed	–	11,622	559
10	Training costs (US $/year)	not informed	–	18,414	0
11	Administrative costs (US$/year)	not informed	–	6943	531
12	Firebreaks expenditures[3] (US $/year)	32,975	19,702	not applicable	–
13	Aircraft Expenditures (US $/hour)[7]	3110	698	not applicable	–
Annual totals (US$/year)		8,289,296	871,432	1,693,832	62,578
Relative values for prevention (US$/ha/year)		0.78[4]	0.90	0.19[5]	0.04
Relative values for suppression (US$/ha/year)		2.48[4]	5.06	15.89[6]	19.99

[1]Includes costs of accommodation and transportation; [2]annual cost of depreciation over the useful life of equipment of collective use; [3]cost per km (we use the value of US$ 37.8/km, according to information provided by firefighter); [4]per area of conservation units; [5]per area of properties; [6]per extent of fires put out or fought; [7]198 flight hours per year, on average, *for annual R$ to US$ exchange rate see Table S3.

2. Forest fire management in Brazil and the overlooked role of fire prevention

Whereas fire is exogenous to the Amazon forests, the Cerrado is a fire-adapted ecosystem. Nevertheless, both biomes are experiencing more frequent and extreme anthropogenic fires (Aragão et al., 2007; Morton et al., 2013; Aragão et al., 2018; Barlow et al., 2019; Oliveira et al., 2021). A combination of climate change and agricultural expansion is increasing the frequency and intensity of forest fires in both biomes, which are impoverishing, as a result, regional ecosystems by reducing biodiversity, carbon biomass stocks and other ecosystem services, such as rainfall cycling (Lovejoy and Nobre, 2018; Strand et al., 2018). In this regard, Brando et al. (2020) suggest that 16% of tropical forests in Southern Amazon will burn in the next few decades, thereby further weakening the climate regulation service of Amazon forests (Morton et al., 2013). In turn, the Cerrado's native vegetation biomass stocks are on a downward trajectory due to recurrent fires (Oliveira et al., 2021), putting the biome on the verge of losing its capacity to maintain biogeochemical cycles and the dispersion of organisms (Hirota et al., 2010).

Although the use of fire is in some cases advantageous to landowners, who apply fire as an affordable tool for clearing land for agricultural production (Nepstad et al., 1999; Cammelli, 2013; Carmenta et al., 2013), uncontrolled fires incur large costs to agriculture and forestry, which remain largely unquantified and therefore disregarded in decision-making processes (Nepstad et al., 2001; Mendonça et al., 2004; Oliveira et al., 2018).

Despite the growing number of national and local governmental and non-governmental bodies stressing the need for fire prevention, investments in fire management in Brazil still tend to prioritize emergencies (Mendes, 2010; Carmenta et al., 2013). The PrevFogo/IBAMA, for example, one of the largest public fire management programs in the country, has mostly focused on fire suppression, especially on indigenous lands (IBAMA, 2017). This program also includes preventive actions, such as training courses and dissemination of environmental education media, but these activities generally do not include reduction of fuelwood loads on the ground (fuel management).

Another major public initiative is the fire suppression and prevention program of the Chico Mendes Institute for Biodiversity Conservation (ICMBio, icmbio.gov.br), which manages federal conservation units (CUs). Initiated in 2001, this this initiative, rather than focusing on suppression alone, has made significant advances by promoting IFM in seven CUs of the Cerrado Biome (Schmidt et al., 2018). ICMBio's IFM involves mitigation strategies that reconcile social, political and environmental aspects inherent to specific landscapes (Myers, 2006; Schmidt et al., 2018). For instance, the Cerrado vegetation, unlike the Amazon, is

