FEDERAL UNIVERSITY OF ACRE
VICE-RECTORATE FOR RESEARCH AND GRADUATE STUDIES
GRADUATE PROGRAM IN FORESTRY SCIENCE

CLIMATE DYNAMICS IN THE WESTERN AMAZON: NEW MODEL OF FIRE RISK, RAINFALL BEHAVIOR AND IMPACT OF ANDEAN SNOW COVER IN ACRE

KENNEDY DA SILVA MELO

MASTER'S DISSERTATION

RIO BRANCO – AC, BRAZIL
OCTOBER 2024

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Ficha catalográfica elaborada pela Biblioteca Central da UFAC

M528d Melo, Kennedy da Silva, 1996 -
Dinâmica climática na Amazônia Ocidental: novo modelo de risco de incêndio, comportamento das chuvas e impacto da cobertura de neve andina no Acre / Kennedy da Silva Melo; orientador: Prof. Dr. Rafael Coll Delgado. – 2024.
62 f.: il.; 30 cm.

Dissertação (Mestrado) – Universidade Federal do Acre, Programa de Pós – Graduação em Ciência Florestal, Rio Branco, 2024.
Inclui referências bibliográficas.

1. Variáveis climatológicas. 2. Queima. 3. Água. I. Delgado, Rafael Coll (orientador). II.Título.

CDD: 634

Bibliotecário: Uéliton Nascimento Torres CRB-11º/1074.

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RIO BRANCO - AC, BRAZIL
OCTOBER 2024

ATA DE SESSÃO PÚBLICA DE DEFESA DE DISSERTAÇÃO DE KENNEDY DA SILVA MELO, DISCENTE DO PROGRAMA DE PÓS - GRADUAÇÃO, STRICTO SENSU, EM CIÊNCIA FLORESTAL, DA UNIVERSIDADE FEDERAL DO ACRE.

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Data: 22 de outubro de 2024
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ACKNOWLEDGMENTS

I would like to thank everyone who contributed to this work.

SUMMARY

LIST OF SYMBOLS

%	percentage
FIRERBR	Rio Branco Fire Risk
m	meter
cm	centimeter
ºC	degrees celsius
km^2	square kilometers
Tmax	maximum air temperature
Tmin	minimum air temperature
ETo	evapotranspiration
mm day^{-1}	millimeters per day
pr	rainfall
u2	wind speed
m s^{-1}	meters per second
UR	relative humidity
Rs	solar radiation
MJ m^{-2} day^{-1}	megajoules per square meter per day
AG	agricultural
FOAA	alluvial open rainforest
FOATB	dense lowland rainforest
Tavg	average air temperature
Temp	harvested areas of temporary crops
Perm	harvested areas of permanent crops
CO^2	carbon dioxide
UR 13H	relative humidity of the air at 13:00
Yi	dependent variable
Xi	independent variable
R^2	coefficient of determination
EPE	standard error of the estimate
M^3 h^{-1}	cubic meters per hour
Km	kilometers

GENERAL INTRODUCTION

Climate change is a reality all over the planet. In South America, several studies indicate a hotter and drier climate in the future, affecting the Amazon ecosystem [1]. In this sense, we have the state of Acre, located in the western region of the Amazon and which has been suffering the consequences of these climate changes in extreme ways.

Due to human action modifying the environment, a greater frequency of extreme droughts and a greater frequency of ignition sources due to anthropogenic activities, forest fires and burnings have become more frequent in recent years [2]. These fire events affect the health of the population through air pollution, cause the loss of biodiversity, contribute to greenhouse gases, among other effects [3,4].

In addition to fires, the state has been suffering more frequently from extreme hydrological events. In 2024 alone, according to data from the civil defense, the capital Rio Branco recorded its second largest flood and its largest drought in history, highlighting the new climate dynamics in the region [5]. During the period from 1987 to 2023, 60% of the extreme events that occurred in Acre were characterized as forest fires or burning in deforested areas, 33% were floods and 6% were water crises [6].

