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Analysis of fire risk in the Amazon: a systematic review

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ABSTRACT

Fires such as those that occurred in 2019 in the Amazon are examples of the intensification of these events in recent years and contradict the claim that forest fires only reach great proportions in years of extreme drought. This is a worrying scenario, as the Amazon Rainforest plays an important role in regional and global climate regulation. This study therefore sought to identify the methodologies used to describe and predict fire events in the Brazilian Amazon. For this, a systematic literature review was carried out in the open access databases Scientific Electronic Library Online (SciELO) and Directory of Open Access Journals (DOAJ) using the descriptors “fire risk” and “Amazon”, and their variants in the Portuguese language and the logical operator “AND” in the search. From the resulting search materia we identified the use of predictive models based on projections for climate change developed by the Intergovernmental Panel on Climate Change (IPCC), which indicate a substantial increase in the probability of fires. Another technique used is the crossing of heat foci data with the forms of land use, evidencing the areas that burn the most and when, as well as the most susceptible areas. There were also studies analyzing the performance of fire risk indexes, demonstrating those that could be used after adaptations to local characteristics. These results allow an understanding of the behavior of fire in the Amazon, since they provide a broad view of how studies on fires have been conducted and what techniques have been used.

Keywords: Amazon biome, climate change, fire behavior, fire hazard, forest fires.

Análise de risco de fogo na Amazônia: uma revisão sistemática

RESUMO

Incêndios como os ocorridos no ano de 2019 na Amazônia representam um exemplo da intensificação destes eventos nos últimos anos e contradizem a afirmação de que incêndios florestais só atingem grandes proporções em anos de seca extrema. Este é um cenário preocupante, uma vez que a Floresta Amazônica executa um importante papel na regulação climática regional e global. Assim, este estudo tem por objetivo identificar quais são as metodologias utilizadas para descrever e prever os eventos de incêndios na Amazônia brasileira. Para isso, realizou-se uma revisão sistemática de literatura nas bases de dados de acesso aberto Scientific Eletronic Library Online (SciELO) e Directory of Open Access Journals (DOAJ) utilizando-se os descritores fire risk e Amazon, suas variantes em Língua Portuguesa e o operador lógico AND na busca. Do material resultante da busca, identificou-se o uso de modelos preditivos baseados nas projeções para as mudanças climáticas desenvolvidas pelo Intergovernmental Panel on Climate Change (IPCC), os quais indicam aumento substancial na probabilidade de incêndios. Outra técnica utilizada é o cruzamento dos dados de focos de calor com as formas de uso do solo, evidenciando as áreas que mais queimam e quando, como também as áreas mais suscetíveis. Houve ainda, estudos analisando o desempenho de índices de risco de incêndio, demonstrando aqueles que poderiam ser utilizados após adequações às características locais. Tais resultados permitem uma compreensão sobre o comportamento do fogo na Amazônia, visto fornecer uma visão ampla sobre como os estudos sobre incêndios vem sendo conduzidos e quais técnicas têm sido utilizadas.

Palavras-chave: bioma Amazônia, comportamento de incêndio, incêndios florestais, mudanças climáticas, perigo de incêndio.

1. INTRODUCTION

Forest fires are complex phenomena dependent on several factors, such as weather conditions, topographic conditions, fuel availability and ignition potential (Matin *et al.*, 2017). In order to mitigate their damage, different fire risk indexes were developed to measure the probability of fire ignition, either due to natural or anthropic causes, in forest areas (Antunes *et al.*, 2011).

In tropical forests such as the Amazon, natural combustion events are rare (Cochrane, 2003; Cammelli *et al.*, 2020). This is explained by the great humidity in these forests from their own trees (Fearnside, 2009; Nobre and Borma, 2009). The maintenance of its always green canopy and moisture comes from the ability of its trees to establish deep roots, preserving these characteristics even in conditions of severe drought and water stress (Cochrane, 2003; Nobre and Borma, 2009).

With the rare episodes of natural fires over the last millennium, the Amazon Forest did not need to develop adaptation mechanisms against fire, such as Cerrado vegetation (Fearnside, 2009). Although it has some resistance to drought, natural dysfunctions and anthropic causes have modified the ability of the tropical forest to maintain its moisture, making it susceptible to burning (Cochrane, 2003; Aragão and Shimabukuro, 2010).

Among these dysfunctions, we highlight the transformations in its landscape promoted by government policies to encourage the occupation of the region, the expansion of agricultural activity and the construction of major infrastructure works such as highways and hydroelectric dams; actions that have historically promoted deforestation in the Amazon (Cochrane, 2003; Becker, 2005; Fearnside, 2006; Ferrante and Fearnside, 2020; Libonati *et al.*, 2021).

