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ASSESSMENT OF THE IMPACT CAUSED BY FIRES IN THE BRAZILIAN LEGAL AMAZON FROM 2001 TO 2020

Wesley Augusto Campanharo

Doctorate Thesis of the Graduate
Course in Remote Sensing,
guided by Drs. Liana Oighenstein
Anderson, and Thiago Fonseca
Morello Ramalho da Silva,
approved in July 29, 2021.

URL of the original document:

<<http://urlib.net/8JMKD3MGP3W34T/455DTUL>>

INPE
São José dos Campos
2021

PUBLISHED BY:

Instituto Nacional de Pesquisas Espaciais - INPE
Coordenação de Ensino, Pesquisa e Extensão (COEPE)
Divisão de Biblioteca (DIBIB)
CEP 12.227-010
São José dos Campos - SP - Brasil
Tel.:(012) 3208-6923/7348
E-mail: pubtc@inpe.br

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INPE
São José dos Campos
2021

Cataloging in Publication Data

Campanharo, Wesley Augusto.

C151a Assessment of the impact caused by fires in the Brazilian Legal Amazon from 2001 to 2020 / Wesley Augusto Campanharo. – São José dos Campos : INPE, 2021.

xx + 156 p. ; (sid.inpe.br/mtc-m21d/2021/07.22.11.18-TDI)

Thesis (Doctorate in Remote Sensing) – Instituto Nacional de Pesquisas Espaciais, São José dos Campos, 2021.

Guiding : Drs. Liana Oighenstein Anderson, and Thiago Fonseca Morello Ramalho da Silva.

1. Wildfire. 2. Amazon. 3. Econometrics. 4. Environmental valuating. 5. Geoprocessing. I.Title.

CDU 630*43:528.8(811)



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BANCA Nº 197/2021 REG 142409/2017

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Título: “ASSESSMENT OF THE IMPACT CAUSED BY FIRES IN THE BRAZILIAN LEGAL AMAZON FROM 2001 TO 2020”

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DON'T PANIC !
[Douglas Adams]

ACKNOWLEDGEMENTS

It has been a long time since this journey began, and it was not easy at all. However, like a rollercoaster, it has its ups and downs, but for a good adventurer this will always be exciting. The scientific side of my life started with the endless curiosity to understand and see how things work and what happens if we change them. However, the desire to get a doctorate degree appeared in the middle of the journey, when I began teaching and instructing how to use SIG programs and how to delimit watersheds.

I am very grateful for all things that already happened to me, and I need to be ready for things that will come. In this doctorate's period, it was not different. I am very thankful for Dr. Liana O. Anderson to have chosen me among other dreamers to guide in this new path, including a brand-new area, the wildfire study. Also, I am grateful to be introduced to Dr. Thiago Morello, who helped me to understand the Econometrics language of Economists and how they behave. Jokes apart, those moments of listening and learning provided by both of them were very important to my personal and professional growth.

In this Doctorate, it is impossible to forget the “sandwiched” period in Italy, where I lived one year under the JRC bubble. It was a world of technology and possibilities inside a small old town, called Ispra. I am very thankful to have met Dr. Jesus San-Miguel and his colleagues, Rosana, Duarte, Tomas, Daniele, David, Alfredo, Pieralberto, Roberto, Hans and Tracy, who helped me in the fire fields research and to survive in Italy.

Besides that, the COVID experience in JRC allowed me to meet Dr. Maria Christofolletti, who showed me the Instrumental Variable method, which solved a big issue that I faced during this thesis. Every burned cake and melted ice-cream were worthy thanks to the thoughts and discussions that followed them.

As said by Emicida, "who has friends, has everything", so I am very lucky to have found such incredible people in this process. I am grateful for Debora, Juliana, Carol, and Jessica, who started a simple and random class work and stayed together during all the journey.

To the Trees lab, for the friendship that was possible to have and the people to interact ("gringos" and native ones). Especially to Celso, Igor José, Thais and Igor Broggio (Former "Sala 02") for all edifying thoughts. Also to Aline, who is a very good friend and an incredible paper partner.

To my fellow roommates, Philip, Andeise, and Victor, for being respectful during a very stressful doctorate life.

And to Diego, that was patient and persistent during this long doctorate process that we both faced almost at the same time, which was many times aggravated by the distance imposed.

I am thankful for all grants received along these years in the doctorate, including the CAPES, CNPq and my mother. Especially the last one, who did not understand very well what I was always looking at on the computer (known as programming process), but never stopped believing in my potential or asking for a full report.

Lastly, but still important, thanks for all those people that directly or indirectly contributed to this Thesis either physically or by helping me to maintain my mental health.

My sincere thanks | Muito Obrigado | Grazie mille

ABSTRACT

Humans were only able to evolve thanks to the use and the control of fire learned some million years ago. However, with great power comes great responsibility, and for now it seems that the fire is uncontrolled or not well managed. The damages documented so far can be sensed directly (human life loss, burning production, damaging infrastructure, reducing biodiversity, affecting cultural resources) or indirectly (changing the climate, increasing hospitalizations, reducing tourism, promoting species migration, and affecting transport of people and goods), both occurring at any kind of scale (locally, regionally, globally). The Amazon region is the primary source of biodiversity in the Neotropics, being the genetic pool to other places and also providing important ecosystem services. The Brazilian Legal Amazon (BLA), is a geopolitical region, that is responsible for 8.5% of the Gross Domestic Product (GDP), besides being home for more than 24 million inhabitants, including indigenous and traditional communities. Only in the past 20 years, severe droughts with major associated wildfires were reported in the region. This phenomenon brings several consequences, and most of them are still uncountable or not well characterized. This thesis, hence, aims to quantify the impact of fire in the BLA in recent years (from 2001 to 2020), accessing the damage either by a monetary aspect or by a tangible form, categorizing it in a disaster context (environmental, material, and human damages). The thesis was based on three main chapters, the first one is a case study, the second is a methodological update, and the third one shows the total damage accounted for the last 20 years. The case study focused on Acre state aimed to establish a methodological basis to allow the up scaling the results to the entire BLA region. In the local scale, the use of fire was closely linked to the agricultural sector, especially connected to large proprietaries as a tool for deforestation and pasture management. The total damages between 2008 and 2012 in Acre caused by fire represents $0.51\% \pm 0.10$ of the state's GDP in normal climatic years, reaching up to $7.03\% \pm 2.45$ in drought years (2010). In this case study, the estimate of the relation between hospitalization and fires was not entirely elucidated. The second chapter, which covers the whole Amazon, therefore, was delineated to use an Instrumental Variable (IV) approach to determine how respiratory hospitalizations are associated with air pollution induced by fires, using a large data set. The results revealed a positive effect of fire-pollution on the hospitalization due to respiratory diseases in general and, specifically, due to Asthma, which the model predicts that approximately 4,000 people are yearly affected. The results indicate that the estimates could have been further improved by using other pollutant indicators, neighborhood effects, time lag or even downscaling the series. Finally, the last chapter analyzes the main pattern of the fire and its impacts over the BLA through the last 20 years. The results exposed that approximately 17% of the BLA region already suffered with fire at least once, mostly in small patches (≤ 40 ha). Nevertheless, this pattern changes over the years, with an increase of: (1) the minimum area per month, (2) the occurrence of anomalous months, and (3) the total burned area of the first months of the year. Over these 20 years, the equivalent damage caused by the use of fire is around $6.28\% \pm 1.1$ p.p per year considering the BLA's GDP. Therefore, this thesis provided a methodological structure and information to understand the extent, the magnitude and the damage caused by fire in the BLA, contributing to assist managers in the construction of public policies and clarifying the side effects of fire over the time.

Keywords: Wildfire. Amazon. Econometrics. Environmental valuating. Geoprocessing.

AVALIAÇÃO DOS IMPACTOS CAUSADOS POR INCÊNDIOS NA AMAZÔNIA LEGAL BRASILEIRA ENTRE 2001 E 2020

RESUMO

A espécie humana só foi capaz de evoluir graças ao uso e ao controle do fogo aprendidos há milhões de anos atrás. Porém, com grande poder vem grande responsabilidade, e por enquanto parece que o fogo está descontrolado ou mal administrado. Os danos documentados até agora podem ser relacionados diretamente (perda de vidas, queimando produções agrícolas, danificando infraestrutura, reduzindo a biodiversidade, impactando recursos culturais) ou indiretamente (mudando o clima, aumentando as hospitalizações, reduzindo o turismo, promovendo a migração de espécies e afetando o transporte de pessoas e bens), ambos ocorrendo em qualquer escala (local, regional, global). A região amazônica é a principal fonte de diversidade na região Neotropical, fornecendo várias linhagens para outras localidades, gerando importantes serviços ecossistêmicos. A Amazônia Legal Brasileira (AMZL), por sua vez, é uma região político administrativa responsável por 8,5% do Produto Interno Bruto (PIB), além de abrigar mais de 24 milhões de habitantes, entre comunidades indígenas e tradicionais. Somente nos últimos 20 anos, secas severas desencadearam grandes incêndios florestais na região. Esse fenômeno traz várias consequências, e a maioria delas ainda são desconhecidas ou mal caracterizadas. Desta maneira esta Tese visa quantificar o impacto do uso do fogo na AMZL nos últimos anos (2001 a 2020), tanto pelo aspecto monetário como também pela forma tangível, categorizando-o sob o contexto de desastre (separando em classes de danos ambientais, materiais e humanos). Para tanto, a tese está fundamentada em três capítulos principais, o primeiro é um estudo de caso, o segundo é uma atualização metodológica e o terceiro mostra os danos totais contabilizados nos últimos 20 anos. O estudo de caso focado no estado do Acre teve como objetivo estabelecer uma base metodológica capaz de ser extrapolada para toda a região da AMZL. Sob esta escala local, o uso do fogo está intimamente ligado ao setor agrícola, principalmente como ferramenta de desmatamento e manejo de pastagens em grandes propriedades. O total de danos causados pelo fogo entre 2008 e 2012 no Acre representa $0,51\% \pm 0,10$ do PIB do estado em anos climáticos normais, chegando a $7,03\% \pm 2,45$ em anos de seca (2010). Porém, neste estudo de caso, a estimativa da relação entre as taxas de hospitalizações e área queimada apresentou-se complexa e não totalmente válida. Assim, o capítulo dois foi delineado para se utilizar uma abordagem econométrica por meio de Variável Instrumental (IV) para determinar as hospitalizações respiratórias associadas à poluição derivadas do uso do fogo na região da AMZL, usando um grande conjunto de dados. Os resultados revelaram um efeito positivo do fogo no total de hospitalizações por doenças respiratórias e também por Asma, prevendo que cerca de 4.000 pessoas sejam afetadas anualmente. Os resultados indicam que as estimativas podem ser melhoradas utilizando outros indicadores de poluentes, efeitos de vizinhança, defasagem de tempo ou mesmo reduzindo a escala da série. Por fim, o último capítulo analisa, o padrão característico do fogo e seus impactos sobre a AMZL ao longo dos últimos 20 anos. Os resultados evidenciaram que cerca de 17% da região já sofreu com incêndios pelo menos uma vez, sendo pequenas manchas (≤ 40 ha) as mais recorrentes. No entanto, esse padrão muda ao longo dos anos, com o aumento:

(1) da área mínima mensal, (2) da ocorrência de meses anômalos e (3) da área total queimada dos primeiros meses do ano. Nestes últimos 20 anos, o dano equivalente causado pelo uso do fogo é de $6.28\% \pm 1.1p.p$ ao ano, considerando o PIB da AMZL. Desta maneira, esta Tese forneceu uma estrutura metodológica e informações para se entender a extensão, a magnitude e os danos causados pelo fogo na AMZL, contribuindo para auxiliar os gestores na construção de políticas públicas e esclarecendo os efeitos colaterais do fogo ao longo do tempo.

Palavras-chave: Incêndios. Amazônia. Econometria. Valoração ambiental. Geoprocessamento.

LIST OF FIGURES

	<u>Page</u>
Figure 2-1. Schematics of Fire impacts in an ecosystem with details of different scales and effect.	6
Figure 2-2. Different effects of burnings over the chemical, physical and biological soil proprieties.	11
Figure 3-1. Location of the study area.	16
Figure 3-2. Workflow for generating the annual maps of remaining and loss of biomass.	24
Figure 3-3. Burn scars in Acre state (Brazil), mapped with 250 m spatial resolution, for the regular climate years of 2008, 2009, 2011, and 2012 (a) and for the 2010 drought year (b).	29
Figure 3-4. Evaluation of the annual burned area time series from 2008 to 2012.	31
Figure 3-5. The proportion of burned area by (a) management types; (b) land use and land cover; (c) propriety class.	32
Figure 3-6. The proportion of burned area by land use and land cover types (a) and by special areas (b), through the years analyzed.	34
Figure 3-7. The proportion of biomass loss (b) and CO ₂ emissions (c) by land use and land cover types and the total biomass loss (a) and total emissions(d) through the years analyzed.	36
Figure 3-8. Correlation between respiratory morbidity and burned area by year analyzed, with the determination coefficient value (r^2), the correlation coefficient value (r), and the specific p-values.	37
Figure 3-9. Percentage of economic loss by type of damage (a), total economic loss (b), and GDP equivalence (c) by year.	38
Figure 3-10. Correlation between GDP of the agricultural sector and burned area.	41
Figure 4-1. Municipalities within the nine states of BLA used in this study.	48
Figure 4-2. Spatialization of the time series average for burned area, AOD and total hospitalizations, aggregated by municipalities.	58

Figure 4-3. Temporal variation in monthly average values for burned area, AOD and total hospitalizations.	58
Figure 4-4. Monthly variation in mean values of burned area (log) considering the predominant wind speed and meteorological direction for the BLA region.	60
Figure 4-5. Estimates of total hospitalizations and Asthma hospitalizations due to fires (%).	63
Figure 4-6. Temporal variation in average monthly values of thermal anomalies for the region.	63
Figure 4-7. Correlation of monthly values of thermal anomalies and burned area, for all-time series and monthly.	68
Figure 5-1. Different delimitation of the Amazon, with focus on the Brazilian Legal Amazon.	72
Figure 5-2. Monthly and total annual variation of the burned area between 2001 and 2020 (left) and monthly average values (right).	85
Figure 5-3. Trend in burned area at a monthly scale for the BLA region.	86
Figure 5-4. Trend in annual maximum, mean and minimum values (left), and monthly burned area anomalies (right).	87
Figure 5-5. Percentage of monthly fire by year, highlighting the fire season for the Brazilian Legal Amazon (BLA) and for each state covered by it.	88
Figure 5-6. Contribution (%) of each state in the total burned area for the BLA, presented in monthly and annual values.	89
Figure 5-7. Spatial distribution of frequency and recurrence of burned areas in the Brazilian Legal Amazon.	90
Figure 5-8. Variation in the proportion of new burned areas and previously affected ones over the analyzed period and per month.	91
Figure 5-9. Variation of events by size class occurred per month (first row) and per year (second row) in the BLA.	91
Figure 5-10. Groups of similar years in relation to the accumulated total and its variation over the months.	92

Figure 5-11. Summary of fire impacts on the LULC over the last 20 years: A - is the fire trend in each LULC class; B - is the LULC map for the year of 2019; C – is the average annual of each class affected by fire; D – historical percentage of each class affected by fire.....	95
Figure 5-12. Summary of fire impacts on land tenure: A – distribution map of land tenure in the BLA region; B – trend in burned area by land tenure class; C – annual average of burned classes; D - average of Public class affected by fire per year.	96
Figure 5-13. Estimate of the number of hospitalizations for respiratory diseases over the last 20 years.	96
Figure 5-14. Estimates of carbon dioxide emission (Tg CO ₂) per month over the 20 years analyzed under the committed and immediate form.	97
Figure 5-15. Total monetary damage caused by fire over the last 20 years in the BLA region, discretized by damage category.	98
Figure 5-16. Ratio between total fire damage and GDP in the region over the time series.	98
Figure B-1. Evolution of LULC for the BLA region and its biomes.	152
Figure B-2. Trends in burned area for each public land tenure.....	153
Figure B-3. Total of municipalities affected by fire per year in the BLA region.....	153
Figure B-4. Total of CO ₂ emission through the years analyzed, considering the National estimate (SIRENE) and the BLA’s immediate fire emission.	154
Figure B-5. Deforestation and Fire relation through the age groups.....	155

LIST OF TABLE

	<u>Page</u>
Table 3-1. Summary of the spatial dataset used.	17
Table 3-2. Costs, prices, and index used.	18
Table 3-3. Summary of TerraClass land use and land cover (LULC) types	19
Table 3-4. Total burned area in hectares (km ²) that burned one time, more than once, and the number of burned scars in sequence of year.....	28
Table 3-5. Summary of burned scars between 2008 and 2012 for Acre state.	30
Table 3-6. Distance, in kilometers, of rivers (Ri) and roads (Rd) to burned scars.....	30
Table 3-7. The proportion of each land use and land cover class in Acre state through the years.....	32
Table 3-8. Number of proprietaries affected by fires through the years.	33
Table 3-9. Area (km ²) of Conservation Units affected by fire through the years analyzed.....	34
Table 3-10. Area (km ²) of Indigenous land affected by fire through the years analyzed.....	35
Table 3-11. Cost in millions of dollars of losses by fire in Acre state between 2008 and 2012, with a percent of total costs (%) and a related percent of total GDP.	38
Table 4-1. Short description of the data, categorized by type.	48
Table 4-2. Descriptive statistics of the data, subdivided by type and calculated at a municipality level and monthly.....	57
Table 4-3. Correlation between the instrumental variables and the explanatory variable.	60
Table 4-4. Summary of the best model fitted of the variation in the Aerosol Optical Depth (AOD) in hospitalization counts due to the thermal anomalies, presented by age and respiratory illness type.....	61
Table 4-5. Correlation among the instrumental variables and the explanatory variable.....	63

Table 4-6. Mean effect of the variation in the Aerosol Optical Depth (AOD) on hospitalization due the thermal anomalies, presented by age and respiratory illness type.	64
Table 5-1. Reclassification of MapBiomass' collection 5 of land use and land cover classes.	73
Table 5-2. Class of land tenure available in the IMAFLORA product, with the indicative of category and group.	75
Table 5-3. Average biomass values by LULC class extracted from the Biomass_CCI product.	76
Table 5-4. Used expressions for uncertainty propagation.	84
Table 5-5. Mean values for each variable used in the characterization of fire, as well as the significance (p.value) of the Kruskal-Wallis test for comparison between means, separated by group of years.	93
Table A-1. Mean effect of the variation in the Aerosol Optical Depth (AOD) on the Total respiratory disease hospitalization counts due to the burned area.	145
Table A-2. Mean effect of the variation in the Aerosol Optical Depth (AOD) on the hospitalization of Small Children due to the burned area.	146
Table A-3. Mean effect of the variation in the Aerosol Optical Depth (AOD) on the hospitalization of children due to the burned area.	147
Table A-4. Mean effect of the variation in the Aerosol Optical Depth (AOD) on the hospitalization of the elderly due to the burned area.	148
Table A-5. Mean effect of the variation in the Aerosol Optical Depth (AOD) on the Asthma hospitalizations due to the burned area.	149
Table A-6. Mean effect of the variation in the Aerosol Optical Depth (AOD) on the Pneumonia hospitalizations due to the burned area.	150
Table A-7. Mean effect of the variation in the Aerosol Optical Depth (AOD) on the Bronchitis hospitalizations due to the burned area.	151
Table B-1. Percentage of each land tenure type and category over the BLA territory.	153
Table B-2. Trends in each state, considering the total burned area by different methods.	154

CONTENTS

	<u>Page</u>
1 INTRODUCTION	1
1.1 Motivation and objectives	2
1.2 Thesis outline.....	4
2 LITERATURE REVIEW	6
2.1 Human damages	7
2.2 Material damages.....	8
2.2.1 Environmental damages	8
3 ECONOMIC LOSSES CAUSED BY FIRES FROM 2008 TO 2012 IN ACRE STATE, BRAZILIAN AMAZON.	13
3.1 Introduction	13
3.2 Materials and methods.....	16
3.2.1 Study area	16
3.2.2 Data.....	17
3.2.3 Data analysis.....	23
3.3 Results	28
3.3.1 Spatiotemporal variability of fire dynamics	28
3.3.2 Fire occurrence and land tenure relationship.....	31
3.3.3 Environmental, social, and economic impacts of fire	35
3.4 Discussion.....	38
3.4.1 Spatio-temporal variability of fire dynamics.....	38
3.4.2 Fire occurrence and land tenure relationship.....	39
3.4.3 Environmental, social, and economic impacts of fire	42
3.5 Conclusions	43
4 HOSPITALIZATION DUE TO FIRE-INDUCED POLLUTION IN THE BRAZILIAN LEGAL AMAZON FROM 2005 TO 2018	45
4.1 Introduction	45
4.2 Material and methods	47
4.2.1 Study area	47
4.2.2 Data.....	48
4.2.3 Spatial aggregation	52
4.2.4 Empirical model	53
4.2.5 Simulation: hospitalizations attributable to fires	56
4.3 Results	57
4.3.1 Database behaviour.....	57

4.3.2	Econometrics estimates	60
4.3.3	Hospitalization attributable to fires	62
4.3.4	Robustness check.....	63
4.4	Discussion.....	65
4.5	Conclusion.....	68
5	TWO DECADES OF FIRE IMPACTS IN THE BRAZILIAN LEGAL AMAZON.....	70
5.1	Introduction	70
5.2	Material and methods	72
5.2.1	Study area	72
5.2.2	Spatial dataset.....	73
5.2.3	Non-explicit spatial datasets.....	77
5.2.4	Data analysis.....	78
5.2.5	Uncertainty	84
5.3	Results	85
5.3.1	Fire pattern in the BLA.....	85
5.3.2	Clustering years	92
5.3.3	Fire impacts	94
5.3.4	Monetary quantification	97
5.4	Discussion.....	99
5.4.1	The main patterns of the burned area in the BLA	99
5.4.2	The magnitude of fire impact over 20 years.....	101
5.4.3	Side effect of fire in national and international environmental targets	105
5.5	Conclusion.....	108
6	GENERAL DISCUSSION.....	110
7	CONCLUDING REMARKS	113
	REFERENCES	114
	APPENDIX A -SUPPLEMENTARY MATERIAL FROM CHAPTER 4	145
	APPENDIX B -SUPPLEMENTARY MATERIAL FOR CHAPTER 5	152

1 INTRODUCTION

This millennium is known as the *Pyrocene*, because humanity is altering the global fire regime (PYNE, 2020; VAUGHAN, 2019). Just during the last years, strong fire events occurred globally, such as those in Portugal in 2017, (TURCO et al., 2019), Greece in 2018 (LAGOUVARDOS et al., 2019), California in 2018 (CAL FIRE, 2021), in the Amazon during 2015/2016 and 2018/2019 (ARAGÃO et al., 2018; BRANDO et al., 2020), in Australia in 2019/20 (HUGHES et al., 2020), and among others places.

This scenario is alarming since weather is becoming more favourable to uncontrolled fires across time, a change that will be exacerbated in the near future according to the available forecasts (IPCC, 2021a). This is true especially in the Brazilian Amazon, where the frequency and intensity of drier conditions are expected (LI; FU; DICKINSON, 2006; AVILA-DIAZ et al., 2020), including the expansion of ecological drought, aridity and fire weather conditions that will affect negatively a wide range of sectors (IPCC, 2021b). In this sense, fire in the Amazon region, which is mainly human driven (ALENCAR; RODRIGUES; CASTRO, 2020; BARLOW et al., 2020), will have a significant transformation potential over the years, either by the economic or by the social impact.

Whereas agricultural fires generate benefits accruing to those that use them, the cost extend to whole society, including loss of human lives (AHRENS; EVARTS, 2020); destruction of productive inputs and outputs (DE MENDONÇA et al., 2004), damage to infrastructure (DIAZ, 2012), reduction of biodiversity (BARLOW et al., 2003; NOLASCO, 2006; BRANDO et al., 2014; PAOLUCCI et al., 2017; SILVA et al., 2018a), impact on cultural heritage (RYAN et al., 2012) and tourism (BOUSTRAS; BOUKAS, 2013), and a massive release of pollution into the atmosphere with health and climate change consequences (ANDREAE et al., 2004; ANDERSON et al., 2011; GONÇALVES; MACHADO; KIRSTETTER, 2015; DERYUGINA et al., 2019; ROCHA; SANT'ANNA, 2020).

Policy and strategic planning are needed to reduce the fire risk and its impacts. However, it is critical to determine and unfold the components associated with specific socio environmental damages caused by fires. Quantification of fires' impacts, by informing policymaking, would contribute to establish a legal basis for managing natural resources,

to the assessment of damage by a wide range of stakeholders, to the development of mechanisms for environmental compensation (MENDELSON; OLMSTEAD, 2009) and to the design of prevention and suppression initiatives (CARMENTA et al., 2013; MORELLO et al., 2017a, 2017b; TASKER; ARIMA, 2016, MOTTA et al., 2002). These achievements would also pave the way to the compliance with international agreements such as the Sendai Framework¹ and the Paris Agreement for climate change mitigation and adaptation².

1.1 Motivation and objectives

Due to the lack of historical information about the social, economic and environmental impact caused by fire across the Brazilian Legal Amazon (BLA), the main objective of this thesis was to establish a methodology capable of quantifying a set of economic, social and environmental impacts caused by fire, and then implement it using the remote sensing product of burned area. With that the thesis answers two main questions (1) what was the magnitude of fire-related losses for the BLA in the last 20 years? and, (2) is this loss significant compared to the total value of goods and services produced, as captured by the gross domestic product in the BLA ?”.

In this way, the quantification of fire impacts conducted in this thesis was supported by three questions detailed below, divided by Chapter. Each Chapter was grounded on specificities of the fire phenomenon as it occurs in the Amazon.

In Chapter 3 it is explored and developed a method for estimating the fires’ economic losses for Acre state, as a pilot Study. The motivation regarding this chapter relies on the fact that Acre, even being among the Amazon states with lower deforestation rate, has registered a growing frequency of fires, especially in extreme drought years. It remains unclear whether the impacts during regular years are substantial enough, compared to extreme drought years, to justify policy action or if policy should prioritize strictly

¹ Sendai Framework is a successor instrument to the Hyogo Framework for Action, whose objective is to substantially reduce the risk of disasters, loss of life, livelihoods, and health, as well as economic, physical, social, cultural and environmental assets of people, companies, communities and countries (UNDRR, 2015).

² 21st Conference of the Parties (COP21) established during the Paris Agreement in 2015 which aims to enhance the global response to the threats of climate change, whose objective is to increase adaptive capacity, strengthen resilience and reduce vulnerability to climate change, with a view to contribute to sustainable development (UNFCCC, 2015).

preparedness for extremely drought years. Therefore, the following question was proposed:

Q1: Is, in the context of Acre state, the impact of fires in terms of greenhouse gases (GHG) emissions, agricultural production losses and health larger in extreme drought years?

- H1.0: no, even with fires being more frequent in extreme drought years, the difference in terms of impact is negligible. This is probably due to the fact that the land use processes that drive fires and are not directly affected by extreme meteorological conditions remain the dominant source of impact.
- H1.1: yes, impacts are larger by orders of magnitude in extreme drought years, so that the contribution of extreme meteorological conditions stands out even after considering land use processes not directly affected by such conditions.

The second research object, covered in the Chapter 4, is the effect on the health of regional inhabitants due to the pollution released by biomass burning. The motivation is based on the knowledge that fire is widely used in the Amazon constituting a persistent land cover change and agricultural practice used for all types of landowners and population. Regardless of its purpose, fires release a large amount of pollutants in the atmosphere, with severe consequences for human health. With that in mind, a question (Q2) was proposed.

Q.2: Is the hospitalization induced by fire-pollution detectable, with the available data, over different ages and correlated diseases across the entire Brazilian Legal Amazon?

- H2.0: no, other causes of hospitalization, such as the decrease in temperature and increase in humidity in the wet season, as well as other non-seasonal factors (such as healthcare supply), have a contribution which masks the fire-affected population data. This way, fire's contribution does not stand out from data analysis.
- H2.1: yes, fire emission plays an important role in the region's hospitalization counts, even after accounting for season and non-seasonal factors. The emission load released by biomass burning leads to an increase in hospitalization, especially during the fire season.

Finally, the third perspective of this research related to the phenomenon is that controlled fires may turn into accidental fire spreads, which affects agricultural production, infrastructure, and it also contributes to global climate change due to the emission of greenhouse gases (GHG). This is explored in Chapter 5. The premise adopted is that the BLA suffers from uncontrolled fires every year, with emphasis on drought-and non-drought-related events that are becoming more frequent. The lack of an estimation of the magnitude of losses, in ecological and monetary terms is a knowledge gap. Filling this gap is crucial to support and design policy to mitigate and prevent such events. This is the background of the third question (Q3).

Q.3: Are the negative impacts caused by fire in BLA over the last 20 years sufficiently large to demand attention in national and international policy?

- H3.0: no, the damage is negligible even accounting for the impacts on climate, agriculture and health.
- H3.1: yes, the damage is considerable both whether totalized or whether its environmental, economic and health dimensions are assessed isolated.

1.2 Thesis outline

This document is organized in a paper-format, which aggregates one paper that has already been published and two in the process of being finalized. In the following sections it will be described: Chapter 2 is a literature review of fire impacts in a context of disaster management, separating the affected components between Environmental, Material and Human damage, and also establishing how each component connects and influences one another; Chapter 3 presents a case study about Acre state, using a few components to determine the damages of fire in normal climatic years and anomalous ones; Chapter 4 introduces an econometric approach to quantify the hospitalizations due to fire-smoke pollution in the BLA region; Chapter 5 presents a monetary quantification caused by fire between 2001 and 2020 in the BLA; Finally, Chapter 6 aggregate the general discussion from the analysis used between the local approach and the regional estimates.

Chapter 2 presents the main concepts used in Brazil about fire, regarding its classification and types. In addition to summarize the main damages caused by fire under an disaster perspective, where those damages were categorized into three class (environmental,

material and human nature damage). With all this discretized, a fire impact chain was produced, showing how each component connects and influences on another, classifying them by category, extension (local, regional or global) and degree of impact (direct and indirect).

The case study of Acre state between 2008 and 2012, aimed for establishing a methodological baseline, which adequate to be extrapolated to the entire BLA region. This chapter brings the quantification of impacts in normal climatic years and in years of extreme drought in the state, accounting for the environmental losses represented by the loss of biomass and the consequent emissions of carbon dioxide (CO₂) into the atmosphere; the social impacts, evaluating hospitalizations due to respiratory diseases during this period; and material impacts, related to the burning of property fence and loss of agricultural production.

Such chapter included a first simplified attempt to quantify health impacts based on the correlation coefficient which is not suitable to measure the causal effect of fires on health and to reveal the precision (or volatility) with which such effect may be estimated (what would be informative regarding the inherent degree of uncertainty). With that in mind, an improved assessment of the health impact was carried out in Chapter 4. The econometric method of Instrumental Variables was used to measure the causal effect of fire-induced pollution on respiratory hospitalizations, thus obtaining more reliable measures given the many tests of methodological consistency and robustness required by the technique.

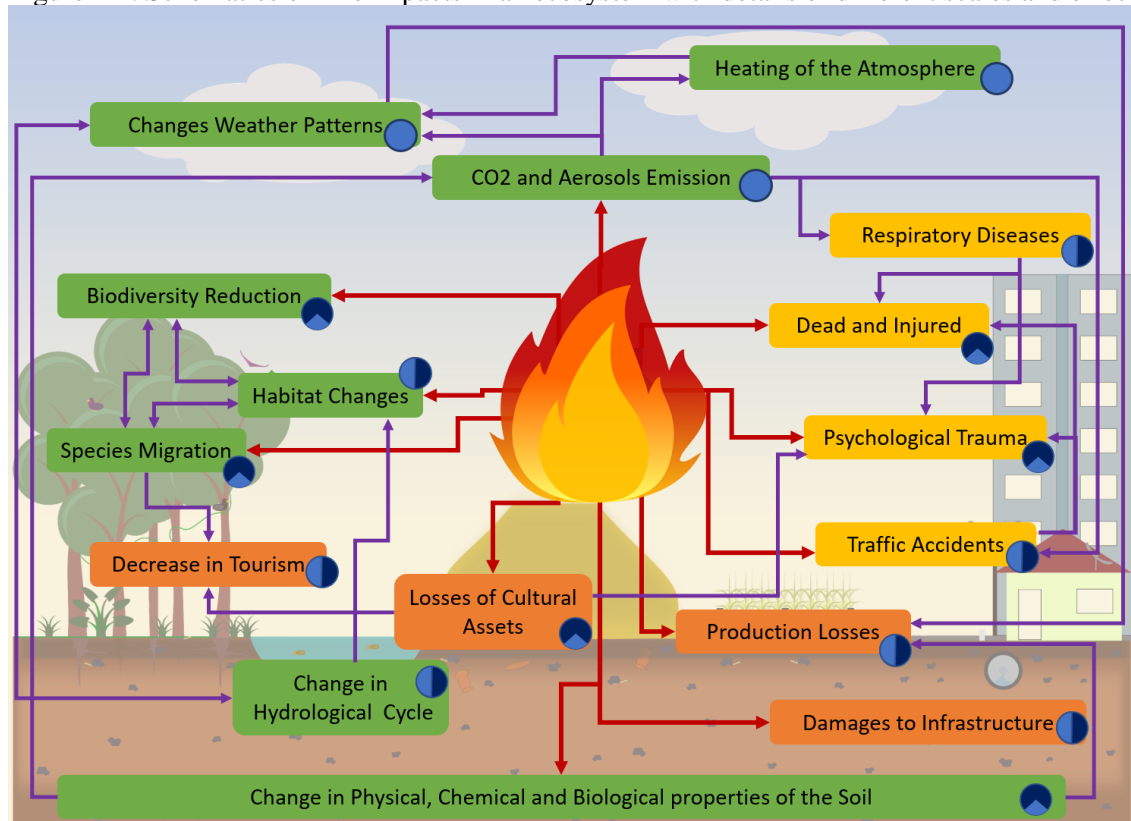
Finally, in Chapter 5, building on Chapters 3 and 4 in terms of the performance of the quantification techniques applied, an integrated analysis was performed for the entire BLA from 2001 to 2020, quantifying and valuing the total damage generated by fires from three sources, namely, production losses, CO₂ emissions and hospitalizations.

2 LITERATURE REVIEW

The impact of the fire in a region is complex because each damaged feature is part of a tangled chain of interconnected cycles, and the consequences can be propagated in different scales and components (RYAN et al., 2012; NELSON et al., 2013). However it can be clarified if the fire were considered as a disasters, because it can be categorized in three major groups (Human, Material and Environmental), as proposed by the Disaster Risk Management Classification (DE CASTRO, 2007).

Based on the most common impacts driven by wildfire, a theoretical fire chain impact (Figure 2-1) was propose, which each point will be discussed in the following sections.

Figure 2-1. Schematics of Fire impacts in an ecosystem with details of different scales and effect.



Legend

Damages:

Environmental (Green box) Human (Yellow box) Material (Orange box)

Scale:

Local (Small blue circle) Regional (Medium blue circle) Global (Large blue circle)

Effect:

Direct (Red arrow) Indirect (Purple arrow)

Note: Human damages – are those related to the people affected by the disasters Material damages – are those associated to goods, proprieties, and facilities. Environmental damages – are those related to the contamination or degradation of the water, soil, air, and biodiversity. Direct effect – is the one caused by the fire itself or by the contact with ashes and smoke. Indirect effect – is second-order effect, caused by the direct effect.

Source: From author.

2.1 Human damages

Forest fires cause serious environmental disasters, they kill and injure people, destroy private and public goods, towns and villages. According to FAO's report (NOLASCO, 2006), during the 1990s, fires in South America caused 742 deaths and 429 people were injured, including volunteers, firefighters and civilians. The National Fire Protection Association (NFPA) (AHRENS; EVARTS, 2020) reports that, for all incidents involving fire in 2019 in The United States of America, the number of people affected was approximately 20.000 across the country, in which 18% died. However, the Federal Emergency Management Agency (FEMA) (FEMA, 2016), indicates that the trend of injured and death rates is in opposite directions, generally because the age groups is a very relevant factor. The agency believes that due to the debilitated cognition and mobility of elderly people, they were less likely to escape from the effects of the fire and therefore suffered fatal injuries.

It is important to point out that during the process of burning, there is a large amount of ashes, smokes and gases being released. These can cause traffic and air accidents, due to the lack of visibility (ANDERSON et al., 2011; NEPSTAD; MOREIRA; ALENCAR, 1999), and hospitalizations owing to the bad air quality (DE MENDONÇA et al., 2004; DERYUGINA et al., 2019; ROCHA; SANT'ANNA, 2020; SHELDON; SANKARAN, 2017; WANG et al., 2020). Health impacts of smoke are determined by: chemical composition and concentrations of pollutants in the smoke; the intensity and duration of exposure to smoke during an event; the protection of individuals from exposure; and the number of individuals exposed (WILLIAMSON et al., 2016). A study carried out by Da Motta et al (2002) found out that in the period from 1996 to 1999, the relation between the total number of respiratory morbidity associated with the smoke by the burning biomass in the Brazilian Amazon varied from 3% to 8%. This percentage depends on the age group, because children and elderly people are more vulnerable and more impacted (ARAGÃO et al., 2016; SMITH et al., 2014). The smoke also has a cross boundary impact in respiratory hospitalization, affecting from regional (WANG et al., 2020) to international scale (SHELDON; SANKARAN, 2017; REDDINGTON et al., 2015). Psychological problems such as posttraumatic stress disorder, depression and adverse physical side effects can also appear in both affected communities (victims, families),

firefighters and associated staff (e.g. police, rescue team) (CAAMANO-ISORNA et al., 2011; LAUGHARNE; VAN DE WATT; JANCA, 2011).

2.2 Material damages

In relation to quantifying wildfire impacts, Diaz (2012) indicates that the most common damages in a community infrastructure are the ones in highways, communication facilities, power lines, and in water delivery systems. Following a report made by the National Agency of Electric Energy (ANEEL), between 2013 and March 2017, more than 14.000 forced energy shutdowns in Brazil were recorded. Of those cases, around 9% was related to uncontrolled fires, representing the fifth main factor of interruption in the system (ANEEL, 2018).

The material impacts of fire, however, go beyond direct and local damages. Economic goods should be also taken into account, for example: services; consumer goods (cars, houses, food); and capital goods (equipment, buildings, installations). De Mendonça et al. (2004) considered the impact of fire for farmers in the Amazon region, registering damages in the production, losses in the pasture and plantations, house destructions, damages in fences and equipment. Boustras and Boulas (2013), additionally, determined the impact of fires on tourism activities in Greece and Cyprus. The authors explain that the impact is multidimensional, going from damages in tourist facilities, signposts, trails, viewpoints and even changes in the tourists' behaviors and in the attractiveness of the landscape. Nonetheless, cultural resources can also be affected by the fire. Those resources are defined by Ryan (2012) as material and non-material items that represent the physical, spiritual presence and practices of society, connecting people with their traditions, histories and their ancestors. The author explains that those resources are often tangible and fragile objects, but they can also be resources that incorporate all elements of the environment that support culture, such as the living organisms (plants, animals) and the physical characteristics of the region (mountains, hills, plains, rivers) which are susceptible to fires.

2.2.1 Environmental damages

Within the environmental damages, the impacts related to the atmosphere, biodiversity, soil, and water are detailed in what follows.

2.2.1.1 Atmosphere

Fires have a great effect on the emission of greenhouse gases and aerosols. Nolasco (2006) shows that in the last decades, the smoke released by forest fires had affected whole urban areas and have caused serious problems to the health and the air traffic. Reductions of scenic beauty and in the market value of real estate can also be consequences of the smoke. For example, in August 2019, the city of São Paulo had a moment that the day became night due to the smoke and ashes from Amazon fires (SETZER, 2019).

The composition of a wildfire smoke depends on the fuel type, the temperature of the fire, and the weather conditions (URBANSKI; HAO; BAKER, 2008). However, the smoke is usually composed by primary pollutants, such particulate matter (PM), carbon monoxide (CO), nitrogen oxides (NO_x), and non-methane organic compounds (NMOC), which some of it react to form secondary pollutants (REISEN et al., 2015).

Da Rocha and Yamasoe (2013), who worked with the aerosol optical depth (AOD) and its correlation with fires in the Amazon, presented that during the fire season, the AOD levels can rise up to 280% in sites with fire, but the effects were also perceived in more distant places. The increase of aerosol levels in the atmosphere, which impacts the human health (showed in the Section 2.1), the smoke and its components affect the weather, for reducing the size of cloud drops; delaying the onset of precipitation; strengthening upward currents, causing intense storms until hail; releasing latent heat in the upper layers of the atmosphere, affecting regional and global circulation systems; and changing the water cycle (ANDREAE et al., 2004; GONÇALVES; MACHADO; KIRSTETTER, 2015).

Fires are also directly associated to greenhouse gas emissions (GATTI et al., 2021). Between 2015 to 2012, the average of CO₂ emissions estimated by (SEEG, 2018) for Brazil, considering all sectors, was 1.352 Tg. Fires associated with deforestation contributed with an annual average of 454 ± 496 Tg of CO₂ per year in the Amazon (ARAGÃO et al., 2018), and these values can be bigger than the emission of deforestation in drought years.