Based on this scenario, several studies have been developed in the South American region using remote sensing, climate data and forecasting models that use this data, to verify the current and future climate behavior, with climate change as a backdrop [7,8]. The MODIS sensor, present in the AQUA and TERRA satellites, has several products that provide data on heat sources, vegetation index, snow cover, among others [9]. In addition, there are satellites that provide global rainfall data, which is useful for forecasts regarding the future dynamics of this climate variable [10].

In addition to the issue of fire and rain, snow is of relevant interest in the Acre region, given the state's proximity to the portion of the Andes Mountains that is in Peru and Bolivia. The concern is due to the decrease in precipitation and an increase in temperature in different parts of the planet, causing a reduction in the area and volume of tropical glaciers, and consequently, increasing surface runoff in several river basins, especially in river basins with tropical glaciers in Peru [11].

In view of this, the present work aimed in its first chapter to investigate the behavior of climate variables and fire in the state of Acre, as well as to propose a new fire risk model for the capital Rio Branco. In the second chapter, the work aimed to investigate rainfall and other climate variables, as well as to verify the snow cover in the region close to the state, to verify the possible impact of thawing in the Acre basin.

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CHAPTER I - ARTICLE I

THE CONSEQUENCES OF CLIMATE CHANGE IN THE BRAZILIAN WESTERN AMAZON: A NEW PROPOSAL FOR A FIRE RISK MODEL IN RIO BRANCO, ACRE

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DOI: https://doi.org/10.3390/f15010211

ABSTRACT

The objective of this study was to verify the link between climate change, changes in land use, and the increasing frequency of forest fires in the state of Acre. Recognizing the importance of an accurate assessment of fire risk, we also proposed a new fire risk index for the capital Rio Branco, using meteorological data. Validated reanalysis data from 1961 to 2020, extracted for Rio Branco and different land uses, were used. Data on fire foci, deforestation, and agricultural crops were also obtained. The new model was based on the Fire Risk Atlantic Forest (FIAF) Index, developed for the Atlantic Forest biome, and was subjected to multiple regression analysis. To validate the new model, projections were calculated using different scenarios from the Intergovernmental Panel on Climate Change (IPCC). The new model, entitled Rio Branco Fire Risk (FIRERBR), revealed an increase in fire risk, especially associated with agriculture, in future scenarios (SSP2-4.5 and SSP5-8.5) from 2023 onward. Rainfall and relative air humidity also showed a reduction in projections, indicating a higher degree of fire danger for the region.

KEYWORDS: climatological variables; burn; anthropic advance; modeling; Amazon.

INTRODUCTION

The current climate change is real and has been intensifying at an astonishing rate in recent years. Its consequences are potentially very serious for humans and the Earth. Numerical simulations indicate that the northern region of South America will gradually become hotter and drier as global temperatures increase, which can seriously alter the ecosystem balance of the Amazon as a whole [1].

The state of Acre, located in the Brazilian Amazon, has been suffering from these changes, through extreme hydrological events. In 2015, the state capital recorded its largest flood, with the Acre River reaching 18 m and 40 cm [2]. In 2016, the same river experienced the most severe drought, recording 1 m and 30 cm [3].

During periods of extreme drought, forest fires are more recurrent. Factors such as high humidity and the lack of ignition of fires in areas far from urban centers prevent fires, but climate forecasts for the future and changes in land use may increase the presence of fires in these areas [4].

Generally, fire in forest areas originates from nearby areas being burned, either as part of the initial deforestation or in the subsequent management of agricultural and livestock systems [5].

In this sense, Acre has been undergoing changes in land use, mainly due to the increasing deforestation. In the Baixo Acre region, where the capital Rio Branco is located, it mainly occurs due to investments in the agricultural and livestock sector, and the increase in cattle herds [6]. The deforestation of areas in the Amazon with natural forest vegetation can change the physical and chemical processes between the atmosphere and terrestrial ecosystems, leading to changes in rainfall, temperature, and air humidity [7].

Changes in climate and land use are transforming the spatial and temporal characteristics of fire regimes in the Amazon, affecting the functioning of dense, open, and transitional rainforests [8]. In addition to the anthropic effect, many researchers associate the increase in fires in regions of South America with megadroughts and oceanic circulations such as the El Niño–Southern Oscillation (ENSO) event [9].