The selective extraction of trees carried out by timber trees also contributes to this process, promoting forest fragmentation (Carvalho Junior *et al.*, 2020). The use of fire is also a recurrent practice of soil management in agricultural activities, generating aerosols that interfere in photosynthetic, radioactive processes and cloud formation (Bowman *et al.*, 2008; Armenteras *et al.*, 2009; Nobre and Borma, 2009; Cammelli *et al.*, 2020; Silva *et al.*, 2020).

All these events promote changes in land use and cover and act synergistically in reducing the forest resilience of the Amazon, causing interference in its biogeochemical cycles, reducing evapotranspiration and modifying the microclimate, thus compromising its existence (Bowman *et al.*, 2008; Nobre and Borma, 2009; Silva *et al.*, 2020). Given the gap in knowledge about the inflection point of the forest, as a precautionary measure strong efforts should be made to conserve the Amazon Forest yet standing (Fearnside, 2009; Nobre and Borma, 2009).

However, the number of fires in the Amazon has intensified in recent years, driven by the increase in deforestation (Silveira *et al.*, 2020; Libonati *et al.*, 2021). About 1/3 of the fire occurrences between 2003 and 2019 occurred up to 1 km away from deforested areas in the same year and up to 500 m from deforested areas in the previous year; in 2019, fires occurred in 45% of the total deforested areas in the Amazon (Silveira *et al.*, 2020). As explained by Barlow *et al.* (2019) and Silveira *et al.* (2020), fire is used to remove the remaining biomass from deforestation, a technique commonly called “cutting and burning”. Subsequently, fire is used as a management tool for deforested areas to be converted into agricultural land (Barlow *et al.*, 2019).

Thus, part of the forest fires in the Brazilian Amazon are linked to two distinct and intrinsically related activities: deforestation and the management of soils destined to agricultural activities (Morello *et al.*, 2020; Oliveira *et al.*, 2020; Penha *et al.*, 2020). Due to poor management in the use of fire, fires get out of control and commonly reach nearby forested areas (Morello *et al.*, 2020; Oliveira *et al.*, 2020).

In 2019, approximately 906,000 hectares of the Amazon Rainforest were lost in fires (Kelley *et al.*, 2021). This year, the fires were devastating both in scale and duration of the burning and were not potentiated by meteorological factors, suggesting that these are linked to changes in land use and cover (Kelley *et al.*, 2021; Li *et al.*, 2020).

Given this scenario of changes and intensification of fire records in the Amazon, this study involved a literature review on the rates of fire risks used in studies of fire in the Brazilian Amazon and was motivated by two questions: i) what methodologies are used to measure the risk of fire in the Brazilian Amazon? and ii) what are the prospects in the current scenario of intense occurrence of fires? Thus, the objective of this research was to identify the methodologies used to describe and predict the occurence of fires in the Amazon.

2. MATERIAL AND METHOD

This study comprised a qualitative research with secondary data collection, analyzed according to the methodological contribution of the systematic literature review. The bibliographic survey was carried out in the scientific databases of open access: the Scientific Electronic Library Online (SciELO) and the Directory of Open Access Journals (DOAJ).

The articles were searched on August 30, 2020, and the descriptors “fire risk” and “Amazon” and their variants in Portuguese were used, applying the use of the logical operator “AND”. The time frame encompassed articles published in the last ten years (2010-2020) and available entirely by electronic means, thus capturing what is most recent in the literature on the subject.

The inclusion criterion of the articles consisted of verifying whether they addressed the theme of forest fire risk in the Amazon and contained the descriptors in their title, abstract or keywords. All articles that did not meet the parameters described were excluded.

3. RESULTS

Fifteen articles were found in the initial search. When applying the temporal filter composed of the period of years between 2010 and 2020 and the inclusion criteria previously established, nine publications remained. Of these, four publications were in the SciELO database and five in the DOAJ database. The articles analyzed in this study are presented in Table 1, organized by source database and year of publication.

Based on the above, it is noted that at the beginning of the decade the theme on the risk of forest fires in the Amazon was addressed in a very incipient way with a study published in each year of 2010, 2011 and 2012. Then there was a lack of indexed publications in the databases consulted, SciELO and DOAJ, comprising the years 2013, 2014, 2015. From 2016, there was the resumption of publications, with one published article, two articles in 2017, two in 2018 and one in 2019.

The methodology and results of these studies are summarized in Table 2 below, according to the date of publication.

Table 1. Articles collected in the DOAJ and SciELO databases on the risk of fires in the Amazon, analyzed in this study.

