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FIRE DYNAMICS IN PRIVATE LANDS IN THE AMAZON FOREST

Nathália Silva de Carvalho

Doctorate Thesis of the Graduate Course in Remote Sensing, guided by Dra. Liana Oighenstein Anderson, approved in August 19, 2022.

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“Ninguém ignora tudo. Ninguém sabe tudo. Todos nós sabemos alguma coisa. Todos nós ignoramos alguma coisa. Por isso aprendemos sempre.”

Paulo Freire

To everyone who believes in science's
importance for advancing knowledge.

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ABSTRACT

The interaction between anthropic activities and extreme climate events is the main drive of fire in the Amazon, impacting biodiversity, carbon emissions, affecting human health and resulting in economic losses. Although the fire occurrence is mainly concentrated in the dry season, the spatiotemporal variation of its dynamics across the basin is still unclear. Furthermore, fire-related forest degradation has not yet been well quantified on private rural lands, which is a critical knowledge gap as fire is a tool widely used by landowners in their rural activities. The general aim of this thesis was to understand the spatially explicit patterns of fire dynamics in the Amazon, considering dry season variations and private land distribution. This thesis is presented as four independent chapters, organized as papers. Initially, I present a literature review on fire monitoring by remote sensing and an overview of environmental and land policy. In the following chapters, I focused on data analysis, integrating data derived from remote sensing. The chapter three was focused on defining an Amazonian fire calendar. By combining time series of rainfall and active fires, the mains results showed a marked seasonality between the dry season end and fire peaks. In 52% of the Amazon basin, fire peaks occurred between August–September and in 48% between October–March, highlighting that assuming a single dry season for the entire basin is not suitable to characterize its fire dynamics. In chapter four, I explored the distribution and overlaps between public and private lands in the Brazilian Amazon, using data from the National Registry of Public Forests and the Rural Environmental Registry (CAR). The results showed a remarkable concentration of private lands, with large properties covering 60% of the area but only 3% of the number of properties. Overlaps among rural properties occurred in 25% of the area enrolled in the CAR. Furthermore, large properties accounted for 47% of the total overlap between rural properties and undesignated public lands, representing almost 80,000 km². In chapter five, I combined forest maps, burned scars and rural properties limits to investigate the occurrence of forest fires on private lands in the Brazilian Amazon. The results highlighted that 20% (3,389 km²) of the total annual burned area on private lands occurred on forests. The burned forest area on large properties was triple the area observed on small and medium properties, corresponding to more than 2,000 km² or 54% of the total forest area affected by the fire on private lands annually. Regionally, only in the states of Acre and Rondônia, small properties represented more than 50% of the burned forest area on private lands. The three data analysis chapters provide information at different scales and levels of detail that can support public policies aimed at the sustainable development of the Amazon. Discussion of these results includes the urgency of strengthening environmental and land policy in the Brazilian Amazon, the need for alternatives to the use of fire by landowners and the importance of recommendations for fire policies based on an Amazonian fire calendar.

Keywords: Dry season. CAR. Forest fires. Environmental policy. Land governance.

DINÂMICA DO FOGO EM TERRAS PRIVADAS NA FLORESTA AMAZÔNICA

RESUMO

A interação entre atividades antrópicas e eventos climáticos extremos é o principal propulsor do fogo na Amazônia, impactando a biodiversidade, as emissões de carbono, afetando a saúde humana e resultando em perdas econômicas. Embora a ocorrência do fogo esteja concentrada principalmente na estação seca, a variação espaço-temporal de sua dinâmica ao longo da bacia ainda não é clara. Além disso, a degradação florestal relacionada ao fogo ainda não foi bem quantificada em terras rurais privadas, o que é uma lacuna crítica de conhecimento, pois o fogo é uma ferramenta amplamente utilizada pelos proprietários em suas atividades rurais. O objetivo geral desta tese foi compreender os padrões espacialmente explícitos da dinâmica do fogo na Amazônia, considerando as variações da estação seca e a distribuição de terras privadas. Esta tese é apresentada em quatro capítulos independentes, organizados como artigos. Inicialmente, apresento uma revisão de literatura sobre monitoramento do fogo por sensoriamento remoto e uma visão geral da política ambiental e fundiária. Nos capítulos seguintes, concentrei-me na análise de dados, integrando dados derivados de sensoriamento remoto. O capítulo três foi focado na definição de um calendário de fogo amazônico. Ao combinar séries temporais de precipitação e focos de calor, os principais resultados mostraram uma marcada sazonalidade entre o final da estação seca e os picos de fogo. Em 52% da bacia amazônica, os picos de fogo ocorreram entre agosto-setembro e em 48% entre outubro-março, destacando que assumir uma única estação seca para toda a bacia não é adequado para caracterizar sua dinâmica de fogo. No capítulo quatro, explorei a distribuição e sobreposições entre terras públicas e privadas na Amazônia brasileira, usando dados do Cadastro Nacional de Florestas Públicas e do Cadastro Ambiental Rural (CAR). Os resultados mostraram uma notável concentração de terras privadas, com grandes imóveis cobrindo 60% da área, mas apenas 3% do número de imóveis. As sobreposições entre imóveis rurais ocorreram em 25% da área cadastrada no CAR. Além disso, os grandes imóveis responderam por 47% da sobreposição total entre imóveis rurais e terras públicas não destinadas, representando quase 80.000 km². No capítulo cinco, combinei mapas de floresta, cicatrizes de área queimada e limites de imóveis rurais para investigar a ocorrência de fogo em áreas florestais em terras privadas na Amazônia brasileira. Os resultados destacaram que 20% (3.389 km²) do total anual de área queimada em terras privadas ocorreu em florestas. A área de floresta queimada nos grandes imóveis foi o triplo da área observada nos pequenos e médios, correspondendo a mais de 2.000 km² ou 54% da área total de floresta afetada pelo fogo em terras privadas anualmente. Regionalmente, apenas nos estados do Acre e Rondônia, os pequenos imóveis representaram mais de 50% da área de floresta queimada em terras privadas. Os três capítulos de análise de dados fornecem informações em diferentes escalas e níveis de detalhamento que podem subsidiar políticas públicas direcionadas ao desenvolvimento sustentável da Amazônia. A discussão desses resultados inclui a urgência de fortalecer a política ambiental e fundiária na Amazônia brasileira, a necessidade de alternativas para o uso do fogo pelos proprietários rurais e a importância de recomendações para políticas de fogo baseadas em um calendário de fogo amazônico.

Palavras-chave**:** Estação seca. CAR. Incêndios florestais. Política ambiental. Governança fundiária.

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LIST OF ACRONYMS AND ABBREVIATIONS

AC	Acre state
AM	Amazonas state
AMO	Atlantic Multidecadal Oscillation
AMZ	Amazon
AP	Amapá state
APPs	Permanent Preservation Areas
AVHRR	Advanced Very High-resolution Radiometer
CAR	Rural Environmental Registry
CCI	Climate Change Initiative
CHIRPS	Climate Hazards Group InfraRed Precipitation with Station data
CO	Carbon Monoxide
CO_2	Carbon Dioxide
COP21	United Nations Conference on Climate Change in Paris
CRA	Environmental Reserve Quota System
ENSO	El Niño–Southern Oscillation
ESA	European Space Agency
FIRMS	Fire Information for Resource Management System
FM	Fiscal module
GABAM	Global Annual Burned Area aps
GFA	Global Fire Atlas
GMSE Sentinel-2	Global Monitoring for Environment and Security - Sentinel-2
GWIS	Global Wildfire Information System
HRV	High Resolution Visible
IBGE	Brazilian Institute of Geography and Statistics
INCRA	National Institute for Colonization and Agrarian Reform
INPE	National Institute for Spatial Research
JRC	Joint Research Centre
LULC	Land-Use and Land-Cover
MA	Maranhão state
MIR	Mid-infrared

MODIS	Moderate-Resolution Imaging Spectroradiometer
MSI	Multispectral Imager
MSS	Multispectral Scanner
MT	Mato Grosso state
NBR	Normalized Burn Ratio
NDVI	Normalized Difference Vegetation Index
NIR	Near Infrared
NOAA	National Oceanographic and Atmospheric Administration
OLI	Operational Land Imager
PA	Pará state
PIN	National Integration Plan
PND	National Development Plan
PPCDAM	Action Plan for the Prevention and Control of Deforestation in the Legal Amazon
PRA	Environmental Regularization Program
REDD+	Reducing Emissions from Deforestation and Degradation
RO	Rondônia state
RP	Rural property
RR	Roraima state
SICAR	National Rural Environmental Registry System
SNUC	National System of Conservation Units
SPOT	Systeme Probatoire d’Observation de la Terre
SUDAM	Superintendence for Development of the Amazon
SWIR	Short-wave infrared
TIR	Thermal infrared
TM	Thematic Mapper
TO	Tocantins state
TREES	Tropical Ecosystems and Environmental Sciences
VGT	Vegetation sensor
VIS	Visible light

SUMMARY

1 INTRODUCTION

Tropical forests are the most biodiverse terrestrial ecosystem on Earth, harbouring 67% of the trees (GATTI et al., 2022) and 60% of vertebrates (PILLAY et al., 2022) species of the world. Tropical forests play a key role in the planet's functioning by regulating global climate through carbon storage, water transpiration and cloud formation and affecting atmospheric circulation (LAWRENCE; VANDECAR, 2015). As an example of their global importance, tropical forests account for one-third of global terrestrial productivity and evapotranspiration (MALHI, 2012), with estimates of carbon stocks above 200 Pg C (BACCINI et al., 2012). Among the tropical forests of America, Africa, Asia and Oceania, the Amazon Forest stands out as the biggest and most biodiverse of them (MITTERMEIER et al., 2003). In the context of global climate, the Amazon plays a key role, as it can be a long-term carbon sink if protected but a carbon dioxide (CO_2) source when deforested or disturbed (GATTI et al., 2021).

Despite the importance of the Amazon for global climate regulation, fire has been a growing threat to this tropical forest due to a combination of anthropic activities and climate change (ARAGÃO et al., 2018; COCHRANE; LAURANCE, 2008). Fire in the Amazon is strongly associated with anthropic ignition sources, with its occurrence mainly concentrated in the dry season (ARAGÃO et al., 2008). However, the Amazon presents large spatio-temporal variability in the rainfall regime, which determine a variation in the onset/end of the dry season across the basin (BERENGUER et al., 2021). Studies have shown that considering the seasonality of the dry season across the Amazon can provide more accurate results spatially and temporally, such as for structural changes in the forest (MOURA et al., 2015) and response to drought events (ANDERSON et al., 2018). Therefore, adopting territorial boundaries or a generalized dry season for the entire basin can produce an inaccurate interpretation of fire dynamics. With a clear spatialization of fire seasonality, actions applied in specific areas at the right time can substantially minimize the impacts of burning. Fire is used for different purposes in the Amazon, and its control should involve specific approaches, such as hiring fire brigades and building firebreaks at the onset of the dry season (RISSI et al., 2017), defining burning periods for those who depend on this tool fire to livelihood (CARMENTA; COUDEL; STEWARD, 2019) and control ignition sources that result in forest fires (BARLOW et al., 2020). In an increasingly resource scarcity scenario, which is seen in the Amazonian countries

(HOPE, 2021; LEVIS et al., 2020; SUAREZ; ÁRIAS-ARÉVALO; MARTÍNEZ-MERA, 2018), this efficiency gains in avoiding uncontrolled fires and enforcement planning becomes necessary to curb forest degradation and reduce carbon emissions.

Another critical issue facing the threats to the Amazon Forest is understanding its territorial planning, which can strengthen land and environmental governance. This understanding is especially important for the Brazilian Amazon, as Brazil encompasses the largest area of the basin, covering more than 60% of its extension (EVA et al., 2005). In this country, the Brazilian National Vegetation Protection Law, also known as the Forest Code, is the law that defines the rules for the use and protection of native vegetation on rural properties in the national territory (BRASIL, 2012a). Forest protection on private lands is a central issue for the conservation of the Brazilian Amazon since rural properties cover 34% of the biome area (SFB, 2019a) and foster large-scale activities such as monoculture, livestock and logging, the main drivers of deforestation and forest degradation in the biome (CONDÉ; HIGUCHI; LIMA, 2019; GODAR; TIZADO; POKORNY, 2012; SIMON; GARAGORRY, 2005). Therefore, clarifying the responsibility of rural actors in non-compliance with land laws and the protection of native vegetation is essential for a better dimensioning of environmental and climate policies in the biome. However, the lack of planning in converting public lands into private lands that started in the 1970s, associated with an obsolete system of land registration in notary offices, has resulted in land concentration and unsuccessful agrarian reform in the Amazon (FEARNSIDE, 2001). The resolution of land tenure problems is important for better territorial planning, including the legal definition of land rights, the determination of restrictions on the use of natural resources on private lands and the urgent need to ensure land rights to the traditional Amazonian people (FEARNSIDE, 2001; SPAROVEK et al., 2019a). In this context, knowledge of the extent to which boundaries of distinct private lands overlap with each other and also with the boundaries of public lands, is an enlightening metric of land tenure problems. Advancing on this issue can help to minimize land conflicts, such as land grabbing, while guiding public policies aimed at the sustainable use of natural resources and monitoring deforestation and forest degradation in rural properties.

Property delimitation has been used to assess the contribution of rural actors to deforestation in the Amazon (GODAR et al., 2012, 2014; GODAR; TIZADO; POKORNY, 2012; L’ROE et al., 2016; MICHALSKI; METZGER; PERES, 2010;

STEFANES et al., 2018); however, fire-related forest degradation has not yet been well quantified on rural properties. This is a critical knowledge gap as fire is a tool widely used by landowners in their rural activities in the Amazon (BARLOW et al., 2020; BOWMAN; AMACHER; MERRY, 2008; SORRENSEN, 2000). This fact can contribute to the uncontrolled use of fire, or the lack of planning for its use can cause accidental fires that can reach unwanted areas of rural property, both productive and forest (MENDONÇA et al., 2004). Studies that addressed the fire occurrence on private lands in the Amazon have focused on small properties (BOWMAN; AMACHER; MERRY, 2008; CARMENTA et al., 2011, 2013; CROMBERG; DUCHELLE; ROCHA, 2014; SORRENSEN, 2000). As these studies mainly use field data, the choice of the same category of the rural actor can be related to the size of the small properties and the proximity between them, making it possible to obtain a larger sample size. However, the lack of information on the fire dynamics on medium and large properties restricts our understanding of fire impacts on forest areas on private lands across the Amazon.

The separation of the size of rural properties is essential for the success of fire policies, as cultural and socioeconomic differences among small, medium and large landowners determine different uses of fire, which implies adopting distinct strategies to deal with the impacts of burning (PACHECO, 2012). Currently, a better stratification of properties can be obtained with the Rural Environmental Registry (CAR, acronym in Portuguese), a georeferenced electronic registry of all rural properties in the Brazilian territory, which the Forest Code implemented to improve the environmental monitoring and enforcement of rural properties, (BRASIL, 2012a). CAR is not a land regularisation tool and does not replace the legal requirements to prove land tenure, but it represents an essential step toward strengthening environmental governance on private lands (ROITMAN et al., 2018). Before CAR, the distribution of private lands was based on information at the municipal level (PACHECO, 2012) and census sectors (GODAR et al., 2014). Despite the self-declaratory nature of the CAR, this registry represents the best level of detail on the distribution of private lands in Brazil today (ROITMAN et al., 2018). CAR has been used to quantify deforestation (COSTA et al., 2018; RICHARDS; VANWEY, 2016) and assesses compliance by landowners with environmental laws (AZEVEDO et al., 2017; L’ROE et al., 2016; PACHECO et al., 2021). However, a detailed analysis of the CAR data itself, including dominance patterns of rural properties and spatial distribution of overlaps between rural properties across the Amazon, is not yet available. Advancing on this issue can provide helpful information for stakeholders and policy makers, supporting to resolve land tenure problems and environmental regularization, in addition to allowing better directing of financial resources for such actions. Additionality, combining property delimitation provided by CAR with data derived from remote sensing, including burn scars to quantify the burned area (ANDERSON et al., 2015; MORTON et al., 2011) and ignition points to overcome uncertainties about the location of the fire's origin (ANDELA et al., 2019), can also contribute to advance our knowledge of fire dynamics on rural properties in the Amazon.

All the context involving land tenure problems and threats imposed by fire to the Amazon motivated the development of this thesis, resulting in four chapters, which were organized into papers as described below. The general aim of this thesis was to understand spatially explicit patterns of fire dynamics in the Amazon, considering regional land distribution and dry season variations. To achieve this objective, in Chapter 2, I started assessing the up-to-date scientific knowledge and developed a literature review on fire monitoring and impacts and environmental policy. In this chapter, I intended to i) show an overview of using remote sensing for fire monitoring, ii) review the history of the Brazilian Amazon occupation and Brazilian environmental law, iii) gather information on the use of the CAR to enforcement and environmental monitoring and finally, iv) to review information on forest fires, including the impacts of extreme drought events in the Amazon. In Chapter 3, I focused on the scale of the Amazon basin to test the hypothesis that spatiotemporal variation in the dry season determines different fire seasons across the basin. I integrated monthly time series of precipitation and active fires to understand the fire dynamics across the basin and define an Amazonian fire calendar, which can be used to plan strategic actions to manage fire across the basin. In the next two chapters, I focused on data analysis for the Brazilian Amazon based on two hypotheses: (i) the size of rural properties affects the distribution and overlaps between public and private lands and (ii) the occurrence of burned forest on private lands depends on the size and spatial distribution of rural properties in the biome. To test the first hypothesis, in Chapter 4, I aimed to analyse the spatial distribution of rural properties in the biome, including an overview of the uncertainties and controversies in land tenure. I used CAR data and the following public lands: conservation units, indigenous lands, settlements and undesignated lands, to investigate the overlap between private and public lands and the overlap among rural properties of different sizes. To test the second hypothesis, in Chapter 5, I aimed to understand the spatial distribution of burned forest on private lands, stratifying the contribution to the burned area of small, medium, and large properties. I used remote sensing-derived burned area data to identify how much each rural property category (small, medium and large) contributes to the forest area affected by fire in the Amazon. Finally, I summarise and discuss the implications of the main findings in the Concluding remarks section, addressing how this thesis can provide a scientific basis to support land and environmental governance to reduce fire activity in the Amazon.

2 LITERATURE REVIEW - PERSPECTIVES ON FIRE MONITORING, IMPACTS AND PUBLIC POLICIES

In this chapter, I have performed an up-to-date scientific knowledge literature review. In this thesis, I applied remote sensing and spatial analysis methods to investigate the fire dynamics in the Amazon basin and address the Brazilian Amazon's land structure. Therefore, in this chapter, I first present an overview of remote sensing techniques applied to fire monitoring, followed by a concise revision of the historical occupation of the Brazilian Amazon and Brazilian environmental legislation. Finally, a review of the types of fires in the Amazon and how extreme droughts can affect their occurrence is also presented.

2.1 Remote sensing of fire

2.1.1 Remote sensing properties and the influence of fire on the spectral behaviour of vegetation

Remote sensors are instruments sensitive to electromagnetic radiation, providing data proportional to the electromagnetic energy reflected or emitted by the targets on the land surface (JENSEN, 2006). However, physical surface characteristics, such as terrain roughness and configuration, and targets' chemical properties (e.g., photosynthetic pigments and moisture content), can influence the response of spectral targets (JENSEN, 2006). In addition, variations in data acquisition geometry (changes in observation and illumination angles) can cause undesirable effects and even create biased results (VERBYLA; KASISCHKE; HOY, 2008). Variations in atmospheric conditions, such as the presence of aerosols and dust particles, can also interfere with the relationship between signal-noise registered by remote sensors (JENSEN, 2006).

Forest fires can be detected by optic sensors sensitive to a region of the electromagnetic spectrum ranging from 0.4 to 2.5 µm, including visible light (blue, green and red), near-infrared (NIR), and short-wave infrared (SWIR) (CHUVIECO et al., 2019). Generally, burned vegetation presents a decrease in NIR reflectance and an increase in SWIR reflectance compared to vegetation that was not burned. In the following sections, the spectral properties of non-burned vegetation and the signal changes after fires will be characterised for each of these wavelengths. Spectral responses in the mid-infrared (MIR) and thermal infrared (TIR) bands will also be addressed. In addition, for the analyses to be representative of the phenomenon under study, besides knowing the spectral response of the vegetation after the fire, it is also important to understand the influence of limiting factors. This joint characterisation is necessary to ensure the right choice of remote sensing products and understand the limitations associated with each data.

2.1.2 Spectral behaviour of visible light, near-infrared (NIR) and short-wave infrared (SWIR)

In general, the presence of photosynthetic pigments reduces the reflectance of healthy vegetation in the visible light region of the electromagnetic spectrum, while histological characteristics of leaves define a high reflectance in the NIR region. In the SWIR region, there is a sensitivity to the leaf's moisture content, with the absorption of electromagnetic radiation at this wavelength. As moisture content increases, there is a tendency to reduce the reflectance in SWIR (HUNT; ROCK, 1989). After a forest fire, the spectral signal of the vegetation is initially influenced by surface carbonisation and deposition of ashes and charcoal from the combustion process (PEREIRA et al., 1999). The period of influence of these factors can be relatively short due to the attenuation caused by rain and wind, whereas the alteration in the structural pattern of the vegetation after the fire, generally referred to as burn scar, can be long-lasting (PEREIRA et al., 1999). Recently burned surfaces tend to be relatively dark in the visible light bands, with low effectiveness in discriminating burned areas in this spectrum region (PEREIRA et al., 1999; TEODORO; AMARAL, 2019). Pereira, 1999 suggests some reasons for this condition: (i) the similarity between the low reflectance of visible light in burned areas and other features, for example, native vegetation and wetlands, makes it difficult to separate these targets in this spectral region; and (ii) the influence of atmospheric noise is predominant in the visible light band, contributing to the contrast loss among the different types of land use and land cover. On the other hand, with recent data availability in new spectral bands, studies have shown success in using red-edge bands to distinguish the burn severity levels (CARVAJAL-RAMÍREZ et al., 2019; FERNÁNDEZ-MANSO; FERNÁNDEZ-MANSO; QUINTANO, 2016).

The recently-burned vegetation presents an opposite behaviour to its healthy condition in the NIR and SWIR bands, with spectral responses more evident in these wavelengths compared to visible light bands (KUMAR; ROY, 2017; OLIVA; MARTÍN; CHUVIECO, 2011; PLENIOU; KOUTSIAS, 2013; TRIGG; FLASSE, 2001). Particularly when the fire reaches the leaves, the reduction in the leaf area index leads to a decrease in the NIR reflectance and the foliage drying results in an increase in the SWIR reflectance (BRIESS et al., 2003; EVA; LAMBIN, 1998; JAISWAL et al., 2002; OLIVA; MARTÍN; CHUVIECO, 2011; PEREIRA, 2003). Frederiksen; Langass; Mbaye, 1990 observed the opposite behaviour in African savanna regions, with a rapid increase in the reflectance of NIR after fires. The authors explained this variation by the change in the fraction of the recently burned area covered by ashes, bare soil, and dry leaves. The occurrence of winds can disperse ash residues, increasing the proportion of bare soil and dry leaves, which become the dominant spectral features. The spectral response of burned vegetation in the SWIR band is useful for classifying fire severity, as changes in canopy cover caused by fire are associated with reflectance variation in this region of the spectrum (HOSCILO; TANSEY; PAGE, 2013; WHITE et al., 1996). However, the spectral responses can be altered due to the pixel's burned area percentage. Pleniou; Koutsias, 2013 showed that areas that were partially burned (45-55%) presented high spectral similarity in the NIR band with completely burned areas, but were spectrally closer to areas with non-burned vegetation in the SWIR band. These differences were attributed to the low and high variance of pixels completely burned in NIR and SWIR bands, respectively.

2.1.2.1 Spectral indices

Spectral indices are dimensionless variables calculated from the contrast between two or more regions of the electromagnetic spectrum to highlight the biophysical characteristics of the targets of interest and minimise the influence of terrain and atmosphere noises (CHAFER, 2008; JI et al., 2011; OLIVA; MARTÍN; CHUVIECO, 2011). The Normalized Difference Vegetation Index (NDVI) is commonly used in research on vegetation remote sensing, with applications in studies of burned areas at regional (ISAEV et al., 2002) and local (CHUVIECO; CONGALTON, 1988) scales. However, factors such as sensitivity to atmospheric conditions and land surface characteristics can limit the application of this index (PEREIRA et al., 1999).

Pereira, 1999 showed that NDVI was not appropriated for mapping and distinguishing burned areas in tropical ecosystems, with the NIR/SWIR spectral space being more adequate when compared to the red/NIR spectral space. In contrast, Mohler; Goodin, 2010 observed that both red and NDVI were able to distinguish burned pastures. However, the authors did not test the ability to detect burned areas in the SWIR band, which could generate different results. Generally, the advantage of using the NIR band is the longer duration of the post-fire signal sensitivity (TRIGG; FLASSE, 2000), an important factor when considering the transitory condition of burn scars. For SWIR, besides being less sensitive to atmospheric noise, the reflectance in this region is higher than in visible light (PEREIRA, 1999). Due to the contrast obtained by decreasing NIR reflectance and moderately increasing SWIR reflectance, the NIR/SWIR ratio has been widely used in spectral indexes to detect burns and/or classify burn severity (CHUVIECO et al., 2019).

Epting; Verbyla; Sorbel, 2005 compared the potential of 13 spectral variables to detect burned areas, including individual bands, band ratio and normalised differences. The authors also observed better performance of indices that used SWIR when compared to indices calculated using red or NIR bands. In general, the authors observed the strongest correlation between the field data and the results extracted by the Normalized Burn Ratio (NBR), which incorporates the NIR and SWIR bands. On the other hand, studies that used recently launched satellites, such as Sentinel-2, showed a good suitability of the NDVI and NBR indices for mapping and classifying burning severity in forested areas (TEODORO; AMARAL, 2019).

2.1.2.2 Spectral behaviour in the mid-infrared (MIR) and thermal infrared (TIR) bands

The 2.5 to 14 μm spectral range is the region in which the Earth's surface is the main energy source (CHUVIECO et al., 2019). The sensors detect the energy emitted by the targets in the mid-infrared (MIR) and thermal infrared (TIR) spectral bands, (PEREIRA et al., 1999). In these bands, the temperature and emissivity characteristics of the targets on the land surface influence the signal detected by remote sensors (JENSEN, 2006). Robinson, 1991 mentions that the contrast between fire and land surface temperatures can saturate the signal detected by remote sensors. Due to lower temperatures, the saturation probability may be lower for data registered at night (SCHROEDER et al., 2016). The fire detection capacity by remote sensors also depends on the affected area and fire intensity (SAN-MIGUEL-AYANZ et al., 2005). The higher the fire temperature, the smaller the area needed to sensitise the sensors.

Fire is a chemical reaction that releases energy in the form of heat, and due to the strong signal emitted at MIR wavelengths, this spectral band has been widely used to detect active fires (CHUVIECO et al., 2019; ROBINSON, 1991). This spectral window is suitable for detecting fires of different temperatures, as it is far from the peak energy emitted by the Earth’s surface (9.7 μm), (ROBINSON, 1991; SAN-MIGUEL-AYANZ et al., 2005). The higher fire emittance in the MIR band compared to the energy emitted by the other targets (ROBINSON, 1991) results in hot spots surrounded by colder areas (SAN-MIGUEL-AYANZ et al., 2005). Studies focusing on active fire detection using the MIR band began in the late 80s, with research developed by the National Oceanographic and Atmospheric Administration (NOAA) (MATSON et al., 1984). On the other hand, in terms of mapping burned area, the MIR band has not been widely used (CHUVIECO et al., 2019). Images acquired in TIR bands have also been little used in studies of burned area classification, perhaps due to the short persistence of post-fire thermal signal (PEREIRA et al., 1999). However, some studies have shown applications of these bands for mapping. The insertion of thermal information in the NBR index has demonstrated promising potential for detecting burned areas (HOLDEN et al., 2005). Finally, Goodwin; Collett, 2014 observed that the insertion of thermal information improved the performance of algorithms to separate burned and non-burned areas.

2.1.3 Influence of environmental and temporal factors on forest fire detection

The characteristics of anthropic actions can influence the ability of remote sensors to detect changes in forest systems. From a remote sensing perspective, the ability to detect fire in vegetation varies with the time scale, with the verticalization of fire within the forest and environmental conditions (CHUVIECO et al., 2019; TRIGG; FLASSE, 2001). The knowledge about the influence of these conditions is fundamental to improving the understanding of the signal registered by remote sensors, helping to recognize patterns of forest degradation by fire.

The detection of forest fires can vary with the interval between the fire occurrence/extinction and the recording of these events by remote sensors, influencing the reflectance characteristics (CHUVIECO et al., 2019). These conditions can limit the use of data from sensors operating in the visible light and near-infrared bands, particularly to monitor tropical forests, which generally present high cloud cover and fast vegetation regeneration (COCHRANE, 2003; SADER; STONE; JOYCE, 1990). A late detection combined with the effects of post-fire regeneration, rain and wind can reduce the burn scars signal, making it difficult to distinguish affected areas from other targets on the land surface (CHUVIECO et al., 2006; LEEUWEN, 2008; VERAVERBEKE et al., 2010). The results presented by Veraverbeke et al., 2010 showed that TM images acquired close to the fire event showed a higher correlation with field data ($R^2 = 0.72$), compared to images acquired one year after the fire ($R^2 = 0.56$). Also, based on field data, Trigg; Flasse, 2000 observed a sensitivity in the NIR reflectance response for at least two weeks for fires in savanna areas.

Detection capacity is also associated with the forest stratum that was affected by the fire. The recording of disturbance in lower strata can be hampered by canopy cover, compromising the detection of understory fires (PEREIRA et al., 2004; PERES; BARLOW; LAURANCE, 2006). This limitation can result in an underestimation of the impacts of anthropic actions on forest ecosystems (PERES; BARLOW; LAURANCE, 2006). In addition, the available fuel load (KAUFFMAN; CUMMINGS; WARD, 1994; SAH et al., 2006), wind speed (BEER, 1990; HARGROVE et al., 2000) and water availability (CHUVIECO et al., 2004; NEPSTAD et al., 1999), interfere on the total heat released and in the potential for fire spread.

2.1.4 Optical sensors and burned area products

Remote sensors have different capabilities for measuring phenomena on the land surface, with a diversity of products separated by their radiometric, spatial, spectral and temporal resolutions (CHUVIECO et al., 2019; COCHRANE, 2003; PEREIRA et al., 1999). The characteristics of the main satellites/sensors used in studies of forest fires are summarised in Table 2.1.

The first remote sensing applications for monitoring forest fires occurred in the 1960s, with airborne scanners sensitive to infrared (CHUVIECO; CONGALTON, 1988). However, the expansion of the monitoring scale was only possible in the 1970s after the launch of the Landsat satellite program. With spectral bands of visible light and NIR, the images from the Multispectral Scanner (MSS) sensor made it possible to start monitoring vegetation at geographic scales that were previously unfeasible. From the perspective of forest fires, MSS images were used to delimit/measure the burned area (HITCHCOCK; HOFFER, 1974; TANAKA; KIMURA; SUGA, 1983) and classify the burning severity (HALL et al., 1980).

The operation of sensors in the SWIR band began in the 1980s, with the launch of the Landsat-4 and Landsat-5 satellites carrying the Thematic Mapper (TM) sensor. With the availability of images in this spectral band, the mapping of burned areas was improved (CHUVIECO; CONGALTON, 1988; MILNE, 1986; WHITE et al., 1996). The highlighting of burned areas in this band also contributed to the creation of spectral indices, initially used to improve the quality of burned area mapping (GARCÍA; CASELLES, 1991). Currently, global and regional scale mappings based on Landsat images have also started to be produced. The Global Annual Burned Area Map (GABAM) is a global product at 30 meters of spatial resolution based on images from Landsat 8 Operational Land Imager (OLI), initially available for the year 2015 (LONG et al., 2019). The algorithm was built on the Google Earth Engine platform, corresponding to an automatic methodology based on random decision forests, using spectral behaviour and indices to calculate each pixel's burned probability (LONG et al., 2019). Another product also developed in the Google Earth Engine platform is the Mapbiomas Fire, a national initiative that has been producing maps of the burned area throughout the Brazilian territory using Landsat images, creating time series since 1985 (ALENCAR et al., 2022). The methodology is based on a Deep Neural Network model, producing monthly and annual maps of burned area in the six biomes of Brazil. On a regional scale, Landsat images have also been used to map forest fires in southwestern Amazonia over a 33-year time series (SILVA et al., 2018). The method includes using fraction images derived from a linear spectral mixing model, manual editing to reduce commission errors and an image-slicing method to define thresholds to identify forest fire scars.

Data from the Advanced Very High-resolution Radiometer (AVHRR) sensor has been presenting great application due to its sensitivity to the emitted energy by the targets on the MIR band (DWYER et al., 2000; KAUFMAN; TUCKER; FUNF, 1989; LANGAAS, 1992). The sensors of the satellite series National Oceanic Atmospheric Administration (NOAA) were the first to collect data in this spectral band. Although the AVHRR was designed to monitor climatic conditions, this data has also been applied to study forest fires. In addition, the spatial resolution of 1km made possible studies on a regional/global scale. Pereira; Setzer, 1993 characterised the occurrence of forest fires associated with deforestation in the Brazilian Amazon, while Li; Nadon; Cihlar, 2000 did the first large-scale study to monitor forest fires in boreal forests in Canada. Dwyer et al., 2000 used the AVHRR time series to develop the first global map of the spatio-temporal distribution of forest fires between 1992 and 1993. The high temporal resolution also allowed the application of AVHRR images in the daily monitoring of fire spread (CHUVIECO; MARTIN, 1994).

The High Resolution Visible (HRV) sensors onboard the Systeme Probatoire d’Observation de la Terre (SPOT-1,2,3) satellites came into operation in 1986 and pioneered the linear push broom technology (JENSEN, 2006). The multispectral bands have a higher spatial resolution (20m) than the TM sensor (30m). However, the imaging area (60 x 60 km) corresponds to 11% of the area covered by TM (185 x 185 km), representing a limiting factor for studies of regional scales. The Vegetation (VGT) sensor was launched onboard the SPOT-4 in 1998 and the SPOT-5 in 2002. Despite the moderate spatial resolution of 1.15 km, the large imaging area (2,250 x 2,250 km) allowed the development of burned area products at a global scale (TANSEY et al., 2004). Multisensor data has also been used to improve fire monitoring programs (CHUVIECO et al., 2019), such as applying AVHRR and VGT data for calibration and accuracy analyses in Canada (LEE et al., 2002).

Table 2.1 - Summary of the main specification of remote sensors used to monitor forest fires. The wavelengths are presented only for the regions of response sensitivity to fire. The electromagnetic spectrum was separated according to the reflected energy in visible light (VIS), near-infrared (NIR), short-wave infrared (SWIR), as well as the energy emitted by mid-infrared (MIR) and thermal infrared (TIR).

			Reflected energy (µm)			**Emitted energy (µm)**		**Resolution**		
Launch date	**Satellite**	**Sensor**	**VIS**	**NIR**	**SWIR**	**MIR**	**TIR**	**Spatial**	**Temporal**	**Imaging range**
1972	Landsat - 1	MSS	0.5 - 0.6 0.6 - 0.7	0.7 - 0.8 0.8 - 1.1	-	-	-	79 x 79 m 240 x 240 m	18 days	185 x 185 km
1975	Landsat - 2				-	-	-			
1978	Landsat - 3				-	-	10.4 - 12.6			
1982	Landsat - 4	TM	0.45 - 0.52 0.52 - 0.60 0.63 - 0.69	0.76 - 0.90	1.55 - 1.75 2.08 - 2.35	-	10. 4 - 12.5	30 x 30 m 120 x 120 m	16 days	185 x 185 km
1984	Landsat - 5									
1993	Landsat - 7	ETM+	0.45 - 0.52 0.52 - 0.60 0.63 - 0.69	0.76 - 0.90	1.55 - 1.75 2.08 - 2.35	-	10. 4 - 12.5	30 x 30 m 60 x 60 m	16 days	185 x 185 km

to be continued.

Table 2.1 – Continuation.

			Reflected energy (µm)			**Emitted energy (µm)**		**Resolution**		
Launch date	**Satellite**	**Sensor**	**VIS**	**NIR**	**SWIR**	**MIR**	**TIR**	**Spatial**	**Temporal**	**Imaging range**
2013	Landsat - 8	OLI / TIRS	0.43 - 0.45 0.45 - 0.51 0.52 - 0.60 0.63 - 0.68	0.84 - 0. 89	1.56 - 1.66 2.10 - 2.30	- - - -	10.6 - 11.2 11.5 - 12.5	30 x 30 m 100 x 100 m	16 days	185 x 185 km
1979 1981 1998	NOAA - 6 NOAA - 7 NOAA - 15	AVHRR	0.58 - 0.68	0.72 - 1.1	- 1.58 - 1.64	3.55 - 3.93	10.5 - 11.5 10.3 - 11.3 11.5 - 12.5	1100 x 1100 m	1 - 2 days	2700 x 2700 km
1986 1990 1993	SPOT - 1 SPOT - 2 SPOT - 3	HRV	0.50 - 0.59 0.61 - 0.68	0.79 - 0.89	-	-	-	20 x 20 m	26 days	60 x 60 km

to be continued.

Table 2.2 – Continuation.

			Reflected energy (µm)			**Emitted energy (µm)**		**Resolution**		
Launch date	**Satellite**	**Sensor**	**VIS**	**NIR**	**SWIR**	**MIR**	**TIR**	**Spatial**	**Temporal**	**Imaging range**
1998 2002	SPOT-4 SPOT-5	HRVIR	0.50 - 0.59 0.61 - 0.68	-	1.58 - 1.75	-	-	20 x 20 m	26 days	60 x 60 km
		VGT	0.43 - 0.47 0.61 - 0.68	0.78 - 0.89	1.58 - 1.75			1150 x 1150 m	1 day	2250 x 2250 km
2012 2014	SPOT-6 SPOT-7	NAOMI	0.45 - 0.52 0.53 - 0.60 0.62 - 0.69	0.79 - 0.89	-	-	-	8 x 8 m	26 days	60 x 60 km

to be continued.

Table 2.1 – Continuation.

			Reflected energy (µm)			**Emitted energy (µm)**		**Resolution**		
Launch date	**Satellite**	**Sensor**	**VIS**	**NIR**	**SWIR**	**MIR**	**TIR**	**Spatial**	**Temporal**	**Imaging range**
1999 2002	Terra Aqua	MODIS	0.62 - 0.67	0.84 - 0.87	-	-	-	250 x 250 m	1 - 2 days	2330 x 2330 km
			0.45 - 0.47 0.54 - 0.56	1.23 - 1.25	1.62 - 1.65 2.10 - 2.15	-	-	500 x 500 m		
			-	-	-	3.60 - 3.84 3.92 - 3.98 3.92 - 3.98 4.02 - 4.08	10.7 - 11.2 11.7 - 12.2	1000 x 1000 m		
2011	Suomi-NPP	VIIRS	-	-	-	3.55 - 3.93 3.59 - 3.79 3.98 - 4.14	10.2 - 11.2	375 x 375m 750 x 750 m	1 day	3000 x 3000 km

to be continued.

Table 2.1. – Conclusion.

			Reflected energy (µm)			Emitted energy (µm)		Resolution		
Launch date	**Satellite**	**Sensor**	**VIS**	**NIR**	**SWIR**	**MIR**	**TIR**	**Spatial**	**Temporal**	**Imaging range**
2015 2016	Sentinel - 2A Sentinel - 2B	MSI	0.49; 0.56 0.66; 0.70 0.74; 0.78	0.84 0.86	1.37 1.61 2.19	-	-	10 x 10 m 20 x 20m 60x 60m	5 days	290 x 290 km

Between the late 1990s and the early 2000s, the Moderate-Resolution Imaging Spectroradiometer (MODIS) sensor was launched onboard the Terra and Aqua satellites. With improvements in radiometric, spatial and temporal resolution, MODIS allowed for eliminating some limitations in using data from previous sensors. With a higher sensitivity to signal saturation, there was an improvement in the ability to detect and monitor active fires (COCHRANE, 2003). In addition to higher saturation temperatures, Cahoon, et al., 2000 also showed an improvement in the detection of the burned area by MODIS. The minimum area detectable by MODIS was 213 m², compared to the area of 435 m² detected by AVHRR. The sensitivity to a higher number (36) of electromagnetic spectrum bands has also contributed to the advances in the investigation of the climatic effects of aerosols, including the release by forest fires (KAUFMAN; TANRÉ; BOUCHER, 2002). Furthermore, due to the availability of global products, the MODIS data has been widely used, both to monitor active fires at 1km spatial resolution (MOD14/MYD14) and to monitor the burned area at a 500 m spatial resolution (MCD64A1), (GIGLIO; SCHROEDER; JUSTICE, 2016; JUSTICE et al., 2002).

Currently, there are also burned area products derived from MODIS images and products, developed by the scientific community at a global scale. The Global Wildfire Information System (GWIS) was developed by the Joint Research Centre (JRC) and corresponds to the grouping of burning pixels identified by the MCD64A1 product, resulting in a 500 m spatial resolution product. The product Fire_cci is generated by the Climate Change Initiative (CCI) program from the European Space Agency (ESA) (CHUVIECO et al., 2016, 2018). Active fires and images from the MOD09GQ and MOD09GA products are used as input parameters for the processing algorithms. The product generated by Tropical Ecosystems and Environmental Sciences (TREES) uses a hybrid classification method, in which images of the product MOD09A1Q1 are used as input in the linear spectral mixture model (ANDERSON et al., 2015, 2017). The product provides burned area maps for the Brazilian Amazon at a spatial resolution of 250m.