Several fire risk classification systems have been developed to help identify forest fires, providing numerical indices that estimate the intensity of possible fires [10]. In Brazil, the modified Monte Alegre Formula (FMA+) has been used in several studies, and it is calculated with the relative air humidity, precipitation, and wind speed as input variables [11,12,13].

Not only in Brazil but also in different regions of the world, new research and fire risk models have been widely tested and used in an attempt to reduce the threat to life and ecosystems in these regions, such as the studies conducted in India [14], Greece [15], and China [16].

Physical–mathematical models that take into account meteorological data input are also tested and used to monitor risks in other parts of the world, such as New Zealand, where the authors of [17] investigated the wind vector change using a model integrated with the Fire Weather Index (FWI). In China, also using the same FWI model, the authors of [18] combined two machine learning models with the FWI, namely the long short-term memory (LSTM) and random forest (RF) models.

Numerous climate models from the Intergovernmental Panel on Climate Change (IPCC) are being used to show future trends more effectively at the global level through distinct climate change scenarios called Shared Socioeconomic Pathways (SSPs) [1]. A study on climate change in South America using these scenarios predicts that, by 2040, there will be a reduction in rainfall, mainly in the north and northeast of South America, during the months of September, October, and November [19], making the climate drier and these regions most susceptible to forest fires.

In addition to the panel models, there are statistical models used by several researchers who seek to simulate the future of regions in South America that are victims of fires and climate change. These models have been widely used because they minimize the costs of field activities and are run with just a few input variables, such as the autoregressive integrated moving average (ARIMA) [19].

The analysis of time series from sensors installed on orbital platforms makes it possible to evaluate the variation in behavior over time. Therefore, these techniques are widely used for various purposes, including monitoring fire foci [20]. The Moderate-Resolution Imaging Spectroradiometer (MODIS) reference sensor for fire foci has been used in studies with this objective [21].

A better understanding of the relationship between meteorological elements and the degree of fire danger in the state of Acre, which is suffering from the advance of the deforestation arc, is important for a greater understanding of the effects of climate change in the Western Amazon and the maintenance of life. For this reason, the present study had the following objectives:

i. Evaluate the impact of meteorological variables and the ENSO phenomenon on the occurrence of fires;
ii. Identify fire risks for different land uses and covers;
iii. Create a fire risk index for the capital Rio Branco, Acre, Brazil;
iv. Evaluate the behavior of fire risk in different IPCC scenarios;
v. Promote this index as a monitoring tool and an alternative for obtaining new information about fires in the Amazon biome.

MATERIAL AND METHODS

STUDY AREA

Acre has the tropical equatorial (Af) and tropical monsoon (Am) climate types, characterized by high temperatures, high levels of rainfall, and high relative humidity. The average temperatures vary from 24.5 °C to 32 °C for the entire state [22]. The average annual precipitation is around 2166 mm [23]. The months of June to September correspond to the driest period of the year in the state, while the months of January to March correspond to the rainiest period [24].

The state is located in the northern region of Brazil (Figure 1), has 22 municipalities in an area of 164,173 km^2, and an estimated population in 2022 of 830,018 inhabitants [25]. It is located in the Brazilian Amazon rainforest, bordering the state of Amazonas to the north and east and Bolivia and Peru to the south and west [26].