2.2.1.2 Biodiversity

When the fire reaches vegetation formations, in addition to consuming the organic material deposited in the soil, it eliminates plants and animals and decreases the local biodiversity. Large or resistant trees that had been damaged are generally able to resist for years, or they die later not necessarily because of the fire, but probably because of the attack of pathogens. The determinant of the mortality will be the consequence of the heat of the organs (leaf, stem and root), which will affect the physiology and other characteristics that change the resilience of the organism, and also by the injuries caused by the fire, opening a space to a pathogens attack (LIESENFELD; VIEIRA; MIRANDA, 2016).

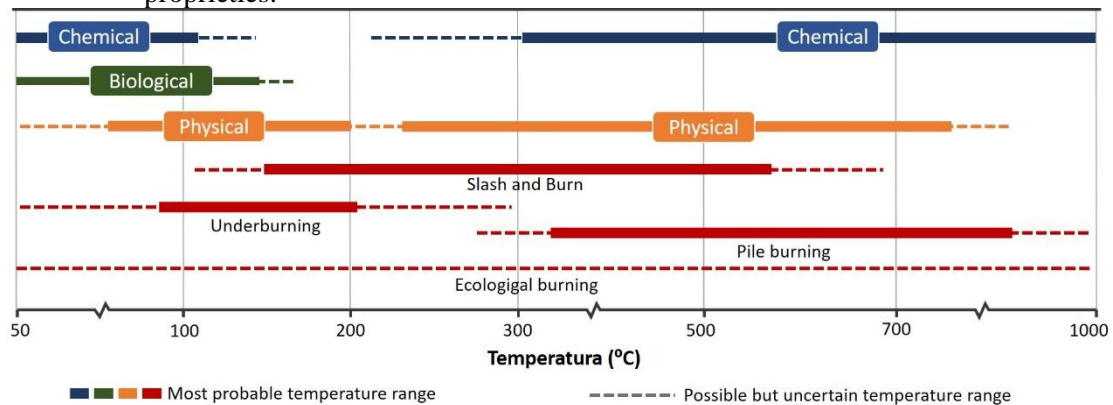
Brando et al. (2014) shows that the tree mortality in the Amazon forest can increase to 226% due to the fire damages, and that number reaches 462% during drier years. It was also registered a cascade effect in deaths of trees, causing a decrease in the canopy cover (23% to 31%), in the above-ground biomass (12% to 30%), and increasing the invasion of grass (80%) over the edge of the forest fragment, where fires are more intense and common. In a long-term, it has been suggested that 36% of the trees will die in the following year and around 48% in the next three years (BARLOW et al., 2003), and this process can continue for up to 8 years after the fire (SILVA et al., 2018a).

Negative effects in large groups of animals, such as birds, mammals and reptiles, have been reported as well. Even though such groups and many mobile animals are able to escape from the flames, the surviving animals may not be able to withstand these frequent fires due to the reduced availability of resources and habitats (NOLASCO, 2006). Paolucci et al. (2017) claims that some groups of animals change because of the degradation of the forest and the consequent changes in the phytophysiology.

2.2.1.3 Soil

Related to the soil damages, Santín and Doerr (2016) summarized the impacts in each soil component, indicating the possible forms of burning and its range (Figure 2-2).

Figure 2-2. Different effects of burnings over the chemical, physical and biological soil proprieties.



Source: Adapted from Santín and Doerr (2016).

The authors found that biological properties, in general, are affected at temperatures below 200°C, in which there is a reduction of microbiotic biomass and a destruction of the seed bank and fine roots. The first group of chemical properties of the soil to be affected is the stored water, which is evaporated. The second group occurs at temperatures above 300°C, related to the combustion of organic matter in the soil, the production of pyrogenic organic matter, the increase in the soil pH, and in the transformation of minerals (Calcium and Iron).

Regarding the physical properties of the soil, in the first moment (temperatures below 200°C) there is an increase in aggregation and water repellency. However, with the increase in temperature, there is a breakdown of clods and repellency, in addition to the collapse and melting of clays. The authors also address that some of the most significant impacts on the soil are indirect and happen gradually during and after the fire, such as an increased runoff, erosion, distribution, and incorporation of ashes into the soil. However, not all impacts are negative, some consequences may have benefits in boosting the soil fertility, organic carbon content, weathering and assisting the formation of organic soils.

2.2.1.4 Water

According to Neary et al. (2005) the main impacts in the water quality are: the introduction of sediments, the potential increase in nitrates, the possible introduction of heavy metals from soils and nearby geological sources.

The introduction of fire-retardant chemicals in streams can reach toxic levels for aquatic organisms, causing an increase in the pH because of the ashes and also an increase in the water temperature, which may also enhance the biological activity. Nonetheless, the fire impacts can indirectly influence water bodies by changing hydrological cycles (see Section 2.2.1.1) that will also change the flow regimes; affecting riparian environments; changing the biodiversity (see Section 2.2.1.2) with consequent changes in the physical properties of the basin (e.g. evapotranspiration, infiltration, surface runoff) that affect the flow regime, and altering the quality of the water, either by the changes in the flow regime and the riparian vegetation or by the deposition of ashes and particulate.

The magnitude of these effects depends on the fire characteristic (size, intensity, and severity), the watershed (topography, land conditions, hydrography), and the weather conditions (precipitation, temperature).

3 ECONOMIC LOSSES CAUSED BY FIRES FROM 2008 TO 2012 IN ACRE STATE, BRAZILIAN AMAZON³

3.1 Introduction

Fire-dependent ecosystems, such as the Brazilian Cerrado and the African Savannah, evolved in the presence of periodic or episodic fires and depend on them for maintaining their ecological processes (PIVELLO, 2011). However, in the Amazon, natural fires are rare in the absence of humans and fire's presence can be an indicator of human activity (BUSH et al., 2004, 2007). The use of fires in this region is a usual agricultural practice for farmers, for both clearing new areas and preparing productive lands (DA MOTTA et al., 2002; DE MENDONÇA et al., 2004), to increase the soil fertility and the amount of organic carbon in a short period (DE SOUZA BRAZ; FERNANDES; ALLEONI, 2013; SANTÍN; DOERR, 2016), and to prevent massive fires by reducing fire fuels (FALLEIRO; SANTANA; BERNI, 2016). Additionally, fire is part of the culture of many indigenous and traditional communities, and is used for hunting and religious rituals as well (POSEY, 1985; MISTRY; BILBAO; BERARDI, 2016).

Over the past 20 years, severe droughts were reported in the Amazon (BRANDO et al., 2014; MARENGO; ESPINOZA, 2016) and major wildfires were associated with them (ARAGÃO et al., 2007; LIMA et al., 2012; ANDERSON et al., 2015; ARAGÃO et al., 2018). Usually, the severe droughts are caused by one or a combination of climatic phenomenon, such as the El Niño-Southern Oscillation (ENSO), the Atlantic Multidecadal Oscillation (AMO), and warming of the Tropical North Atlantic (TNA), where the environmental conditions, characterized by high temperatures and low air humidity, are more suitable for the rapid spread of fires (BRANDO et al., 2014; MARENGO; ESPINOZA, 2016).

Moreover, many studies suggest an increase in drought frequencies in the Amazon (LI; FU; DICKINSON, 2006; AVILA-DIAZ et al., 2020) with a collateral increase of fires in forests adjacent to anthropic areas (SILVA JUNIOR et al., 2018). As a consequence, burnings can escape and escalate into wildfires, causing several environmental and

³ This chapter is a adapted version of the paper: CAMPANHARO, W.A.; LOPES, A.P.; ANDERSON, L.O.; SILVA, T.F.M.R.; ARAGAO, L.E.C.O. Translating Fire Impacts in Southwestern Amazonia into Economic Costs. **Remote Sensing**, v11, (2019).

socioeconomic losses (SILVA; LIMA, 2006; DA ROCHA; YAMASOE, 2013; BRANDO et al., 2014; NEPSTAD et al., 2014; SMITH et al., 2014; ARAGÃO et al., 2016). With that, this phenomena may have a greater environmental change potential than the drought event itself (ARAGÃO et al., 2007; LIMA et al., 2012; BRANDO et al., 2014).

The State of Acre, located in the southwestern flank of the Brazilian Amazon, has suffered from the high frequency of extreme climatic events since 2005 (LEWIS et al., 2011; MARENGO et al., 2011; MARENGO; ESPINOZA, 2016) and more recently in 2016 and 2017 (DOLMAN et al., 2018). In the first two decades of the 21st century, socioeconomic impacts, caused by such events, have been particularly critical in Acre, especially in relation to the direct and indirect impacts of wildfires (ARAGÃO et al., 2016; BROWN et al., 2006, 2011). Brown et al. (2006), for instance, estimated that during the 2005 drought, more than 400 thousand people were affected by fire-related air pollution and over 300 thousand hectares of forests burned, with direct losses surpassing US\$ 50 million and approximately US\$100 million in economic, social, and environmental losses.

As a consequence of the 2005 drought, Acre's authorities created a temporary Situation Room to effectively monitor forest fires and gather meteorological data for fire risk analysis, aiming to assist the placement of fire-fighting crews in the field (BROWN et al., 2011). In 2013, after many extreme events such as floods, droughts, and wildfires, the Situation Unit of Hydrometeorological Monitoring was permanently established under the Secretariat of the Environment of Acre, for following purposes: Monitoring critical hydrologic events, supporting prevention actions to cope with extreme events, gathering information about critical events, and managing platforms for collecting and integrating pluvial and fluviometric data (REIS et al., 2015).

Additionally, in the last decade, Acre State established environmental policies for reducing deforestation, designing mechanisms of payments for environmental services, and creating new governmental and non-governmental sectors to directly deal with solutions for mitigating disasters in the region. All these policies are aligned with the Sendai Framework, of which Brazil has been a signatory country since 2015. This framework includes measures to reduce direct economic losses due to disasters, as well

as the establishment of techniques for assessing losses associated with economic, social, environmental, and cultural heritage (UNDRR, 2015). Nevertheless, information on economic losses from disasters remains critically lacking for entities and governmental institutions, especially in countries under development. The United Nations Office for Disaster Risk Reduction - UNDRR (WALLEMACQ; HOUSE, 2018) showed that only 37% of all disasters cataloged between 1998 to 2017 had estimated economic losses, suggesting that the direct costs of the majority of disasters (63%) worldwide are unknown or not well documented.

Techniques for valuing disaster-related environmental and socioeconomic costs have a great and critical role in public policies. These techniques are essential for characterizing the magnitude of the problem and for supporting regional development models (DA MOTTA et al., 2002). Moreover, information on costs can facilitate the communication of the value of nature or any affected good to different people using a unique language that unites political and economic visions (KUMAR et al., 2013). Finally, this type of analysis can provide a legal basis for managing natural resources, assessing damage, and developing mechanisms for environmental compensation (MENDELSON; OLMSTEAD, 2009).

It is clear that quantitative information about the impact of wildfires on ecosystems and humans is mandatory for supporting the development of strategies and public policies for the prevention of disasters and related impact assessment. Therefore, in this study, our objective is to investigate the spatiotemporal pattern of fires, their attribution regarding fire occurrence and land tenure, and the environmental, social, and economic impacts of fire in Acre state. More specifically, this study aims to answer the following: (1) What are the spatiotemporal variabilities of fires during anomalously dry years and years with regular climatic conditions? (2) Who are the actors, in terms of land tenure, to which fire occurrence can be attributed to? and (3) What is the potential magnitude of the environmental, social, and economic impact caused by fires and their consequences for Acre's economy?

In this study, we go beyond the analysis of ecological impacts on natural resources to show that, during droughts, the increase in fire events, in comparison to normal climatological years, raises the annual estimated cost related to infrastructure damages,

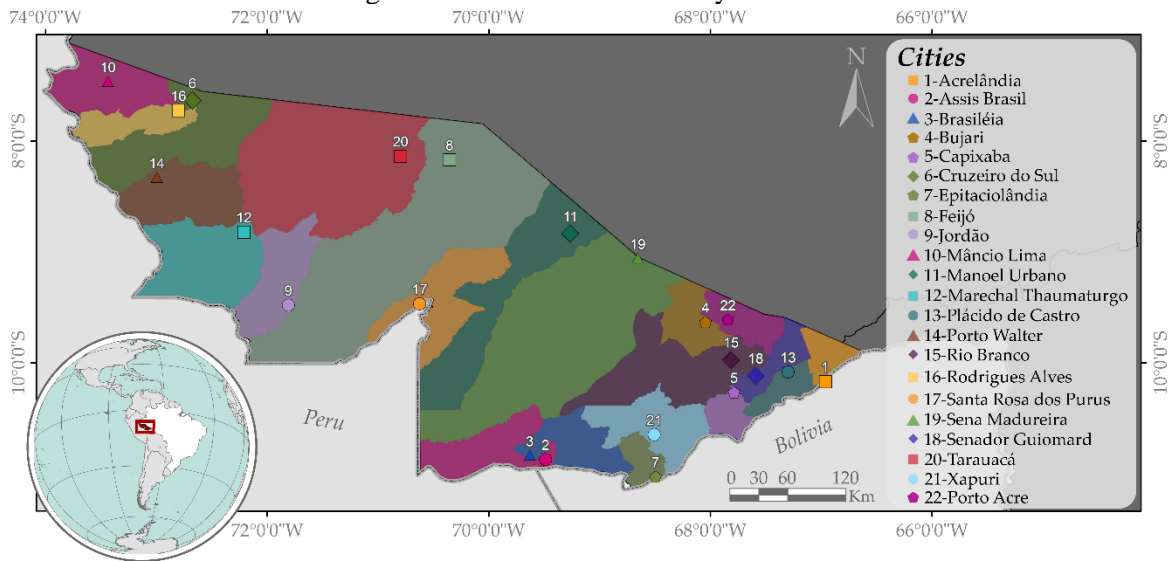
production losses, CO₂ emissions, and respiratory morbidities around 15-fold. This estimate represents 7.03±2.45% of Acre’s gross domestic product (GDP). The observed increment in costs was driven by the spatially extensive impact of fires on forests, which enhanced gross carbon emission from biomass burning and its associated costs to society.

3.2 Materials and methods

3.2.1 Study area

Acre state has an area of approximately 164,124 km² and is located in the southwest flank of the Brazilian Amazon, with borders with Peru and Bolivia (Figure 3-1). Approximately 68,000 km² (41%) of its territory is covered by conservation units, including indigenous areas. Approximately 12% of its total area was deforested until 2010 (INPE, 2021b), concentrated in Acre’s southeastern region, around urban centers, and along the state’s road network, especially BR-364, BR-317, and AC-40. Although deforestation rates decreased between 2004 and 2010, forest clearing and burning for agricultural activities are still the major agents of regional landscape transformation (RODRIGUES, 2014).

Figure 3-1. Location of the study area.



Source: From Author.

The climate in this region is characterized, under the Köppen system, as tropical (A) with 30% of the state area in a tropical monsoon climate (Am), characterized by the compensation of the short dry season by large amounts of precipitation throughout the

year. The other 70% of the state is classified as a tropical rainforest climate (Af), which is characterized by average precipitation of at least 60 mm in every month (ALVARES et al., 2013). The rainy season occurs from October to April and the dry season between June and August, while May and September are characterized as transition months among these seasons (DUARTE, 2006).

3.2.2 Data

This study integrates different spatial data products (Table 3-1) and non-spatial datasets (Table 3-2). The spatially explicit information refers to georeferenced vector and raster data, while the non-spatial datasets are composed of tables and numerical values. All the data and products were gathered from open-source repositories and official government databases, journal articles, market research, and web-pages from governmental and non-governmental organizations. Details of each dataset are presented below.

Table 3-1. Summary of the spatial dataset used.

Data	Structure	Spatial Resolution	Period	Source
Burned area map	Raster	250 m	2008 to 2012	Anderson et al. (2015)
Aboveground carbon density map	Raster	30 m	2000s	Baccini (2017)
Land use and land cover map (LULC)	Raster	30 m	2010, 2008, and 2012	Almeida et al. (2016)
Rivers and Roads	Polygons	Multi-scale	2016	(IBGE, 2018a)
Property boundaries and protected private areas (APPs and LRs)	Polygons	Multi-scale	2017	(SFB, 2018)
Rural module specifications	Table**	-	2013	(INCRA, 2018)
Municipal boundaries	Polygons	Multi-scale	2015	(IBGE, 2018a)
Conservation units (UCs) and Indigenous Lands (ILs)	Polygons	Multi-scale	2016	(MMA, 2018) e (FUNAI, 2018)

Source: From Author.

Table 3-2. Costs, prices, and index used.

Variable	Un.	Ag	2008	2009	2010	2011	2012	References
Morbidity cases (Jun–Dec)	#		2776	2708	2545	2706	2657	*(DATASUS, 2020)
Cost of morbidity	MUS\$		34.25	24.87	28.76	36.58	41.27	
Fence recovery	US\$/m	mn	49.46	42.24	33.12	38.01	22.20	*(DNIT, 2018)
		sd	18.32	15.35	11.67	12.86	7.10	
Pasture reestablishment	US\$/ha	mn	883.27 ¹	883.27 ¹	883.27	883.27 ¹	883.27 ¹	***(TOWNSEND; COSTA, 2010)
		sd	300.01 ¹	300.01 ¹	300.01	300.01 ¹	300.01 ¹	
Agriculture reestablishment	US\$/ha		813.62 ¹	813.62 ¹	813.62	813.62 ¹	813.62 ¹	
Maize productivity	t/ha		1.75	1.83	2.00	2.21	2.27	*(CONAB, 2021a)
Maize price	US\$/t	mn	182.27	201.29	215.29	269.54	243.20	***(CEPEA, 2018)
		sd	22.70	12.97	37.93	11.51	29.33	
Cassava productivity	t/ha		21.71	18.73	20.67	19.00	15.33	*(IBGE, 2017)
Cassava price	US\$/t	mn	62.39	86.62	134.14	103.60	107.09	***(CEPEA, 2018)
		sd	2.44	17.27	9.79	12.69	27.72	
Cattle Density ²	#/ha		1.80	1.86	1.88	1.85	1.79	*(IBGE, 2018b) / ***(ALMEIDA et al., 2016)
Cattle productivity	@/ha/y		4.06 ³	4.06	4.06 ³	4.06 ³	4.06 ³	*(SÁ; ANDRADE; VALENTIM, 2010)
Cattle price	US\$/@	mn	36.10	45.32	53.15	54.26	46.40	***(CEPEA, 2018)
		sd	3.06	1.71	6.97	1.59	1.30	
CO ₂ price	€/t	mn	13.69 ³	13.69	11.98	13.06	7.50	***(MARKETS INSIDERS, 2018)
		sd	0.68 ³	0.68	5.42	3.35	0.72	
Euro change	US\$/€	mn	1.15	1.59	1.40	1.24	1.23	*(BCB, 2018)
		sd	0.10	0.10	0.07	0.04	0.07	
Cumulative Inflation	%b.y		32.51	32.46	32.41	32.35	32.29	*(IPEA, 2018)
US\$ changes ⁴	US\$/R\$		0.43	0.57	0.60	0.53	0.49	*(IPEA, 2018)

Un. – Unit of measurement; Ag – type of aggregation, as mean value (mn) or standard deviation (sd); *-data from governmental institutes; **-data from literature; 1 –Used values from 2010; 2 – Calculated by the total of cattle from PPM-IBGE divided by the pasture area from TerraClass ;3 – Used values of 2009; 4 – Used to convert the market prices as *reais* to US dollars.

Source: From Author.

3.2.2.1 Spatial datasets

Maps containing burned area information from 2008 to 2012 were provided by the Tropical Ecosystems and Environmental Science Laboratory (TREES) at the Brazilian National Institute for Space Research (INPE). This dataset was generated following a well-established methodology (ANDERSON et al., 2005; SHIMABUKURO et al., 2009; ANDERSON et al., 2015, 2017). These maps are derived from MODIS surface reflectance products collection 5, which were resampled to 250 m of spatial resolution and subsequently processed by applying a Spectral Mixture Analysis (SMA) with vegetation, soil, and shade endmembers (SHIMABUKURO; SMITH, 1991). Based on

the shade fraction image, a region growth segmentation procedure was applied, followed by a manual post-classification edition (ANDERSON et al., 2015). The final maps display information on the yearly burned area, corresponding to the cumulative burned area occurring during the dry season of each year. The validation of this product at a significance level of 5%, exhibited an overall accuracy of 99.20% with a lower and upper confidence interval of 97.67% to 99.48%, respectively, for forest areas and an overall accuracy of 96.30%, with a lower and upper confidence interval of 92.88% to 98.55%, respectively, for non-forest areas (ANDERSON et al., 2017).

For characterizing land use and land cover (LULC) in the region, we used maps provided by the TerraClass project (INPE, 2018) for the years 2008, 2010, and 2012. TerraClass is a project for monitoring LULC in the Brazilian Legal Amazon, providing 15 LULC types. To retrieve classes of LULC within the TerraClass project, an analysis of Landsat-5/TM images using SMA is performed, followed by a slicing procedure and visual interpretation. This analysis is supported by temporal information based on the normalized difference vegetation index (NDVI) product from MODIS (Moderate Resolution Imaging Spectroradiometer) and the mask of deforestation, forest, and hydrography from the PRODES project (ALMEIDA et al., 2016; COUTINHO et al., 2013).

For this study, we aggregated the LULC thematic classes into the following three generalist categories: Forests, agriculture, and pastures (Table 3-3). The land cover class “Forests” refers to old-growth and secondary forests. The “Agriculture” class refers to annual crops, generally mechanized agriculture, and the mosaic of uses, which is a mix of agriculture and pastures. Finally, the land use class “Pastures” refers to areas where pastures dominate the landscape. Seven LULC thematic classes were not used in this research because their contribution in terms of area coverage in the Acre state territory was not representative (<1%).

Table 3-3. Summary of TerraClass land use and land cover (LULC) types.

TerraClass LULC types	Grouped LULC categories
Primary forests and secondary vegetation	Forests
Annual crops and Mosaic of uses	Agriculture
Herbaceous pasture, Scrubby pasture, Pasture with exposed soil and Regeneration with pasture	Pastures

Source: From Author.

Data on aboveground carbon density (ACD) was acquired from three datasets. First, for the Forest category, we assigned the respective value of the pantropical biomass map developed by Baccini et al. (2017). This product consists of a single raster map at 30-meter resolution, representing the ACD of live woody vegetation for the 2000–2009 decade, created based on field measurements, vegetation height maps from GLAS-Lidar (Geoscience Laser Altimeter System), a digital elevation model from SRTM (Shuttle Radar Topography Mission), and Landsat-7 ETM+ surface reflectance products.

Secondly, for the Agriculture category we identified maize and cassava as the main agricultural crops of Acre state, according to the Brazilian Institute of Geography and Statistics -IBGE (IBGE, 2017). Due to the lack of regional reports, the maize values were based on dry biomass for the whole aerial part of plantations located in southern Brazil (VIAN et al., 2016), added by the maize grain mean annual yield in the own state of Acre (FNP, 2012), estimated at $3.07 \pm 0.72 \text{ Mg.ha}^{-1}$. The cassava's biomass was based on the aboveground dry biomass of plantations in central Brazil (FERNANDES et al., 2009), estimated at $5.48 \pm 0.43 \text{ Mg.ha}^{-1}$. To convert these biomass values to ACD, we used a conversion factor of 0.4, as described by Redin (2010). This can be considered as a conservative value of *C* content in the vegetation biomass. These reference studies reported intensive and homogeneous plantations, with a certain degree of technology, like those indicated by the TerraClass annual crop category. Therefore, for the agriculture land cover class, we attributed the mean ACD value of 1.71 MgC.ha^{-1} , calculated from the maize and cassava ACD, with a standard deviation of 0.17, estimated through the uncertainty propagation method (Equation 3.1 and Equation 3.2) (VUOLO, 1996).

$$\sigma_w^2 = \sigma_x^2 + \sigma_y^2 \quad (3.1)$$

$$\sigma_w = |e| \cdot \sigma_x \quad (3.2)$$

where σ_w is the uncertainty resultant; σ_x and σ_y are the uncertainty of X and Y; *W* is the final result; and *e* is a constant error-free.

Finally, for the “Pasture” category, we used an average value of $38.61 \text{ MgC.ha}^{-1}$, with a standard deviation of 16.54, based on the sum of the total alive pools of aboveground wood biomass, grasses and herbaceous dicots, and the dead pools of fine litter and wood

debris, found in three different pasture areas in the Brazilian states of Rondônia and Pará (BOONE KAUFFMAN; CUMMINGS; WARD, 1998).

The final ACD map corresponds to the year 2008, with *C* values associated to each class, as follows: Forest, agriculture, and pasture, at each spatial location, as mapped by the TerraClass product for this same year.

The territorial information about land tenure was based on official data provided by the Brazilian government. We have integrated information from different databases, encompassing the following data: Rural private property boundaries, rural module specifications, protected private areas (Areas of Permanent Preservation, APPs, and Legal Reserves, LRs), and governmental protected areas (Conservation Units, CUs, and Indigenous Lands, ILs).

The boundaries of private rural properties and their respective APPs and LRs were obtained at the Rural Environmental Registry System (SICAR). These two kinds of protected areas are mandatory for all private property, according to the actual Brazilian Forest Code (FC, Federal Law n° 12.651 of 2012) (BRASIL, 2012). The LR is an area of native vegetation that must occupy at least 80% of the property area in the Amazonian biome, excluding the environmentally sensitive areas (e.g. riparian and hilltop zones), which are titled APPs (SOARES-FILHO et al., 2014).

We classified each private property according to the rural module (r.m.) specifications of each municipality. This classification was defined according to the Federal Law n° 8.629 of 25 February 1993 (BRASIL, 1993), which classifies the properties in smallholdings (area ≤ 1 r.m.), small ($1 < \text{area} \leq 4$ r.m.), medium ($4 < \text{area} \leq 15$ r.m.), and large properties (area > 15 r.m.). The rural module size for the Acre State ranges from 70 to 100 ha per municipality and it was defined in 2013 by the National Institute for Settlement and Agrarian Reform – INCRA (INCRA, 2018).

3.2.2.2 Non-spatial datasets

Records of hospitalization cases caused by respiratory illness and the total cost of treatments are provided by the Brazilian Unified Health System (SUS). In its information system (Tabnet-DATASUS) (DATASUS, 2020), we searched for the number of hospitalization cases and the total economic cost according to the place of residence,

filtered for respiratory system diseases and distinguished by municipality and year/month of occurrence.

Among all the costs related to infrastructure, we computed only the impacts on the property fences due to the unavailability of data on all other costs and, thus, the infrastructure damage costs due to fires can be considered underestimated. This information was obtained from the National Department of Transport Infrastructure (DNIT), which provides the reference costs to repair and reconstruct different kinds of fences. Thus, we calculated the mean price of all the kinds of build and repair, which were described by DNIT annual reports (DNIT, 2018).

We assume that the cost related to land recovery was US\$ 813.62 ha⁻¹ for agriculture and US\$ 883.27 ha⁻¹ for pasture, both obtained by Townsend and Costa (2010) for areas in the Brazilian Amazon region. The costs of forest restoration were not considered because such practice is not usual in the region.

The value of crop production was generated by multiplying the productivity values by their market price in each year. For maize and cassava production (Table 3-2), we used the values provided by the National Supply Company – CONAB (CONAB, 2021a) and IBGE (IBGE, 2017) systems. The mean productivity for 2008 to 2012 was 2.01 t.ha⁻¹ for maize and 19.08 t.ha⁻¹ for cassava. The mean cattle weight gain for 2009 was 60.09 kg.ha⁻¹.y⁻¹, a value based on a technical report of the Brazilian Agricultural Research Corporation – EMBRAPA (SÁ; ANDRADE; VALENTIM, 2010). Market prices for those products were provided at an annual time-scale by the Center for Advanced Studies in Applied Economics (CEPEA) system (CEPEA, 2018).

For forest-related losses, we only considered commercial wood stocks, due to the data availability. For this, we used the value of US\$ 5 ha⁻¹, quantified by De Mendonça et al. (2004), which denotes the mean price of marketable adult trees after a fire event that the lumber mill would be willing to pay to the landowners in an exploited forest in Eastern Amazonia.

Carbon emission values were accounted by using the market prices of carbon available at the Carbon Emission Future system (MARKETS INSIDERS, 2018) between 2009 and 2012 (Table 3-2). As these prices were in Euros, we converted these values into US

dollars using the exchange rates available from the Brazil Central Bank (BCB) system (BCB, 2018).

3.2.3 Data analysis

In the next sections, we describe all the procedures that were carried out to reach our three research goals. We also present a section of assumptions and uncertainties of our data and analysis.

3.2.3.1 Quantifying the spatiotemporal variability of fire dynamics

To analyze the spatial dynamics of the burned areas, first we quantified the total burned areas by year, the wildfire frequency and recurrence, and the burned area anomalies. To understand how remotely fire sources could be inside Acre's territory, excluding common anthropic ignitions such as roads and urban centers, we built a grid of Euclidian distance from rivers and roads and then we determined the mean distance and standard deviation of burned areas by intersecting the fire scars and the Euclidian distance grid from these features.

3.2.3.2 Fire occurrence and land tenure relationship

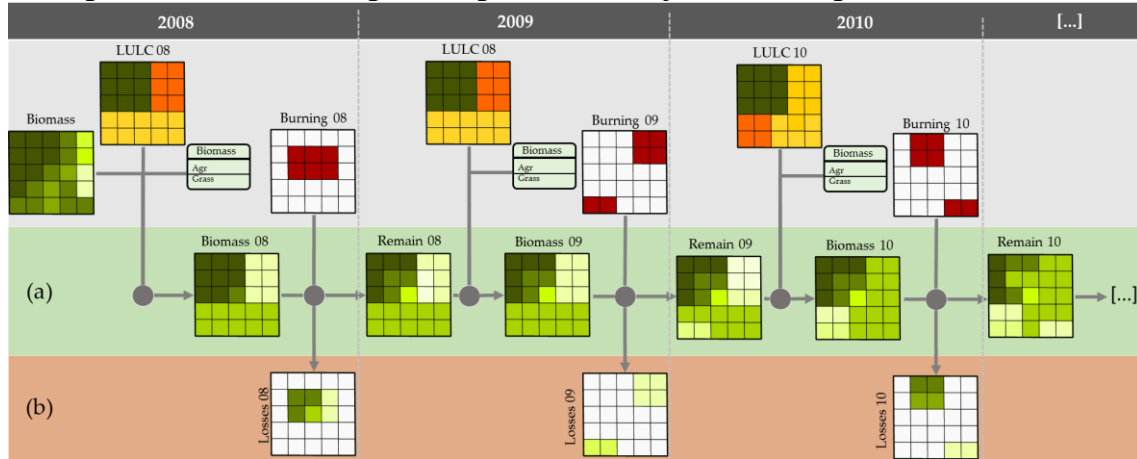
An intersection between burned area and the spatial data of land tenure and LULC was carried out for determining the areas affected by fires. Then, the annual burned areas were stratified by each LULC class, land tenure and protected areas inside and outside private properties. The year of 2010 was excluded from the time-series mean average due to the anomalous drought that occurred during that year, leading to extensive fires (ANDERSON et al., 2015).

3.2.3.3 Estimating the environmental, social, and economic impacts of fires

The environmental impact is represented here by biomass loss and gross carbon emission by fire. It is quantified for each year, as shown in Figure 3-2. To determine the annual post-fire biomass loss, we first used the 2008 biomass map and then applied the relationship of biomass loss developed by Anderson et al., (2015), which states that the remaining above-ground biomass after fire is a function of the above-ground biomass prior the fire event. Then, for the areas mapped as Agriculture and Pastures, the reference biomass values (1.71 and 38.61 MgC.ha⁻¹, respectively) were attributed to the remaining

biomass map in order to simulate their seasonal renewal, resulting in the following year biomass map. For 2010 and 2012, we not only updated the biomass values but also dynamically revised the spatial location of Agriculture and Pasture areas, according to the available LULC maps.

Figure 3-2. Workflow for generating the annual maps of remaining and loss of biomass.



(a) The green panel represents the 2008–2010 annual potential biomass maps, which were processed from the annual burned area maps; 2008, 2010, and 2012 land use and land cover (LULC) maps; and a table of reference biomass values for each grouped LULC classes. (b) The red panel represents the 2008–2010 annual biomass loss maps, derived from an empirical relationship between pre and post-fire biomass applied to the potential biomass maps where a fire event was depicted by the burned area maps.

Source: From Author.

Finally, to quantify the total annual gross carbon emissions, we applied the CO₂ gross emission model (Equation 3.3) to the biomass loss maps (Figure 3-2b).

$$F_{CO_2} = \theta * (1 - \alpha) * \sum_{j=1}^2 \lambda_j * \sum_x \sum_y Bi_{(x,y,j)} * A_{(x,y)} \quad (3.3)$$

where F_{CO_2} is the carbon dioxide gross emission (Mg CO₂) in the year of interest (immediate flux to the atmosphere); θ converts carbon to carbon dioxide (3.67); α is the slope of Anderson et al. (2015) equation's ($\alpha = 0.7084 \pm 0.034$); λ_j is the release constant specific for forest ($j=1, \lambda=50\%$) and non-forest covers ($j=2, \lambda=100\%$); $Bi_{(x,y,j)}$ is the pre-burn biomass (Mg C.ha⁻¹) for the pixel at the location (x,y) , distinguished for forest and non-forest covers (j); and $A_{(x,y)}$ is the burned area (ha) at the pixel (x,y) , for which the value in our studies is 0.09 ha at burned pixels.

The health data, considered here as social impact, was determined by building a relationship between fire and respiratory morbidity in Acre state. We computed a linear

correlation between the total burned area and the total cases of hospitalization by municipality and year. First, we summarized the total burned area by municipalities and aggregated the number of cases grouped in last semester, which includes the peak of the fire occurrence, in September. The dry season period was extended for three months in this analysis because not all health case manifests were registered at the same time as the fires.

We calculated five types of economic losses divided into two categories, directly and indirectly fire-related. The first direct cost is associated with infrastructure damages, for which we assume only fence losses. The second and third direct costs are the production losses, for which we considered costs related to crop reestablishment and affected future production. Finally, the quantified indirect costs were related to CO₂ emissions and respiratory morbidities.

Fence losses were calculated using the land property boundaries over burned Pasture and Agricultural fields, then extracting these vector lengths. This analysis can be considered conservative since fences are also usually used to separate pasture from agriculture inside the same property. The wildfire factor was applied and then the total cost of the fence reconstruction and repair was calculated using the respective prices for each year (Table 3-2).

Production losses were estimated by multiplying the production and reestablishment coefficients for each class and their market prices for each year. Just for the Agriculture class, we assume that there was the same proportion of cassava and maize crops.

Not all burned areas in rural properties are intentional, but the main losses are caused when fires escape and accidentally spread to adjacent areas. For that reason, we considered the wildfire factor of 45%, estimated by De Mendonça et al. (2004), to calculate the economic losses of infrastructure damages, crop reestablishment, and affected future production. This factor was estimated using an econometric model in the database from field research done by the Amazon Environmental Research Institute (IPAM). The database is related to an information set, acquired between 1994 and 1995, of 202 properties spread over five municipalities in the “Arco do Desmatamento” region,

specifically at Paragominas, PA, Santana do Araguaia, PA, Alta Floresta, PA, Ariquemes, RO, and Rio Branco, AC.

To quantify the costs of CO₂, we multiplied the total CO₂ emissions by the market prices and exchange rates. So, we didn't use the wildfire factor because the CO₂ emission is independent of the fire aim.

To evaluate the illness costs, we assumed that a factor of only 8% of respiratory morbidities can be attributed to smoke from fires and wildfires, as shown by De Mendonça et al. (2004), and then applied the respiratory morbidity costs for June to December.

Finally, we updated all values to the same year (2017), using the cumulative inflation rates (Table 3-2), available at the Brazilian Central Bank (BCB) (BCB, 2018) website using Equation 4. All the economic costs in Brazilian currency (*Reais*) were converted to US dollars, using an average exchange value of 0.31±0.01, which referred to the 2017 quotation given by the BCB (BCB, 2018).

$$V_f = V_p * (1 + \sum IPCA_y) \quad (3.4)$$

where V_f is the future value; V_p is the present value; and $IPCA_y$ is the annual inflation tax

3.2.3.4 Assumptions and uncertainties

Assumptions were made in order to accommodate the limited data available with the method we developed. First, we assumed that (1) the TerraClass Agriculture and Mosaic of Uses classes cover all crops over the Acre state, ranging from mechanized to traditional agriculture; (2) the class Mosaic of Uses from TerraClass are a mix of agriculture and pasture of traditional agriculture, but it is reclassified in our analysis as Agriculture class as it is more representative of the landscape in these areas; (3) the delimitation of properties, APP and LR from Rural Environmental Registry (acronym CAR) have no remarkable spatial overlaps; and (4) the entire biomass loss is immediately combusted and released to the atmosphere, being accounted only in the period of one year, thus no decay rate or emissions from the decomposing pool were considered.

The CAR dataset is not used as official territorial delimitation due to overlaps between different properties, boundaries, and special areas, however, this dataset is the best spatially explicit public information on land tenure from the Brazilian Amazon.

The economic costs errors were estimated using the values and errors of the burned area, CO₂ equivalent emission, asset prices, and dollar exchange, by applying the methods of uncertainty propagation to compute each category uncertainty, and the total economic uncertainty, through the multiplication method, according to Vuolo (1996). Details about the method are provided below.

For the burned area error, we used the lower and upper values of the confidence interval of each land cover class related to the TREES product to estimate the uncertainty of the burned area. Thus, we propagated each burned class error to the total burned area error using the sum method (Equation 3.1).

The biomass error was first calculated using a multiplication method of uncertainty propagation (Equation 3.5) to estimate the uncertainty of each class, and second, the sum method (Equation 3.1) quantified the total biomass loss uncertainty. We used the burned area, the burned area uncertainty, the biomass value, and a standard deviation of each class. To the Agriculture and Pasture classes, we used a standard deviation available in the consulted literature. For the Forest class, we calculated the total standard deviation, based on the uncertainty map provided by Baccini et al. (2017). Therefore, the total forest biomass uncertainty was the product of the uncertainty map and the biomass map, with a subsequent numeric scale correction (dividing each pixel value by 1000) and a spatial scale correction from unit per pixel to hectares (multiplying each pixel value by 0.09 ha). Finally, we used a sum method of uncertainty propagation (Equation 3.1) to estimate the total standard deviation of the Forest class biomass.

The CO₂ emissions error followed the same principle of biomass error estimation, where the biomass total value, a biomass error, a CO₂ equivalence conversion, and its error were used in a multiplication method of uncertainty (Equation 3.5), achieving the class error. This value was then applied to the sum method (Equation 3.1) to estimate the total CO₂ equivalent emission error.

$$\left(\frac{\sigma_w}{w}\right)^2 = \left(\frac{\sigma_x}{x}\right)^2 + \left(\frac{\sigma_y}{y}\right)^2 \quad (3.5)$$

where σ_w is the uncertainty resultant; σ_x and σ_y are the uncertainty of X and Y; X and Y are the measures values, and; W is the final result

3.3 Results

3.3.1 Spatiotemporal variability of fire dynamics

During all the analyzed years, more than 2577 km² were burned. Of these, approximately 12% burned more than once and 3% occurred in following years, with a maximum three-year sequence (Table 3-4). Burning events in Acre (Figure 2) were concentrated near the major urban centers (Rio Branco, Cruzeiro do Sul, Sena Madureira, Tauaracá, Feijó, and Brasília), highways (BR-364, BR-317, AC-040, and AC-075) and waterways (Iaco, Muru, Acre, and Envira rivers).