In 2011, with the launch of the Visible Infrared Imaging Radiometer Suite (VIIRS), a new generation of moderate spatial resolution data began (375 m and 750 m). VIIRS is considered a hybrid sensor of AVHRR and MODIS instruments (CAO et al., 2014; JUSTICE et al., 2011). The sensor operates in 22 spectral bands and has specific bands for fire monitoring (CAO et al., 2014). Similar to the MODIS thermal anomalies calculation (GIGLIO et al., 2003), the VIIRS algorithm for detecting active fires is based on the high saturation temperature of the MIR (634 K) and also on the energy emitted from the TIR (SCHROEDER et al., 2014). These characteristics allow the detection of smaller fires and a better refinement in mapping larger fires (SCHROEDER et al., 2014). The potential of this data has been explored in a near-real time methodology to classify fire events according to four different Amazonian fire types, defined as deforestation fires, understory forest fires, small clearing or agricultural fires and savanna and grassland fires (ANDELA et al., 2022). In the methodology, active fires are aggregated into individual fire events and combined with information on land cover and fire characteristics, resulting in specific signatures related to each fire type.

In 2015, the Global Monitoring for Environment and Security – Sentinel-2 (GMSE Sentinel-2) mission began. It was designed to provide land surface observations with high spatial resolution and unprecedented detail level at a global scale (DRUSCH et al., 2012). The Multispectral Imager (MSI) sensor onboard the Sentinel-2A and Sentinel 2-B satellites collect information in 13 spectral bands distributed among visible light, NIR and SWIR, with spatial resolution from 10 to 60 meters. The similarity of the visible light bands with the data from the Landsat and SPOT programs allows a complementary use, particularly for the classification of land use and land cover (LI; ROY, 2017). A differential of this sensor is the collection of data in four red-edge bands, providing important information about the condition of the vegetation in a spatial resolution of 20 x 20 m. These images have been applied in combination with OLI images to generate maps of burned area (QUINTANO; FERNÁNDEZ-MANSO; FERNÁNDEZ-MANSO, 2018) and to classify the burn severity (FERNÁNDEZ-MANSO; FERNÁNDEZ-MANSO; QUINTANO, 2016).

2.1.5 Advances in the remote sensing science

The monitoring of forest fires started in the 1970s allows us to understand some important facts about the science of remote sensing:

(i) Over time, there has been a change in the perspective of observation of the land surface. Initially, the use of remote sensing data was mainly associated with mapping land use and land cover, with medium spatial resolution sensors operating in the visible and NIR bands. With the launch of Landsat-5/TM, forest fires analyses were improved due to the incorporation of the SWIR band. During this period, the concern with field validation of observed data was also notable (FREDERIKSEN; LANGASS; MBAYE, 1990; HALL et al., 1980; TRIGG; FLASSE, 2000). Subsequently, new instruments began to be designed to generate meteorological data, with sensors operating in a larger range of spectral bands, which were also sensitive to the emitted energy by the targets on the land surface. AVHRR pioneered the production of data in the MIR band. Multispectral images were used not only as a source for target visualisation and delimitation, but their radiometric properties also began to be explored to obtain data on the physicochemical properties of the targets in the surface.

(ii) Active fires detection was not addressed for nearly three decades (1972 – 2000). During this period, fire detection was performed using data generated for other purposes, mainly for meteorological studies (CAHOON, et al., 2000). AVHRR data allowed advancing knowledge of forest fires' global distribution, improving biomass loss estimates (DWYER et al., 2000). However, specific products for monitoring forest fires became available in the early 2000s, after the launch of the MODIS sensor onboard the Terra and Aqua satellites.

(iii) Open data policy has created a new dimension of data analysis (HANSEN; LOVELAND, 2012). This condition allowed and encouraged the construction of time series, which have contributed to improving the spatiotemporal understanding of land use and land cover change. Furthermore, with a greater variety of data available, more global products began to be produced by the scientific community (CHUVIECO et al., 2016, 2018). Recently, the Google Earth Engine, a cloud computing platform for visualising, analysing, and processing spatial big data, has provided a new level of access and processing of data derived from remote sensing, with a variety of data available for academic, business or government purposes (AMANI et al., 2020).

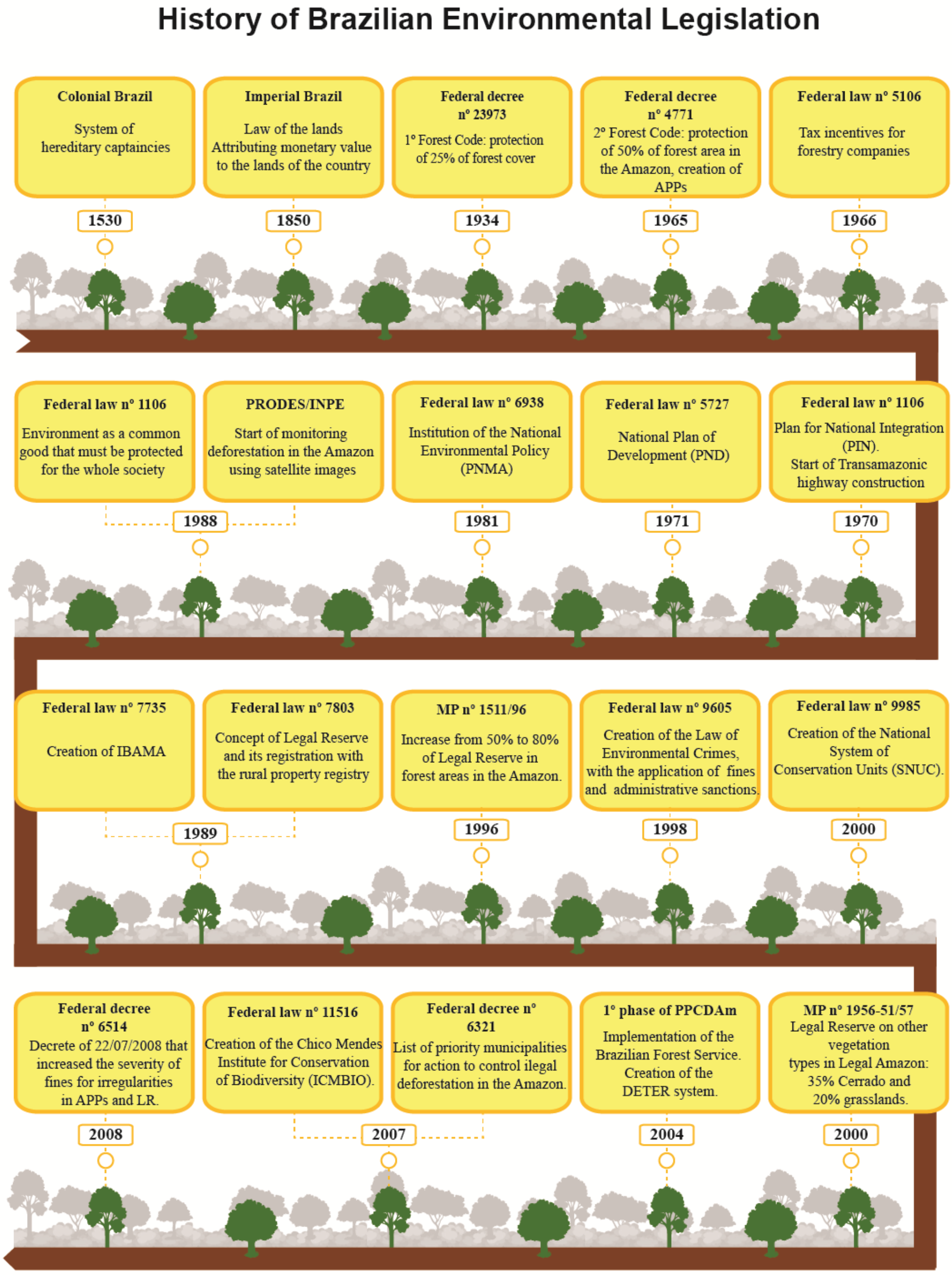
(iv) In the open data scenario, we have also observed advances in remote sensors designed to obtain data at medium and moderate spatial resolution. Following the improvements initiated with MODIS, the launch of the VIIRS sensor in 2011 represented a new milestone in data acquisition with global application. Remote sensors with land use and land cover mapping applications have also evolved in their spectral ranges. For example, the Sentinel-2 mission incorporated imaging in the *red-edge* spectral band, providing multispectral images with a 20 m spatial resolution.

(v) Remote sensing data can contribute to the management of public forests, providing information to support decision making. Data derived from remote sensing provide information on the spatial distribution of burn scars (CHUVIECO et al., 2018), allow the detection of active fires (JUSTICE et al., 2002), and generate estimates of greenhouse gas emissions from burning native vegetation (ARAGÃO et al., 2014, 2018). In the latter case, these data can play a fundamental role in environmental and climate policies, with important applications in projects of global scope, such as the Kyoto Protocol, the agreements of the United Nations Conference on Climate Change in Paris (COP21) and the Sendai Framework for Disaster Risk Reduction 2015-2030 (CHUVIECO et al., 2019).

2.2 History of occupation and environmental legislation in the Brazilian Amazon

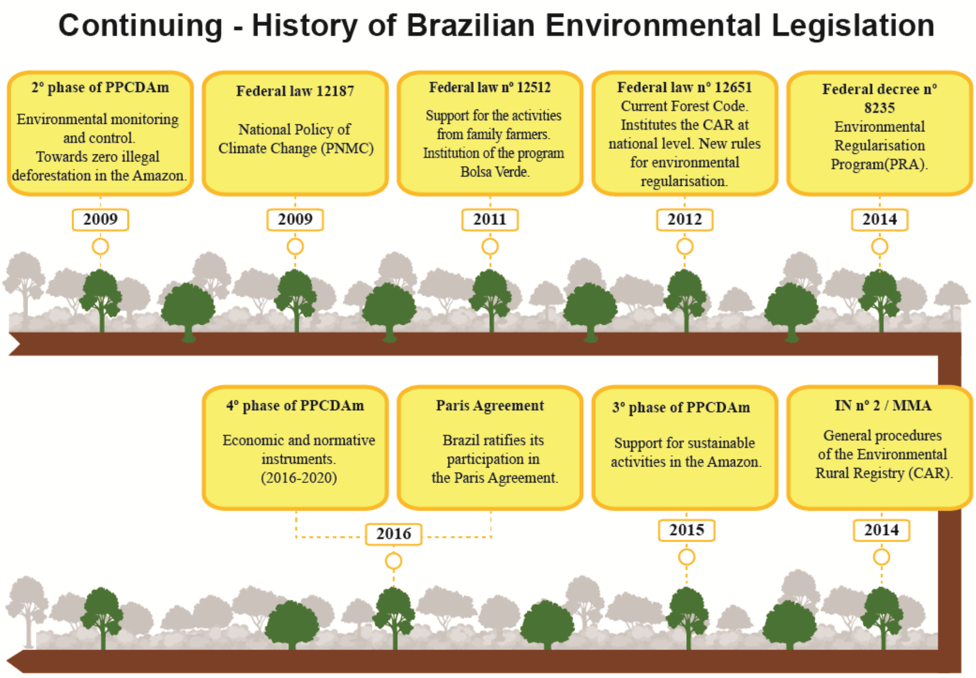
A summary of the history of environmental legislation and the allocation of private lands in Brazilian territory is presented in Figure 2.1. In this timeline, four periods before the colonization process of the Amazon influenced the current pattern of land distribution in the region: (i) land concentration process started in the colonial period (1530 - 1822) with the system of hereditary captaincies, which were generally donated to nobles of the Portuguese Crown; (ii) establishment of the Land Law in 1850, which restricted land access only through purchase, but due to the high added value, the power of large landowners over the territory was reinforced; (iii) beginning of recognition of the importance of protecting native vegetation, with the creation of the first Forest Code in 1934 and; (v) industrialization process in Brazil started in the 60s, which influenced the land issue in the following years (BECKER, 2016; BORGES; REZENDE; PEREIRA, 2009; FELDMAN, 2001; LOUREIRO; PINTO, 2005; SPAROVEK et al., 2010).

Figure 2.1 - Context of Brazilian environmental legislation. The timeline shows the main laws instituted during this period, the main environmental agencies created, and strategies implemented to curb deforestation and forest degradation in the biome.



(To be continued)

Figure 2.1 – Conclusion.



Source: Author's production.

The occupation of the Amazon began in the 1970s in synergy with the advance of the agricultural frontier to the northern region of Brazil. In addition to the income concentration from large investors attracted to the region by government incentives, this period is also marked by land conflicts triggered by converting public lands into private lands (BECKER, 1980, 1985; LOUREIRO; PINTO, 2005). With a policy of exclusion of local populations, the legitimacy of land grabbing and/or lands illegally acquired by large investors generated land problems that have effects until the present day (LOUREIRO; PINTO, 2005). Rather than promoting the socio-economic development of traditional Amazonian populations, most government initiatives were focused on expanding large-scale activities (BECKER, 1980, 1985; LAURANCE et al., 2001; LOUREIRO; PINTO, 2005). This expansion resulted in a rapid clearing of forest areas to open roads and develop activities such as mining, logging and livestock (AUBERTIN, 2015; LAURANCE et al., 2001).

At the same time that economic development advanced towards the northern region, there was also a need to review the legislation that guaranteed forest protection on private lands in the country. Until the mid-1960s, forest protection was determined by the first Brazilian Forest Code (Decree nº 23.793/1934), established in 1934, which required the maintenance of at least 25% of the forest area on private lands. However, the forest area should not necessarily correspond to native vegetation. Revised in 1965, the Forest Code presented a more conservationist perspective, with more restrictive measures for forest exploitation. For example, protection categories such as Permanent Preservation Areas (APPs, acronym in Portuguese) were included in the law with the aim of conserving forests, soil and water resources. The minimum area required as a Legal Reserve started to vary with the geographical location of the rural property. In this case, clear-cutting in the northern region was limited by maintaining at least 50% of the forest area of the rural property. In other regions of the country, at least 20% of the rural property area should be kept as a Legal Reserve.

In 1966, the Superintendence for Development of the Amazon (SUDAM) was created. In the same year, the law on tax incentives for forestry companies was also published, in which the government allowed the deduction of up to 50% of income tax with proof of investment of this amount in activities such as reforestation (NASCIMENTO; LIMA, 2005). This incentive further strengthened the income concentration of large timber sector investors, who benefited from the tax incentives but did not comply with the reforestation requirements.

While tax incentives were granted to large landowners, the government was looking for labour to populate the Amazon region. In 1970, the National Institute for Colonization and Agrarian Reform (INCRA, acronym in Portuguese) was created, and many migrants were taken to colonize the regions along the Trans-Amazonian road (FEARNSIDE, 1987; FEARNSIDE et al., 2005). The combination of easy access promoted by roads and government colonization programs mainly promoted the occupation of the southern region of Pará and portions of the Western Amazon in the states of Rondônia and Mato Grosso (HURTIENNE, 1999). In a decade, the Amazon population almost doubled, surpassing more than 4 million people living in the region, with 60% residing in rural areas (IBGE, 2010).

In the 1970s, the National Integration Plan (PIN, acronym in Portuguese) and the I National Development Plan (PND, acronym in Portuguese) were also published. These programs further encouraged the expansion of the agricultural frontier and resulted in a period known as the “economic miracle”. (VELOSO; VILLELA; GIAMBIAGI, 2008). Between 1968-1973, the Brazilian GDP grew at a rate of 11% per year, almost three times higher than that achieved between 1964-1967 (VELOSO; VILLELA; GIAMBIAGI, 2008). At the same time, several tax incentives were granted by the Brazilian government until the 1980s, further accelerating the occupation process of the Amazon (FEARNSIDE et al., 2005). Between 1970 and 1985, the number of rural properties in the northern region reached more than 500 thousand, corresponding to a growth of 46% in a period of 15 years (IBGE, 2019).

This unbridled economic growth resulted in the rapid devastation of the Amazon forest. In 1995, Brazil reached the highest historical rate of deforestation in the Amazon, registering almost 30,000 km² of clear-cutting (INPE, 2019a). From this period on, a series of Provisional Measures were adopted by the Brazilian government in an attempt to curb the advance of deforestation in the biome. Among the measures, in 1996, the MP n° 1,511/1996 changed the minimum Legal Reserve in forest areas, increasing the percentage from 50% to 80%. In 1998, the Environmental Crimes Law was created (Law n° 9,605/1998), establishing criminal and administrative sanctions for environmental damage (BRASIL, 1998). In 2000, the National System of Conservation Units (SNUC, acronym in Portuguese, Law n°9,985/2000) was created to expand protected areas on public lands (BRASIL, 2000). In parallel, from 1996 to 2001, reductions in deforestation rates in the Amazon were also controlled by macroeconomic factors, such as inflation and the availability of capital, which affected the availability of public subsidies for large rural landowners (ASSUNÇÃO; GANDOUR; ROCHA, 2015; FEARNSIDE, 2005).

In 2004, the second largest deforestation peak was observed in the Amazon, reaching almost 28,000 km² (INPE, 2019a). This area can again be mainly attributed to the activities of large rural landowners, who were advancing with deforestation to expand soy and accompany the international growth of the beef market (ASSUNÇÃO; GANDOUR; ROCHA, 2015; FEARNSIDE, 2005). In 10 years (1996-2006), the area of pastures grew 40% in the Amazon, totalling almost 10 million ha (IBGE, 2006). In 2005, Brazil's soybean production in the northern region increased by 86% compared to 2000 (IBGE, 2004).

Again, new measures were adopted by the Brazilian government to curb deforestation. In 2004, the Action Plan for the Prevention and Control of Deforestation in the Legal Amazon (PPCDAM, an acronym in Portuguese) was launched, which significantly contributed to the decrease in the deforestation rate in the following years (ASSUNÇÃO; GANDOUR; ROCHA, 2015). DETER was created within the scope of PPCDAM, a near real-time deforestation detection system, that strengthened environmental governance in the Amazon, providing data to guide environmental enforcement in the field (ANDERSON et al., 2005; DINIZ et al., 2015). In 2010, the annual rate of deforestation in the Amazon reduced by 57% compared to the average value observed in the 1990s (INPE, 2019a). Faced with a new environmental context, the agribusiness sector made the period favourable to propose a revision of the Forest Code, alleging a limitation in Brazilian agricultural development (SOARES-FILHO et al., 2014). Amid controversies, the Forest Code was revised again, with new environmental protection regulations instituted by Law n° 12,651/2012 (BRASIL, 2012a). This law included the addition of "carrots" to reduce environmental liabilities on rural properties and the insertion of "sticks", when implementing the Rural Environmental Registry (CAR, acronym in Portuguese) at the national level (SANTIAGO; CAVIGLIA-HARRIS; PEREIRA DE REZENDE, 2018).

The main alterations in the Forest Code included changes in the environmental regularization of the vegetation deficit on private lands. With the new law, Brazil's total "environmental debt" was reduced by 58%, with the largest impact on the existing deficit in the Amazon (SOARES-FILHO et al., 2014). Part of the environmental amnesty was associated with (i) the reduction of minimum restoration widths in APPs along the rivers; (ii) the reduction of the minimum percentage of Legal Reserve for rural properties that had on 22 July 2008, up to four fiscal modules and (iii) inclusion of the APPs in the calculation of the Legal Reserve (SANTIAGO; CAVIGLIA-HARRIS; PEREIRA DE REZENDE, 2018). In addition, participation in the Environmental Regularization Program (PRA, an acronym in Portuguese) guaranteed the landowners the suspension of fines issued before 22 July 2008.

Despite the environmental setback, the New Forest Code established the CAR at the national level, a public electronic tool for environmental monitoring and enforcement of all rural properties in the country (AZEVEDO et al., 2017; ROITMAN et al., 2018). CAR is the first step towards the environmental regularization of rural properties, providing an initial diagnosis of the situation of environmental liabilities/assets. This registry provided a new level of knowledge about the distribution of private lands in the country, providing public data on the location, area and perimeter of each rural property, in addition to information on APPs and Legal Reserve areas of the properties (ROITMAN et al., 2018; STEFANES et al., 2018). In addition to the transparency of the information declared, the CAR is the precursor for implementing the Environmental Regularization Program (PRA) and the Environmental Reserve Quota system (CRA, acronym in Portuguese). PRA aims to establish a commitment between the environmental agency and the landowner to define strategies for recovering environmental liabilities. CRA aims to stimulate trade among landowners with environmental assets/liabilities, promoting environmental compensation by purchasing and selling native vegetation on rural properties. This program has the potential to be the largest market for the forest trade in the world (SOARES-FILHO et al., 2016).

2.3 The role of private lands in protecting forest areas

Creating protected areas is a strategy to protect biodiversity and maintain ecosystem services, in addition to representing an important tool to stop deforestation and forest degradation (PFAFF et al., 2015; WALKER et al., 2009). In the Brazilian Amazon, about 54% of the forest area is under public protection, within indigenous territories and conservation units (SOARES-FILHO et al., 2010). The remaining area is housed in private lands under the protection of the Brazilian Forest Code. This law establishes the general rules to guarantee the preservation of native vegetation and the exploitation of its natural resources, mainly through the requirements of protected areas such as the Legal Reserve and Permanent Preservation Areas (APPs).

The Brazilian Forest Code requires that at least 80% of the forest area of every rural property in the Legal Amazon be kept as a Legal Reserve, to ensure the sustainable use of its natural resources. However, the deficit of 21 ± 1 Mha (SOARES-FILHO et al., 2014) of native vegetation in this biome shows that landowners have neglected the minimum percentages of protection required by the law. Several studies have demonstrated a relationship between the distribution of forest area and the size of rural properties (GODAR et al., 2012, 2014; GODAR; TIZADO; POKORNY, 2012; L'ROE et al., 2016; MICHALSKI; METZGER; PERES, 2010; STEFANES et al., 2018). However, studies on the biome scale are scarce, with the smallest unit of analysis limited to the scale of municipalities (PACHECO, 2012) or census sectors (GODAR et al., 2014). In both cases, to analyse the contribution of different actors in the deforestation of the Legal Amazon, the authors combined remote sensing data with data from the agricultural census carried out by the Brazilian Institute of Geography and Statistics (IBGE, Portuguese acronym).

At the municipal level, Pacheco, 2012 classified the development and expansion of agricultural frontiers in the Amazon, considering the extent of deforestation in each of the 726 evaluated municipalities according to the dominance of rural actors. Godar et al. (2014), used data from the agricultural census to assess rural actors' specific contributions to deforestation and forest degradation in the Legal Amazon. In this case, instead of using the 771 municipalities in the study area, the region was subdivided into 13,303 census sectors. With this approach, the authors provided the first assessment at the sub-municipality level. However, despite the better refinement of the scale, there is still no individual analysis of rural properties, with rural actors being defined according to the dominance of rural properties in each census sector.

More specific knowledge about the contribution of each rural actor is essential for implementing more effective strategies for conserving native vegetation (GODAR et al., 2012, 2014; L'ROE et al., 2016; POKORNY et al., 2013). Godar et al. (2012) argue that the inadequate differentiation between the rural actors harms the application of social and environmental policies in the Amazon region since the observed growth has not resulted in improvements in the situation of the local populations, usually represented by small landowners. In addition, there is expressive inequality in the land distribution, making it necessary to understand not only which policies are most effective for economic development coupled with forest conservation, but also which rural actors can benefit from such instruments (PACHECO, 2012). In this case, the delimitation of rural properties can support a more detailed analysis of who is the main responsible for the conversion of forest areas, indicating the possible actors that should be penalized for neglecting to comply with environmental laws (L'ROE et al., 2016).

2.4 Rural Environmental Registry and monitoring of deforestation and forest degradation

In the mid-2000s, the Brazilian states of Mato Grosso and Pará were pioneers in implementing the CAR (ALIX-GARCIA et al., 2018; AUBERTIN, 2015). In 2012, the revision of the Forest Code generated great environmental losses due to the amnesty of vegetation deficits in rural properties. On the other hand, with the implementation of the CAR at the national level, a new tool was created to monitor and enforce native vegetation on private lands throughout the Brazilian territory (SOARES-FILHO et al., 2014). Recent studies have used this data to generate information at the state level, with a new level of detail on the influence of rural actors in the conversion of native vegetation (RICHARDS; VANWEY, 2016; STEFANES et al., 2018).

Before the CAR, studies evaluating the relationship between deforestation and the size of properties based on individual rural properties were limited to small geographic scales, making it difficult to generalize the results obtained. In general, these studies used data from field interviews and/or data with geographic information available for small areas (GODAR et al., 2012; GODAR; TIZADO; POKORNY, 2008; WALKER; MORAN; ANSELIN, 2000). With the implementation of the CAR at the state/federal level, it became possible to develop studies on broader scales.

L'Roe et al. (2016) evaluated whether the registration of rural property in the CAR influences the occurrence of deforestation in Mato Grosso. The response to CAR enrolment varied with rural property size, with significant results for small properties with an area between 100 ha and 300 ha. In this case, registered properties had a 9% reduction in the probability of deforestation compared to properties not yet declared in the CAR. For this same size class, rural properties registered in the CAR and also registered in Terra Legal, (a government program aimed at allocating and regularizing the acquisition of public lands by giving landowners a land title), showed a 30% drop in the probability of deforestation. In this government program, compliance with environmental policies facilitates the land acquisition process. During the payment period of the property to the government, the existence of environmental infractions can trigger the cancellation of the purchase.

In addition to supporting environmental monitoring, classifying rural properties registered in the CAR into size classes can show how native vegetation, deforestation and carbon stocks are distributed among small, medium and large properties. Richards; Vanwey, 2016, addressed this issue for the state of Mato Grosso and found that about 80% of the native vegetation declared in the CAR is located on large rural properties (greater than 1,000 ha). In this case, only 6% of the carbon stocks are allocated in settlements or rural properties with up to 250 ha. Furthermore, when considering only the portions of the state located in the Amazon biome, properties larger than 1,000 ha accounted for the loss of 38% of the forest area. In contrast, settlements and small rural properties accounted for less than 16% of the observed forest loss in the state. The results also showed that deforestation rates are higher on small properties, however, rates recorded on large properties can result in higher carbon emissions. In this case, the large rural properties have the largest forest area in the state, with about 2,000 properties with an area greater than 5,000 ha, housing the equivalent of 500 Tg C in above-ground living biomass. Finally, the authors suggest that environmental policies for the enforcement of deforestation should be directed to large properties, where the largest forest area is located.

The classification of rural actors based on the property size gives the advantage of generating comparisons between studies that explore the influence of small, medium and large rural properties on land use and land cover change. In the literature, in general, properties with an area of less than 100 ha and greater than 1,000 ha are classified as small and large rural properties, respectively (Table 2.2). However, we observed that this classification is affected by the extent of the study area. In this case, the studies that evaluated the contribution of actors to deforestation throughout the Legal Amazon (GODAR et al., 2014; PACHECO, 2009, 2012), classified properties smaller than 100 ha as small rural properties (Table 2.2). However, we did not observe this consistency in the other size classes. For example, we observed that properties with an area between 500 ha and 1,000 ha can be classified in both the medium and large properties category. (Table 2.2). The analysis scale may be the explanatory factor for this variation, as while Pacheco, 2012 addressed the dominance of rural properties at the municipal level, Godar et al. (2014) evaluated it at the level of census sectors.

State-level studies developed for Mato Grosso (RICHARDS; VANWEY, 2016) and Mato Grosso do Sul (STEFANES et al., 2018) showed a greater division in size classes, however, there is still no standardization of thresholds for the definition of small, medium and large properties. Rural properties with an area between 2,500 ha and 5,000 ha were classified as large rural properties in Mato Grosso and as very large in Mato Grosso do Sul (Table 2.2). Likewise, in Mato Grosso, only properties with an area of less than 100 ha were considered small, while in Mato Grosso do Sul, this limit was up to 150 ha (Table 2.2). Finally, the greatest variation is observed in studies carried out on a local scale in the Amazon (GODAR et al., 2012; GODAR; TIZADO; POKORNY, 2008; MICHALSKI; PERES; LAKE, 2008; WALKER; MORAN; ANSELIN, 2000). In this case, we observed that large rural properties had an area ranging from 150 ha to over 1,000 ha (Table 2.2). These studies were mainly based on questionnaires and/or individual data from a few properties, which may restrict the variability of the sample size of the properties, creating a classification that may not portray the real distribution of small, medium and large rural properties.

Table 2.3 - Classification of the rural property size according to the approaches used in different studies.

	Rural property area (ha)				
	Very small	**Small**	**Medium**	**Large**	**Very large**
Godar et al. (2008)	-	100-200	200-600	>600	-
Pacheco (2009)	-	<100	100-1,000	>1,000	-
Michalski et al. (2010)	-	<150	-	>150	-
Walker et al. (2010)	-	50-100	-	>1000	-
Godar et al. (2012)	-	<200	200-600	>600	-
Pacheco (2012)	-	<100	100-1,000	>1,000	-
Godar et al. (2014)	-	<100	100-500	500-2500	>2,500
Richards et al. (2016)	<100	100-250	250-1,000	1,000-5,000	>5,000
Stefanes et al. (2018)	1-150	150-400	400-1,000	1,000-2,500	>2,500

The variation of the threshold chosen for the classification of rural properties makes it difficult to compare studies and generalize results, which may have implications for implementing environmental policies. Given this variation, using the fiscal module concept may be a better way to maintain standardization in data analysis. A fiscal module is an agrarian unit of measure expressed in hectares that indicates the minimum area for a productive area to be considered economically viable (LANDAU et al., 2012). The fiscal module size varies among municipalities, considering factors such as the predominant production systems in the region and the average income obtained from them, (Law n° 6,746/1979, BRASIL, 1979). Based on these criteria, rural properties can be classified into very small (up to one fiscal module), small properties (between one and four fiscal modules), medium properties (between four and fifteen fiscal modules) and large properties (more than fifteen fiscal modules), (BRASIL, 1993). In addition to allowing a more standardized analysis, this classification is also used in environmental policies aimed at protecting and conserving forests. In the current Brazilian Forest Code, the fiscal module represents a legal instrument for defining the benefits attributed to small properties and the minimum areas for maintaining the Legal Reserve and/or recomposing Permanent Preservation Areas (BRASIL, 2012a).

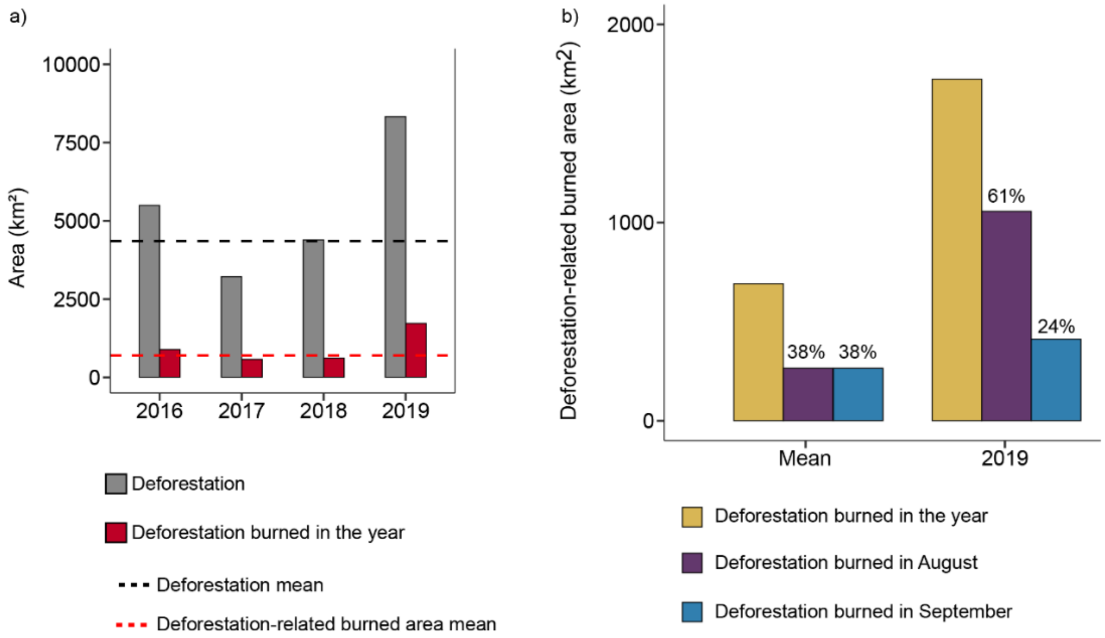
2.5 Types of fire in the Amazon

Natural fires are rare in the Amazon forest, as this biome does not have an evolutionary dynamic linked to fire (COCHRANE; SCHULZE, 1998). Fires in the Amazon are consequences of the interaction between anthropic actions and climate change. In this biome, fire results from its intentional use after deforestation and in land management activities, such as pasture maintenance and removing fallow vegetation (BARLOW et al., 2020; NEPSTAD; MOREIRA; ALENCAR, 1999). However, when fires get out of control, they can cause economic damage to landowners and also result in forest fires (MENDONÇA et al., 2004).

In deforestation-related fire, the felled biomass is burned after being left in the ground to dry (BARLOW et al., 2020). The main causes of deforestation-related fire are related to commodity prices (VERBURG et al., 2014), speculation and concentration of lands (ARMENTERAS et al., 2019), public land grabbing (AZEVEDO-RAMOS; MOUTINHO, 2018) and weak environmental and land governance (REYDON; FERNANDES; TELLES, 2020). Deforestation-related fire produces a huge amount of smoke due to a large amount of fuel load available for burning (Barlow et al. 2020), which affects air quality (BUTT et al., 2020; REDDINGTON et al., 2015) and increases the occurrence of respiratory diseases (MACHADO-SILVA et al., 2020). In the Amazon, not all fire comes from deforestation, but all (or most) deforestation will result in fire (BARLOW et al., 2020). In 2019, amid a political and environmental crisis, the Brazilian Amazon was exposed to a large-scale fire event, attracting international media attention to Brazil. In August 2019, almost 31,000 active fires were registered in the Brazilian Amazon, an increase of 200% over the same period in 2018 (INPE, 2021). This situation caused damage to the population and local ecosystems, in addition to generating far-reaching impacts. Plumes of smoke were carried by the winds reaching the southeastern region of Brazil (LOVEJOY; NOBRE, 2019). This year, Amazonian states such as Acre and Amazonas presented anomalous patterns of deforestation and active fires (SILVEIRA et al., 2020). Given that the highest fire occurrence is concentrated in August and September in the Brazilian Amazon (CARVALHO et al., 2021), I combined data derived from DETER-B (INPE, 2019b) and MODIS/MCD64A1 (GIGLIO et al., 2018) product to estimate the deforested area that is burned in these months in the biome. On average (2016-2018), 38% of the total deforested and burned area in the same year is burned in

August in the Brazilian Amazon, totalling 265 km^2 (Figure 2.2). In August 2019, this value was 61%, totalling 1,050 km^2, a burned area four times greater than the mean for this month (Figure 2.2). It is important to mention that these values are probably underestimate, as the deforestation area detected by PRODES, the official deforestation measure for the Amazon, is 1.54 higher than DETER-B (BARLOW et al., 2020).

Figure 2.2 – a) Deforestation alerts registered by DETER-B from 2016 to 2019 in the Brazilian Amazon. For each year, deforestation-related burned area was calculated from the MODIS/MDC64A1 product. Dashed lines represent the mean of both variables. B) Annual deforestation-related burned area and the percentage of this area burned in August and September.



Source: Author’s production.

Fire is also widely used in rural activities to reduce production costs, representing a tool for land management in agricultural and livestock activities (CARMENTA et al., 2013). Fire is used during deforestation process to burn residues released by the slashing of vegetation (BARLOW et al., 2020; MENDONÇA et al., 2004). It is also used to manage or replace pasture infested by weeds that does not feed cattle properly (BARLOW et al., 2020; MENDONÇA et al., 2004). The socioeconomic context can also define dependence on the use of fire for land management by landowners. Faced with financial limitations, small areas of small properties are converted to crop production, with great dependence on the use of fire for land management (CAMMELLI et al., 2020; CAMMELLI; ANGELSEN, 2019; CARMENTA; COUDEL; STEWARD, 2019b; NEPSTAD et al., 2001). In these properties, the agricultural production is destined for crops such as cassava, rice, corn and beans (CARMENTA et al., 2013; DENICH et al., 2004, 2005). In the family farming system, crop management is associated with fallow cycles, with periods of cultivation/harvest interspersed with slash-and-burn of secondary vegetation (DENICH et al., 2005; SÁ et al., 2007). In these case, fire, in addition to reducing production costs, ashes from burning provide nutrients for crops and reduces soil acidity (DENICH et al., 2004). The slash-and-burn system is also commonly used by indigenous and traditional Amazonian peoples, corresponding to a cultural condition related to their subsistence activities (PIVELLO, 2011).

The use of fire in both deforestation and land management produces ignition sources that can escape beyond the intended areas and result in economic losses and forest fires. Accidental fires affect timber with economic value on properties, damage fences and impact pastures, harming their productivity (ALENCAR et al., 1997). Hoch; Pokorny; Jong, 2012, estimated an average risk of 0.5% to 2% per year in the probability of fire in agricultural areas of small properties. Between 1996 and 1999, Mendonça et al., 2004, estimated fire-related economic losses in Amazon agricultural production between US$87 and 168 million. Oliveira et al., 2018 estimated losses of US$39 ± 2 ha/year for activities such as sustainable timber harvest in the Brazilian Amazon. Economic losses can be even greater when combined with the added effect of extreme climate events. In the 2010 drought, the area affected by forest fires in southwestern Amazonia was 16 times larger than in no-drought years, resulting in an economic loss estimated at US$ 243 ± 85 million (CAMPANHARO et al., 2019).

When forests are affected by fire, the impacts affect biodiversity, carbon stocks and the long-term functioning of the forest. The floristic composition in forests affected by high-intensity fires or exposed to high frequency of burning is modified, with species typical of altered environments (XAUD; MARTINS; DOS SANTOS, 2013). Fire also impacts fauna, with effects on species composition and abundance and changes in microclimate representing a threat primarily to specialist species (ANDRADE et al., 2017). Fire impacts can last for years after forest burning, especially on carbon stocks. Fire-degraded forests can have almost 50% less carbon than intact forests, even after 15 years of regrowth (RAPPAPORT et al., 2018). In addition, carbon stocks can be stabilized 30 years after burning, but due to factors such as late tree mortality, the values can be 24.8(±6.9%) lower than in an intact forest (SILVA et al., 2018a). When fires and extreme droughts occur in synergy, the mortality of large trees can double (BARLOW et al., 2003). The influence of drought events on the occurrence of forest fires is detailed in the next section.

2.6 Droughts and forest fires

Droughts in the Amazon can be attributed to changes in climate cycles that lead to a warming of the Atlantic and Tropical Pacific oceans, triggering events such as the Atlantic multidecadal oscillation (AMO) and El Niño–Southern Oscillation (ENSO), respectively (COELHO et al., 2012; LEWIS et al., 2011; MARENGO; NOBRE; TOMASELLA, 2008). These oceanic oscillations can act alone or together. ENSO tends to affect mainly the central and northern portion of Amazonia, while events such as AMO have a greater influence on the southwestern portion (ARAGÃO et al., 2007; ESPINOZA et al., 2011; MARENGO; NOBRE; TOMASELLA, 2008).

Large forest fires have occurred in drought years in the Amazon. In the 1997/1998 drought, which was associated with an El Niño event, more than 9,000 km² of forests were burned in Roraima (ELVIDGE et al., 2001). The 2005 and 2010 droughts were associated with the anomalous warming of the Atlantic Ocean, attributed to the phenomenon of the Atlantic Multidecadal Oscillation (ARAGÃO et al., 2007a; MARENGO; NOBRE; TOMASELLA, 2008; SILVA JUNIOR et al., 2019). In Acre, the epicentre of the 2005 and 2010 droughts, 90% of the forest area affected by fire, considering the occurrence in a 33-year time series, was concentrated in these two years (SILVA et al., 2018c). The 2015/2016 drought was induced by anomalous warming of the Atlantic and Pacific oceans (SILVA JUNIOR et al., 2019). In 2015, the rainfall deficit exceeded the amplitude and spatial extent of the two previous events, affecting more than 80% of the Amazon basin (PANISSET et al., 2017). In this year, the scarcity of rain resulted in the largest water deficit (-95 mm month^{-1}) recorded between 2003-2015 in the Brazilian Amazon (ARAGÃO et al., 2018). The effects of this drought lasted until 2016, and the burned forest area in both years totalled almost 10,000 km² in the Brazilian Amazon (SILVA JUNIOR et al., 2019).

The Amazon forest becomes more flammable in drought years because it loses the ability to maintain natural barriers against fire, such as the ecological firebreaks formed by the forest canopy (BRANDO et al., 2020). As the rainfall volume reaches the Amazon is reduced, the groundwater recharge is insufficient, and the trees respond by dropping their leaves to decrease water loss through evapotranspiration (NEPSTAD et al., 2004). The structural change of the canopy causes an increase in the light incidence within the forest, turning the environment hotter, drier and more susceptible to fire (COCHRANE et al., 1999). This scenario is aggravated by forest fragmentation, which causes a greater exposure of forest to edge effects, and consequently makes it more fire-prone (SILVA-JÚNIOR et al., 2018), and by deforestation-related fire that increases the ignition sources (BRANDO et al., 2020).