Data base	Year Publication	Authors	Title	Journal
DOAJ	2010	LIBERATO, A. M.; BRITO, J. I. B.	Influence of changes in the water balance of the Western Amazon	Revista Brasileira de Geografia v. 3, p. 170-180, 2010.
DOAJ	2011	MÉLO, A. S.; JUSTINO, F.; LEMOS, C. F.; SEDIYAMA, G.; RIBEIRO, G.	Susceptibility of the environment to occurrences of fires under current climatic conditions and future global warming	Revista Brasileira de Meteorologia v. 26, n. 3, p. 401-418, 2011.
DOAJ	2017	ANDERSON, L. O.; YAMAMOTO, M.; CUNNINGHAM, C.; FONSECA, M. G.; FERNANDES, L. K.; PIMENTEL, A.; BROWN, F.; SILVA JR, C. H. L.; LOPES, E. S. S.; MOREIRA, D. S.; SALAZAR, N.; ANDERE, L.; ROSAN, T. M.; REIS, V.; ARAGÃO, L. E. O. C.	Use of orbital data from heat sources to characterize forest fire risks and prioritize areas for decision making	Revista Brasileira de Cartografia v. 1, n. 69, p. 163-177, 2017.
DOAJ	2017	PAGE, Y. L.; MORTON, D.; HARTIN, C.; BOND-LAMBERTY, B.; PEREIRA, J. M. C.; HURTT, G.; ASRAR, G.	Synergy between land use and climate change increases future fire risk in Amazon forests	Earth System Dynamics v. 8, p. 1237-1246, 2017.

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DOAJ	2018	SODRÉ, G. R. C.; SOUZA, E. B.; OLIVEIRA, J. V.; MORAES, B. C.	Risk calculation and fire detection: an analysis in the Eastern Amazon	Revista Brasileira de Ciências Ambientais v. 49, p. 1-14, 2018.
SciELO	2012	RIBEIRO, L.; SOARES, R. V.; BEPLLER, M.	Mapping the risk of forest fires in the municipality of Mundo Novo, Mato Grosso, Brazil	CERNE v. 18, n. 1, p. 117-126, 2012.
SciELO	2016	SILVA, P. R. S.; IGNOTTI, E.; OLIVEIRA, B. F. A.; JUNGER, W. L.; MORAIS, F.; ARTAXO, P.; HACON, S.	High risk of respiratory diseases in children in the fire period in Western Amazon	Revista de Saúde Pública v. 50, n. 29, p. 1-11, 2016.
SciELO	2018	WHITE, B. L. A.	Spatiotemporal variation in fire occurrence in the state of Amazonas, Brazil, between 2003 and 2016	Acta Amazonica v. 48, n. 4, p. 358-367, 2018.
SciELO	2019	CASAVECCHIA, B. H.; SOUZA, A. P.; STANGERLIN, D. M.; ULIANA, E. M.; MELO, R. R.	Fire hazard indices in a Cerrado-Amazon transition area	Revista da Sociedade de Ciências Agrárias de Portugal v. 42, n. 3, p. 842-854, 2019.

Table 2. Methodology used and results described in the studies analyzed in this study.