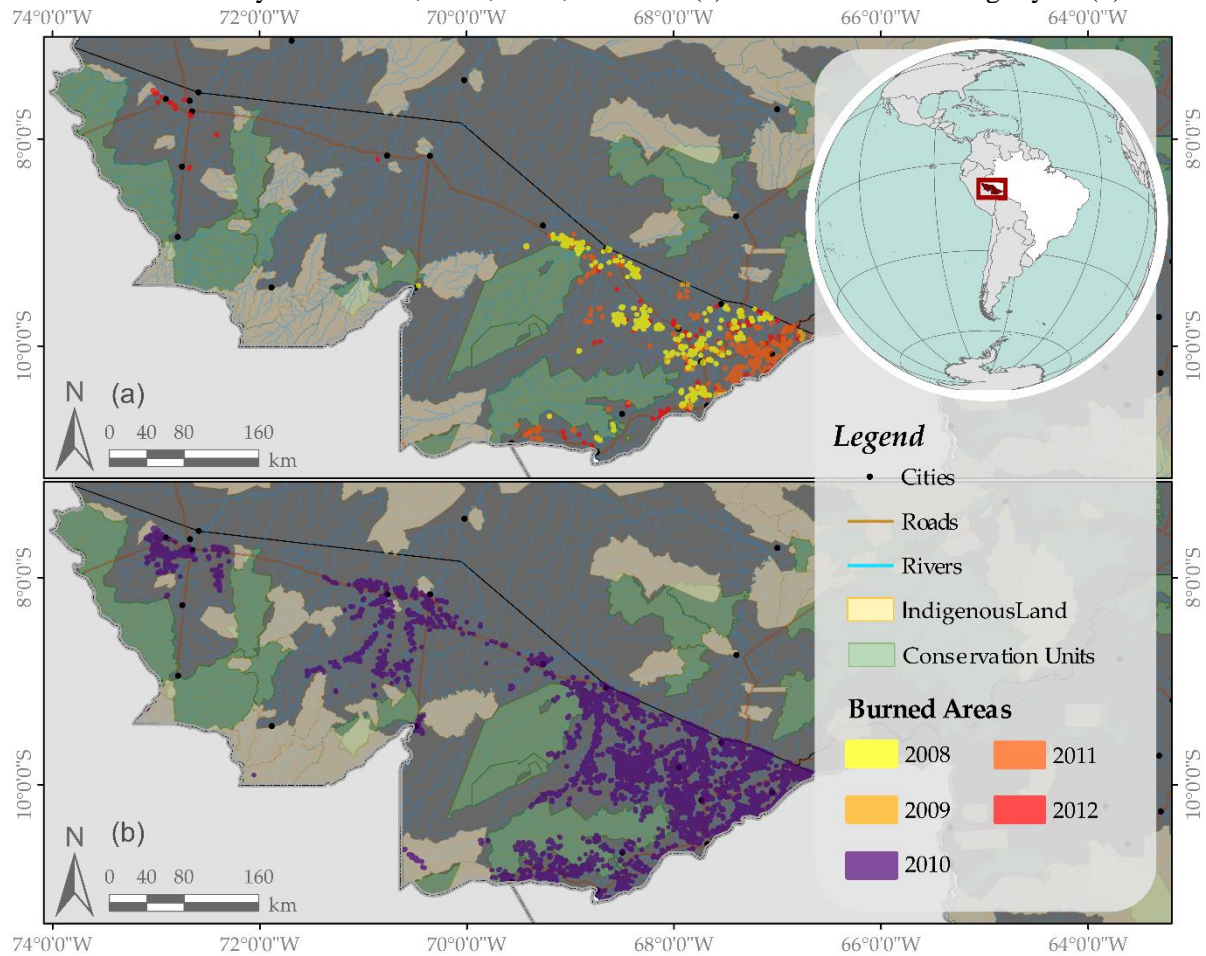
Table 3-4. Total burned area in hectares (km²) that burned one time, more than once, and the number of burned scars in sequence of year.

Year	Total	Frequency		Recurrence		
		One	> One	1 Years	2 Years	3 Years
2008	218.85	218.85	161.82	57.04	2.47	0.53
2009	33.33	33.33	8.43	24.9	13.32	2.37
2010	2056.80	2056.8	1928.22	128.58	29.83	4.22
2011	178.52	178.52	135.74	42.78	8.5	0
2012	90.05	90.05	34.2	55.86	0	0
Total	2577.55	2577.55	2268.41	309.16	54.12	7.12

Source: From Author.

Every year new burn scars were mapped (Table 3-5). However, the number of polygons varied substantially (24–3521). Their size also had a large annual standard deviation (SD). The maximum SD reached 2.54 km² in 2010, while the minimum SD of 1.28 km² was recorded in 2011. In 2010 the highest number of polygons were observed (3521) and the largest total burned area (2056.8 km²) among all years analyzed was expressed, respectively, 19 times larger and 16 times higher than the mean of the other four years. The largest polygon observed in our time-series had more than 100 km², which occurred in 2010, while, in any other year the largest burned polygon had an area of 16.90 km².

Figure 3-3. Burn scars in Acre state (Brazil), mapped with 250 m spatial resolution, for the regular climate years of 2008, 2009, 2011, and 2012 (a) and for the 2010 drought year (b).



Source: From Author.

Considering that Acre's dry season (months with monthly rainfall < 100 mm) in 2010 extended by one month, totaling four months in this year, the 3521 observed burn scars (2056.8 km²) corresponded to around 29 burning events per day in the dry season, with an average of 16.85±0.52 km² each. During the three dry months of the regular climate year of 2012, conversely, only 146 burn scars (90 km²) were detected, corresponding to about 2 burning events per day in the dry season, with an average of 0.98±0.04 km² burned daily.

Analyzing the distance to roads (Table 3-6), we found that, in 2010, burn scars reached longer distances from the main highways (11.15±9.67 km) than the average distance of other years (7.27±6.52 km). These burned scars also occurred closer to the waterways in 2010 (1.49±1.15 km) than during the other years (1.66±1.13 km).

Table 3-5. Summary of burned scars between 2008 and 2012 for Acres state.

Variable	Years				
	2008	2009	2010	2011	2012
Number of scars	267	24	3521	324	146
Total area (km ²)	218.85	33.33	2056.80	178.52	90.05
Maximum area (km ²)	16.41	5.03	104.34	16.90	10.74
Mean area (km ²)	0.82	1.39	0.58	0.55	0.62
Minimum area (km ²)	0.07	0.07	0.02	0.0009	0.01
Standard deviation	1.50	1.38	2.54	1.28	1.39
Variance	225.09	190.09	644.56	162.88	192.70
Anomaly of quantity	-0.44	-0.62	1.99	-0.40	-0.53
Anomaly of area	-1.32	-2.54	2.39	-2.07	-2.21

Source: From Author.

Table 3-6. Distance, in kilometers, of rivers (Ri) and roads (Rd) to burned scars.

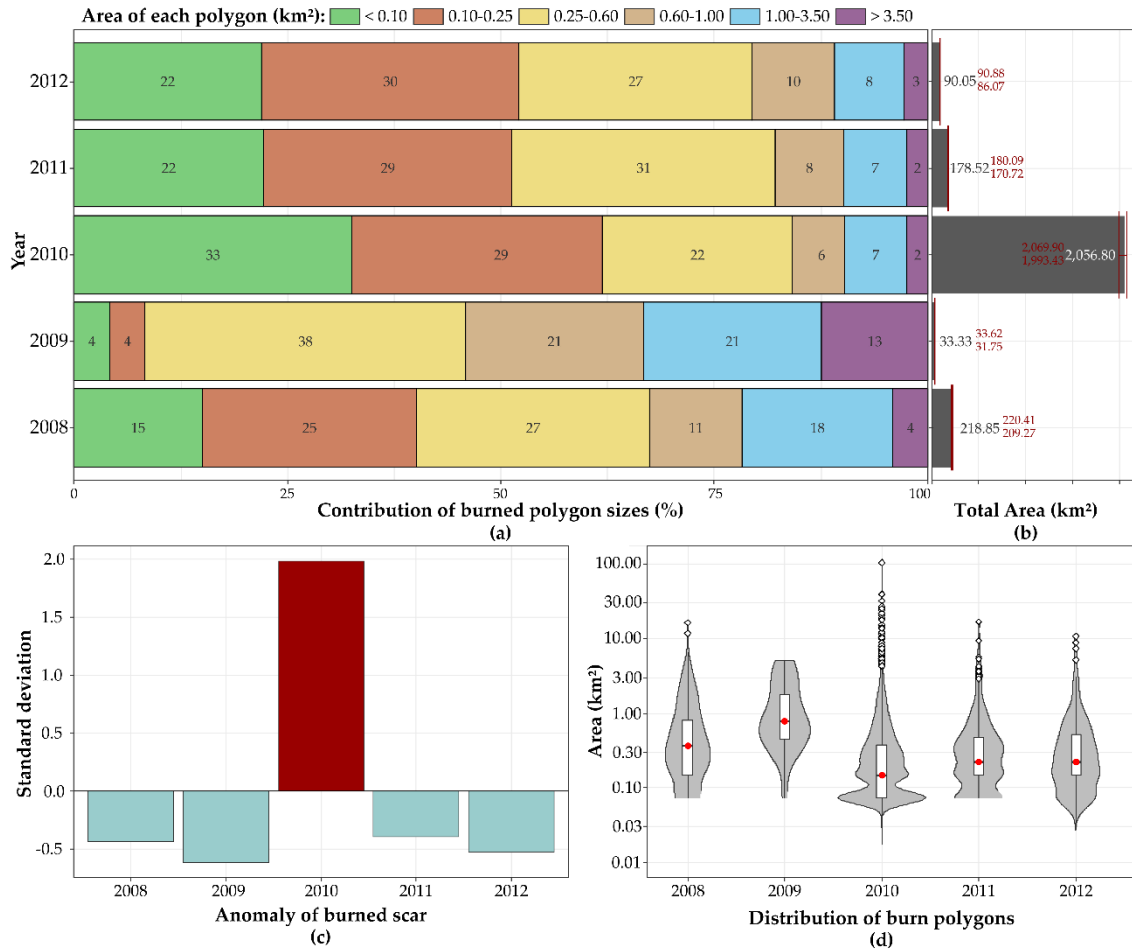
Distance (km)	2008		2009		2010		2011		2012	
	Ri	Rd	Ri	Rd	Ri	Rd	Ri	Rd	Ri	Rd
Minimum	1.28	6.89	0.98	10.29	1.21	10.80	1.26	5.71	1.53	4.27
Mean	1.68	7.36	1.52	10.99	1.49	11.15	1.58	6.10	1.86	4.65
Maximum	5.39	28.88	3.72	41.86	6.20	56.54	5.69	34.28	5.73	24.81
Standard deviation	1.12	5.51	0.93	9.94	1.15	9.67	1.12	5.86	1.34	4.77
Variance	1.27	30.35	0.86	98.88	1.32	93.51	1.25	34.32	1.79	22.74

Source: From Author.

In all the analyzed years, there was a dominance of burned scars with areas up to 0.60 km² (Figure 3-4a). However, in 2009 there was a significant change in the proportions of burned scar classes, where the larger polygons (>0.25 km²) stood out over small polygons (< 0.25 km²).

In 2010, we observed the largest burned area (2056.80 km²) among all years analyzed, making this year anomalous in relation to the average burned area value (+2.39 SD, Table 3-5) and also to a number of burned scars (+1.99 SD, Figure 3-4b, and Table 3-5). Additionally, this year presented the larger number of outliers compared to the other years (Figure 3-4c and Table 3-5).

Figure 3-4. Evaluation of the annual burned area time series from 2008 to 2012.

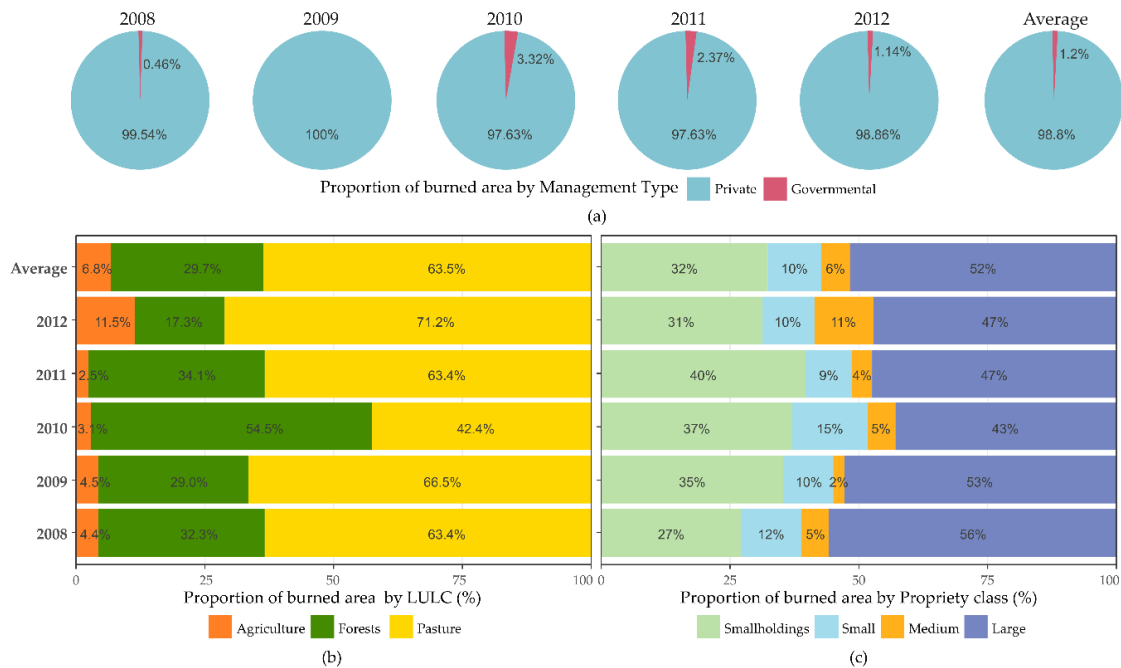


(a) Contribution of each burned polygon size to the total burned area; (b) total burned area (ha) with upper and lower limits; (c) anomaly of number of burned scars, normalized by its standard deviation (σ) for the 2008–2012 period; (d) Distribution of burn polygon sizes, where the sides of each violin is a kernel density function; the red dot represents the median; the white bar indicates the interquartile range; the straight vertical line represents the 95% confidence interval; and the white dots represent outlier polygons.
 Source: From Author.

3.3.2 Fire occurrence and land tenure relationship

Usually, the extent of the fires' impact was greatest for private areas (98.8%) than for public governmental lands (1.2%). Burned areas were not observed in governmental lands in 2009 and were lower than 1% in 2008. However, in 2010, fire occurrences increased by 2.86 percentage points (p.p) within the areas managed by governmental institutes (Figure 3-5a).

Figure 3-5. The proportion of burned area by (a) management types; (b) land use and land cover; (c) propriety class.



Source: From Author.

The dominant LULC in Acre is the Forest class (Table 3-7), representing 91% of all territory in the period studied. The area of Pasture and Agriculture corresponded to 8.3% and 0.7% of the territory, respectively. The Pastures class was the LULC predominantly affected by fire during regular years (63.5%). For the same period, the areas of Forests and Agriculture affected by fires corresponded, respectively, to 29.7% and 6.8% of Acre’s territorial extent (Figure 3-5b). On the other hand, during the 2010 drought, the burned area increased by almost 25 p.p. in forests (contributing to 54.5% of the total area burned) and decreased in the other two classes (totaling 42.4% of Pasture and 3.1% of Agriculture).

Table 3-7. The proportion of each land use and land cover class in Acre state through the years.

LULC	2008	2010	2012	Average
Forest	91.0%	91.2%	90.5%	91.0%
Agriculture	0.9%	0.6%	0.7%	0.7%
Pasture	8.1%	8.2%	8.8%	8.3%

Source: From Author.

Acre registered, by 10 January 2018, 31901 proprieties with the Rural Environmental Registry (acronym CAR). From this total, 78% were classified as smallholdings, 18.5% as small, 1.9% as medium, and 1.5% as large properties. In regular years, around 38 large proprieties, 19 medium, 438 smallholdings, and 68 small proprieties were affected by fires. These numbers represent, for each class area respectively, 8%, 3.2%, 1.8%, and 1.2%. This same pattern persisted during 2010, with a change in the total amount of proprieties affected (Table 3-8). This pattern was not observed when we analyzed the total of the burned area (Figure 3-5c). Interestingly, a new configuration emerged in all regular climate and anomalous years, with large properties contributing to the largest affected areas, followed by smallholdings, then small, and finally medium properties.

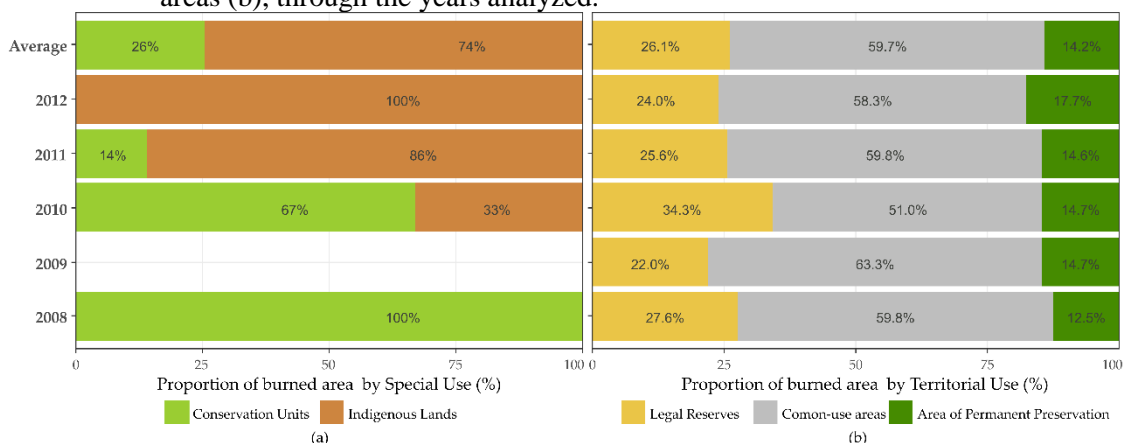
Table 3-8. Number of proprieties affected by fires through the years.

Class of Proprieties	Total	2008	2009	2010	2011	2012	Average
Smallholdings	24964	658 (2.6%)	80 (0.3%)	6394 (25.6%)	672 (2.7%)	341 (1.4%)	438 (1.8%)
Small	5867	126 (2.1%)	14 (0.2%)	1368 (23.3%)	91 (1.6%)	42 (0.7%)	68 (1.2%)
Medium	593	35 (5.9%)	3 (0.5%)	215 (36.3%)	22 (3.7%)	16 (2.7%)	19 (3.2%)
Large	477	60 (12.6%)	15 (3.1%)	258 (54.1%)	46 (9.6%)	30 (6.3%)	38 (8.0%)
Total	31901	879 (2.8%)	112 (0.4%)	8235 (25.8%)	831 (2.6%)	429 (1.3%)	563 (1.8%)

Source: From Author.

When analyzing the occurrence of burned areas in governmentally protected areas (CU and IL), we found that the total burned area was predominant in 2008 and 2012, respectively by CU and IL (Figure 3-6a). In 2009, burned areas did not occur in governmentally protected areas. Inside the boundaries of private areas, common-use areas (AUC, 59.7%) were more affected by fires than protected areas (LR, 26.1% and APP, 14.2%) (Figure 3-6b).

Figure 3-6. The proportion of burned area by land use and land cover types (a) and by special areas (b), through the years analyzed.



Source: From Author.

Five of the eleven CUs in Acre were affected by fires between 2008 and 2012 (Table 3-9). The RESEX Chico Mendes was the only one to burn every time that CU was affected. During 2010, we observed the highest number of CUs affected, reaching a total of 45.63 km² of area burned. In addition, less than 1% of the burnings occurred in Integral Protection reserves (PARNA Serra do Divisor), while about 99% occurred in sustainable-use reserves, such as the RESEX Chico Mendes (34.73 km²), RESEX Cazumbá-Iracema (7.76 km²), FLONA Santa Rosa dos Purus (1.87 km²), and ARIE Seringal Nova Esperança (1.26 km²).

Table 3-9. Area (km²) of Conservation Units affected by fire through the years analyzed.

Type	Class (Acronym)	Nome	2008	2009	2010	2011	2012
UIP	National Park (PARNA)	Serra do Divisor	0.00	0.00	0.02	0.00	0.00
USU	Area of Relevant Ecological Interest (ARIE)	Seringal Nova Esperança	0.00	0.00	1.26	0.00	0.00
USU	National Forest (FLONA)	Santa Rosa do Purus	0.00	0.00	1.87	0.00	0.00
USU	Extractive Reserve (RESEX)	Cazumbá-Iracema	0.64	0.00	7.76	0.00	0.00
USU	Extractive Reserve (RESEX)	Chico Mendes	0.37	0.00	34.73	0.59	0.00
Total			1.00	0.00	45.63	0.59	0.00

UIP – Integral Protection; USU – Sustainable use.

Source: From Author.

In relation to the 31 ILs existing in Acre, only eleven of them were affected by fires between 2008 and 2012 (Table 3-10), which were the following: Alto Rio Purus;

Cabeceira do Rio Acre; Igarapé do Caucho; Kampa do Rio Amonea; Kampa e Isolados do Rio Envira; Katukina/Kaxinawá; Kaxinawá Colônia Vinte e Sete; Kaxinawá do Rio Humaitá; Mamoadate; and Poyanawa. The Mamoadate land had the greatest burned extent in 2010 (11.20 km²) and was the only one to burn in 2011.

Table 3-10. Area (km²) of Indigenous land affected by fire through the years analyzed.

Terra Indígena	2008	2009	2010	2011	2012
Alto Rio Purus	0.00	0.00	0.33	0.00	0.00
Cabeceira do Rio Acre	0.00	0.00	0.00	0.00	0.00
Igarapé do Caucho	0.00	0.00	0.96	0.00	0.00
Kampa do Rio Amonea	0.00	0.00	2.93	0.00	0.00
Kampa e Isolados do Rio Envira	0.00	0.00	0.15	0.00	0.00
Katukina/Kaxinawá	0.00	0.00	0.15	0.00	0.00
Kaxinawá Colônia Vinte e Sete	0.00	0.00	0.29	0.00	0.00
Kaxinawá do Rio Humaitá	0.00	0.00	0.13	0.00	0.00
Mamoadate	0.00	0.00	11.20	3.64	0.00
Poyanawa	0.00	0.00	6.46	0.00	1.03
Total	0.00	0.00	22.59	3.64	1.03

Source: From Author.

3.3.3 Environmental, social, and economic impacts of fire

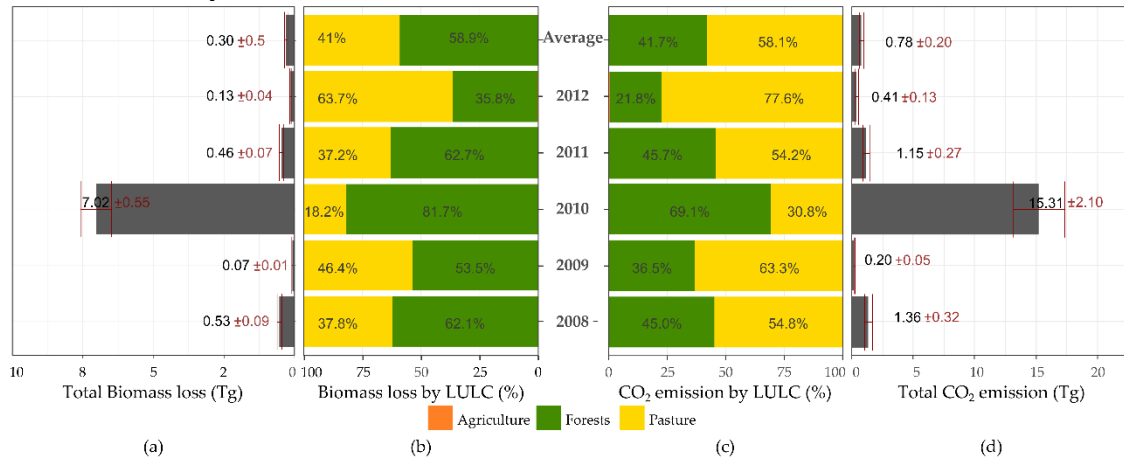
The average biomass loss during normal climate years was about $0.3 \pm 0.5 \text{ Tg.y}^{-1}$, however, this value increased to $7.02 \pm 0.55 \text{ Tg.y}^{-1}$ in 2010 (Figure 3-7a). Fires in forested areas were responsible for almost 59% of biomass loss in Acre during all years, except for 2012 (Figure 3-7b)

Pastures contributed with approximately 58% of the total CO₂ emissions in normal years ($0.78 \pm 0.20 \text{ Tg.y}^{-1}$) (Figure 3-7c). The Agriculture class, on the other hand, contributed less than 0.2% of emissions, on average. During 2010, however, forests alone contributed to 69% of the total CO₂ emission from fires in Acre (Figure 3-7c), corresponding to $15.31 \pm 2.10 \text{ Tg.y}^{-1}$ (Figure 3-7d).

By analyzing the social impacts, we observed up to 2500 respiratory morbidity cases during the second semester of all the analyzed years. In the normal climate years (2008, 2009, 2011, and 2012), the mean cases of respiratory illness were around 2711. Surprisingly, the lowest record of respiratory morbidity cases (2545 cases in total) was

found during 2010. Rio Branco, Cruzeiro do Sul, and Sena Madureira were the main municipalities in number of respiratory illness cases in all years.

Figure 3-7. The proportion of biomass loss (b) and CO2 emissions (c) by land use and land cover types and the total biomass loss (a) and total emissions(d) through the years analyzed.

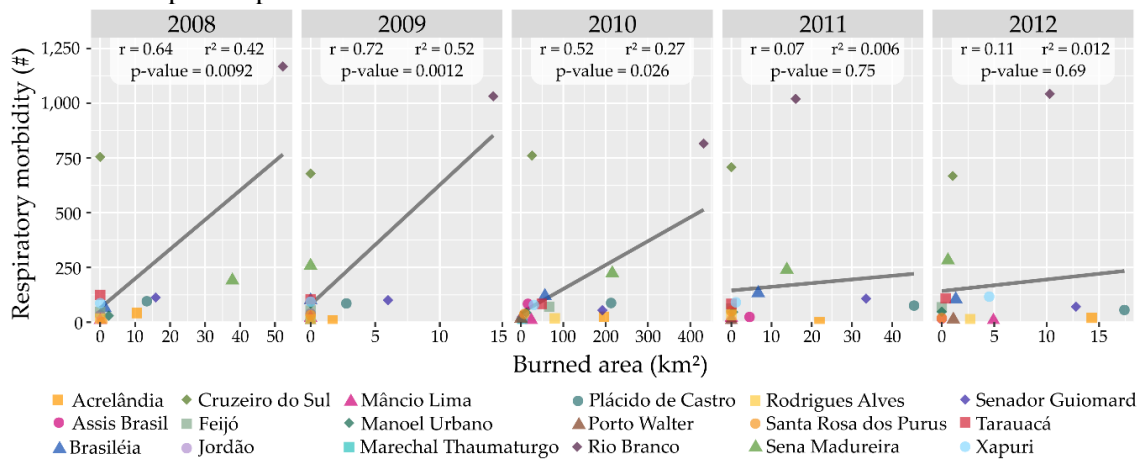


Source: From Author.

The relationship between respiratory morbidity cases and burned area during the extend dry season (Figure 3-8), suggests that Rio Branco is an outlier, with a higher amount of burned area and a high number of hospitalizations in the first three years analyzed. Meanwhile, Plácido de Castro, Senador Guimard, and Acrelândia had an increase in burned area through the years, while their numbers of respiratory cases remained approximately the same. Contrarily, Cruzeiro do Sul persisted with almost the same number of hospitalizations and burned area through all the years analyzed.

After designing a linear regression where respiratory morbidity was the dependent variable and respiratory morbidity cases was the independent variable, modeled for each year (Figure 3-8), we observed a positive correlation coefficient ($r > 0$) more explicit for 2008 ($r = 0.64$, $r^2 = 0.42$, p -value = 0.0092), 2009 ($r = 0.72$, $r^2 = 0.52$, p -value = 0.0012), and 2010 ($r = 0.52$, $r^2 = 0.27$, p -value = 0.026) years. This result suggests that an increase in the burned area will lead to an increase in the number of hospitalizations. However, the quality of those models described by the determination coefficient (r^2), indicates that 2009 exhibited a better model fit than the others years. The 2008, 2009, and 2010 year models indicate that the burned area is relevant to explaining the respiratory morbidity cases, using a 5% significance level.

Figure 3-8. Correlation between respiratory morbidity and burned area by year analyzed, with the determination coefficient value (r^2), the correlation coefficient value (r), and the specific p-values.

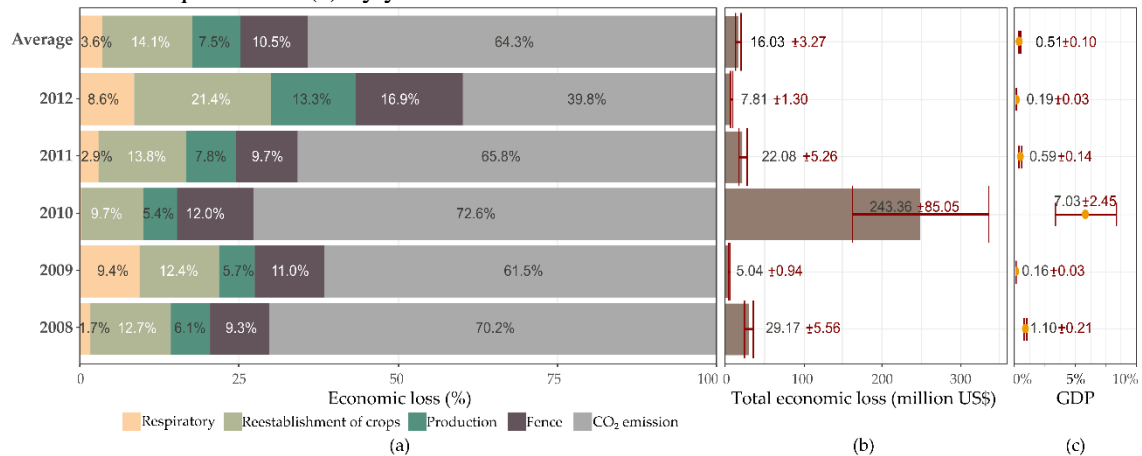


Source: From Author.

The fire-mediated economic losses in Acre between 2008 and 2012 are discriminated in Figure 3-9 and Table 3-11, where the values are specified by damage type, summarized with its total deviation and GDP equivalence. CO₂ emissions represented the greatest contribution to the total economic loss, ranging from 40% to 73%. Respiratory illness costs had the smallest contribution, representing up to 9.4% of all costs in 2009. In 2010, there was an increase of 8 percentage points in the CO₂ emission contribution for the total economic loss, compared to the average of the normal climatic years. Losses in propriety infrastructure (fences) represented 12% in 2010, the most representative year before 2012.

As expected, 2010 had the highest economic loss, corresponding to a total of US\$ 243.36±85.05 million, representing around 7±2.45% of Acre's GDP for that year. Nevertheless, during normal climate years, the average loss was around US\$ 16.03±3.27 million, representing 0.51±0.10% of the mean GDP.

Figure 3-9. Percentage of economic loss by type of damage (a), total economic loss (b), and GDP equivalence (c) by year.



Source: From Author.

Table 3-11. Cost in millions of dollars of losses by fire in Acre state between 2008 and 2012, with a percent of total costs (%) and a related percent of total GDP.

Type of Impact	2008	2009	2010	2011	2012	Average
Fence	2.72(9.3%)	0.55(11%)	29.27(12%)	2.14(9.7%)	1.32(16.9%)	1.68(10.5%)
Reestablishment	3.70(12.7%)	0.63(12.4%)	23.63(9.7%)	3.05(13.8%)	1.67(21.4%)	2.26(14.1%)
Production	1.78(6.1%)	0.29(5.7%)	13.11(5.4%)	1.72(7.8%)	1.04(13.3%)	1.21(7.5%)
CO ₂ emission	20.49(70.2%)	3.10(61.5%)	176.77(72.6%)	14.52(65.8%)	3.11(39.8%)	10.31(64.3%)
Respiratory	0.49(1.7%)	0.47(9.4%)	0.57(0.2%)	0.65(2.9%)	0.67(8.6%)	0.57(3.6%)
Total	29.17 ± 5.56	5.04 ± 0.94	243.36 ± 85.05	22.08 ± 5.26	7.81 ± 1.30	16.03 ± 3.27
% GDP	1.10% ± 0.21	0.16% ± 0.03	7.03% ± 2.45	0.59% ± 0.14	0.19% ± 0.03	0.5% ± 0.10

Source: From Author.

3.4 Discussion

3.4.1 Spatio-temporal variability of fire dynamics

The eastern flank of Acre was the region with the greatest extent of burned area. This region is historically the epicenter for land use and land cover change, with up to 10% of forests burning twice between 1999–2010 (MORTON et al., 2013) and up to three times, when expanding the time-window from 1984 to 2016 (SILVA et al., 2018b), mostly occurring in Acre’s frontier with Pando (Bolivia), Amazonas (Brazil), and Pucallpa (Peru).

The widespread occurrence of fires in 2010 is attributed to the severe drought that occurred in Amazonia as a consequence of the El Niño-Southern Oscillation (ENSO) phenomenon, intensified by the warming of the tropical North Atlantic Ocean (LEWIS et al., 2011; MARENGO et al., 2011). In 2010, the total area burned increased by 16 times in relation to the 2008–2012 average. Using the Burn Damage and Recovery (BDR) algorithm applied to MODIS and LANDSAT images, Morton et al. (2013) found that the total extent of burned forests in 2010 was 9.14 times greater in southern Amazonia than during the 2008–2009 mean. Silva et al. (2018b), applying the Burn Scar Index (BSI) to LANDSAT images in Acre state, found an increase of 166.9 times in the total burned forest area in 2010, when compared to the 2008–2012 mean. These increases were associated with the environmental conditions during severe drought years when fires rapidly spread into forest areas, a fact that does not occur during regular climate years (BRANDO et al., 2014). This statement is supported by the exacerbation of burn scars' occurrence in areas distant from roads and rivers and the total affected forests areas in 2010.

3.4.2 Fire occurrence and land tenure relationship

Pasture was the first LULC type burned more in all the regular climatic years. Usually, pasture management with fire during the dry season aims to eliminate accumulated dead material on the ground, which represents a physical barrier to the development of new plants, more palatability, and with a higher nutritive value (COSTA et al., 2011; COSTA, 2008). Furthermore, according to Costa (2008), in the northern Amazon, fire is a widespread practice for increasing pastures' productivity.

Observing at property scales, 8% of the large rural properties presented 52% of the burned areas while less than 2% of the small properties, where there is the prevalence of small producers and family farmers, accounted for 32% of the burnings. This indicates that fire is a widespread tool for management, independently of the land tenure.

Despite this, Soares-Filho et al. (2014) reported that, with the New Forest Code accession, the vegetation management within private properties becomes increasingly essential to mitigate global climate change effects, since about 53% of vegetation is located in these properties. In addition, with the possibility of delimitation and spatial location of properties and preservation areas in the SICAR system, environmental agencies have a

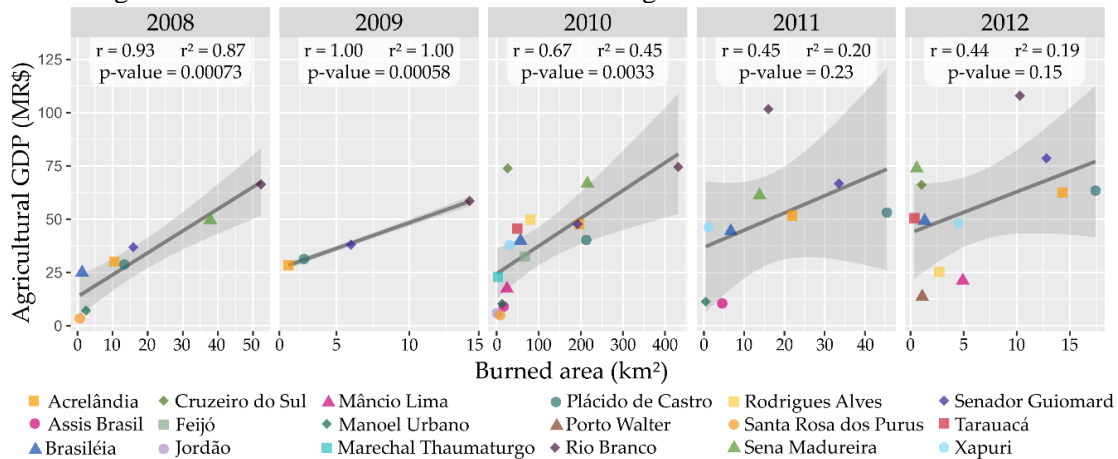
supporting tool to inspect forest management and protected areas in private properties, increasing law enforcement.

Currently, the three main fire-dependent activities in Acre are deforestation, undertaken by all classes of landholders (GODAR et al., 2014), subsistence agriculture by smallholders and pasture management, and recovery by small and medium cattle ranchers. Deforestation-related fires decreased with the reduction in deforestation (ARAGAO; SHIMABUKURO, 2010), a change which is part of a slowdown of the boom-and-bust dynamics of frontier expansion (WEINHOLD; REIS; VALE, 2015). In fact, the "bust" stage appeared to be replaced by the decoupling of agriculture and the rest of the economy from forest suppression and degradation, as evidenced by Weinhold et al. (2015), Tritsch and Arvor (2016), and Caviglia-Harris et al. (2016). In this new development paradigm, which is more adherent to the "industry life cycle" thesis (HALL; CAVIGLIA-HARRIS, 2013), the two other fire causes remain. The first is due to the still limited inclusion of smallholders in the formal economy, as they remain located mainly in remote government-administered settlements with low capacities to generate income and obtain funding (GUEDES et al., 2012). Secondly, barriers to income and funding, which limit capitalization of landholders, also contribute to perpetuating the low-input and extensive cattle ranching, which remains the rule in Amazon (SÁ; ANDRADE; VALENTIM, 2010).

The decrease in fires due to agricultural expansion and intensification is, in fact, a global trend, as argued by Andela et al. (2017) and endorsed for Western Amazonia by our results, where large properties decrease its contribution in 9 percentage points through the years, and additionally by the non-correlation between fires and the economic data of the agricultural sector after 2010 (Figure 3-10).

This detachment of fire as a management tool could be explained by the increased effectiveness of agricultural sustainability policy within the context of policies, such as the REDD+ for Early Movers (SILLS et al., 2014), the Sustainable Development Plan (BID, 2011), the farm certification program (AMARAL et al., 2018), the rural-environmental registry (SFB, 2018), the Integrated Plan for prevention and control of deforestation and fires (CEGDRA, 2011), Brazil's Low-Carbon Agriculture (ABC) Plan (MAPA, 2012), or even for a combination of them.

Figure 3-10. Correlation between GDP of the agricultural sector and burned area.



Source: From Author.

Most of those policies are addressed to private properties, however, governmental areas represented, on average, 1.2% of the total burned area in Acre, where Indigenous Lands are often found (~74%). Fire in these lands is part of several subsistence techniques of land clearing, agricultural management, hunting, planting, and religious rituals, being used with precaution and caution in all applications (GRAF, 2016; LEONEL, 2000; PIVELLO, 2011). Graf (2016) argues that fire use for deforestation and soil enrichment for those communities has been gradually eliminated in Acre, thanks to the inclusion of mitigation measures of the Environmental and Territorial Indigenous Management Plans (PGATIs) and through the formation of indigenous agroforestry agents (AAFI) at these communities.

Another type of protected government area counted in this study were Conservation Units (CU). In Brazil there are two types, one that aims to preserve nature where only the indirect use of its natural resources is allowed, called Units of Integral Protection (UIP), and the other denominated Units of Sustainable Use (USU), that aim to make nature conservation compatible with the sustainable use of a portion of their natural resources and with human occupation. Each CU has their own groups. For UIP there are five types, ecological stations; biological reserves; national parks; natural monuments; and wildlife refuges. For USU, the groups are environmental protection areas; areas of relevant ecological interest; national forests; extractive reserves; wildlife reserves; sustainable development reserves; and private reserves of the natural patrimony (BRASIL, 2000).

In Acre, extractive reserves were the ones with the largest burning throughout the analyzed period (44.09 km², Table 3-9). In these areas, the traditional communities, whose subsistence activities are based on extractives, subsistence farming, and raising small animals, are allowed (BRASIL, 2000). The study of Torres et al. (2017), using a Brazilian firefighters database, revealed that the fire use for land clearing is the main cause of wildfires in the CUs. Incendiarism was the second recurrent cause of wildfires in CUs. With these two anthropogenic causes at the top, the authors showed that there is a strong human pressure on CUs, mainly on their borders. Allied to this, there is an existing agricultural pressure in this region of the Amazon as a whole, as it is now considered a new frontier for agricultural expansion.

3.4.3 Environmental, social, and economic impacts of fire

The impact of fire can be felt by different groups and at different scales (NELSON et al., 2013). Here, we look through five distinct components, CO₂ emissions, respiratory morbidity, infrastructure damages, future production losses, and crop reestablishment. Our analysis can be considered conservative because these five components are a small part of the whole impact and are at a low scale of what fire impact can influence.

Using deforestation rates given by PRODES (INPE, 2021b) as a baseline and the mean biomass value proposed by Salimon et al. (2011), the average biomass removed by deforestation in Acre between the 2008–2012 period was approximately 6.19±2.26 Tg. This is much higher than the average biomass committed by fire in the same period (0.30±0.5 Tg). However, the fire impacted more biomass (7.02±0.55 Tg) than deforestation (6.37±2.33 Tg) in 2010, due to the extreme drought. Thus, even though the emissions reduction by deforestation in Acre was about 85 Tg CO₂ between 2006 and 2010 (NEPSTAD et al., 2012), with the increasing probability of extreme droughts predicted due to climate change and the consequent collateral increasing of fires, the fire-related carbon emissions can substantially increase.

We did not find a clear temporal relationship between the number of cases of respiratory morbidities and the total area burned in each year. However, we found a strong relationship between these variables during the anomalous year. These results confront some of the studies already carried out for the Amazon (DE MENDONÇA et al., 2004; SMITH et al., 2014) or even for Acre (SILVA; SILVEIRA; SILVEIRA, 2008). This

divergence may be associated with other factors or a combination of factors, not accounted here, that could influence illness prevalence (such as vehicle pollution, and access to health assistance). The top three cities in the occurrence of respiratory illness (Rio Branco, Cruzeiro do Sul, and Sena Madureira) are the main centers of each microregion in Acre, being the most populated and developed (IBGE, 2021a). Hence, these cities are likely to concentrate all medical assistance for each region, inflating the amount of hospitalization, even while not showing a higher burned area.