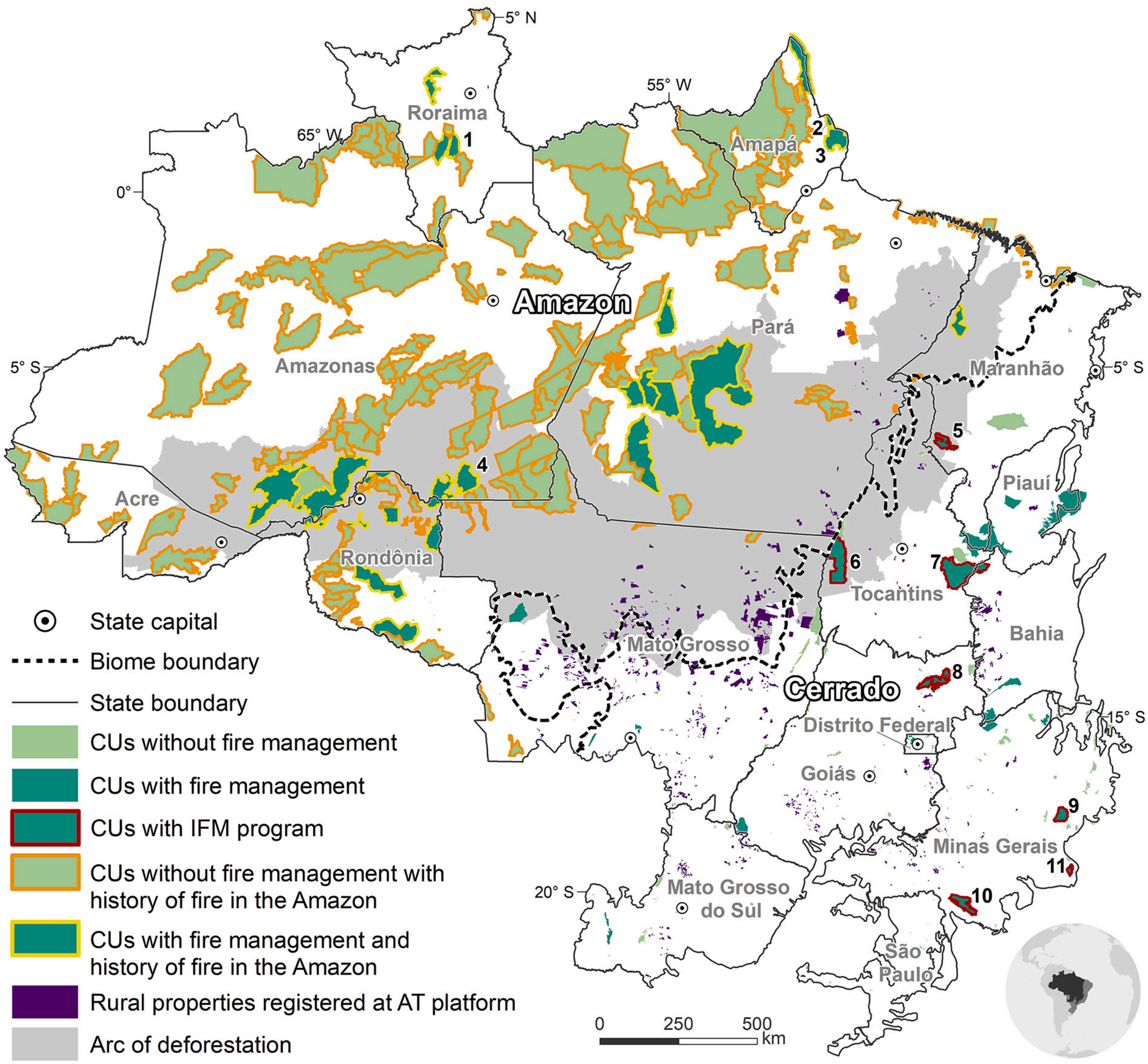

Fig. 1. Federal CUs per category and PPs registered on the AT Socioenvironmental Platform. Arc of deforestation is represented in light gray. CUs cited in the text are: 1 - Viruá; 2 - Maracá-Jipioca; 3 - Lago Piratuba; 4 - Campos Amazônicos; 5 - Chapada das Mesas; 6 - Araguaia; 7 - Serra Geral do Tocantins; 8 - Chapada dos Veadeiros; 9 - Sempre-Vivas; 10 - Serra da Canastra; 11 - Serra do Cipó.

adapted to fire and thus allows prescribed burning (fuel management), albeit in many cases under considerable uncertainty (Pivello, 2017).

Some initiatives oriented towards private rural properties (PPs) have also promoted fire management in Brazil. Notable examples are the “Green Municipalities” (Guimarães et al., 2013), the “Green Flame” (Vilhena, 2016), and the Aliança da Terra (AT) (aliancadaterra.org) programs. While the former two develop regional measures to reduce fire and deforestation in the Amazon, the AT program focuses on improving sustainable agricultural practices in PPs distributed across Brazil. Initiated by this non-profit organization in 2006, it has supported over 1000 PPs in improving land-use practices and developing fire management. Landowners registered at the AT socioenvironmental platform receive technical assistance for environmental and land regularization, sustainable production practices, and fire management. The program also maintains a fire brigade stationed in the eastern Xingu region (Soares-Filho et al., 2012) that combats fire on farms, rural settlements, indigenous lands and state CUs in Mato Grosso. Despite having a large outreach, one of its main challenges remains to convince rural landowners that investing in preventive actions brings benefits given that economic losses are avoided and ecosystem services are maintained (Oliveira et al., 2018; Strand et al., 2018).

The initiatives of ICMBio and AT represent important advances in forest fire management. To date, however, no study has evaluated whether investments in such management programs pay off in terms of burned area reduction. This implies that decisions by both rural landowners and policy-makers on how to reduce the damages of forest fires are still based on incomplete information. Quantifying the budget costs of prevention and suppression programs alongside their effectiveness in reducing burned areas could provide important lessons for filling in this knowledge gap. Here, we address these issues by analyzing the fire management programs of ICMBio and AT in CUs and PPs, respectively, across the Cerrado and the Amazon biomes.

3. Methods

We gathered annual budget costs of fire management between 2012 and 2016 by ICMBio and AT, categorizing, where possible, costs into prevention and suppression activities (Section 3.1). We then compared burned areas in managed and non-managed areas in both the Amazon and Cerrado biomes (Section 3.2). To do so, we applied the Wilcoxon–Mann–Whitney method (Mann and Whitney, 1947).