In drought years, forest fires play a key role in carbon emissions in the Amazon. In non-drought years, emissions in the Brazilian Amazon are estimated at -0.24 Pg C year^{-1} (-0.16 to -0.35), but in drought years, they are practically doubled, totalling -0.46 Pg C year $^{-1}$, (-0.24 to -0.74), (ARAGÃO et al., 2014). Forest fires and tree mortality represent the main carbon sources in drought years, accounting for 48% of the total carbon emitted (ARAGÃO et al., 2014). In the 2010 drought, the total carbon emitted in the Legal Brazilian Amazon forest fires corresponded to 86% of the target established in the National Climate Change Plan (Decree N°. 9,578/2018) for deforestation reduction (ANDERSON et al., 2015).

Projections have indicated a trend towards a greater recurrence of droughts in the Amazon, with more frequent, extensive, and severe events (PANISSET et al., 2017). These climate events can lead to increased forest fires, tree mortality and higher carbon emissions to the atmosphere, with critical implications for climate policies. However, despite the crucial role in forest degradation and the carbon balance of the Amazon, forest fires have been largely ignored in Reducing Emissions from Deforestation and Degradation (REDD+) programs (BARLOW et al., 2012). This is worrying for the global climate scenario because, in drought years, forest fires can offset carbon emission reductions achieved with a decrease in deforestation (ARAGÃO et al., 2018).

Furthermore, actions proposed to achieve the emission reduction targets have been directed mainly to curb deforestation, not to mention the importance of preventing and controlling forest fires in the Amazon. Although droughts are uncontrollable climate events, we can still control the effects of anthropic actions. Tackling ignition sources will ultimately decrease the likelihood of fires escaping into forests, reducing impacts on carbon emissions and global climate change.

3 SPATIO-TEMPORAL VARIATION IN DRY SEASON DETERMINES THE AMAZONIAN FIRE CALENDAR [1]

3.1 Introduction

Anthropogenic activities and extreme droughts are the main drivers of fire in the Amazon (ARAGÃO et al., 2007; COCHRANE; LAURANCE, 2008). Amazonian fires are strongly linked to deforestation (ARAGÃO et al., 2008) and public land grabbing (AZEVEDO-RAMOS; MOUTINHO, 2018). Fire is also used for pasture maintenance and weed control by cattle ranchers and in family farming by smallholders, indigenous and traditional peoples (BARLOW et al., 2020). In addition, fires can also accidentally advance to nearby forest areas and in a fire-sensitive system such as the Amazon Forest, result in increased tree mortality (BARLOW et al., 2003; PONTES-LOPES et al., 2021), changes in forest structure and composition (BARLOW; PERES, 2008; BOND; KEELEY, 2005) and long-term reductions in carbon stocks (SILVA et al., 2018a). The synergy between anthropogenic ignition sources and extreme droughts tends to intensify forest fires, resulting in a 50% increase in carbon emissions compared to non-drought years (ARAGÃO et al., 2018). The societal consequences of fires in the Amazon are evidenced by the harming the health of local populations (REDDINGTON et al., 2015; SMITH et al., 2014) and by the huge economic losses, with regional estimates indicating a loss of 9.07 ± 2.46% of gross domestic product (GDP), in southwestern Brazilian Amazon (CAMPANHARO et al., 2019).

Understanding of fire seasonality is critical for a better allocation of resources for socioeconomic and environmental policies, especially when budgets for these proposals are restricted. Indeed, the scarcity of financial resources is a reality faced by several countries in the Amazon basin (HOPE, 2021; LEVIS et al., 2020; SUAREZ; ÁRIAS-ARÉVALO; MARTÍNEZ-MERA, 2018). Thus, actions taken in key months of the fire calendar could help strengthen the tracking of criminal fires and reduce the risk of fires

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[1] - This chapter is based on the paper: Carvalho, N.S., Anderson, L.O., Nunes, C.A., Pessôa, A.C.M., Silva Junior, C.H.L., Reis, J.B.C., Shimabukuro, Y.E., Berenguer, E., Barlow, J., Aragão, L.E.O.C. Spatiotemporal variation in dry season determines the Amazonian fire calendar. Environmental Research Letters, 16 (2021) https://doi.org/10.1088/1748-9326/ac3aa3. This work is licensed under the Creative Commons Attribution 4.0 International License. To view a copy of this license, visit http://creativecommons.org/licenses/by/4.0/ or send a letter to Creative Commons, PO Box 1866, Mountain View, CA 94042, USA.

escaping from anthropogenic areas to surrounding forests. Furthermore, knowing the fire seasonality is equally important to define the periods when controlled burning is allowed, an essential practice for people who depend on it to guarantee their livelihoods (ELOY et al., 2018; MISTRY; BILBAO; BERARDI, 2016), and can have the right of use ensured by law (BRASIL, 2012a). Clarifying fire seasonality is also necessary to reduce uncertainty in estimates of fire-associated carbon emissions in the Amazon, as fire in the onset, middle and end of the dry season have different behaviours (AMARAL et al., 2019; RISSI et al., 2017). Combustion becomes more efficient as the dry season progresses, resulting in reduced carbon monoxide (CO) and increased carbon dioxide (CO_2) emissions (HOFFA et al., 1999).

Fire dynamics are often described in terms of the size, frequency or duration of burn scars (ANDELA et al., 2019). However, despite the clear seasonal coupling between rainfall and fire in the Amazon (ARAGÃO et al., 2008), marked spatial differences in the onset, length, and peak of the dry seasons (ANDERSON et al., 2018; BERENGUER et al., 2021; MOURA et al., 2015), and the strong interannual variation in the hydrological cycle (VILLAR et al., 2009), this variability is rarely included in research. For example, researchers often depict a generalized dry season that has been fixed between July-September (SALESKA et al., 2007; SAMANTA et al., 2010; XU et al., 2011), July-October (COX et al., 2008; MARENGO et al., 2011) or August-October (XU et al., 2020). However, when spatio-temporal variation in the rainfall regime over the Amazon is disregarded, variations in the fire dynamics can consequently be misinterpreted (BERENGUER et al., 2021). Few studies have addressed fire occurrence according to regional dry season patterns (ALENCAR et al., 2015; ARMENTERAS-PASCUAL et al., 2011; MCDANIEL; KENNARD; FUENTES, 2005; ROMERO-RUIZ et al., 2010), but knowledge of this relationship is still unclear for the entire Amazon.

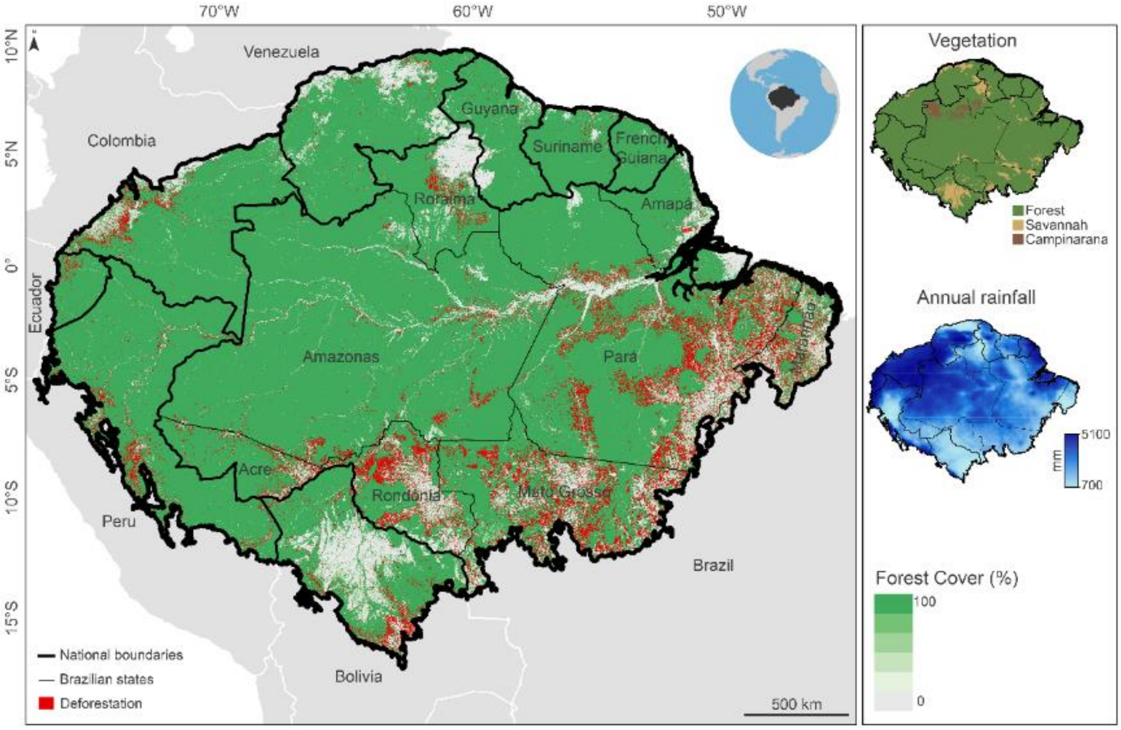
Here, we investigated in detail the interaction between rainfall and fire across the Amazon. With a spatio-temporal stratification of the dry season, we seek to overcome the constraints in understanding the fire dynamics imposed by the variability of the rainfall regime. We aimed to (1) produce spatially explicit maps of the Amazon basin according to the onset, end, and length of the dry season, (2) characterize the fire seasonality according to the variation of the dry season, and (3) define the months with the highest occurrence of active fires, which could be used to inform policy. Given that we are interested in the timing of the fire and not what is burning, we do not attempt to divide fires into their different types. We discuss our results showing the importance of considering the spatio-temporal variations in the dry season across the Amazon to improve the monitoring of the fire occurrence and provide recommendations that can be useful for decision-makers in the strategic management planning across the fire season.

3.2 Methods

3.2.1 Study area

The study area encompasses an area above 6.5 million km² of the Amazon basin, including nine countries in South America, with Brazil accounting for the largest area, covering 63% (Figure 3.1). About 31% is concentrated in the Andean countries Peru (9%), Colombia (7%), Venezuela (7%), Bolivia (7%) and Ecuador (1%). The remaining area occurs in Guyana (3%), Suriname (2%) and French Guiana (1%). In addition to forest areas, savanna patches occur mainly in Bolivia, in the far north of Brazil and Venezuela (Figure 3.1). The Amazon has one of the highest rainfall regimes globally (VILLAR et al., 2009), reaching annual values above 5,000mm in some parts of the basin (Figure 3.1).

Figure 3.1 - Study area in the Amazon basin. The percentage of forest cover and deforestation observed between 2000 and 2020 were extracted from the Global Forest Change data (HANSEN et al. 2013). Vegetation was defined by combining data from global biomes (OLSON et al., 2001) and regional mapping of the Brazilian Amazon (RADAMBRASIL, 1983). Mean annual rainfall was calculated using Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) from 1981 to 2019.



Source: Author's production.

3.2.2 Data and analysis

3.2.2.1 Stratifying the Amazon basin according to dry season variation

We calculated the mean monthly rainfall of each pixel using a 39-year time series (1981 to 2019) from Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS). The CHIRPS algorithm incorporates satellite data, precipitation estimates, and records of in situ pluviometric stations, providing a product since 1981 with a daily frequency and spatial resolution of 5.4 km (FUNK et al., 2015). This is a recent dataset, which has already performed well in several regions of the world (DUAN et al., 2016;

KATSANOS; RETALIS; MICHAELIDES, 2016; PERDIGÓN-MORALES et al., 2018). For Amazon, the validation of these data showed that CHIRPS explains 73% of the data from rain gauge stations (ANDERSON et al., 2018).

We resampled the data to a spatial resolution of 10 km using the bilinear method. We adopted a threshold of 100 mm to define the dry season, as this is the mean monthly evapotranspiration value of tropical forests (ROCHA et al., 2004; SHUTTLEWORTH, 1989; VON RANDOW et al., 2004). With the persistence of rainfall below 100 mm, evapotranspiration exceeds rainfall, which can be used as an indicator of water deficit in tropical forests (ARAGÃO et al., 2007; MALHI et al., 2002). This threshold is also in accordance with the value considered for Amazonian savannas (BIDDULPH; KELLMAN, 1998). We defined the dry season timing by grouping pixels that share the same month for the onset and end of the dry season. We defined the dry season length as the number of consecutive months with rainfall lower than 100 mm. The differentiation between timing and length of the dry season is important because pixels with the same dry season length can have a different dry season timing. For example, if in a pixel the dry season began in June and ended in September, it has a different dry season timing from a pixel that had the onset of the dry season in May and the end in August, although both have a four-month dry season length. All raster files of the dry season (onset, end, and length) are available at Zenodo (https://doi.org/10.5281/zenodo.5706455).

3.2.2.2 Fire seasonality

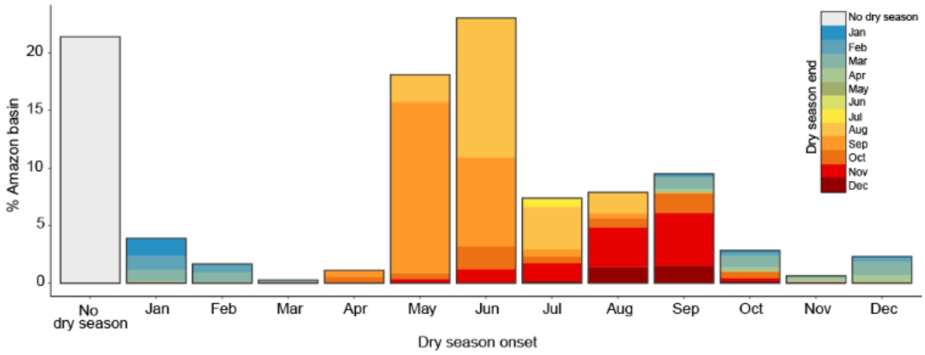
We used active fires data from the Fire Information for Resource Management System (FIRMS), available between 2003 and 2019 (NASA, 2020). We used the standard product of the Aqua/MODIS Collection 6 (GIGLIO et al., 2018), which comprises daily observations and represents the centre of a pixel with a spatial resolution of 1 km. We only considered active fires with a confidence level above 80%.

To characterize the fire seasonality in each cell, we calculated the mean of cumulative active fires on the annual and monthly scales. We also calculated the monthly percentage of fire, expressed as the mean (2003-2019) of the percentage ratio between the number of active fires each month and the total active fires accumulated in the respective year. We defined the fire peak month as the month with the highest monthly percentage of fire.

3.2.2.3 Critical Fire Period

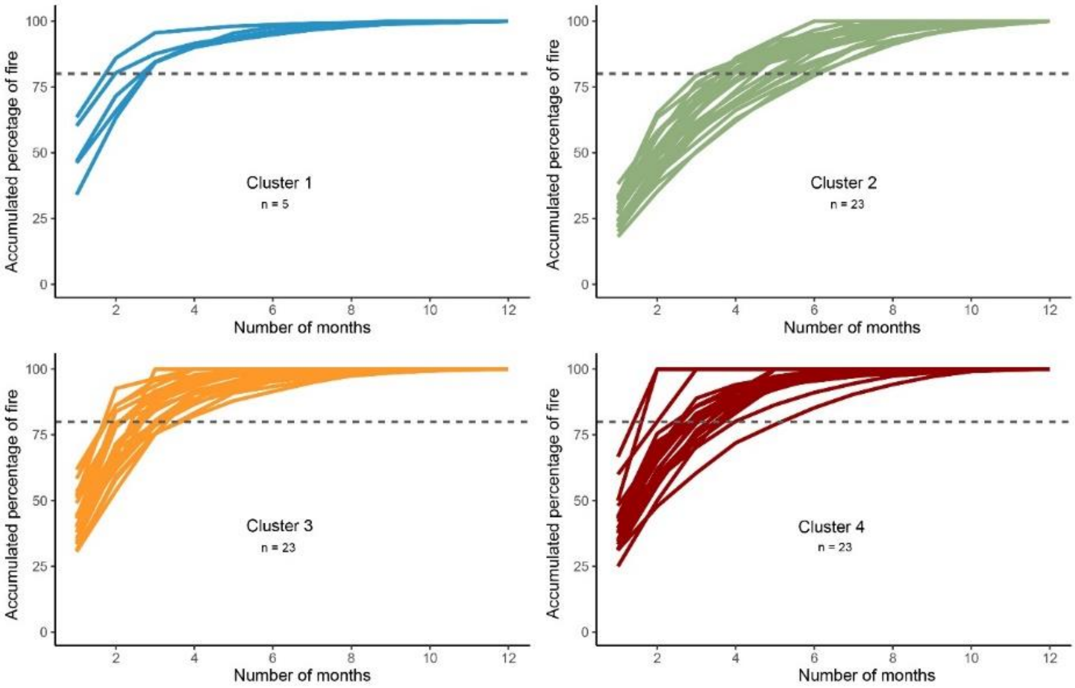
To define Critical Fire Periods across the Amazon, (i) we classified the cells with fire activity considering the dry season regions, which were previously defined according to the dry season timing, (Figure 3.2) and then (ii) we used the k-means clustering method (MacQueen, 1967) to group the regions according to similar behaviour in terms of the monthly percentage of fire. In this step, we first calculated the optimal number of clusters, expressed as the number of clusters for which the decay still results in a high differentiation from the others. Then, the Euclidean distance was considered for clustering in the k-means method, such that regions of the same cluster have high intraclass similarity and low interclass similarity for the other clusters (KASSAMBARA, 2017). For each region of each cluster, we defined the Critical Fire Period as the consecutive months in which the sum of the monthly percentage of fire was above 80%. This threshold was defined to capture both the period of maximum fire activities and a minimum number of months that can be used for strategic planning (Figure 3.3).

Figure 3.2 – Percentage of the Amazon basin covered for each dry season timing (onset-end). Cells that shared the same month for the onset and end of the dry season were grouped in the same dry season timing, resulting in 74 different combinations.



Source: Author’s production.

Figure 3.3 – Accumulated percentage of fire in function of the number of months accumulated. The figure shows the graphs for each Cluster (C1, C2, C3 and C4) and the lines are regions within each Cluster. The dashed line shows the 80% threshold from which adding more months would not result in significant accumulation in the monthly percentage of fire. "n" is the number of regions within each Cluster.



Source: Author's production.

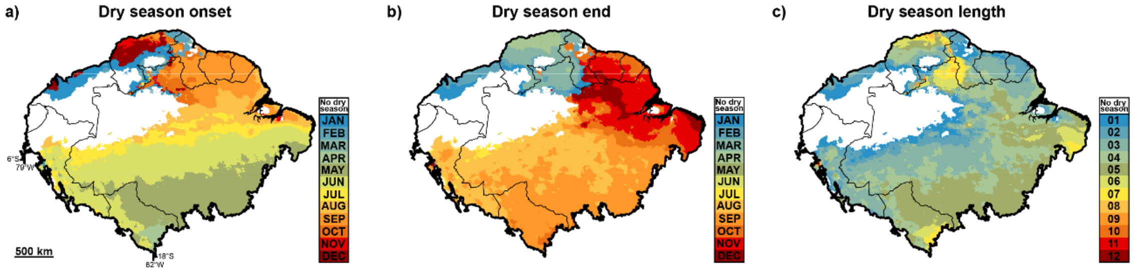
3.3 Results

3.3.1 Spatio-temporal variation of the dry season

The seasonal variation in rainfall was spatially distributed, resulting in 74 regions with different dry season timings (Figure 3.2, Figure 3.4). There is no dry season in 21% of the Amazon, with the largest area, concentrated close to the equator, northwest of the basin (Figure 3.4, Table 3.1). For the remaining area, we observed the expected opposite seasonal patterns between the north and south hemispheres. The dry season between May and September represents 41% of the area and covers most of the basin (Figure 3.4a-b). In the northern hemisphere, in the west part, the dry season occurs between November and April, while in the east, it is concentrated between August and December, encompassing 7% and 14% of the area, respectively (Figure 3.4a-b). In 58% of the

Amazon, the dry season length varied among three (20%), four (17%), and five (21%) months (Figure 3.4c, Table 3.1). The shortest dry season lengths, one and two months, covered 14% of the basin and were adjacent to the aseasonal region. Dry season length of more than five months represented only 6% of the area and was restricted mainly to the north and northeast of the basin (Figure 3.4c, Table 3.1).

Figure 3.4 – Spatio-temporal patterns of the dry season in the Amazon Basin were calculated using CHIRPS data from 1981 to 2019 at a spatial resolution of 10 km. The dry season includes the months with mean monthly rainfall below 100mm. The onset/end months of the dry season are shown in Figure 3.4a-b, respectively. The dry season length is the number of consecutive months of the dry season (Figure 3.4c).



Source: Author's production.

Table 3.1 – Area of the Amazon basin in each onset, end, and length of the dry season. Jan: January, Feb: February, Mar: March, Apr: April, Jun: June, Jul: July, Aug: August, Sep: September, Oct: October, Nov: November, Dec: December.

Onset			End			Length		
Month	**km²**	**%**	**Month**	**km²**	**%**	**Duration**	**km²**	**%**
No dry season	1,427,300	21.40	**No dry season**	1,427,300	21.40	**0**	1,427,300	21.40
Jan	259,700	3.89	**Jan**	139,400	2.09	**1**	378,900	5.68
Feb	111,100	1.67	**Feb**	177,200	2.66	**2**	558,000	8.37
Mar	14,200	0.21	**Mar**	360,400	5.40	**3**	1,301,900	19.52
Apr	75,200	1.13	**Apr**	135,000	2.02	**4**	1,142,900	17.14
May	1,204,300	18.06	**May**	1,200	0.02	**5**	1,405,100	21.07
Jun	1,535,000	23.02	**Jun**	2,200	0.03	**6**	272,200	4.08
Jul	495,400	7.43	**Jul**	57,800	0.87	**7**	146,400	2.20
Aug	524,300	7.86	**Aug**	1,317,800	19.76	**8**	25,800	0.39
Sep	636,800	9.55	**Sep**	1,628,200	24.42	**9**	6,600	0.10
Oct	189,100	2.84	**Oct**	440,800	6.61	**10**	700	0.01
Nov	42,300	0.63	**Nov**	756,000	11.34	**11**	100	0.00
Dec	153,700	2.30	**Dec**	225,100	3.38	**12**	2,500	0.04
Total	**6,668,400**	**100%**	**Total**	**6,668,400**	**100%**	**Total**	**6,668,400**	**100%**

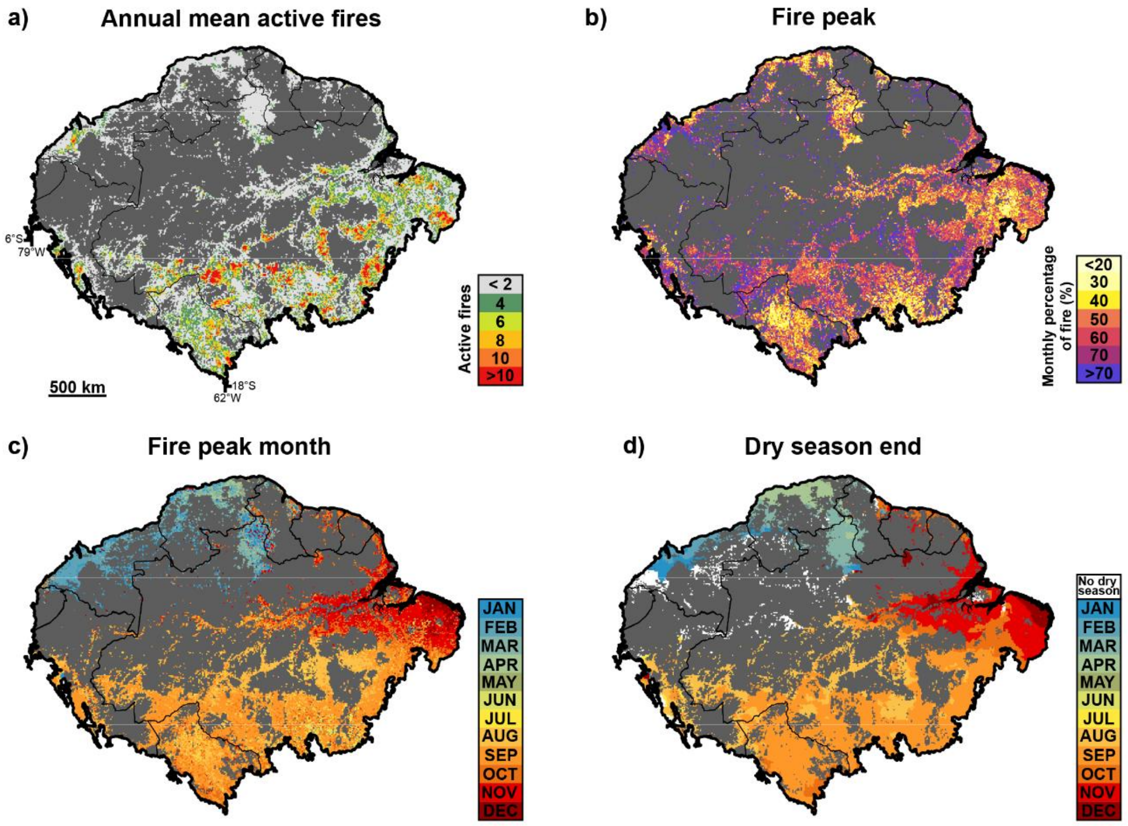
3.3.2 Spatio-temporal relationship between the dry season and fire occurrence

From 2003-2019, an annual average of 63,710 (± 31,088) active fires were observed in an area that covered 42% of the Amazon (Figure 3.5a, Table 3.2). The annual mean was less than two active fires in 62% of cells, corresponding to 18% of observations (Table 3.2). Although only 10% of the cells had more than six active fires, they accounted for 39% of the annual mean (24,752, Table 3.2).

Table 3.2. Cells with active fires were divided into six classes according to the number of active fires observed (<2, 2-4, 4-6, 6-8, 8-10 and >10). The table shows the total cells and annual mean active fires observed in each class.

Class	Cells		Annual mean active fires	
	Number	**%**	**Number**	**%**
<2	17,322	62.47	11,637.94	18.27
2-4	5,243	18.91	15,266.00	23.96
4-6	2,453	8.85	12,053.65	18.92
6-8	1,293	4.66	8,987.06	14.11
8-10	664	2.39	5,939.12	9.32
>10	753	2.72	9,825.82	15.42
Total	**27,728**	**100**	**63,709.59**	**100**

Figure 3.5 - a) Annual mean active fires observed in each cell considering the period between 2003 and 2019. b) Monthly percentage of fire observed in the peak month, the highest burning activity observed in each cell during the year. The monthly percentage of fire was calculated as the mean percentage ratio between the number of active fires each month and the total active fires accumulated in the respective year. Figures 3.5c and 3.5d show the month of the fire peak and the dry season end, respectively. Cells without active fires are shown in dark grey on all maps.



Source: Author's production.

Considering the distribution of fire activity throughout the year, more than half of the annual mean active fires (32,246) occurred in the peak month of each cell (Table 3.3). In 43% of the cells, 30% to 50% of the year's monthly fire percentage occurred in the peak month (Figure 3.5b, Table 3.4a). These contributions were greater in cells with up to six active fires in the peak month (Table 3.4b). Cells with a monthly percentage of fire in the peak month between 50-70% added up to 28% of the cells, with the highest occurrence of these percentages in cells with more than six active fires in the month with the highest burning activity (Figure 3.5b, Table 3.4). Furthermore, the shorter the dry season length, the more concentrated the burning activity was in the peak month, with a predominance of the monthly percentage of fire above 70% in cells with a dry season varying between zero and three months (Figure 3.6).

Table 3.3 - Mean of active fires observed in the year and fire peak month. The percentage of active fires in the fire peak to the total annual is also shown. Values are presented for the Amazon basin, as well as for Amazon countries and Brazilian states.

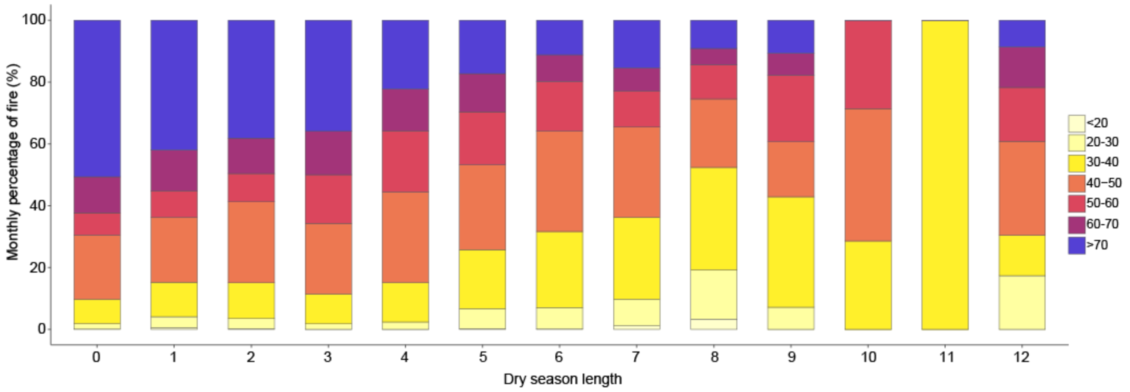
		Mean of active fires		
		Annual	**Fire peak month**	
			Total	**%**
	Amazon Basin	**63,709.59**	**32,245.65**	**50.61**
Country	**Bolivia**	8,439.59	3,897.59	46.18
	Brazil	50,036.88	25,381.29	50.73
	Colombia	1,800.65	1,158.82	64.36
	Ecuador	7.18	5.24	72.95
	French Guiana	65.35	37.65	57.61
	Guyana	241.00	94.29	39.13
	Peru	1,976.59	1,158.88	58.63
	Suriname	79.47	43.41	54.63
	Venezuela	1,062.88	468.47	44.08
Brazilian state	**Acre**	2,196.41	1,315.82	59.91
	Amazonas	3,355.88	1,797.24	53.55
	Amapá	636.82	348.06	54.66
	Maranhão	4,168.47	2,009.82	48.21
	Mato Grosso	12,782.94	6,103.24	47.75
	Pará	18,475.47	9,446.59	51.13
	Rondônia	7,259.53	3,834.94	52.83
	Roraima	978.06	439.76	44.96
	Tocantins	183.29	85.82	46.82

Table 3.4 - Fire occurrence in the peak month. Table 3.4a shows the distribution of cells with burning activity according to the monthly percentage of fire observed in the peak month (10-20%, 20-30%, 30-40%, 40-50%, 50-60%, 60-70% and >70%). Table 3.4b shows the cells divided into six classes according to the accumulated active fires in the peak month (<2, 2-4, 4-6, 6-8, 8-10 and >10) and their distribution considering the classes of the monthly percentage of fire.

a)	**Monthly percentage of fire (%)**							
	10-20	**20-30**	**30-40**	**40-50**	**50-60**	**60-70**	**>70**	**Total**
Cells	62	1,269	4,417	7,474	4,398	3,392	6,716	27,728
%	0.22	4.58	15.93	26.95	15.86	12.23	24.22	100

b) **Active fires**	**Cells**	**Monthly percentage of fire (%)**							
		10-20	**20-30**	**30-40**	**40-50**	**50-60**	**60-70**	**>70**	**Total (%)**
<2	22,776	0.27	5.31	17.14	26.92	12.72	10.90	26.74	100
2-4	3,334	0.03	1.65	12.96	28.61	28.25	16.56	11.94	100
4-6	1,043	0.00	0.38	6.33	26.56	32.69	19.85	14.19	100
6-8	391	0.00	0.00	3.32	18.93	38.36	25.58	13.81	100
8-10	128	0.00	0.00	2.34	24.22	35.94	23.44	14.06	100
>10	56	0.00	0.00	0.00	10.71	39.29	35.71	14.29	100
Total	27,728	-	-	-	-	-	-	-	-

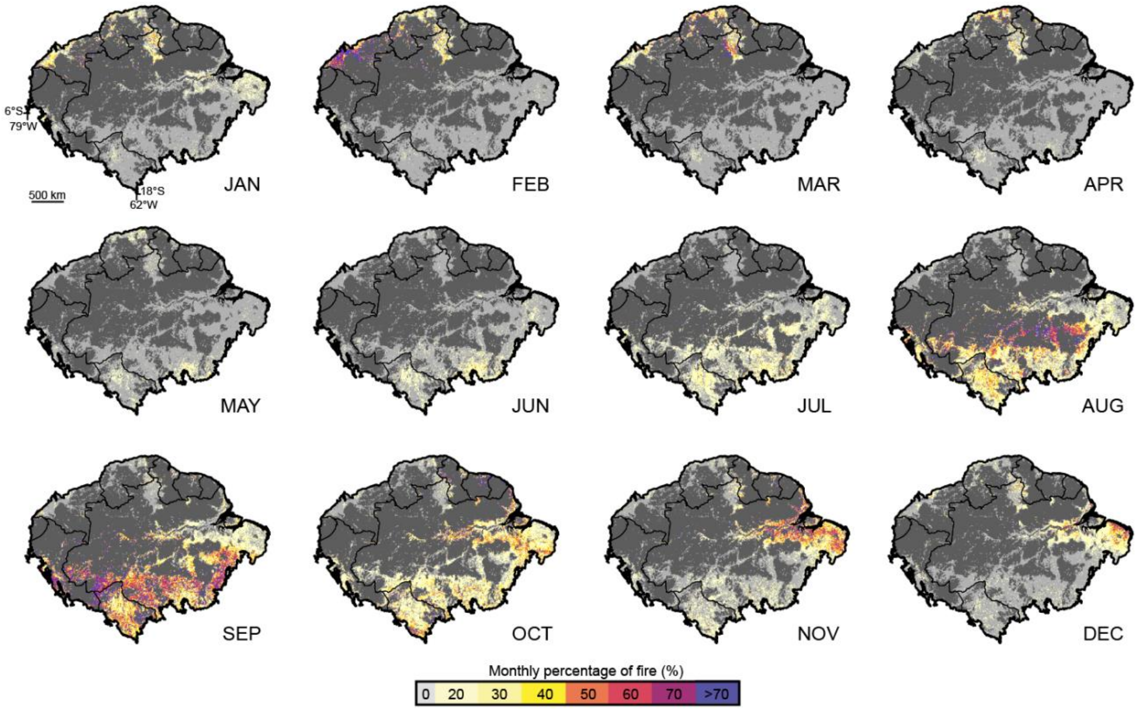
Figure 3.6 - Cell distribution for each dry season length according to the monthly percentage of fire observed in the peak month (<20%, 20-30%, 30-40%, 40-50%, 50-60%, 60-70% and >70%).



Source: Author's production.

We observed two opposite fire seasons in the northern and southern hemispheres, concentrated at the beginning and end of the year, respectively (Figure 3.7). Furthermore, we observed a well-defined spatio-temporal relationship between the fire peak and the dry season end (Figure 3.5c-d). As the dry season end, the fire peak month showed three clear patterns throughout the basin with different seasons among the south, north, and eastern Amazon (Figure 3.5c-d, Table 3.5). In 52% of the cells, mainly covering the centre-south of the basin, the fire peak occurred in August (17%) and September (35%) (Figure 3.5c, Table 3.5a). Concentrated in the eastern Amazon, 28% of the cells presented the fire peak in the last trimester of the year. In 14% of them, the peak occurred in October, 11% in November and 4% in December (Figure 3.5c, Table 3.5a). Conversely, in the north of the basin, the fire peak occurred in the first three months of the year, encompassing 14% of the cells distributed in January (4%), February (6%) and March (4%), (Figure 3.5c, Table 3.5a).

Figure 3.7 – Monthly percentage of fire observed throughout the year. The monthly percentage of fire was calculated as the mean percentage ratio between the number of active fires each month and the total active fires accumulated in the respective year. Cells without active fires are shown in dark grey on all maps.



Source: Author’s production.

Table 3.5 - Table 3.5a shows the total of cells with burning activity, and Table 3.5b shows the total of active fires observed in the fire peak month. According to the fire peak month, percentage distribution of cells and active fires is presented in Table 3.5a and 3.5b, respectively. Values are presented for the Amazon basin, as well as for Amazon countries and Brazilian states. Jan: January, Feb: February, Mar: March, Apr: April, Jun: June, Jul: July, Aug: August, Sep: September, Oct: October, Nov: November, Dec: December.

a)			**Distribution of cells according to fire peak month (%)**											
		Cells	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
	Amazon Basin	27,728	4.10	6.37	3.99	1.58	0.35	0.97	2.59	16.77	34.91	13.57	11.19	3.60
Country	**Bolivia**	3,318	0.09	0.03	0.00	0.12	0.21	0.51	3.22	20.92	55.76	17.96	1.08	0.09
	Brazil	19,063	2.10	1.49	2.01	0.39	0.40	1.30	2.95	18.41	36.33	14.57	15.34	4.72
	Colombia	1,531	21.75	66.82	7.71	0.59	0.07	0.00	0.00	0.26	1.18	0.33	0.26	1.05
	Ecuador	41	43.90	34.15	0.00	0.00	0.00	0.00	0.00	7.32	4.88	2.44	7.32	0.00
	French Guiana	91	0.00	1.10	0.00	0.00	0.00	0.00	0.00	0.00	12.09	69.23	17.58	0.00
	Guyana	486	16.05	8.44	16.67	14.61	0.21	0.41	0.21	0.82	6.17	23.25	9.47	3.70
	Peru	1,459	2.81	1.30	0.07	0.21	0.14	0.21	3.22	29.68	55.04	4.80	1.58	0.96
	Suriname	209	2.39	0.96	2.87	3.83	0.48	0.00	0.00	0.00	13.40	55.02	17.22	3.83
	Venezuela	1,530	16.99	24.97	33.66	17.58	0.59	0.00	0.07	0.20	0.92	1.44	1.05	2.55
State	**Acre**	983	0.00	0.00	0.00	0.00	0.00	0.00	0.51	24.11	74.47	0.92	0.00	0.00
	Amazonas	2,690	2.94	2.57	0.63	0.07	0.11	0.45	4.05	34.46	33.05	14.91	5.54	1.23
	Amapá	519	0.58	0.00	0.00	0.00	0.00	0.00	0.00	0.19	3.28	35.26	51.83	8.86
	Maranhão	1,238	0.48	0.08	0.00	0.00	0.08	0.16	0.48	2.58	13.33	20.84	41.52	20.44
	Mato Grosso	4,039	0.35	0.10	0.17	0.20	1.71	5.42	7.18	14.73	55.56	13.64	0.74	0.20
	Pará	6,532	0.81	0.02	0.00	0.00	0.00	0.15	1.88	20.42	22.32	17.25	29.35	7.79
	Rondônia	1,906	0.00	0.00	0.00	0.00	0.10	0.16	1.36	19.15	70.78	8.24	0.16	0.05
	Roraima	1,007	24.23	20.56	35.75	6.36	0.10	0.00	0.00	0.30	0.30	3.67	3.97	4.77
	Tocantins	149	0.67	1.34	0.00	0.00	0.00	0.67	2.68	10.07	45.64	36.91	1.34	0.67

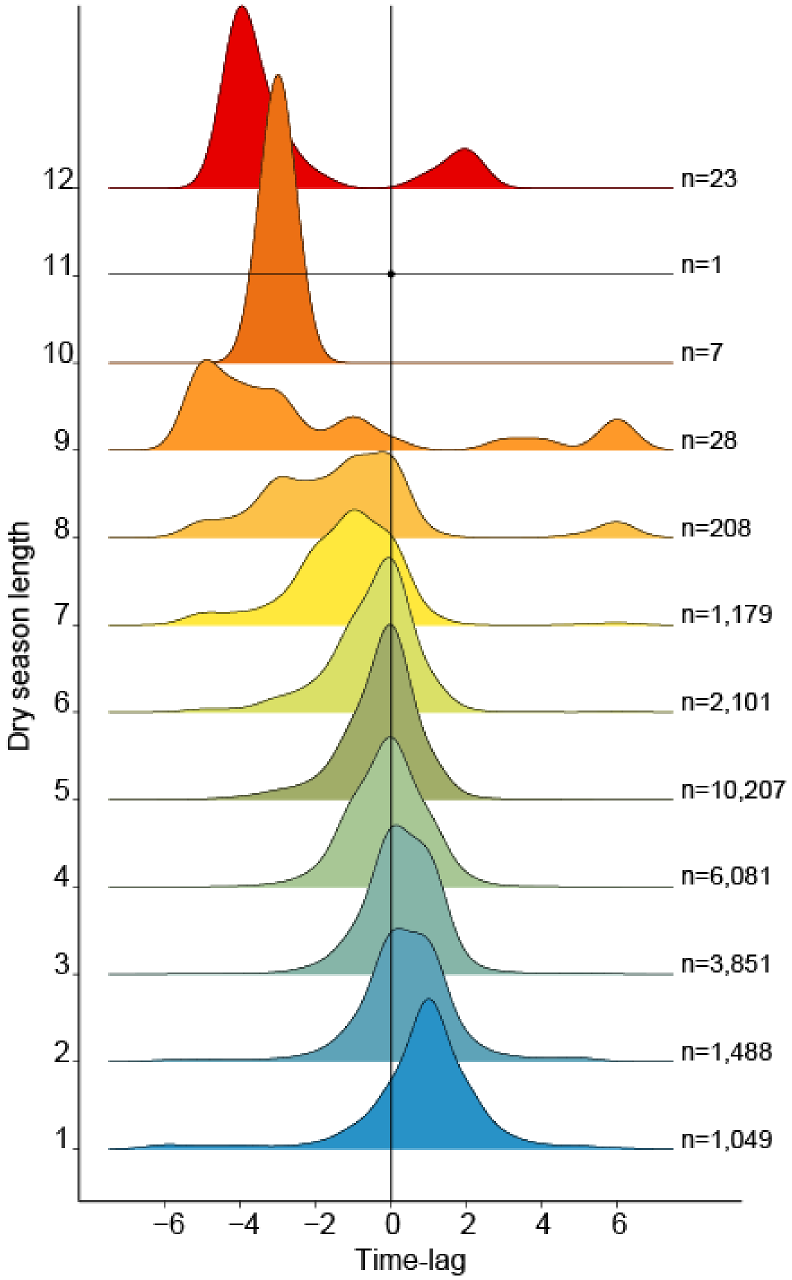
b)			**Distribution of active fires according to fire peak month (%)**											
		Active fires	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
	Amazon Basin	32,245.65	0.92	3.74	1.47	0.42	0.10	0.52	1.01	20.39	47.95	9.71	11.28	2.48
Country	**Bolivia**	3,897.59	0.01	0.00	0.00	0.01	0.03	0.07	1.37	20.99	60.90	16.36	0.27	0.00
	Brazil	25,381.29	0.38	0.35	0.98	0.06	0.12	0.65	1.06	21.69	48.08	9.39	14.17	3.07
	Colombia	1,158.82	8.73	87.09	3.33	0.07	0.01	0.00	0.00	0.03	0.30	0.04	0.05	0.36
	Ecuador	5.24	42.70	43.82	0.00	0.00	0.00	0.00	0.00	4.49	4.49	1.12	3.37	0.00
	French Guiana	37.65	0.00	0.31	0.00	0.00	0.00	0.00	0.00	0.00	4.22	87.50	7.97	0.00
	Guyana	94.29	14.16	4.62	13.85	11.85	0.12	0.19	0.06	0.87	3.93	33.31	13.60	3.43
	Peru	1,158.88	1.15	0.24	0.01	0.02	0.01	0.03	0.41	21.55	75.11	1.18	0.20	0.10
	Suriname	43.41	1.22	0.27	2.44	2.98	0.14	0.00	0.00	0.00	10.03	61.25	19.65	2.03
	Venezuela	468.47	14.48	21.17	37.26	22.75	0.23	0.00	0.06	0.06	0.53	0.87	0.59	2.01
State	**Acre**	1,315.82	0.00	0.00	0.00	0.00	0.00	0.00	0.03	8.68	90.83	0.47	0.00	0.00
	Amazonas	1,797.24	0.62	0.91	0.24	0.01	0.01	0.04	0.76	51.58	34.48	8.74	2.41	0.21
	Amapá	348.06	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.05	2.74	30.44	57.46	9.26
	Maranhão	2,009.82	0.07	0.00	0.00	0.00	0.00	0.03	0.16	2.00	12.72	23.61	46.97	14.45
	Mato Grosso	6,103.24	0.02	0.01	0.01	0.01	0.49	2.63	3.36	13.04	73.21	7.06	0.14	0.02
	Pará	9,446.59	0.08	0.00	0.00	0.00	0.00	0.02	0.39	31.17	27.36	11.07	25.26	4.64
	Rondônia	3,834.94	0.00	0.00	0.00	0.00	0.01	0.03	0.20	17.61	78.85	3.29	0.01	0.00
	Roraima	439.76	17.17	16.45	55.22	3.42	0.05	0.00	0.00	0.05	0.11	1.40	3.04	3.08
	Tocantins	85.82	0.07	0.21	0.00	0.00	0.00	0.21	0.89	7.81	52.64	36.94	1.10	0.14

Regarding the time-lag to the dry season end, fire peaks were concentrated in the last two months of the dry season and the first month of the subsequent rainy season. In 47% of the cells that had a dry season defined, the fire peak and dry season end occurred in the same month (Figure 3.5c-d, Table 3.6). 40% of the cells had a one-month lag between the dry season end and the fire peak, of which 20% had a fire peak one month before the dry season end, and 20% had a fire peak in the month after the end of the dry season (Figure 3.5c-d, Table 3.6). Considering the dry season length of the cells, the time-lag revealed a unimodal distribution for most lengths (Figure 3.8). The greatest correspondence between the fire peak and the dry season end occurred in the dry season length of five months, accounting for 56% of the total cells (Figure 3.8, Table 3.7). We also observed that the longer the dry season length, the greater the number of cells with the fire peak in the months before the end of the dry season (Figure 3.8). Conversely, fire peaks after the dry season end were more frequent in cells with a dry season length of less than three months, occurring mainly in the first month of the rainy season and representing 36% to 48% of the total cells (Figure 3.8, Table 3.7).