The quantified fire-mediated impacts for the normal years amounted to $0.51 \pm 0.10\%$ of the Acre's GDP for the analyzed period. During 2010 these impacts represented $7.03 \pm 2.45\%$ of the GDP, considering just a restrained part of the direct losses (fences, agriculture production, and CO₂ emissions) and indirect losses (respiratory illness). By conducting a more comprehensive assessment of direct and indirect impacts, these values will certainly be higher, with larger impacts upon the local economy. Brown et al. (2011) estimated that the economic, social, and environmental losses related to the 2005 burning events in Acre were to the order of US\$100 million, which is equivalent to around 0.9% of the GDP. Additionally, De Mendonça et al. (DE MENDONÇA et al., 2004) calculated an economic loss related to 0.2 to 0.9% of the GDP for the Amazon from 1996 to 1999, considering the impact of fire on agriculture, forests, CO₂ emissions, and hospitalizations due to respiratory problems.

3.5 Conclusions

In five years, fire affected a total area of 2577 km², which represents around 2% of Acre's territorial area, or 1.6 times the area of São Paulo city. Just in 2010, as a consequence of the extreme droughts associated with El Niño and the subsequent warming of the Tropical North Atlantic, the total burn area was 2057 km². We demonstrated that drought effect on fire patterns favors spreading to places farther from the main means of ignition, such as roads and highways, entering protected areas (UC and IL), and areas with restricted use (APP and RL).

Interestingly, the pattern of use of fire in Acre has changed since 2010. The fire was closely linked to the agricultural sector, especially connected to large proprietaries, as a tool for deforesting and also for pasture management. However, possibly due to some governmental policies, international pressure, and even the socioeconomic impacts of the

2010 fires, this relationship weakened after the 2010 drought. Additionally, during this later period, the number of properties that use fire as a tool for pasture management and subsistence has decreased.

Fire in traditional communities in the state is small compared to private properties, nonetheless, special projects and policies for these communities must continue and the existing ones should be shared with other communities, and even across the Amazon, to ensure minimum fire usage.

The impact of fire is more expressive than we anticipated, however, those five direct and indirect components that were calculated indicated an expressive influence on Acre's economy, representing $0.16 \pm 0.03\%$ to $7.03 \pm 2.45\%$ of the state's total GDP. The total CO₂ emission from fire can be more expressive than deforestation in extreme drought years, while infrastructure damages and production losses represented 27% to 52% of all fire costs.

Quantifying social fire impacts related to respiratory morbidity is complex. The difficulty to establish a robust diagnostic of cause and effect, with relation to fires and respiratory illness, introduces large uncertainties for defining the proportional contribution of these costs to the total economic loss estimates.

Our study showed that the economic impacts of fire can be large, especially in years of extreme drought. The state of Acre must take advantage of the National Policy on Climate Change (PNMC), instituted by Law 12,187/2009, which aims to encourage the development and improvement of actions mitigating greenhouse gas emissions in Brazil and to improve the formulation of environmental policies to restrain fire usage.

4 HOSPITALIZATION DUE TO FIRE-INDUCED POLLUTION IN THE BRAZILIAN LEGAL AMAZON FROM 2005 TO 2018

4.1 Introduction

Biomass burning in agriculture is, globally, a source of air pollution, and consequently, of morbi-mortality. The practice, which is more frequent in developing countries, especially China, India and Brazil (CASSOU, 2018), but also Indonesia (WATTS et al., 2019), has been evidenced as a source of respiratory illnesses and related hospitalizations (ARBEX et al., 2007; DO CARMO; ALVES; HACON, 2013; KUMAR; KUMAR; JOSHI, 2015, cap. 3; CHAGAS; AZZONI; ALMEIDA, 2016; SHELDON; SANKARAN, 2017; WATTS et al., 2019). Besides having thousands of lives impaired and eventually prematurely taken (REDDINGTON et al., 2015), the supply gaps of the national healthcare are widened and the human and physical resources are even more overloaded.

The Amazon biome is the region with the biggest amount of thermal anomalies of fire in Brazil (INPE, 2020). Historically, fires are set as part of the processes of deforestation, fallow and pasture management, but they may also run out of control and cause forest fires (ALENCAR; RODRIGUES; CASTRO, 2020). In addition to the fact that these events in the Amazon are mainly driven by humans, they are also boosted by climate extremes, such as the anomalous temperatures and droughts (ARAGÃO et al., 2007, 2018), that were stronger and more frequent over the years (1997/98, 2005, 2010, 2015/16).

These fire events release a massive load of pollutants in the atmosphere. Fire smoke is usually composed of primary pollutants, such as particulate matter (PM), carbon monoxide (CO), nitrogen oxides (NO_x), and non-methane organic compounds (NMOC), and some of them react to form secondary pollutants such Ozone (O₃) and onther secondary organic aerosols (SOA) (REISEN et al., 2015). When in contact with the human respiratory system, these components cause several negative consequences for the health. For instance, CO₂ exposure can induce a shortness of breath, cough, fatigue and can also lead to convulsions, coma and death depending on its concentration (PERMENTIER et al., 2017).

Since the process that connects pollution and health is a result of spontaneous social and atmospheric forces, and not a consequence of a controlled experiment randomly assigning pollution levels to locations, the available data for analysis is observational. It thus reveals variations of health measures, like hospitalizations, which are not only due to the variation of pollution. In this case, the econometric approach of quasi-experimental identification is useful, because under reasonable assumptions and after considering the variation of key variables, it manages to retrieve the random portion of pollution variation. This is exactly what the Instrumental Variable (IV)⁴ technique does (WOOLDRIDGE, 2018), as it was used elsewhere to identify the effects of pollution on health (SHELDON; SANKARAN, 2017; DERYUGINA et al., 2019; HE; LIU; ZHOU, 2020). This approach is also applied here for the specific case of the Brazilian Amazon in the last two decades (2001-2020).

It should be highlighted that, in this chapter, fire is used as an instrumental variable to support the identification of the effect of pollution on hospitalizations, exploring the positive relationship these two variables generally exhibit (SHELDON; SANKARAN, 2017; GONÇALVES et al., 2018; HE; LIU; ZHOU, 2020). This also allowed, as an useful additional benefit, to account for fire's contribution to hospitalizations (HE; LIU; ZHOU, 2020). The latter was assessed both statistically, with results from the first-stage regression, and numerically, as the fraction of hospitalizations that would be avoided if fires were suppressed. Besides fire and following Deryugina et al. (2019) and Sheldon and Sankaran (2017), wind speed and wind direction were used as additional instrumental variables.

Despite having a huge literature branch that investigates the health consequences of Amazon fires, our contribution is original in addressing two key gaps. The first is the absence of an identification strategy that biases the available estimates of fire-induced pollution on health (that applies, for instance, to Do Carmo et al. (2013), Smith et al. (2014) and Machado Silva et al. (2020)). Secondly, studies that cover the whole Amazon in long periods are rare, with most evidences belonging to Amazon states or smaller regions and to generally particularly fire-critical periods including one to a few

⁴ An instrument variable is a proxy used to substitute the explanatory variable in the main model. Such variable needs to preserve the causal-effect context and the nature of the relationship among the explanatory and the response variables. In addition the IV must satisfy two statistical criteria: (1) it must be exogenous, that is, uncorrelated with the error term of the structural equation; (2) it must be partially correlated with the endogenous explanatory variable.(WOOLDRIDGE, 2018).

years (the case of De Mendonça et al. (2004), Carmo et al. (2010), Jacobson et al. (2014) and Machado-Silva et al. (2020)).

We use a dataset composed of municipal-level data of 805 Brazilian municipalities with four combinations among the three instrumental variables, four types of hospitalization diseases, three age groups, and 12 control variables. All data were monthly aggregated, totalizing 118,335 observations. Our estimates suggest a positive effect of fire in the hospitalization due to respiratory diseases in general and due to asthma in particular. Considering the total range of respiratory diseases, an increase in 1% of fire in the region leads to an average of 0.1383% in the hospitalization numbers, with higher levels of cases during the fire season (Aug-Oct)..

This chapter is structured in five sections, and firstly there is a brief introduction. The second section we describe the data used subdivided by its use in the model (instrumental variable, independent variable and control variable), then explain the way that we aggregated those data in municipality levels and lastly, how we performed the simulation of hospitalization attributable to fires. The third section presents the main results of the data behaviour for the region, the estimates of the econometrics model, the result of the simulation and one validity test. Fourth section introduces a discussion of the results, comparing them to the ones previously observed in the region, also pointing out some improvements in the model. Finally, the fifth section exhibits the main conclusion in the estimation of hospitalization counts due to fire-induced smoke in the Brazilian Legal Amazon over the past 20 years.

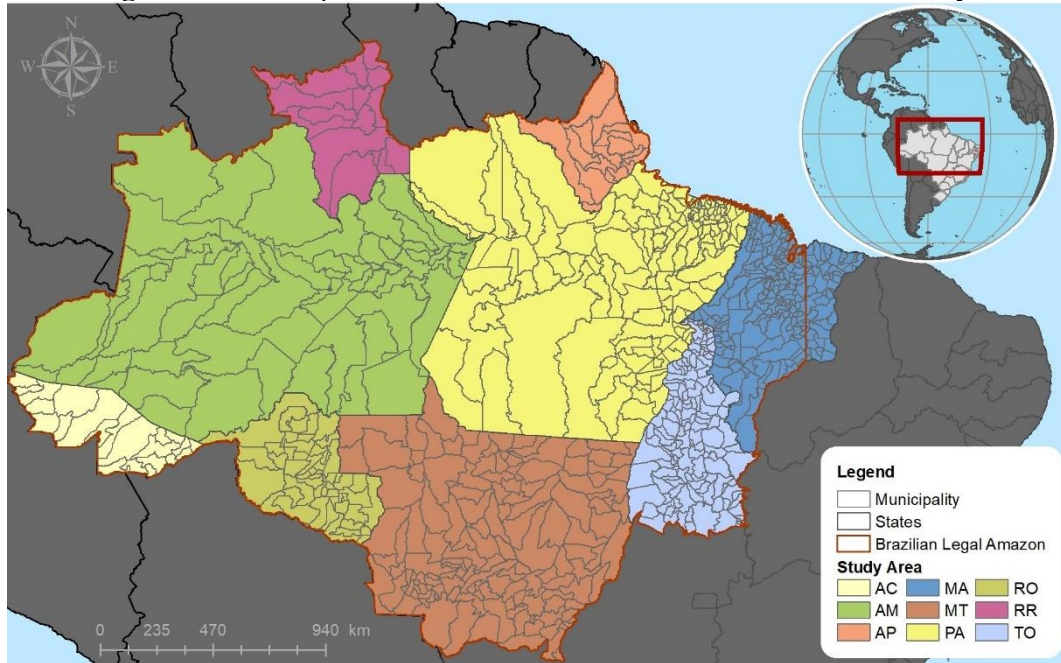
4.2 Material and methods

4.2.1 Study area

The study area comprises the Brazilian Legal Amazon (BLA), that covers approximately 5 million km² and includes the states of Acre, Amapá, Amazonas, Mato Grosso, Rondônia, Roraima, Tocantins, Pará and only the Maranhão's municipalities over the 44th Meridian (BRASIL, 2007). This area represents around 59% of the Brazilian territory (IBGE, 2020).

However, due to the availability of some data, we consider the full territory of all the states that are within the BLA (Figure 4-1), thus, we used 805 municipalities over the nine states of the BLA.

Figure 4-1. Municipalities within the nine states of BLA used in this study.



Data base from IBGE (2019).
Source: From Author.

4.2.2 Data

According to the econometric technique, three groups were organized: instrumental variables (IV), independent variables (IdV), and control variables (CtV) data (Table 4-1).

Table 4-1. Short description of the data, categorized by type.

tp.	Variable			Time			Spatial		Source
	abr.	description	agg.	period	res.	agg	res.	agg.	
IV	BA	Burned Area	Sum	2000-2020	d	m	250m	mc	MCD64A1
	TA	Thermal anomalies*	Sum	2003-2020	m	m	250m	mc	MYD14A1
	WDirec	Wind direction (degree)	Mean	2001-2020	m	m	0.25°	mc	ERA5
	WSpeed	Wind speed (m/s)							
IndV	AOD	Land Aerosol Optical Depth (AOD)	Mean	2001-2020	m	m	1km	mc	MCD19A2
	Hosp.	Hospitalization due to respiratory disease (Cap X), by location of residence, and age	Sum	2001-2020	m	m	-	mc	DataSUS

Continues

Table 4-1. Conclusion.

IndV	Asthma	Hospitalization due to asthma, by location of residence	Sum	2001-2020	m	m	-	mc	DataSUS
	Pneumonia	Hospitalization due to pneumonia, by location of residence							
	Bronchitis	Hospitalization due to bronchitis, by location of residence							
CtV	Pop	Estimated population	Sum	1992-2019	y	y	-	uf	DataSUS
	GDP	Gross domestic product in thousands of reais	Sum	2002-2017	y	y	-	mc	IBGE
	Chd_d	Infant mortality by location of residence	Sum	01/2001-12/2018	m	m	-	mc	DataSUS
	Crn_d	Chronic disease mortality By location of residence, which we considered the sum of the respiratory, cardiovascular, diabetes, and cancers mortality	Sum	01/2001-12/2018					
	Employe	Number of health professionals	Sum	08/2005-12/2019					
	Beds	Number of hospital beds	Sum	10/2005-05/2020					
	Faci.	Number of facilities	Sum	08/2005 - 05/2020					
	Temp	Mean, minimum and maximum temperature (kelvin)	Min Mean Max	2001-2020					
	Precp	Rainfall	Mean	2001-2020	m	m	0.05°	mc	Chirps
	Road	Road density (m/m ²)		2019	-	m	-	mc	OSM
	Urb	Urban zones	Sum	2001-2020	y	y	30m	mc	MapBiomias
	Cars	Fleet of Cars registered	Sum	2005-2019	m	m	-	mc	Denatran

Variable Tp - Variable type data, among :IV (Instrumental variable data); IdV (Independent variable data), and; CtV (Control variable data); **Variable Abr.** – Abreviation; **Variable Agg.** – Aggregation method; **Time Res** - Is the time resolution of the data, as: d (daily); m (montly), and; y (yearly). **Time Agg.** – Is the time aggregation method used; **Spatial Res.**- is the spatial resolution of the source; **Spatial Agg.** – Is the spatial aggregation used, as by municipality (mc) or states (uf). * Thermal anomalies was used as instrumental variable only in the robustness procedures.

Source: From Author.

4.2.2.1 Instrumental variable data

We use the MCD64A1-v6, product of burned area by Moderate Resolution Imaging Spectroradiometer (MODIS) of Terra and Aqua satellite, collected using the R package “MODISrsp” (BUSETTO; RANGHETTI, 2016). The MCD64A1 has a monthly periodicity, spatial resolution of 500 meters, and its data began in November of 2000. This product uses an association of surface reflectance with active fires, and an algorithm

that checks the temporal changes in the vegetation index (GIGLIO, LOUIS et al., 2015). Globally, it presented 99.7% of overall accuracy, with 40.2% commission error and 72.6% omission error (BOSCHETTI et al., 2019). In the Amazon region, it showed a great similarity to regional and supervised-based product, underestimating 2.9% of the total burned area, but detecting more fires in the north and northwest areas than in the southwest (PESSÔA et al., 2020).

For thermal anomalies, we use the collection 6 from the product MYD14A1 from Aqua MODIS, available on the BDQueimadas website (INPE, 2021a) . This product presents the active fire with date and quality indexes at a global scale, reproducing at 1 km of spatial resolution (GIGLIO, LOUIS; JUSTICE, CHRISTOPHER, 2015). This product is considered a "reference satellite" to *Progama Queimadas* from INPE, and it is the base for comparisons and trend analysis for all the Brazilian territory.

The wind data was obtained using the ERA5 monthly aggregate product, which combines model data with observations across the world, providing a global monthly product with 0.25 degrees spatial resolution (COPERNICUS CLIMATE CHANGE SERVICE, 2019). This product provides the U and V components of the wind, that we convert into wind speed and direction using the “rWind” package (FERNÁNDEZ-LÓPEZ; SCHLIEP, 2019).

4.2.2.2 Independent variable data

Pollutant information was introduced by the Land Aerosol Optical Depth (AOD), gathered by the MCD19A2 version 6 data product and reported in blue band (0.47 μm). This product is a daily MODIS Terra and Aqua combined multi-angle implementation of atmospheric correction (MAIAC) at 1km spatial resolution (LYAPUSTIN, ALEXEI; WANG, YUJIE, 2018).

The measures of AOD reflect the “sum of aerosols from natural and anthropogenic sources, such as emission from industries, vehicles, water vapor, dust and burned biomass (KUMAR, 2010). The product presents a high overall correlation with the ground measurements ($\cong 95\%$) over South America, and is better over the forest, savanna, grassland, and cropland (MARTINS et al., 2017). Moreover, the AOD has been widely used to estimate highly dangerous pollutants for the human respiratory system with

considerable accuracy, such as the particulate matter (PM) (GUO et al., 2017; CHUDNOVSKY et al., 2013).

Hospitalization counts were gathered into TabNet (DATASUS, 2020), which is a governmental platform maintained by the DataSUS (*Departamento de Informaço es do SUS*). We collect four different morbidities that are most related to the long exposure to fire pollution: disease of the respiratory system (ICD-10: X.⁵); Asthma (ICD10: J45-J46); Pneumonia (ICD-10: J12-J18); and Bronchitis (ICD-10: J20-J21).

This information was filtered by municipalities, place of residence and month of attendance. Due to the vulnerability of children and elderly people to fire pollution, we also collected the amount of hospitalizations caused by respiratory issues by age groups, totalizing 4 variables: small children (≤ 4 years old), children (between 5 and 14 years old), elderly (≥ 65 years old), and total (all age range).

4.2.2.3 Control variable data

Estimated population data was collected from DataSUS portal (DATASUS, 2020), that compiles the yearly IBGE estimates produced to compatible data to the Brazilian legal provisions. This data is available yearly for each Brazilian municipality from 1992 until 2019.

Gross Domestic Product (GDP) is provided by the IBGE (IBGE, 2021b), and it is released yearly by municipality, in current prices and aggregated.

Infant Mortality and Chronic diseases are variables of the health level, as proposed respectively by Aquino et al. (2009) and Harris & Kohn (2018). The information was collected from DataSUS portal, filtering by municipality of residence and month of attendance. Infant mortality refers to the death of fetal and children under one year old. As Chronical disease, we considered four groups, like determined by Malta et al. (2014). These groups are: mortality caused by cardiovascular diseases (ICD-10: I00 to I99), cancer (ICD-10: C00 to C97), respiratory issues (ICD-10: J30 to J98), and diabetes (ICD-10: E10 to E14).

⁵ Hospitalization code following the International Classification of Disease (ICD-10), where disease of the respiratory system were those between J00 and J99.

Other data used and related to the capacity of attendance were: the number of employees, the number of beds and the number of facilities. They were also obtained from DataSUS portal.

Weather information came from two different products. The temperature was acquired from MOD11A2, which provides an average 8-day of Land Surface Temperature with a 1 km spatial resolution (WAN, ZHENGMING; HOOK, SIMON; HULLEY, GLYNN, 2015).

The precipitation data came from CHIRPS (The Climate Hazards Group InfraRed Precipitation with Station data), which is a global rainfall dataset with 0.05° spatial resolution (FUNK et al., 2015). The product has a good performance either globally and locally, and particularly in the BLA its values explain 73% of the precipitation with a root mean square error (RMSE) below 15 mm (ANDERSON et al., 2018).

In order to infer about urban pollution, data related to road density, fleet of cars and urban zones were used. To generate road density, the road component was extracted from the total roads network provided by the Open Street Map (OSM, 2020) and the area of municipalities was provided by the IBGE. Fleet of cars was found on the DENATRAN website (MINFRA, 2020), which provides the number of registered cars by month and by municipality.

Lastly, urban density was measured using the MapBiomas product. This land use and land cover data are available annually from 1985 to 2018 with 30m of spatial resolution, based on Landsat images and produced using a pixel base classification and machine learning (MAPBIOMAS, 2021a; SOUZA et al., 2020).

4.2.3 Spatial aggregation

To the spatial data (BA, TA, Wind, AOD, Temperature, Precipitation, Roads and Urban zones) we used the *Google Earth Engine* to clip and aggregate them by municipality. Then, the exported tables were processed in the *RStudio* environment to merge all variables (spatially and non-spatially explicitly) into one single table compatible to *Stata* format.

It is worth mentioning that along 20 years of data, the municipalities boundaries suffered several legal updates, including the creation of new municipalities. To follow those changes, we used each annual current delimitation provided by IBGE to perform each clip and aggregation.

4.2.4 Empirical model

Let the hypothesis grounding data analysis, which is suggested by atmospheric science and epidemiological literature, be presented (CARMO et al., 2010; IGNOTTI et al., 2010; GONÇALVES et al., 2018). Once burnings of considerable size and number occur in a location, pollutants are released and transported through the atmosphere causing considerable appearance or exacerbation of respiratory illnesses. This process is a function of many variables. Fire emissions are, primarily, affected by the fuel type, the temperature of the fire and climatic conditions (URBANSKI; HAO; BAKER, 2008). In the atmosphere, fire pollution may be mixed with pollutants of vehicular or industrial sources, and is also affected by weather conditions (BERNARD et al., 2001). Finally, the number of hospitalizations is influenced by the number of inhabitants, their levels of health and income and the availability of health facilities and staff (CHAGAS; AZZONI; ALMEIDA, 2016; LIU; AO, 2021).

With that in mind, to evaluate the impact of fire-induced pollution on health, we follow the methodology proposed by (SHELDON; SANKARAN, 2017; DERYUGINA et al., 2019; ROCHA; SANT'ANNA, 2020; HE; LIU; ZHOU, 2020), who use the Instrumental Variable (IV), as an approach in which the wind is the exogenous source of variation used to identify the effect of pollution on respiratory morbidity – He et al. (2020) and Sheldon and Sankaran (2017) also adopt fire as a second instrument. The IV Method is based on the two-stage least squares estimator (2SLS) that corresponds to the Equation 4.1 and Equation 4.2 below, with “i” indexing spatial unit and “t” time period.

$$\text{LogAOD}_{it} = \alpha_0 + \alpha_1 IV_{it} + \alpha_2 CrV_{it} + b_i + \varepsilon_{it} \quad (4.1)$$

$$\text{LogHosp}_{it} = \beta_0 + \beta_1 \widehat{\text{LogAOD}}_{it} + \beta_2 CrV_{it} + c_i + u_{it} \quad (4.2)$$

LogAOD_{it} is the logarithm of atmospheric optical depth; IV_{it} is a set of instrumental variables; CrV_{it} is the control variable vector; LogHosp_{it} , which is the logarithm of hospitalization count, is the independent variable; α_{it} and β_{it} are time-invariant unobserved

heterogeneity terms; ε_{it} and u_{it} are the error of the model, b_i . and c_i . are unknown parameters.

Regarding the IV_{it} vector, three instrumental variables were employed, burned area (Ba) in logarithmic form (LogBA), wind direction (WDirec) and wind speed (WSpeed). These were combined, either in original form or as interactions (denoted with “*”), into four alternative sets of variables. All of them included LogBA separately. The first and most comprehensive included the two interactions of burned area with the two wind measures (i.e., Ba * WSpeed and Ba * WDirec). The second and third sets included only one of the possible fire-wind interactions (either Ba * WSpeed or Ba * WDirec). The fourth and least comprehensive did not include any interactions (only LogBA). The last three sets were used as potential alternatives to estimation in case the most comprehensive set was rejected in its validity by the tests employed. In this way, the least comprehensive was the last possible alternative in case the two double instrument sets were rejected.

Now regarding the CrV_{it} vector, the control variables captured factors influencing supply and demand for health care. They were structured to indicate:

- Health level of the population, represented by infant mortality (Chd_d) (AQUINO; DE OLIVEIRA; BARRETO, 2009; BARUFI; HADDAD; PAEZ, 2012) and chronic disease mortality (Crn_d);
- Healthcare supply capacity represented by the number of health professionals (Emp), number of hospital beds (Beds) and number of health facilities (Faci);
- Sociodemographic factors, such as: estimated population (Pop), gross domestic product (GDP), urban zones (Urb), road density (Road) and fleet of cars (Cars);
- Weather, indicated here by: the temperature (Temp) and rainfall (Precp).

Those variables are crucial in estimation, once they address weather and socioeconomic confounders that could bias the estimation of the causal effect of pollution on hospitalizations. If these variables were not included, the factors that they capture would be left to the disturbance terms, thus creating omitted variable bias (WOOLDRIDGE, 2018).

The identification strategy was applied to the whole count of hospitalizations and to counts associated with specific ages and illnesses. Confounders, whose influence is

mitigated by the IV approach, may affect illness propensity in the form of viral, bacteriological and environmental factors varying across illnesses (POPE 3RD, 2000; NUNES; IGNOTTI; HACON, 2013). Therefore, by adopting alternative dependent variables, the performance of identification strategy was more broadly assessed, which was based on amounts of hospitalization due to asthma, pneumonia and bronchitis and as well as hospitalization of small children (aged 0 to 4), children (5 to 14) and elderly people (> 65).

The estimation was carried out on *Stata 14.1* program, with a balanced panel structure (at a monthly-municipal level) with fixed effects (state, year and month) and a heteroskedasticity-autocorrelation “robust” variance-covariance estimator. To check if the approach used was valid, the following testing sequence was adopted:

- 1 Generalized Hausman test for the null of consistency of the random-effects estimator (no omitted heterogeneity bias) against the alternative of consistency of the fixed-effects estimator. Applying the “xtoverid” command from Schaffer and Stilman (2006);
- 2 Pollution exogeneity test for the null that ordinary least squares (OLS) would yield consistent estimates over the IV estimates, i.e., pollution is exogenous. For this, “dmexogxt” command from Baum and Stillman (1999) was applied;
- 3 Sargan’s overidentification test for instrument validity which assumes validity under the null hypothesis that all instruments are valid, while rejection is interpreted as indicating that at least one of the instruments is not valid (CAMERON; TRIVEDI, 2009). For this, the “xtoverid” from Schaffer and Stilman (2006) command was used;
- 4 Tests for instrument weakness in the first stage, which was based on postestimation procedures with robust covariance matrix:
 - a. Joint significance of the instruments (robust F test), with the test statistic compared to the rule-of-thumb value of 10, as proposed by Staiger and Stock (1997 apud; SHAO et al., 2019)⁶;

⁶ The IV rule of thumb is a practice in the econometric field when you are using the instrumental variable technique. That suggest a minimum value of test F, which is 10 (STAIGER; STOCK, 1997 apud; SHAO et al., 2019).

- b. Stock and Yogo IV weakness test, which presumes homoscedastic errors in the instruments, and its null hypothesis is that the instrument is weak. This is rejected whenever the "minimum eigenvalue statistic" (CAMERON; TRIVEDI, 2009) exceeds the "critical value" of the (2SLS) estimator at 10% level.

When exogeneity was not rejected in step 2, OLS estimation was applied. Conversely, IV estimation was pursued, and for this, all four instruments were initially used. Then, if this set of instruments was not accepted in step 3, the list was piecewisely reduced until no instrument was deemed invalid or only one instrument remained.

4.2.5 Simulation: hospitalizations attributable to fires

In order to estimate the percentage of hospitalizations attributable to fires, the following procedure was pursued. It is important to have the corrections suggested by Wooldridge (2018, cap. 6) initially clarified, for models estimated with logarithmic forms, which were applied to end with predicted hospitalizations in non-logarithmic form. The predictions for the logarithm of hospitalizations were exponentiated, generating $\widehat{m}_i = \exp(\widehat{\log y}_i)$; then a simple linear regression was run, with a null intercept, between the observed values (y_i) and the predicted ones (\widehat{m}_i); finally, the slope of this regression was extracted, and this was considered the correction factor of the values ($\check{\alpha}_0$), which can also be described by the following equation (Equation 4.3).

$$\check{\alpha}_0 = \left(\sum_{i=1}^n \widehat{m}_i y_i \right) \cdot \left(\sum_{i=1}^n \widehat{m}_i^2 \right)^{-1} \quad (4.3)$$

The correction consisted of taking $\check{\alpha}_0 \widehat{m}_i$ as the prediction. With this, the count of hospitalizations attributable to fires was calculated as the difference between hospitalizations predicted for the observed level of fires and for a counterfactual null fire level. This was pursued, as detailed in equations below, starting with the first-stage fire-pollution model (4.4.c and 4.4.e), then proceeding to the second stage pollution-hospitalization model (4.4.b and 4.4.d).

$$\text{Hospitalizations attributable to fires} \equiv \check{\alpha}_0 \widehat{Hosp}_{it}^0 - \check{\alpha}_0 \widehat{Hosp}_{it}^1 \quad (4.4.a)$$

$$\widehat{Hosp}_{it}^0 = \widehat{\beta}_0 + \widehat{\beta}_1 \widehat{LogAOD}_{it}^0 + \widehat{\beta}_2 CrV_{it} \quad (4.4.b)$$

$$\widehat{LogAOD}_{it}^0 = \widehat{\alpha}_0 + \widehat{\alpha}_1 IV_{it} + \widehat{\alpha}_2 CrV_{it} \quad (4.4.c)$$

$$\widehat{Hosp}_{it}^1 = \widehat{\beta}_0 + \widehat{\beta}_1 \widehat{LogAOD}_{it}^1 + \widehat{\beta}_2 CrV_{it} \quad (4.4.d)$$

$$\widehat{LogAOD}_{it}^1 = \widehat{\alpha}_0 + \widehat{\alpha}_1 \cdot 0 + \widehat{\alpha}_2 CrV_{it} \quad (4.4.e)$$

4.3 Results

4.3.1 Database behaviour

Despite having available data of the last two decades (2001-2020), some of them are not accessible, therefore, the time windows analysis is between August 2005 and December 2018. The main descriptive metrics of all data used is listed on Table 4-2. For the main variables (Burned area, AOD and Hospitalizations) we also presented the descriptive statistic spatially (Figure 4-2) and in a temporal way (Figure 4-3).

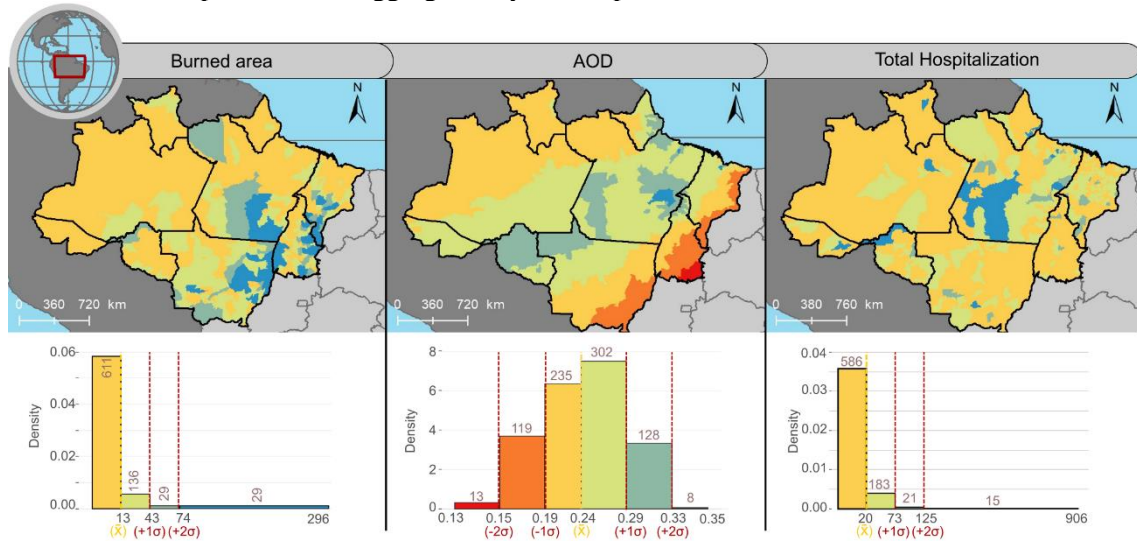
Table 4-2. Descriptive statistics of the data, subdivided by type and calculated at a municipality level and monthly.

Type	Variable	Unit.	Mean	Std. Devia.	Min	Max
IV	BA	km ²	13.1	87	0	5,010
	TA	#	14.25	73.06	0	6,814
	WDirec	degree	1.39	1.02	0.002	7.72
	WSpeed	m/s	235.68	42.48	0.03	359.95
IndV	AOD	-	0.24	0.17	0.03	3.35
	Hosp.	#	20.62	56.31	0	1,676
	Small Children	#	7.98	31.31	0	1215
	Children	#	2.54	7.60	0	232
	Elders	#	3.61	8.46	0	210
	Asthma	#	3.10	10.42	0	424
	Pneumonia	#	11.34	33.39	0	1092
	Bronchitis	#	0.73	5.42	0	264
CtV	Pop	#	32,295	100,855	931	2,130,264
	GDP	mil R\$	463,997	2,493,686	5,606	73,200,000
	Chd_d	#	0.83	2.69	0	71
	Crn_d	#	0.53	2.34	0	72
	Employe	#	288	1,159	0	28,166
	Beds	#	65	267	0	5,099
	Faci.	#	24	91	0	1,999
	Temp_max	K	309.7	4.7	299.0	353.9
	Temp_med	K	303.6	3.3	290.6	320.0
	Temp_min	K	297.3	6.0	247.7	314.8
	Precp	mm	5.24	4.46	0.00	29.05
	Road	m/m ²	4.65	14.41	0.01	242.00
	Urb	%	0.33	1.73	0.00	30.29
	Cars	#	6,780.07	29,523.87	1.00	689,937

IV (Instrumental variable data); IdV (Independent variable data), and; CtV (Control variable data).

Source: From Author.

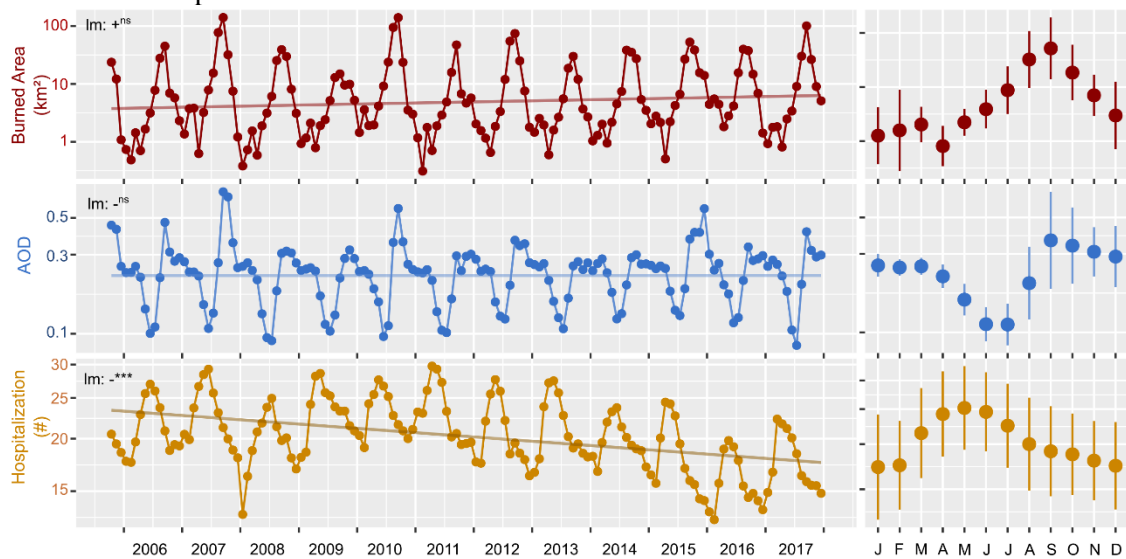
Figure 4-2. Spatialization of the time series average for burned area, AOD and total hospitalizations, aggregated by municipalities.



Note: The bar plot represents the histogram of the spatialized variable, where the bar shows the number of municipalities in each class, and the vertical lines exhibit the mean (yellow) and de first and second deviation (red).

Source: From Author.

Figure 4-3. Temporal variation in monthly average values for burned area, AOD and total hospitalizations.



Source: From Author.

The average burned area by municipality is about 13 km² (± 87 km²), and the highest values were found on the triple border of Mato Grosso-Tocantins-Pará and in the border between Tocantins and Maranhão. The distribution of the values is asymmetrical for the region, with more municipalities with values below the time series average (2005-2018). Among the 805 municipalities that belong to the database, approximately 11.20% of the

municipalities (90 ± 88) have a monthly burned area above the average, while 88.80% (715 ± 88) of them have values below. Of those municipalities with values below the average, approximately 75% (538 ± 163) do not have values for burned area, but this feature varies throughout the year, reaching the maximum of 783 municipalities at the beginning of the year, and the minimum of 203 during the burning season.

On average, hospitalizations due to Pneumonia (11.34) are higher than Asthma (3.10) and Bronchitis (0.73). Considering their proportion among the total hospitalizations due to respiratory diseases, we have a contribution, respectively, of 55%, 15% and 4%. Thus, these illnesses together represent around 74% of all hospitalizations, while the other 26% are composed of other respiratory diseases such as pharyngitis, laryngitis and flu. The distribution of hospitalizations for respiratory diseases follows the asymmetric pattern, where the 15 municipalities with the highest values (over 2 deviations) are mostly in the state of Pará.

From the age group perspective, the average monthly contribution of the Small Children group represents approximately 39% of the total, while Children and Elders represent, respectively, 12% and 18%. Thus, the contribution of Small Children and Elders, together, represents more than half of those hospitalized monthly for respiratory diseases, emphasizing once again the vulnerability of these groups.

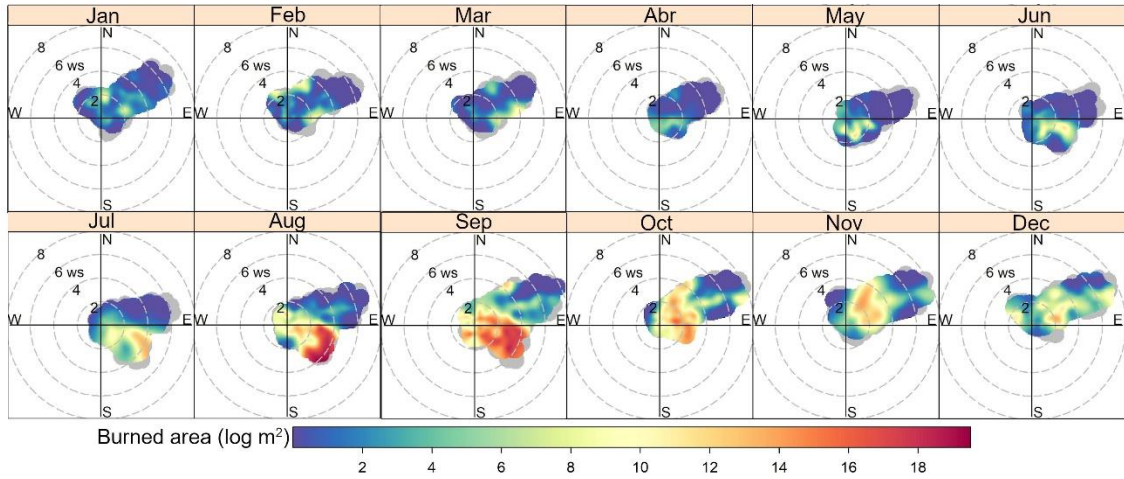
The AOD values vary between 0.03 and 3.35, with an average of 0.24 for the region. Its distribution follows a normal pattern, in which extreme values are found at the border of the BLA (less than 2 deviations) and in an area that goes from Rondônia to the northern border of Pará with Maranhão (greater than 2 deviations).

The variation of the main variables over the time (Figure 4-3) shows that the peaks between the variables are not the same. For the burned area, the average monthly values show two distinct peaks, one at the beginning of the year (Feb-Mar) and another at the end (Aug-Sep), the AOD values show a valley in the middle of the year (Jun-Jul) and the hospitalizations peak is in May.

The Figure 4-4 presents the monthly variation of the burned areas considering the wind speed and the prevailing wind direction. Between June and September, the period that covers the burning season in the region, there is the presence of winds coming from the

Northwest, and the average speed increases reaching the maximum between Aug-Sep, the peak of fire. Subsequently, the wind pattern returns to the Southwest direction, with winds that can reach up to 8 m/s.

Figure 4-4. Monthly variation in mean values of burned area (log) considering the predominant wind speed and meteorological direction for the BLA region.



Source: From Author.

4.3.2 Econometrics estimates

A first and descriptive assessment of “weak instrument”, that is, of the possibility that the instrument is not significantly related with pollution, is provided by the correlation between the instruments and the pollution (explanatory variable), and it is shown on Table 4-3. Only the logarithm of burned area (LogBA) did not exhibit a significant correlation with pollution, violating the instrument relevance requirement. Nevertheless, this is not a final evidence as it is biased by socioeconomic and weather confounders that are addressed by the multivariate approach afterwards (see “weak instrument test” in table 4-4).