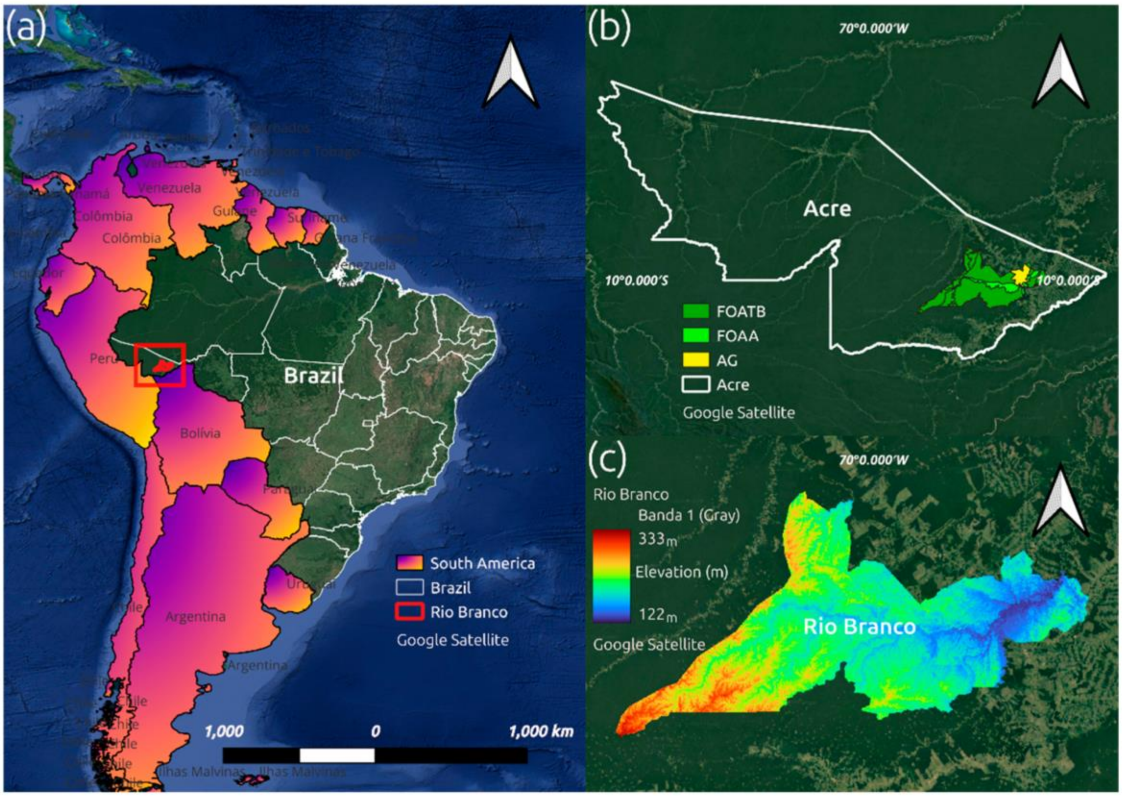

Figure 1. (a) Geographic location of the study with the state and municipality of Rio Branco, Acre, highlighted in red on the left; (b) the state of Acre and the land use and cover used in the municipality of Rio Branco, Acre; (c) digital elevation model of the municipality of Rio Branco, Acre.

OBSERVED METEOROLOGICAL DATA AND FIRE DATA

The observed meteorological data (also called baseline in this article) were validated for the entire Brazilian territory [27]. Reanalysis data are widely used in scientific studies in Brazil that aim to assess climate trends [21,28]. Daily data on maximum and minimum air temperature (Tmax; Tmin; °C), evapotranspiration (ETo; mm day^{-1}), rainfall (pr; mm), wind speed (u2; m s^{-1}), relative air humidity (RH; %) and solar radiation (Rs; MJ m^{-2} day^{-1}) were obtained. The period under study was from 1961 to 2020.

These data were extracted for the municipality of Rio Branco considering three types of land use and cover (Figure 1b), namely agricultural (AG), alluvial open rainforest (FOAA), and lowland dense rainforest (FOATB) [29] according to the RADAMBRASIL project. The extraction was carried out in R Studio version 4.3.1, using the readxl, raster, rgdal, maptools, RSAGA, and ncdf4 libraries. After data extraction, the average air temperature (Tavg; °C) was obtained using the maximum and minimum air temperature values. To generate the maps, the QGIS software version 3.28.10-Firenze was used.

To verify the accuracy of the new fire risk index, monthly fire outbreak data for 2001–2022 were downloaded from the Fire Information for Resource Management System (FIRMS) platform (https://firms.modaps.eosdis.nasa.gov/, accessed on 1 September 2023). The information was for the municipality of Rio Branco considering the three types of land use and cover.