Table 3.6 - Total of cells observed in each time-lag between the months of the fire peak and dry season end. Cells with active fires, but no dry season, were not considered.

Time-Lag	Cells	%
-6	34	0.13
-5	130	0.50
-4	207	0.79
-3	594	2.27
-2	1,368	5.22
-1	5,343	20.38
0	12,454	47.49
1	5,193	19.80
2	611	2.33
3	125	0.48
4	63	0.24
5	62	0.24
6	39	0.15
Total	**26,223**	**100%**

Figure 3.8 – Distribution of cells according to the time-lag between the fire peak and dry season end, considering their dry season length. The number of cells observed for each dry season length is shown on the right of each distribution graph. Cells without time-lag had the dry season end and fire peak in the same month. Negative and positive time-lags indicate fire peaks occurring in the months before and after the end of the dry season, respectively. Cells with active fires but no dry season are not shown.



Source: Author’s production.

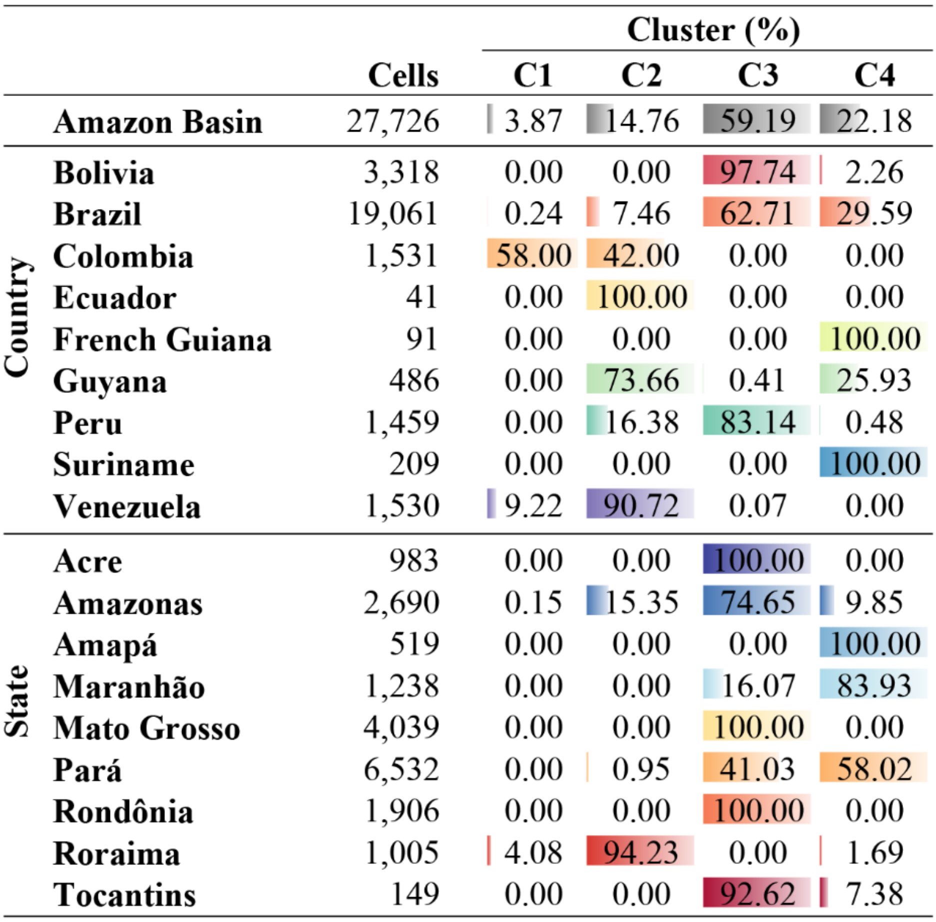
Table 3.7 – Total of cells with burning activity observed in each dry season length. The table also shows the percentage distribution of cells according to the time-lag between the months of the fire peak and dry season end. Cells without time-lag had the dry season end and fire peak in the same month. Negative and positive time-lags indicate fire peaks occurring in the months before and after the end of the dry season, respectively.

			Time-lag												
Dry season length (months)		**Cells**	**-6**	**-5**	**-4**	**-3**	**-2**	**-1**	**0**	**1**	**2**	**3**	**4**	**5**	**6**
	1	1,049	1.33	0.86	1.05	0.67	1.53	6.01	17.16	47.66	17.35	4.00	1.14	0.95	0.29
	2	1,488	0.47	0.74	0.54	0.81	2.35	10.01	38.98	36.42	5.78	1.75	0.87	1.21	0.07
	3	3,851	0.08	0.13	0.16	0.49	2.34	11.35	44.72	36.67	2.65	0.65	0.23	0.47	0.08
	4	6,081	0.02	0.08	0.18	0.99	4.09	25.09	46.24	20.36	2.47	0.23	0.15	0.05	0.05
	5	10,207	0.08	0.14	0.80	2.73	5.04	21.23	56.49	12.32	0.72	0.17	0.18	0.09	0.02
	6	2,101	0.00	1.05	0.90	4.33	7.81	26.32	48.83	9.85	0.67	0.00	0.05	0.00	0.19
	7	1,179	0.08	3.82	3.39	6.11	22.65	33.67	26.55	2.71	0.08	0.00	0.00	0.17	0.76
	8	208	0.00	5.29	5.29	18.27	14.90	23.08	25.48	1.44	0.00	0.00	0.00	0.96	5.29
	9	28	0.00	28.57	17.86	17.86	3.57	10.71	3.57	0.00	0.00	3.57	3.57	0.00	10.71
	10	7	0.00	0.00	0.00	100.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	11	1	0.00	0.00	0.00	0.00	0.00	0.00	100.00	0.00	0.00	0.00	0.00	0.00	0.00
	12	23	0.00	0.00	60.87	17.39	4.35	0.00	0.00	4.35	13.04	0.00	0.00	0.00	0.00

3.3.3 Critical fire period

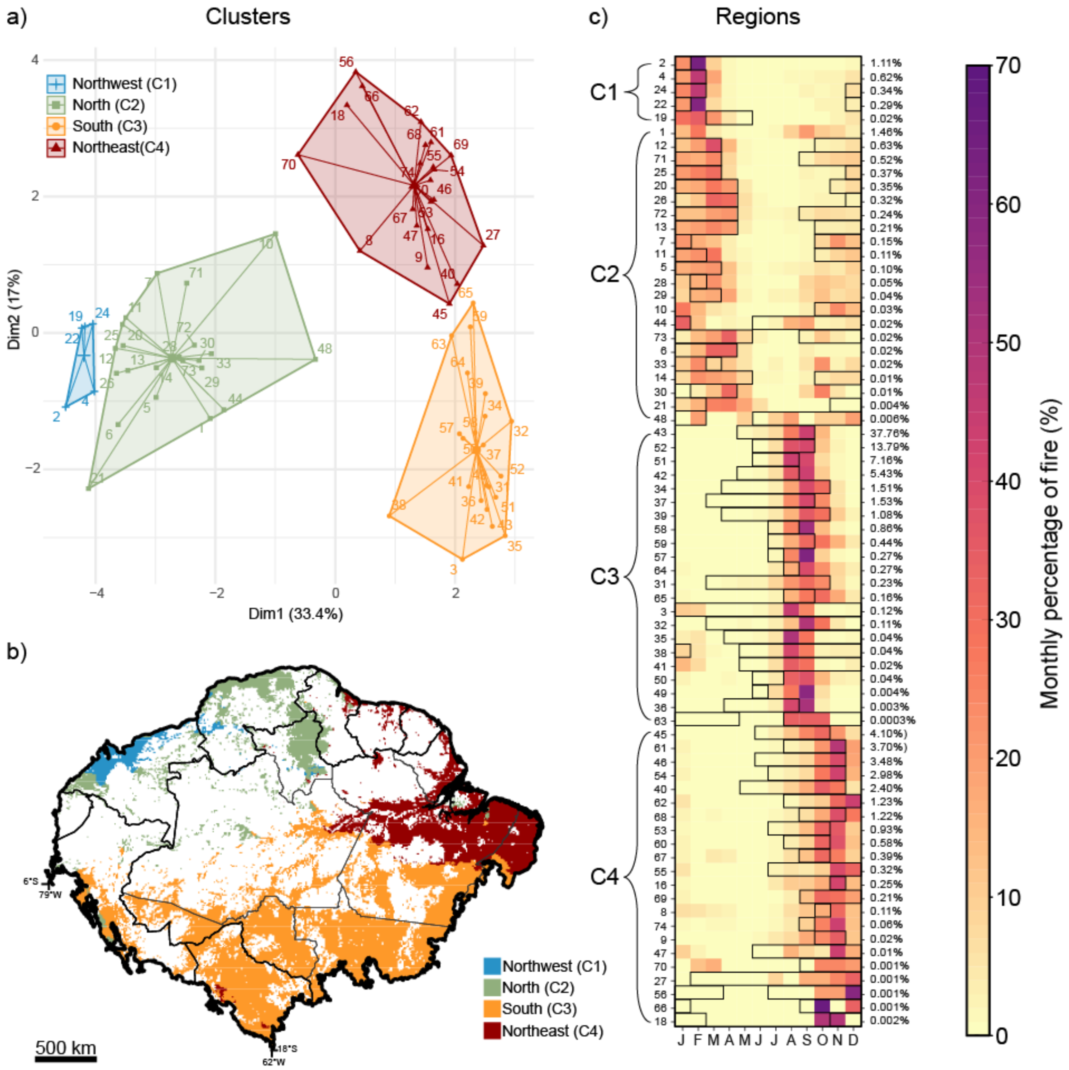
We found four clusters with clear spatial patterns distributed among the northwest (C1), north (C2), south (C3), and northeast (C4) (Table 3.8, Figure 3.9a-b). C1 covered regions with a dry season length of less than three months and occurring at the beginning of the year. This cluster concentrated 2.38% (1,519) of the annual mean active fires, with most critical periods start in January and last two to three months, which can encompass the entire dry season, as well as the subsequent onset of the rainy season (Figure 3.9c). The longest critical periods were observed in C2, located in the savanna areas of northern Brazil and Venezuela, ranging from four to seven months (Figure 3.9b-c). C2 concentrated 4.68% (2,984) of the annual mean active fires, and the regions with the highest burning activity had critical periods ending in March/April (Figure 3.9c). These regions showed a dry season length of four to seven months and had a more equitable distribution of the monthly percentage of fire during the critical period, with values mainly ranging between 10% and 30% (Figure 3.9c). C3 covered the basin area with the highest burning activity, with critical periods mainly beginning in August and lasting for two to three months in the six regions that added up to 67% (42,837) of the annual mean active fires (Figure 3.9c). In general, this period included the dry season end and the rainy season onset, with mean monthly percentages of fire for August, September, and October of 31%, 41% and 18%, respectively (Figure 3.9c). The critical periods in C4 mainly included three to four months, ending in November/December. In the eight regions that concentrated 20% (12,766) of the annual mean active fires, the critical period was concentrated in the last two months of the dry season and the first month of the rainy season subsequent, accounting for about 62% and 23% of the monthly percentage of fire of the year, respectively.

Table 3.8 - Percentage distribution of cells according to clusters C1, C2, C3 and C4. Clusters were defined considering the similar behaviour of the monthly percentage of fire in regions with burning activity. Values are presented for the Amazon basin, as well as for Amazon countries and Brazilian states.



			Cluster (%)			
		Cells	**C1**	**C2**	**C3**	**C4**
	Amazon Basin	27,726	3.87	14.76	59.19	22.18
Country	**Bolivia**	3,318	0.00	0.00	97.74	2.26
	Brazil	19,061	0.24	7.46	62.71	29.59
	Colombia	1,531	58.00	42.00	0.00	0.00
	Ecuador	41	0.00	100.00	0.00	0.00
	French Guiana	91	0.00	0.00	0.00	100.00
	Guyana	486	0.00	73.66	0.41	25.93
	Peru	1,459	0.00	16.38	83.14	0.48
	Suriname	209	0.00	0.00	0.00	100.00
	Venezuela	1,530	9.22	90.72	0.07	0.00
State	**Acre**	983	0.00	0.00	100.00	0.00
	Amazonas	2,690	0.15	15.35	74.65	9.85
	Amapá	519	0.00	0.00	0.00	100.00
	Maranhão	1,238	0.00	0.00	16.07	83.93
	Mato Grosso	4,039	0.00	0.00	100.00	0.00
	Pará	6,532	0.00	0.95	41.03	58.02
	Rondônia	1,906	0.00	0.00	100.00	0.00
	Roraima	1,005	4.08	94.23	0.00	1.69
	Tocantins	149	0.00	0.00	92.62	7.38

Figure 3.9 - The regions defined according to the dry season timing (onset/end) were grouped into four clusters (C1, C2, C3 and C4), considering the similar behaviour of the monthly percentage of fire (Figure 3.9a). The monthly percentage of fire in each region was calculated as the mean percentage ratio between the number of active fires each month to the total active fires accumulated in the respective year. The spatial distribution of the four clusters is illustrated in Figure 3.9b. The monthly percentage of fire for each region in each cluster is illustrated in Figure 3.9c. The regions are ranked in descending order within each cluster according to the percentage of active fires in relation to the annual mean active fires (63,710) observed in the Amazon basin. Black rectangles illustrate the dry season timing of each region.



Source: Author's production.

3.4 Discussion

Although the dry season plays a key role in the fire occurrence, the spatio-temporal relationship between these variables was not clear for the Amazon. We advanced on this issue, stratifying the Amazon into dry season regions and showing spatially explicit results of the fire calendar for each of them. The characteristics of the dry season allowed us to describe a spatio-temporal variation beyond those widely reported in the main deforestation epicentres in the Amazon (ARAGÃO et al., 2008; MAEDA et al., 2009). We outline the importance of the fire calendar for (i) research examining fire dynamics and (ii) policy and management.

3.4.1 Analytical importance

Our analysis clearly shows that fire analyses that disregard the seasonality of the dry season will misrepresent fire dynamics in several parts of the Amazon (BERENGUER et al., 2021). For example, an approach that uses the epicentres of deforestation to fix a single dry season for the entire basin would misinterpret the fire dynamics in about 48% of the Amazon (Table 3.5a). This includes some notable fire hotspots such as Roraima, the location of the 1997-98 megafires (ELVIDGE et al., 2001); Colombia, where deforestation-related fires are expanding in recent years (ARMENTERAS-PASCUAL et al., 2011); and the eastern Amazon, including some of the deforested regions where both indigenous peoples and endemic species are highly threatened (SILVA JUNIOR et al., 2020). The importance of these regions demonstrates the fact that Amazon-wide assessments of fire must consider seasonality.

Defining the present-day fire calendar could also help track how climate change could modify fire seasons, which is important given fire’s key role in any large-scale forest dieback (NOBRE et al., 2016). Extreme droughts are affecting the Amazon with greater frequency, extension and severity (PANISSET et al., 2017). Furthermore, the dry season is becoming longer (ANDERSON et al., 2018), with some regions in the Southern Amazon extending by one week per decade (FU et al., 2013). Changes in the timing and length of the dry season can modify the fire-prone period throughout the year, and the calendar presented could help to track changes in fire seasonality more clearly. In the last 40 years, some parts of the Amazon have seen a 34% reduction in rainfall between August and October, in addition to temperature increases of up to 2.5°C (GATTI et al., 2021). As our results show that 65% of the Amazon has a fire peak between August and October, these changes may be relevant to the fire calendar, particularly in the south and east regions (Table 3.5a). In a trend towards a warmer dry season and even drier months, we can also expect a change in the fire type occurring, mainly due to an increase in forest fires, as these conditions boost the flammability of the forest, making it a fire-prone system (BRANDO et al., 2020). Linking fire seasonality to fire type is challenging (CHEN et al., 2013) but remains an important research priority to track the impacts of fire (Barlow et al. 2020).

3.4.2 Fire policy and practice

Fire prevention/fighting actions are more successful when a fire calendar is available (ANDERSON et al., 2021; MCKEMEY et al., 2021), and its lack has led to actions that do not fully contemplate fire planning, prevention and mitigation. For example, in August 2019, the Brazilian Amazon was exposed to a large increase in the fire that drew the world's attention (BARLOW et al., 2020). To curb this environmental crisis, the Brazilian government enacted decrees prohibiting the use of fire until the end of October. However, the control did not last long, and as soon as the law validity expired, fire rose again in November (SILVEIRA et al., 2020). Our analysis shows territorial boundaries are not the most suitable limits for defining seasonally-dependent environmental policies, especially in countries like Brazil with continental dimensions. We defined three different fire periods in the Brazilian Amazon, which should be considered for more specific policy making (Table 3.8, Figure 3.9). This is especially important for a Bill to develop a National Integrated Fire Management Policy in Brazil, which has been in progress since 2018 (BRASIL, 2018); our results would provide science-based guidelines to incorporate the seasonality and spatio-temporal variation of the fire in the region. The fire calendar can also improve policy at smaller scales: for example, Pará, one of the Brazilian states with the highest burning activity, has two distinct fire seasons (Figure 3.9).

The fire calendar can also help define when prevention/firefighting actions need to be implemented in relation to the dry season onset. In general, the shorter the dry season length, the faster these actions must be taken to ensure its effectiveness. This is particularly important in countries such as Colombia, where favourable conditions for fire have a shorter duration, and for this reason, the burning activity begins as soon as the dry season starts. Importantly, we found that longer dry seasons do not imply a longer Critical Fire Period, except for savanna areas where dry season length can extend beyond six months; these savannas have evolved with fire and active fires were distributed more evenly during the dry season. However, in most of the basin, if fire containment interventions were concentrated for three to four months, the reduction could reach more than 80%. Furthermore, it is interesting to note that the Critical Fire Period can also cover the rainy season onset. As the fuel load at the end of the dry season is in its driest condition, the fire can still be sustained at the onset of the subsequent rainy season, stressing the need to monitor this period.

Our research did not differentiate fire types, which is an important element of determining fire containment measures. In many cases, fire is just a signal of deforestation (ARMENTERAS-PASCUAL et al., 2011); here, efforts should go on detecting and combating forest loss, not fire per se. Fire is often used by those who depend on it for their livelihood, consisting, in these cases, the only viable tool to guarantee food production. However, it is necessary to implement a fire calendar indicating allowed burning periods and how the practice should be carried out to reduce the risk of fires escaping into the remaining forests. At the same time, environmental enforcement must focus on the Critical Fire Periods, ensuring greater success in actions to curb the illegal use of fire in agriculture. By defining these periods, it is possible to make the best use of the scarce resources across Amazon countries (HOPE, 2021; LEVIS et al., 2020; SUAREZ; ÁRIAS-ARÉVALO; MARTÍNEZ-MERA, 2018), and would help them meet their commitments to reduce carbon emissions from forest degradation. Finally, to support decisions and policy makers, we provide a user-friendly interface with our results: https://amazonianfirecalendar.shinyapps.io/fire_amazon/.

3.5 Conclusion

In this study, we focused on clarifying how the dry and fire seasons are related in the Amazon. We show two key insights. First, by combining satellite-derived datasets of rainfall and active fires, we observed that the marked seasonality in the fire peaks was linked to the regional variation of the dry season end, which is consistent with the results of studies carried out on smaller scales in the northwest (ARMENTERAS-PASCUAL et al., 2011; ROMERO-RUIZ et al., 2010), southeast (BRANDO et al., 2016) and east

(ALENCAR et al., 2015) of the Amazon. This shows that assuming a single dry season for the entire Amazon is not suitable to characterize the fire occurrence. Second, our approach defines fire calendars for the Amazon, specifying different Critical Fire Periods. This could help support policies and management interventions that target illegal agricultural fires, reduce deforestation and subsequent burning, and support smallholders in developing fire-safe practices under changing climatic conditions. Further efforts are still needed to investigate the seasonality of each fire use and how extreme droughts influence their occurrence. However, the results achieved with this study already provide strategic information that can support decision makers in successful fire management plans and contingency actions.

4 ASSESSING THE DISTRIBUTION AND OVERLAP OF PUBLIC AND PRIVATE LANDS IN THE BRAZILIAN AMAZON [2]

4.1 Introduction

Although protected areas have been a mainstay of tropical forest conservation (NAUGHTON-TREVES; HOLLAND; BRANDON, 2005), there has been growing recognition of the potential importance of private lands in recent years (KAMAL; GRODZIŃSKA-JURCZAK; BROWN, 2015). This is critically important in Brazil, where about 53% of native vegetation is within private lands (SOARES-FILHO et al. 2014) and where the protection rules are established according to the Brazilian National Vegetation Protection Law (nº12.651/2012), (BRASIL, 2012a).

The accurate delimitation and registration of rural properties contribute to the accountability of rural landowners for non-compliance with environmental laws (L'ROE et al., 2016), in addition to assisting in the implementation of policies focused on REDD+ programs (NAUGHTON-TREVES; WENDLAND, 2014) and payment for environmental services (RUGGIERO et al., 2019). Yet, for private lands to work as a conservation solution, there must be a clear understanding of land ownership. In Brazil, a historical system of registering land titles in local solicitor offices obfuscated ownership and supported decades of land speculation and deforestation (FEARNSIDE, 2001). In 2012, with the implementation of the Rural Environmental Registry (CAR), a self-declaratory and mandatory public registry for all rural properties, a new level of information was reached on the distribution of private lands in Brazil (ROITMAN et al., 2018; STEFANES et al., 2018). CAR is not a land tenure regularization mechanism and has no legal validity as proof of land tenure, but is a tool to strengthen the environmental governance of private lands and monitor compliance with environmental legislation by rural landowners (ROITMAN et al., 2018). Its success in monitoring private lands is fundamental to Brazil's ability to meet its Paris agreement commitments and zero-deforestation commitments of the 26th United Nations Climate Change Conference (COP26).

2- This chapter is based on the manuscript under review in the Land Use Policy: Carvalho, N.S., Anderson, L.O., Pessôa, A.C.M., Silva Junior, C.H.L., Reis, J.B.C., Aragão, L.E.O.C, Barlow, J. Assessing the distribution and overlap of public and private lands in the Brazilian Amazon.

Despite CAR’s potential to support climate and environmental policies, there are concerns that this registry has been used to claim ownership of invaded public lands, targeting future legalization of these areas and land tenure rights (AZEVEDO-RAMOS et al., 2020; AZEVEDO et al., 2017). Recent flexibilities proposed in Brazilian land legislation (BRASIL, 2020, 2021a) and the increase in Amazonian deforestation due to land grabbing (AZEVEDO-RAMOS; MOUTINHO, 2018) reinforce the urgent need to identify where the invaded public areas are, in order to stop the advance of this illegal process of land tenure. Between 2019 and 2021, 51% of the deforestation in the Amazon occurred in undesignated public forests, resulting in a loss of a public good that belongs to the entire Brazilian society (ALENCAR; SILVESTRINI; GOMES, 2022). Despite the worrying increase in deforestation and disputes between public lands and private land titles, it is still unclear how rural properties are distributed in the Brazilian Amazon or how much they overlap between themselves and with public lands.

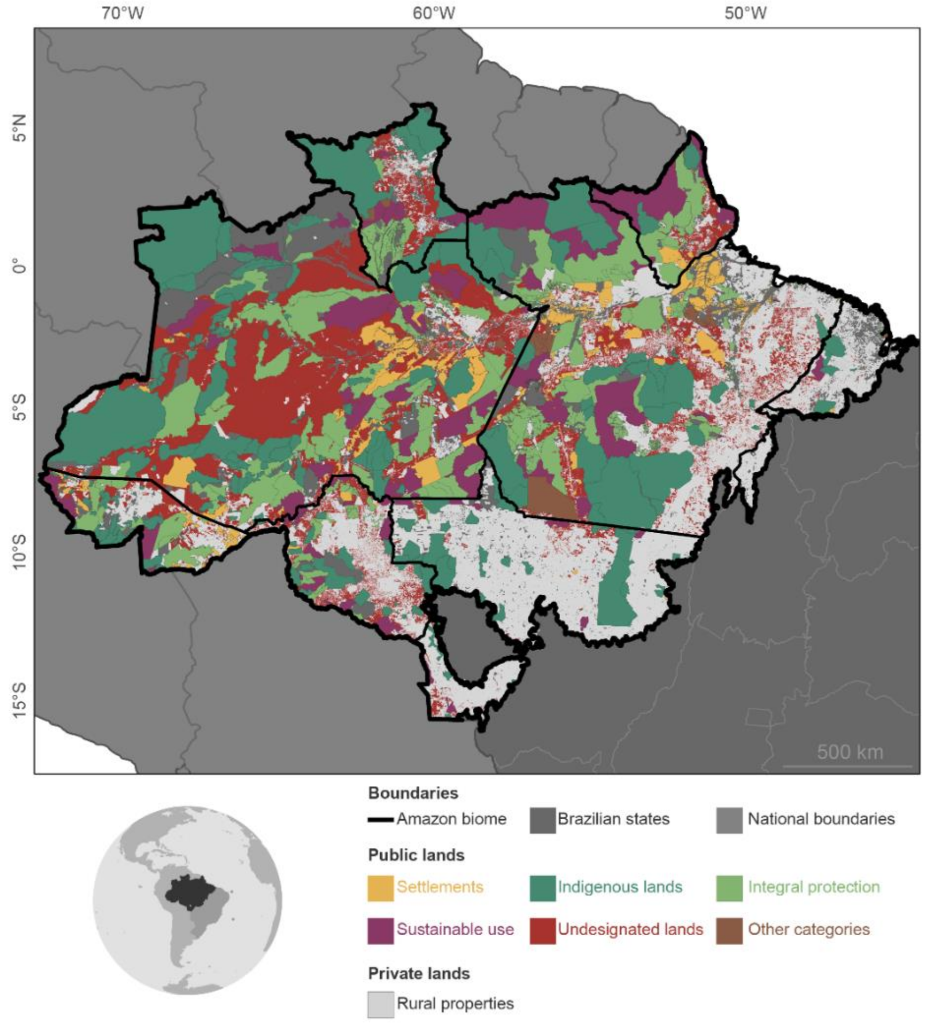
Here, we used the CAR database to make the first spatially explicit assessment of the distribution of private lands in the Brazilian Amazon and their overlap with public lands in the biome. We ask the following research questions: (1) What is the total number and area of rural properties, and how are they distributed across size classes and states? (2) What is the degree of overlap between rural properties, and how is this overlap distributed across the size classes? (3) What is the degree of overlap between rural properties and public forests, and how is this overlap distributed across property size classes and public forest categories? We discuss our results highlighting how this overview of the structure of the private lands in the Amazon could support decision makers in the land governance in the biome.

4.2 Material and methods

4.2.1 Study area

The study area comprises the entire Brazilian Amazon biome, including the states of Acre, Amapá, Amazonas, Pará, Rondônia and Roraima and the Amazonian parts of the states of Maranhão, Mato Grosso and Tocantins. Public and private lands covered an area of 4,093,533 km² in the biome, of which 66% are in the first category and 34% in the second (Figure 4.1). We detailed the dataset used to analyse land distribution in the Amazon below.

Figure 4.1 - Distribution of public and private lands in the Brazilian Amazon. Data from the National Registry of Public Forests were used to extract the public forests in settlements, indigenous lands, integral protection conservation units, sustainable use conservation units and undesignated lands. Other categories include public forests in areas such as military use and forest management. Private lands include the rural properties enrolled in the Rural Environmental Registry available on the CAR's Public Consultation platform.



Source: Author's production.

4.2.2 Public forests

We used data from the National Registry of Public Forests (SFB, 2020) to obtain the spatial location of public forests in the Brazilian Amazon. Public forests are forested areas located in public lands belonging to the entire Brazilian society, whose management responsibility is attributed to the government or the private sector through forest concessions (BRASIL, 2006). Public forests aim to guarantee the protection and conservation of the environment, the sustainable use of their resources and ensure the livelihoods of traditional peoples (BRASIL, 2006). According to the protection purpose, they are included in categories such as conservation units of integral protection or sustainable use, indigenous lands, settlements, military use, and other categories defined by Brazilian law. Public forests that do not yet have a legal definition of their protection status are classified as undesignated lands. In this study, as military use and categories such as forest management were not the focus of our analysis, we grouped them into the same class, named as other categories.

Some public forests may be included in more than one category because there is still no legal definition of their territory. Therefore, we disregarded public forests in overlapping categories to avoid overestimating the analysed area, which accounted for 5 % (142,965 km²) of the total area. After this filter, we considered an area of 2,698,675 km² of public forests in the Amazon, of which 35% were in conservation units, including areas of integral protection (14%) and sustainable use (21%), 35% in indigenous lands, 6% in settlements and 2% in other categories. Undesignated lands totalled 607,008 km², corresponding to 22% of the public forest area in the Amazon (Figure 4.1).

4.2.3 Private lands

We used data from rural properties in the Brazilian Amazon available on the CAR's Public Consultation platform (SFB, 2019a), (Figure 4.1). We downloaded the rural property information for each Amazonian municipality (n = 548) in April 2019, and 100% of the area eligible for registration was already enrolled in the CAR (SFB, 2019b). CAR is a mandatory electronic public registry for all rural properties implemented by the Brazilian National Vegetation Protection Law to provide information for monitoring, enforcement, and environmental regularization of private lands in Brazil (BRASIL, 2012a, 2012b). The data provide geographic information on location, perimeter, land use and land cover, and the native vegetation in protected areas (Legal Reserve, Permanent Preservation Areas) of each property in the national territory. As in this study, we focused on private lands defined as rural properties, we only considered the "IRU" category (rural property; 540,977 registers) from the CAR database. Registers declared as “AST” (settlement; 6,940 registers) and “PCT” (traditional people; 190 registers) were disregarded.

After the enrolment in the CAR, the registration is verified by automatic filters in the National Rural Environmental Registry System (SICAR, acronym in Portuguese) and can be classified as active, pending, or cancelled. These filters resulted in 426,735 rural properties classified as active, 109,644 pending and 4,598 cancelled. If the automatic filters do not identify inconsistencies in the declared information, the CAR is classified as active. It can also be classified as active after analysis by the environmental agency, with verification of the regularity of the documentation of the rural property and compliance with environmental legislation. The pending status can be attributed to the CAR if the automatic filters identify overlaps with indigenous lands, protected areas, or embargoed areas or if the environmental agency identifies inconsistencies/incorrect data in the declared information or non-compliance with environmental legislation. The cancelled status may occur when the information declared is totally or partially false, misleading, or omitted and/or due to non-compliance with the deadlines by the landowner for meeting the notifications issued by the environmental agency. The registration of a rural property can only be cancelled by the environmental agency responsible for analysing the CAR. The CAR with cancelled status does not represent a valid registration; therefore, to avoid overestimation and to reduce uncertainties in the analysis, we only considered rural properties with active and pending status. Finally, we also verified geometry problems in the declared limits of the rural properties. We removed rural properties registered incorrectly or with topology problems, such as geometries with an area equal to zero. We found 39 rural properties in this condition. All these filters removed 0.85% of the rural properties registered in the CAR, and the final dataset used in our analysis was 536,340 rural properties.

4.2.3.1 Classification of the rural properties

We classified the rural properties according to the number of fiscal modules in each municipality. The fiscal module is an agrarian measurement unit expressed in hectares that indicates the minimum area for a production unit to be considered economically viable (BRASIL, 1979). The fiscal module is variable among municipalities, influenced by factors such as the predominant agricultural exploitation and the average income obtained from this activity (LANDAU et al., 2012). The number of fiscal modules of a rural property is defined by the ratio between its area and the area corresponding to one fiscal module in the municipality where it is located. According to the number of fiscal modules (FM), a rural property (RP) can be classified as small (RP < 4FM), medium (4FM ≤ RP ≤ 15FM), or large (RP > 15FM). We considered this classification in our analysis since the number of fiscal modules is the legal instrument used in the Brazilian National Vegetation Protection Law to define the rules for the maintenance and/or regularization of native vegetation on rural properties (BRASIL, 2012a).

4.2.4 Distribution of private lands in the Brazilian Amazon

We calculated the total area and number of rural properties in the categories of small, medium, and large properties for the Amazon and each state in the biome. To calculate the total overlap area registered in the CAR, we extracted the area of each rural property also registered by other rural properties. To obtain a spatial view of the distribution of private lands, we also calculated the total area of rural properties and the area of overlap in a 10x10 km grid. We also calculated the spatial dominance of small, medium, and large properties across the Amazon in the grid analysis. In this case, for each cell, we calculated the percentage ratio between the area of each of the three categories of rural properties and the total area of private lands observed in the cell.

4.2.5 Overlap between public forests and rural properties

We calculated the area of each public forest category (conservation units of integral protection and sustainable use, indigenous lands, settlements, undesignated lands, and other categories) overlapped by small, medium, and large properties. When the public forest overlapped with more than one rural property category, we defined the private land category as multiple, including overlaps with small-medium, small-large, medium-large, and small-medium-large properties. We used a 10x10 km grid to identify the spatial distribution of the overlap areas between public forests and private lands. We calculated the total area of each category of public forest and its percentage overlapped by rural properties for each cell.

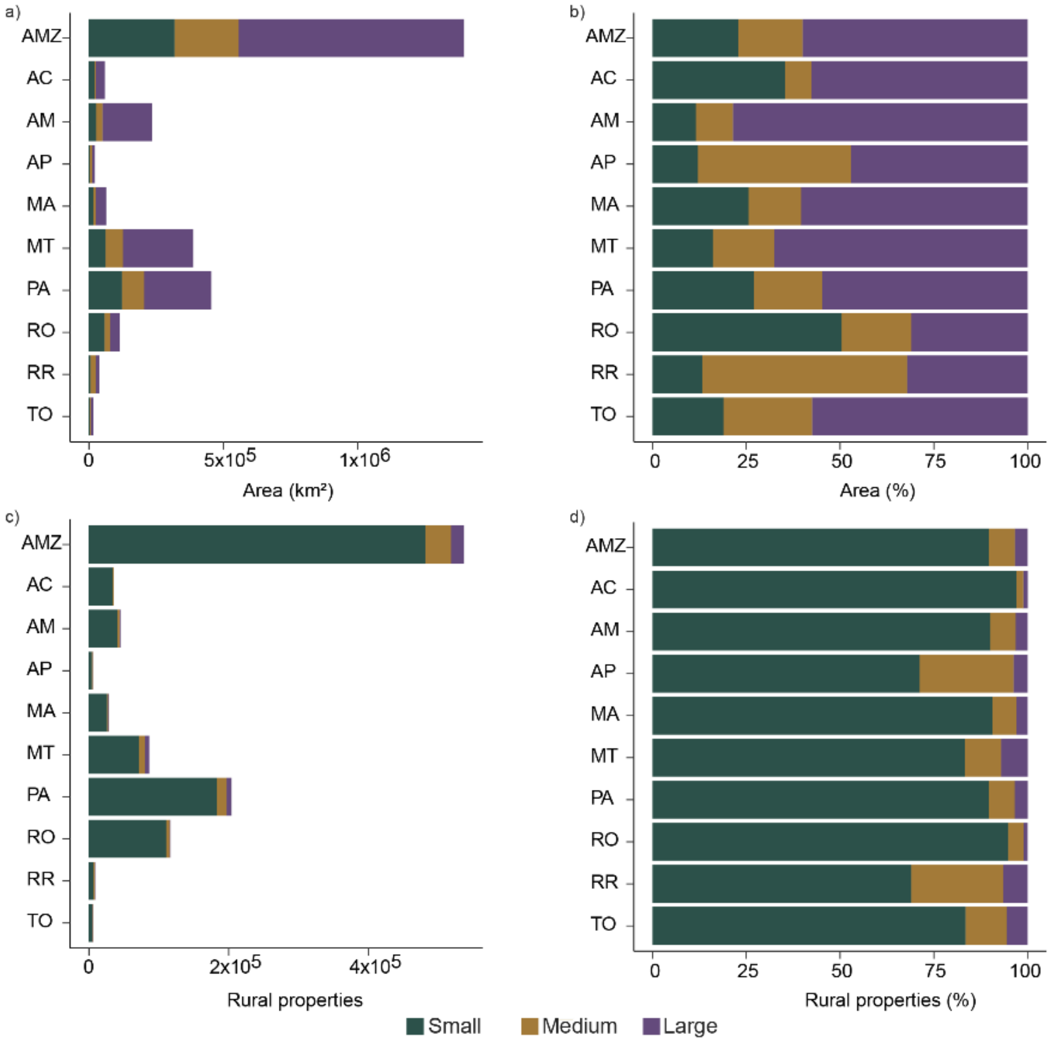
4.3 Results

4.3.1 Private lands distribution

The total area declared as private lands in the CAR was 1,394,858 km², distributed in 536,340 rural properties throughout the Amazon (Figure 4.2). Pará concentrated the largest area (454,869 km²) and the number of rural properties (204,063) in the biome, accounting for more than 30% of the total (Figure 4.2, Figure 4.3). The land concentration across the biome was evident in the cumulative area plot, showing the top 5% of the rural properties, with the largest area covered around 70% of the area (Figure 4.4). Large properties added 60% of the area (837,672 km²), which was equivalent to only 3% (18,309) of the rural properties (Figure 4.2). In contrast, small properties accounted for 90% (480,954) of the total rural properties but covered just 23% (318,086 km²) of the total area registered (Figure 4.2).