Table 4-3. Correlation between the instrumental variables and the explanatory variable.

	LogBA	BaWSpeed	BaWDirec
AOD	0.0023 ^{ns}	-0.0672***	-0.0644***

Significance level: “****” p<0.001, “***” p<0.01, “**” p<0.05, “.”p<0.1, “ns” not significant.

Source: From Author.

The Table 4-4 presents the results obtained with the estimator that was indicated by the four-step test procedure for each dependent variable. Detailed estimation results, also containing control variables and all the set of instruments (LogBA, BAWSpeed and

BAWDirec) and estimators (OLS, 2SLS, fixed effects and random effects) are presented in the APPENDIX A -.

Table 4-4. Summary of the best model fitted of the variation in the Aerosol Optical Depth (AOD) in hospitalization counts due to the thermal anomalies, presented by age and respiratory illness type.

Disease	Respiratory System				Asthma	Pneumonia	Bronchitis
	All	Small children	Children	Elderly	All	All	All
Age							
Estimator	IV	IV	IV	OLS	IV	IV	OLS
IV set	IVc01	IVc04	IVc04	-	IVc01	IVc04	-
Pollution coefficient	0.1383***	-0.3381***	-0.1815*	0.00215***	0.0792***	-0.1790 ^{ns}	0.0103**
IV exogeneity and validity tests							
Exog	13.82***	20.9530***	7.6436**	-	6.63**	7.6513**	-
Overid	1.20 ns	-	-	-	3.56 ns	-	-
Weak Instrument tests							
Joint	1103.36	252.589	252.589	-	1103.36	252.589	-
Yogo: stat	1445.95	282.652	282.652	-	1445.95	282.652	-
Yogo: crit	22.3	16.38	16.38	-	22.3	16.38	-
Fixed effects	Y	Y	Y	Y	Y	Y	Y
Controls	Y	Y	Y	Y	Y	Y	Y
Obs.	118,335	118,335	118,335	118,335	118,335	118,335	118,335

Notes: Estimator: IV is for instrumental variable two-stage least squares method; and OLS is for Ordinary Least Squares. IV Set is the possible instrumental combination: IVc01 is the Log_Ba plus the BaWSpeed and the BaWDirec; IVc02 is the Log_Ba plus the BaWSpeed; IVc03 is the Log_Ba plus the BaWDirec, and; IVc04 is only Log_Ba. "Exog.", computes a test of exogeneity for pollution based on a fixed-effect regression estimated via instrumental variables; "Overid" is the Sargan-Hansen statistic for instrument overidentification test. "Joint", for the joint significance test of the instruments in the first stage regression; "Yogo: stat", is the value of the Stock and Yogo test for instrument weakness; "Yogo: crit", is the table value for the Stock and Yogo test. Significance level: "****" p<0.001, "***" p<0.01, "**" p<0.05, "."p<0.1, "ns" not significant.

Source: From Author.

It should be noted that for all models tested, the value of the *Hausman* test indicated a significant difference between the coefficients generated by the fixed and random effects estimators, indicating consistency only for the first.

Among the four batch of instruments, the IV sets IVc01 (LogBa + BaWSpeed + BaWDirec) and IVc02 (LogBa + BaWSpeed) was the one that met all criteria in the four-step testing for a valid instrument (Section 4.2.4) for the total hospitalization dependent variable. However, according to the pre-defined testing order, the larger set, IVc01, was considered the main one for estimating the effect of pollution from fires on Total

hospitalizations for respiratory diseases in the BLA. According to the model, if the AOD increase 1% it causes an increase of approximately 0,1383% in the total of hospitalizations in the region, considering a regular increase of 1 SD (0.17) it will imply an increase of 2.35% in the hospitalizations.

Positive values, in addition to that presented for the Total hospitalizations, were also estimated for Asthma, whose estimates using the set of instruments IVc04 determined an increase of approximately 0.08% in hospitalizations for each rise of 1 % in AOD levels.

On the other hand, a negative coefficient was estimated for Small Children, Children and Pneumonia. For all of these models, the set IVc04 (LogBa) passed the four-step test for a valid instrument, indicating that each increase of 1% in AOD levels decreases the hospitalization of Small Children in 0.34% ($p < 0.001$), 0.18% ($p < 0.01$) in Children, and 0.18% ($p > 0.1$) for Pneumonia. The last one presented a higher global significance (p -value), which indicates that changes in the Pneumonia's hospitalizations are not associated with the AOD.

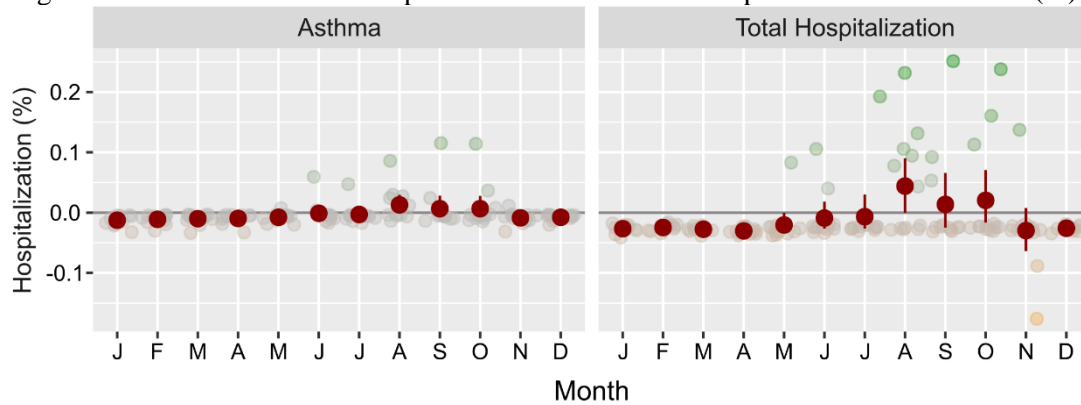
For Elderly and Bronchitis equations, pollution was exogenous and thus OLS estimation was implemented, resulting in, respectively, 0.002% ($p < 0.001$) and 0.0103% ($p < 0.01$) effects on hospitalization.

4.3.3 Hospitalization attributable to fires

Based on the best set of instruments observed for each group of respiratory diseases, we perform the estimates of the hospitalizations. Thus, Figure 4-5 shows the average percentage of projected monthly hospitalizations for the Total Hospitalization and for Asthma, both using the set IVc01.

Total Hospitalization due to fires varies from 42 cases (0.25% in September) to minus 30 cases (-0.17% in November), with a positive monthly average only for the months of August (8 cases , 0.044%), September (3 cases, 0.014%) and October (3 cases, 0.020%). On the other hand, Asthma hospitalizations due to fires ranged from 4 individuals (0.115% in September) to minus 1 (0.03% in April), with a positive monthly average for the months of August (0.4 cases, 0.013%), September (0.3 cases, 0.007%) and October (0.2 cases, 0.007%).

Figure 4-5. Estimates of total hospitalizations and Asthma hospitalizations due to fires (%).



Source: From Author.

4.3.4 Robustness check

In order to verify the sensitivity of the effects and the general consistency of the results obtained, a robustness test was carried out by replacing the values of burned area for thermal anomalies. The correlation of the rebuilt instruments with the explanatory variable (AOD), is shown on Table 4-5, where all the new instruments presented positive and significant values.

Table 4-5. Correlation among the instrumental variables and the explanatory variable.

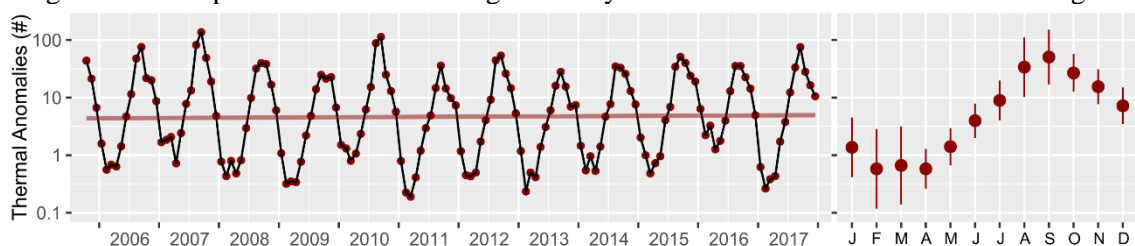
	Log_TA	TaWSpeed	TaWDirec	Log_BA
AOD	0.1672***	0.0323***	0.1002***	0.6892***

Significance level: "****" $p < 0.001$, "***" $p < 0.01$, "**" $p < 0.05$, "." $p < 0.1$, "ns" not significant.

Source: From Author.

The variation among the years and its average by month (Figure 4-6), show a similar seasonality as presented by the burned area, in which the count increases from May on, reaching its peak in Aug-Sep. However, the low peak of the beginning of the year (Feb-Mar) is not visible as observed for the burned area.

Figure 4-6. Temporal variation in average monthly values of thermal anomalies for the region.



Source: From Author.

The Table 4-6 presents the best results obtained from each of the seven models analysed, using thermal anomalies as an instrumental variable, as well as their interaction with the wind direction and the wind speed. The use of this product returned negative results for all models in which method IV was satisfactory (Total, Small Children, Children, Elders, Pneumonia and Bronchitis), whereas for the only model estimated by the OLS method (Asthma) the effect of AOD on hospitalizations for respiratory diseases was positive.

Table 4-6. Mean effect of the variation in the Aerosol Optical Depth (AOD) on hospitalization due the thermal anomalies, presented by age and respiratory illness type.

Disease	Respiratory System				Asthma	Pneumonia	Bronchitis
	All	Small Children	Children	Elders	All	All	All
Age							
OLS							
AOD	0.0443 *** (0.0072)	0.0177 ** (0.0067)	-0.0061 ^{ns} (0.0051)	0.0215 *** (0.0051)	0.0265 *** (0.0060)	0.059401 *** (0.0069)	0.0103 ** (0.0032)
OLS sig.	2925.84 ***	2114.69 ***	1139.8 ***	1460.89 ***	1040.86 ***	2391.69 ***	677.16 ***
2SLS							
AOD	-0.0799 * (0.0333)	-0.2493 *** (0.0349)	-0.1250 ***	-0.0405 * (0.0190)	0.0483 ** (0.0176)	-0.1237 *** (0.0351)	-0.0488 ** (0.0155)
1S sig.	***	***	***	***	***	***	***
2S sig.	***	***	***	***	***	***	***
Set of Instr.	4	4	4	2	1	4	4
Exogeneity and IV validity tests:							
Exog.	20.71 ***	128.64 ***	38.12 ***	14.79 ***	3.06.	49.23 ***	22.67 ***
Overid.	-	-	-	0.4 ^{ns}	8.25 *	-	-
Week Instrument tests:							
Joint	2876.23 ***	2876.23 ***	2876.23 ***	2177.03 ***	2482.61 ***	2876.23 ***	2876.23 ***
Yogo: stat	4782.32	4782.32	4782.32	3915.95	4311.03	4782.32	4782.32
Yogo: crit	16.38	16.38	16.38	19.93	22.30	16.38	16.38

Notes: "OLS sig.", is the global significance calculated by the *Wald*; "1s sig.", stands for the global significance of test *F* for the first stage; "2s sig." is the global significance *Wald* test for the second stage; "Set of Instr." is the order of the instrument set, where: 1 are LogTA + TaWSpeed + TaWDirec; 2 are LogTA + TaWDirec; 3 are LogTA + TaWSpeed; 4 is LogTA. "Exog.", computes a test of exogeneity for a fixed-effect regression estimated via instrumental variables; "Overid" is the Sargan-Hansen statistic for instrument overidentification test. "Joint", for the joint significance test of the instruments in the first stage regression; "Yogo: stat", is the value of the Stock and Yogo test for instrument weakness; "Yogo: crit", is the table value for the Stock and Yogo test. Significance level: "****" p<0.001, "***" p<0.01, "**" p<0.05, "." p<0.1. Blue-colored cells represent the best method fit for the model.

Source: From Author.

4.4 Discussion

The coefficient (0.1383%) estimated for Total Hospitalization was tenfold larger than the one calculated by Rocha and Sant'anna (2020) for BLA⁷, in which using the interaction between the wind direction and pollutants from neighboring municipalities as an instrumental variable, they found out that the increase of 17.3 μm^3 (one standard deviation or 107% increased upon the average) in PM2.5 levels causes on average about 1.5% (0.95 hospitalizations per 100 thousand inhabitants) in total hospitalizations.

Additionally, the negative coefficient obtained for *Small Children* and *Children* is the opposite from the results previously found in the BLA by Carmo et al. (2010), Jacobson et al. (2014) and Rocha & Sant'anna (2020). It can be a reflex of the data used in the analysis, which present a difference peak between fire and hospitalization (which is in the humid season); and the measured impact is linked to the short-term response, while the pollution effect is accumulated over the time. Or as presented by Andrade Filho et al. (2013), some regions in the Amazon the hospitalizations due to respiratory diseases, especially in Children, are more associated with the humidity than the pollution aerosols.

For Elderly and Bronchitis the IV approach was not significant, being used the OLS method to obtain the estimates. This result is the opposite of those founded by Deryugina et al. (2019) and Rocha & Sant'anna (2020), which the IV method was able to estimated positive values for the Elderly and Bronchitis hospitalizations using the concentration of PM2.5 attributed to fires instead of AOD.

It should be noted that the estimates from OLS do not separate effects caused specifically by fires, so the effect related to AOD may include other sources of aerosol emissions, such as deserts, oceans, forest, industry and fossil fuel burning (LENOBLE; REMER;

⁷ The authors used: monthly data of PM2.5, a reanalysis product from CAM (Copernicus Atmosphere Monitoring Service) with spatial resolution of 12.5 km and obtained through the SISAM (portugues acronymun to Environmental Information System Integrated to Health) platform; Hospitalization data were obtained from SUS focusing on the total number of hospitalizations for respiratory diseases in children (age less than or equal to 5 years) and the elderly (over 60 years), all normalized per 100 thousand inhabitants; Thermal anomalies are gathered from MODIS/Aqua obtained in the INPE platform; Wind direction data were obtained from the product ERA-Interim, which is a global atmospheric reanalysis with a spatial resolution of 12.5 km, also available in SISAM platform; Control data were, precipitation (CPC/NOAA), relative humidity (ERA-Interim) and temperature (ERA-Interim), all available in SISAM. The data were grouped for each 772 municipalities of BLA, covering the period from January 2010 to December 2019, where they structured a balanced panel, with fixed effects.

TANRÉ, 2013). Specially in BLA, the amount of AOD can be influenced by: dust coming from the Sahara desert (BEN-AMI et al., 2010); water particles coming from Oceans (FISCH; MARENGO; NOBRE, 1996); pollutants from urban zones, industry and from the fossil fuels burning (SHRIVASTAVA et al., 2019); and biogenic aerosols from the forest (ARTAXO et al., 2009).

The low coefficient estimate for the hospitalization groups reflects on hospitalization counts for the region, which are below from those already estimated by other authors using a similar methodology for the Amazon region (DE MENDONÇA et al., 2004; MENDONÇA; SACHSIDA; LOUREIRO, 2006). However, the model follows the fire seasonality in BLA, when the peak of estimates is from July to November, mainly the pattern of the states with the largest contributions in burned area of the region (MT, RO, TO).

The difficulty to establish a clear cause-effect of fire-pollutants in hospitalizations is also revealed by a description of data. At first, when considering only the spatial distribution of the main variables (Burned Area, AOD and Hospitalizations for respiratory diseases), a positive relationship between, from one side, burned area, and, from another side, pollution and hospitalizations, is only observed in the South-Centre of Pará, while for the other regions with a large burned area, AOD and Hospitalizations are low. Despite these spatial patterns presenting few regions with higher concomitant values of pollutants, fire and hospitalization seem to be prevalent, because it was also indicated by Souza et al. (2020) analyzing the relationship between deforestation, hot spots, pollutants (PM_{2.5}) and hospitalizations of indigenous people from the BLA.

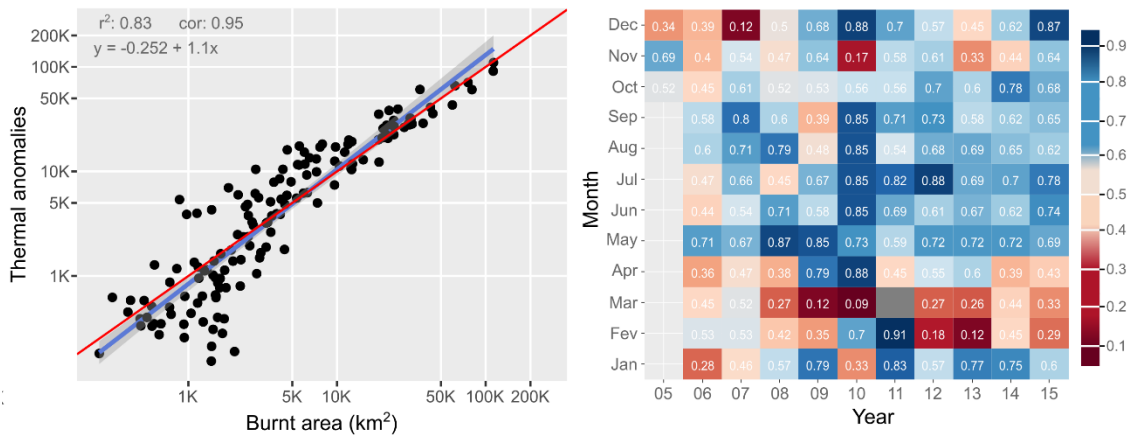
Hospitalization data is also limited. It only includes the patient who remains at the hospital under supervision for a period equal or longer than 24 hours (BRASIL, 2002). In these cases, care and clinical diagnoses for patients with mild symptoms are excluded. As a result, the number of patients related to fire exposure accounted may be underestimated, since out-patients are ignored. Or, in another perspective, the required level of exposure to the pollutant for a person to be hospitalized is higher than in cases of outpatient visits, whose information is not easily available through the health systems.

The wind analysis follows the patterns presented by Gatti et al. (2014) and Cassol et al. (2020) for the Amazon region, including the dispersion of aerosols, in which there is a change in the predominant wind direction at the beginning of the fire season. This factor can spread and direct smoke plumes to neighbouring municipalities and other Amazonian countries, making a transboundary issue exemplified by the study of Sheldon & Sankaran (2017). In this way, neighbourhood factor can be a complement for further analysis, as assessed by some authors (JACOBSON et al., 2014; RANGEL; VOGL, 2019; ROCHA; SANT'ANNA, 2020). This factor consists of taking the amount of fire and then the pollution produced by each neighbouring municipality into account, by using spatial weight matrix to describe the dependency among the municipalities. This new approach will improve the data outside and inside the fire season.

This difficulty to establish a good estimate among all variables (age and illness group) and pollution, continues through the robustness check. In five out of seven dependent variables, the sign of estimates differed when based on burned area and on thermal anomalies.

It shows that besides the substantial correlation between point and areal fire detections (0.95; Figure 4-7), their statistical behaviour is not similar enough regarding the relationship between pollution and hospitalizations. Even with the higher frequency of point detections by the TA product (GIGLIO et al., 2020), the correlation with BA at low levels (less than 5 thousand km²), specially between February and April (Figure 4-7), leads to a disarrangement in the early peak of burned area that matches the increasing stage of hospitalizations (Figure 4-3 and Figure 4-6). This may have favoured the appearance of negative estimates in the robustness check, due to the appearance of a well-defined valley.

Figure 4-7. Correlation of monthly values of thermal anomalies and burned area, for all-time series and monthly.



Source: From Author.

4.5 Conclusion

In this chapter, we estimate the hospitalization attributable to fire-induced pollution in the Brazilian Legal Amazon (BLA) using a balanced panel structured in a monthly-municipal level, with available data from the last twenty years (2005-2018). Our strategy was based on capturing this influence by increasing the possible connections that fire-pollution has in different ages and illnesses, applying an instrumental variable method with a set of instruments that relies on wind speed and direction, over three classes of diseases and four age group. Thus, contributing to expand the evidence of hospitalizations due to fire-induced pollution and primarily by considering the effect in the whole BLA and using a long time series.

In general, among the seven hospitalization variables evaluated, four variables (Total, Elderly, Asthma, Bronchitis) were significantly positive, one (Small Children) significantly negative and the others (Children and Pneumonia) were not significant. Thus, demonstrating that there is a positive effect of pollutants on the levels of hospital admissions for respiratory diseases in the BLA.

Estimates of total hospitalizations based on the IV model indicated that during the fire season (Aug-Oct), hospitalizations caused by pollutants generated by fire per municipality are 5 individuals on average, resulting in approximately 4 thousand for all BLA territory.

The observed effects were not consistent when applying the robustness test, in which the burned area was replaced by thermal anomalies, showing a fragility of the estimates of the causal-effect of fire and hospitalizations. Therefore, it is essential to make new estimates considering other pollutant indicators, neighborhood effects, time lag of variables, or even downscaling the time aggregation to capture inter-monthly peaks.

5 TWO DECADES OF FIRE IMPACTS IN THE BRAZILIAN LEGAL AMAZON

5.1 Introduction

Anthropogenic fires are observed across all the Brazilian territory, mostly as agricultural burnings for land preparation, varying by the scale of production, mechanization and modernization degrees (EMBRAPA, 2000). The National Institute for Space Research (INPE, 2020) monitors the fire condition and demonstrates that among all Brazilian phytogeography domains, the Tropical Forest (Amazonia) and the Savannah (Cerrado) are the most exposed to fire along the years, representing, in average, 49% and 31% respectively, of all fires in Brazil.

Historically in the Amazon region, the use of fire is a cultural and basic practice related to the human activities (DA MOTTA et al., 2002). Due to these antropogenic features, the three main kinds of fires in the region are: the deforestation fire, the agricultural manage fire, and the wildfire caused by the lack of control of one of the previous types (ALENCAR; RODRIGUES; CASTRO, 2020).

As the benefit of using fire is proven in a short term, the losses are higher for all society, either directly, such as: human lives loss (AHRENS; EVARTS, 2020), burning production (DE MENDONÇA et al., 2004), damaging infrastructure (DIAZ, 2012), reducing biodiversity (BARLOW et al., 2003; BRANDO et al., 2014; SILVA et al., 2018a), affecting cultural resources (RYAN et al., 2012), or indirectly: such as changing the climate (ANDREAE et al., 2004; GONÇALVES; MACHADO; KIRSTETTER, 2015), increasing the hospitalizations rates due to respiratory problems (DERYUGINA et al., 2019; ROCHA; SANT'ANNA, 2020), reducing tourism (BOUSTRAS; BOUKAS, 2013), promoting species migration (NOLASCO, 2006; PAOLUCCI et al., 2017), and affecting aerial and terrestrial transport of people and goods (ANDERSON et al., 2011).

In addition to the fact that in the Amazon these events are mainly human driven, they are also boosted by climate extremes, such as anomalous temperatures and droughts (ARAGÃO et al., 2007, 2018), with increased intensity during the most recent drought events (1997/98, 2005, 2010, 2015/16). Only during the last five years of this decade, the Amazon region faced two large-scale fire events, one in 2015/16, associated with the El

Niño, and the other more recently in 2018/2019, associated with an increase in the deforestation and weakening of environmental protection (ARAGÃO et al., 2018; BRANDO et al., 2020), with several local, regional and global scale impacts.

Thus, to quantify and understand the process related to the fire patterns, such as size, frequency, intensity, seasonality and extent, it is extremely useful to plan mitigation strategies, control measures and if necessary, suppression actions. Moreover, by performing such diagnosis, it is possible to predict fire patterns and inform managers and governmental institutions, identifying the environmental and human exposure and vulnerabilities to fires (ARCHIBALD et al., 2013).

The assessment of the impact of fire in a region is complicated by the complex feedback chain propagating impact across multiple scales and stakeholders (NELSON et al., 2013). One solution is to decompose impacts according to a conceptual classification criteria, which is commonly applied to quantify environmental disasters. In this context, we can split the impact into Material, Human and Environmental damages (DE CASTRO et al., 2003).

To communicate the importance of the fire threat to different social actors, it is necessary to estimate the size of the associated damage (DA MOTTA et al., 2002). Monetary quantification is adopted here mainly for being a pragmatic and dimensionally rigorous way to convert qualitatively different impacts into a single number, which is also useful as basis for estimation of environmental compensation mechanisms (MENDELSON; OLMSTEAD, 2009; KUMAR et al., 2013).

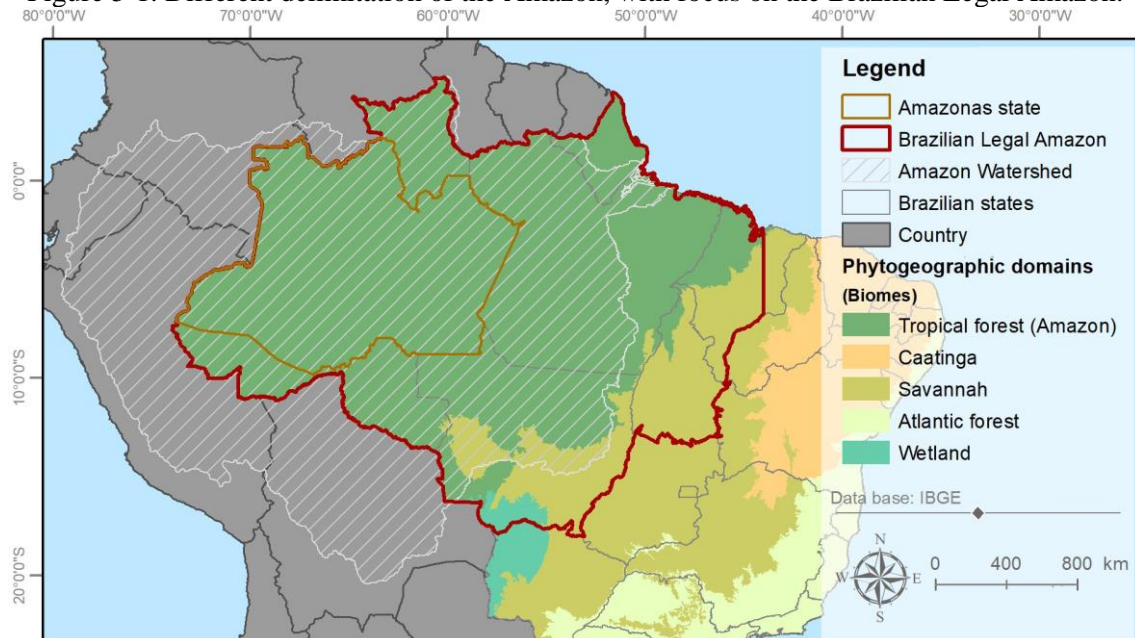
This chapter uses a 20-year set of fire data (2001-2020) to analyze its pattern and impacts over the Brazilian Legal Amazon (BLA), aiming to answer three major questions: (Q1) What are the main patterns of the burned area in the BLA?; (Q2) What is the potential magnitude of the fire impact over those 20 years?; (Q3) What are the effects on national and international environmental targets?

5.2 Material and methods

5.2.1 Study area

There are many delimitations of the Amazon region, like phytogeographic, climatic, hydrological, and political (Figure 5-1). In this chapter the political delimitation, known as Brazilian Legal Amazon (BLA) was used. The BLA consists of the states of Acre, Amapá, Amazonas, Mato Grosso, Rondônia, Roraima, Tocantins, Pará and west of Meridian 44° of Maranhão (BRASIL, 2007). This region represents 60% of the Brazilian territory, which is around 5 million km² (IBGE, 2021a).

Figure 5-1. Different delimitation of the Amazon, with focus on the Brazilian Legal Amazon.



Source: From Author.

The BLA has three phytogeographic domains: 90% of Amazon (Rainforest), 7% of Cerrado (Savannah) and 3% of Pantanal (Wetland). Around 24% of its population is situated in rural areas (IBGE, 2021a). The economy is based on services, except in the states of Amazonas and Mato Grosso, where the industrial sector and the agricultural sector, respectively, are the most representative. All region contributes an average of 8.45% to the Brazilian GDP (SUDAM, 2016).

5.2.2 Spatial dataset

5.2.2.1 Burned area

We use the Moderate Resolution Imaging Spectroradiometer (MODIS Terra e Aqua) burned area product MCD64A1-v6. This product has a monthly periodicity, spatial resolution of ~500 meters, and its data started in November of 2000. It uses an association of surface reflectance with active fires, and an algorithm that checks the temporal changes in the vegetation index (GIGLIO, LOUIS et al., 2015). Globally this product presented 99.7% of overall accuracy, with 40.2% commission error and 72.6% omission error (BOSCHETTI et al., 2019). In the Amazon region, this product showed a great similarity to regional and supervised-based product, detecting more fires in north and northwest areas than southwest (PESSÔA et al., 2020). Therefore, the results presented in this study can be considered conservative.

5.2.2.2 Land use and land cover

The land use and land cover data used were the collection 5.0 of MapBiomas (MAPBIOMAS, 2021a). This product is based on Landsat images and machine learning procedures over a pixel base classification, generating an annually product with ~30m of spatial resolution from 1985 to 2019.

The classes used, are the 7 main types aggregated form the 31 MapBiomas level-2 classes (Table 5-1) plus the “Old-growth” and “Secondary Forest” class derived from the main Forest using the methodology proposed by Nunes et al. (2020) and Silva Júnior et al. (2020) from information between 1985 to 2019. The classified LULC map of 2019 was replicated to expand the analysis until 2020.

Table 5-1. Reclassification of MapBiomas’ collection 5 of land use and land cover classes.

MP_ID	MapBiomas C5 Class	New Category
1	Forest	Forest
2	Natural forest	Forest
3	Forest formation	Forest
4	Savanna formation	Forest
5	Mangrove	Forest
9	Forest plantation	Forestry
10	Non forest natural formation	Natural Field
11	Wetland	Natural Field
12	Grassland	Natural Field
32	Salt flat	Natural Field

Continues

Table 5-1. Conclusion.

MP_ID	MapBiomass C5 Class	New Category
15	Pasture	Pasture
14	Farming	Agriculture
18	Agriculture	Agriculture
19	Temporary crop	Agriculture
39	Soybean	Agriculture
20	Sugar cane	Agriculture
41	Other temporary crops	Agriculture
36	Perennial crop	Agriculture
21	Mosaic of agriculture and pasture	Agriculture
31	Aquaculture	Agriculture
29	Rocky outcrop	Other
13	Other non-forest formations	Other
22	Non vegetated area	Other
23	Beach and Dune	Other
24	Urban infrastructure	Other
30	Mining	Other
25	Other non-vegetated area	Other
27	Non observed	Other
26	Water	Water
33	River, Lake and Ocean	Water

MP_ID is the identification number of each MapBiomass classes.

Source: From Author.

5.2.2.3 Land tenure

Information related to Land Tenure was provided by Imaflores through the Agricultural Atlas of 2018 (FREITAS et al., 2018). This product gathered information of all different territorial types respecting legal determination of each land category in one national map.

Imaflores's product organizes and adjusts overlapping features, both within each category and between categories. The hierarchy used within each feature is based on the removal of invalid and duplicated geometries, in addition to prioritizing more reliable geometries, either by the demarcation stage (in the case of indigenous lands and public forests), registration date (as in the case of properties of INCRA) or by the registration system (properties of INCRA, SIGEF/SNCI).

The hierarchy between categories is premised on “[...] the reliability of the available information, considering the recognition of rights and domain over land and the possibility of future change in the current occupation” (FREITAS et al., 2018, p. 8). Thus, the authors emphasize that this prioritization is not based on an order of environmental importance or the right to land, but on the legal security of law, the accuracy of geospatial information, the possibility of receiving overlap and the possibility of changing domains.

With this methodology, it was possible to map and reconstruct the land tenure of 82.6% of the Brazilian territory, more precisely 91% in the BLA⁸.

Following the descriptions of each land tenure class of the IMAFLORA product, the three public classes were allocated to the “Not Designated” class. The classes “Undesignated land from Terra Legal Program”, “Undesignated public forests” and “Public properties at INCRA system” do not have a specific destination and are characterized by governmental agencies as "not intended". In this way, these classes together with the category of “No information” were named “Not designated”.

Table 5-2. Class of land tenure available in the IMAFLORA product, with the indicative of category and group.

Description	Category	Group
Without information	Not Designated	-
Undesignated land from Terra Legal Program	Not Designated	-
Undesignated public forests	Not Designated	-
Public properties at INCRA system	Not Designated	-
CAR premium	Private	Properties at CAR system
CAR poor	Private	Properties at CAR system
Private properties at INCRA system	Private	Properties at INCRA system
Private properties from Terra Legal Program	Private	Properties at Terra Legal program
Rural settlements	Public	Rural settlements
Communitarian lands	Public	Rural settlements
Military areas	Public	Military areas
Quilombola lands	Public	Quilombola lands
Homologated indigenous land	Public	Indigenous lands
Non-homologated indigenous land	Public	Indigenous lands
Full protection conservation unit	Public	Conservation Units
Sustainable use conservation unit	Public	Conservation Units
Water bodies	Urban, Water	-
Transportation network	Urban, Water	-
Urban areas	Urban, Water	-

Source: Adapted from Agricultural atlas (2018) and Freitas et al. (2018).

5.2.2.4 Biomass

The biomass values for each LULC class were obtained based on the Biomass_CCI product (European Space Agency-ESA), and on the LULC classes of MapBiomass previously reclassified.

For the studied region, the version 2 available for 2010, 2017 and 2018 with a spatial resolution of 100 meters and on a global scale was used. This product utilizes a repository of Synthetic Aperture Radar (SAR) images from the C-band (Envisat ASAR for 2010 and

⁸ We make this account by clipping the values to the BLA region. The full result are specify in Table B-1.

Sentinel-1 for 2017-18) and L-band (ALOS-1 PALSAR-1 for 2010 and ALOS-2 PALSAR-2 for 2017-18) to estimate the forest structure parameters and subsequently the biomass value. The larger range in the characteristics for the years 2017 and 2018 leads this set to improve estimates in areas close to the tropics and in regions with low biomass (SANTORO; CARTUS, 2021).

To minimize errors within each LULC class, the average of the biomass was calculated for the three years of data, thus obtaining the values presented in Table 5-3.

Table 5-3. Average biomass values by LULC class extracted from the Biomass_CCI product.

Class	Biomass (Mg/ha)
Old growth	223.28 (± 73.5)
Secondary Forest	110.03 (± 36.7)
Forestry	59.86 (± 22.4)
Pasture	24.73 (± 8.18)
Natural fields	26.85 (± 9.15)
Agriculture	7.32 (± 2.4)

Source: From Author.

5.2.2.5 Ecosystem services

Monetary information of silvicultural production was obtained through the ecosystem service products estimated by Strand et al. (2018). The products use marginal economic value estimation models based on spatially explicit local and regional data to estimate average annual income values. These incomes reflect the marginal value of ecosystem services (US\$ ha⁻¹ yr⁻¹) that would be lost with each additional hectare of forest removed.

Among the products available, the following were chosen to compose the total value for the Forest class: the annual income estimates in sustainable wood production (Timber), the average economic return in rubber production (Rubber), and the average income in Brazil Nut extraction (Nuts).

All these products were built for the Amazon biome. Thus, it was necessary to carry out a complete data collection for municipalities that are outside the biome but included within the study territory. For this purpose, the average value for each municipality within the biome was initially aggregated. Then, a spatial interpolation based on a neighborhood matrix was applied (GOLGHER, 2015). Neighbors were defined as municipalities either sharing boundaries with or within 1 km of the reference municipality. The matrix was

used to replace the missing values of the municipalities outside the biome for the average value across neighbors inside the biome. Relying on the structure of neighboring links in the matrix, the interdependence of municipalities (the fact that each one is a neighbor of its own neighbors) was the basis for multiple interactions of replacement in two stages. In the first, all missing values were replaced starting with municipalities closer to those in the biome. Undesirably, the average assigned to each municipality accounted only for neighbors that were closer to the biome along the particular direction in which the replacement process was feasible. That was clearly biased and corrected in the second stage by iterating replacement until municipalities' values became fixed with arbitrary precision ($<10^{-5}$).

5.2.2.6 Political boundaries

The political-administrative division of the BLA territory was obtained from the Brazilian Institute of Geography and Statistics – IBGE website. The product is compatible with the 1:250,000 scale and represents the current situation of state and municipality boundaries (IBGE, 2021c).

Along 20 years, the number and area of municipalities, as well as the political boundaries of some states have changed. Therefore, the statistical information for each state was used based on the official boundaries provided by IBGE for each year.

5.2.3 Non-explicit spatial datasets

Data on total hospitalizations for respiratory diseases were obtained from the TabNet portal (DATASUS, 2020), filtering the values by respiratory diseases (ICD-10: X), municipalities, place of residence and month of treatment. The data comes from the SUS' Hospital Information System, managed by the Ministry of Health, in which every hospital unit (public or private) associated with SUS sends information on carried out hospitalizations. The total number of admissions in the period and the total hospitalization cost were also used.

The rate of hospitalizations resulted from an increase in pollutants derived from fire in the region was obtained from the estimates presented in Chapter 4 of this thesis, in which the calculation was performed by using the Instrumental Variable method.

Other data that are not spatially explicit and were used in the process of monetarily quantifying are described in Section 5.2.4.4.

5.2.4 Data analysis

5.2.4.1 Fire pattern

First the MCD64A1 product was clipped to the AMZL region and set as a binary – fire affected areas and not affected areas. After, in order to determine the total amount of burned area, the raster map was converted to a vector and changed its projection of World Geodetic System (WGS84) to South America Albers Equal Area Conic. This procedure is fundamental to guarantee the value of each burned area in a metric scale.

The Recurrence and Frequency of fires in the region was calculated using all monthly burned area product layers from January of 2001 to December of 2020. The frequency of fires represents how many times the same area was burned in the period, with the maximum possible value of 240, considering the total number of months in the period. The recurrence represents the amount of fire events in the mentioned years, with a maximum value of 20.

To determine trends in the period, we use three different approaches. First a regular Linear Model (LM), second a Maan-Kendall test (MK), and third a Season Maan-Kendall (SMK). The LM was used because it is a simple index and is highly disseminated both within and outside the scientific community. The MK test is a non-parametric analysis used to track trend in time series (HIPEL; MCLEOD, 1994, cap. 23). Finally, the SMK, which is a modification of the MK test, was used because it considers seasonality in the data and also looks up trends in individual months (HIPEL; MCLEOD, 1994, cap. 23; POHLERT, 2020).

The fire season was defined as the contiguous month that comprehended more than or equal 80% of all burned area (ARCHIBALD et al., 2013).

Related to the fire size classes, the aggregation proposed by Heinselman (1978 apud; COVINGTON; MOORE, 1994) was adopted. This method is based on seven classes of the USDA-Forest Service Wildfire, which are merged into four: patches smaller than 99 acres (≤ 40 ha) are identified as “Small”; while patches between 100 acres and 999 acres

(40 to 404 ha) are considered as “Medium”; in turn patches between 1000 acres and 9999 acres (404 to 4,046 ha) are identified as “Large”; and finally patches larger than 10,000 acres ($\geq 4,046$ ha) are classified as “Very Large”.

5.2.4.2 Clustering years

In order to determine similar years and behaviors over time, two forms of grouping were carried out: the first refers to the establishment of groups based on the data, and the second part dividing the time series into four groups of five years each.

In this way, years with similar characteristics were initially grouped using the evolution of fire in the intra-annual period. Thus, firstly, it was used the Dynamic Time Warping (DTW) technique to determine the similarity between the data series. After, the Multi-Dimensional Scale (MDS) algorithm was used to reduce the dissimilarity matrix in a pair of coordinates and determine the groups, using the Hierarchical method. The entire process was carried out on the RStudio platform, using the “dtw” (GIORGINO, 2009) and “MASS” (VENABLES; RIPLEY; VENABLES, 2002) libraries.

From a temporal perspective, the series was divided into groups of 5 contiguous years, obtaining 4 groups. In this step, a distinction of normal climate years and anomalous ones was not made. Within each group, the characterization of the fire regime was carried out based on Archibald et al. (2013) methodology, obtaining the values for the following parameters: average monthly area, maximum annual area, minimum annual area, average size of burned areas, average number of events, number of months describing the burning season, number of months with fire anomalies, and number of affected municipalities per year. The groups were submitted to the *Wilcoox* test for comparison between means to obtain similar groups and verify disaggregation within the series.

5.2.4.3 Fire impacts

To determine the fire impact over different land cover, first we downscaled the burned area to the same resolution of LULC maps, and then performed a monthly intersection between them, preserving the reference of each year. All procedures were based on a pixel level. The same procedure was applied to extract burned areas over different types of land tenure.

The extraction of these data supported the quantification of economic impacts, whether in the agricultural sector (Agriculture, Pasture and Natural Field classes) or in the forestry sector (Forestry, Old growth and Secondary Forests), which will be described in section 5.2.4.4. This same strategy supported the estimates of environmental damage by quantifying gross carbon dioxide emissions for each category.