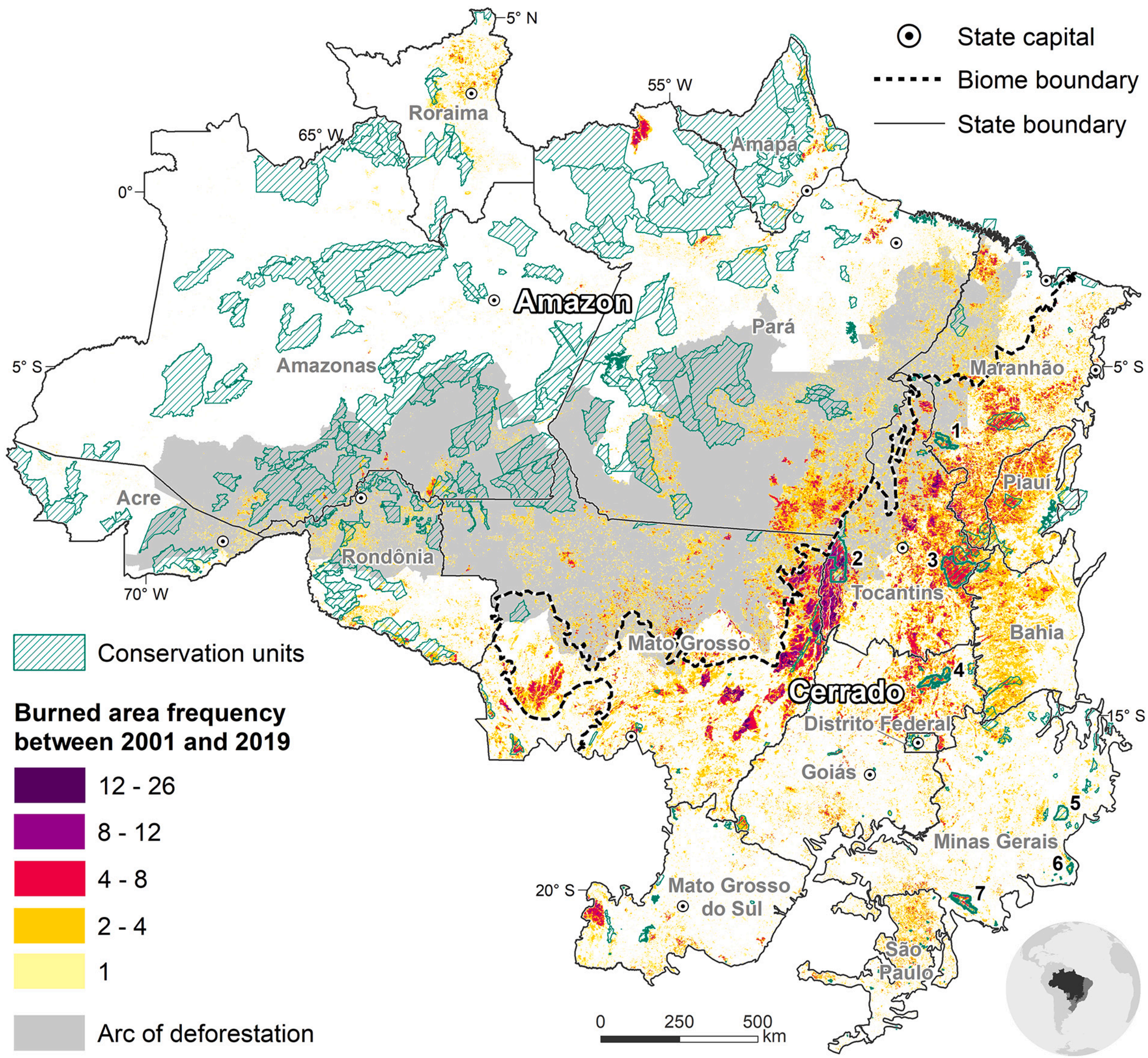

Fig. 2. Burned areas frequency between 2001 and 2019 in the Amazon and Cerrado biomes from the MODIS Fire Disturbance Product—MCD64A. CUs with IFM program: 1 - Chapada das Mesas; 2 - Araguaia; 3 - Serra Geral do Tocantins; 4 - Chapada dos Veadeiros; 5 - Sempre-Vivas; 6 - Serra do Cipó; 7 - Serra da Canastra.

3.1. Budget costs of fire management

We interviewed both technical (environmental analysts) and operational staff (brigade chiefs and firefighters) and gathered data (reports, spreadsheets) from the ICMBio and AT between 2012 and 2016. Both institutions hire firefighters on an annual basis. ICMBio brigades, however, only work during the dry season (August to December), while the AT brigade works all year round (Table 1).