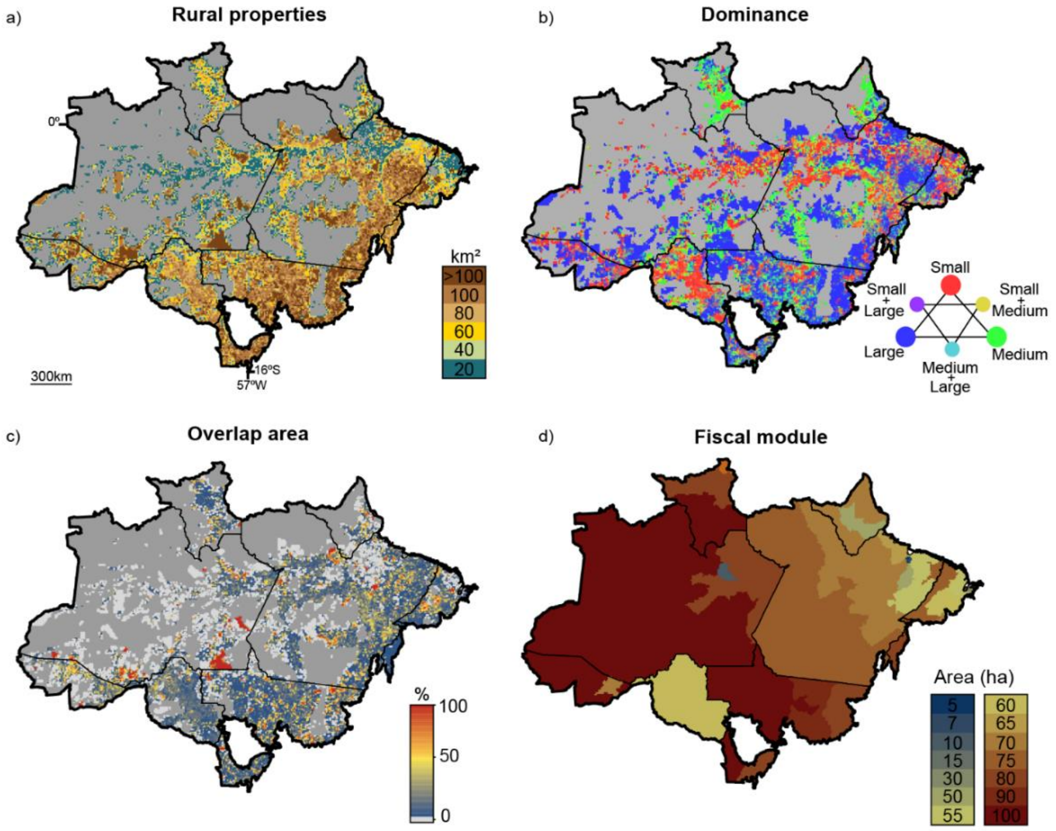
The spatial dominance of properties varied across states: large properties occupied more than 50% of the registered area in five of the nine states of the Amazon (Figure 4.2a-b, Figure 4.3b), while small and medium properties accounted for more than half of area registered only in Rondônia and Roraima, respectively (Figure 4.2a-b, Figure 4.3b).

Figure 4.2 – Distribution of private lands registered in the CAR by the size of rural property according to the total area and the number of rural properties. The percentage values, considering the total area and number of rural properties in the biome and each state, are also shown. In all graphs, the values are presented considering the total observed in the Amazon and each state in the biome. Rural properties (RP) were classified according to the number of fiscal modules (FM) as small (RP<4FM), medium (4MF ≤ RP ≤ 15MF) and large (RP>15MF). AMZ: Amazon biome, AC: Acre, AM: Amazonas, AP: Amapá, MA: Maranhão, MT: Mato Grosso, PA: Pará, RO: Rondônia, RR: Roraima, TO: Tocantins.



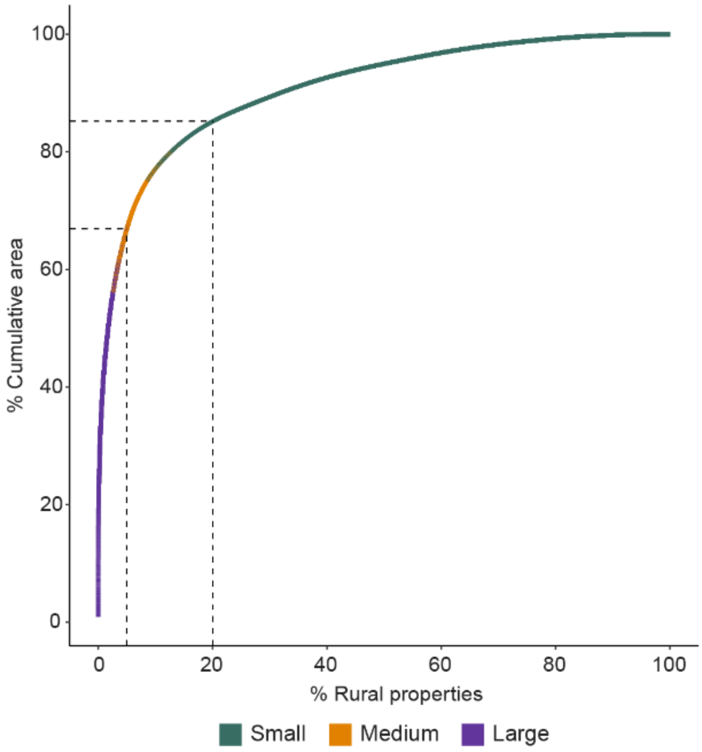
Source: Author’s production.

Figure 4.3 – Spatial distribution of private lands in the Amazon considering a 10 x 10 km grid. (a) Total area registered as rural properties in the CAR. (b) The dominance of small, medium and large properties considering for each cell the relationship between the total area registered in the CAR and the area occupied by each category of rural property. (c) Percentage of the total area registered in each cell that presented overlap among rural properties. The light grey cells are regions that presented no overlap in the registered area, and the red cells presented total overlap. (d) Area in hectares equivalent to one fiscal module for each municipality in the Amazon. Cells without rural properties registered in the CAR are shown in dark grey on all maps.



Source: Author’s production.

Figure 4.4 – Cumulative area of the 536,340 rural properties registered in the Rural Environmental Registry, totalling 1,394,858 km². Rural properties were classified in descending order according to their area. The size of the rural properties (RP) was defined according to the number of fiscal modules (FM) as small (RP<4FM), medium (4MF ≤ RP ≤ 15MF), and large (RP>15MF). Due to the difference in fiscal modules in the municipalities, rural properties with similar areas can be classified into different size categories.



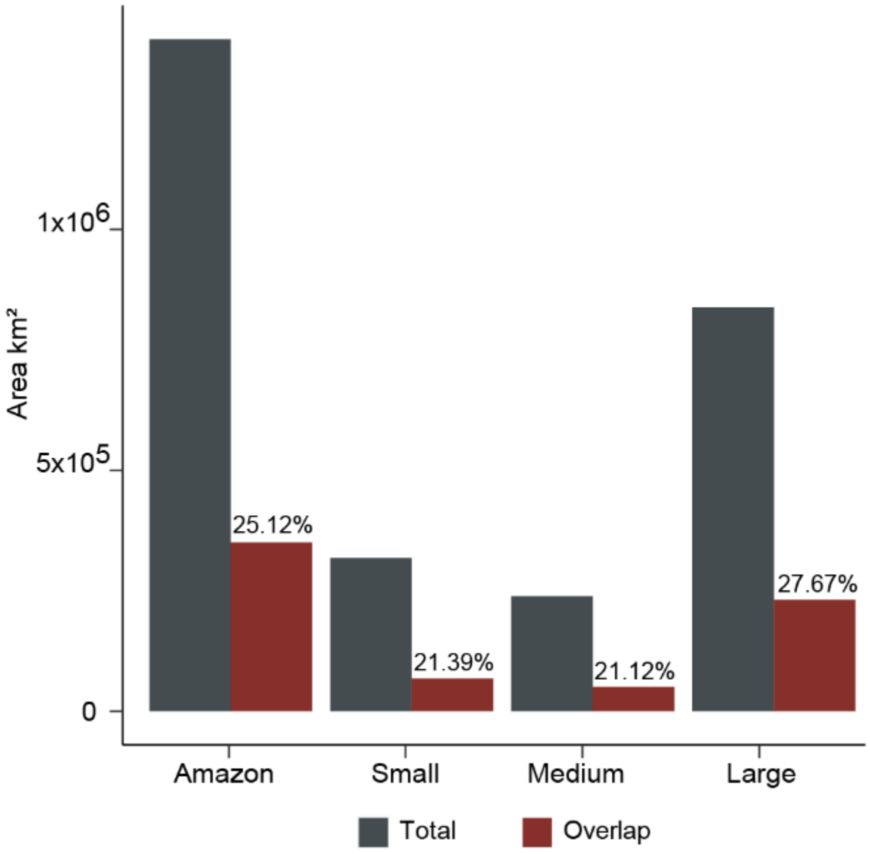
Source: Author's production.

4.3.2 Overlap among rural properties

In total, 25% (350,356 km²) of the area declared as private land in the Amazon overlapped with other rural properties (Figure 4.5). Stratifying this overlap by rural property size revealed that 67% (231,799 km²) of this overlap occurred in large properties, equivalent to 28% of the total area of this category registered in CAR (Figure 4.5). Small and medium properties totalled 19% (68,053 km²) and 14% (50,504 km²) of overlapping conflicts, which corresponded to 21% of the total area registered in each category (Figure 4.5).

The overlap was distributed across the biome, with 52% (11,658) of the cells with private lands showing the overlap in up to 20% of the area registered in the CAR (Figure 4.3c, Table A1). In some regions, such as southern Amazonas and northern Pará, the overlap between rural properties exceeded the maximum cell area, resulting in 100% overlap (Figure 4.3a-c). We did not observe overlaps in 23% (5,073) of the cells, mainly concentrated in regions with rural properties covering an area below 20km², such as in central Amazonas, northeastern Pará and Maranhão (Figure 4.3a-c, Table A1).

Figure 4.5 - Total area registered in the CAR for the Amazon biome and each rural property category. The overlap area is the fraction of the total area registered by more than one rural property in the CAR. The values for the percentage ratio between the total area registered in the CAR and the overlap area in each category are also shown.

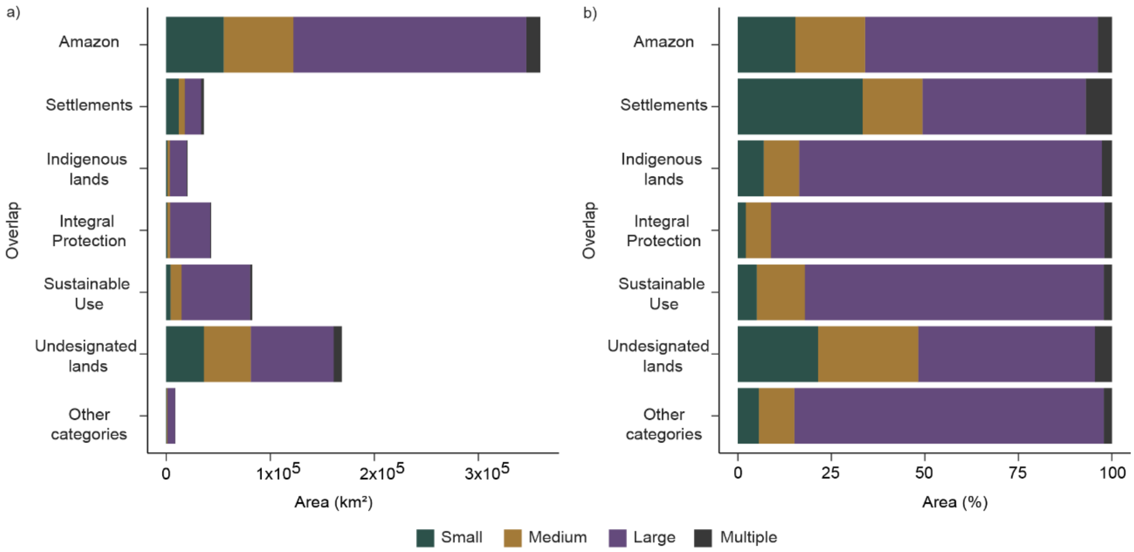


Source: Author's production.

4.3.3 Overlap between public forests and rural properties

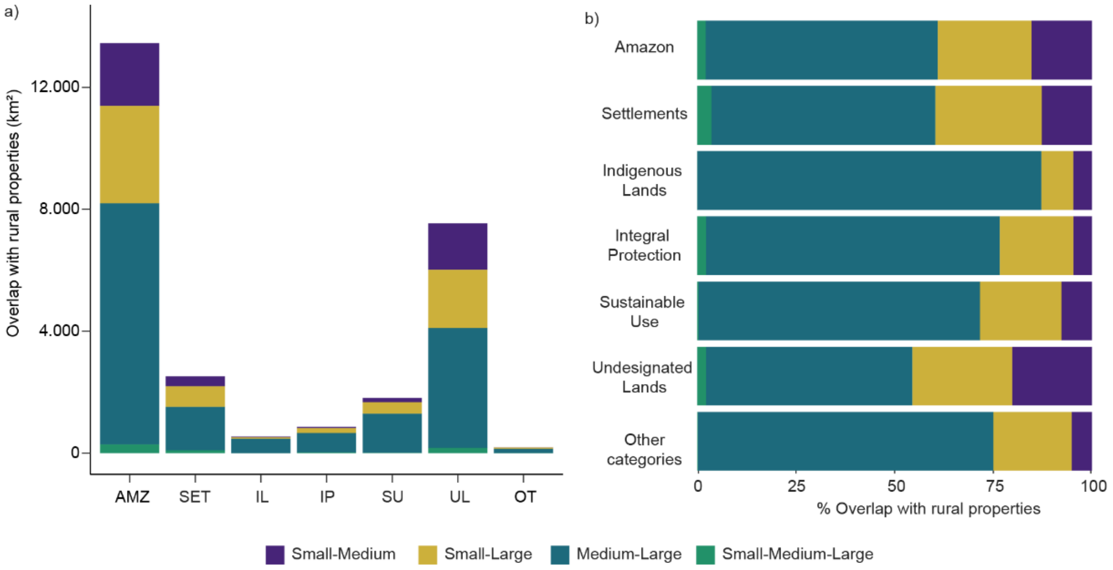
We found 359,482 km² of public forests overlapped by private lands, with the largest areas occurring with undesignated lands and conservation units, which represented 47% (168,624 km²) and 35% (125,770 km²) of the total, respectively (Figure 4.6). Although overlaps with indigenous lands represented only 6% of the total, this was equivalent to more than 20,000 km² (Figure 4.6). For undesignated lands, 47% (79,855 Km²) of the overlaps occurred with large properties and 27% (45,108 km²) with mediums (Figure 4.6). Large properties also accounted for the largest overlap area with conservation units and indigenous lands, concentrating more than 80% of the total observed in these categories (Figure 4.6). We also observed 13,449 km², 4% of the total overlap area, overlapping with more than one category of rural property, covering mainly medium and large properties (Figure 4.6, Figure 4.7).

Figure 4.6 - Public forest area overlapped by each category of the rural property considering the absolute values (4.6a) and percentage values (4.6b). The total overlap area is shown for the entire Amazon and each category of public forest in the biome (settlements, indigenous lands, integral protection conservation units, sustainable use conservation units, undesignated lands, and other categories). Public forest areas overlapped by more than one rural property category are presented in the category named multiple.



Source: Author's production.

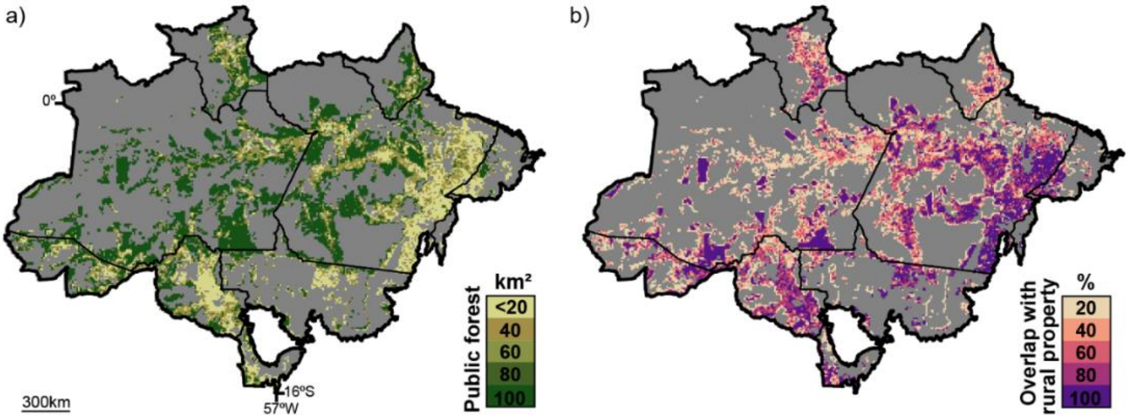
Figure 4.7 - Public forest area overlapped by more than one category of rural property, including conflict areas that occurred with small-medium, small-large, medium-large, and small-medium-large properties. The overlap area is shown in absolute values (4.7a) and percentage values (4.7b). The values are presented for the entire Amazon and each category of public forest in the biome (settlements, indigenous lands, integral protection conservation units, sustainable use conservation units, undesignated lands, and other categories).



Source: Author's production.

In terms of spatial distribution, in 41% (6.435) of the cells with overlaps, conflicts occurred with more than 80% of the area of public forest observed (Figure 4.8, Table 4.1). Pará and Amazonas concentrated the largest overlaps areas in the biome, accounting for 37% (134,119 km²) and 35% (124,657 km²) of the total area, respectively (Figure 4.8, Table 4.2).

Figure 4.8 – Spatial distribution of overlap between public forests and rural properties in the Brazilian Amazon considering a 10x10 km grid. Figure 4.8a shows the total area of public forest observed in the cell, considering the sum of the areas located in settlements, indigenous lands, integral protection conservation units, sustainable use conservation units, undesignated lands, and other categories. The percentage of the total area overlapped by rural properties is shown in Figure 4.8b.



Source: Author's production.

Table 4.1 – Distribution of the overlap area between public forests and rural properties considering a 10x10km grid in the Brazilian Amazon. Public forests were classified according to the area observed in the cell (0-20km², 20-40km², 40-60km², 60-80km², 80-100km² and >100km²) and with their percentage overlapped by rural properties (0%, 0-20%, 20-40%, 40-60%, 60-80%, 80-100%).

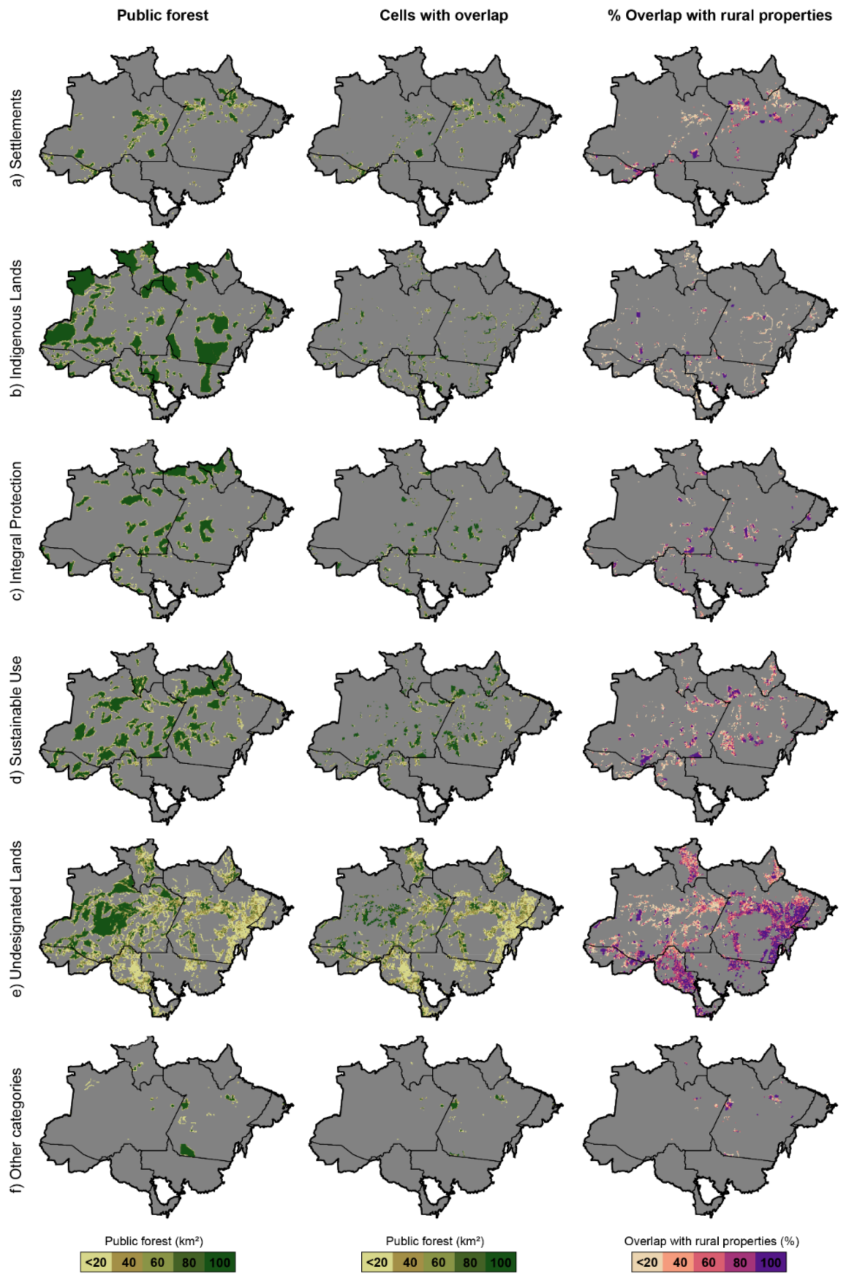
		Overlap with rural properties (%)					
Public forest	**Cells**	**0-20**	**20-40**	**40-60**	**60-80**	**80-100**	**Total (%)**
0-20km²	**5,342**	4.90	2.99	3.39	4.26	18.33	**33.87**
20-40km²	**2,255**	2.81	1.83	1.56	1.79	6.31	**14.30**
40-60km²	**2,170**	3.43	1.98	1.79	1.77	4.79	**13.76**
60-80km²	**2,265**	4.71	2.46	1.82	1.46	3.91	**14.36**
80-100km²	**3,738**	9.68	3.24	1.88	1.44	7.46	**23.70**
Total (%)	**-**	**25.52**	**12.50**	**10.44**	**10.73**	**40.81**	**100**
Cells	**15,770**	**4,025**	**1,972**	**1,646**	**1,692**	**6,435**	**-**

Table 4.2 – Total overlap area between public forests and rural properties in settlements, indigenous lands, integral protection conservation units, sustainable use conservation units, undesignated lands, and other categories. All values are presented for the Brazilian Amazon and each state of the biome.

	Settlements		**Indigenous lands**		**Integral protection**		**Sustainable use**		**Undesignated lands**		**Other categories**		**Total**	
	km²	**%**	**km²**	**%**	**km²**	**%**	**km²**	**%**	**km²**	**%**	**km²**	**%**	**km²**	**%**
Acre	5,249.4	14.5	99.0	0.5	2,220.8	5.1	957.2	1.2	8,799.1	5.2	0.0	0.0	**17,325.5**	**4.8**
Amazonas	9,403.7	26.0	8,165.7	40.1	15,399.6	35.7	39,262.5	47.5	51,816.2	30.7	609.1	7.1	**124,656.9**	**34.7**
Amapá	533.7	1.5	0.5	0.0	22.9	0.1	4,723.4	5.7	4,831.3	2.9	4.5	0.1	**10,116.3**	**2.8**
Maranhão	119.3	0.3	476.9	2.3	1,972.4	4.6	32.8	0.0	925.8	0.5	1.8	0.0	**3,528.9**	**1.0**
Mato Grosso	60.2	0.2	7,418.3	36.4	5,647.1	13.1	534.0	0.6	8,298.4	4.9	23.2	0.3	**21,981.2**	**6.1**
Pará	19,580.0	54.2	3,279.4	16.1	10,628.3	24.6	31,385.4	38.0	61,290.3	36.3	7,955.1	92.3	**134,118.5**	**37.3**
Rondônia	1,162.4	3.2	580.7	2.9	4,604.2	10.7	3,990.9	4.8	17,591.6	10.4	6.7	0.1	**27,936.4**	**7.8**
Roraima	0.0	0.0	340.0	1.7	2,668.5	6.2	1,633.3	2.0	15,055.6	8.9	19.0	0.2	**19,716.4**	**5.5**
Tocantins	0.0	0.0	0.0	0.0	16.5	0.0	70.3	0.1	15.5	0.0	0.0	0.0	**102.3**	**0.0**
Amazon biome	**36,108.6**	**100**	**20,360.4**	**100**	**43,180.3**	**100**	**82,589.8**	**100**	**168,623.9**	**100**	**8,619.4**	**100**	**359,482.3**	**100**

Considering each category of public forest, overlaps with settlements, indigenous lands and conservation units were mainly concentrated in cells with more than 80km² of public forest, where up to 20% of their area was overlapped by rural properties (Figure 4.9a-b-c-d, Table A2-5). However, we also observed extensive areas of public lands practically encompassed by private lands, where overlaps exceeded 80%. For example, in Amazonas, in 12% of the cells of indigenous lands and 20% of those in integral protection conservation units, overlaps occurred with at least 64 km² of the public forest area in the cell (Figure 4.9b-c, Table A3-4). For undesignated lands, Pará and Amazonas accounted for 67% of the overlap with rural properties, each concentrating more than 50,000 km² (Table 4.2). Rondônia accounted for 10%, corresponding to almost 18,000 km² (Table 4.2). In Amazonas, the overlaps occurred in cells predominantly dominated by undesignated lands, with 17% occurring in areas above 80km² and with up to 20% overlap (Figure 4.9e, Table A6). In contrast, the greatest conflicts for Pará and Rondônia were concentrated in cells that presented a small area of undesignated lands but with high pressure from rural properties. For both states, more than half of the conflicts occurred in cells with less than 20km² of undesignated lands and overlaps exceeding 60% of the area (Figure 4.9e, Table A6). We found this pattern in more than 35% of the cells in Pará and Rondônia (Table A6).

Figure 4.9 – Spatial distribution of the public forests in the Brazilian Amazon considering their location in a) settlements, b) indigenous lands, c) integral protection conservation units, d) sustainable use conservation units, e) undesignated lands, and f) other categories. The first column shows the total area of public forest for each 10x10 km cell. Only the cells that presented overlapping areas between public forests and rural properties are shown in the second column. The last column shows the percentage values of the overlapping area with rural properties compared to the total area of public forest in the cell.



Source: Author's production.

4.4 Discussion

4.4.1 Distribution of private lands in the Amazon

Our analysis of more than half a million rural properties enrolled in the CAR revealed the inequality in the distribution of private lands in the Amazon, with around 70% of the land in the largest 5% of the properties. This dominance pattern agrees with previous studies developed at the level of municipalities (PACHECO, 2012) or census sectors (GODAR et al., 2014) of the Amazon and results from expanding the agricultural frontier to the biome began in the 1970s. In this period, the Brazilian government granted financial incentives and tax breaks to investors to develop large-scale activities in the Amazon, such as logging and cattle, making them large landowners in the biome (SIMMONS, 2004; SIMMONS et al., 2007). At the same time, federal programs created numerous settlement projects, dividing the public lands into lots smaller than 100 ha, which were sold to colonists to populate regions close to highways (FEARNSIDE, 2001). This economic development model resulted in conflicts over land tenure, land speculation, deforestation, and marginalization of the small landowners and traditional Amazonian people (FEARNSIDE, 2001; SIMMONS, 2004). In the following sections, we discussed the land structure in the Amazon, approaching the main drivers of overlap, before highlighting some ways that CAR needs to be improved to support land governance of the Amazon.

4.4.2 Overlaps among rural properties and land problems

The CAR is not a mechanism for land regularization, but the resolution of land tenure uncertainties is a fundamental prerequisite for environmental agencies to be able to proceed with the CAR analysis and verification of compliance with environmental legislation by landowners. Indeed, one of the main challenges faced by environmental agencies in the CAR analysis is the overlap among rural properties, which portrays not only the self-declaratory nature of the registration but also historic issues before the CAR.

With a high turnover of lands, tracking the purchase and sale of rural properties was difficult due to registrations in local notaries and inconsistencies in the domain chain of the property (FEARNSIDE, 2001; LUDEWIGS et al., 2009; REYDON; FERNANDES; TELLES, 2015). Lands were also sold more than once to different landowners, and inconsistencies between the area registered and the field area were frequent, generating overlaps and duplicate registrations (BARRETO et al., 2008). Many areas were also incorporated into neighbouring properties or abandoned and exposed to invasions (FEARNSIDE, 2001). In addition, as land titling is a bureaucratic and costly process, many changes in the boundaries of the properties were not officially recognized (ARAUJO et al., 2009). This intricate system has also favoured land grabbing, adding further confusion to land tenure in the biome (ARAUJO et al., 2009; BRANNSTROM, 2001; OLIVEIRA, 2013). The georeferenced delimitation of rural properties in the CAR contributed to making all these issues quantifiable and evident. However, the resolution of these problems is often hampered by the precariousness of landowners' land documentation, violent conflicts over the land tenure and lack of financial resources and support from agencies responsible for land governance (ALSTON; LIBECAP; MUELLER, 2000; ARAUJO et al., 2009; BARRETO et al., 2008; BRITO; BAIMA; SALLES, 2013; BRITO; BARRETO, 2011). Without a clear definition of land tenure, the CAR implementation as an environmental control, planning and monitoring tool remains ineffective.

4.4.3 Overlaps and the public land grabbing

The 360,000 km² overlap between rural properties and public lands is the greatest concern from a social and environmental perspective. However, not every private land within public land indicates irregularities in the occupation process. Overlaps with settlements may correspond to areas incorrectly registered as rural properties in the CAR. INCRA is the Brazilian public agency responsible for registering the settlements in the CAR, which is carried out using a platform with restricted access and specific to registrations in this category (SFB, 2016a). However, many settlers registered their lots as rural properties on the CAR's public access platform, resulting in overlaps between the two categories. Overlaps with public lands may also result from policies that attempted to curb the advance of deforestation in the Amazon. After creating the Brazilian System of Conservation Units, in seven years more than 500,000 km² of public lands were converted into conservation units in the biome (VERÍSSIMO et al., 2011). However, Amazonian people who already lived within these areas were kept outside the territorial ordering, resulting in land conflicts and unsuccessful expropriations (VERÍSSIMO et al., 2011).

On the other hand, invasions of conservation units and indigenous lands are common in the Amazon, which in addition to triggering huge environmental impacts, may decimate traditional peoples along with their culture and knowledge (MUELLER, 2022; VILLÉN-PÉREZ et al., 2022). The irregular occupation occurs mainly with the expectation of changes in the territorial limits of these protected areas so that later invaders can claim land tenure (KLINGLER; MACK, 2020). Laws and bills that propose reductions in the legal demarcation of protected areas are spreading across the world and in the Amazon (GOLDEN KRONER et al., 2019), and these changes are increasing the pressure on many of these areas, as recently observed in two conservation units in Rondônia (BRASIL, 2021b). Although the enrolment in the CAR has no legal value to claim land tenure, the georeferenced demarcation of rural property has been used as a strategy by land grabbers to indicate land tenure (AZEVEDO-RAMOS et al., 2020; KLINGLER; MACK, 2020). Local studies showed that rural properties covered up to 94% of indigenous land in central Pará (CONCEIÇÃO et al., 2021). For the entire Brazilian Amazon, we observed overlaps above 80% in three indigenous lands in Pará, four in Amazonas and one in Mato Grosso, with rural properties occupying areas between 765 ha and 122,410 ha. All these conflicts jeopardize the survival of traditional Amazonian people and prevent the achievement of conservation and protection objectives in protected areas. Therefore, to stop the invasion of protected areas in the biome is necessary an articulation of public policies that ensure the land tenure rights of traditional Amazonian people and, at the same time, guarantee the territorial consolidation of conservation units and indigenous lands.

Finally, the most critical land overlap exposed in the CAR is the grabbing of undesignated lands. Almost 50% of the overlaps between rural properties and public lands occurred with undesignated lands, which represents an illegal appropriation of public goods of more than 160,000 km², a land problem that has already been highlighted in the literature (ALENCAR et al., 2021; ALENCAR; SILVESTRINI; GOMES, 2022; AZEVEDO-RAMOS et al., 2020). The history of land regularization in the Amazon includes laws that provided amnesty for deforesters, legitimizing illegal occupation of public lands (BRASIL, 2009, 2012a). This represents a clear message that deforestation and land grabbing are profitable activities, encouraging land grabbers and fostering land speculation in the Amazon (ARMENTERAS et al., 2019; AZEVEDO-RAMOS; MOUTINHO, 2018). Currently, the bill PL-510/2021, in progress in the Brazilian

National Congress, aims to legitimize the occupation of public lands that occurred before 2012 with up to 2,500 ha (BRASIL, 2021a). In this case, 98% of the rural properties overlapping with undesignated lands fit the area requirement, representing a potential regularization of 111,768 km² (Table 4.3). This area would correspond to giving legal status to 66% of the area of undesignated lands overlapping rural properties. Furthermore, the weakening land governance since 2018 has encouraged further speculation and deforestation on undesignated lands, based on the assumption that amnesties will continue to occur (ALENCAR et al., 2021). To reverse this scenario, it is urgent to define strategies to tackle the land grabbing of undesignated lands. It is necessary to identify the irregular occupations to carry out the immediate expropriation of and the cancellation of the CAR. These actions should also be linked to strengthening the land governance, avoiding flexibilities in legislation, and adopting zero-tolerance policies for deforestation.

Table 4.3 - Overlap between rural properties and undesignated lands, considering the total number of properties and only those that meet the maximum area defined in bill PL-510/2021. According to this bill, rural properties whose area, including their overlap with public lands, is less than 25 km² may be eligible for regularization. The total overlap area and only that which can be regularized are also shown.

	Properties overlapping undesignated lands			**Total overlap**	**Overlap with rural properties <25km²**	
State	**Total**	**<25 km²**	**%**	**Area (km²)**	**Area (km²)**	**%**
Acre	4,932	4,783	97.0	8,799.1	2,859.3	32.5
Amazonas	24,405	23,940	98.1	51,816.2	23,464.6	45.3
Amapá	2,916	2,856	97.9	4,831.3	3,125.6	64.7
Maranhão	1,663	1,605	96.5	925.8	639.9	69.1

To be continued.

Table 4.3 – Conclusion.

Mato Grosso	6,093	5,793	95.1	8,298.4	5,812.2	70.0
Pará	61,374	60,172	98.0	61,290.3	45,830.2	74.8
Rondônia	38,238	38,053	99.5	17,591.6	15,338.2	87.2
Roraima	4,793	4,743	99.0	15,055.6	14,692.9	97.6
Tocantins	41	35	85.4	15.5	5.4	34.8
Amazon biome	**144,455**	**141,980**	**98.3**	**168,623.9**	**111,768.3**	**66.3**

4.4.4 Improving CAR

All the overlapping issues and the self-declaratory nature of the register underline the importance of validating the information declared in the CAR by environmental agencies responsible for the territorial management of the Amazon. This process has been ongoing since 2016, including requesting supporting documentation from the landowners and analysing georeferenced data from rural properties (SFB, 2016b, 2018). States such as Acre and Rondônia have also invested in improvements in CAR enrolment and analysis systems to minimize inconsistencies in the information declared by landowners and to promote greater celerity in validating the registrations (ICV, 2019a, 2019b). However, the analysis of more than half a million rural properties in the Amazon is challenging and to advance with the legal application of the CAR, it is crucial that the problems of land legitimacy evidenced by the overlaps are resolved first.

The CAR's effectiveness depends on complementary policies that focus on resolving land tenure, including the compensation payment for legal expropriations, improvements in the infrastructure of notary offices, and government measures that discourage deforestation and land grabbing. Furthermore, financial support and the expansion of technical teams are also necessary for the Amazonian states to be able to advance in the CAR analysis (SPAROVEK et al., 2019b). Finally, it should be clear that the CAR is not a land tenure regularization policy but an environmental policy with potential application to reduce deforestation in the Amazon (L'ROE et al., 2016). Improvements in land governance and commitment to the environmental agencies responsible for analysing the CAR are essential to ensure an effective application of this registry as a tool to support environmental enforcement.

4.5 Conclusion

In this study, we focused on understanding the distribution patterns of rural properties in the Brazilian Amazon and investigating the conflicts between public forests and private lands in the biome. Despite the issues related to the self-declaratory nature of the CAR, land problems encompassing overlaps among rural properties, illegal land tenure claims, and public lands grabbing have been revealed in a spatially explicit way for the entire Amazon. We found (i) land concentration in large properties that accounted for 60% of the area registered in the CAR; reflecting the history of the expansion of the agricultural frontier for the Amazon; (ii) a high level of overlap between rural properties distributed throughout the area registered in the CAR, likely resulting from the obsolete and decentralised registry system, and (iii) high pressure from rural properties on public forests, reflecting weak land governance and the use of CAR as a tool to formalize land grabbing, especially in undesignated lands. All these issues highlight the challenges of CAR implementation and analysis by Amazonian states. However, without a correct differentiation of rural actors, land problems will continue to occur, and accountability for environmental damage in public and private lands will remain ineffective. Despite all the land issues addressed in this study, CAR has provided substantial information on the distribution of private lands in the Amazon. Therefore, given the importance of additional CAR validation for territorial management, our future efforts will be concentrated on providing detailed information on the distribution of rural properties and their overlaps for each Amazonian municipality. On the other hand, the data from this study (including the tables available in Appendix A, Table A7-A13) can already strengthen land governance and forest policies in the Amazon by guiding environmental agencies in planning for CAR analysis and defining strategies to resolve land problems and public land grabbing in their territory.

5 UNVEILING THE CONTRIBUTION OF RURAL PROPERTIES TO FOREST FIRES IN THE BRAZILIAN AMAZON

5.1 Introduction

Forest fires are historically rare in tropical forests but are becoming an increasingly prominent component in the Amazon due to the synergy between anthropic and climatic factors (ARAGÃO et al., 2018; COCHRANE et al., 1999). Forest degradation caused by fire is one of the main causes of forest degradation in the Amazon (MATRICARDI et al., 2020). Furthermore, about 28% of the Brazilian Amazon is exposed to human pressure related to fire activities (BARRETO et al., 2006). As fire is an inexpensive alternative, it is widely used by rural landowners for cleaning and preparing the soil, maintaining pastures, controlling invasive plants and removing biomass after deforestation (BARLOW et al., 2020; DE MENDONÇA et al., 2004; DENICH et al., 2004). All these activities act as ignition sources, increasing the likelihood of fire escaping to nearby forest areas, which can cause large forest fires (COCHRANE; SCHULZE, 1998). These activities, combined with exposing the forest to edge effects (SILVA-JÚNIOR et al., 2018) and logging (GERWING, 2002), make the forest even more fire-prone. In addition, extensive forest fires have coincided with drought years in the Amazon (ALENCAR et al., 2015; ALENCAR; SOLÓRZANO; NEPSTAD, 2004; ANDERSON et al., 2018; ARAGÃO et al., 2018; ELVIDGE et al., 2001; SILVA et al., 2018b; SILVA JUNIOR et al., 2019)(ANDERSON et al., 2018; ARAGÃO et al., 2018; ELVIDGE et al., 2001; SILVA et al., 2018d; SILVA JUNIOR et al., 2019), when the forests become drier and more susceptible to fire events.

Although the greatest incidence of forest fires is associated with anthropic causes in the biome (BARLOW et al., 2020; REIS et al., 2021), understanding its occurrence on private lands remains poorly understood. This lack of information ends up portrayed in public policies, with an inconsistency between the regulations for the use of fire and its applications by rural landowners (CARMENTA et al., 2013). Fire policies determine when and what can be burned (BRASIL, 2012a), but they are generic regulations that do not consider the socioeconomic context of rural landowners. Differences in financial power and land occupation history influence how landowners modify and use land in the

Amazon, consequently influencing the fire dynamics on their properties (PACHECO, 2012). In addition, the regional variability of the dry season can also influence the fire dynamics in rural properties. In this case, it is already clear that the dry season end determines different fire seasons across the Amazon (CARVALHO et al., 2021). However, we still need to understand how the dry season length influences the duration and speed of fire, which can determine distinct fire behaviour on rural properties across the biome.