For the “Forest” and “Forestry” classes, we used the fire loss equation (Equation 5.1), proposed by Anderson et al. (2015) and updated by Pêsoa et al. (2020) to estimate the amount of committed carbon emissions. The equation considers a biomass density gradient, in which places with lower biomass have greater carbon loss due to fire, and in forest formations, due to the microclimate generated within the canopy, there is a reduction in fire intensity and susceptibility, causing partial loss of biomass. In this way, the value of committed carbon in tons per hectare was quantified by subtracting the value of the final biomass in relation to the initial biomass and applying the conversion factor of 1,835 to retrieve the carbon dioxide (Equation 5.2). For the other classes (Agriculture, Pasture and Natural Field), the total conversion of biomass into carbon was considered, thus only the conversion factor was applied to the total biomass committed.

$$Bf = 0.05 * Bi^{1.47} \quad (5.1)$$

$$CO_2 = 1.835 * (Bi - Bf) \quad (5.2)$$

Bf is the total aboveground biomass after a fire in $Mg.ha^{-1}$, Bi is the initial biomass in $Mg.ha^{-1}$, and CO_2 is the total carbon dioxide committed in $MgCO_2.ha^{-1}$.

Immediate emissions were quantified using the total biomass aboveground and the conversion factor to Standing biomass and Surface litter, followed by the complete combustion factors, indicated by Van Der Werf et al. (2017) for South America. The values were quantified only for forest classes (Primary Forest, Secondary Forest and Forestry) due to their long-term stay in the atmosphere.

It is worth mentioning that vegetation growth rates for none of these classes were considered, nor the variation in emissions due to the repetition of fire in the same area. Thus, biomass values were applied each month in relation to each land use affected by the fire, and the total carbon loss in the year reflects a base value for quantifying the total

annual loss. The committed biomass loss was calculated for purposes of biomass quantification, but it was not included in the annual scale valuation analysis.

5.2.4.4 Monetary damages

To access the total monetary damage caused by fire in the BLA region, a microeconomic approach was used. The technique chosen is based on the revealed preference methods, that are useful in gathering values using existing or surrogates markets (OECD, 2006).

Related to production damage, for the “Old growth” class, the digital map produced by Strand et al. (2018) of potential net revenue related to the extraction of wood and non-wood products was used.

Considering that from a certain age “Secondary forests” can provide ecosystem services similar to “Old growth”, an age threshold was established for each type of wood and non-wood product. Thus, rubber extraction was considered from 10 years old, because the production of latex in commercial plantations stabilizes at this age (MORAES; MORAES; MOREIRA, 2008; PEREIRA; LEAL; CASTRO, 2003); Brazil nuts extraction for forests older than 12 years old (MÜLLER et al., 1995); and the extraction of commercial wood from 25 years old, due to the minimum time for the cutting cycle in Sustainable Forest Management Plans (PMFS) in the BLA, regulated by the Normative Instruction n°.05/2006 (MINISTÉRIO DO MEIO AMBIENTE, 2006).

For the “Natural field” and “Pasture” classes, production loss and restoration values were not used, since in most pastures in the region, management and conservation practices are not frequently parts of the agriculture. However, the cost of leasing new pastures for animal exploitation was accounted for a period of 90 days, a period equivalent to the regrowth of vegetation (TOWNSEND; COSTA; PEREIRA, 2012), a proxy for the impact of fire on pasture. These values were obtained on *Fundação Getúlio Vargas* data portal (FGV IBRE, 2021) by selecting the states that compose the region.

The leasing data series is part of the free data set, however discontinued by the Foundation since 2014. In this way, to expand the series until 2020, we used variations in the price of live cattle, since it is common to use this index to estimate the land lease value (PEREIRA et al., 2020). Thus, live cattle prices were extracted from the historical series of the Center for Advanced Studies in Applied Economics – CEPEA (CEPEA, 2021).

For the “Agriculture” class, initially the main agricultural crops (annual and perennial) were determined based on the value of production and harvesting area, reported by the Municipal Agricultural Production survey (PAM- IBGE) (IBGE, 2021d). Then, it was found out that soybean and corn are the foremost crops in the BLA, representing together 67% of all production and 78% of total harvest area, between 2001 and 2019. In possession of this information and the calendar for the Northern region made by the Ministry of Agriculture, Livestock and Supply (MAPA), an annual production system was set up. The months from October to May are intended to soybeans and the ones from June to September are designed to corn.

Once the agricultural calendar of the region was set up, the net income was quantified based on estimates of production costs and total income for each crop over the period. The cost values were obtained from the website of the National Supply Company – CONAB (CONAB, 2021b), separating the total operating cost for the total. Income was calculated from average production estimates for both crops (CONAB, 2021a) with prices paid to the producer (CONAB, 2021c), both made by CONAB.

In certain years, corn production has a negative net income value, mainly due to expenditure on pesticides, fertilizers, and machinery. This happens because the accounting data provided by CONAB assumes high technology, overestimating the regional average cost, given the heterogeneity in the adoption of technology in the region, including small producers that do not use mechanization or agrochemicals (ALVES; MODESTO JÚNIOR, 2020; BÖRNER; MENDOZA; VOSTI, 2007; CAVIGLIA-HARRIS, 2018; FONTES; PALMER, 2018). In this way, it was assumed that when a corn crop that produces a negative profit is burned, the loss will be null rather than negative. This reasoning not only allows the mitigation of excessive cost, which is one of the causes of negative values for profit, but also it is consistent with the economic concept of sunk cost, which is understood as comprising irreversible expenses at the time the decision is taken (VARIAN, 2010, sec. 20.6), like those imposed by the fire. In fact, the expenditure on land preparation (including mechanization and agrochemicals) becomes irrecoverable soon after it is carried out. Therefore, the economically adequate measure of damage is, in the particular case, the unrealized profit. In such cases that this would be negative, there is, therefore, no damage.

In order to quantify the total number of hospitalizations because of smoke generated by fires in the region and the amount spent on the treatment of respiratory diseases, the monthly percentages of hospitalizations due to fire-smoke pollutants calculated in Chapter 4 were applied to all time series used in this chapter.

The values per ton of carbon dioxide emitted correspond to the equilibrium price of the European Union Emissions Trading System (EU-ETS), the largest and oldest carbon trading system in the world, obtained from the World Bank portal (THE WORLD BANK, 2021). It was considered only prices from the third phase of the EU-ETS (2013-2020), the most recent, and, thus, less subjected to the influence of market failures that were gradually repaired along the existence of the scheme. Carbon taxes were ignored for being regulated prices, thus not reflecting the actual marginal cost of carbon abatement (GOULDER; SCHEIN, 2013; MEADOWS; VIS; ZAPFEL, 2020). The period between 2018-2020 was excluded because of market functioning amendments, including approval of a cancellation mechanism in 2018⁹ (CARLÉN et al., 2019; HINTERMAYER, 2020) and the market stability reserve introduced in 2019¹⁰ (CARLÉN et al., 2019; EUROPEAN COMMISSION, 2021), which increased the carbon price in an over threefold larger average.

In this way, the average value between 2013-2018 was attributed to the year with the smallest difference and subsequently monetarily corrected (inflated and deflated) for the rest of the time series using the Harmonized Index of Consumer Prices (HICP) index of European Union inflation provided by the European Commission via the EUROSTAT portal (EUROSTAT, 2021).

The final value of the damage by emissions was quantified only for immediate emissions from the combustion process of the forest classes, since these LULC classes present, once burned, a potential long-term contribution to climate change in relation to other classes,

⁹ In 2018, the cancellation mechanism, a "quantity-based instrument", was approved to be implemented in 2023, consisting in cancelling allowances in the reserve exceeding the allowances exchanged in the previous year (CARLÉN et al., 2019; HINTERMAYER, 2020). This could have had an anticipated effect on price.

¹⁰ In 2019, the market stability reserve was introduced (CARLÉN et al., 2019; EUROPEAN COMMISSION, 2021), resulting "on higher and more robust carbon prices and helped to ensure a year on year total emissions reduction of 9% in 2019, with a 14.9% reduction in electricity and heat production and a 1.9% reduction in industry", and could have been anticipated in 2018 by traders thus anticipating price increase (anticipatory behaviour is assumed by (HINTERMAYER, 2020).

in which the rapid growth of vegetation removes carbon emissions generated during the burning from the atmosphere.

The values of forest products (timber and non-timber) together with the carbon values were available in dollars, and using the exchange rates provided by the Institute for Applied Economic Research (IPEA, 2021), they were converted into reais throughout the time.

Finally, to obtain the magnitude of the monetary damage caused by fire over these 20 years, the values obtained were converted into percentages equivalent to the Gross Domestic Product (GDP), obtained from the IBGE portal for Brazil (IBGE, 2021e) and for AMZL through the grouping of the municipalities that are part of the region (IBGE, 2021f).

It should be noted that to obtain comparable values within the series, the final value of monetary damage was corrected to current prices (January 2021) through the IPCA index (Extended Consumer Price Index) provided by IBGE for the entire series (IBGE, 2021g).

5.2.5 Uncertainty

The uncertainties measurement involves the propagation of the variance (σ) of the variables used and the equations that follow it. For this, the uncertainty propagation equations presented by Vuolo (1996, cap. 8) and explained in Table 5-4 were used, especially for the following situations: sum of variables (Equation 5.3); product between variables (Equation 5.4); product of a constant (Equation 5.5).

Table 5-4. Used expressions for uncertainty propagation.

Initial equation	Expression to determine the uncertainty	Eq.
$w = x + y$	$\sigma_w^2 = \sigma_x^2 + \sigma_y^2$	(5.3)
$w = x \cdot y$	$\left(\frac{\sigma_w}{w}\right)^2 = \left(\frac{\sigma_x}{x}\right)^2 + \left(\frac{\sigma_y}{y}\right)^2$	(5.4)
$w = a \cdot x$	$\sigma_w = a \cdot \sigma_x$	(5.5)

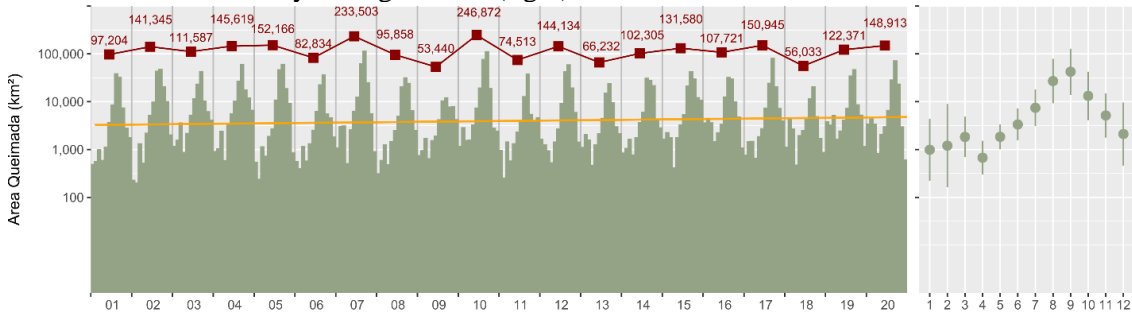
Source: Adapted from Vuolo (1996).

5.3 Results

5.3.1 Fire pattern in the BLA

Figure 5-2, the graph on the left shows the history of monthly burned area in the BLA between 2001 and 2020, in which the monthly average was 10,271 km², approximately the size of Três Lagoas, a municipality of Mato Grosso do Sul. The three highest values were registered in 09/2007 (112,016 km²), 09/2010 (110,641 km²) and 09/2017 (79,565 km²), whilst the lowest values were registered in 02/2002 (196 km²), 01/2002 (225 km²) and 02/2005 (234 km²).

Figure 5-2. Monthly and total annual variation of the burned area between 2001 and 2020 (left) and monthly average values (right).



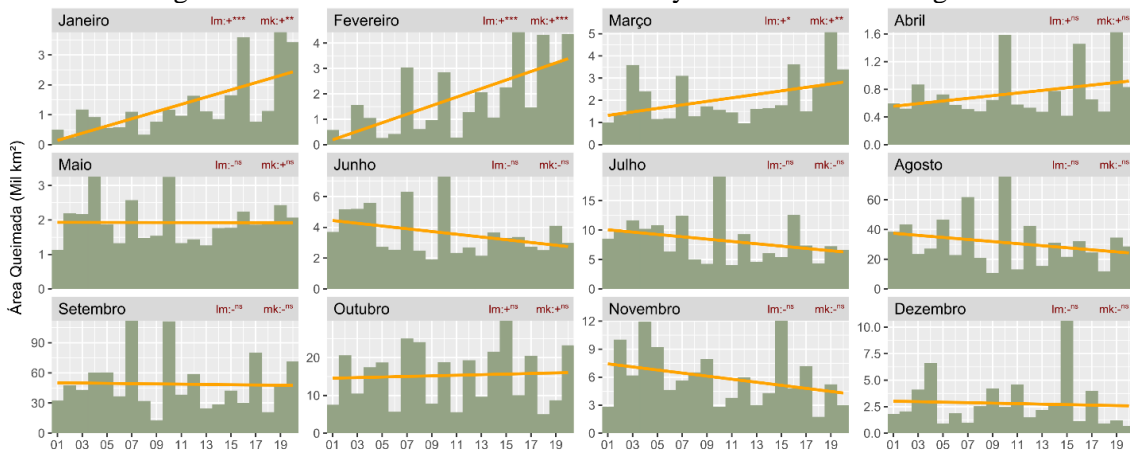
Note: The bars represent the monthly total of burned area, where the yellow line shows the linear trend of this data; the graph of lines and dots at the top represent the annual accumulated, and; the graph on the right represents the average value of the burned area and its variation over the months.

Source: From Author.

In relation to the annual burned area (graph of points in Figure 5-2), we found an average of $123,259 \pm 51,262$ km², which is close to the size of England (130,000 km²). The years with the highest records of accumulated area were 2010 (246,872 km²) and 2007 (233,503 km²), while the smallest areas were observed in the years of 2009 (53,440 km²) and 2018 (56,032 km²).

No significant trends were found over the total annual burned area values, using both Linear and Mann-Kendall tests. On the other hand, the analysis of the monthly totals showed an increase in the levels of burned area using the non-parametric analysis (Mann-Kendall). Thus, the monthly trends are presented in Figure 5-3, and a significant increase in burned areas was identified in the months of January, February and March.

Figure 5-3. Trend in burned area at a monthly scale for the BLA region.



Note: the yellow line represents the linear trend of the data. The trend can be positive (+) or negative (-) and is obtained through: linear trend (lm) and Maan-kendal (mk). Significance levels: “***” $p < 0.01$, “**” $p < 0.05$ and “*” $p < 0.1$.

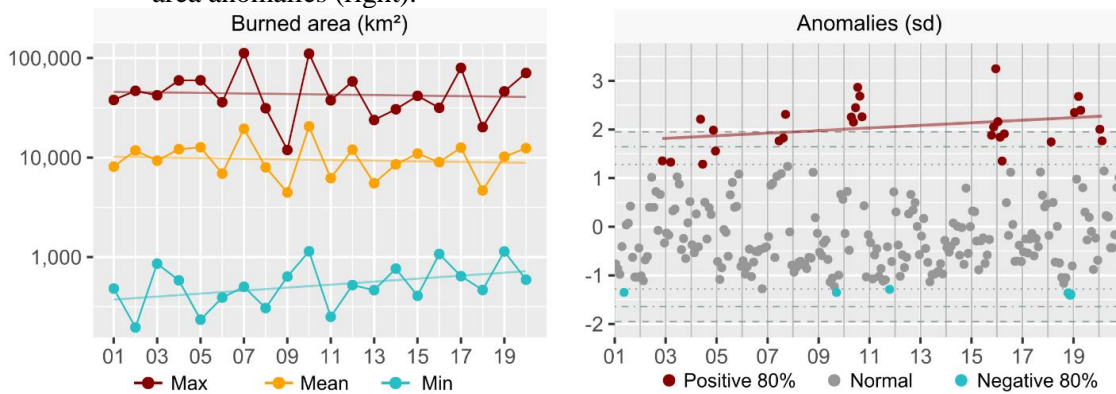
Source: From Author.

The temporal pattern of fire existing in the BLA (Figure 5-2 right) is characterized by its onset in February-March, with a small peak in the burned area values which together represents approximately 3.54% ($\pm 2.08p.p$) of the annual burned area. The month of April, in turn, registered the lowest value in the series, with an average of $736 \pm 370 \text{ km}^2$, representing about 0.65% ($\pm 0.32p.p$) of the total area affected by fire annually. Since then, the series shows an increase in the values of burned area, reaching the maximum in August-September (average of $39,858 \text{ km}^2$), which can represent up to 80% of the annual burned area. The year is ended with a decrease in the values until the cycle is restarted.

Over this 20-year period, there is an increase of 1.5% ($p < 0.1$) in the magnitude of the minimum monthly values, while the average and maximum monthly values are statically stable (Figure 5-4 left). However, anomalous events¹¹ showed an increase in their recurrence over these 20 years (Figure 5-4 right), in which half of the series (2002, 2003, 2004, 2007, 2010, 2015, 2016, 2018, 2019 and 2020) presented at least one month above 80% of the data. Among these anomalous events, the year of 2010 stands out, when half of the months were characterized as a positive anomaly of the burned area, then the years of 2004 and 2016, in which 1/3 of the months were characterized as positive anomalies.

¹¹ Anomalous events are events that deviate from the average of the data. In this study, they are months whose burned area value is greater than 80% of all burned areas recorded in that month, considering the last 20 years.

Figure 5-4. Trend in annual maximum, mean and minimum values (left), and monthly burned area anomalies (right).

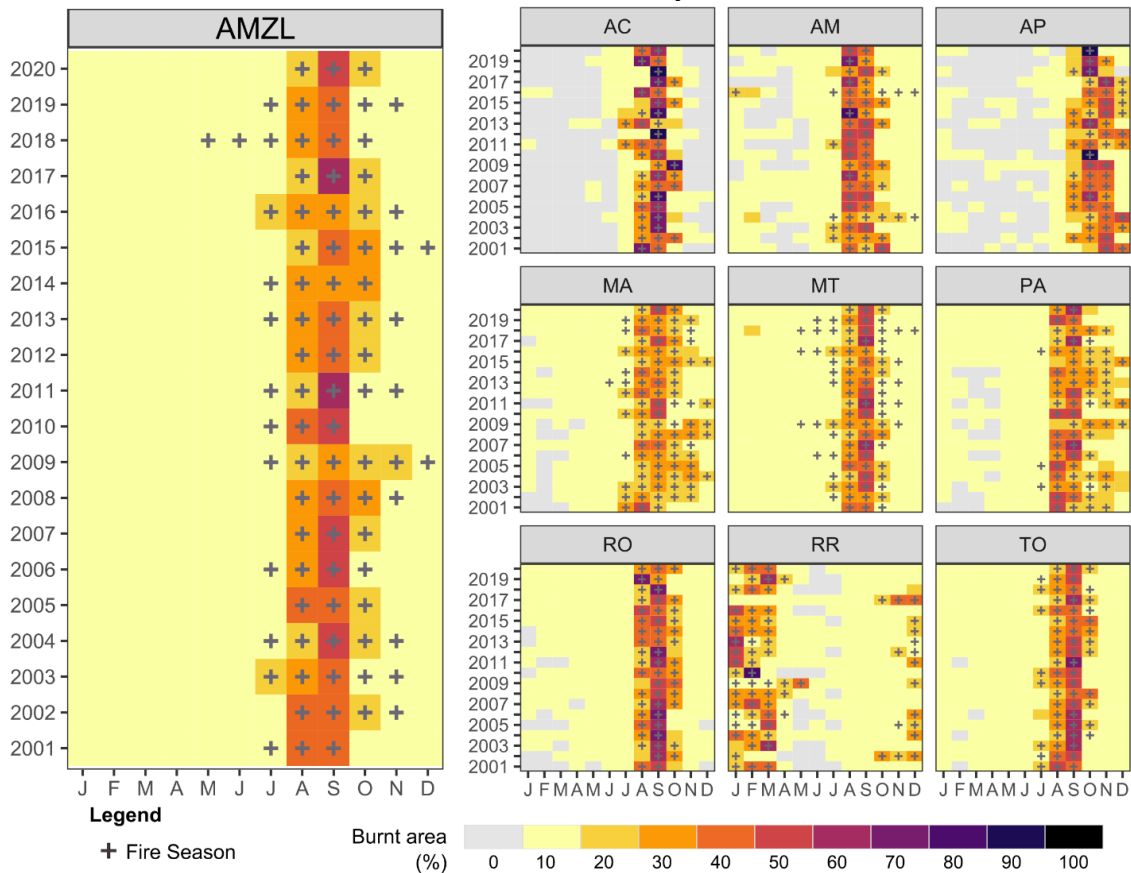


Note: On the left plot red dots represents an descriptive statistic over the total monthly burned area, where red is the maximum, yellow the average and blue the minimum. On the right plot, each dot represents an anomaly of the total monthly burned area, where the greater (red) and the lower values (blue) were highlighted. Lines, in both plots, represents the Linear trend over the respective colored values.

Source: From Author.

The months characterized as fire season for the BLA region and its states are presented in Figure 5-5. Predominantly, the months of August, September and October represent the fire season for the BLA region. This pattern is also observed for the states of MA, MT, PA, RO and TO. A variation without the month of October is found for the states of AC and AM. However, for the state of Amapá (AP) the months with the highest occurrence of fires are October and November, and for the state of Roraima (RR), the peak is in January, February and March.

Figure 5-5. Percentage of monthly fire by year, highlighting the fire season for the Brazilian Legal Amazon (BLA) and for each state covered by it.

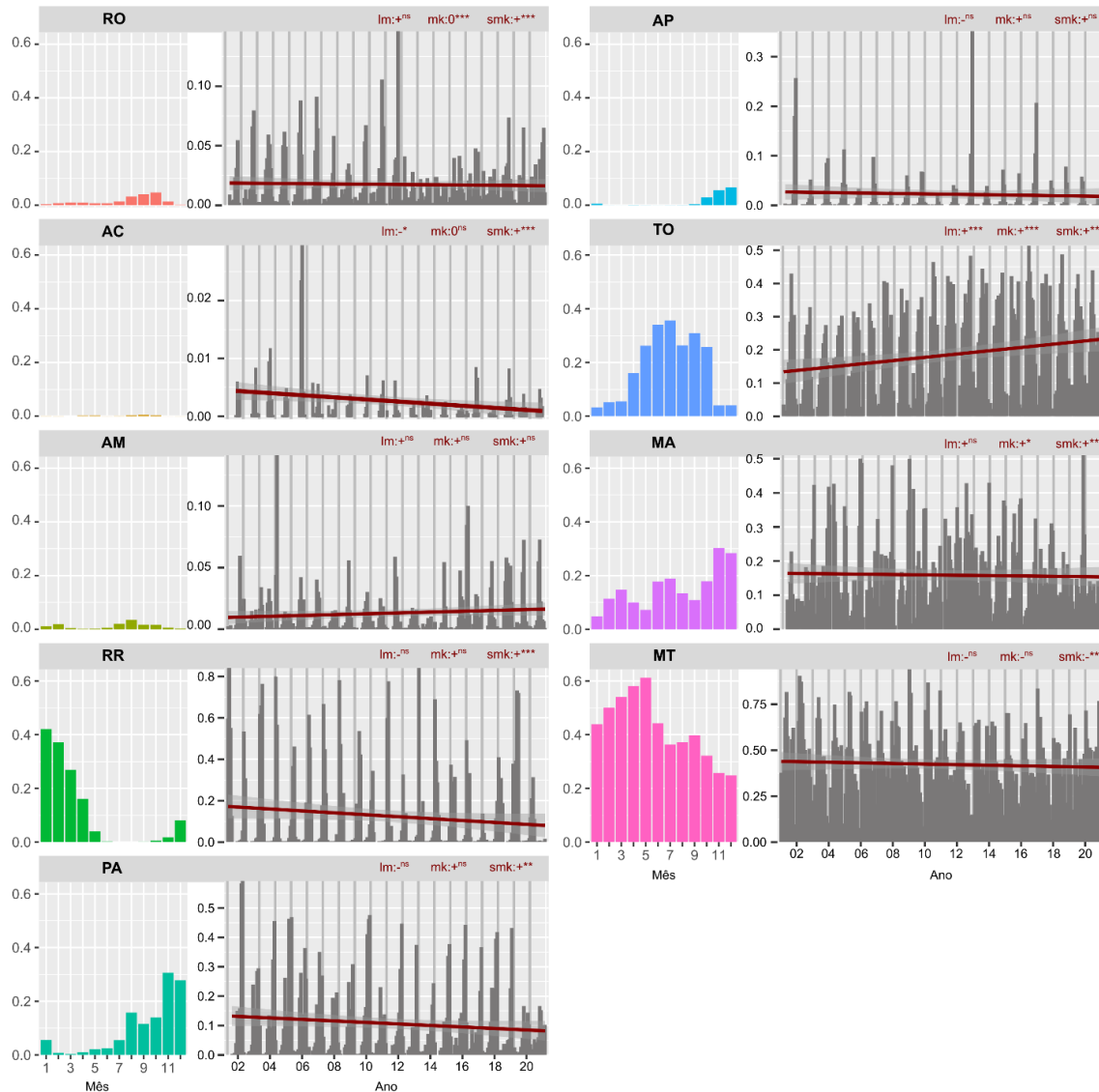


Source: From Author.

Among the nine states that are part of the BLA, the order of average contribution is: MT, TO, MA, RR, PA, AP, RO, AM and AC. However, the contribution levels throughout the year vary (Figure 5-6), such as between the months of January and April, when the contribution of RR is greater than that of TO, but this dynamic is inverted in the following months, when the values of TO remain high (around 30%) while the ones of RR cease. MT in turn has a high average contribution value throughout the year, but its highest percentages are found until May, a divergent peak from the fire season for the state.

During the analyzed period, considering a linear trend, there was an increase in the contribution of TO in the total burned area values for the BLA, and in contrast the state of AC recorded a decline in burned area values (Figure 5-6). However, from a seasonal perspective, the states that showed a positive and significant trend were: RO, AC, RR, PA, TO and MA, while a negative trend was observed only in MT.

Figure 5-6. Contribution (%) of each state in the total burned area for the BLA, presented in monthly and annual values.



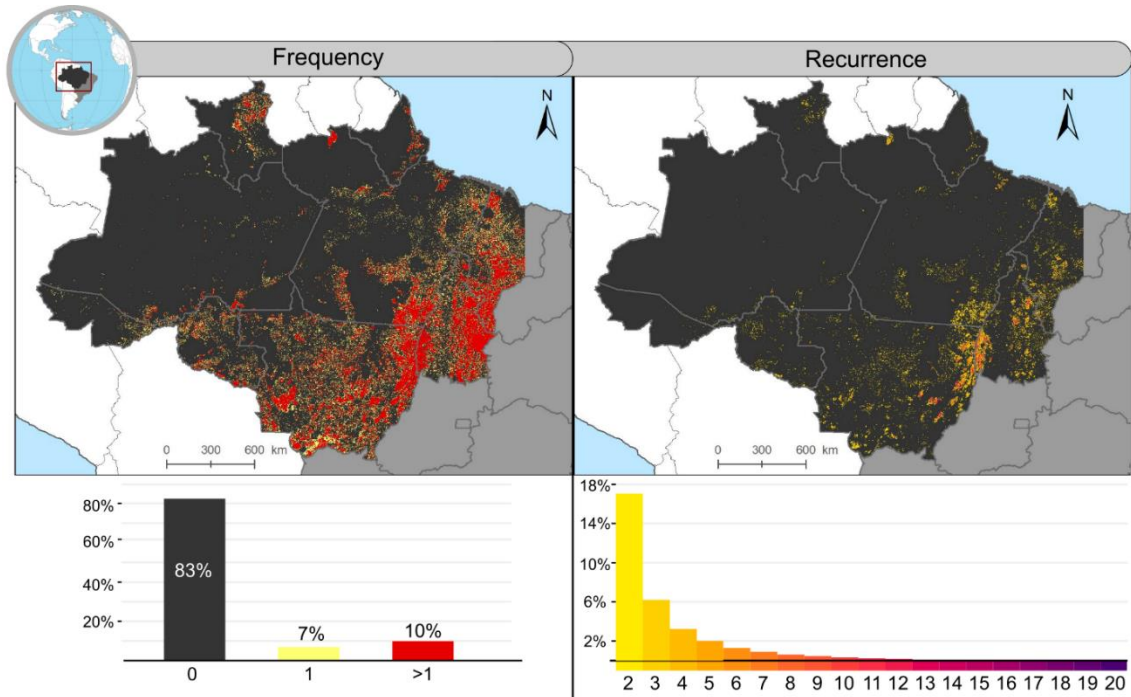
Note: the red line represents the linear trend of the data. The trend can be positive (+) or negative (-) and is obtained through: linear trend (lm), Maan-kendal (mk) and Maan-kendal considering seasonality (smk). Significance levels: “****” $p < 0.01$, “***” $p < 0.05$ and “**” $p < 0.1$.

Source: From Author.

In the last 20 years, about 2,465,176 km² have already been affected by fire in the region, but considering the total extension between new and overlapping areas, the region presented 17% (\approx 840,163 km²) of its total area affected by fires (Figure 5-7), almost the size of the state of Mato Grosso. Of this total, 346,956 km² burned only once, while 493,206 km² burned more than once. Of the areas hit more than once by fire, approximately 17% only burned two years in a row, 0.34% was affected for ten consecutive years and the areas that fire has always been used represent approximately

67 km² (less than 0.01% of the total already burned). These areas where there has always been fire are located in the border between the states of MA and TO, and between TO and MT, more specifically in the municipalities of Campinápolis-MT, Barra do Garças-MT, Ribeirão Cascalheira-MT, Paranatinga-MT, Canarana -MT, Formoso do Araguaia-TO, Goiatins-TO and Balsas-MA.

Figure 5-7. Spatial distribution of frequency and recurrence of burned areas in the Brazilian Legal Amazon.



Source: From Author.

The proportion of new burned areas (36%) is low compared to the occurrence of fire in previously affected areas (64%). Monthly, (Figure 5-8) the new burned areas have their lowest values in the middle of the year (Jun-Jul), later they show a growth following the period of burning in the region (Aug-Oct) reaching their maximum at the beginning of the year (Jan-Feb). On the other hand, the proportion of old areas affected has grown in March, reaching its maximum between June and July.

Figure 5-8. Variation in the proportion of new burned areas and previously affected ones over the analyzed period and per month.

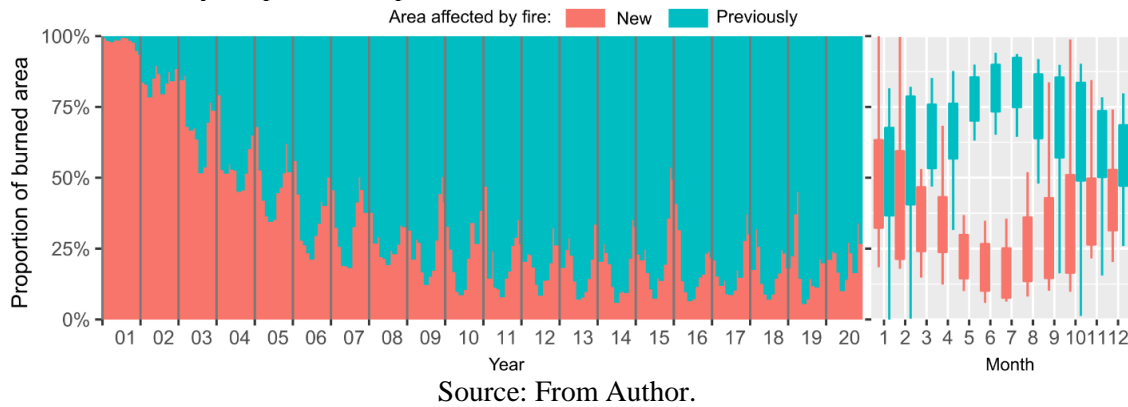
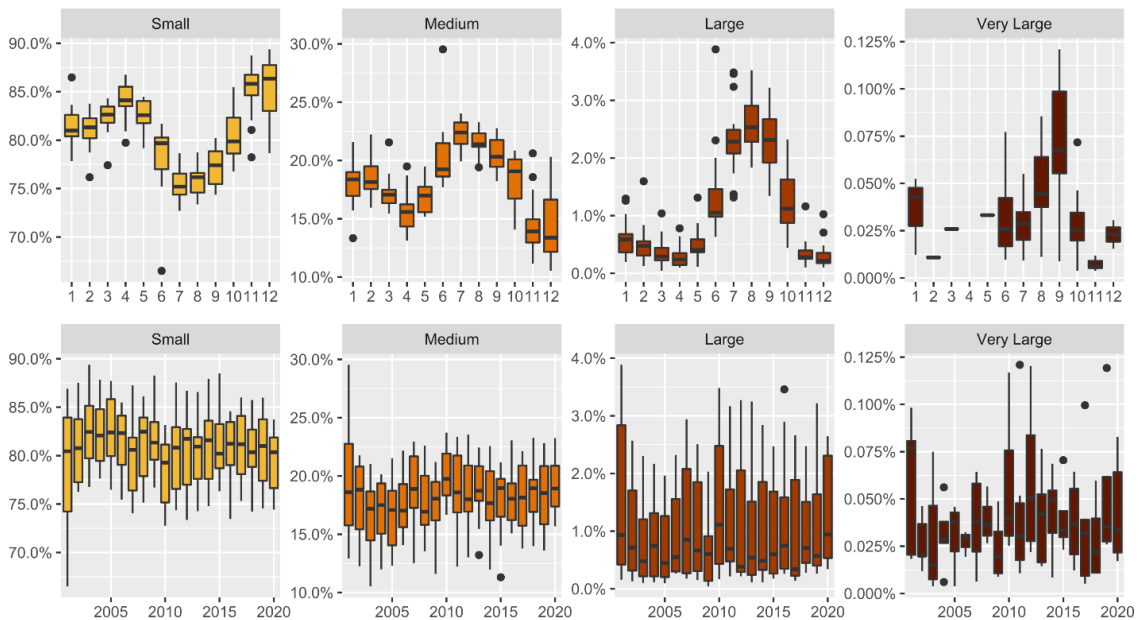


Figure 5-9 presents the proportion of events according to size classes. Events of low extension (Small class) are the majority in the region, which annually represent about 80%. “Large” and “Very Large” events together represent an average of 1.5% of the total in terms of fire-affected area contribution. The months with the highest concentration of “Large” events are the months from June to September, when there is a reduction of almost 10 percentage points in the amount of “Small” events.

Figure 5-9. Variation of events by size class occurred per month (first row) and per year (second row) in the BLA.



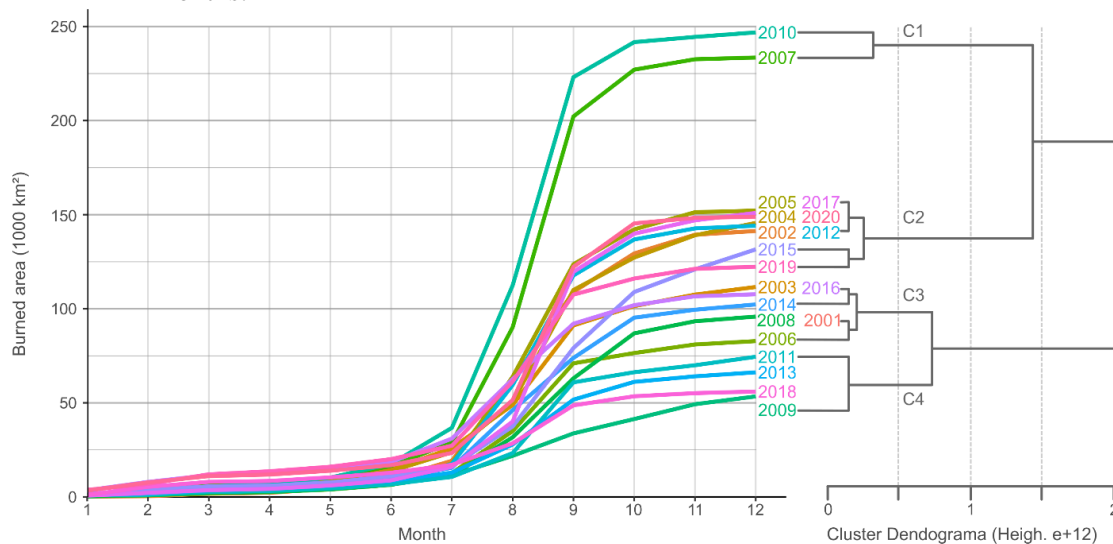
Size classes where: Small are patches smaller than 40 ha; Medium are patches between 40 and 404 ha; Large are burned areas between 404 and 4,046 ha, and; Very Large are patches with an area greater than 4,046 ha.

Source: From Author

5.3.2 Clustering years

At first, years with similar characteristics in relation to fire seasonality can be grouped into four categories (Figure 5-10): group 1 (C1) is composed of the extreme years with the largest annual burned area, which are 2010 and 2007; group 2 (C2) are the years with high values, consisting of the years 2020, 2019, 2017, 2015, 2012, 2005, 2004 and 2002; group 3 (C3) is the intermediate values, which are composed by the years 2016, 2014, 2008, 2006, 2003 and 2001; the last group (C4) are the years with the lowest values (2018, 2013, 2011 and 2009).

Figure 5-10. Groups of similar years in relation to the accumulated total and its variation over the months.



Note: Groups determined using the DTW to verify the dissimilarity in the series, the MDS to reduce the dimensions, and cluster hierarchization for groupings.

Source: From Author.

Under the temporal perspective, which divided the series into 4 periods, we did not find significant differences at 5% (Table 5-5) regarding to: annual burned area; maximum monthly burned area; minimum monthly burned area; average annual amount of patches; percentage of patches by size; number of months within the fire season; number of months with anomalies and number of municipalities affected annually.

However, divergences were found in the monthly scales for: monthly total area, for February; average amount of patches, in January and February; and for the average number of affected municipalities, in February and March. The last group (G4: 2016 to

2020) presented the highest and significantly divergent values from the other groups, especially compared to the first one (G1: 2001 to 2005).

These changes are also detected in relation to the damage, as in: the annual average of LULC affected by fire, especially in the Agriculture, Pasture and Forestry classes; the annual average of land tenure affected by fire, which the Urban class shows a decrease in the area; and in the equivalence of monetary damage in relation to the Brazilian GDP.

Table 5-5. Mean values for each variable used in the characterization of fire, as well as the significance (p.value) of the Kruskal-Wallis test for comparison between means, separated by group of years.

VARIABLE	G1 2001-2005	G2 2006-2010	G3 2011-2015	G4 2016-2020	p.value	
Annual burned area (km ²)	129,584	142,501	103,753	117,197	0.6975	
Maximum monthly burned area (km ²)	49,270	60,379	38,381	49,679	0.6075	
Minimum monthly burned area (km ²)	471	596	482	783	0.2989	
Monthly total area (km ²)	Jan	658	763	1,221	2,515	0.0535
	Feb	710 ^(a)	1,551 ^(a)	1,362 ^(a)	3,533 ^(b)	0.0218
	Mar	1,866	1,737	1,457	3,220	0.1447
	Apr	651	750	546	1,001	0.2621
	May	2,109	2,012	1,492	2,091	0.1566
	Jun	4,433	4,080	2,779	3,096	0.2608
	Jul	10,086	9,345	5,749	7,505	0.1520
	Aug	35,308	38,010	24,246	25,848	0.5319
	Sep	48,020	60,379	37,818	49,236	0.6975
	Oct	14,758	16,101	17,030	13,314	0.8964
	Nov	7,955	54,30	5,759	4,319	0.4515
	Dec	3,032	23,44	4,294	1,518	0.1940
Amount of patches (#)	Annual	3,762	3,663	2,831	3,062	0.4476
	Jan	352 ^(a)	444 ^(a)	631 ^(ab)	1,303 ^(b)	0.0288
	Feb	359 ^(a)	838 ^(a)	854 ^(ab)	1,778 ^(b)	0.0263
	Mar	1,061	1187	940	1,743	0.1130
	Apr	478	451	393	660	0.1884
	May	1,143	831	889	1,149	0.1581
	Jun	1,478	1,284	1,124	1,174	0.8040
	Jul	2,728	2,170	1,459	1,781	0.0605
	Aug	8,474	7,935	5,172	6,218	0.3934
	Sep	10,717	13,063	7,599	9,603	0.5760
	Oct	5,226	5,067	4,911	3,939	0.6075
	Nov	4,292	3,191	2,907	2,347	0.2773
Dec	2,452	1,365	2,887	966	0.1331	
Percentage of patches by size class (%)	small	81.50%	80.63%	80.54%	80.39%	0.3569
	medium	17.49%	18.29%	18.41%	18.48%	0.2711
	large	1.01%	1.06%	1.07%	1.13%	0.6509
	very large	0.03%	0.04%	0.04%	0.04%	0.6674
Number of months within the fire season (#)	4.00	4.00	4.40	4.40	0.8571	
Number of months with anomalies (#)	1.40	2.00	0.80	2.40	0.4610	

Continues

Table 5-5. Conclusion.