Deforestation and Agricultural Crop Data

Deforestation data of Acre were obtained from 2001 to 2022 using the PRODES project, available at <https://www.dpi.inpe.br/prodesdigital/prodesmunicipal.php/> (accessed on 1 September 2023). The project involves the satellite monitoring of deforestation through clearcutting in the Legal Amazon and, since 1988, has presented annual deforestation rates in the region [30]. According to the PRODES system [30], deforestation by clearcutting is defined as deforestation that results in the complete removal of forest cover in a short period of time. In this process, the forest cover is completely removed and replaced by other covers and uses such as agricultural crops, urban areas, hydroelectric plants, and others, and can also be abandoned and enter a regeneration process. Data were also obtained from areas harvested from temporary crops (Temp; sugarcane, maize, and soybean; hectares) and permanent crops (Perm; banana, coffee, and orange; hectares) in the state for the same period [31].

IPCC Scenarios—SSP2-4.5 and SSP5-8.5 (Future)

For the future analysis of the new fire risk index, the Japanese MIROC6 model was chosen, as it is widely used in other similar studies. Meteorological data were downloaded for scenarios SSP2-4.5 and SSP5-8.5, adopting the period from 2021 to 2041. The SSP2-4.5 scenario is considered intermediate according to the IPCC [1] until mid-century CO^2 concentrations remain around current levels with values above 410 ppm CO2. The very high-emission scenario in IPCC SSP5-8.5 results in the estimation that, by 2050 and 2100, CO^2 concentrations will be doubled compared to current levels [1].

Daily data (future) were obtained for the maximum and minimum air temperature (°C), wind speed (m s^{-1}), and rainfall (mm). These data were derived from the sixth phase of a project called the Coupled Model Intercomparison Project (CMIP6) [32].

The model in question does not include the relative air humidity (%) at 13:00, a component of the equation for the new fire risk index to be proposed. The estimation of this variable was made according to the work methodology in the Itatiaia National Park, in the Atlantic Forest [13]. The model data were also extracted for the three types of land use and cover, in the same way as the reanalysis data.

FIRE RISK INDEX AND ENSO EVENTS

To estimate the fire risk for the city of Rio Branco, a modified Monte Alegre Formula was used, a methodology also adopted in the study conducted in the Itatiaia National Park [13]. Daily data on the relative air humidity at 13:00 (RH 13h; %), rainfall (mm), and wind speed (m s^{-1}) from 1961 to 2020 were used. The calculation was performed using the SISCLASS spreadsheet developed by [12] and was also performed for AG, FOAA, and FOATB.

The data were classified by ENSO events. The years from 1961 to 2020 were classified as neutral (NE), weak El Niño (WE), moderate El Niño (ME), strong El Niño (SE), very strong El Niño (VSE), weak La Niña (WL), moderate La Niña (ML), and strong La Niña (SL). This classification (Table 1) was based on data available at <https://www.webberweather.com/ensemble-oceanic-nino-index.html/> (accessed on 1 September 2023) to verify the behavior of these variables and the fire risk per event.

Table 1. Classification of baseline years by ENSO events.

YEARS	ENSO EVENT	YEARS	ENSO EVENT	YEARS	ENSO EVENT
1961	NE	1981	NE	2001	NE
1962	NE	1982	VSE	2002	ME
1963	ME	1983	WL	2003	NE
1964	WL	1984	ML	2004	WE
1965	SE	1985	NE	2005	WL
1966	NE	1986	ME	2006	WE
1967	NE	1987	SE	2007	SL
1968	ME	1988	SL	2008	WL
1969	WE	1989	WL	2009	SE
1970	ML	1990	NE	2010	SL
1971	WL	1991	SE	2011	ML
1972	VSE	1992	NE	2012	NE
1973	SL	1993	NE	2013	NE
1974	WL	1994	ME	2014	WE

1975	ML	1995	WL	2015	VSE
1976	ME	1996	NE	2016	WL
1977	ME	1997	VSE	2017	WL
1978	WL	1998	ML	2018	WE
1979	WE	1999	SL	2019	WE
1980	NE	2000	WL	2020	ML