Our analysis distinguishes between sustainable use (CUsu) and strictly protected (CUsp) conservation units in the Amazon (Brazil, 2000). Whereas the former allows human occupation and sustainable use of its resources, the latter is strictly for conservation purposes (Soares-Filho et al., 2010). For the Cerrado, our analysis covers only the strictly protected category, since 96% of its CUs with fire management fall within this category. Our assessment encompasses all CUs attended to by brigades in both biomes, namely 23 out of 607 in the Amazon and 21 out of 353 in the Cerrado (Fig. 1 and Table S4). For CUs that do not have prevention programs, the total budget costs refer exclusively to suppression activities, as is the case of the Amazon CUs. ICMBio's IFM program includes mainly fuel reduction by prescribed burning, firebreaks, and brigade team training. Of the Cerrado CUs, only seven have IFM programs (Table S4). We therefore differentiate between prevention and suppression costs for those units. Prevention costs do not include aircraft deployment, but include firebreak making. For CUs that have only suppression, the costs refer to the sum of all costs except those of firebreaks. These costs are calculated annually per CU in an absolute manner and relative to the CU area (Eqs. (1) to (4)) as follows:

$$\pi t \leftrightarrow \pi s = \left.\sum_{i=1}^{n}\left[(b^{*}rb+ch)+(b^{*}pi)\right]+i\right] \Big/ a \tag{1}$$

$$\pi t = \left.\sum_{i=1}^{n}\left[(b^{*}rb+ch)+(b^{*}pi)\right]+p\right] \Big/ a \tag{2}$$

$$\pi p = \sum\nolimits_{i=1}^{n}(y^{*}\pi t+fb) \Big/ a \tag{3}$$

$$\pi s = \sum\nolimits_{i=1}^{n}((1-y)^{*}\pi t+v) \Big/ a \tag{4}$$

where, πt is total cost; πp is total cost of the prevention; πs is total cost of the suppression; and : b - number of firefighters; *rb* - income of firefighters; *ch* - income of brigade chief; *pi* - cost of individual equipment per firefighter; i - other expenditures (travel and food costs, including aircraft lease); p - total cost of other expenditure (without firebreaks and aircraft); fb - cost of firebreaks; v- cost of aircraft, a – CU area and y is percentage of prevention costs.

For CUs that have both prevention and suppression, we differentiate the costs as follows. In each CU, a "y" amount of investment relative to the costs from item 1 to 11 of Table 1 is for prevention activities. The rest (1-y) are applicable to direct firefighting (suppression). Thus, prevention costs are tantamount to "y" plus the costs of firebreaks. The suppression costs amount to "1-y" plus costs of aircrafts, which are deployed only for uncontrolled fires (ICMBio and MMA, 2018). We estimate the value of y as about 20%, on average, based on interviews with ICMBio staff.

For AT, we evaluate fire reduction within PPs (1029 in both biomes, 764 in Cerrado and 265 in the Amazon) after joining the AT socio-environmental registry program (Fig. 1). However, economic data are only available for the state of Mato Grosso that contains half of the registered PPs and 97% of brigade activities (Fig. S1). The costs for AT (Eq. 5 to 7) are as follows:

$$\pi t = \sum_{i=1}^{n}\left[(b^{*}rb + ch) + (b^{*}pi)\right] + i + m + c\Big] \quad (5)$$

$$\pi p = \sum\nolimits_{i=1}^{n}(y^{*}\pi t + t) \Big/ a_p \quad (6)$$

$$\pi s = \sum\nolimits_{i=1}^{n}((1-y)^{*}\pi t) \Big/ a_i \quad (7)$$

where m is maintenance costs (equipment and vehicles), c communication costs; t training costs, a_p properties area, a_i extent of fires put out or fought. All other variables are described above.

3.2. Role of fire management in reducing burned areas

ICMbio firefighting brigades based on specific CUs began in 2001 (Table S4), while AT's socioenvironmental registry program started in 2006. We evaluated whether there was a reduction in burned areas in CUs and PPs that received public (ICMbio) and private (AT) investments, respectively. To do so, we applied the Wilcoxon–Mann–Whitney test. This nonparametric statistical method essentially calculates the difference between two non-paired groups and analyzes the differences to establish whether the groups are statistically significantly different from one another (Mann and Whitney, 1947). For this test, we used maps of burned areas between 2001 and 2019 (Fig. 2) from the MODIS Fire Disturbance Product—MCD64A (Boschetti et al., 2019; NASA, 2019). Our analysis considers only burned areas larger than 100 ha, given the spatial resolution of ≈250 m of the MODIS Fire Disturbance Product. Statistical analyses were performed using the BioDinamica package of Dinamica EGO freeware (Oliveira et al., 2019). We developed five tests as follows:

1. Given the paucity of annual burned area records before the Amazon CUs began the fire suppression program, we tested whether there is a difference in burned areas between groups of Amazon CUs with and without fire brigade. Because the period of burned areas for both groups is the same, so is the climate variation. Yet the extent of burned areas within CUs varies as a function of CU size and location. Since there is an association of fire with deforestation in the Amazon (Barlow et al., 2019), we firstly tested whether the level of deforestation threat (Soares-Filho et al., 2010) in control CUs (without brigade) differs from that of CUs with brigade and also tested whether the climatic conditions—annual mean temperature and rainfall from WordClim dataset (Hijmans et al., 2005)—are randomly distributed across the two groups using the same the Wilcoxon–Mann–Whitney test. In addition, the test considers only CUs with history of fire (463 of 607) and only the burned areas in the 23 CUs after the initiation of their brigade operation. Finally, to account for areal difference, we used a ratio between burned areas and CU area.
2. We replicated the above test, now analyzing separately groups of strictly protected CUs with and without brigades and the same for groups of sustainable use CUs.
3. Also due to limited time-period of burned area records before the beginning of fire management programs, we compared the ratio between burned areas and CU area for groups of CUs of the Cerrado with and without brigades. We also tested whether climatic—annual mean temperature and rainfall from WordClim dataset (Hijmans et al., 2005)—and anthropic conditions—accessibility map (Weiss et al., 2018)—are randomly distributed across both groups of CUs using the Wilcoxon–Mann–Whitney test.
4. For testing the effect of fire prevention management, we compared the ratio between burned areas and CU area for groups of CUs of the Cerrado with only fire suppression with the ones that also carry out fire prevention as part of their IFM program.
5. We tested whether the AT socioenvironmental registry had an effect in reducing burned areas. To do so, we compared burned areas within PPs before and after their entering the registry. Interannual climate variation is assumed random due to the large number of properties (1029 PPs in both biomes), with each property entering the registry at a particular year. We also disaggregated this analysis for the two biomes.

The Wilcoxon–Mann–Whitney test only identifies whether the difference between the groups is statistically significant. Nevertheless, we potentially gauge the magnitude of difference between the groups, if we find them different, by calculating the percentage of difference between the CU groups' mean burned area ratio (i.e. burned areas divided by the respective CU area) or for the AT's private properties, the mean burned area within PPs before and after their registering.

4. Results

4.1. Costs and effectiveness of fire management by ICMBio in the Amazon

In the Amazon, the budget costs of ICMBio's fire management, which include only fire suppression for both CU categories, average US$ 3 million year^{-1} or US$ 0.51 ha^{-1} yr^{-1}. CUs situated in Pará and Amazonas states have the highest absolute cost of US$ 1.13 million year^{-1} (Fig. 1). This region encompasses the largest number of CUs attended to by brigades in the Amazon (5 CUsp and 4 CUsu) (Fig. 1). The CUsu with the highest absolute costs in the Amazon are *Viruá* with US$ 310 thousand year^{-1}, *Lago Piratuba* with US$ 228 thousand year^{-1} and *Campos Amazônicos* with US$ 216 thousand year^{-1}. The northern Amazon (Amapá and Roraima states) contains the CUs with the highest relative costs, amounting to US$ 1.00 ha^{-1} yr^{-1}. The CUs that contribute most to these costs are the *Maracá-Jipioca* with a cost of US$ 2.80 ha^{-1} yr^{-1} and *Viruá* with costs of US$ 1.44 ha^{-1} yr^{-1} (Fig. 1, Table S5). On average, investments in CUsp are three times greater than investments in CUsu in all regions. In absolute terms, CUsp have a total budget cost of US$ 2.15 million year^{-1} (72% of CUs' costs), or US$ 0.52 ha^{-1} yr^{-1}. In turn, CUsu budget costs amount to US$ 845 thousand year^{-1}, or US$ 0.39 ha^{-1} yr^{-1}.

The Wilcoxon-Mann-Whitney test for checking whether the two groups of Amazon CUs differ in terms of level of threat and climatic conditions showed no statistically significant difference ($p = 0.4644$, $p = 0.4214$, $p = 0.3738$, for level of threat, annual mean temperature, and rainfall, respectively). Therefore, we were able to compare the groups for difference in burned areas. Test #1 for the two groups of Amazon CUs without and with brigades showed that the average ratio between burned areas and CU area is 64% lower (p-value <2.2e-16) for the latter. Further, test # 2 indicated a tantamount reduction (63%, p-value <2.2e-

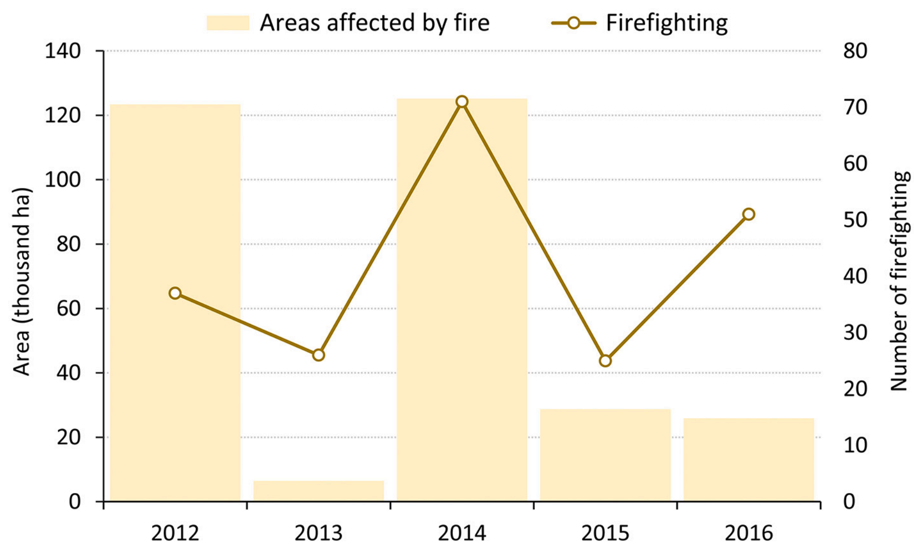

Fig. 3. Areas affected by fire and firefighting actions by AT brigades between 2012 and 2016.