VARIABLE	G1 2001-2005	G2 2006-2010	G3 2011-2015	G4 2016-2020	p.value	
Number of municipalities affected annually (#)	Annual	255	252	244	252	0.92
	Jan	108	110	127	133	0.6697
	Feb	54 ^(a)	77 ^(a)	77 ^(a)	127 ^(b)	0.0228
	Mar	77 ^(a)	90 ^(a)	87 ^(a)	121 ^(b)	0.0111
	Apr	87	91	89	111	0.3124
	May	152	151	143	175	0.0592
	Jun	223	216	213	228	0.8714
	Jul	317	294	257	280	0.0866
	Aug	448	429	379	409	0.1385
	Sep	527	512	488	488	0.4573
	Oct	509	498	470	442	0.4556
	Nov	342	335	326	305	0.7819
	Dec	220	225	269	207	0.5856
Annual average of LULC affected by fire (%)	Agriculture	18.11 ^(a)	25.45 ^(ab)	27.98 ^(b)	28.87 ^(b)	0.007
	Natural Field	31.42	32.70	32.91	30.23	0.643
	Pasture	20.59 ^(a)	16.32 ^(ab)	13.42 ^(b)	13.97 ^(b)	0.008
	Forestry	0.01 ^(a)	0.02 ^(a)	0.03 ^(ab)	0.05 ^(b)	0.036
	Old growth	24.51	21.22	21.01	21.83	0.374
	Secondary Forest	4.76	3.82	4.24	4.44	0.345
Annual average of land tenure affected by fire (%)	Private	60.35	60.86	60.32	59.76	0.917
	Public	26.33	26.31	26.98	26.73	0.9775
	Not Designed	12.20	11.89	11.87	12.64	0.8617
	Urban	1.11 ^(a)	0.94 ^(ab)	0.82 ^(b)	0.87 ^(b)	0.0231
Total CO ₂ immediate emission (TgCO ₂)	799.58	937.55	663.27	729.68	0.9016	
Equivalence of monetary damage in relation to Brazilian GDP (%)	0.94 ^(a)	0.41 ^(ab)	0.21 ^(b)	0.28 ^(b)	0.0171	

Note: Equal letters within parentheses represent the similarity between the means.

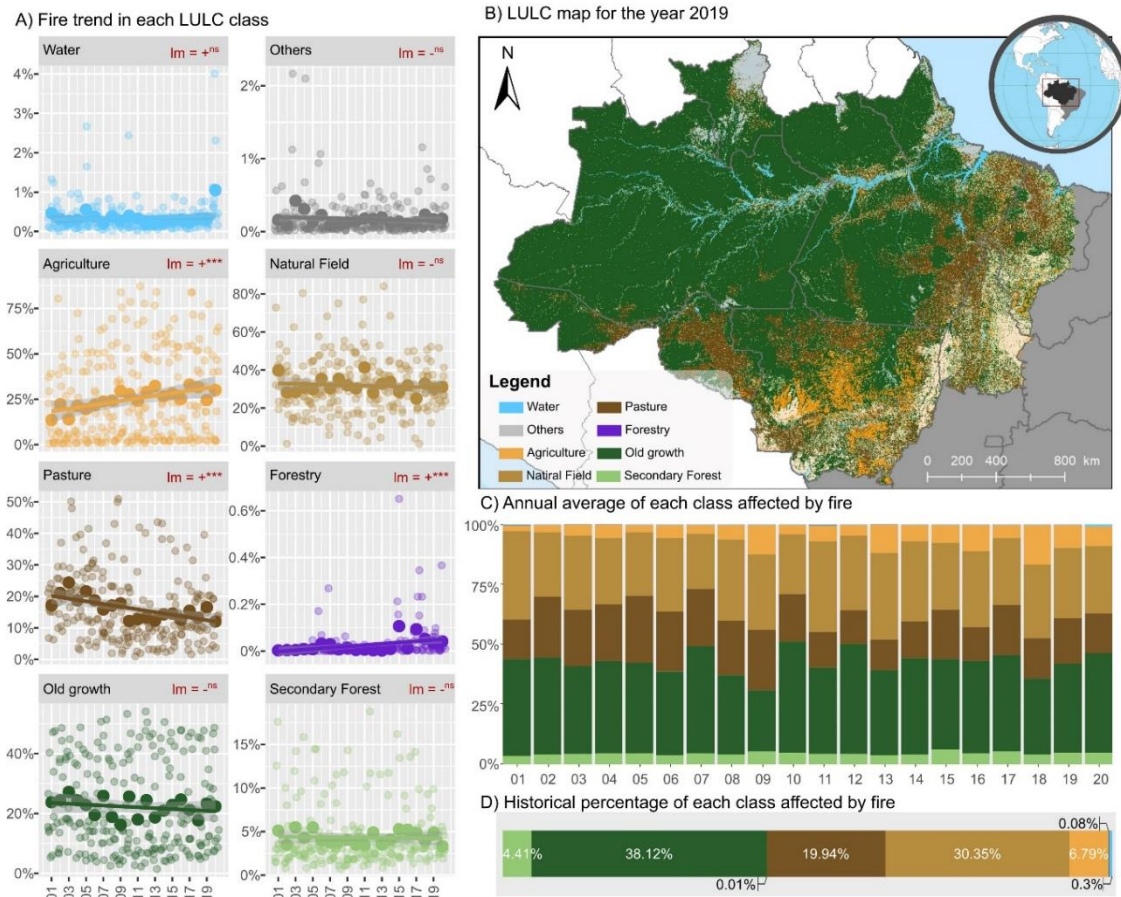
Source: From Author.

5.3.3 Fire impacts

The proportion of LULC classes derived from the reclassification of the MapBiomass product can be seen in APPENDIX B - Figure B-1, where it is verified that the forest class (Old growth and Secondary) represents 75% of the total of the Brazilian Legal Amazon region in 2020. If we analyze the classes impacted by fire over the last 20 years (Figure 5-11), the class “Old growth” was the most affected (38.73%), followed by “Natural Field” (30.21%), “Pasture” (19.74%), “Agriculture” (6.47%), “Secondary Forest” (4.62%), “Water” (0.3%), “Others” (0.09%) and “Forestry” (0.01%).

During this period, there was an increase in the average levels of the burned area for the “Agriculture” and “Forestry” classes, while for the “Pasture” class there was a decline and for the others the trend was not significant.

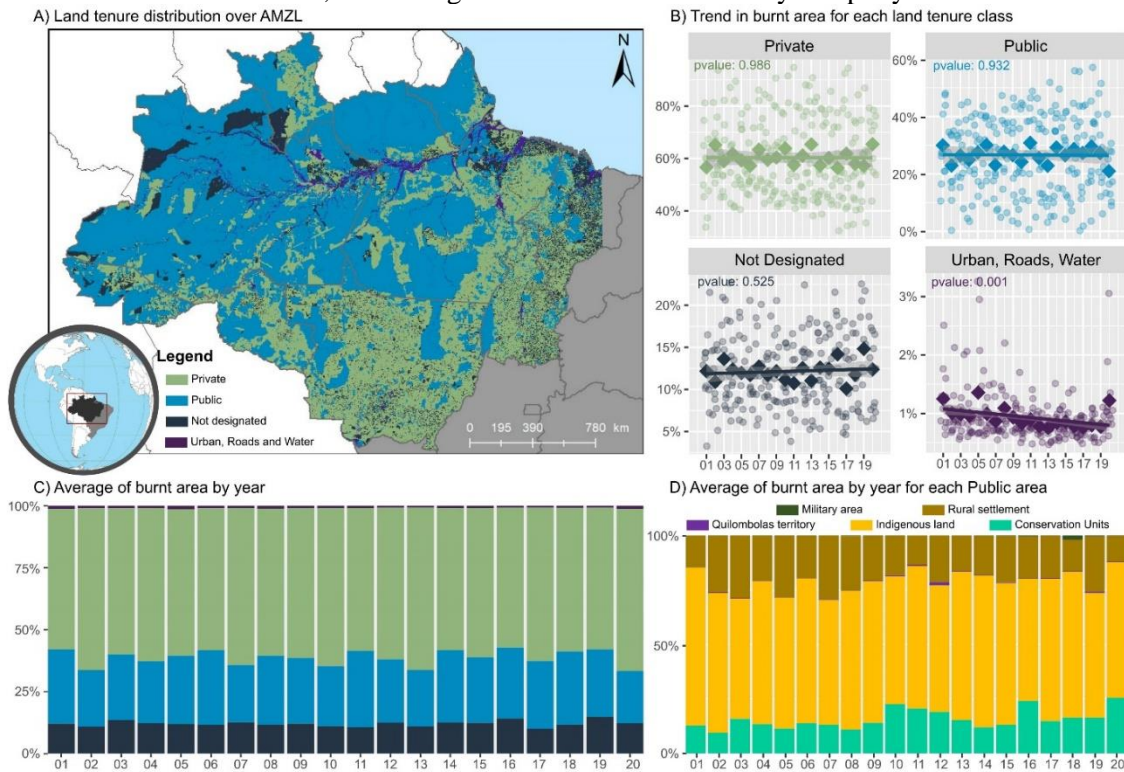
Figure 5-11. Summary of fire impacts on the LULC over the last 20 years: A - is the fire trend in each LULC class; B - is the LULC map for the year of 2019; C – is the average annual of each class affected by fire; D – historical percentage of each class affected by fire.



Source: From Author.

From the legal perspective of land tenure (Figure 5-12), we find that historically "Private" areas are the most affected, accounting for 60.3% of all fires, followed by "Public" (26.6%) and "Not Designated" areas (12.2%), in which didn't show a trend over the 20 years analyzed. In turn, the "Urban" areas, which are "Urban", "Highways" and "Water" classes, present a significant downward trend over the years, however this class has a low contribution to the total affected area, around 0.9%.

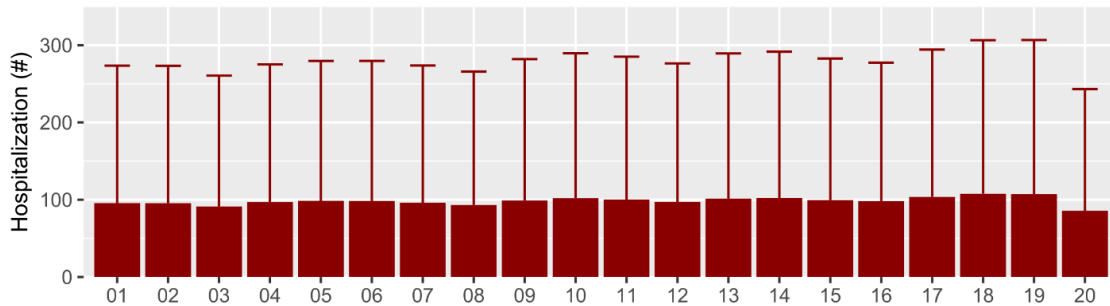
Figure 5-12. Summary of fire impacts on land tenure: A – distribution map of land tenure in the BLA region; B – trend in burned area by land tenure class; C – annual average of burned classes; D - average of Public class affected by fire per year.



Source: From Author.

The average number of hospitalizations resulting from fire in the region (Figure 5-13) is approximately 98 hospitalizations annually. There is also a low value for the year 2020, however these values may be associated with the lack of updating of the system by the municipal and state health agencies during the COVID-19 pandemic.

Figure 5-13. Estimate of the number of hospitalizations for respiratory diseases over the last 20 years.

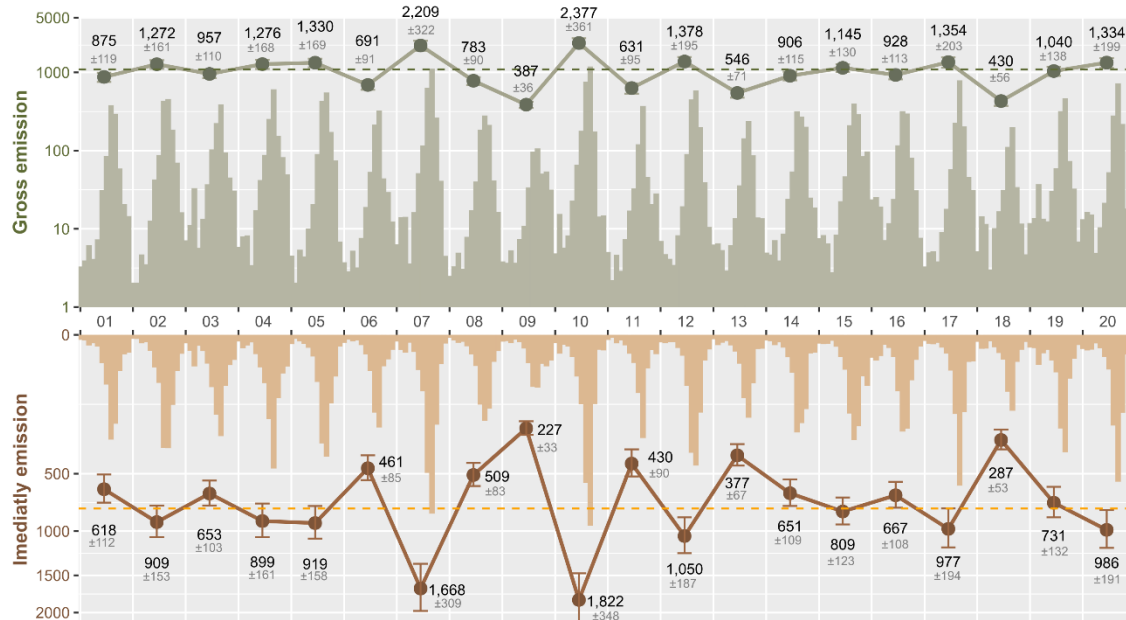


Source: From Author.

The estimated carbon dioxide values for the region during the analyzed period are presented in Figure 5-14. The bars represent the monthly values, the points the annual accumulated values and the dashed line the average annual value for the period. Both from gross and immediately emission.

When it comes to gross emissions, the region, on average, is responsible for 1,092 TgCO₂ annually, with average monthly contributions of 92 TgCO₂. While the immediately emission, here accounted only from the forest physiognomies (Old growth, Secondary Forest and Forestry classes), it is observed monthly contributions in the order of 65 TgCO₂ and an annual average of 782 TgCO₂.

Figure 5-14. Estimates of carbon dioxide emission (Tg CO₂) per month over the 20 years analyzed under the committed and immediate form.



Note: The bars represent the monthly values, the dots represent the accumulated annual values and the dashed line the average annual value for the period. Gross emissions represent the total CO₂ that can be emitted immediately and later with the decomposition process. Immediate emissions refer to the total CO₂ emitted by the complete combustion of biomass from the forest classes (Old growth, Secondary Forest and Forestry).

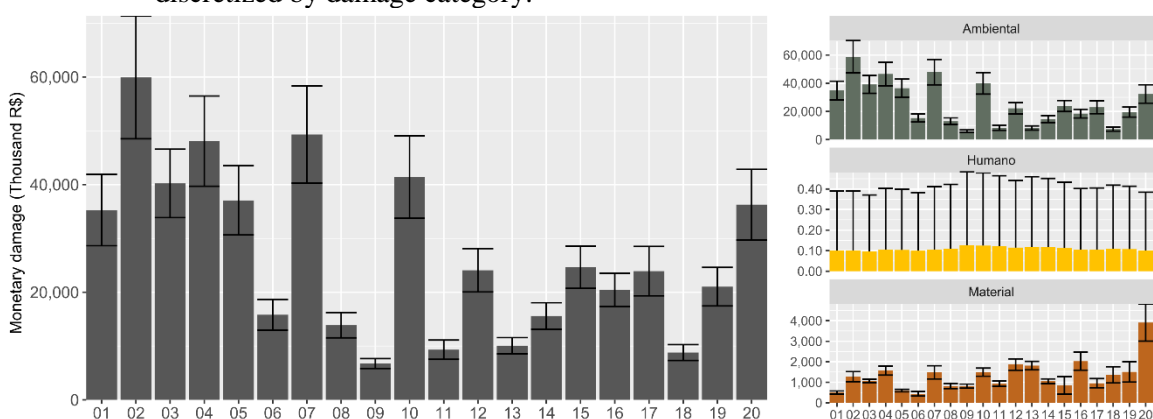
Source: From Author.

5.3.4 Monetary quantification

The total damage over these 20 years sums around R\$ 541 billion (Figure 5-15). The years of 2002 (R\$ 59.91 ± 11.41 billion), 2007 (R\$ 49.31 ± 9.02 billion) and 2004 (R\$ 48.07 ± 8.38 billion) were the ones that accumulated the largest monetary damage

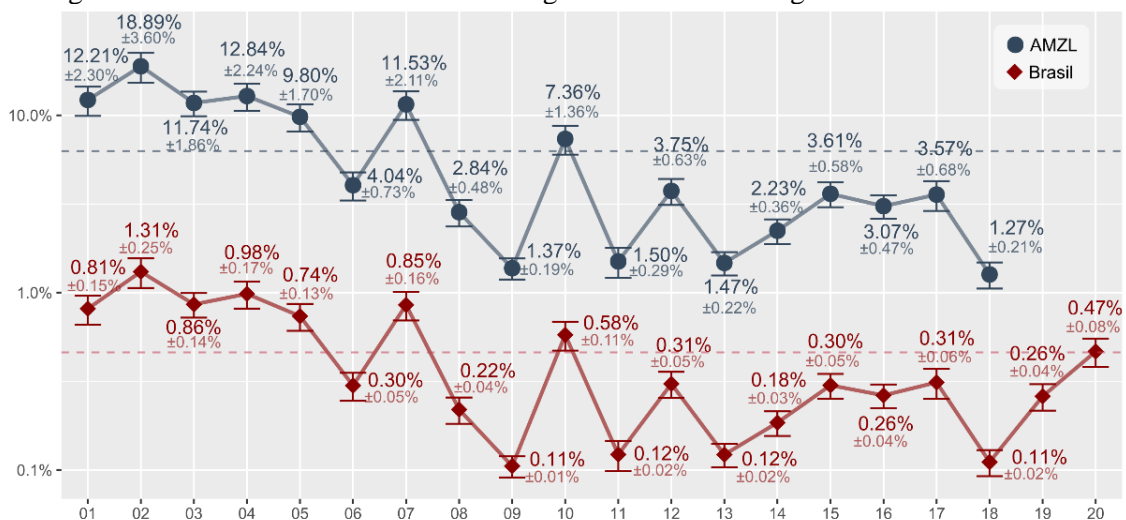
over the period. The total damage ratio represented an average $6.28\% \pm 1.1\text{p.p}$ of AMZL's GDP, ranging between $18.89\% \pm 3.60\text{p.p}$ (2002) and $1.27\% \pm 0.21\text{p.p}$ (2018), while for Brazil's GDP the damage represented an average of $0.46\% \pm 0.08\text{p.p}$ ranging between $1.31\% \pm 0.25\text{p.p}$ (2002) and $0.11\% \pm 0.02\text{p.p}$ (2018), as it is seen in Figure 5-16. Environmental damage, accounted here only for the CO₂ emission, corresponded to the largest fraction of the total damage, followed by material damage (accounted by loss of agroforestry production) and human damage (values for hospital admissions).

Figure 5-15. Total monetary damage caused by fire over the last 20 years in the BLA region, discretized by damage category.



Note: Values corrected to current prices (January 2021) through the IPCA index provided by IBGE (2021b).
 Souce: From Author.

Figure 5-16. Ratio between total fire damage and GDP in the region over the time series.



Source: From Author.

5.4 Discussion

5.4.1 The main patterns of the burned area in the BLA

The total burned area values are similar to those provided by global monitoring platforms, such as the GWIS -Global Wildfire Information System¹², (GWIS, 2021), which has one of its bases the MCD64A1 burned area product, with territorial and global analysis. In an annual comparison, maximum variations of 4% were obtained, mainly explained by the different methodologies for quantifying the total area. In comparison with national burning monitoring platforms, such as BDQueimadas (INPE)¹³, the values presented in this study show the same high and low trends that occurred for the Amazon biome, but on average 40% higher.

Usually, optical satellite images only capture forest fires when the crowns of the trees are directly or indirectly affected. This technical limitation excludes other types of fires, such as the ground fires or understory fire, which do not have enough strength to be detectable by the satellite or to reach the canopy to the point to cause a detectable impact on the crown (CHUVIECO et al., 2019). Consequently, global fire products are often not accurate in detecting and estimating the total burned area in regions of dense forest cover (GIGLIO et al., 2009), such as the Amazon. Therefore, it is important to consider that all estimates derived from burned area products are potentially underestimated.

Among the 20 years analyzed, a negative linear trend was found in the monthly and annual burned area, but not significantly. This decrease pattern is also identified on a global and continental scale within the period from 2003 to 2015, based on burned area data using the MCD64A1 (ANDELA et al., 2017), in which the authors determined a significant decline of 1.15% per year globally and 1.4% per year for South America. In a longer series (2001 to 2016), but with hotspot data, Earl and Simmonds (2018) determined a significant 10% decline for the Amazon region. Both works are supported by the fact

¹² Data are available by states, thus the comparison were made by summarizing the total values of the nine states that are part of the BLA (AC, AM, AP, PA, MA, MT, RR, RO, TO).

¹³ The AQ1Km product is built from MODIS data collection 6 from the concomitant AQUA and TERRA satellites, with low spatial resolution (1 km), and is made available by Biome, in this way the comparison was performed only with data for the Amazon biome.

of having a strong link between deforestation and fires, with the latter showing a large reduction in the period between 2011 and 2016.

However, there was a separation of these processes throughout the course of the Action Plan for Prevention and Control of Deforestation in the Legal Amazon - PPCDAm, (ARAGÃO et al., 2018; LIBONATI et al., 2021). Thus, this initial relationship, which would be leading to a negative trend until mid-2016 (Figure B-5), currently becomes non-significant and in positive parts due to the increase in the levels of burned area at the end of the series (Figure 5-2) and mainly by increasing trends in the first four months of the year (Figure 5-3). The full evolution is presented in the Appendix B.1.

Regulation and restrictions policies about the use of fire in states that have the greatest contribution in the total BLA's burned area, such as those in the state of Mato Grosso (MATO GROSSO, 2019, 2020, 2021), may be conditioning the trend in the BLA to be stable. However, it was found that even with these restrictions on controlled burning, as in the case of Tocantins (TOCANTINS, 2018, 2019, 2020), there was an increase of 10 percentage points in the contribution to the BLA's total burned area (Figure 5-6), leading to believe that these restrictions are not enough to prevent such growth or that other forms of fire, not subject to the mentioned restrictions, have become more relevant.

Repeated use of fire in the same place could be a sign of a specific land management practice, such as slash-and-burn agriculture. As pointed out by Costa (2008), fire is a widespread practice for increasing pastures and productivity in the northern Amazon. This practice has a high probability to create uncontrolled burning that reaches other areas, especially forests, due to the high flammability of grassland. The place with the highest frequency and recurrence of fire (Figure 5-7) is located in the middle-east of Mato Grosso, south-west of Tocantins and south of Maranhão, where the agriculture is expanding (FREITAS; MACIENTE, 2015), besides being the centre of the so-called "Arc of Deforestation".

Mato Grosso is also pointed out as the top state with repeated fires by Morton et al. (2013), in the study of forest fires between 1999 and 2010¹⁴. The authors found that the maximum frequency of repeated burning was five years, whereas our study points some places out

¹⁴ The authors use fire patches greater than 50 ha to account the fire frequency in the Amazon region.

where they burn every year. These differences are linked to the size of the spots used in each methodology and the time series analysis.

Despite the reduction in the cost of agricultural land preparation due to the use of fire, repeated burning can trigger negative effects in the physical, chemical and biological soil properties (SANTÍN; DOERR, 2016), reflecting in more effort in the crop management. In the physical attributes, frequent burning increases the bulk density, decreases the hydraulic conductivity and the water conducts macroporosity (MAGOMANI; VAN TOL, 2019). Related to the chemical soil attributes, the effects are into changing carbon and nitrogen storage and also reducing decomposition rates of the organic matter (PELLEGRINI et al., 2020).

Regarding to forests, repeated burning causes impoverishment of biodiversity in forest ecosystems (NASI et al., 2002) and even when due to natural causes, they can reduce the height and diameter of vegetation in new regrowth (MEDEIROS; MIRANDA, 2005). Thus, the recurrence of fires can lead to drastic changes in the structure and composition of the forest, generating a sequence of transforming effects after each fire event (BARLOW; PERES, 2008).

Most areas affected by fire (64% of events) are in regions that have already suffered at least once from this type of phenomenon. Thus, when considering fire as a strategy for opening new areas and for agricultural expansion, the values presented are similar to those found by Aragão et al. (2008), in which the authors determined that approximately 60% of fire in the BLA region during 2005 was in deforested areas.

5.4.2 The magnitude of fire impact over 20 years

Approximately 17% ($\approx 840,163 \text{ km}^2$) of the BLA has already suffered from fire over 20 years, the land size is approximately equal to Mato Grosso state. This value is not far from those presented by the MapBiomias-Fogo project, which using Landsat images, determined that between 2001 and 2019 approximately 10% of the Amazon biome was damaged by fire, while approximately 18% of Brazil's territory was already impacted by this event (MAPBIOMAS, 2021b).

Among the main LULC, "Old growth" is the most affected class in the region, a fact linked both to the lack of fire control in agricultural areas and the consequent incidence

in this land cover, as well as to the use of fire in the expansion of areas. However, the alert is given in areas of the “Agriculture” class, where there has been a significant increase in its contribution over the years, leaving 13.6% in 2001 and reaching the 30% mark in 2020. This fact is evidenced by the significant difference between the beginning of the series (G1: 2001-2005) and the end (G4: 2015-2020), Table 5-5. However, due to the characteristics in the construction of the use and coverage product, fire may have been used to open new agricultural areas or for handling an existing crop, and this methodology cannot be used to separate them.

Thus, if we consider that the BLA has already burned at least 17% of its territory in the last 20 years and that fire affects an average of about 123,259 km² per year, approximately 36% (44.373 km²) of these are in a new area. Also, considering that out of the 5 million km² that the region covers and following the MapBiomass classification that only 2% are areas without vegetation, we can infer that if these rates remain constant, in approximately 46 years we will have burned half of the region and in 92 years the entire legal Amazon will have been affected by fire.

The responsibility for fire mostly rests with private properties, where an average of 60.3% (Figure 5-12) of all the fire is in this kind of territory, even though they only cover 30.69% of the region (Table B-1). Within public responsibility, the areas with the highest incidence are: Indigenous Lands (TI: 63.11%) followed by Rural Settlements (Aru: 20.52%), Conservation Units (UC: 15.71%), Quilombolas (Qu: 0.39%) and Military Areas (ArM: 0.28%).

Among these, the UCs, ArM showed a positive trend in the burned areas and is significant at 5% (Figure B-2). On the other hand, ARu showed negative trends in the occurrence of fire along the years, but significant only at 10%. Finally, TI and Qu did not present a significant trend in the burned area along the analyzed years.

Even without an established trend over the years, TI are the territorial units that suffer from the increase in illegal activities that threaten their delimitation and the safety of those who live there (FELLOWS et al., 2021), this factor may be leading the high levels of area burned during the entire period. However, it is good to mention that the delimitation of land tenure by the IMAFLORA is static over time, thus it is not possible to separate the

use of fire before the approval of public lands. On the other hand, according to Veríssimo et al. (2011), the greatest increase in the extension of indigenous lands was in two periods prior to the data series used in this study, one in 1990/1994 and the other in 1995/1998. Therefore, most of the fires that occurred inside the TI was an attempt for invasion and illegal appropriation of land, like the work presented by Fellows et al. (2021), in which 83% of all TI in the Amazon region suffered from cases of invasion using fire and deforestation.

Among these illegal activities, land grabbing is an integral part of Brazilian land tenure history (MARTINS, 1994 apud; TORRES; CUNHA; GUERRERO, 2020), especially in the Amazon region where it is closely linked to the expropriation of traditional people and communities. During the process of recognition of Indigenous territories, the lack of official boundaries motivates a wave of invasions that expect to have legal rights over the TI area due to breaches and flexible regulations in the current law (TORRES; CUNHA; GUERRERO, 2020). Or in newly created UCs that suffers a pressure for occupation or for implementation of economic activities (agriculture, logging and mining) that are not consistent with the preservation class or legal activity within the buffer zone (DUARTE; SILVA; CERQUEIRA; et al., 2019).

This pressure is also perceived in the classes that are still in process to have a recognized destination, in the case of “Not Designated” category, which grouped “Public properties”, “Public Forest”, “Undesignated land” and areas without a legal information. This category shows a high stability along the years (average $12.2\% \pm 1.1p.p$ of all fire registered), however it presented two big events in the last 5 years, one in 2019 (15%) and other in 2016 (14%). This was also sensed in the work by Alencar et al. (2020), using thermal anomalies, in which they found that 30% of all fire in 2019 occurred in the “not designated forest” and “without information” classes, assigning those values to the increase in illegal occupation of these territories without official records.

Translating all these damages over the years into monetary values, we saw that Environmental damage has the greatest influence in this quantification. This component shows large fluctuations over these 20 years, in which the first quarter of the series (2001 to 2005) is strongly related to emissions from the “Pasture” and “Forest” classes, which

are the greatest potentials for emissions. However, this pattern is changed at the end of the first decade for a bigger contribution of emissions by the “Agriculture” class.

This relation follows the pattern of deforestation in the region that was strongly linked to the fire at the beginning of the 21st century, and after the deforestation started to decrease (ARAGÃO et al., 2018; LIBONATI et al., 2021). This relation induces high values in normal climate years, like the ones registered in 2004, which present monetary values similar to drought years (2002, 2005 and 2007) in the same decade.

The second decade is characterised by smaller values at the beginning with a gradual increase, reaching in 2020 the same levels of 2002-2004. In this second half, the value added by the Material component is highlighted in relation to the first half, while the Environmental component follows the pattern of lower emissions due to the change in the LULC. However, both components (Environmental and Material damages) are influenced by the combination of inflation and the dollar price, associated with this combination, the profit on soybean production in 2020 was three times higher than in previous years, and with that, there was a significant increase in this year in relation to the others, impacting not only this class but also the total damage.

The average annual damage in the BLA is around R\$ 27.1 billion per year (~US\$ 5.22 billion)¹⁵. If an average of 123,259 km² burns per year, it implies that each km² burned refers to a damage of R\$ 219,778. The annual damage is two times greater than those estimated by De Mendonça et al. (2004), which indicate a damage of R\$ 11.5 billion per year (maximum of R\$ 22.79 billion and minimum of R\$ 0.41 billion)¹⁶. The authors also predicted values above R\$ 40 billion in years of severe droughts. Similar to the values presented in this chapter, the total damage was mainly influenced by the CO₂ estimate.

These damages compared to the Brazilian Gross Domestic Product are on average 0.46%±0.08p.p, and for the BLA region it is approximately 6.28%±1.1p.p. This value is greater to that found by De Mendonça et al. (2004) which is around 0.2% and 0.9% in relation to the region. However, it is noteworthy that in this study we focused on three

¹⁵ Considering the exchange rate of US\$1 as R\$5.16, exchange value in earlier 2021 (IPEA, 2021).

¹⁶ The authors estimate the annual costs, in 1998, of approximately US\$ 90 to US\$ 5,055 million, reaching US\$ 9 billion in El Niño years. To bring it to the same period that are in this chapter (January of 2021), we convert the values to reais using the 1998 exchange rate by (IPEA, 2021) and then uses the IPCA index by (IBGE, 2021g), making the values comparable with those founded in this chapter.

out of the various components that fire can interfere and also on a single scale of impact, the regional one. Thus, the values presented here, regarding the multidimensionality of the damage, omit some components (eg, loss of biodiversity, impacts on land and air transport, and tourism).

Although fires have a significant impact on the economy of a region, the available budget by the federal government for fire control and management in the BLA is around US\$ 3.1 million per year, about 1% of the entire budget allocated for the Ministry of the Environment (MORELLO et al., 2020), a value that is 1,683 times lower than the average annual damage. This available value represents, by the indices and values found here, the equivalent of the annual damage of an area of approximately 70 km² (7,000 hectares), same amount that on average impacts 4 municipalities in a year. Considering that the BLA has 772 municipalities and along these 20 years, around 674 (87%) municipalities were impacted by fire every year (Figure B-3), the budget allocated to control and manage all territory is very low.

The budget allocation is primarily for firefighting and suppression actions in detriment to prevention and control actions, such as the creation and maintenance of monitoring systems; brigade training; community support, and environmental education (MORELLO et al., 2017b). Adopting only suppression measures is trying to mitigate damage that has already been caused and they do not allow society to change its habit, either by introducing production practices with less impact (including for example, low-carbon agriculture (MAPA, 2012), no-till system, agroforestry systems) or by having environmental education for sustainability. Within this context, it is essential to develop a management system that encompasses a broader structure through the integration of actors, researchers, monitoring entities at a federal and a state level, with agencies of education, communication, training, prevention and response at lower levels (State and Municipal) in order to deal with this phenomenon that is directly linked to human activities (ANDERSON et al., 2019).

5.4.3 Side effect of fire in national and international environmental targets

After years of degradation and exploration of the BLA's environmental matrix, the effects of the use of fire are already felt in milestones and guidelines for environmental protection and conservation, in internal policies or in established international agreements.

In a national context, analysis of forest cover through the years indicates that the percentage of forest cover (Old growth and Secondary Forest) for the BLA region (Figure B-1) is below that one established by law, regarding protection of forest resources. This value is lower than the 80% established for Legal Reserve, according to the New Brazilian Forest Code (BRASIL, 1998, cap. IV, 2012). Considering a region that has 7% of its territory made up of strict protection Conservation Units (Table B-1), and that, in addition to legal reserve areas and the presence of permanent preservation areas is mandatory, the value allocated for the protection of forests is way less than what is required by law.

However, the percentage to be destined varies according to the predominant phytophysiology of the place. Thus, properties within the Amazon biome must make 80% of their territory available for this purpose, while in properties within Savannah formations this value is 35%, and in other phytophysionomies this value drops to 20% (BRASIL, 2012). Performing these separations based on the delimitation of Brazilian biomes according to IBGE (Figure B-1), it was found that the value of forest cover within the Amazon biome from 2018 onwards is below that one required by law, and in 2020 it represented 1.2% less than the required only for the Legal Reserve item, a liability of 6,217 km². These values can be much higher, since after the consolidation of the New Brazilian Forest Code many properties were granted amnesty, removing the responsibility for restoration or compensation (SOARES-FILHO et al., 2014).

Another guideline found is the negligence or low effectiveness of policies to regulate the use of fire in emerging states, such as the one found for the state of Tocantins, which presented an increase of 10p.p in its contribution to the total burned in the AMZL region. This increase in the contribution may, at first, be related to the decrease in the contribution of other key states. However, throughout the series, the absolute values for this state showed an upward trend (Table B-2), especially when considering the seasonality of the data.

Within the category of reduction of greenhouse gas (GHG) emissions, the carbon dioxide estimates made by the National Emission Registry System - SIRENE (MCTIC, 2019)¹⁷

¹⁷ Among the possible methods to quantify emission from burned areas are: the burning of agricultural residues for the agriculture sector, which is based on the area planted with sugarcane; and the burning associated with deforestation, within the Land Use Change sector, in which it is accounted from the remaining dry matter in the field after a vegetal extraction.

do not consider those from forest fires, neglecting the entire effect that fire has contributed to the pollutant load. Our estimates point to an emission load up to $2,377 \pm 361$ TgCO₂ in extreme years, which can be gradually release in 30 years (SILVA et al., 2020). In an immediate way, it is quantified that in extreme years, around $1,822 \pm 348$ TgCO₂ is emitted, its represents 6 times greater than the total computed for the category of “Land Use Change” for the whole year of 2010 by SIRENE. The non-incorporation of these immediate issues and over 30 years, leads to underestimating and sometimes generating unrealistic rates, which at first can create a feeling of a completed goal, but there is much to be done ahead.

If these estimates were included in the national accounts, only the immediate emission from fires in forest formations in the BLA region would contribute, on average, to an 50% increase in values, reaching 152% in years of extreme drought (for example, in 2010), reflecting on average 31% in the contribution with a maximum of 60% (Figure B-4).

One of the first targets for regulating the reduction of greenhouse gas emissions, as a result of an international commitment, was the institutionalization of the National Policy on Climate Change (PNMC), governed by Law N°. 12,187 of 2009 and regulated by Decree N°. 9,578 /2018. It predicts a reduction between 1,168 TgCO₂eq and 1,259 TgCO₂eq of emissions by 2020. However, considering the immediate emissions from forest formations only for the BLA region, this target was not achieved, thus when considering fires in other Brazilian regions, this scenario is even worst

After this initiative, and still following the guidelines taken during the United Nations Framework Conventions on Climate Change (UNFCCC), Brazil implemented the Determined National Contribution (NDC) in 2016, and in 2020 an update was made (BRASIL, 2020; UNFCCC, 2021), which undertakes, among other measures, a 37% reduction in greenhouse gas by 2025 and 43% by 2030, based on the estimate in 2005. Considering the estimates presented in this chapter and the extrapolation of official data for 2020¹⁸, the reduction rates are in 14%. This shows the need to adopt stricter measures

¹⁸ The national estimate provided by the SIRENE (MCTIC, 2019) is only until 2016. For the remaining years, we use the trend in each category to extrapolate, with exception for the land use change category that we use the correlation of it with deforestation rates provided by Terrabrasilis (INPE, 2021b).

to restrain the increase in the emissions levels by the main contributors to GHG, which currently are the LULC changes and forest fires that are not totally accounted for.

It should be noted that these estimates are including only the immediate emission by completely combustion of forest and only for the BLA region. It is not taking into account the gradual degradation of the burned matter, which is released over a 30-year period (SILVA et al., 2020), nor other regions, like the entire Savannah, which is the second biome with the highest records of fire in Brazil (INPE, 2020), or the contribution of anomalous events from other regions that face irregular fire events, such the ones occurred in the Wetland biome in 2020 (PLETSCH et al., 2021) that presented an expressive impact, demonstrating that the guidelines and national measurements must be revised over the years, in order to properly include those effects.

5.5 Conclusion

This chapter quantified the damage caused by fire over 20 years in the Brazilian Legal Amazon, highlighting its main components, temporal trend, and geographic distribution. Geoprocessing methods, statistical and economic analysis were combined in an innovative way, generating a satisfactorily broad understanding of the multidimensionality of the impact caused by fire. Worryingly, the results revealed a sizeable damage that is not following a decreasing trend, which is a call for a more effective policy.

The region has burned areas throughout the year, with a monthly average of 10.271 km², mostly consisting of small patches up to 40 ha. The fire season is concentrated between the months of August and October, when there is an increase in large (404 to 4,046 ha) and very large ($\geq 4,046$ ha) patches, the same period in which most of the affected areas have already suffered from some burnings in previous months/years. In total, approximately 840,163 km² of the area have already been burned, this is the equivalent of 17% of the total area of the BLA. The recurrence of fire in the region is high, with emphasis on agricultural expansion zones (MT, MA and TO) where burning was recorded every year.

Burned areas presented an increasing trend in the minimum area per month; in the occurrence of anomalous months; and in the burned area of the first months of the year.

Compared to previous years, the years from 2015 to 2020 already showed evidence of changes in the fire pattern at the beginning of the year (January and February), especially regarding to the increase in the burned area, the increase in the number of events during the month, and in the number of municipalities that are affected.

The impact of this phenomenon over the years is represented by the equivalent damage of an average of $6.28\% \pm 1.1\text{p.p.}$ per year of the BLA's GDP, $0.46\% \pm 0.08\text{p.p.}$ per year of the Brazilian GDP. The first 10 years of the series showed the highest damages, however, there is an increase in the damage again in relation to the last 3 years of the series. The Environmental component (CO_2 emissions) is the largest fraction of the total damage and its estimate can destabilize national and international short and long-term reduction targets.

The monetary quantification presented in this chapter is limited firstly by the burned area product and its specificities; later by the quantity, type and scale of components affected by fire chosen, and finally by the microeconomic approach used in the monetary quantification which is based on established or surrogate markets. Therefore, supporting more studies over the other components affected by fire, including different scales, can provide more information about the real impact of fire in a region. Besides this, adopting other and more accurate burned area products or including information of fire power levels will refine the impact caused by the fire and expand the perception of its magnitude. Then, with a common methodology, it will be possible to incorporate monetary quantification in a monitoring system, enabling new perspectives of risk assessment and impact of fire.

6 GENERAL DISCUSSION

Chapter 3 presented the quantification of the damage caused by fires in the state of Acre, west of the Legal Amazon, between 2008 and 2012. From five impacts, subdivided into three groups, it was possible to determine the total damage caused during this period, with emphasis on years with extreme droughts (2010).

In this case study, the increase in fire events in a year of extreme drought was evident, mainly due to the determination of burned areas farther away from the main sources of fire propagation in the region (roads and rivers). These effects were reflected in the total damage that occurred during these climatically anomalous years, reaching up to 16 times greater compared to normal ones.

Within this chapter, the introduction of a more robust methodology for quantifying CO₂ is highlighted, through the insertion of a remaining carbon stock after a burning event, being considered for the subsequent burning months, describing in a better perspective the effect that recurrent burns have on total emissions.

One of the limitations found in this chapter was a non-identification of a clear relationship between the number of respiratory cases and the total burned area. However, estimates made with the OLS method do not separate the specific effects of fire. In addition, the performed analysis did not consider the existing chain of events to link burned area and respiratory hospitalization, among other aspects such as variables that can control demand and supply of this cause-effect chain.