REGRESSION MODEL AND STATISTICAL ANALYSIS OF FIRERBR

For the new fire risk model for the capital of Acre, a multiple regression analysis was carried out, considering the following independent variables: relative air humidity at 13:00 (%), rainfall (mm), and wind speed (m s^{-1}). The dependent variable (Yi) was the FMA+ value calculated from the independent variables (Xi, i = 1, 2, …, k). The equation of the new model was based on the equation used for calculating the Fire Risk Atlantic Forest (FIAF) Index [13]. Called the Rio Branco Fire Index (FIRERBR), the statistical regression model is given as follows:

$$YFIRERBR = 13{,}33046 + (-0{,}13753 \times RH\ 13h) + (-5{,}43237 \times u2) \quad (1)$$

The new model was presented for statistical analysis, presenting a coefficient of determination (R2) of 0.70 and a standard error of estimation (SEE) of 22.08 (Figure 2).

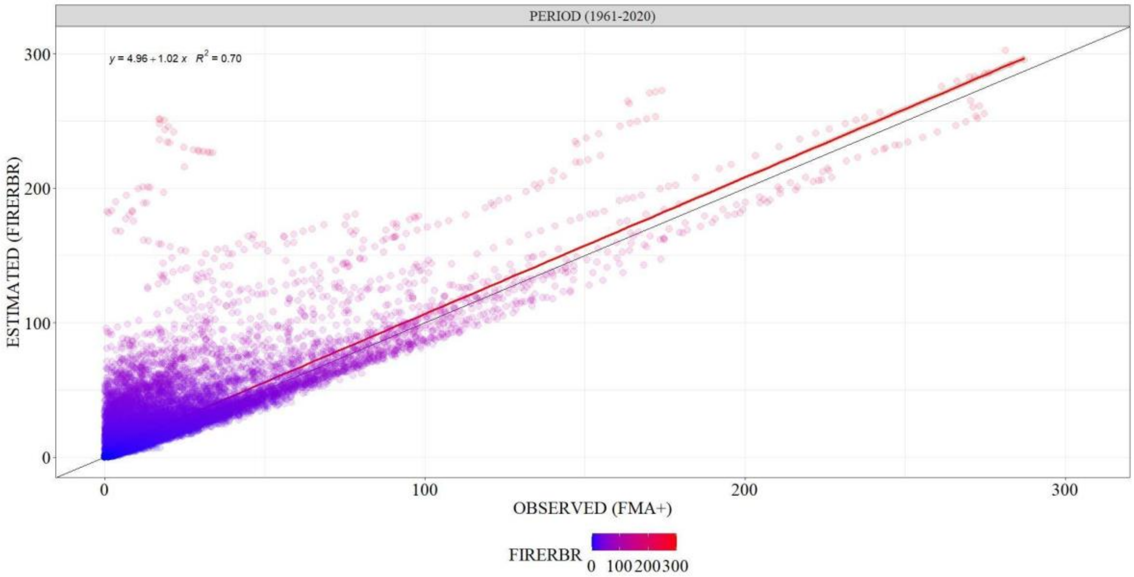

Figure 2. Regression analysis of observed data using the FMA+ model (Eugenio) vs. data estimated with FIRERBR.

Statistical analysis

For trend analysis, the Mann–Kendall [33,34] test (Equation (2)) was applied to the observed meteorological data (baseline), fire foci data, and deforestation and agricultural crop data. The test was applied in R Studio version 4.3.1, using the Kendall library.

$Zmk = S - 1/\sqrt{Var\ S}$, when S > 0, (2)

$Zmk = 0$, when S = 0,

$Zmk = S + 1/\sqrt{Var\ S}$, when S < 0.

Where Z_{mk} is the Z index of the Mann–Kendall test, S is the "score" statistic, and Var (S) is the variance of the statistical value S. The presence of a statistically significant trend was evaluated according to the Z index of the test, with positive values indicating an increasing trend and negative values indicating a decreasing trend.