In contrast to studies that assessed deforestation on rural properties in the Amazon (GODAR et al., 2012, 2014; GODAR; TIZADO; POKORNY, 2008; MICHALSKI; METZGER; PERES, 2010; PACHECO, 2009, 2012; RICHARDS; VANWEY, 2016; STEFANES et al., 2018), studies that addressed the fire occurrence are restricted to local scales and mainly focused on the fire dependence by small landowners for land management (CARMENTA et al., 2011). The targeted choice for small landowners generates a biased understanding of the impacts and dependence on the use of fire by rural landowners. These studies generally are based on a sample size limited to a few hundred properties and are related to the management practices (SORRENSEN, 2000), fire prevention expenses (BOWMAN; AMACHER; MERRY, 2008), advantages of using fire-free management (COSTA, 2012; DENICH et al., 2004, 2005) and lack of conformity between fire policies and land management practices (CARMENTA et al., 2013). This biased sampling can lead to formulating environmental policies and decision-making based on incomplete information about fire occurrence at the rural property level.

Information derived from remote sensing data has highlighted where fire occurs (ALENCAR et al., 2022; ELVIDGE et al., 2001; GIGLIO et al., 2018; MORTON et al., 2011); when it occurs (CARVALHO et al., 2021), and what is burning (ANDELA et al., 2022; ANDERSON et al., 2015). However, we still need to advance our knowledge of who is burning the Amazon (ALENCAR et al., 2020; ALENCAR; RODRIGUES; CASTRO, 2020). Implemented by the Brazilian National Vegetation Protection Law (Law n°12.651/2012), the CAR presented a new perspective on the spatial distribution of private lands in the Brazilian territory, with an unprecedented level of detail of rural properties in the country (L’ROE et al., 2016; STEFANES et al., 2018). Analyses of CAR data have supported tracking illegal deforestation (RAJÃO et al., 2020), identifying conflicts between public and private lands (SPAROVEK et al., 2019, CARVALHO et al., submitted in 2022) and monitoring compliance with environmental laws (ALIX-GARCIA et al., 2018; L'ROE et al., 2016) in the Brazilian Amazon. Understanding how forest fires are distributed on rural properties in the Brazilian Amazon can contribute to developing more assertive policies to reduce forest fires and protect native vegetation on private lands in the biome.

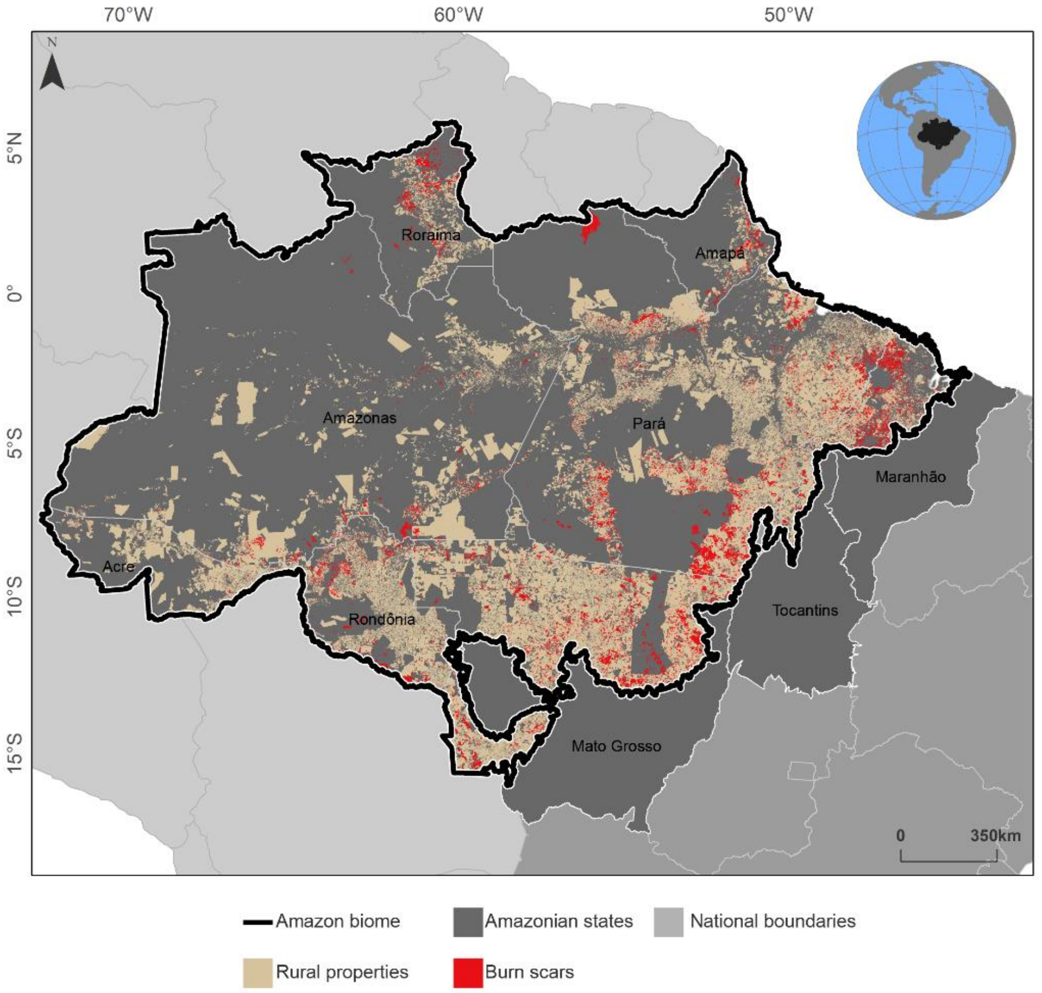
To advance in the issue of who is burning the Amazon, we investigated the occurrence of forest fires on rural properties in the Brazilian Amazon. Our main objective was to assess the occurrence of forest fires in small, medium and large properties. To do that, we measured the total burned area and the sizes of burned area polygons within each property size category, considering the Brazilian Amazon limits and also separately for each Amazonian state. We also investigated the behaviour of forest fires in terms of duration, speed and fire expansion according to the spatial variation of the dry season length in the biome. Finally, we discuss our results addressing the importance of identifying the origin of burning in rural properties to reduce the forest fires incidence on private lands, and we also provide information to support forest and climate policies in the Amazon.

5.2 Methods

5.2.1 Study area

The study area encompasses the Brazilian Amazon biome, covering an area of 4,207,893 km² (Figure 5.1). Three Brazilian states cover 79% (3,306,714 km²) of the biome's area, with 37% in Amazonas, 29% in Pará and 12% in Mato Grosso. The remaining area is in Rondônia (6%), Roraima (5%), Acre (4%), Amapá (3%), Maranhão (3%) and Tocantins (1%). Between 2012 and 2018, the period analysed in this study, the forest area of the biome reduced by 45,238 km², totalling 3,286,945 km² in the last year of this time series (MAPBIOMAS, 2022). In the same period, agriculture and pasture areas increased by 8%, reaching 608,799 km² in the biome (MAPBIOMAS, 2022).

Figure 5.1 - Study area in the Brazilian Amazon, including the distribution of rural properties registered in the Rural Environmental Registry (CAR). Burn scars observed from 2012 to 2018 across the biome were extracted from Global Fire Atlas data.



Source: Author's production.

5.2.2 Data

5.2.2.1 Rural properties

We used the boundaries of the rural properties enrolled in the CAR. We downloaded the dataset for each Amazonian municipality (n=548) available on the CAR public consultation platform (SFB, 2019a). We obtained this database in April 2019, when 100% of properties eligible for registration were already enrolled in the CAR (SFB, 2019b). CAR is a mandatory register for all rural properties in the Brazilian territory, which must include the geographic coordinates of the boundaries the property and information about the land use and land cover, including the protected areas of Legal Reserve and Permanent Preservation Areas (ROITMAN et al., 2018). This register is the first step towards the environmental regularization of rural property, providing an initial diagnosis of environmental liabilities and assets in accordance with the requirements of the Brazilian National Vegetation Protection Law (ROITMAN et al., 2018).

According to the methodology applied by Carvalho et al., (submitted in 2022), we removed from our analyses the rural properties with cancelled registers and with topological inconsistencies, resulting in a dataset of 536,340 rural properties. We classified the size of the rural property (RP) according to the definition used in the Brazilian National Vegetation Protection Law (BRASIL, 2012a), which is based on the number of fiscal modules of the property. A fiscal module (FM) is an agrarian measure expressed in hectares and variable among municipalities (LANDAU et al., 2012). For example, in the Amazon biome, one fiscal module ranges from 5 to 100 ha (LANDAU et al., 2012). Based on the area of the rural property (RP) and the fiscal module (FM) of the municipality in which it is located, a rural property can be classified as small ($RP \leq 4FM$), medium ($4FM<RP\leq 15FM$) or large ($RP>15FM$).

5.2.2.2 Burn scars

To calculate the burned area in rural properties, we used the Global Fire Atlas (GFA) data (ANDELA et al., 2019). The GFA is a global burned area data derived from processing MODIS/MCD64A1 – Collection 6 product and is available from 2003 to 2018. The GFA provides vector data of the burned scars derived from the underlying 500 m MODIS data, including information about individual fire size, duration (days), speed (km day^{-1}), expansion (km^2 day^{-1}), day of the burn, location of the ignition points and other attributes. GFA algorithm individualizes the burned scars based on estimated burn dates on the MCD64A1 product. Filters are applied to separate individual burned scars that are adjacent, but that occur on different dates and to correct outliers on the burn date at the edges of large fires. More details about MODIS/MCD64A1-Collection 6 are described in Giglio et al. (2018), and the GFA processing and validation methodology are presented in Andela et al. 2019.

According to the Brazilian agricultural census, we observed a high dynamic in the rural property size in the last two decades in the Amazon (IBGE, 2006, 2019). For this reason, to ensure that our analyses were representative of the current distribution pattern of private lands in the biome, we used the burned area data available between 2012 and 2018. We defined 2012 as the initial year because it marks the changes in Brazilian legislation that regulate the protection of native vegetation within private lands in the national territory (Law n°12.651/2012).

5.2.2.3 Forest mask

We used the data from the Brazilian Annual Land-Use and Land-Cover (LCLU) Mapping Project – MapBiomas (Collection 6) (MAPBIOMAS, 2022). The MapBiomas project produces annual maps to understand the LCLU dynamics in the Brazilian territory, based on the Landsat dataset available in the Google Earth Engine platform from 1985 to the present. The mapping methodology is pixel-based and machine learning algorithms, considering spatial and temporal attributes to better discriminate the LCLU classes and produce maps with a 30m spatial resolution. More information about the methodology is available in Souza et al. (2020).

We used the maps available for the Amazon biome between 2012 and 2018. We reclassified them into binary maps, considering non-forest and forest classes. The non-forest class included all other land-use and land-cover classes, such as savanna, wetlands, grassland, pasture, agriculture, and others.

5.2.2.4 Dry season length

We used data from the Amazonian fire calendar (CARVALHO et al., 2021) to investigate the fire dynamics according to the spatial variation of the dry season length in the biome. The data are based on processing a 39-year time series (1981 to 2019) from the Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) and are available for the Amazon basin at a spatial resolution of 10m.

The Amazon dry season length is defined by the number of consecutive months with precipitation below 100 mm. This threshold is based on the relationship between monthly rainfall and evapotranspiration values for tropical forests. The mean monthly evapotranspiration of tropical forests is 100 mm (ROCHA et al., 2004; VON RANDOW et al., 2004) and when the monthly rainfall is below this value, the forest enters into a water deficit (ARAGÃO et al., 2007).

5.2.3 Analysis

We conducted all the analyses considering the distribution of rural properties throughout the biome and in each Amazonian state. The steps to calculate the burned forest area and attributes related to the fire dynamics on private lands are described below.

5.2.3.1 Burned forest area

To investigate the occurrence of forest fires in private lands in the Amazon, we extracted the total burned area in non-forest and forest for each rural property category (small, medium, large and multiple) using the binaries maps created from the MapBiomas data. We also extracted the total forest in each rural property category.

For each year of the time series, we calculated the total burned forest in each rural property category and how much each category contributed to the total burned forest observed in the year. In this case, we calculated the ratio between the total burned forest in each rural property category and the total burned forest in private lands. We also calculated how much forest fires represented the total burned on private lands as the ratio between the total burned forest in each rural property category and the total burned (non-forest and forest) in the same category. Finally, we investigated how much forest areas on private lands were affected by the fire. For this, we calculated the burned forest per forest area unit in each rural property category. For each rural property category, we also classified the burned forest scars according to the polygon size into five classes: <5 ha, 5-20ha, 20-50ha, 5-100ha and >100ha.

5.2.3.2 Duration, speed, and expansion of fire

We fitted linear regression models to understand the effect of dry season length on the duration (days), expansion ($km^2\ day^{-1}$) and fire speed ($km\ day^{-1}$) in the burned forest scars. We considered the centroid of each burn scar to extract the dry season length. To obtain the model response variables, we calculated the mean values of fire duration, expansion and speed in the burn scar for each dry season length. We adopted the significance level of 95% (p-value < 0.05).

5.3 Results

5.3.1 General pattern

More than 55,000 km² of forests were burned in the Brazilian Amazon between 2012 and 2018 (Table 5.1). Of this total, 49% (26,871 km²) occurred in rural properties, with an annual mean of 3,839 km² (± 2,417 km²) of burned forest (Table 5.1). In the seven years evaluated, large properties encompassed the largest burned forest area, accounting for 55% (14,884 km²) of the total observed on private lands (Table 5.2).

Table 5.1 - Total burned forest in the Brazilian Amazon between 2012 and 2018. The fraction of this total observed in rural properties is also shown in absolute and percentages.

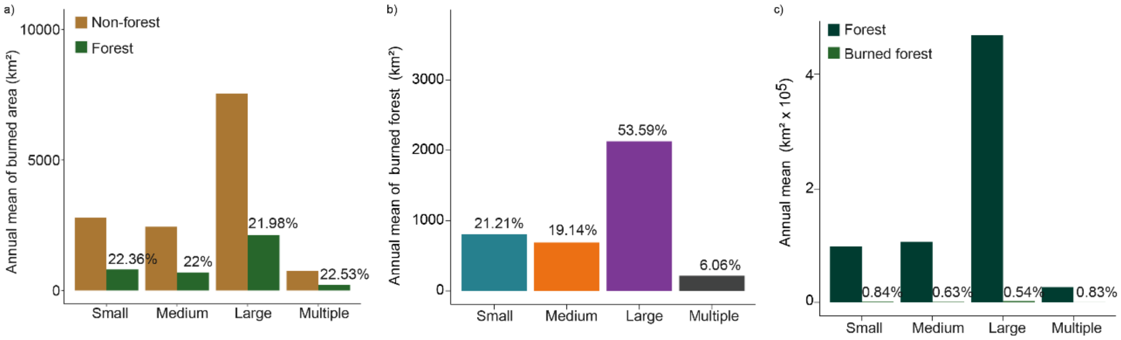
	Burned forest (km²)		
Year	**Amazon biome**	**Rural properties**	**%**
2012	7,143.87	3,436.96	48.11
2013	2,265.16	1,213.66	53.58
2014	5,147.49	2,680.76	52.08
2015	14,038.28	6,378.57	45.44
2016	7,864.46	3,085.15	39.23
2017	15,468.45	8,398.89	54.30
2018	3,374.40	1,677.19	49.70
Total	55,302.11	26,871.18	48.59
Mean	7,900.30	3,838.74	48.92
SD	4,710.80	2,416.59	4.9

Table 5.2 – Total burned forest in rural properties between 2012 and 2018, according to rural property category. Considering the number of fiscal modules (FM), each rural property (RP) was classified as small (RP ≤ 4FM), medium (RP<4FM≤15FM) or large (RP > 15FM). Burned areas that occurred in more than one category were only included in the multiple category.

Year	Small	Medium	Large	Multiple	Total
2012	990.61	651.08	1,571.07	224.20	**3,436.96**
2013	239.01	223.87	669.15	81.62	**1,213.66**
2014	628.55	493.85	1,396.36	162.01	**2,680.76**
2015	1,597.12	992.63	3,414.92	373.90	**6,378.57**
2016	555.78	791.96	1,540.53	196.88	**3,085.15**
2017	1,336.99	1,312.17	5,373.63	376.10	**8,398.89**
2018	293.72	357.17	918.30	107.99	**1,677.19**
Total	**5,641.78**	**4,822.74**	**14,883.97**	**1,522.69**	**26,871.18**
Mean	**805.97**	**688.96**	**2,126.28**	**217.53**	**3,838.74**

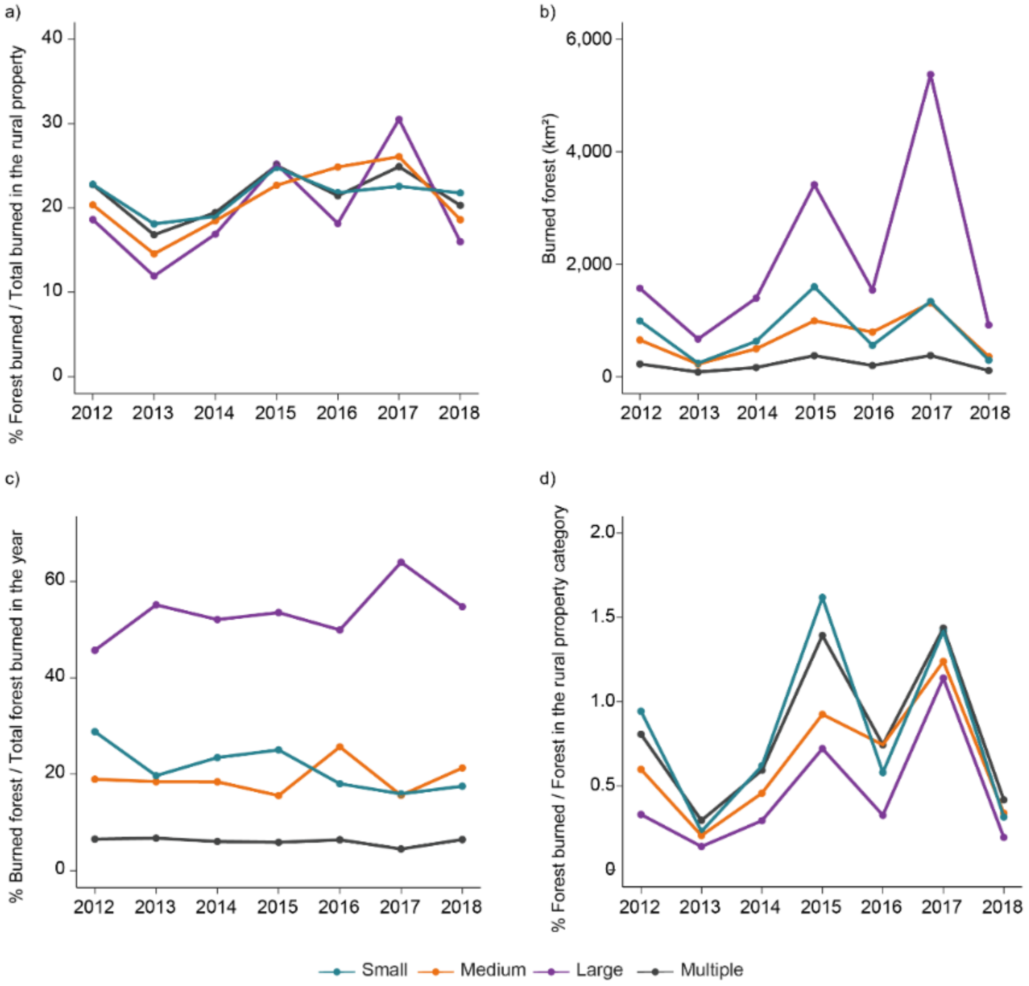
We observed that ~22% of the total area burned annually in each category of rural property corresponded to forest areas (Figure 5.2a, Figure 5.3a). This percentage corresponded to an annual mean of 2,126 km² (± 1,682 km²) of burned forest in large properties, triple the area observed in small and medium properties (Figure 5.2b, Figure 5.3b). This pattern resulted in an annual mean contribution of 54% (± 6%) of large properties to the total burned forest per year in private lands, while the contribution of small and medium properties was below 21% (Figure 5.2b, Figure 5.3c). Although we observed the largest burned forest in large properties, this burned area corresponded to 0.45% (± 0.33%) of the total forest in this category (Figure 5.2c, Figure 5.3d). On the other hand, the annual mean of 806 km² (± 481 km²) burned forest in small properties corresponded to 0.82% (± 0.49%) of the total forest in the category, twice the value observed for large properties (Figure 5.2c, Figure 5.3d). Furthermore, in 2015, the percentage of forest affected by fire in small properties was the highest in the time series, reaching 1.62% (1,597 km²) (Figure 5.3d).

Figure 5.2 – Annual means of the burned area observed in rural properties between 2012 and 2018. The total burned in non-forest and forest areas is shown in Figure 5a. Figure 5b shows the contribution of each rural property to the annual mean of burned forest observed on private lands. Figure 5c shows the annual mean of forest and burned forest for each rural property size. The relationship between the total burned forest and the total forest in each category is also presented in percentage values. All values are presented considering the rural properties categories of small (RP ≤ 4FM), medium (RP<4FM≤15FM) and large (RP > 15FM). Burned areas that occurred in more than one category were only included in the multiple category.



Source: Author’s production.

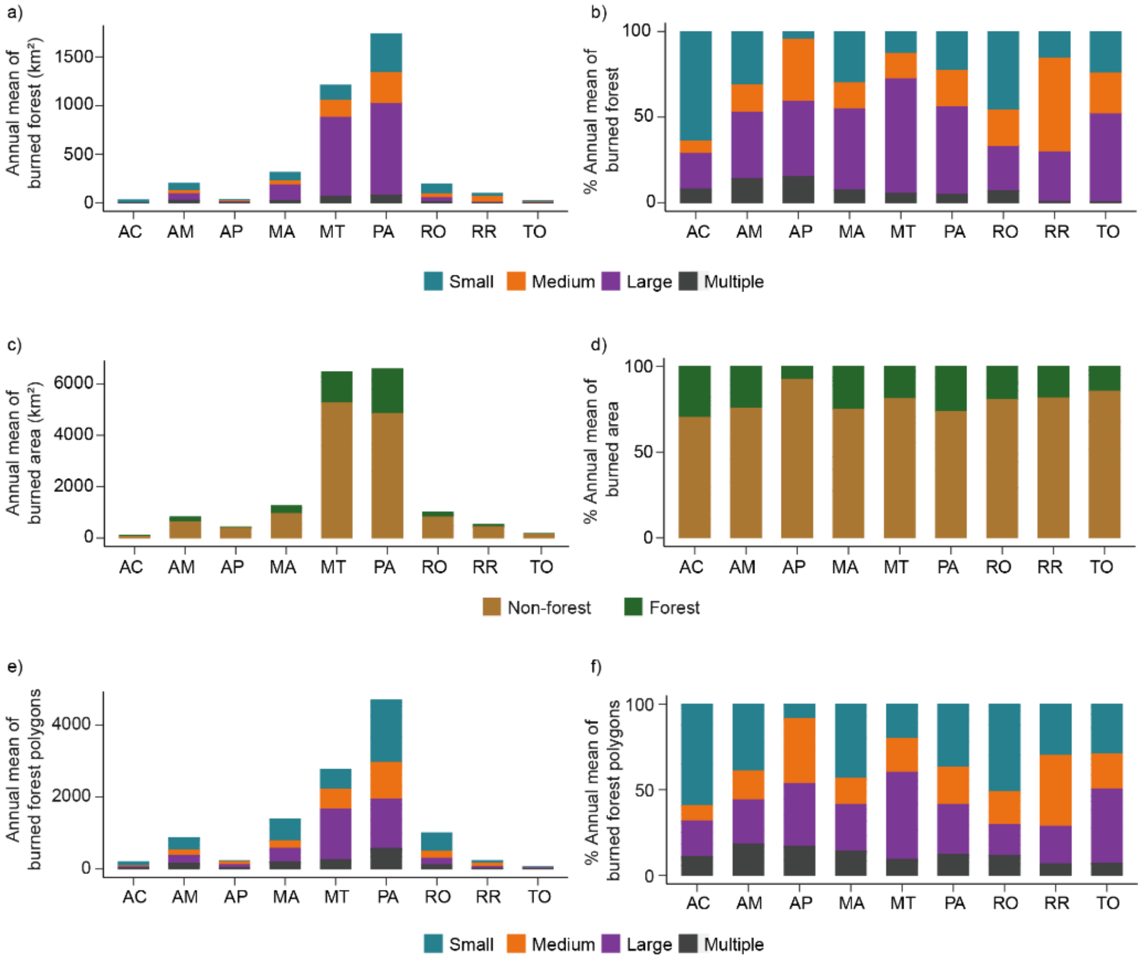
Figure 5.3 – Time series of the burned forest area in rural properties between 2012 and 2018. Figure 5.3a shows the percentage relationship between the burned forest area and the total burned area (non-forest and forest) in each rural property category. The temporal pattern of the burned forest area is presented in Figure 5.3b. Figures 5.3c shows the percentage relationship between the burned forest area in the rural property category and the total burned forest observed in all categories of rural properties. Figure 5.3d shows the percentage relationship between the burned forest area in the rural property category and its total forest area.



Source: Author's production.

Regionally, forests fires were mainly concentrated on rural properties in Pará, and Mato Grosso, which added 74% (2,947 km²) of the total burned forest in private lands annually, presenting annual means of 1,738 km² (± 1,646 km²) and 1,209 km² (± 553 km²), respectively, (Figure 5.4a). We also observed that 68% (825 km^2 ± 454 km^2) of the burned forest in Mato Grosso occurred in large properties, which was six and five times higher than in small and medium properties of the state, respectively (Figure 5.4a-b). Although forest fires predominated on large properties in most of the biome, 60% (17 km^2 ± 11km^2) of the burned forest in Acre and 46% (90 km^2 ± 44 km^2) in Rondônia were concentrated in small properties, while in Roraima, medium properties accounted for 61% (60 km^2 ±122 km^2) of the annual mean (Figure 5.4a-b).

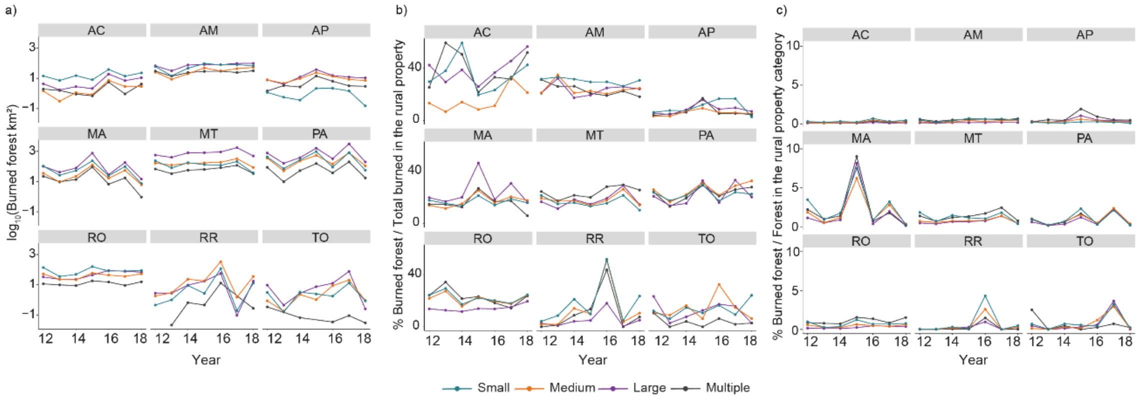
Figure 5.4 – Annual mean of the burned forest in rural properties between 2012 and 2018 according to each state of the Amazon biome. Figure 5.4a and Figure 5.4b show the annual mean of burned forest area observed in each state. The annual mean according to the burned scars observed in non-forest and forest areas are shown in Figure 5.4c and Figure 5.4d. The annual mean of burned forest polygons is shown in Figure 5.4e and Figure 5.4f. All values are presented considering the contribution of each rural property category (small, medium, large and multiple) in absolute values and percentages.



Source: Author’s production.

We also observed that Acre presented the highest percentage of burned forest compared to the annual total of non-forest and forest burned in the state, accounting on mean for 33% (29 km² ± 18 km², Figure 5.4c-d). In this state, the burned forest area exceeded the non-forest burned area in some years, as observed in 2013 for the multiple category, in 2014 for small and in 2018 for large properties (Figure 5.5a-b). In these years, the contribution of the burned forest reached almost 60% of the total, adding 2 km², 15 km² and 11 km² of the total burned area, respectively (Figure 5.5a-b). In drought years, we observed a burned forest area of 761 km² in large properties in Maranhão in 2015 and 117 km² in small properties in Roraima 2016 (Figure 5.5a-b). The forest area affected by fire in these years was the highest in the time series among all states, representing 8% of the forest in large properties in Maranhão and 4% of small properties in Roraima, respectively (Figure 5.5c).

Figure 5.5 – Each Amazonian state's burned forest area in rural properties from 2012 to 2018. Figure 5.5a shows the total burned forest area in each rural property category. Figure 5.5b shows the relationship between the burned forest area and the total burned area (non-forest and forest) in each rural property category. Figure 5.5c shows the percentage relationship between the burned forest area in the rural property category and its total forest area. AC: Acre, AM: Amazonas, AP: Amapá, MA: Maranhão, MT: Mato Grosso, PA: Pará, RO: Rondônia, RR: Roraima, TO: Tocantins.

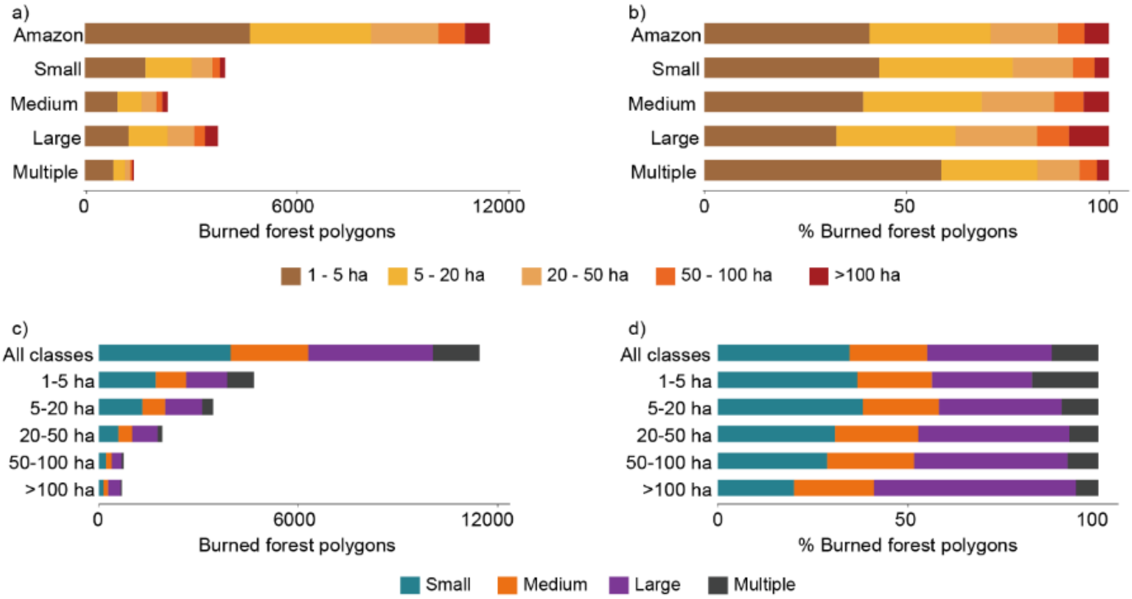


Source: Author's production.

5.3.2 Size of burned forest polygons

We found an annual mean of 11,446 (± 4,554) burned forest polygons in the Amazon, with 35% (3,964 ±1,832) occurring in small and 33% (3,762 ± 1,262) in large properties (Figure 5.6). Polygons less than 20 ha were numerous in all categories of rural properties, accounting for 62% to 82% of the total observed in each category of rural property (Figure 5.6a-b). We also found that 40% (300) and 53% (368) of the polygons in the 50-100 ha and >100ha classes occurred in large properties, respectively (Figure 5.6c-d).

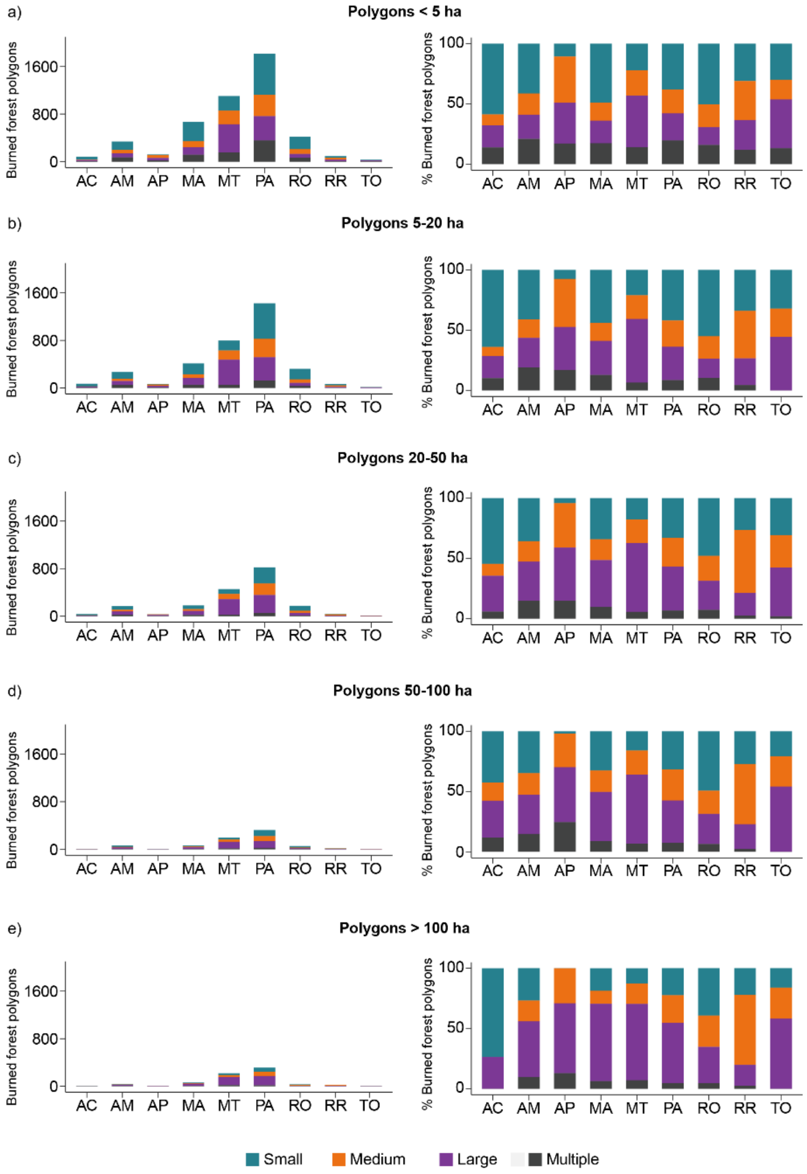
Figure 5.6 - Distribution of the number of burned forest polygons by category of rural property (5.6a-b) and size of the burn scar (5.6c-d). Rural properties (RP) were classified according to the number of fiscal modules (FM) as small (RP<4FM), medium (4MF ≤ RP ≤ 15MF) and large (RP>15MF). Burn scars were classified according to their size into five classes: 1-5 ha, 5-20 ha, 20-50 ha, 50-100 ha and >100 ha. In all figures, the dependent variable is shown on the x-axis for visual purposes.



Source: Author's production.

Regionally, although we observed that the largest area of burned forest occurred in large properties in Amazonas, Maranhão and Pará, in these states, the largest number of polygons occurred in small properties, which concentrated up to 43% of the total burned scars observed and presented mainly a size of less than 5 ha (Figure 5.4a-b; e-f, Figure 5.7). However, burned areas larger than 100 ha were still predominant in large properties in the three states, which concentrated 46% to 64% of the polygons in this size class among all categories of rural properties (Figure 5.7c-d). We also observed that only in Acre the polygons of this category were predominant in small properties (Figure 5.7-c).

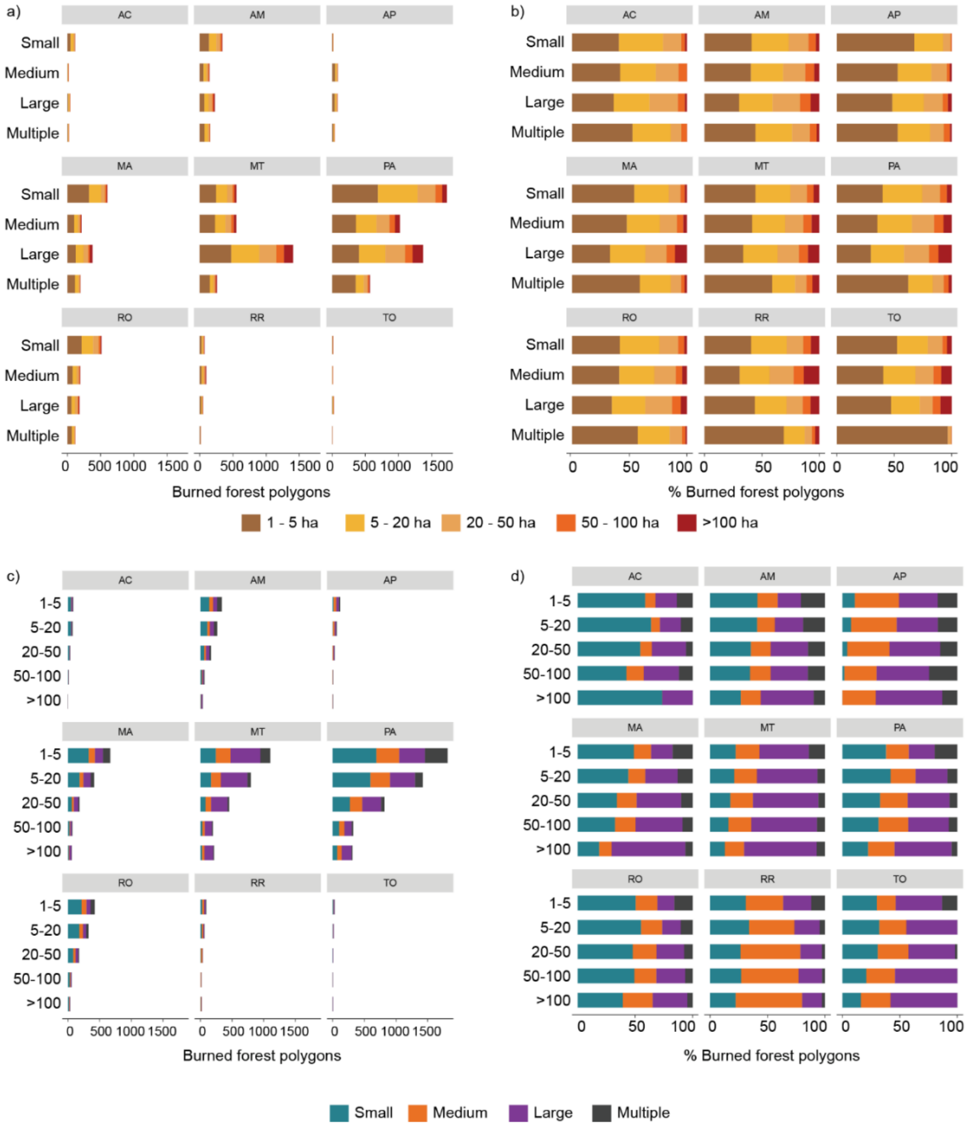
Figure 5.7 - Distribution of burned forest polygons in each size class of the burn scar for each Amazonian state. Burn scars were classified according to their size into five classes: 1-5 ha, 5-20 ha, 20-50 ha, 50-100 ha and >100 ha. AC: Acre, AM: Amazonas, AP: Amapá, MA: Maranhão, MT: Mato Grosso, PA: Pará, RO: Rondônia, RR: Roraima, TO: Tocantins.



Source: Author's production.

Considering the distribution of polygons in each state, we observed that in Roraima, polygons larger than 100 ha represented 10% (22) of the annual mean of burned scars in the state. On the other hand, we also observed the smallest contribution of polygons of this category in Acre, adding 1% (3) of the total observed in the state (Figure 5.8).

Figure 5.8 - Burned forest polygons in each Amazonian state, considering their distribution according to the rural property category (5.8a-b) and burn scar size (5.8c-d). Rural properties (RP) were classified according to the number of fiscal modules (FM) as small (RP<4FM), medium (4MF ≤ RP ≤ 15MF) and large (RP>15MF). Burn scars were classified according to their size into five classes: 1-5 ha, 5-20 ha, 20-50 ha, 50-100 ha and >100 ha. AC: Acre, AM: Amazonas, AP: Amapá, MA: Maranhão, MT: Mato Grosso, PA: Pará, RO: Rondônia, RR: Roraima, TO: Tocantins.