Year Publication	Title of the article	Methodology	Result found
2010	Influence of changes in the water balance of the Western Amazon	Calculation of water balance and estimation of climatic indices using the methodology proposed by Thornthwaite & Mather (1957) and modified by Krishan (1980) with the calculation of potential evapotranspiration estimated by the Thornthwaite method (1948). The input variables of the model were average air temperature and monthly rainfall totals from 1961 to 2005, coming from INMET weather stations.	In the projections made in two scenarios (A2 and B2) of the IPCC, with an increase in temperature in the order of 3.8ºC and 1.3ºC, respectively, there was a trend of drier climate, reduction of humidity, and reduction of river flow, which will lead to an increase in the risk of fire in the Western Amazon.
2011	Susceptibility of the environment to occurrences of fires under current climatic conditions and future global warming	Evaluation of atmospheric conditions favorable to the occurrence of fire by Haines Index. The calculation of the Haines Index has as input data the differences in air temperature and temperature of the dew point according to altitude. Simulations are generated in the current scenario and in a global warming circumstance (IPCC scenario A1B) using the ECHAM5/MPI-OM model of the MaxPlanck Institute of Meteorology.	The risks of fires in Brazil were found in the current situation and future scenario for the months of June to October. Currently, the risk of fire is concentrated in the Midwest and North, mainly in august; in the projection (2080-2100), in a global warming scenario, there is an increase in the size of areas exposed to fire risks, especially in the Amazon.
2012	Mapping the risk of forest fires in the municipality of Novo Mundo, Mato Grosso, Brazil	Generation of maps of land use and cover classification and digital elevation model of the terrain and used as input variables the slope of the terrain, hydrographic network and road network. From the overlay of the maps (overlay technique), weights from 0 to 5 were assigned according to their risk potential and the degree of fire risk was categorized as null, low, moderate, high, very high and extreme.	A forest fire risk map was generated for the municipality of Novo Mundo-MT, which indicates that 95% of the municipality area is at high risk and very high risk of fire incidence. It was found that forests near pasture areas and roads are the most susceptible to fires.
2016	High risk of respiratory diseases in children in the fire period in Western Amazon	Continuous monitoring of air performed hourly for measurement of fine particulate matter and ozone. The 2B Tech meter was installed near the public school unit in order to monitor the quantitative pollutants present in the air to which children aged 6 to 14 years are exposed.	There was high exposure of school-age children to ozone (O_3) and fine particulate matter with toxicological risk during the dry season in the city of Rio Branco-AC, where 19% of the children presented asthma. The pollutants present in the air come from the burning of forest biomass and their high concentration occurs mainly during the dry season, when the volume of fires increases.
2017	Use of orbital data from heat foci to characterize forest fire risk and prioritize areas for decision making	Crossing the records of heat foci captured from 2000 to 2014 by different satellites with data of land structure of the State of Acre. With this, they obtained information about areas that burn the most and when they burn, categorized by land structure of occurrence.	A fire risk map was generated for the State of Acre, based on the spatial-temporal analysis of fire outbreaks recorded by different orbital sensors, in order to spatialize the risk of fire. It was found that the highest volume of heat foci was in Settlement Projects and the lowest volume occurred in Indigenous Lands.

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2017	Synergy between land use and climate change increases future fire risk in Amazon forests	Use of the HESFIRE model parameterized for fires in the understory, in which interactions between anthropic activity and current (1990-2010) and future (scenario 2080-2100) were tested. THE HESFIRE consists of three modules: ignition, propagation and finalization and each module is adjusted according to values described in the literature and field data. The input data of the model consist of frequency of anthropic ignition of fire, land use, GDP, weather conditions, soil moisture, fuel type, fuel availability, fire suppression effort.	Projection was carried out in two scenarios: in a scenario of low effort of change in land use and mitigation of climate change, fires in the understory of the Amazon Forest would increase by 4 to 28 times, while in a scenario of active mitigation against climate change and containment of changes in land use, the increased risk of fire would be 0.9 to 5.4 times higher than the current one.
2018	Risk calculation and detection of fires: an analysis in the Eastern Amazon	The calculation of the Fire Risk used in the study is that developed by INPE and is based on meteorological data. The input data of the index are precipitation, temperature of the relative humidity, use and cover of the soil in three categories (forest, agriculture and pasture) and heat foci. The risk of fire is categorized into five classes: minimal, low, medium, high and critical. The study carried out an analysis from 2000 to 2017 and considered the occurrence of the meteorological phenomena El Niño and La Niña.	The areas with pasture concentrated 47.3% of the fire records. On the other hand, the agriculture areas centralized 32.8% of the records, while the forested areas presented 19.9% of the heat foci. It was found that the Fire Risk Index based so only on meteorological data is not suitable for use as a fire prediction index, limited to an environmental indicator.
2018	Spatiotemporal variation in fire occurrence in the state of Amazonas, Brazil, between 2003 and 2016	Crossing the data of heat foci provided by INPE, recorded between 2003 and 2016 in the State of Amazonas, with data on temperature, precipitation, population density, deforested area, agricultural area and pasture areas. The data were quantified monthly and individualized by municipality of occurrence.	The year with the lowest incidence was 2008 and the highest was in 2015. The month that registers the most outbreaks of fire is the month of September. Lábrea is the municipality with the most registered outbreaks and Japurá with the lowest record. The municipalities with a high number of heat foci also showed higher deforestation. The most affected areas are the South and East region of the State of Amazonas.
2019	Fire hazard indices in a Cerrado-Amazon transition area	The performance of seven fire risk indexes was evaluated: Monte Alegre Formula (FMA) and Modified Monte Alegre (FMA+), Nesterov, Telitsyn, Ängstrom, P-EVAP and EVAP/P in an Amazon-Cerrado transition area by the Skill Score method. The input data used were air temperature, humidity, rain and wind speed provided by INMET.	Regarding the prediction of heat foci, the Telitsyn index presented 94.8% of correct answers. The Ängstrom index showed 74.7% of correct answers for non-occurrences of fires. In the general evaluation, it was found that the Ängstrom Index was the one that presented the best suitability for the Sinop-MT region, with a performance of 84.9% in the evaluation by the Skill Score.