16), when comparing strictly protected groups of CUs without and with brigades, whereas the comparison between groups of Sustainable Use CUs with and without brigades showed virtually no reduction (0.26%, p-value <2.2e-16).

4.2. Costs and effectiveness of fire management by ICMBio in the Cerrado

Total budget costs of suppression in Cerrado for all 21 CUs with brigades are US$ 4.79 million year[1] (Fig. 1, Table S5), while costs including prevention and suppression amount to US$ 5.29 million year^{-1} or US$ 5.32 ha^{-1} yr^{-1}. These costs are almost the double of those of Amazon CUs. IFM programs occur only in seven CUs in the Cerrado. For these CUs, we estimate that the average costs of prevention campaigns amount to US$ 504 thousand year^{-1}, while suppression costs reach up to US$ 2.02 million year^{-1}, or US$ 0.78 ha^{-1} yr^{-1} and US$ 3.10 ha^{-1} yr^{-1}, respectively.

The test for checking whether the two samples of Cerrado CUs differ in terms of anthropic pressure and climatic conditions showed no statistically significant difference (annual mean temperature: $p = 0.3534$, annual mean rainfall: p: 0.07928 and accessibility: $p = 0.3107$). Test #3 for the two groups of Cerrado CUs without and with brigades showed that the average ratio between burned areas and CU area is 12% lower (*p*-value <2.2e-16) for the latter. In addition, test # 4 indicated an average reduction of 6% (p-value <2.2e-16) between CUs with prevention practices and those with only brigades.

Among CUs with IFM programs including prevention and suppression (Fig. 1, Table S5), *Serra da Canastra* received the largest investment (US$ 555 thousand year^{-1}, the equivalent to US$ 2.81 ha^{-1} yr^{-1}). *Serra do Cipó* also received one of the largest investments of the Cerrado CUs (US$ 449 thousand year^{-1} or US$ 14.18 ha^{-1} yr^{-1}). *Chapada dos Veadeiros*, which recently underwent a large expansion, received US$ 364 thousand year^{-1} or 5.62 ha^{-1} yr^{-1}. In turn, *Sempre-Vivas* received US$ 273 thousand year^{-1} (US$ 2.20 ha^{-1} yr^{-1}) and the cost for the *Chapada das Mesas* is US$ 207 thousand year^{-1} (US$ 1.30 ha^{-1} yr^{-1}). *Serra Geral do Tocantins*, where ICMbio firstly adopted the IFM program, had investments of US$ 405 thousand year^{-1} (US$ 0.57 ha^{-1} yr^{-1}). Finally Araguaia received US$ 270 thousand year^{-1} (US$ 0.49 ha^{-1} yr^{-1}). Despite these investments in IFM, wildfires continue to ravage most of the aforementioned units, showing recurrent surges in burnings, with only a slightly declining trend, except for the rising trend of the Araguaia Park, which cannot be ascribed with scientific certainty to IFM interventions (Fig. S3). Regarding the latter CU, it is worth mentioning that this is one the regions most affected by fire in the Cerrado, with large burnings every year (Fig. 2).

4.3. Costs and effectiveness of Aliança da Terra's fire management program

As explained in Section 3, our analysis of AT's budget costs is restricted to the state of Mato Grosso (Table S2). Direct firefighting by AT brigades costs eight times more, on average, than prevention measures including training and capacitation and registering of properties on the AT socioenvironmental platform. AT invested an average of US$ 75 thousand year^{-1} in prevention and US$ 311 thousand year^{-1} in suppression. As a result, suppression costs (Eq. 7) are equivalent to 81% of total costs (Eq. 6).

Test # 5 pointed out that PPs in both biomes showed an average reduction of 50% in burned areas (p-value <2.2e-16) after entering the socioenvironmental registry of AT. In the Amazon biome, a total of 265 rural properties are registered in the AT platform, 68% of which occupied a large part of the arc of deforestation in northern Mato Grosso (Fig. 1, S1). Amazon landowners have managed to reduce burned areas by 35% after joining the AT initiative despite being located in a region of high deforestation rates (Fig. S2). In the Cerrado biome, there are 764 PPs registered in the AT platform, who were able to reduce burned areas within their lands by 58% (p-value <2.2e-16) after joining the AT socioenvironmental program.

The relative cost of suppression is equivalent to US$ 15.89 ha^{-1} yr^{-1} derived from firefighting 310 thousand ha (Fig. 3) between 2012 and 2016. In the same period, the AT brigade carried out 210 firefighting actions (Fig. S1), which is equivalent to an average investment of US$ 9.32 thousand per fire combat. The relative cost of prevention was US$ 0.19 ha^{-1} yr^{-1} for fire mitigation in 1.9 million hectares of PPs.