The Pettitt [35] test was applied to fire foci data, with the aim of identifying the main significant changes during the time series used, based on the main inflection of the extreme years. With this information, the kernel density for the area was determined. The test was applied in R Studio version 4.3.1, using the trend library.

The average fire risk values for each of the ENSO events were compared according to the type of land use and land cover. In this way, the average fire risk for the neutral event years in AG was compared with the same average in FOAA and the same average in FOATB. This process was carried out for the other seven events, resulting in an analysis of the fire risk frequency for each of the events, taking the use with the highest average as a reference.

Spearman's correlation coefficient was determined using data on evapotranspiration (mm day^{-1}), rainfall (mm), the relative air humidity (%), solar radiation (MJ m^{-2} day^{-1}), the average air temperature (°C), wind speed (m s^{-1}), fire foci (number), deforestation (hectares), and temporary (hectares) and permanent (hectares) agricultural crops. For the correlation, data from 2001 to 2020 were used.

Results

Fire foci

The behavior of fire foci in Rio Branco from 2001 to 2022 can be seen in Figure 3. The year 2005 presented many fire foci, concentrated in the months of August and September (dry season) and in the lowland dense rainforest. Another year that stood out was 2022, presenting more than 900 fire foci in the month of September alone, in the same vegetation. The other years in the time series presented monthly values below 900.

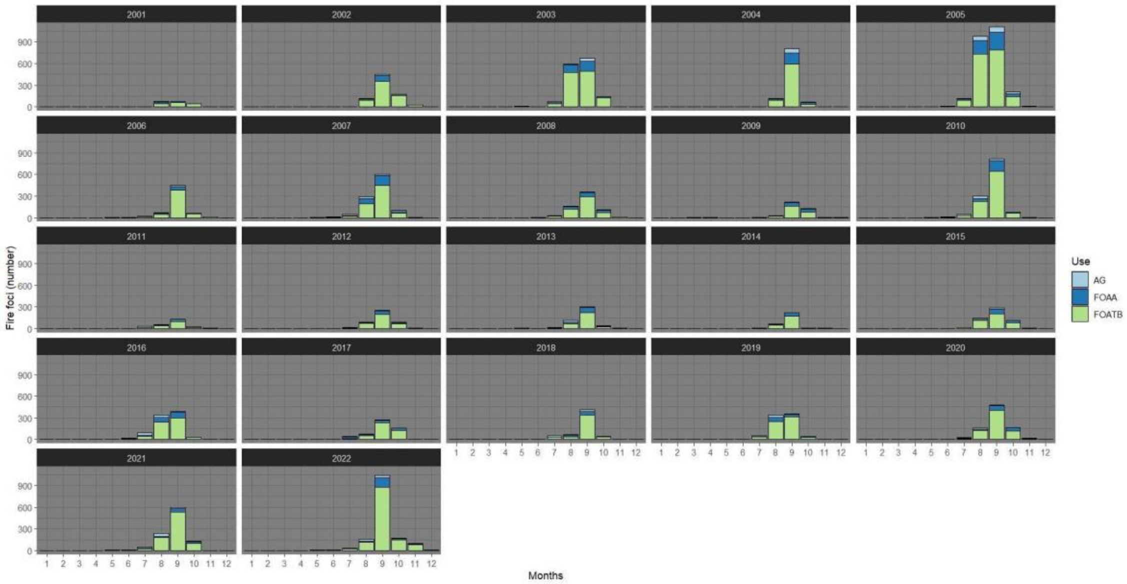

Figure 3. Annual temporal analysis of fire foci for different types of land use and cover (2001–2022), for Rio Branco, Acre, Brazil. AG = agriculture; FOAA = alluvial open rainforest; FOATB = lowland dense rainforest.

Through the analysis presented in Figure 4, it is possible to verify the density of these fire foci over the analyzed months for the three types of land use and cover considered in this study. Agriculture presented values close to 60 fire foci in the month of September. The alluvial open rainforest, in turn, presented values close to 250 in the same month. This month was also the one with the highest concentration in the lowland dense rainforest, with values reaching 750 foci. The pattern of concentration of outbreaks in the months corresponding to the dry season remained the same for the three land uses.