Due to this lack of relationship using the initial data series of Chapter 3, which accounted for only 5 years, Chapter 4 was built with more improved techniques to estimate hospitalizations attributable to pollution of burned areas within a larger data series.

Thus, Chapter 4 is based on the premise that once fires of considerable size and number occur in one location, the load of pollutants released and transported to populated areas will cause considerable onset of respiratory diseases (CARMO et al., 2010; IGNOTTI et al., 2010; GONÇALVES et al., 2018). This effect is different between vulnerable groups, either because of the difference in age or by type of correlated disease.

Therefore, this relationship was estimated through the application of the instrumental variable method under a balanced panel at a municipal and monthly level of data. Therefore, a positive effect was found between fire-pollutants and the number of hospitalizations due to respiratory diseases, with the main emphasis on the 65-year-old age group and the group of diseases related to Asthma and Bronchitis. This positive effect was previously found by other studies with similar methodological strategies (CARMO et al., 2010; JACOBSON et al., 2014; DERYUGINA et al., 2019; ROCHA; SANT'ANNA, 2020).

This new methodology indicated that during the burning season (Aug-Oct) approximately 4,000 people are hospitalized for some respiratory-related disease in the BLA region. However, new estimates must be carried out in order to incorporate other related events, such as the effect of other pollutant sources; the weight that neighboring municipalities can exert both on the load of pollutants and also on the hospitalizations counts, and the effect of the lag between fire and hospitalization values.

In the Chapter 5 it was applied the initial methodology provided for Chapter 3 with the updated hospitalizations rate found in Chapter 4 for the entire Legal Amazon region, but using a 20-year time scale (from 2001 to 2020), also including the description of the fire occurrence pattern throughout the months and its evolution during the data series.

At first, there was no significant tendency in the increasing in burned areas in the time series, as shown by Andela et al. (2017) and Earl & Simmonds (2018) in which this characteristic is mainly explained by the existing fluctuation between deforestation and fire. However, there was an increase in the minimum monthly burned area, and in the frequency of anomalies in burned months, especially during the last years.

Agricultural activities were highlighted both in the local context (Chapter 3), where the "Pasture" class was the most affected by fire, and in the regional context (Chapter 5) where the "Agriculture" class presented the largest increase (17 percentage points) throughout the series. It indicates that the BLA still has fire as a recurrent agricultural practice.

This dynamic is also notable from the perspective of territorial responsibility, in which most of the burned areas were found in private areas (60.3% in BLA and 98.4% in AC).

Considering the public management areas, Indigenous Lands have a relevant role in the amount of burned area, and this is due more to the fact that indigenous territories suffer from the increase in illegal activities, such as “land grabbing” (FELLOWS et al., 2021), than the use of fire as an agricultural practice or religious ritual (LEONEL, 2000; PIVELLO, 2011; GRAF, 2016).

The damages occurred during these 20 years when compared to the Brazilian Gross Domestic Product (GDP) it is equivalent to an average of $0.46\% \pm 0.08\text{p.p}$ while for the BLA region these values are close to $6.28\% \pm 1.1\text{p.p}$. Within the state scale (Chapter 3), damages in normal climate years are equivalent to approximately $0.51\% \pm 0.10\text{p.p}$ of Acre's GDP, and in anomalous years it can represent $7.03\% \pm 2.4\text{p.p}$. However, the real magnitude of these values are higher, since this thesis only counted few components impacted, not considering others impacts such, biodiversity reduction; habitat changes; species migration; decrease in tourism; losses of cultural assets; change in the hydrological cycle; change in the soil properties; psychological traumas; car accidents; or infrastructure losses.

Finally, the recurring erosion of BLA's environmental matrix over the time begins to be felt, among other aspects, in milestones and guidelines for the protection and conservation of the environment, whether in non-compliance with the Forest Code (BRASIL, 2012) or in an incompatibility with the goal of reducing greenhouse gas emissions ratified by law, first by the National Policy on Climate Change – PNMC (BRASIL, 2009), which foresees reductions until 2020, and later with the low reductions conquered until now, but still far from those established in the Paris Agreement, through the Nationally Determined Contribution - NDC (BRASIL, 2020; UNFCCC, 2021).

7 CONCLUDING REMARKS

This thesis provided support to understand the extent, the magnitude and the damage caused by the use of fire in the Brazilian Legal Amazon during the last 20 years, which can subsidize the planning of public investments, policies and mitigating measures to decrease the region vulnerability to fires.

The region is affected by fire throughout the year, with a monthly average of 10,271 km², with the fire peak between the months of August and October, presenting small differences between the fire regimes in the Northern states than in the Southern ones, where the initial months are gaining greater proportions.

The change in the way of quantifying the rate of hospitalizations due to respiratory illnesses, obtained in Chapter 3 and Chapter 4, improved the estimates in addition to contributing to the understanding of the relationship between fire-induced smoke in hospitalization due to respiratory illness in the BLA region. These estimates indicated a positive effect of pollutants on hospitalization levels for the region, and it can be estimated that around 4,000 people are hospitalized annually during the fire season.

Fire has a complex and interconnected chain of direct and indirect effects that can make the study of its impact challenging. A few items, such as those used in this thesis (losses in agroforestry production, carbon dioxide emissions and hospitalizations for respiratory diseases) can cause great harm, which for the whole BLA was found, on average, the equivalent to $6.28\% \pm 1.1\text{p.p.}$ of GDP reaching a maximum of $18.89\% \pm 3.6\text{p.p.}$ In some cases, these damages are much greater, with a maximum recorded of 7.03% of GDP as observed in Acre, during anomalous dry years.

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APPENDIX A - SUPPLEMENTARY MATERIAL FROM CHAPTER 4

Table A-1. Mean effect of the variation in the Aerosol Optical Depth (AOD) on the Total respiratory disease hospitalization counts due to the burned area.

	IVc01			IVc02			IVc03			IVc04		
OLS												
AOD (OLS)	0.0443*** (0.0072)	0.0925*** (0.0072)	0.0455*** (0.0067)	0.0443*** (0.0072)	0.0925*** (0.0072)	0.0455*** (0.0067)	0.0443*** (0.0072)	0.0925*** (0.0072)	0.0455*** (0.0067)	0.0443*** (0.0072)	0.0925*** (0.0072)	0.0455*** (0.0067)
# obs.	118,335	118,335	118,335	118,335	118,335	118,335	118,335	118,335	118,335	118,335	118,335	118,335
IV												
AOD (2SLS)	0.1383*** (0.0294)	0.0771* (0.0321)	0.1359*** (0.0243)	0.1336*** (0.0315)	-0.9626*** (0.105)	0.1361*** (0.0262)	0.1401** (0.0466)	0.0942** (0.0322)	0.1389*** (0.0383)	0.0461 (0.1037)	-12.9107*** (2.5574)	2.2891 (3.1566)
# obs.	118,335	118,335	118,335	118,335	118,335	118,335	118,335	118,335	118,335	118,335	118,335	118,335
Fixed effect	Y	N	Y	Y	N	Y	Y	N	Y	Y	N	Y
Controls	Y	Y	N	Y	Y	N	Y	Y	N	Y	Y	N
Exogeneity and IV validity tests												
Exog	13.82***	0.24 ^{ns}	21.50***	11.59***	120.06***	20.07***	4.33*	0.0027 ^{ns}	5.58*	0.0006 ^{ns}	742.87***	7.18**
Overid	1.204 ^{ns}	779.886***	4.41 ^{ns}	0.774 ^{ns}	549.951***	4.409*	1.176 ^{ns}	741.718***	4.396*	-	-	-
Weak Instrument tests												
Joint	1103.36	945.817	2617.91	1396.41	250.833	1396.41	576.324	576	991.908	252.589	20.5295	252.589
Yogo: stat	1445.95	2087.78	2764.63	1703.26	330.615	1703.26	1045.85	1045.85	1729.91	282.652	26.7979	282.652
Yogo: crit	22.3	22.3	22.3	19.93	19.93	19.93	19.93	19.93	19.93	16.38	16.38	16.38

Notes: Set of instruments: IVc01 is the Log_Ba plus the BaWSpeed and the BaWDirec; IVc02 is the Log_Ba plus the BaWSpeed; IVc03 is the Log_Ba plus the BaWDirec, and; IVc04 is only Log_Ba. "Exog.", computes a test of exogeneity for a fixed-effect regression estimated via instrumental variables; "Overid" is the Sargan-Hansen statistic for instrument overidentification test. "Joint", for the joint significance test of the instruments in the first stage regression; "Yogo: stat", is the value of the Stock and Yogo test for instrument weakness; "Yogo: crit", is the table value for the Stock and Yogo test. Significance level: "****" p<0.001, "***" p<0.01, "**" p<0.05, "."p<0.1, "ns" not significant.

Source: From Author.

Table A-2. Mean effect of the variation in the Aerosol Optical Depth (AOD) on the hospitalization of Small Children due to the burned area.

	IVc01			IVc02			IVc03			IVc04		
OLS												
AOD (OLS)	0.0177** (0.0068)	0.0700*** (0.0056)	0.0222** (0.0073)	0.0177** (0.0068)	0.0700*** (0.0056)	0.0222** (0.0073)	0.0177** (0.0068)	0.0700*** (0.0056)	0.0222** (0.0073)	0.0177** (0.0068)	0.0700*** (0.0056)	0.0222** (0.0073)
# obs.	118,335	118,335	118,335	118,335	118,335	118,335	118,335	118,335	118,335	118,335	118,335	118,335
IV												
AOD (2SLS)	0.0760** (0.0271)	-0.0403 ^{ns} (0.0258)	0.1129*** (0.0241)	0.0761** (0.0292)	-0.4136*** (0.0797)	0.1187*** (0.0258)	-0.0210 ^{ns} (0.0476)	-0.0422 ^{ns} (0.0259)	0.0865* (0.0422)	-0.3381*** (0.1047)	-11.5719*** (2.2816)	5.6374 ^{ns} (7.5374)
# obs.	118,335	118,335	118,335	118,335	118,335	118,335	118,335	118,335	118,335	118,335	118,335	118,335
Fixed effect	Y	N	Y	Y	N	Y	Y	N	Y	Y	N	Y
Controls	Y	Y	N	Y	Y	N	Y	Y	N	Y	Y	N
Exogeneity and IV validity tests												
Exog	7.23**	19.35***	29.26***	6.73**	39.26***	30.77***	0.91 ^{ns}	19.84***	3.59.	20.9530***	929.26***	60.23***
Overid	21.757***	906.273***	32.163***	21.753***	833.464***	31.481***	15.014***	912.353***	31.604***	-	-	-
Weak Instrument tests												
Joint	1103.36	945.817	2617.91	1396.41	250.833	1396.41	576.324	576.324	991.908	252.589	20.5295	252.589
Yogo: stat	1445.95	2087.78	2764.63	1703.26	330.615	1703.26	1045.85	1045.85	1729.91	282.652	26.7979	282.652
Yogo: crit	22.3	22.3	22.3	19.93	19.93	19.93	19.93	19.93	19.93	16.38	16.38	16.38

Notes: Set of instruments: IVc01 is the Log_Ba plus the BaWSpeed and the BaWDirec; IVc02 is the Log_Ba plus the BaWSpeed; IVc03 is the Log_Ba plus the BaWDirec, and; IVc04 is only Log_Ba. "Exog.", computes a test of exogeneity for a fixed-effect regression estimated via instrumental variables; "Overid" is the Sargan-Hansen statistic for instrument overidentification test. "Joint", for the joint significance test of the instruments in the first stage regression; "Yogo: stat", is the value of the Stock and Yogo test for instrument weakness; "Yogo: crit", is the table value for the Stock and Yogo test. Significance level: "****" p<0.001, "***" p<0.01, "**" p<0.05, "."p<0.1, "ns" not significant.

Source: From Author.

Table A-3. Mean effect of the variation in the Aerosol Optical Depth (AOD) on the hospitalization of children due to the burned area.

	IVc01			IVc02			IVc03			IVc04		
OLS												
AOD (OLS)	-0.0061 ^{ns}	0.0500***	-0.0047	-0.0061 ^{ns}	0.0500***	-0.0047	-0.0061 ^{ns}	0.0500***	-0.0047	-0.0061 ^{ns}	0.0500***	-0.0047 ^{ns}
	(0.0051)	(0.0039)	(0.0053)	(0.0051)	(0.0039)	(0.0053)	(0.0051)	(0.0039)	(0.0053)	(0.0051)	(0.0039)	(0.0053)
# obs.	118,335	118,335	118,335	118,335	118,335	118,335	118,335	118,335	118,335	118,335	118,335	118,335
IV												
AOD (2SLS)	0.0094 ^{ns}	-0.0464*	0.0223	0.0177 ^{ns}	-0.5826***	0.0312.	-0.0765*	-0.0347.	-0.0291 ^{ns}	-0.1815*	-4.3372***	2.7389 ^{ns}
	(0.0201)	(0.0182)	(0.0164)	(0.0212)	(0.0598)	(0.0173)	(0.0364)	(0.0182)	(0.0306)	(0.0761)	(0.8896)	(3.7735)
# obs.	118,335	118,335	118,335	118,335	118,335	118,335	118,335	118,335	118,335	118,335	118,335	118,335
Fixed effect	Y	N	Y	Y	N	Y	Y	N	Y	Y	N	Y
Controls	Y	Y	N	Y	Y	N	Y	Y	N	Y	Y	N
Exogeneity and IV validity tests												
Exog	0.84 ^{ns}	29.78***	3.98*	1.79 ^{ns}	135.56***	6.48*	4.58*	22.86***	0.74 ^{ns}	7.6436**	264.49***	21.68***
Overid	10.966**	308.79***	20.107***	8.499**	167.23***	15.235***	2.895.	254.004***	15.81***	-	-	-
Weak Instrument tests												
Joint	1103.36	945.817	2617.91	1396.41	250.833	1396.41	576.324	576.324	991.908	252.589	20.5295	252.589
Yogo: stat	1445.95	2087.78	2764.63	1703.26	330.615	1703.26	0.0174	1045.85	1729.91	282.652	26.7979	282.652
Yogo: crit	22.3	22.3	22.3	19.93	19.93	19.93	19.93	19.93	19.93	16.38	16.38	16.38

Notes: Set of instruments: IVc01 is the Log_Ba plus the BaWSpeed and the BaWDirec; IVc02 is the Log_Ba plus the BaWSpeed; IVc03 is the Log_Ba plus the BaWDirec, and; IVc04 is only Log_Ba. "Exog.", computes a test of exogeneity for a fixed-effect regression estimated via instrumental variables; "Overid" is the Sargan-Hansen statistic for instrument overidentification test. "Joint", for the joint significance test of the instruments in the first stage regression; "Yogo: stat", is the value of the Stock and Yogo test for instrument weakness; "Yogo: crit", is the table value for the Stock and Yogo test. Significance level: "****" p<0.001, "***" p<0.01, "**" p<0.05, "."p<0.1, "ns" not significant.

Source: From Author.

Table A-4. Mean effect of the variation in the Aerosol Optical Depth (AOD) on the hospitalization of the elderly due to the burned area.

	IVc01			IVc02			IVc03			IVc04		
OLS												
AOD(OLS)	0.0215*** (0.0051)	0.0218*** (0.0045)	0.0290*** (0.0052)	0.0215*** (0.0051)	0.0218*** (0.0045)	0.0290*** (0.0052)	0.0215*** (0.0051)	0.0218*** (0.0045)	0.0290*** (0.0052)	0.0215*** (0.0051)	0.0218*** (0.0045)	0.0290*** (0.0052)
# obs.	118,335	118,335	118,335	118,335	118,335	118,335	118,335	118,335	118,335	118,335	118,335	118,335
IV												
AOD(2SLS)	0.0428* (0.0206)	0.0344. (0.0204)	0.0590*** (0.0167)	0.0581** (0.0218)	0.3074*** (0.0624)	0.0722*** (0.0179)	-0.0596. (0.0352)	0.0187 (0.0205)	-0.0211 (0.0294)	-0.0720 (0.0719)	-6.2621*** (1.2516)	1.9639 (2.7017)
# obs.	118,335	118,335	118,335	118,335	118,335	118,335	118,335	118,335	118,335	118,335	118,335	118,335
Fixed effect	Y	N	Y	Y	N	Y	Y	N	Y	Y	N	Y
Controls	Y	Y	N	Y	Y	N	Y	Y	N	Y	Y	N
Exogeneity and IV validity tests:												
Exog	1.47 ^{ns}	0.40***	4.77*	3.94*	21.74***	9.11**	6.02*	0.02	3.15.	2.1189 ^{ns}	428.08***	10.58**
Overid	12.241**	508.117***	17.086***	3.733.	470.484***	7276**	0.041 ^{ns}	428.019***	7.856**	-	-	-
Week Instrument tests:												
Joint	1103.36	945.817	2617	1396.41	250.833	1396.41	576.324	576.324	991.908	252.589	20.5295	252.589
Yogo: stat	1445.95	2087	2764	1703.26	330.615	1703.26	1045.85	1045.85	1729.91	282.652	26.7979	282.652
Yogo: crit	22.3	22.3	22.3	19.93	19.93	19.93	19.93	19.93	19.93	16.38	16.38	16.38

Notes: Set of instruments: IVc01 is the Log_Ba plus the BaWSpeed and the BaWDirec; IVc02 is the Log_Ba plus the BaWSpeed; IVc03 is the Log_Ba plus the BaWDirec, and; IVc04 is only Log_Ba. "Exog.", computes a test of exogeneity for a fixed-effect regression estimated via instrumental variables; "Overid" is the Sargan-Hansen statistic for instrument overidentification test. "Joint", for the joint significance test of the instruments in the first stage regression; "Yogo: stat", is the value of the Stock and Yogo test for instrument weakness; "Yogo: crit", is the table value for the Stock and Yogo test. Significance level: "****" p<0.001, "***" p<0.01, "**" p<0.05, "."p<0.1, "ns" not significant.

Source: From Author.

Table A-5. Mean effect of the variation in the Aerosol Optical Depth (AOD) on the Asthma hospitalizations due to the burned area.

	IVc01			IVc02			IVc03			IVc04		
OLS												
AOD(OLS)	0.0265*** (0.006)	0.0532*** (0.0047)	0.0295*** (0.0059)	0.0265*** (0.006)	0.0532*** (0.0047)	0.0295*** (0.0059)	0.0265*** (0.006)	0.0532*** (0.0047)	0.0295*** (0.0059)	0.0265*** (0.006)	0.0532*** (0.0047)	0.0295*** (0.0059)
# obs.	118,335	118,335	118,335	118,335	118,335	118,335	118,335	118,335	118,335	118,335	118,335	118,335
IV												
AOD(2SLS)	0.0792*** (0.0244)	-0.0356 (0.0217)	0.0844*** (0.0204)	0.0865*** (0.0254)	-0.9181*** (0.0754)	0.0921*** (0.0214)	0.0147 (0.0433)	-0.0111 (0.0218)	0.0394 (0.0352)	-0.0423 (0.0843)	-2.4134*** (0.5755)	2.3085 (3.2576)
# obs.	118,335	118,335	118,335	118,335	118,335	118,335	118,335	118,335	118,335	118,335	118,335	118,335
Fixed effect	Y	N	Y	Y	N	Y	Y	N	Y	Y	N	Y
Controls	Y	Y	N	Y	Y	N	Y	Y	N	Y	Y	N
Exogeneity and IV validity tests												
Exog	6.63**	17.72***	11.53***	7.96**	224.02***	13.95***	0.09 ^{ns}	9.21**	0.09 ^{ns}	0.8569 ^{ns}	58.47***	10.87***
Overid	3.5598 ^{ns}	228.13***	8.627*	2.52 ^{ns}	16.728***	7.011**	0.727 ^{ns}	55.595***	7.406**	-	-	-
Week Instrument tests:												
Joint	1103.36	945.817	2617	1396.41	250.833	1396.41	576.324	576.324	991.908	252.589	20.5295	252.589
Yogo: stat	1445.95	2087.78	2764	1703.26	330.615	1703.26	1045.85	1045.85	1729.91	282.652	26.7979	282.652
Yogo: crit	22.3	22.3	22.3	19.93	19.93	19.93	19.93	19.93	19.93	16.38	16.38	16.38

Notes: Set of instruments: IVc01 is the Log_Ba plus the BaWSpeed and the BaWDirec; IVc02 is the Log_Ba plus the BaWSpeed; IVc03 is the Log_Ba plus the BaWDirec, and; IVc04 is only Log_Ba. "Exog.", computes a test of exogeneity for a fixed-effect regression estimated via instrumental variables; "Overid" is the Sargan-Hansen statistic for instrument overidentification test. "Joint", for the joint significance test of the instruments in the first stage regression; "Yogo: stat", is the value of the Stock and Yogo test for instrument weakness; "Yogo: crit", is the table value for the Stock and Yogo test. Significance level: "****" p<0.001, "***" p<0.01, "**" p<0.05, "."p<0.1, "ns" not significant.

Source: From Author.

Table A-6. Mean effect of the variation in the Aerosol Optical Depth (AOD) on the Pneumonia hospitalizations due to the burned area.

	IVc01			IVc02			IVc03			IVc04		
OLS												
AOD (OLS)	0.0594*** (0.0069)	0.0244*** (0.0064)	0.0663*** (0.0069)	0.0594*** (0.0069)	0.0244*** (0.0064)	0.0663*** (0.0069)	0.0594*** (0.0069)	0.0244*** (0.0064)	0.0663*** (0.0069)	0.0594*** (0.0069)	0.0244*** (0.0064)	0.0663*** (0.0069)
# obs.	118,335	118,335	118,335	118,335	118,335	118,335	118,335	118,335	118,335	118,335	118,335	118,335
IV												
AOD (2SLS)	0.1207*** (0.0281)	-0.1005*** (0.0287)	0.1544*** (0.0242)	0.1285*** (0.0303)	-0.4372*** (0.088)	0.1655*** (0.0262)	0.0122 ^{ns} (0.0477)	-0.1046*** (0.0288)	0.0928* (0.0396)	-0.1790 ^{ns} (0.1098)	-12.6441*** (2.4844)	5.2789 ^{ns} (6.9921)
# obs.	118,335	118,335	118,335	118,335	118,335	118,335	118,335	118,335	118,335	118,335	118,335	118,335
Fixed effect	Y	N	Y	Y	N	Y	Y	N	Y	Y	N	Y
Controls	Y	Y	N	Y	Y	N	Y	Y	N	Y	Y	N
Exogeneity and IV validity tests												
Exog	6.36*	20.07***	22.24***	7.51**	28.92***	26.26***	1.13 ^{ns}	21.25***	0.49 ^{ns}	7.6513**	889.09***	42.23***
Overid	11.308**	868***	27.217***	9.99**	818.263***	23.546***	4.768*	865.478***	23.765***	-	-	-
Week Instrument tests:												
Joint	110336	945.817	2617	1396	250.833	1396.41	576.324	576.324	991.908	252.589	20.5295	252.589
Yogo: stat	1445.95	2087	2764	1703	330.615	1703.26	1045	1045.85	1729.91	282.652	26.7979	282.652
Yogo: crit	22.3	22.3	22.3	19.93	19.93	19.93	19.93	19.93	19.93	16.38	16.38	16.38

Notes: Set of instruments: IVc01 is the Log_Ba plus the BaWSpeed and the BaWDirec; IVc02 is the Log_Ba plus the BaWSpeed; IVc03 is the Log_Ba plus the BaWDirec, and; IVc04 is only Log_Ba. "Exog.", computes a test of exogeneity for a fixed-effect regression estimated via instrumental variables; "Overid" is the Sargan-Hansen statistic for instrument overidentification test. "Joint", for the joint significance test of the instruments in the first stage regression; "Yogo: stat", is the value of the Stock and Yogo test for instrument weakness; "Yogo: crit", is the table value for the Stock and Yogo test. Significance level: "****" p<0.001, "***" p<0.01, "**" p<0.05, "."p<0.1, "ns" not significant.

Source: From Author.

Table A-7. Mean effect of the variation in the Aerosol Optical Depth (AOD) on the Bronchitis hospitalizations due to the burned area.

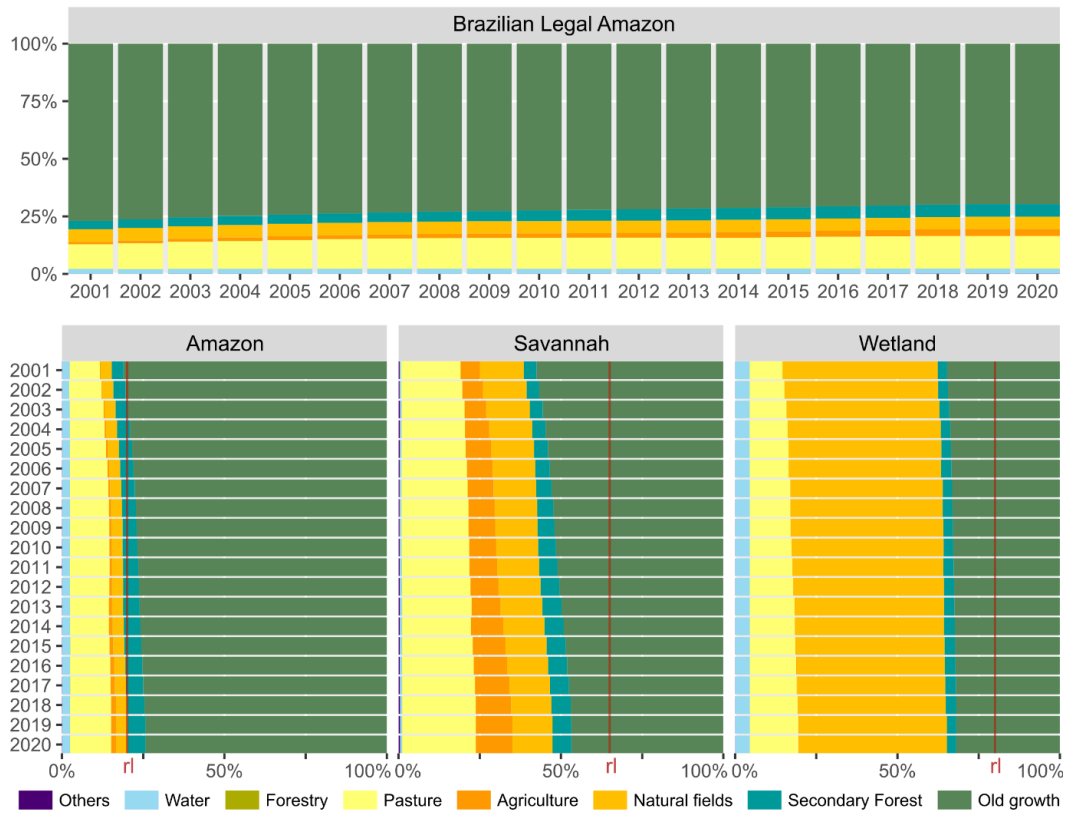
	IVc01			IVc02			IVc03			IVc04		
OLS												
AOD (OLS)	0.0103** (0.0032)	0.0075*** (0.002)	0.0121*** (0.0037)	0.0103** (0.0032)	0.0075*** (0.002)	0.0121*** (0.0037)	0.0103** (0.0032)	0.0075*** (0.002)	0.0121*** (0.0037)	0.0103** (0.0032)	0.0075*** (0.002)	0.0121*** (0.0037)
# obs.	118,335	118,335	118,335	118,335	118,335	118,335	118,335	118,335	118,335	118,335	118,335	118,335
IV												
AOD (2SLS)	0.0011 ^{ns} (0.0139)	0.0111 ^{ns} (0.0099)	0.0072 ^{ns} (0.0127)	-0.0023 ^{ns} (0.0151)	-0.0958*** (0.0299)	0.0046 (0.0138)	0.0169 ^{ns} (0.0215)	0.0149 ^{ns} (0.0099)	0.0240 ^{ns} (0.0191)	-0.0020 ^{ns} (0.0412)	0.4608** (0.1709)	0.1545 ^{ns} (0.4591)
# obs.	118,335	118,335	118,335	118,335	118,335	118,335	118,335	118,335	118,335	118,335	118,335	118,335
Fixed effect	Y	N	Y	Y	N	Y	Y	N	Y	Y	N	Y
Controls	Y	Y	N	Y	Y	N	Y	Y	N	Y	Y	N
Exogeneity and IV validity tests												
Exog	0.60 ^{ns}	0.14 ^{ns}	0.28 ^{ns}	1.06 ^{ns}	12.24***	0.62 ^{ns}	0.11 ^{ns}	0.59 ^{ns}	0.46 ^{ns}	0.0867 ^{ns}	9.54**	0.14 ^{ns}
Overid	0.854 ^{ns}	29.635***	1.042 ^{ns}	0 ^{ns}	14.716***	0.127 ^{ns}	0.276 ^{ns}	9.267**	0.095 ^{ns}	-	-	-
Week Instrument tests:												
Joint	1103.36	945.817	2617.91	1396.41	250.833	1396.41	576.324	576	991.908	252.589	20.5295	252.589
Yogo: stat	1445.95	2087.78	2764.63	1703.26	330615	1703.26	1045	1045	1729.91	282.652	26.7979	282.652
Yogo: crit	22.3	22.3	22.3	19.93	19.93	19.93	19.93	19.93	19.93	16.38	16.38	16.38

Notes: Set of instruments: IVc01 is the Log_Ba plus the BaWSpeed and the BaWDirec; IVc02 is the Log_Ba plus the BaWSpeed; IVc03 is the Log_Ba plus the BaWDirec, and; IVc04 is only Log_Ba. "Exog.", computes a test of exogeneity for a fixed-effect regression estimated via instrumental variables; "Overid" is the Sargan-Hansen statistic for instrument overidentification test. "Joint", for the joint significance test of the instruments in the first stage regression; "Yogo: stat", is the value of the Stock and Yogo test for instrument weakness; "Yogo: crit", is the table value for the Stock and Yogo test. Significance level: "****" p<0.001, "***" p<0.01, "**" p<0.05, "." p<0.1, "ns" not significant.

Source: From Author.

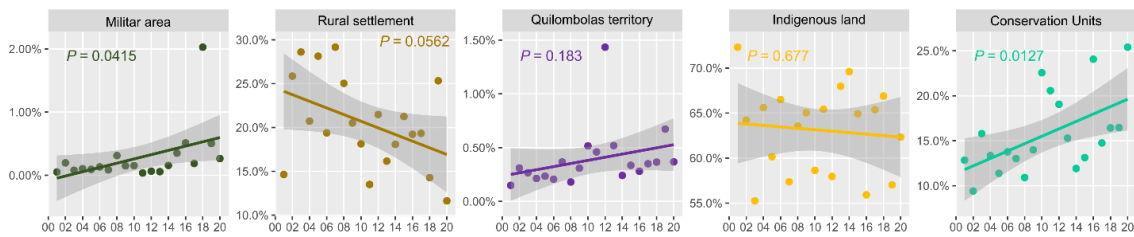
APPENDIX B - SUPPLEMENTARY MATERIAL FOR CHAPTER 5

Figure B-1. Evolution of LULC for the BLA region and its biomes.



Notes: rl represents the minimum percentage of forest cover for each phytophysognomy within the BLA region, following the instruction of legal reserve established in the New Forest Code (BRASIL, 2012).
 Source: From Author.

Figure B-2. Trends in burned area for each public land tenure.



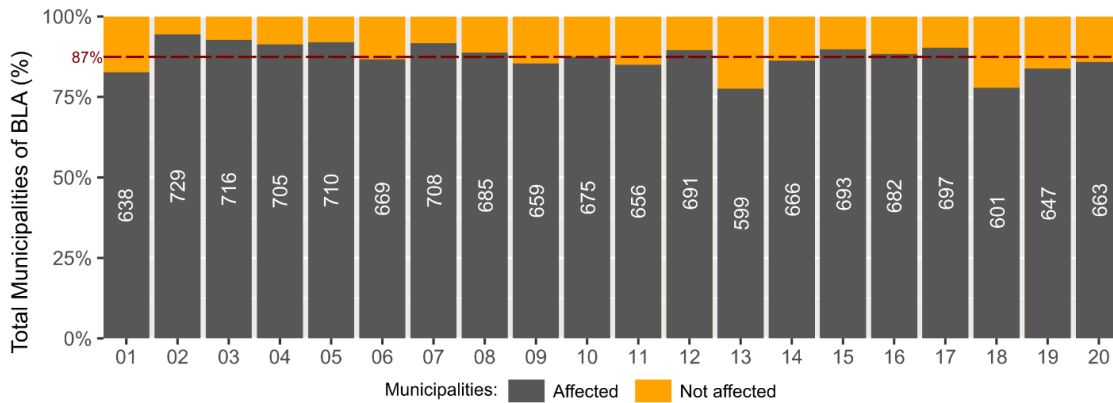
Source: From Author.

Table B-1. Percentage of each land tenure type and category over the BLA territory.

Category	Type	Area (%)	
		by Type	by Category
Not Designated	Without information	8.85%	19.69%
	Undesignated land from Terra Legal Program	3.89%	
	Undesignated public forests	6.02%	
	Public properties at INCRA system	0.94%	
Private	CAR premium	3.48%	30.69%
	CAR poor	7.79%	
	Private properties at INCRA system	17.47%	
	Private properties from Terra Legal Program	1.95%	
Public	Rural settlements	6.61%	47.03%
	Communitarian lands	0.35%	
	Military areas	0.56%	
	Quilombola lands	0.47%	
	Homologated indigenous land	21.44%	
	Non-homologated indigenous land	0.41%	
	Full protection conservation unit	7.18%	
	Sustainable use conservation unit	10.01%	
Urban, Water	Water bodies	2.17%	2.58%
	Transportation network	0.33%	
	Urban areas	0.08%	

Source: From Author.

Figure B-3. Total of municipalities affected by fire per year in the BLA region.



Note: Red line represents the average of municipalities affected by fire along the 20 years.

Source: From Author.

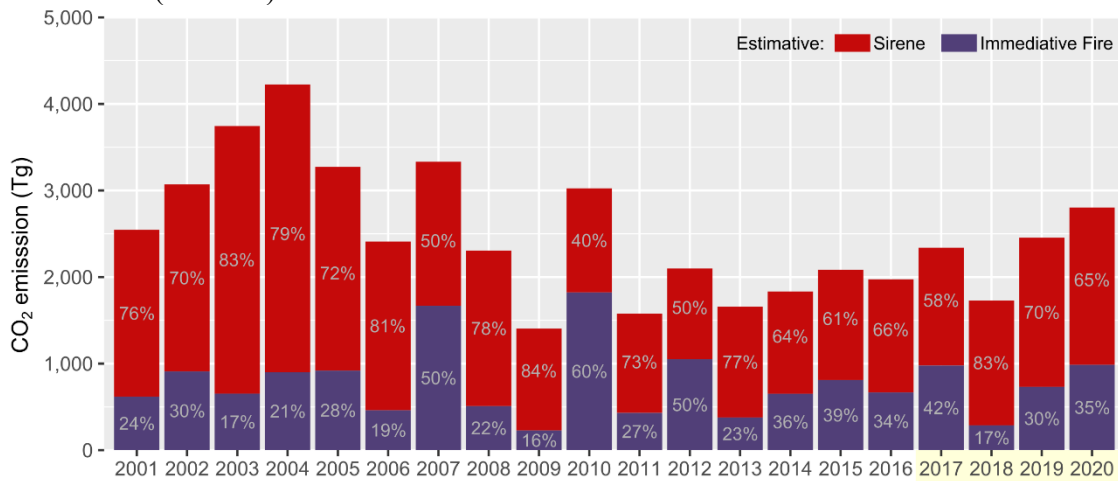
Table B-2. Trends in each state, considering the total burned area by different methods

UF	Linear			Mann-kendal			Seasonal Mann-kendall		
	COEF	pval		Tau	pval		Tau	pval	
RO	-0.243	0.207	ns	0.113	0.009	***	0.119	0.011	**
AC	-1.616	0.085	*	0.025	0.593	ns	-0.043	0.436	ns
AM	0.593	0.088	*	0.023	0.599	ns	0.042	0.381	ns
RR	0.469	0.169	ns	0.038	0.390	ns	0.053	0.264	ns
PA	-0.029	0.532	ns	0.057	0.187	ns	0.104	0.028	**
AP	-0.562	0.537	ns	-0.002	0.964	ns	-0.048	0.336	ns
TO	0.008	0.762	ns	0.110	0.011	**	0.210	0.000	***
MA	0.032	0.610	ns	0.052	0.236	ns	0.049	0.300	ns
MT	-0.007	0.710	ns	0.068	0.118	ns	0.020	0.667	ns

Note: significance levels: “***” p<0.01, “**” p<0.05, “*” p<0.1 e “ns” not significant.

Source: From Author.

Figure B-4. Total of CO2 emission through the years analyzed, considering the National estimate (SIRENE) and the BLA’s immediate fire emission.



Note: Following the estimate of the 5th national emission report until 2016 (MCTIC, 2019). For the remaining years (2017-2020), we use the trend in each category to extrapolate, with exception of the land use change category that we use the correlation of it with deforestation rates by Terrabrasilis (INPE, 2021b). Source: From Author.

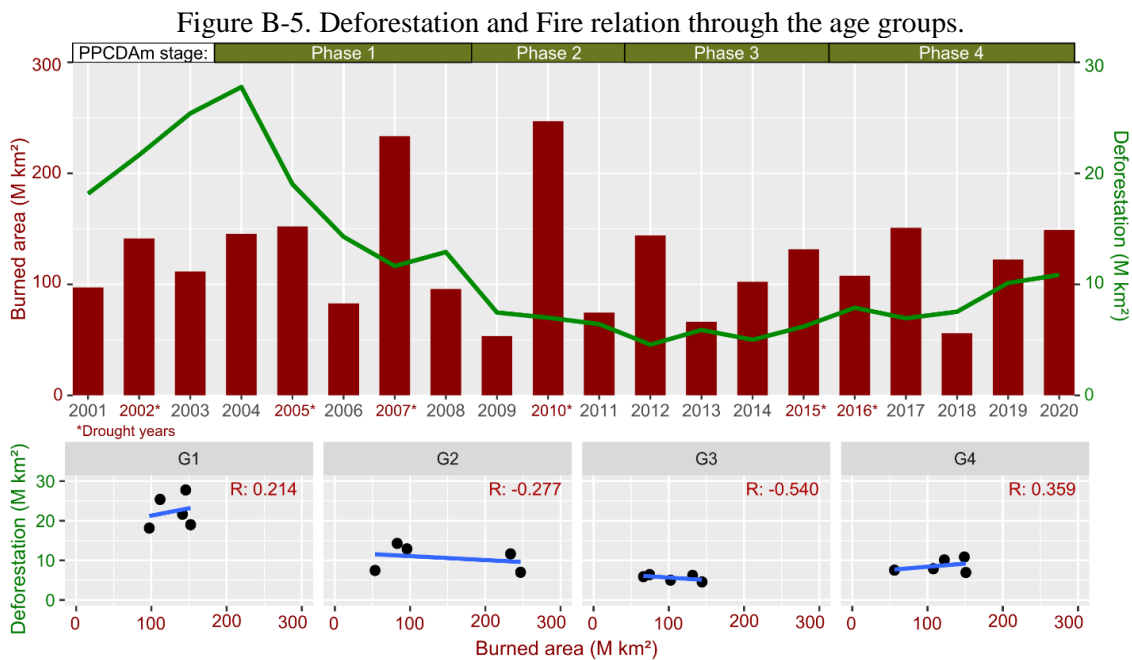
B.1. Fire and its evolution with deforestation

Considering the interannual subdivision of the series into four groups (G1, G2, G3 and G4) some relations with deforestation were made (Figure B-5). The first group, from 2001 to 2005 is characterized by its majority of years before the PPCDAm measures. In this period, the highest deforestation rates were observed (average of 22,399 km²) while the total burned area remained constant and high (average of 129,584 km²), in which about

26% of the total burned area in the time series occurred. During this period the use of fire is closely related to deforestation (ARAGÃO et al., 2008).

The second group (G2: from 2006 to 2010) covers the end of phases 1 and part of phase 2 of the plan, which is characterized by the greatest drop in deforestation levels for the region (reduction of approximately 7.286 km²), while the temporal pattern of the burned area remained with higher average (142,501 km²) in relation to previous years, mainly taken by the years 2007 and 2010, years of El Niño, when the change in weather patterns causes a significant increase in the occurrence of fires in the region. During this period, the highest amounts of burned area for the region were recorded, representing 29% of the total burned during the last 20 years.

The third group (G3: from 2011 to 2015) in turn, covers the end of phase 2 and phase 3 in full. In this period, deforestation levels are the lowest in the entire series (average of 5,620 km²), however, an increase in rates begins, mainly in recent years. During the same period, there is an increase in the levels of burned area for the region, but there is no significant correlation between these variables. This phase is the one with the lowest total value of burned area, representing approximately 21% of the total burned within the analyzed time series.



Source: From Author.

Finally, the fourth group (G4: from 2016 to 2020) covers the years of phase 4 of the PPCDAm program, in addition to including a year of extreme drought and significant changes in policy with the weakening, among others, of the environmental agenda. In this period, the average of the burned area is in the order of 117.196 km², similar to those at the beginning of the data series (G1). The burned area data is beginning to resemble the deforestation data, presenting the last two years with high rates.