5. Discussion

Our results demonstrate that, in general, investments in fire management initiatives reduce burned areas. However, investments in both fire prevention and suppression in the Amazon and Cerrado biomes in Brazil remain small compared with those of the Global North countries. Our results also indicate that these investments are not evenly distributed and that their effectiveness is not homogeneous. More specifically, our results suggest that (1) there is an overemphasis on fire suppression; (2) public fire management program (ICMBio) in the Amazon is only effective for strictly protected CUs; (3) Cerrado CUs receive insufficient investments in IFM despite recurrent wildfires, and 4) landowners

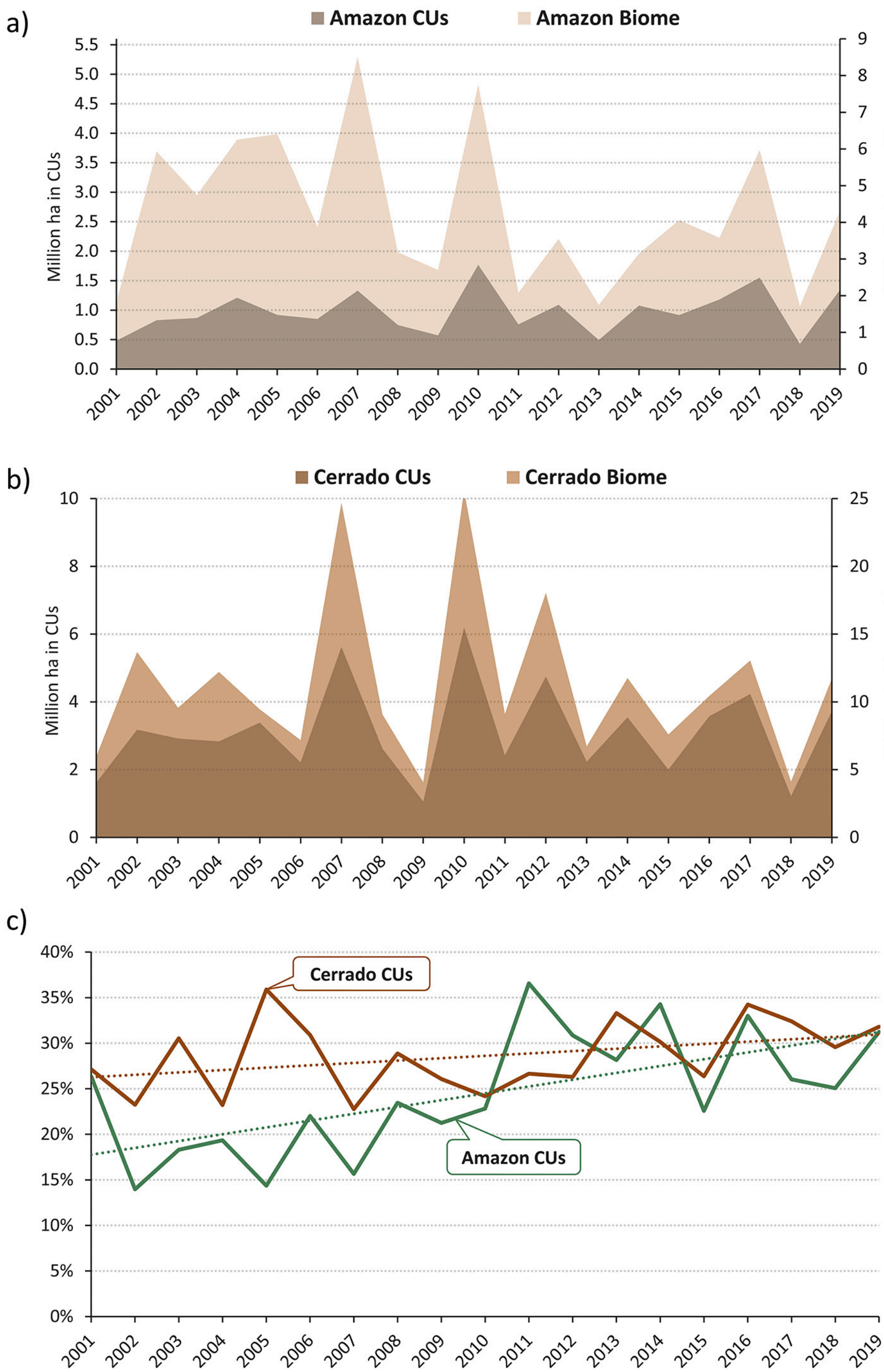

Fig. 4. a) Burned areas in the Amazon and within its CUs. b) Burned areas in the Cerrado and within its CUs. c) Proportion of burned areas within CUs in relation to the entire biome.

respond well when trained to prevent fire.