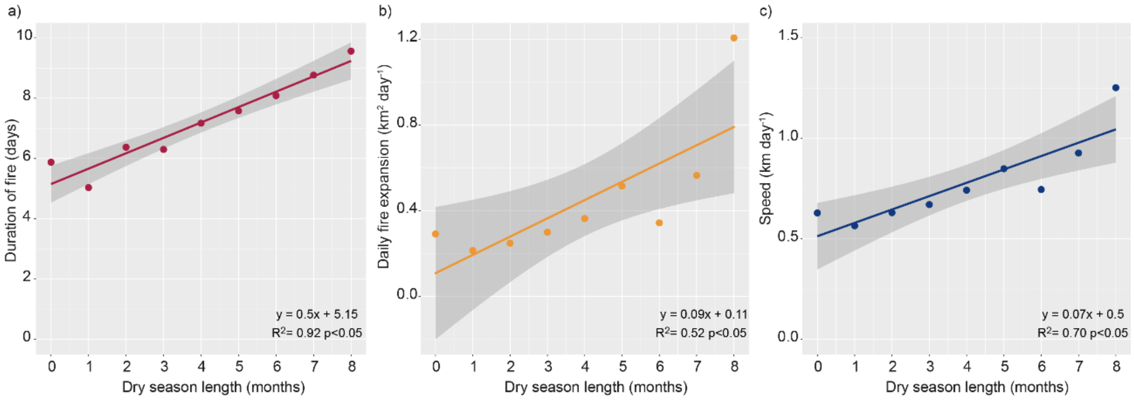


Source: Author's production.

5.3.3 Duration, expansion and speed of fire

We found a strong positive relationship between the duration of the fire and the dry season length, with a linear increase in fire days with the prolongation of the dry season ($R^2=0.92$, $p<0.05$). We observed that forest fires can last up to six days in regions with a dry season length less than three months (Figure 5.9a). On the other hand, this duration can be increased by one to four days as the dry season becomes longer (Figure 5.9a). We also observed positive relationships between the daily expansion and fire speed variables with the dry season length, showing R^2 values of 0.52 and 0.7, respectively (Figure 5.9b-c). Compared to the shortest dry season lengths, up to three months, fire expansion can be four to six times faster in areas with an eight-month dry season, reaching 1.21 $km^2\ day^{-1}$ (Figure 5.9b). Considering this comparation for fire speed, the values can be duplicated, reaching the maximum of 1.25 $km\ day^{-1}$ (Figure 5.9c).

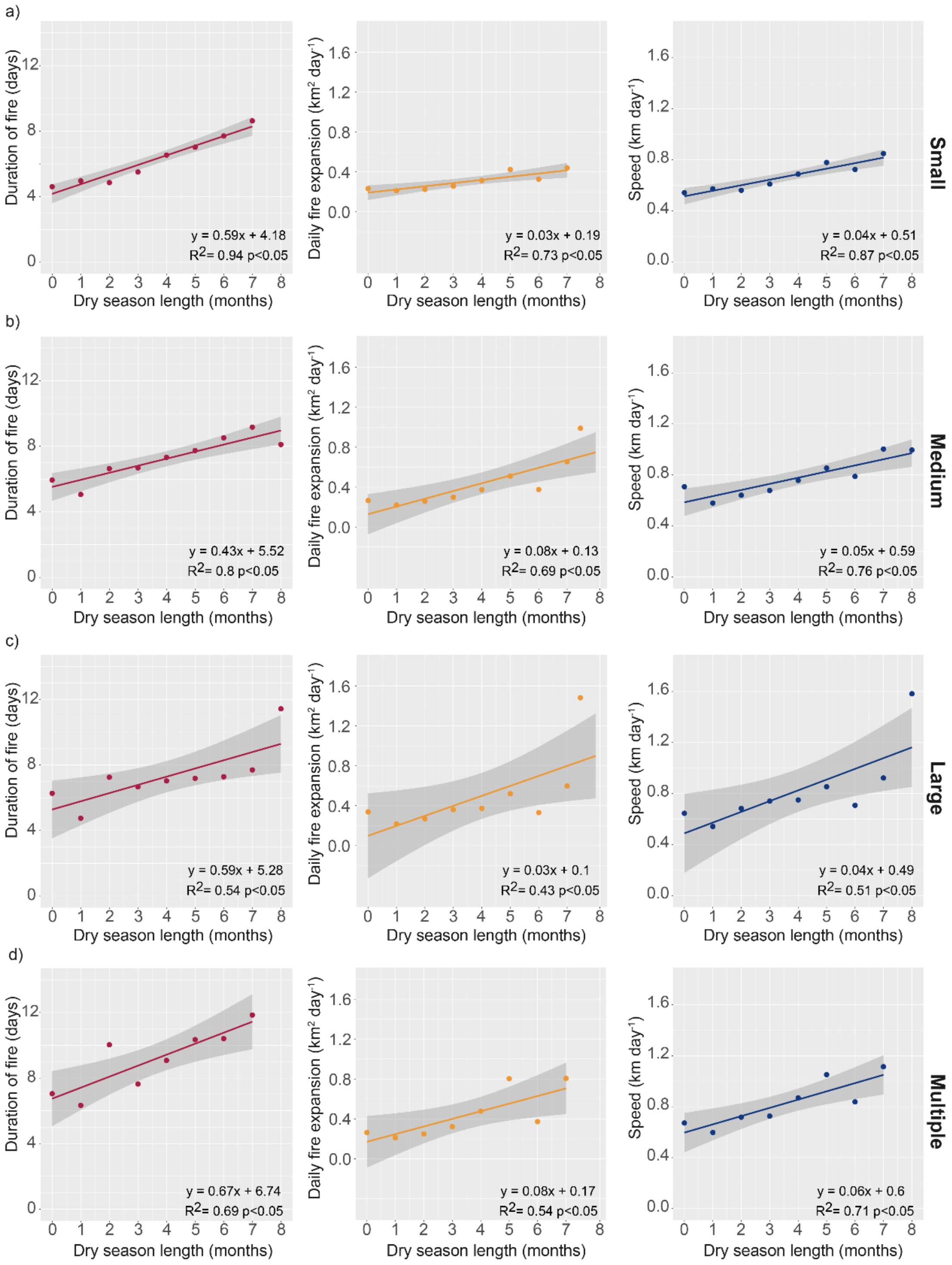
Figure 5.9 - Variation of fire duration (days, 5.9a), expansion ($km^2\ day^{-1}$, 5.9b) and speed ($km\ day^{-1}$, 5.9c) in burned forest scars in rural properties according to the dry season length. The dry season length is defined as the number of consecutive months with rainfall below 100mm. Shaded grey areas represent 95% confidence intervals.



Source: Author's production.

Considering the fire duration for each category of rural property, we observed values above ten days only in the categories of large and multiple properties (Figure 5.10). We also observed that forest fires had the highest speed in the longest dry season length (eight months) on large properties, reaching 1.58 $km\ day^{-1}$ (Figure 5.10c).

Figure 5.10 - Fire duration (days, 5.10a), expansion (km² day^{-1}, 5.10b) and speed (km day^{-1}, 5.10c) in burned forest scars according to the rural property size (small, medium, large, and multiple) and the dry season length. Shaded grey areas represent 95% confidence intervals.



Source: Author's production.

5.4 Discussion

5.4.1 Forest fires in rural properties

We investigated the fire occurrence on rural properties and evaluated its impacts on the Brazilian Amazon Forest. We showed that the largest impact on the forest occurred on large properties, which concentrated more than 50% of forest fires, equivalent to more than 2,000 km² annually and three times the burned forest area in small/medium properties annually. On the other hand, the percentage of burned forest per unit of area was higher in small properties, which was expected since they covered only 14% (98,914 km²) of the forest area observed in private lands, and proportionally a larger forest area is exposed to fire within these properties. Our results were similar to the patterns observed for deforestation on private lands, for which small properties accounted for 12% (GODAR et al., 2014) to 16% (PACHECO, 2012) of the total deforestation, while large properties represented from 50% (GODAR et al., 2014) to 55% (PACHECO, 2012). The strong link between fire and deforestation in the Amazon (ARAGÃO et al., 2008) may explain why forest fires were more frequent on large properties. As large amounts of biomass are burned after deforestation on large properties, there are a great number of ignition sources and a higher likelihood of them reaching nearby forests. Furthermore, the longer duration of fire on large properties may be associated with their concentration in the southeastern Amazonia (Carvalho et al., submitted in 2022), where deforestation related to large-scale commodities aggravates climatic impacts, with local conditions more susceptible to higher temperatures and less precipitation (MAEDA et al., 2021).

In general, we observed that about 20% of the burned area on rural properties corresponded to forest, which was equivalent to burning from 0.5% to 0.8% of the total forest on private lands every year. However, our estimates are probably underestimated, as remote sensing instruments hardly detect understory fires that do not reach the canopy (MORTON et al., 2011; PESSÔA et al., 2020). We also observed that the additional effect of droughts can result in a burned forest area four times larger than in non-drought years, as observed for Maranhão in the 2015 drought (Figure 5.5c). As the volume of rainfall that reaches the Amazon is reduced in drought years, the groundwater does not recharge enough, and trees respond by dropping leaves to reduce water loss through evapotranspiration (NEPSTAD et al., 2004). These structural changes in the canopy increase the incidence of light inside the forest, making the environment hotter, drier and reducing the litter moisture content (BRANDO et al., 2020; COCHRANE et al., 1999). With abundant load fuel, favourable climatic conditions and ignition sources from anthropic activities, fire has all factors that allow it to remain and spread in the forest.

Drought events potentiate the occurrence of fire in the Amazon, but the human component is the main driver of forest fires in the biome (COCHRANE; BARBER, 2009). The intentional use of fire by landowners generates different amounts of fuel load, which affects the potential for accidental forest fires. In the family farming, small landowners use the fire to burn fallow vegetation in the early stages of succession, generating a lower fuel load due to the low biomass (SORRENSEN, 2000). In contrast, as almost half of deforestation on private lands in the Brazilian Amazon occurs on large properties (GODAR et al., 2014), this biomass provides enough fuel load to trigger huge forest fires, generating risks mainly in more fragmented landscapes, as observed in these rural properties (GODAR et al., 2014; POKORNY et al., 2013). This pattern may explain the largest burned forest area on large properties and the concentration above 50% of burned forest polygons >100 ha in this category of rural property.

The Amazon forest is not a fire-adapted ecosystem, and when the forest burns, impacts include damage to fauna (ANDRADE et al., 2017), flora (BARLOW; PERES, 2008; XAUD; MARTINS; DOS SANTOS, 2013) and increased carbon emissions(ARAGÃO et al., 2018). Fire also has long-term impacts on the forest, with carbon emissions that can prevail for decades and are not quickly offset by regeneration (SILVA et al., 2018a). With climate change, droughts are becoming more frequent, extensive, and severe in the Amazon (PANISSET et al., 2017), and fire will be an increasingly present factor in forest degradation. While extreme events are uncontrollable, we can tackle ignition sources to decrease the likelihood of forest fires, reducing impacts on carbon emissions and global climate change. Fire has long-term and far-reaching consequences, and without changes in its use for land management, forest fires will be increasingly recurrent in the Amazon. In the next section, we discuss solutions for using fire by landowners, considering the economic, environmental, and social benefits of the proposed alternatives.

5.4.2 Solutions to reduce forest fires on private lands

The largest area of burned forest occurred in large properties, which justifies investigating their causes and proposing solutions to reduce their environmental, social, and economic impacts. Additionally, as small properties showed the highest percentage of forest burned per unit of area, small property fires should also be addressed as a relevant issue in policy recommendations. However, most government initiatives to promote rural development in the Amazon do not consider the particularities of the production systems of each rural actor (GODAR et al., 2012; SORRENSEN, 2009). In this case, while large landowners are subsidised to expand and intensify land use, with public and private companies managing tens to thousands of hectares of land (BAUHUS et al., 2010), small landowners are kept out of rural development in the Amazon (POKORNY et al., 2013). Small landowners have already shown interest in technological development to boost production (MORELLO et al., 2019). However, resources for acquiring machinery and fertilizers are often inaccessible, and the cost-benefit of use of fire makes this practice the best economic strategy for land management by small landowners (CARMENTA et al., 2013; MISTRY; BIZERRIL, 2011).

The use of machinery in small properties leads to increased productivity and time savings, also contributing to improving the quality and competitiveness of products (MODESTO JÚNIOR; ALVES, 2014). Additionality, the adoption of low carbon technologies, such as no-tillage systems, can contribute to soil carbon storage (CERRI et al., 2009) and carbon emission reductions (GOUVELLO et al., 2010). However, a technological change requires public policies that subsidise mechanisation and assist small landowners' production flow (MORELLO et al., 2019; STABILE et al., 2020). It is also necessary to reformulate social policies to support training programs, providing knowledge and tools to ensure the successful implementation of technologies and the use of agricultural machinery. It is also important to point out that mechanisation is a good alternative, but it cannot be treated as the only option to reduce forest fires on small properties. In remote regions in the Amazon, the difficulty of access can make it unfeasible to arrive and use tractors, for example, and fire can be the only tool available for land management (BRONDIZIO; MORAN, 2008). In these cases, solutions should focus on the adoption of good fire use practices, such as building firebreaks (BOWMAN; AMACHER; MERRY, 2008), defining fire seasons (CARVALHO et al., 2021) and implementation of fire warning systems (MELO et al., 2021) in the rural properties. These actions must involve a collective effort, as neighbouring properties that do not take precautionary actions become focal points for the accidental spread of fire (CAMMELLI; COUDEL; ALVES, 2019; NEPSTAD et al., 2001).

While the socioeconomic condition makes fire an essential land management tool for small landowners, its use by medium and large landowners to remove the dead wood from deforestation can be seen as an obsolete technique and misalignment with sustainable development. Solutions to reduce deforestation-related fire should involve strengthening environmental enforcement and improving productivity per unit of area, promoting the vertical growth of rural properties. Examples of government actions from past decades have already shown that it is possible to achieve these goals. The slowdown in Amazon deforestation achieved with soybean and beef moratoria already showed that it is possible to increase production without expanding productive areas (ASSUNÇÃO; GANDOUR; ROCHA, 2015; NEPSTAD et al., 2014). Furthermore, technologies for monitoring deforestation in near real-time have also shown satisfactory results (DINIZ et al., 2015); however, their results depend on environmental governance committed to curbing deforestation and fires in the Amazon.

The Amazon has different socioeconomic realities that must be considered to deal more effectively with the impacts of fire on the forest. Behind forest fires on private lands in the Amazon is an agricultural development policy that urgently needs a reformulation to ensure economic growth in line with sustainable development in the biome. We reinforced that public policies should consider the origin and cause of the fire in rural properties, avoiding a paradigm of banning its use. Investment in technologies and/or the adoption of fire-free policies should not be treated as the only alternative. The use of fire should be ensured for those who depend on it for subsistence, but it needs to be guided by management plans with viable alternatives for small producers to maintain their production system (CARMENTA; COUDEL; STEWARD, 2019). In terms of fire-free policies, financial incentives to encourage mechanization on small properties can reduce the slash-and-burn practice (MORELLO et al., 2019), and enforcement and zero tolerance of illegal deforestation on medium and large rural properties can reduce the fuel load and ignition points (BARLOW et al., 2020).

5.5 Conclusion

In this study, we advanced our knowledge of fire dynamics on private lands in the Brazilian Amazon, investigating the burned forest area according to the rural property size. Our key finding showed that large properties were the main protagonists of forest fires, accounting for more than 50% of the annual average of burned forest. On the other hand, the burned forest per unit of forest area of the rural property category, was double in small properties compared to large properties. Considering the different uses of fire by landowners is critical to successfully curbing forest fires in the Brazilian Amazon. Focusing on reducing deforestation-related fire on large properties and ensuring safe practices in using fire by small landowners are important measures that should be addressed in forest policies. More studies are still needed to investigate the location of ignition points to generate even more assertive information about the fire origin in rural properties. Though, addressing the occurrence of forest fires by the properties' size is already an important step to pave the way towards sustainable fire management in the Amazon.

6 CONCLUDING REMARKS

In this thesis, I focused on integrating remote sensing-derived data to address knowledge gaps related to spatiotemporal patterns of land tenure and fire dynamics in the Amazon, providing results that can support environmental and climate policies in the biome. Next, I summarise the main findings and highlight the key message when these results are approached together.

In Chapter 3, I focused on understanding the spatiotemporal relationship between the dry season and fire occurrence in the Amazon basin. Although the relationship between dry season and fire is well established, the regional variability of this interaction was still unclear. The results showed that stratifying the Amazon beyond its political territorial boundaries is necessary to better understand the fire occurrence in the basin. The main founds showed a well-defined seasonal relationship between the dry season end and the occurrence of fire peaks, ranging from August to March throughout the Amazon basin. In terms of public policies, these results showed that considering the fire calendar can help to develop strategies and solutions for fire management and control in a more targeted way, supporting Amazonian countries to better allocate financial resources destined for these purposes.

The results from Chapter 4 showed a huge concentration of private lands in the Brazilian Amazon, where large properties encompassed 60% of the area but covered only 3% of the rural properties. The results also showed the challenges to defining the land tenure of private lands, as 25% of the area enrolled in the CAR presented overlaps among rural properties. Overlaps were even more worrisome when considering conflicts between public and private lands. Undesignated land was the most affected category, accounting for 62% of the overlapping area with rural properties, equivalent to more than 160,000 km². In addition, more than 20,000 km² of indigenous lands were overlapped by rural properties. These results are important because they not only showed the challenges to defining land tenure in the Brazilian Amazonian territory but also clarified the land grabbing and threats that traditional Amazonian people have been facing to ensure their land tenure rights.

By partitioning the burned forest area according to different rural actors in Chapter 5, it was possible to advance our knowledge about the fire dynamics on private lands. The results showed that, annually, almost 4,000 km² of forest were affected by fire on rural properties, with large properties concentrating more than 50% of this total, equal to three times the area observed in small and medium properties. These discrepancies in the burned forest area on private lands demonstrated that although studies have addressed mainly the use of fire by small landowners, they are not primarily responsible for forest fires in the Brazilian Amazon. In terms of fire policies, they should not be the same when their objectives are aimed at controlling and curbing forest fires in private lands. Fires on rural properties have different causes, which require different approaches, including fire-free strategies for land management, enforcement of deforestation and guaranteeing the use of fire for those who need it for subsistence. Furthermore, the forest area impacted by the fire followed the pattern of dominance of rural properties in each Amazonian state. This pattern indicates that strategies should also be locally thought about, considering the socioeconomic context of rural landowners and the pattern of land distribution in the region. Finally, it is also urgent to resolve uncertainties in land tenure to hold rural actors accountable for non-compliance with environmental laws, such as forest degradation by fire.

Addressed together, the results of Chapters 4 and 5 showed, notably, challenges to protect the Amazon due to forest degradation, land tenure problems, land grabbing and marginalisation of traditional people. All these problems distance Brazil from achieving goals in international agreements to minimize the impacts of global climate change, moving in the opposite direction of sustainable development. This lack of alignment between public policies and international commitments, such as the goals proposed by Brazil in its National Determined Contribution (NDC), reinforce the urgent need to develop collaborative strategies that enable the fulfilment of such commitments, integrating environmental, social, and economic interests. From the CAR analysis data, including dominance patterns of rural properties and the occurrence of forest fires, the results of this thesis can strengthen the implementation of the Brazilian National Vegetation Protection Law (nº12.651/2012) at the federal, state, and municipal levels. Although there are issues related to the self-declaratory nature of CAR, in this thesis, I provided tools and information to support the analysis of this data by the environmental agencies better to guide efforts and financial resources for such activity. CAR is not a land regularization tool, but the overlapping problems highlighted in this thesis can guide decision-makers in identifying priority areas to solve land tenure problems, whether between rural properties or between public and private lands. In terms of tackling land grabbing, efforts should go beyond the cancellation of the CAR but should mainly include policies that penalize land grabbers for the illegal appropriation of a public good. This data can also support climate policies, as focusing on solutions for using fire by rural landowners can help reduce the fire impacts on the forest and the carbon emission from forest fires. Although the impacts of forest fires are still neglected in inventories and estimates of carbon emissions, this is an increasingly present impact in the Amazon due to the synergy of human actions and climate change, that have made the biome a fire-prone environment.

The results of this thesis advanced towards filling important knowledge gaps but also highlighted new research questions that still need to be addressed. Efforts are still needed to investigate the temporal dynamics of rural properties in the Brazilian Amazon, to understand how changes in the number and area of small, medium, and large properties over time affect land dynamics, deforestation and forest degradation patterns. Furthermore, it is also necessary to characterize the land use and land cover associated with the use of fire by landowners. Extracting these metrics can provide a more representative scenario of dependence on using fire in rural activities. Finally, given the changes in the fire dynamics in the Amazon due to anthropogenic actions and climate change, exploring the influence of extreme events on the behaviour of the dry season and its impacts on the occurrence of fires is extremely relevant.

In summary, taken together, the results of this thesis provide data at different scales (Amazon basin, Amazonian countries, and Brazilian states), with maps, a user-friendly interface and tables that provide relevant information for the scientific community and decision makers concerned with the future of the Amazon. We urgently need to resolve land tenure problems in the Brazilian Amazon, overlaps between indigenous territories and rural properties can no longer be tolerated. Demarcation and land rights of traditional Amazonian people must be prioritized, as they have a cultural relationship with the Amazon forest and play a key role in protecting its natural resources. Laws criminalizing the illegal CAR register on public lands and strengthening environmental enforcement are also crucial to supporting land and environmental governance. Additionality, the occurrence of forest fires must be highlighted in the environmental and climate agendas of the Amazon. With an increasingly fire-prone environment, actions to control the use of fire in rural activities and directed according to regional variations in the Amazon fire calendar are fundamental to reducing forest degradation's impacts. An economic growth focused on the maximum exploitation of Amazon's natural resources cannot be more acceptable, and converging efforts towards sustainable development is crucial to mitigate the impacts of climate change before a tipping point is reached.

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APPENDIX A – SUPPLEMENTARY FIGURES AND TABLES

Table A.1 - Overlap area among rural properties considering their distribution in a 10x10km grid. Private lands were divided according to the total area of rural properties in the cell (0-20km^2, 20-4pode m0km^2, 40-60km^2, 60-80km^2, 80-100km^2 and >100km^2) and their percentages that presented overlap (0%, 0-20%, 20-40%, 40-60%, 60-80%, 80-100%).

			Overlap among rural properties (%)						
	Area (km^2)	**Cells**	**0**	**0-20**	**20-40**	**40-60**	**60-80**	**80-100**	**Total (%)**
Amazon biome	**0-20**	**5,356**	13.71	8.10	1.00	0.42	0.15	0.31	**23.70**
	20-40	**2,800**	2.82	7.48	1.34	0.42	0.17	0.16	**12.39**
	40-60	**2,767**	1.52	8.02	1.90	0.49	0.20	0.12	**12.24**
	60-80	**3,489**	1.07	10.47	2.71	0.86	0.20	0.12	**15.44**
	80-100	**5,128**	3.33	14.53	3.39	1.01	0.32	0.11	**22.69**
	>100	**3,058**	0.00	2.98	3.16	2.78	2.32	2.30	**13.53**
	Total (%)	-	**22.45**	**51.59**	**13.49**	**5.99**	**3.37**	**3.12**	**100.00**
	Cells	-	**5,073**	**11,658**	**3,049**	**1,353**	**761**	**704**	**22,598**

			Overlap among rural properties (%)						
	Area (km^2)	**Cells**	**0**	**0-20**	**20-40**	**40-60**	**60-80**	**80-100**	**Total (%)**
Acre	**0-20**	**246**	13.75	6.88	2.16	0.98	0.20	0.20	**24.17**
	20-40	**134**	4.52	6.19	1.87	0.10	0.20	0.29	**13.16**
	40-60	**124**	3.54	5.21	2.55	0.49	0.10	0.29	**12.18**
	60-80	**148**	2.26	6.58	4.13	1.28	0.20	0.10	**14.54**
	80-100	**201**	3.63	6.88	6.68	2.06	0.29	0.20	**19.74**
	>100	**165**	0.00	3.44	5.21	4.42	2.26	0.88	**16.21**
	Total (%)	-	**27.70**	**35.17**	**22.59**	**9.33**	**3.24**	**1.96**	**100.00**
	Cells	-	**282**	**358**	**230**	**95**	**33**	**20**	**1,018**

			Overlap among rural properties (%)						
	Area (km^2)	**Cells**	**0**	**0-20**	**20-40**	**40-60**	**60-80**	**80-100**	**Total (%)**
Amazonas	**0-20**	**2,005**	27.81	12.12	1.11	0.44	0.17	0.53	**42.18**
	20-40	**790**	5.81	8.39	1.47	0.48	0.17	0.29	**16.62**
	40-60	**508**	3.03	4.92	1.70	0.61	0.15	0.27	**10.69**
	60-80	**339**	2.31	2.36	1.26	0.78	0.19	0.23	**7.13**
	80-100	**586**	8.60	1.85	0.82	0.72	0.19	0.15	**12.33**
	>100	**526**	0.00	1.14	1.11	1.43	2.21	5.17	**11.06**
	Total (%)	-	**47.56**	**30.77**	**7.49**	**4.46**	**3.07**	**6.65**	**100.00**
	Cells	-	**2,261**	**1,463**	**356**	**212**	**146**	**316**	**4,754**

to be continued.

Table A.1 – Continuation.

	Overlap among rural properties (%)								
	Area (km^2)	**Cells**	**0**	**0-20**	**20-40**	**40-60**	**60-80**	**80-100**	**Total (%)**
Amapá	**0-20**	**204**	22.65	12.15	1.29	0.92	0.00	0.55	**37.57**
	20-40	**119**	4.97	13.08	2.03	1.10	0.37	0.37	**21.92**
	40-60	**86**	3.68	7.55	2.58	1.29	0.55	0.18	**15.84**
	60-80	**45**	1.10	3.13	2.21	0.92	0.74	0.18	**8.29**
	80-100	**41**	1.66	2.03	1.66	1.10	0.74	0.37	**7.55**
	>100	**48**	0.00	1.10	1.10	3.68	1.66	1.29	**8.84**
	Total (%)	-	**34.07**	**39.04**	**10.87**	**9.02**	**4.05**	**2.95**	**100.00**
	Cells	-	**185**	**212**	**59**	**49**	**22**	**16**	**543**

	Overlap among rural properties (%)								
	Area (km^2)	**Cells**	**0**	**0-20**	**20-40**	**40-60**	**60-80**	**80-100**	**Total (%)**
Maranhão	**0-20**	**312**	10.42	17.33	2.14	0.39	0.10	0.00	**30.38**
	20-40	**186**	0.88	12.37	3.60	1.17	0.10	0.00	**18.11**
	40-60	**164**	0.19	9.83	5.16	0.68	0.10	0.00	**15.97**
	60-80	**136**	0.00	8.67	2.82	1.46	0.29	0.00	**13.24**
	80-100	**123**	0.10	7.79	2.24	0.68	1.07	0.10	**11.98**
	>100	**106**	0.00	0.58	1.27	2.43	3.41	2.63	**10.32**
	Total (%)	-	**11.59**	**56.57**	**17.23**	**6.82**	**5.06**	**2.73**	**100.00**
	Cells	-	**119**	**581**	**177**	**70**	**52**	**28**	**1,027**

	Overlap among rural properties (%)								
	Area (km^2)	**Cells**	**0**	**0-20**	**20-40**	**40-60**	**60-80**	**80-100**	**Total (%)**
Mato Grosso	**0-20**	**275**	3.08	2.22	0.26	0.18	0.09	0.22	**6.04**
	20-40	**270**	0.94	3.96	0.55	0.13	0.09	0.26	**5.93**
	40-60	**413**	0.83	7.03	0.73	0.24	0.20	0.04	**9.07**
	60-80	**810**	0.59	13.93	2.26	0.66	0.26	0.09	**17.80**
	80-100	**1,685**	2.22	29.49	3.93	0.94	0.37	0.07	**37.02**
	>100	**1,098**	0.00	6.42	6.48	5.05	3.43	2.75	**24.13**
	Total (%)	-	**7.67**	**63.04**	**14.22**	**7.21**	**4.44**	**3.43**	**100.00**
	Cells	-	**349**	**2,869**	**647**	**328**	**202**	**156**	**4,551**

	Overlap among rural properties (%)								
	Area (km^2)	**Cells**	**0**	**0-20**	**20-40**	**40-60**	**60-80**	**80-100**	**Total (%)**
Pará	**0-20**	**1,445**	11.47	6.77	0.90	0.53	0.14	0.24	**20.04**
	20-40	**787**	2.25	6.82	1.25	0.42	0.17	0.01	**10.92**
	40-60	**908**	1.00	8.89	2.00	0.47	0.17	0.07	**12.59**
	60-80	**1,283**	0.79	12.02	3.73	0.97	0.15	0.12	**17.79**
	80-100	**1,806**	2.27	16.23	4.88	1.30	0.28	0.08	**25.05**

to be continued.

Table A.1 – Conclusion.

	>100	**981**	0.00	3.55	3.63	2.75	2.36	1.32	**13.61**
	Total (%)	**-**	**17.78**	**54.29**	**16.39**	**6.44**	**3.26**	**1.84**	**100.00**
	Cells	**-**	**1,282**	**3,914**	**1,182**	**464**	**235**	**133**	**7,210**

Rondônia			**Overlap among rural properties (%)**						
	Area (km^2)	**Cells**	**0**	**0-20**	**20-40**	**40-60**	**60-80**	**80-100**	**Total (%)**
	0-20	**309**	7.97	6.62	1.15	0.10	0.05	0.21	**16.10**
	20-40	**215**	1.93	7.76	0.99	0.36	0.16	0.00	**11.20**
	40-60	**286**	0.73	10.94	2.66	0.36	0.21	0.00	**14.90**
	60-80	**503**	0.68	21.16	3.91	0.31	0.10	0.05	**26.21**
	80-100	**521**	1.46	21.00	4.06	0.52	0.05	0.05	**27.15**
	>100	**85**	0.00	0.94	1.30	1.35	0.68	0.16	**4.43**
	Total (%)	**-**	**12.77**	**68.42**	**14.07**	**3.02**	**1.25**	**0.47**	**100.00**
	Cells	**-**	**245**	**1,313**	**270**	**58**	**24**	**9**	**1,919**

Roraima			**Overlap among rural properties (%)**						
	Area (km^2)	**Cells**	**0**	**0-20**	**20-40**	**40-60**	**60-80**	**80-100**	**Total (%)**
	0-20	**286**	15.86	12.51	1.29	0.22	0.54	0.43	**30.85**
	20-40	**186**	2.37	14.24	2.05	0.86	0.32	0.22	**20.06**
	40-60	**190**	0.43	15.75	2.27	1.08	0.86	0.11	**20.50**
	60-80	**148**	0.43	11.00	2.27	1.94	0.32	0.00	**15.97**
	80-100	**76**	0.22	3.67	1.73	1.51	0.86	0.22	**8.20**
	>100	**41**	0.00	0.22	0.65	1.62	1.19	0.76	**4.42**
	Total (%)	**-**	**19.31**	**57.39**	**10.25**	**7.23**	**4.10**	**1.73**	**100.00**
	Cells	**-**	**179**	**532**	**95**	**67**	**38**	**16**	**927**

Tocantins			**Overlap among rural properties (%)**						
	Area (km^2)	**Cells**	**0**	**0-20**	**20-40**	**40-60**	**60-80**	**80-100**	**Total (%)**
	0-20	**12**	1.57	3.15	0.00	0.00	0.00	0.00	**4.72**
	20-40	**32**	0.79	11.81	0.00	0.00	0.00	0.00	**12.60**
	40-60	**55**	0.39	20.47	0.79	0.00	0.00	0.00	**21.65**
	60-80	**67**	0.39	25.98	0.00	0.00	0.00	0.00	**26.38**
	80-100	**84**	0.00	32.28	0.79	0.00	0.00	0.00	**33.07**
	>100	**4**	0.00	1.18	0.00	0.39	0.00	0.00	**1.57**
	Total (%)	**-**	**3.15**	**94.88**	**1.57**	**0.39**	**0.00**	**0.00**	**100.00**
	Cells	**-**	**8**	**241**	**4**	**1**	**0**	**0**	**254**

Table A.2 - Overlap area between settlements and rural properties considering a 10x10km grid. The cells were classified according to the public forest area (0-20km², 20-40km², 40-60km², 60-80km², 80-100km² and >100km²) and the percentage of overlap between these areas and rural properties (0 - 20%, 20-40%, 40-60%, 60-80%, 80-100%). Values are shown for each state of the Brazilian Amazon.

	Overlap between settlements and rural properties (%)						
Acre	**0-20**	**20-40**	**40-60**	**60-80**	**80-100**	**Total (%)**	**Cells**
0-20km²	11.21	5.14	3.74	4.67	7.94	**32.71**	**70**
20-40km²	6.07	1.40	2.80	4.67	4.21	**19.16**	**41**
40-60km²	4.21	0.93	2.34	4.21	3.27	**14.95**	**32**
60-80km²	1.40	1.40	1.87	4.21	2.80	**11.68**	**25**
80-100km²	3.27	0.93	3.74	7.94	5.61	**21.50**	**46**
Total (%)	**26.17**	**9.81**	**14.49**	**25.70**	**23.83**	**100.00**	**-**
Cells	**56**	**21**	**31**	**55**	**51**	**-**	**214**

Amazonas	**0-20**	**20-40**	**40-60**	**60-80**	**80-100**	**Total (%)**	**Cells**
0-20km²	12.53	3.23	2.22	2.02	5.05	**25.05**	**124**
20-40km²	7.27	2.63	1.21	0.40	0.81	**12.32**	**61**
40-60km²	7.47	2.02	1.41	0.40	0.61	**11.92**	**59**
60-80km²	10.10	1.82	0.81	1.21	1.01	**14.95**	**74**
80-100km²	17.98	3.84	1.01	2.42	10.51	**35.76**	**177**
Total (%)	**55.35**	**13.54**	**6.67**	**6.46**	**17.98**	**100.00**	**-**
Cells	**274**	**67**	**33**	**32**	**89**	**-**	**495**

Rondônia	**0-20**	**20-40**	**40-60**	**60-80**	**80-100**	**Total (%)**	**Cells**
0-20km²	16.95	6.78	0.00	6.78	6.78	**37.29**	**22**
20-40km²	6.78	0.00	5.08	5.08	0.00	**16.95**	**10**
40-60km²	0.00	5.08	5.08	3.39	1.69	**15.25**	**9**
60-80km²	3.39	0.00	0.00	0.00	3.39	**6.78**	**4**
80-100km²	0.00	8.47	5.08	8.47	1.69	**23.73**	**14**
Total (%)	**27.12**	**20.34**	**15.25**	**23.73**	**13.56**	**100.00**	**-**
Cells	**16**	**12**	**9**	**14**	**8**	**-**	**59**

Roraima	**0-20**	**20-40**	**40-60**	**60-80**	**80-100**	**Total (%)**	**Cells**
0-20km²	0.00	0.00	0.00	0.00	0.00	**0.00**	**0**
20-40km²	0.00	0.00	0.00	0.00	0.00	**0.00**	**0**
40-60km²	0.00	0.00	0.00	0.00	0.00	**0.00**	**0**
60-80km²	0.00	0.00	0.00	0.00	0.00	**0.00**	**0**
80-100km²	0.00	0.00	0.00	0.00	0.00	**0.00**	**0**
Total (%)	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**-**
Cells	**0**	**0**	**0**	**0**	**0**	**-**	**0**

to be continued.

Table A.2 – Continuation.

Mato Grosso	**0-20**	**20-40**	**40-60**	**60-80**	**80-100**	**Total (%)**	**Cells**
0-20km²	34.48	17.24	3.45	0.00	10.34	**65.52**	**19**
20-40km²	13.79	3.45	0.00	0.00	0.00	**17.24**	**5**
40-60km²	10.34	0.00	0.00	0.00	0.00	**10.34**	**3**
60-80km²	3.45	0.00	0.00	0.00	0.00	**3.45**	**1**
80-100km²	3.45	0.00	0.00	0.00	0.00	**3.45**	**1**
Total (%)	**65.52**	**20.69**	**3.45**	**0.00**	**10.34**	**100.00**	**-**
Cells	**19**	**6**	**1**	**0**	**3**	**-**	**29**

Pará	**0-20**	**20-40**	**40-60**	**60-80**	**80-100**	**Total (%)**	**Cells**
0-20km²	9.91	5.11	4.28	2.61	7.92	**29.82**	**286**
20-40km²	5.42	3.65	2.50	2.40	2.09	**16.06**	**154**
40-60km²	5.01	3.13	1.25	1.25	1.98	**12.62**	**121**
60-80km²	5.74	1.36	1.46	1.67	2.40	**12.62**	**121**
80-100km²	11.37	4.07	3.86	4.07	5.53	**28.88**	**277**
Total (%)	**37.43**	**17.31**	**13.35**	**11.99**	**19.92**	**100.00**	**-**
Cells	**359**	**166**	**128**	**115**	**191**	**-**	**959**

Amapá	**0-20**	**20-40**	**40-60**	**60-80**	**80-100**	**Total (%)**	**Cells**
0-20km²	23.40	8.51	2.13	0.00	0.00	**34.04**	**16**
20-40km²	2.13	0.00	4.26	4.26	0.00	**10.64**	**5**
40-60km²	10.64	2.13	0.00	0.00	0.00	**12.77**	**6**
60-80km²	6.38	0.00	0.00	0.00	2.13	**8.51**	**4**
80-100km²	21.28	4.26	4.26	4.26	0.00	**34.04**	**16**
Total (%)	**63.83**	**14.89**	**10.64**	**8.51**	**2.13**	**100.00**	**-**
Cells	**30**	**7**	**5**	**4**	**1**	**-**	**47**

Tocantins	**0-20**	**20-40**	**40-60**	**60-80**	**80-100**	**Total (%)**	**Cells**
0-20km²	0.00	0.00	0.00	0.00	0.00	**0.00**	**0**
20-40km²	0.00	0.00	0.00	0.00	0.00	**0.00**	**0**
40-60km²	0.00	0.00	0.00	0.00	0.00	**0.00**	**0**
60-80km²	0.00	0.00	0.00	0.00	0.00	**0.00**	**0**
80-100km²	0.00	0.00	0.00	0.00	0.00	**0.00**	**0**
Total (%)	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**-**
Cells	**0**	**0**	**0**	**0**	**0**	**-**	**0**

To be continued.

Table A.2 – Conclusion.

Maranhão	**0-20**	**20-40**	**40-60**	**60-80**	**80-100**	**Total (%)**	**Cells**
0-20km²	38.89	11.11	11.11	0.00	11.11	**72.22**	**13**
20-40km²	11.11	0.00	0.00	0.00	0.00	**11.11**	**2**
40-60km²	5.56	0.00	0.00	0.00	0.00	**5.56**	**1**
60-80km²	0.00	0.00	0.00	5.56	0.00	**5.56**	**1**
80-100km²	0.00	5.56	0.00	0.00	0.00	**5.56**	**1**
Total (%)	**55.56**	**16.67**	**11.11**	**5.56**	**11.11**	**100.00**	**-**
Cells	**10**	**3**	**2**	**1**	**2**	**-**	**18**

Table A.3 - Overlap area between indigenous land and rural properties considering a 10x10km grid. The cells were classified according to the public forest area (0-20km², 20-40km², 40-60km², 60-80km², 80-100km² and >100km²) and the percentage of overlap between these areas and rural properties (0 - 20%, 20-40%, 40-60%, 60-80%, 80-100%). Values are shown for each state of the Brazilian Amazon.

	Overlap between indigenous land and rural properties (%)						
Acre	**0-20**	**20-40**	**40-60**	**60-80**	**80-100**	**Total (%)**	**Cells**
0-20km²	29.63	2.47	0.00	0.00	2.47	**34.57**	**28**
20-40km²	14.81	0.00	0.00	0.00	0.00	**14.81**	**12**
40-60km²	16.05	0.00	0.00	0.00	0.00	**16.05**	**13**
60-80km²	13.58	0.00	0.00	0.00	0.00	**13.58**	**11**
80-100km²	20.99	0.00	0.00	0.00	0.00	**20.99**	**17**
Total (%)	**95.06**	**2.47**	**0.00**	**0.00**	**2.47**	**100.00**	**-**
Cells	**77**	**2**	**0**	**0**	**2**	**-**	**81**

Amazonas	**0-20**	**20-40**	**40-60**	**60-80**	**80-100**	**Total (%)**	**Cells**
0-20km²	19.10	2.26	1.51	1.26	7.29	**31.41**	**125**
20-40km²	7.79	1.01	0.75	1.01	3.02	**13.57**	**54**
40-60km²	6.78	0.25	1.01	0.25	4.52	**12.81**	**51**
60-80km²	7.54	0.75	0.25	0.50	2.01	**11.06**	**44**
80-100km²	13.07	2.01	2.51	2.01	11.56	**31.16**	**124**
Total (%)	**54.27**	**6.28**	**6.03**	**5.03**	**28.39**	**100.00**	**-**
Cells	**216**	**25**	**24**	**20**	**113**	**-**	**398**

to be continued.

Table A.3 – Continuation.