The study by Liberato and Brito (2010) presents projections based on the report released by the Intergovernmental Panel on Climate Change (IPCC) on climate change and global warming. In this, the risk of fire in the Western Amazon rises considerably in these conditions. The authors used the Thornthwaite & Mather Method (1975) adapted by Krishan (1980) to elaborate the water balance.

With this, the authors do not use a fire risk index to verify the increase in the probability of fires in the Amazon. They infer the possibility of increased fires from the intensification of the consequences caused by climate change, such as reduction of soil moisture, surface and subsurface runoff, which decreases the flow of rivers and makes the forest less humid, favorable conditions for the occurrence of fires (Liberato and Brito, 2010).

The study by Mélo *et al.* (2011) is also based on the projections disclosed in the IPCC report and uses the Haines Index to calculate the risk of fire. The authors consider the months of June to October, because these are those that present favorable atmospheric conditions for the occurrence of fires. According to the authors, certain atmospheric conditions and the amount of water vapor in the atmosphere would be related to the spread of the fire.

The Haines Index would be an indicator of the potential condition for the occurrence of fires from vertical temperature and air humidity calculated in the low, medium and high atmosphere. The study by Mélo *et al.* (2011) is based on the monthly climatology of two periods: a current scenario (1980-2000) and a future scenario (IPCC projection A1B, 2080-2100), and the projected results indicate a substantial increase in the area at risk of fire in the Amazon.

An important factor highlighted by the authors regards the ignition of fire in the Amazon being of anthropic cause, mainly linked to agropastoral activities. In this context, in future scenario projections, even if atmospheric conditions are conducive to the occurrence of burning, human behavior may differ and the number of fires may be lower (Mélo *et al.*, 2011).

On the other hand, the research conducted by Ribeiro *et al.* (2012) considers the anthropic aspect in fire ignition and resulted in a map outlining the zoning of the risk of fires for the municipality of Novo Mundo-MT. The authors based their estimates on the characterization of land use and cover from orbital image classification and considered as input variables the slope of the terrain, hydrographic and road network.

In this sense, the authors emphasize the openness and proximity to highways as a factor of intensification of the risk of fire due to the accumulation of combustible material on their margins, increased human occupation and ease of access to forested areas, which may contribute to wood extraction and forest fragmentation (Ribeiro *et al.*, 2012).

While water bodies can influence both the negative aspect (attraction of people for recreation and consequent inappropriate use of fire) and the positive aspect (such as fire-containment barrier). The slope of the terrain acts on the speed of fire propagation, where in sloped areas the fire propagates faster than in non-sloped areas. In relation to soil cover, agropastoral areas are very close to forested areas and the use of fire as a soil management tool considerably increases the risk of forest fire (Ribeiro *et al.*, 2012).

The study conducted by Silva *et al.* (2016) presented the results of a research conducted in the health area on the exposure of children to pollutants present in the air from biomass burning, in the city of Rio Branco-AC, part of the "deforestation arc". The burning of volatile organic compounds (VOC) present in forest biomass generates Ozone (O_3) and this has a high degree of toxicity causing respiratory problems to the exposed population.

Although the research of Silva *et al.* (2016) does not explore the risk of fire in the Amazon, the study exposes the impacts to public health caused by fire. As reported by the authors, even if a particular municipality or state area is not the place of occurrence of the fire, air currents transport pollutants from the fires and reach distant areas, thereby affecting more people (Silva *et al.*, 2016).

The work of Anderson *et al.* (2017) was also conducted in the State of Acre and resulted in a map presenting the spatialization of fire risk to the State, based on the State's land organization. Data from heat foci captured by several satellites between 2000 and 2014 were used. Based on the historical-spatial analysis of the heat foci register, the authors produced a map showing the fire-risk classification categorized into eight levels: no risk, very low risk, low risk, observation, attention 1, attention 2, alert, maximum alert.

As stated by the authors, the technique of crossing historical data with the land structure is simple but efficient for analyzing fires of anthropic cause. The data generated can also be incorporated into models based on climate data, optimizing the analysis of fire risk (Anderson *et al.,* 2017).

The research of Page *et al.* (2017) also correlates fire data with forms of land use and presents projections in climate change scenarios, considering the scenarios contained in the IPCC. These projections consider scenarios of mitigation and not mitigation of climate change. In both scenarios, the risk of fires in the Amazon increases; however, when there is no control regarding the form of land use, the risks increase substantially (Page *et al.*, 2017).