Both private (AT) and public (ICMBio) investments have prioritized fire suppression over fire prevention. Only seven of 353 CUs in the Cerrado have fire prevention activities, while CUs in the Amazon exclusively invested in suppression activities. Overall, ICMBio spent only 6% of its budget on prevention practices. At the same time, our results indicate that those CUs that invested in fire prevention are more effective as they further reduced by 6% burned areas from CUs that exclusively carried out fire suppression. Private investments by AT showed similar results, spending more on fire suppression (US$ 311 thousand year^{-1}) than on fire prevention (US$ 75 thousand year^{-1}). These figures are contrary to what is recommended by various scholars, who argue for a better balance between fire suppression and prevention investments (Lankoande, 2005; Snider et al., 2006; Gebert et al., 2008; Mendes, 2010).

In addition to a clear need for more investments in fire prevention, our results also point to some regions that require particular attention from fire management programs. Particularly the southern fringe of the Amazon biome along the Cerrado, known as the arc of deforestation (Fig. 1 and S2), is prone to wildfires due to high deforestation rates and gradual transition to a drier climate (Lovejoy and Nobre, 2018). The Cerrado biome also demands more comprehensive fire control policies (Moura et al., 2019). Despite receiving larger investments than the Amazon CUs, current fire budget expenditures do not suffice to tame the recurrent wildfires that plague the Cerrado CUs almost every year (Fig. 4b). Nevertheless, this picture could be even worse without those investments given the rising trend in the concentration of burnings in both Amazon and Cerrado CUs (Fig. 4a, b, and c).

Rural properties reduced burned areas by 50% (35% and 58% in the Amazon and Cerrado, respectively) after entering the socio-environmental registry. This suggests that landowners respond well when trained to prevent fire. Conversely, fire management by ICMBio in CUs faces some substantial social challenges. Particularly, frequent and large burnings still occur in the Cerrado CUs, especially in units with land conflicts due to prior and current inholdings not yet financially compensated for land expropriation, such as the examples of *Chapada dos Veadeiros* and *Serra da Canastra* (Röper, 2000; Rodrigues et al., 2018).

Even though our results point out to a reduction in burned areas where there is a combination of fire prevention and suppression, we observe that there is still an emphasis on the latter. Land managers (both public and private) are often reluctant to invest in IFM (Nepstad et al., 2001). Nevertheless, investments in IFM yield higher benefits rather than incur costs to both public and private lands, especially if we account for avoided economic losses (Oliveira et al., 2018). According to Zybach et al. (2009), economic losses due to fire can be up to 50 times greater than investments in IFM. For example, a 29% reduction in the likelihood of fires in the Amazon potentially avoids economic losses in rural properties from US$ 90 million to US$5 billion year^{-1} (Mendonça et al., 2004).

All of this thus suggests an excellent cost-benefit of fire prevention. However, fire suppression activities continue to be much more prominent than those of prevention (Mavsar et al., 2013) in Brazil and other countries as well. As such, our study underscores the opportunity for a better integration between these two fire management components in a way that could be beneficial not only for Brazil but also for other similar contexts. The challenges to reduce fire in the Amazon and Cerrado will increase due to climate change. This requires a comprehensive approach that includes more investments in an optimal mix of private and public programs for research, education, and training that complement public policies for forest protection and climate change mitigation and adaptation. For example, prioritizing investments in regions with high risk of fire propagation indicated by using state-of-art computer modeling may have positive impacts in reducing burned areas (FIP-CERRADO, 2020 - csr.ufmg.br/fipcerrado). Unfortunately, such investments have diminished drastically. Although Brazil started drafting a national policy to reduce damages due to forest fires in 2017, large budget cuts in 2019–2021 for fire management brought those policies to a halt. As a result, a recent surge of wildfires associated with steep rise in deforestation rates devastated vast areas of the Amazon and the Pantanal entailing grave consequences to the environment (Sokolik et al., 2019; INPE, 2020).

6. Final remarks

Designing cost-effective fire management in large regions, such as the Amazon and Cerrado biomes in Brazil, is very challenging. Here we calculated that average budget spending on fire management in CUs is US$ 0.51 ha^{-1} yr^{-1} in the Amazon and US$ 5.32 ha^{-1} yr^{-1} in the Cerrado. On private lands, average budget spending is US$ 15.89 ha^{-1} yr^{-1}. Roughly, 94% of public investments are assigned to suppression activities, alone. However, preventive measures as part of IFM strategy in Cerrado CUs have further reduced burned areas compared with CUS that only carried out suppression activities. Our results support the need for a more comprehensive IFM approach that, in addition to ground activities, includes cost-effectiveness fire analyses together with territorial intelligence based on state-of-art computer modeling able to pinpoint in near real time the risk of fire propagation. All of this will help direct efforts to tame the ever-increasing risks of wildfire due to a warmer climate and continued deforestation.

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.

Acknowledgements

We are thankful to Aliança da Terra and ICMBio (Instituto Chico Mendes de Conservação da Biodiversidade) for providing data for this research. We acknowledge funding from the Forest Investment Program (FIP), World Bank Project no. P143185: “Development of systems to prevent forest fires and monitor vegetation cover in the Brazilian Cerrado”. BS received support from the Alexander von Humboldt foundation, BS and RJ are also supported by Climate and Land Use Alliance (CLUA) and Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPQ). AO was supported by CAPES (Coordenação e Aperfeiçoamento de Pessoal de Nível Superior).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.forpol.2021.102447.

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