Rondônia	**0-20**	**20-40**	**40-60**	**60-80**	**80-100**	**Total (%)**	**Cells**
0-20km²	26.99	4.87	0.00	1.33	2.21	**35.40**	**80**
20-40km²	12.83	0.88	0.00	0.44	0.00	**14.16**	**32**
40-60km²	15.93	0.44	0.88	0.00	0.00	**17.26**	**39**
60-80km²	10.18	0.00	0.44	0.44	0.00	**11.06**	**25**
80-100km²	20.35	0.44	1.33	0.00	0.00	**22.12**	**50**
Total (%)	**86.28**	**6.64**	**2.65**	**2.21**	**2.21**	**100.00**	**-**
Cells	**195**	**15**	**6**	**5**	**5**	**-**	**226**

Roraima	**0-20**	**20-40**	**40-60**	**60-80**	**80-100**	**Total (%)**	**Cells**
0-20km²	21.62	0.00	0.68	0.00	1.35	**23.65**	**35**
20-40km²	18.92	0.00	0.00	0.00	0.00	**18.92**	**28**
40-60km²	16.89	0.00	0.00	0.68	0.00	**17.57**	**26**
60-80km²	12.16	0.68	0.00	0.68	0.00	**13.51**	**20**
80-100km²	24.32	0.68	1.35	0.00	0.00	**26.35**	**39**
Total (%)	**93.92**	**1.35**	**2.03**	**1.35**	**1.35**	**100.00**	**-**
Cells	**139**	**2**	**3**	**2**	**2**	**-**	**148**

Mato Grosso	**0-20**	**20-40**	**40-60**	**60-80**	**80-100**	**Total (%)**	**Cells**
0-20km²	17.88	1.57	0.59	0.59	4.32	**24.95**	**127**
20-40km²	9.82	0.39	0.79	0.00	1.18	**12.18**	**62**
40-60km²	11.20	0.39	0.98	0.59	1.57	**14.73**	**75**
60-80km²	8.84	0.39	0.59	0.79	1.57	**12.18**	**62**
80-100km²	20.24	3.73	4.52	2.95	4.52	**35.95**	**183**
Total (%)	**67.98**	**6.48**	**7.47**	**4.91**	**13.16**	**100.00**	**-**
Cells	**346**	**33**	**38**	**25**	**67**	**-**	**509**

Pará	**0-20**	**20-40**	**40-60**	**60-80**	**80-100**	**Total (%)**	**Cells**
0-20km²	20.93	1.40	1.16	0.70	2.79	**26.98**	**116**
20-40km²	8.84	0.70	0.47	0.00	0.93	**10.93**	**47**
40-60km²	11.86	0.70	0.47	0.00	0.47	**13.49**	**58**
60-80km²	11.40	1.40	0.47	0.23	0.23	**13.72**	**59**
80-100km²	25.12	5.58	1.63	0.00	2.56	**34.88**	**150**
Total (%)	**78.14**	**9.77**	**4.19**	**0.93**	**6.98**	**100.00**	**-**
Cells	**336**	**42**	**18**	**4**	**30**	**-**	**430**

to be continued.

Table A.3 – Conclusion.

Amapá	0-20	20-40	40-60	60-80	80-100	Total (%)	Cells
0-20km²	0.00	0.00	0.00	0.00	0.00	0.00	0
20-40km²	0.00	0.00	0.00	0.00	0.00	0.00	0
40-60km²	66.67	0.00	0.00	0.00	0.00	66.67	2
60-80km²	0.00	0.00	0.00	0.00	0.00	0.00	0
80-100km²	33.33	0.00	0.00	0.00	0.00	33.33	1
Total (%)	100.00	0.00	0.00	0.00	0.00	100.00	-
Cells	3	0	0	0	0	-	3

Tocantins	0-20	20-40	40-60	60-80	80-100	Total (%)	Cells
0-20km²	50.00	0.00	0.00	0.00	0.00	50.00	1
20-40km²	50.00	0.00	0.00	0.00	0.00	50.00	1
40-60km²	0.00	0.00	0.00	0.00	0.00	0.00	0
60-80km²	0.00	0.00	0.00	0.00	0.00	0.00	0
80-100km²	0.00	0.00	0.00	0.00	0.00	0.00	0
Total (%)	100.00	0.00	0.00	0.00	0.00	100.00	-
Cells	2	0	0	0	0	-	2

Maranhão	0-20	20-40	40-60	60-80	80-100	Total (%)	Cells
0-20km²	23.94	0.00	0.00	0.00	1.41	25.35	18
20-40km²	22.54	0.00	0.00	1.41	0.00	23.94	17
40-60km²	7.04	0.00	0.00	0.00	0.00	7.04	5
60-80km²	8.45	1.41	1.41	1.41	0.00	12.68	9
80-100km²	22.54	4.23	1.41	2.82	0.00	30.99	22
Total (%)	84.51	5.63	2.82	5.63	1.41	100.00	-
Cells	60	4	2	4	1	-	71

Table A.4 - Overlap area between integral protection conservation units and rural properties considering a 10x10km grid. The cells were classified according to the public forest area (0-20km^2, 20-40km^2, 40-60km^2, 60-80km^2, 80-100km^2 and >100km^2) and the percentage of overlap between these areas and rural properties (0 - 20%, 20-40%, 40-60%, 60-80%, 80-100%). Values are shown for each state of the Brazilian Amazon.

	Overlap between integral protection and rural properties (%)						
Acre	**0-20**	**20-40**	**40-60**	**60-80**	**80-100**	**Total (%)**	**Cells**
0-20km^2	6.56	0.00	0.00	1.64	4.92	**13.11**	**8**
20-40km^2	3.28	1.64	0.00	0.00	3.28	**8.20**	**5**
40-60km^2	4.92	3.28	0.00	0.00	1.64	**9.84**	**6**
60-80km^2	3.28	1.64	0.00	0.00	3.28	**8.20**	**5**
80-100km^2	16.39	8.20	8.20	9.84	18.03	**60.66**	**37**
Total (%)	**34.43**	**14.75**	**8.20**	**11.48**	**31.15**	**100.00**	**-**
Cells	**21**	**9**	**5**	**7**	**19**	**-**	**61**

Amazonas	**0-20**	**20-40**	**40-60**	**60-80**	**80-100**	**Total (%)**	**Cells**
0-20km^2	6.46	1.34	2.23	0.45	5.12	**15.59**	**70**
20-40km^2	4.68	2.23	0.67	0.22	5.12	**12.92**	**58**
40-60km^2	4.23	0.67	0.22	0.45	1.34	**6.90**	**31**
60-80km^2	4.68	2.00	0.67	0.45	3.34	**11.14**	**50**
80-100km^2	16.93	6.90	4.45	5.12	20.04	**53.45**	**240**
Total (%)	**36.97**	**13.14**	**8.24**	**6.68**	**34.97**	**100.00**	**-**
Cells	166	59	37	30	157	-	449

Rondônia	**0-20**	**20-40**	**40-60**	**60-80**	**80-100**	**Total (%)**	**Cells**
0-20km^2	10.05	3.35	3.83	2.39	9.09	**28.71**	**60**
20-40km^2	7.66	2.39	0.00	0.96	1.91	**12.92**	**27**
40-60km^2	5.26	0.48	0.48	0.96	3.83	**11.00**	**23**
60-80km^2	4.78	1.91	0.48	0.00	2.39	**9.57**	**20**
80-100km^2	15.79	6.22	2.39	3.83	9.57	**37.80**	**79**
Total (%)	**43.54**	**14.35**	**7.18**	**8.13**	**26.79**	**100.00**	**-**
Cells	**91**	**30**	**15**	**17**	**56**	**-**	**209**

to be continued.

Table A.4 – Continuation.

Roraima	**0-20**	**20-40**	**40-60**	**60-80**	**80-100**	**Total (%)**	**Cells**
0-20km²	4.60	4.60	5.75	3.45	6.90	**25.29**	**22**
20-40km²	6.90	0.00	2.30	1.15	2.30	**12.64**	**11**
40-60km²	4.60	2.30	4.60	2.30	3.45	**17.24**	**15**
60-80km²	4.60	1.15	0.00	1.15	1.15	**8.05**	**7**
80-100km²	3.45	4.60	6.90	10.34	11.49	**36.78**	**32**
Total (%)	**24.14**	**12.64**	**19.54**	**18.39**	**25.29**	**100.00**	**-**
Cells	**21**	**11**	**17**	**16**	**22**	**-**	**87**

Mato Grosso	**0-20**	**20-40**	**40-60**	**60-80**	**80-100**	**Total (%)**	**Cells**
0-20km²	6.50	4.00	2.50	3.50	16.00	**32.50**	**65**
20-40km²	1.50	3.00	2.00	2.00	5.50	**14.00**	**28**
40-60km²	3.00	2.00	1.50	0.00	8.50	**15.00**	**30**
60-80km²	2.00	0.50	1.00	1.50	3.50	**8.50**	**17**
80-100km²	9.00	5.00	2.50	2.50	11.00	**30.00**	**60**
Total (%)	**22.00**	**14.50**	**9.50**	**9.50**	**44.50**	**100.00**	**-**
Cells	**44**	**29**	**19**	**19**	**89**	**-**	**200**

Pará	**0-20**	**20-40**	**40-60**	**60-80**	**80-100**	**Total (%)**	**Cells**
0-20km²	11.81	0.96	2.41	1.20	6.51	**22.89**	**95**
20-40km²	5.06	0.72	0.96	0.48	0.72	**7.95**	**33**
40-60km²	4.82	0.96	0.72	0.24	0.72	**7.47**	**31**
60-80km²	5.06	0.24	0.24	0.72	0.24	**6.51**	**27**
80-100km²	22.65	8.67	4.34	4.58	14.94	**55.18**	**229**
Total (%)	**49.40**	**11.57**	**8.67**	**7.23**	**23.13**	**100.00**	**-**
Cells	**205**	**48**	**36**	**30**	**96**	**-**	**415**

Amapá	**0-20**	**20-40**	**40-60**	**60-80**	**80-100**	**Total (%)**	**Cells**
0-20km²	13.33	0.00	0.00	0.00	6.67	**20.00**	**3**
20-40km²	20.00	0.00	0.00	0.00	0.00	**20.00**	**3**
40-60km²	20.00	0.00	0.00	0.00	0.00	**20.00**	**3**
60-80km²	13.33	0.00	0.00	0.00	0.00	**13.33**	**2**
80-100km²	26.67	0.00	0.00	0.00	0.00	**26.67**	**4**
Total (%)	**93.33**	**0.00**	**0.00**	**0.00**	**6.67**	**100.00**	**-**
Cells	**14**	**0**	**0**	**0**	**1**	**-**	**15**

to be continued.

Table A.4 – Conclusion.

Tocantins	**0-20**	**20-40**	**40-60**	**60-80**	**80-100**	**Total (%)**	**Cells**
0-20km²	25.00	25.00	0.00	0.00	0.00	**50.00**	**2**
20-40km²	25.00	0.00	0.00	0.00	0.00	**25.00**	**1**
40-60km²	0.00	25.00	0.00	0.00	0.00	**25.00**	**1**
60-80km²	0.00	0.00	0.00	0.00	0.00	**0.00**	**0**
80-100km²	0.00	0.00	0.00	0.00	0.00	**0.00**	**0**
Total (%)	**50.00**	**50.00**	**0.00**	**0.00**	**0.00**	**100.00**	**-**
Cells	**2**	**2**	**0**	**0**	**0**	**-**	**4**

Maranhão	**0-20**	**20-40**	**40-60**	**60-80**	**80-100**	**Total (%)**	**Cells**
0-20km²	6.25	2.08	2.08	4.17	14.58	**29.17**	**14**
20-40km²	2.08	0.00	0.00	0.00	6.25	**8.33**	**4**
40-60km²	6.25	2.08	0.00	6.25	2.08	**16.67**	**8**
60-80km²	0.00	0.00	0.00	2.08	2.08	**4.17**	**2**
80-100km²	2.08	2.08	2.08	10.42	25.00	**41.67**	**20**
Total (%)	**16.67**	**6.25**	**4.17**	**22.92**	**50.00**	**100.00**	**-**
Cells	**8**	**3**	**2**	**11**	**24**	**-**	**48**

Table A.5 - Overlap area between sustainable use conservation units and rural properties considering a 10x10km grid. The cells were classified according to the public forest area (0-20km², 20-40km², 40-60km², 60-80km², 80-100km² and >100km²) and the percentage of overlap between these areas and rural properties (0 - 20%, 20-40%, 40-60%, 60-80%, 80-100%). Values are shown for each state of the Brazilian Amazon.

	Overlap between sustainable use and rural properties (%)						
Acre	**0-20**	**20-40**	**40-60**	**60-80**	**80-100**	**Total (%)**	**Cells**
0-20km²	15.47	2.21	2.21	1.10	1.66	**22.65**	**41**
20-40km²	13.81	1.66	0.55	0.00	0.55	**16.57**	**30**
40-60km²	10.50	1.10	1.10	0.00	0.00	**12.71**	**23**
60-80km²	12.71	0.00	1.10	0.00	0.00	**13.81**	**25**
80-100km²	29.28	2.76	1.10	1.10	0.00	**34.25**	**62**
Total (%)	**81.77**	**7.73**	**6.08**	**2.21**	**2.21**	**100.00**	**-**

to be continued.

Table A.5 – Continuation.

Cells	**148**	**14**	**11**	**4**	**4**	**-**	**181**

Amazonas	**0-20**	**20-40**	**40-60**	**60-80**	**80-100**	**Total (%)**	**Cells**
0-20km²	6.01	2.42	1.84	1.00	5.34	**16.61**	**199**
20-40km²	3.51	1.59	1.09	0.75	2.50	**9.43**	**113**
40-60km²	3.34	1.17	0.50	1.25	2.25	**8.51**	**102**
60-80km²	4.26	1.84	1.25	1.09	2.67	**11.10**	**133**
80-100km²	20.20	7.10	3.84	5.51	17.70	**54.34**	**651**
Total (%)	**37.31**	**14.11**	**8.51**	**9.60**	**30.47**	**100.00**	**-**
Cells	**447**	**169**	**102**	**115**	**365**	**-**	**1,198**

Rondônia	**0-20**	**20-40**	**40-60**	**60-80**	**80-100**	**Total (%)**	**Cells**
0-20km²	15.02	4.10	5.12	2.05	4.10	**30.38**	**89**
20-40km²	9.22	3.41	0.68	0.68	1.37	**15.36**	**45**
40-60km²	6.83	1.37	1.37	0.34	2.73	**12.63**	**37**
60-80km²	9.22	1.02	1.37	0.34	0.34	**12.29**	**36**
80-100km²	16.38	4.44	3.07	1.02	4.44	**29.35**	**86**
Total (%)	**56.66**	**14.33**	**11.60**	**4.44**	**12.97**	**100.00**	**-**
Cells	**166**	**42**	**34**	**13**	**38**	**-**	**293**

Roraima	**0-20**	**20-40**	**40-60**	**60-80**	**80-100**	**Total (%)**	**Cells**
0-20km²	8.00	1.00	0.00	1.00	2.00	**12.00**	**12**
20-40km²	7.00	3.00	0.00	0.00	1.00	**11.00**	**11**
40-60km²	9.00	1.00	4.00	0.00	0.00	**14.00**	**14**
60-80km²	16.00	0.00	5.00	2.00	2.00	**25.00**	**25**
80-100km²	21.00	4.00	5.00	5.00	3.00	**38.00**	**38**
Total (%)	**61.00**	**9.00**	**14.00**	**8.00**	**8.00**	**100.00**	**-**
Cells	**61**	**9**	**14**	**8**	**8**	**-**	**100**

Mato Grosso	**0-20**	**20-40**	**40-60**	**60-80**	**80-100**	**Total (%)**	**Cells**
0-20km²	15.91	2.27	6.82	6.82	13.64	**45.45**	**20**
20-40km²	4.55	11.36	6.82	2.27	2.27	**27.27**	**12**
40-60km²	4.55	2.27	9.09	2.27	2.27	**20.45**	**9**
60-80km²	0.00	0.00	4.55	0.00	0.00	**4.55**	**2**
80-100km²	2.27	0.00	0.00	0.00	0.00	**2.27**	**1**
Total (%)	**27.27**	**15.91**	**27.27**	**11.36**	**18.18**	**100.00**	**-**
Cells	**12**	**7**	**12**	**5**	**8**	**-**	**44**

Pará	**0-20**	**20-40**	**40-60**	**60-80**	**80-100**	**Total (%)**	**Cells**
0-20km²	8.85	2.72	3.26	2.33	5.51	**22.67**	**292**
20-40km²	4.81	1.71	1.86	0.85	1.24	**10.48**	**135**

to be continued.

Table A.5 – Conclusion

40-60km²	5.43	1.09	1.94	1.71	1.32	**11.49**	**148**
60-80km²	3.65	1.55	1.71	1.79	2.17	**10.87**	**140**
80-100km²	17.93	6.83	6.37	5.05	8.31	**44.49**	**573**
Total (%)	**40.68**	**13.90**	**15.14**	**11.72**	**18.56**	**100.00**	**-**
Cells	**524**	**179**	**195**	**151**	**239**	**-**	**1,288**

Amapá	**0-20**	**20-40**	**40-60**	**60-80**	**80-100**	**Total (%)**	**Cells**
0-20km²	8.55	1.71	1.28	1.71	1.71	**14.96**	**35**
20-40km²	5.13	2.99	1.71	0.85	0.85	**11.54**	**27**
40-60km²	4.27	2.56	0.85	2.14	1.28	**11.11**	**26**
60-80km²	3.42	1.28	0.85	0.00	0.43	**5.98**	**14**
80-100km²	25.64	13.25	10.26	6.41	0.85	**56.41**	**132**
Total (%)	**47.01**	**21.79**	**14.96**	**11.11**	**5.13**	**100.00**	**-**
Cells	**110**	**51**	**35**	**26**	**12**	**-**	**234**

Tocantins	**0-20**	**20-40**	**40-60**	**60-80**	**80-100**	**Total (%)**	**Cells**
0-20km²	0.00	14.29	0.00	28.57	28.57	**71.43**	**5**
20-40km²	0.00	0.00	0.00	14.29	0.00	**14.29**	**1**
40-60km²	0.00	0.00	0.00	14.29	0.00	**14.29**	**1**
60-80km²	0.00	0.00	0.00	0.00	0.00	**0.00**	**0**
80-100km²	0.00	0.00	0.00	0.00	0.00	**0.00**	**0**
Total (%)	**0.00**	**14.29**	**0.00**	**57.14**	**28.57**	**100.00**	**-**
Cells	**0**	**1**	**0**	**4**	**2**	**-**	**7**

Maranhão	**0-20**	**20-40**	**40-60**	**60-80**	**80-100**	**Total (%)**	**Cells**
0-20km²	33.33	5.56	5.56	5.56	22.22	**72.22**	**13**
20-40km²	11.11	5.56	0.00	0.00	0.00	**16.67**	**3**
40-60km²	11.11	0.00	0.00	0.00	0.00	**11.11**	**2**
60-80km²	0.00	0.00	0.00	0.00	0.00	**0.00**	**0**
80-100km²	0.00	0.00	0.00	0.00	0.00	**0.00**	**0**
Total (%)	**55.56**	**11.11**	**5.56**	**5.56**	**22.22**	**100.00**	**-**
Cells	**10**	**2**	**1**	**1**	**4**	**-**	**18**

Table A.6 - Overlap area between undesignated lands and rural properties considering a 10x10km grid. The cells were classified according to the public forest area (0-20km², 20-40km², 40-60km², 60-80km², 80-100km² and >100km²) and the percentage of overlap between these areas and rural properties (0 - 20%, 20-40%, 40-60%, 60-80%, 80-100%). Values are shown for each state of the Brazilian Amazon.

	Overlap between undesignated lands and rural properties (%)						
Acre	**0-20**	**20-40**	**40-60**	**60-80**	**80-100**	**Total (%)**	**Cells**
0-20km²	12.24	5.71	5.31	6.53	**17.55**	**47.35**	**232**
20-40km²	4.69	1.84	1.63	2.24	5.71	**16.12**	**79**
40-60km²	4.29	2.04	0.61	0.82	3.47	**11.22**	**55**
60-80km²	3.06	0.82	1.84	1.84	1.22	**8.78**	**43**
80-100km²	4.08	1.84	2.45	2.45	5.71	**16.53**	**81**
Total (%)	**28.37**	**12.24**	**11.84**	**13.88**	**33.67**	**100.00**	**-**
Cells	**139**	**60**	**58**	**68**	**165**	**-**	**490**

Amazonas	0-20	20-40	40-60	60-80	80-100	Total (%)	Cells
0-20km²	9.50	4.21	3.14	2.31	7.22	**26.38**	**789**
20-40km²	5.28	3.78	2.51	1.40	1.84	**14.81**	**443**
40-60km²	6.19	2.77	2.01	1.47	1.34	**13.77**	**412**
60-80km²	6.22	2.61	2.14	0.87	1.54	**13.37**	**400**
80-100km²	16.68	4.58	3.51	2.04	4.85	**31.66**	**947**
Total (%)	**43.86**	**17.95**	**13.31**	**8.09**	**16.78**	**100.00**	**-**
Cells	**1312**	**537**	**398**	**242**	**502**	**-**	**2,991**

Rondônia	0-20	20-40	40-60	60-80	80-100	Total (%)	Cells
0-20km²	6.81	5.55	9.62	19.73	18.89	**60.60**	**863**
20-40km²	1.90	2.25	4.35	7.51	5.76	**21.77**	**310**
40-60km²	0.63	1.54	2.74	3.23	1.97	**10.11**	**144**
60-80km²	0.42	1.12	1.62	1.62	0.77	**5.55**	**79**
80-100km²	0.49	0.35	0.35	0.49	0.28	**1.97**	**28**
Total (%)	**10.25**	**10.81**	**18.68**	**32.58**	**27.67**	**100.00**	**-**
Cells	**146**	**154**	**266**	**464**	**394**	**-**	**1,424**

to be continued.

Table A.6 – Continuation.

Roraima	**0-20**	**20-40**	**40-60**	**60-80**	**80-100**	**Total (%)**	**Cells**
0-20km²	9.59	4.80	6.54	6.69	6.10	**33.72**	**232**
20-40km²	2.76	5.09	3.92	3.05	2.18	**17.01**	**117**
40-60km²	2.47	2.03	4.65	4.51	2.76	**16.42**	**113**
60-80km²	1.60	3.63	5.52	2.76	2.33	**15.84**	**109**
80-100km²	1.89	3.63	4.36	3.49	3.63	**17.01**	**117**
Total (%)	**18.31**	**19.19**	**25.00**	**20.49**	**17.01**	**100.00**	**-**
Cells	**126**	**132**	**172**	**141**	**117**	**-**	**688**

Mato Grosso	**0-20**	**20-40**	**40-60**	**60-80**	**80-100**	**Total (%)**	**Cells**
0-20km²	7.91	5.87	7.65	13.90	37.50	**72.83**	**571**
20-40km²	0.89	1.28	2.55	3.44	5.36	**13.52**	**106**
40-60km²	0.64	1.02	1.28	2.04	2.68	**7.65**	**60**
60-80km²	0.26	0.51	0.64	0.64	1.66	**3.70**	**29**
80-100km²	0.26	0.26	0.51	0.51	0.77	**2.30**	**18**
Total (%)	**9.95**	**8.93**	**12.63**	**20.54**	**47.96**	**100.00**	**-**
Cells	**78**	**70**	**99**	**161**	**376**	**-**	**784**

Pará	**0-20**	**20-40**	**40-60**	**60-80**	**80-100**	**Total (%)**	**Cells**
0-20km²	6.16	6.03	8.63	10.75	25.12	**56.69**	**2,162**
20-40km²	1.05	1.42	3.28	5.56	9.36	**20.66**	**788**
40-60km²	0.60	1.15	1.86	3.30	3.93	**10.85**	**414**
60-80km²	0.52	0.42	1.42	1.81	2.10	**6.27**	**239**
80-100km²	1.13	1.05	1.05	1.05	1.26	**5.53**	**211**
Total (%)	**9.47**	**10.07**	**16.23**	**22.47**	**41.77**	**100.00**	**-**
Cells	**361**	**384**	**619**	**857**	**1593**	**-**	**3,814**

Amapá	**0-20**	**20-40**	**40-60**	**60-80**	**80-100**	**Total (%)**	**Cells**
0-20km²	11.08	7.69	5.23	3.69	6.77	**34.46**	**112**
20-40km²	6.77	6.46	6.46	2.77	1.54	**24.00**	**78**
40-60km²	3.38	4.92	3.08	1.23	3.38	**16.00**	**52**
60-80km²	3.08	3.38	3.08	0.92	1.23	**11.69**	**38**
80-100km²	5.54	3.69	2.15	0.92	1.54	**13.85**	**45**
Total (%)	**29.85**	**26.15**	**20.00**	**9.54**	**14.46**	**100.00**	**-**
Cells	**97**	**85**	**65**	**31**	**47**	**-**	**325**

to be continued.

Table A.6 – Conclusion.

Tocantins	**0-20**	**20-40**	**40-60**	**60-80**	**80-100**	**Total (%)**	**Cells**
0-20km²	25.71	17.14	11.43	5.71	34.29	**94.29**	**33**
20-40km²	2.86	2.86	0.00	0.00	0.00	**5.71**	**2**
40-60km²	0.00	0.00	0.00	0.00	0.00	**0.00**	**0**
60-80km²	0.00	0.00	0.00	0.00	0.00	**0.00**	**0**
80-100km²	0.00	0.00	0.00	0.00	0.00	**0.00**	**0**
Total (%)	**28.57**	**20.00**	**11.43**	**5.71**	**34.29**	**100.00**	**-**
Cells	**10**	**7**	**4**	**2**	**12**	**-**	**35**

Maranhão	**0-20**	**20-40**	**40-60**	**60-80**	**80-100**	**Total (%)**	**Cells**
0-20km²	14.86	13.06	13.06	18.47	33.78	**93.24**	**207**
20-40km²	0.90	0.45	0.90	0.45	2.25	**4.95**	**11**
40-60km²	0.00	0.00	0.00	0.45	1.35	**1.80**	**4**
60-80km²	0.00	0.00	0.00	0.00	0.00	**0.00**	**0**
80-100km²	0.00	0.00	0.00	0.00	0.00	**0.00**	**0**
Total (%)	**15.77**	**13.51**	**13.96**	**19.37**	**37.39**	**100.00**	**-**
Cells	**35**	**30**	**31**	**43**	**83**	**-**	**222**

Table A.7 - Distribution of small, medium and large rural properties for each Amazonian state according to the total area and the number of properties. The percentage values, considering the total area and number of rural properties, are also shown. The overlap area is also presented.

	Fiscal Module (ha)	**Rural properties**				**Area**				**Overlap area**				
		Number	**Small**	**Medium**	**Large**	**Total (km^2)**	**Small**	**Medium**	**Large**	**Total (km^2)**	**Percentage of the total area (%)**	**Small**	**Medium**	**Large**
				%				**%**					**%**	
Acre	70-100	35,433	97.0	1.8	1.2	59,414.0	35.3	7.1	57.6	15,074.2	25.4	53.4	8.0	38.7
Amazonas	10-100	45,166	90.0	6.8	3.2	235,038.9	11.5	9.9	78.6	88,264.8	37.6	6.7	7.8	85.5
Amapá	50-70	5,667	71.2	25.0	3.8	22,326.7	12.1	40.8	47.1	6,213.4	27.8	12.6	42.0	45.4
Maranhão	15-75	28,541	90.6	6.3	3.1	63,956.3	25.6	14.0	60.4	27,793.6	43.5	16.7	7.5	75.8
Mato Grosso	60-100	86,119	83.2	9.7	7.1	388,182.6	16.0	16.4	67.5	88,230.8	22.7	12.6	14.9	72.5
Pará	5-75	204,063	89.6	6.9	3.5	454,868.6	26.9	18.2	54.8	99,319.4	21.8	27.5	16.6	55.9
Rondônia	60	116,462	94.8	4.1	1.1	114,688.2	50.4	18.6	31.0	16,661.5	14.5	57.0	18.5	24.6
Roraima	80-100	9,111	68.9	24.5	6.6	39,447.7	13.2	54.6	32.2	8,498.4	21.5	8.1	58.6	33.3
Tocantins	80	5,778	83.4	11.0	5.6	16,935.1	18.9	23.6	57.5	299.6	1.8	16.3	24.5	59.2
Amazon biome	**5-100**	**536,340**	**89.7**	**6.9**	**3.4**	**1,394,858.1**	**22.8**	**17.1**	**60.1**	**350,355.7**	**25.1**	**19.4**	**14.4**	**66.2**

Table A.8 - Total area of public forests in the Settlements in each state of the Amazonian state and the area overlapped by the small, medium, large and multiple rural properties.

Settlements	**Public Forest (ha)**	**Overlap area**		**Overlap area by rural property size**							
				Small		**Medium**		**Large**		**Multiple**	
		Area (ha)	**%**	**Area (ha)**	**%**	**Area (ha)**	**%**	**Area (ha)**	**%**	**Area (ha)**	**%**
Acre	1,113,940.7	524,937.4	47.1	486,435.9	92.7	22,454.9	4.3	8,699.3	1.7	7,347.3	1.4
Amazonas	7,728,480.1	940,366.0	12.2	99,077.0	10.5	100,872.8	10.7	652,558.4	69.4	87,857.8	9.3
Amapá	601,983.9	53,366.6	8.9	2,839.5	5.3	4,876.2	9.1	44,605.6	83.6	1,045.3	2.0
Maranhão	35,022.2	11,928.6	34.1	1,631.8	13.7	137.0	1.1	9,445.0	79.2	714.8	6.0
Mato Grosso	57,985.4	6,018.9	10.4	2,247.8	37.3	1,227.2	20.4	1,708.8	28.4	835.2	13.9
Pará	5,539,776.0	1,957,996.4	35.3	533,148.5	27.2	416,069.8	21.2	857,188.8	43.8	151,589.4	7.7
Rondônia	252,074.3	116,242.0	46.1	77,453.0	66.6	33,119.8	28.5	3,832.9	3.3	1,836.3	1.6

Table A.9 - Total area of public forests in the indigenous land in each state of the Amazonian state and the area overlapped by the small, medium, large and multiple rural properties.

Indigenous land	Public Forest (ha)	Overlap area		Overlap area by rural property size							
				Small		Medium		Large		Multiple	
		Area (ha)	%	Area (ha)	%	Area (ha)	%	Area (ha)	%	Area (ha)	%
Acre	1,479,580.3	9,896.6	0.7	2,566.2	25.9	296.5	3.0	6,827.3	69.0	206.7	2.1
Amazonas	23,426,388.5	816,565.9	3.5	27,035.3	3.3	23,445.9	2.9	763,602.9	93.5	2,481.8	0.3
Amapá	1,054,542.9	50.9	0.0	6.7	13.1	3.2	6.3	41.0	80.6	0.0	0.0
Maranhão	1,244,969.3	47,686.9	3.8	2,464.0	5.2	2,470.9	5.2	42,403.4	88.9	348.7	0.7
Mato Grosso	9,265,348.4	741,827.7	8.0	21,125.3	2.8	74,639.7	10.1	632,288.3	85.2	13,774.4	1.9
Pará	20,111,109.6	327,939.9	1.6	55,564.9	16.9	61,326.2	18.7	175,764.1	53.6	35,284.6	10.8
Rondônia	3,646,791.5	58,067.0	1.6	29,984.7	51.6	10,979.4	18.9	16,968.6	29.2	134.4	0.2
Roraima	10,127,931.9	34,002.6	0.3	1,366.4	4.0	20,230.0	59.5	10,796.2	31.8	1,610.0	4.7
Tocantins	3,338.4	1.3	0.0	0.0	0.0	0.0	0.0	1.3	100.0	0.0	0.0

Table A.10 - Total area of public forests in the integral protection conservation units in each state of the Amazonian state and the area overlapped by the small, medium, large and multiple rural properties.

Integral Protection Conservation Units	Public Forest (ha)	Overlap area		Overlap area by rural property size							
				Small		Medium		Large		Multiple	
		Area (ha)	%	Area (ha)	%	Area (ha)	%	Area (ha)	%	Area (ha)	%
Acre	1,563,173.7	222,076.9	14.2	69.6	0.0	392.4	0.2	221,614.6	99.8	0.4	0.0
Amazonas	10,798,262.4	1,539,964.5	14.3	14,460.4	0.9	28,894.7	1.9	1,474,954.9	95.8	21,654.5	1.4
Amapá	803,797.2	2,290.5	0.3	330.4	14.4	1,942.3	84.8	17.8	0.8	0.0	0.0
Maranhão	269,724.5	197,242.2	73.1	504.6	0.3	9,178.5	4.7	174,019.7	88.2	13,539.3	6.9
Mato Grosso	1,075,664.0	564,705.8	52.5	28,685.2	5.1	73,966.4	13.1	424,243.0	75.1	37,811.1	6.7
Pará	11,193,864.6	1,062,827.3	9.5	18,622.1	1.8	38,316.1	3.6	998,417.9	93.9	7,471.2	0.7
Rondônia	2,120,024.6	460,418.2	21.7	3,069.9	0.7	18,213.9	4.0	437,792.6	95.1	1,341.8	0.3
Roraima	1,016,472.4	266,849.6	26.3	24,531.8	9.2	117,341.4	44.0	120,586.6	45.2	4,389.9	1.6
Tocantins	6,239.1	1,651.0	26.5	1,651.0	100.0	0.0	0.0	0.0	0.0	0.0	0.0

Table A.11 - Total area of public forests in the sustainable use conservation units in each state of the Amazonian state and the area overlapped by the small, medium, large and multiple rural properties.

Sustainable Use Conservation Units	**Public Forest (ha)**	**Overlap area**		**Overlap area by rural property size**							
				Small		**Medium**		**Large**		**Multiple**	
		Area (ha)	**%**	**Area (ha)**	**%**	**Area (ha)**	**%**	**Area (ha)**	**%**	**Area (ha)**	**%**
Acre	3,495,367.4	95,723.1	2.7	35,253.7	36.8	5,117.4	5.3	54,358.0	56.8	993.9	1.0
Amazonas	24,120,596.6	3,926,254.1	16.3	73,896.9	1.9	160,176.4	4.1	3,635,369.8	92.6	56,811.0	1.4
Amapá	4,064,778.6	472,342.6	11.6	30,313.5	6.4	328,744.9	69.6	98,408.4	20.8	14,875.7	3.1
Maranhão	37,918.0	3,280.8	8.7	1,231.4	37.5	86.5	2.6	1,962.8	59.8	0.0	0.0
Mato Grosso	131,590.0	53,397.8	40.6	3,536.9	6.6	18,886.8	35.4	29,278.3	54.8	1,695.9	3.2
Pará	17,071,118.4	3,138,544.2	18.4	204,490.9	6.5	373,806.7	11.9	2,470,381.4	78.7	89,865.3	2.9
Rondônia	2,149,605.8	399,085.6	18.6	63,133.6	15.8	68,908.0	17.3	253,155.1	63.4	13,888.9	3.5
Roraima	2,719,909.3	163,328.0	6.0	796.7	0.5	103,878.5	63.6	56,033.1	34.3	2,619.7	1.6
Tocantins	9,070.5	7,028.6	77.5	2,953.3	42.0	3,416.0	48.6	653.1	9.3	6.2	0.1

Table A.12 - Total area of public forests in the undesignated lands in each state of the Amazonian state and the area overlapped by the small, medium, large and multiple rural properties.

Undesignated land	**Public Forest (ha)**	**Overlap area**		**Overlap area by rural property size**							
				Small		**Medium**		**Large**		**Multiple**	
		Area (ha)	**%**	**Area (ha)**	**%**	**Area (ha)**	**%**	**Area (ha)**	**%**	**Area (ha)**	**%**
Acre	1,924,770.1	879,912.3	45.7	128,187.2	14.6	57,197.4	6.5	632,818.3	71.9	61,709.4	7.0
Amapá	1,340,046.3	483,131.7	36.1	65,344.6	13.5	160,137.8	33.1	225,835.6	46.7	31,813.8	6.6
Maranhão	148,028.1	92,578.2	62.5	21,234.4	22.9	16,038.9	17.3	50,213.7	54.2	5,091.2	5.5
Mato Grosso	1,258,848.3	829,843.0	65.9	106,194.2	12.8	268,856.3	32.4	430,667.0	51.9	24,125.5	2.9
Pará	9,590,178.5	6,129,029.6	63.9	1,504,643.5	24.5	1,689,303.6	27.6	2,704,555.6	44.1	230,526.9	3.8
Rondônia	3,012,743.1	1,759,162.2	58.4	661,172.0	37.6	512,728.5	29.1	528,683.2	30.1	56,578.5	3.2
Roraima	2,988,312.5	1,505,560.6	50.4	149,763.3	9.9	983,784.1	65.3	299,585.4	19.9	72,427.8	4.8
Tocantins	2,856.7	1,546.0	54.1	210.9	13.6	150.4	9.7	1,183.0	76.5	1.7	0.1

Table A.13 - Total area of public forests in other categories in each Amazonian state and the area overlapped by the small, medium, large and multiple rural properties.

Other categories	**Public Forest (ha)**	**Overlap area**		**Overlap area by rural property size**							
				Small		**Medium**		**Large**		**Multiple**	
		Area (ha)	**%**	**Area (ha)**	**%**	**Area (ha)**	**%**	**Area (ha)**	**%**	**Area (ha)**	**%**
Amazonas	274,939.4	60,913.6	22.2	12,450.9	20.4	7,884.5	12.9	39,482.1	64.8	1,096.1	1.8
Amapá	7,100.4	445.6	6.3	241.3	54.2	204.3	45.8	0.0	0.0	0.0	0.0
Maranhão	62,361.1	175.0	0.3	1.6	0.9	161.4	92.2	12.1	6.9	0.0	0.0
Mato Grosso	2,639.9	2,322.6	88.0	55.7	2.4	1,155.9	49.8	1,109.6	47.8	1.4	0.1
Pará	3,568,815.2	795,514.4	22.3	35,166.5	4.4	71,245.9	9.0	671,351.3	84.4	17,750.8	2.2
Rondônia	904.3	666.8	73.7	268.0	40.2	398.8	59.8	0.0	0.0	0.0	0.0
Roraima	2,882.8	1,897.1	65.8	0.0	0.0	1,251.6	66.0	639.5	33.7	6.0	0.3

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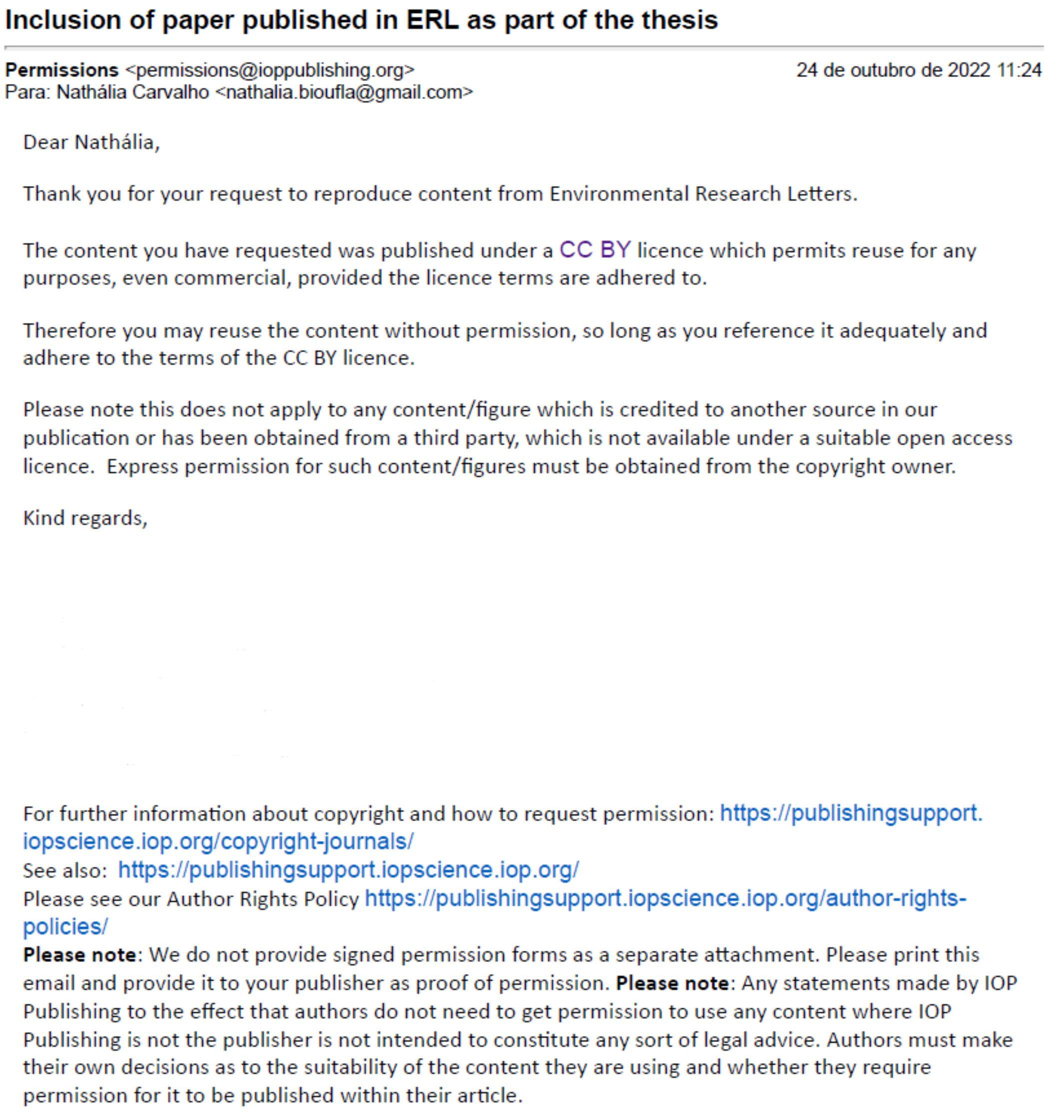

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