The authors point out that fires in the Amazon are anthropically ignited, and that their origin may be deforestation or agricultural practices. In this context, the study considers in its analysis the human factor regarding fire ignition and climate change mitigation. In case of continued intensive use of natural resources, the Amazon would be at risk both for the consequences of climate change and for the severity and volume of fires (Page *et al.*, 2017).

Looking at the impact of the anthropic aspect on the occurrence of fires in Amazonia, the study presented by Sodré *et al.* (2018), held in Paragominas/PA, emphasizes that about 80% of heat foci in the region originate in areas modified by human action. Thus, the authors perform a space-time analysis of fires detected via satellite in contrast to the Fire Risk developed by the National Institute of Space Research (INPE) that considers only environmental variables.

The Fire Risk developed by INPE measures the susceptibility of the environment to combustion, regardless of the form of fire ignition (whether natural or anthropic). By contrasting the record of heat foci with the Fire Risk alert, the authors found the occurrence of fires even when the risk was considered minimal. The authors also found that, when there is an increase in the number of fires in agricultural areas, there is also an increase in forested areas, demonstrating the close connection between anthropic activities and the registration of forest fires. This is due to the proximity between these two forms of cover and land use, aggravated by the effects of edge and forest fragmentation (Sodré *et al.*, 2018).

The research developed by White (2018) performed a spatial and temporal analysis of the record of heat foci in the State of Amazonas between the years 2003 and 2016, categorizing the municipalities into five classes (very low, low, medium, high and very high) according to the number of heat foci recorded per km^2 of area of the municipality. The study performed statistical analyses seeking the correlation of the variable heat foci with variables that can influence the occurrence of fires, such as: air temperature, precipitation, population density, deforestation, agricultural areas and pastures.

Like the study by Anderson *et al.* (2017), White's study (2018) does not analyze the applicability of a given fire risk, but part of the analysis regards the temporal and spatial history of the heat foci register, correlating it with forms of land use and environmental variables. From this, information is generated about the areas that burn the most and when they burn, a condition that allows us to infer about behavior in the near future, if there are no circumstantial changes.

In addition, the analysis of historical recurrences favors the understanding of fire behavior in years of occurrence of climatic events such as El Niño and La Niña as proposed by Sodré *et al.* (2018), also pointed out by White (2018), when identifying interannual changes in his temporal analysis. Using geoprocessing techniques, White (2018) highlights that these results can be crossed with different thematic maps, expanding the scope of analysis and understanding of the phenomenon.

Finally, the work developed by Casavecchia *et al.* (2019) evaluates the performance of fire risk indexes in an Amazon-Cerrado transition area. The Monte Alegre Formula (FMA) and Modified Monte Alegre (FMA+), Nesterov, Telitsyn, Ängstrom, P-EVAP and EVAP/P are evaluated by the Skill Score method. All indexes have weather information input data. The standard indices used in Brazil are FMA and FMA+, which are used in the calibration of indexes not developed for Brazilian climatic conditions (Casavecchia *et al.*, 2019).

According to the authors, changes in rainfall regimes and relative humidity are the factors that most interfere in the performance of the indices. In this sense, Casavecchia *et al.* (2019) highlight the importance of adjusting the indices for local climatic conditions, aiming to mitigate mistaken results, as well as the need for daily calculation and maintenance of records to control fire occurrences.

4. DISCUSSION

In the Brazilian Amazon, the use of fire is a common practice for soil cleaning for agricultural use (Cammelli *et al.*, 2020). However, its indiscriminate use goes beyond the intended areas and reaches forested areas in the surroundings (Campanharo *et al.*, 2019; Barlow *et al.*, 2019). These occurrences tend to be aggravated by climatic events that cause an increase in temperature and low air humidity,as well as forest fragmentation promoted by selective logging and by deforestation promoted by illegal land ownership (Campanharo *et al.*, 2019; Azevedo-Ramos *et al.*, 2020; Carvalho Junior *et al.*, 2020).

Considering climate change as a threat factor to the Amazon Forest, three studies (Liberato and Brito, 2010; Mélo *et al.*, 2011; Page *et al.*, 2017) analyzed in this study made projections with different methodologies, and all scenarios indicated an increase in the occurrence of forest fires in the region. The increase in temperature and the reduction of air humidity that has made tropical forests less humid and susceptible to fires (Barlow *et al.*, 2019).

Barlow *et al.* (2019) highlight that the number of fires in 2019 was three times higher than in 2018 and is the highest recorded since 2010, although 2019 has not had an extreme weather event record this year. The increase in the number of fires was accompanied by a high increase in deforestation, in which it is estimated that more than 10,000 km^2 of forest is lost between 2018-2019, constituting the largest deforestation/year recorded since 2008 (Barlow *et al.*, 2019).

Even recognizing that climatic projections are imprecise and that they are also dependent on human behavior (Mélo *et al.*, 2011), it is possible to identify certain results by direct experience (Fearnside, 2009). In this sense, each year new scars caused by fires and fragmentation points in the forest are identified (Campanharo *et al.*, 2019; Carvalho *et al.*, 2020).

Considering the scenario of intensification of land use and changes in land cover, with and without behaviors to mitigate climate change, Page *et al.* (2017) projected an increased risk of fires in the understory of the Amazon Rainforest. Forest fires of this type, even low intensity, kill approximately 50% of the trees (Barlow *et al.*, 2019).

Since the ignition of forest fires in the Brazilian Amazon is of anthropic causes, fire risk indexes that consider only climatic factors tend to be inappropriate (Silva *et al.*, 2020), reaffirming what was determined by Sodré *et al.* (2018). According to the authors, the calculation of fire risk (RF) created by INPE and used in the study was developed to monitor rainfall indices, so the fire risks did not efficiently represent the occurrence of fires (Sodré *et al.*, 2018).

In the seventeen years of analysis that comprised the study (2000-2017), Sodré *et al.* (2018) found that 47.3% of the fires occurred in pasture areas, followed by agriculture areas with 32.8% and forest with 19.9%. In the years in which the occurrence of the La Niña phenomenon was identified, which generates more precipitation in the Amazon, heat foci are concentrated in the second half, when the influence of the climatic event decreases in intensity. However, in years of El Niño occurrence, which decreases precipitation, fire outbreaks were recorded in the first and second semester (Sodré *et al.*, 2018).

The largest forest fires recorded in the Amazon in the last twenty years coincided with years of more intense drought associated with the El Niño phenomenon, which provides high temperatures and lower humidity (Campanharo *et al.*, 2019). In this context, it is urgent to use reliable fire risk indices that can be applied in the development of policies for planning, prevention and combating forest fires (Silva *et al.*, 2020).

Among the studies analyzed in this study, the research conducted by Casavecchia *et al.* (2019) analyzed seven fire-risk indexes: Monte Alegre Formula (FMA) and Modified Monte Alegre (FMA+), Nesterov, Telitsyn, Ängstrom, P-EVAP and EVAP/P. The one that presented the best performance was the Ängstrom index, followed by FMA and FMA+ for the Sinop-MT region, an Amazon-Cerrado transition area.

Regarding FMA, Silva *et al.* (2020) highlight that the human factor is not explicitly considered and that it was created based on the characteristics of a region with humid subtropical climate. In the Amazon, the climate is hot equatorial super humid (Silva *et al.*, 2020). Pertinently, Casavecchia *et al.* (2019) reinforced the need for regional adjustments in indices based on local characteristics.

The FMA was the first fire risk index developed in Brazil in the 1970s (Silva *et al.*, 2020). The FMA and FMA+ are the standard indices used in Brazil; from them, the calibration of indexes not developed for the Brazilian climatic characteristics was performed. The Ängstrom Index, which does not present fire risk classes, was therefore adapted from the classes contained in the FMA+ index and the literature (Casavecchia *et al.*, 2019).

Spatialization in maps of areas susceptible to fires are important and necessary to the fire risk index, and in this sense, three studies analyzed herein objectively addressed this goal: those of Ribeiro *et al.* (2012), Anderson *et al.* (2017) and White (2018). Ribeiro *et al.* (2012) worked on a municipal scale, while Anderson *et al.* (2017) and White (2018) dedicated themselves to the state scale to present their results.

Addressing the risk of fire in the state land organization, Anderson *et al.* (2017) identified that indigenous lands are the areas least prone to fire risk. According to Paiva *et al.* (2020), the designation of protected areas (Conservation Units and Indigenous Lands) is an effective measure for biodiversity conservation, deforestation prevention and forest fragmentation.

White (2018) classified municipalities according to the heat foci quantified in relation to the total area of the municipality, and thus found that the area that most records fires is located in the south of the State of Amazonas. This region coincides with the location of the "Deforestation Arc" and concentrates a high percentage of deforestation along the southern and eastern edges of the Amazon Forest (Fearnside, 2009; Nobre and Borma, 2009).

Contemplating a local scale, the municipality of Novo Mundo-MT, Ribeiro *et al.* (2012) developed thematic fire risk maps considering a certain degree of risk according to terrain slope, hydrography, road network and soil cover. The authors found that the road network and the form of land use are the variables that most generate fire risks, where forests near roads and pastures would be more susceptible to burning (Ribeiro *et al.*, 2012). The areas of the forest edge are hotter and drier than the interior of the forest, being more sensitive to fire (Fearnside, 2006; 2009; Aragão and Shimabukuro, 2010).

The recognition of vulnerable areas allows the elaboration of more precise prevention and relocation plans for human and financial efforts in the fight against forest fires (Ribeiro *et al.*, 2012; Anderson *et al.*, 2017). The identification of the population living in these areas would allow community training on fire prevention and correct management, since small farmers are the main actors involved in fighting fires that occur (Cammelli *et al.*, 2019).

Since the use of fire is a culturally consolidated practice essential to the guarantee of subsistence of economically disadvantaged populations living in the Amazon (White, 2018; Barlow *et al.*, 2019), control and management policies are more likely to achieve positive results than prohibitions (Cammelli *et al.*, 2019). Understanding the use and control of fire is essential for the preservation of the Amazon Forest, which requires the execution of complementary public policies (Cammelli and Angelsen, 2019).

In addition to environmental damage, forest fires expose the populations of affected areas to a large amount of pollutants, characterized by plumes of smoke from the burning of plant biomass (Barlow *et al.*, 2019). In this sense, burning would become a public health problem, as evidenced in the study developed by Silva *et al.* (2016), analyzed in this work.

In this study, the authors evaluated the toxicological risk of exposure to ozone (O_3) and fine particulate matter present in the air during the dry season – a circumstance in which there is an increase in the number of fires in the Amazon – and identified a high incidence of respiratory infections (Silva *et al.*, 2016).

It is emphasized that forest degradation is also a source of pollutants, such as carbon dioxide, methane and nitrous oxide, into the atmosphere (Fearnside, 2009; Celentano *et al.*, 2018). In addition to this, the emission of pollutants generated in fires would cancel the carbon sink consumed by untouched forests, invalidating compensation mechanisms such as those proposed by the Reducing Emissions from Deforestation and Forest Degradation (REDD) (Nobre and Borma, 2009; Aragão and Shimabukuro, 2010). Of course, government action and the engagement of actors involved in the ignition of fires are essential to prevent this scenario (Cammelli *et al.*, 2019; Cammelli and Angelsen, 2019).

5. FINAL CONSIDERATIONS

Several studies have proposed methodologies for the measurement and analysis of fire risk, using the application of remote-sensing techniques; geoprocessing; climate modelling; measurement of economic costs; space-time analysis of heat foci; verification of the adequacy of risk indices; analysis of health impacts, among others.

Given the different possibilities of analysis and the current Amazonian scenario, the questions emerged about what methodologies would be used to study the risks of fire in the Brazilian Amazon and what are the future perspectives in the current scenario of intense fire occurrence.This work answers these questions by analyzing nine studies published in the last ten years and indexed in the databases of free access DOAJ and SciELO. These studies examined forest fires in the Brazilian Amazon using different methodologies, which allows a broad perspective of the solutions developed on the subject, which synthesized herein.

Three studies analyzed presented results of climatic modeling, the projections of which indicate marked increase in the risk of Amazonian fires. This would be due to the intensification of land use and changes in land cover, increased temperature and decreased rainfall in the Amazon. These results show the risks that climate change imposes on the Amazon and how these are intensified by anthropic actions, in a circular dynamic.

The analysis of the historical information of the fire registry along with forms of land use were the object of study in three other studies, which returned information about the areas that suffer the most from the incidence of fires and when they occur, in addition to providing relevant data on the behavior of the fire in years of recording climatic extremes. The results of these studies also demonstrated the upward trend of increase in the recording of heat foci over the years.

Regarding the analysis of fire-risk indexes, two studies addressed the issue and used indexes whose input data are meteorological data. It is recognized in the literature that the ignition of fires in the Amazon is of anthropic origin. Due to the specificities of the environment, the analyzed indexes required adjustment and adaptation in order to be applied to other regions or proved inappropriate to predict the risk of burning.

Given the above, an immediate improvement in the management and use of natural resources is required, and urgent action on the part of all involved. Fire control deserves special attention, due to the historic roots of its use in local culture. It is noted that the use of fire contributes greatly to the degradation of the Amazonian environment, producing negative impacts in all spheres: environmental, economic and social.

Due to the relevance of the theme, we believe that this work contributes to the existing literature in that it provides a systematized and comprehensive view of recent studies on fires in the Amazon, which highlight areas that deserve attention. The work also provides a future perspective of the scenario. An understanding of the behavior of fire provided by the studies favors its control and management through the precise targeting of human and economic resources in the fight against Amazonian forest fires.

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