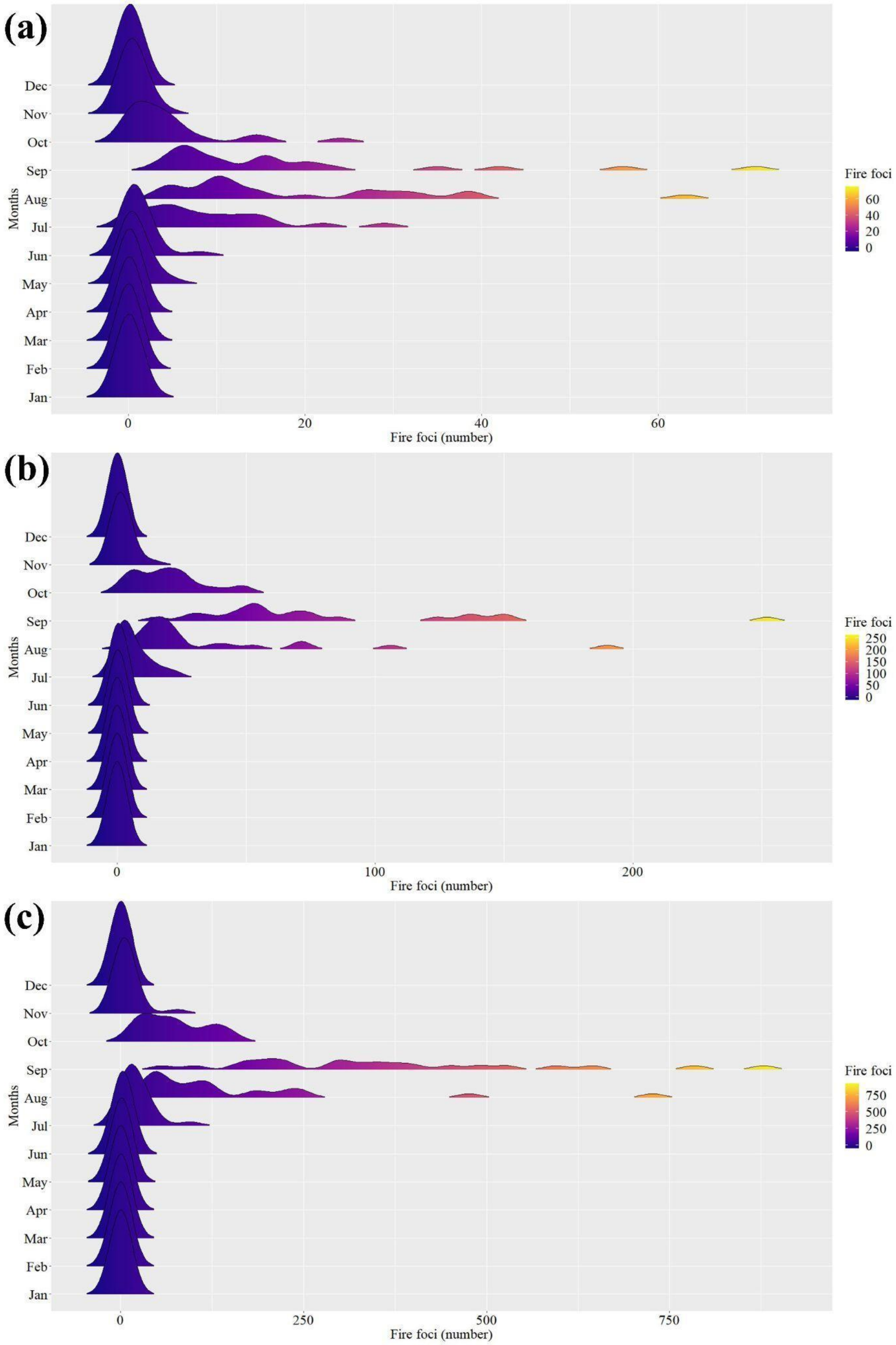

Figure 4. Annual temporal analysis of fire foci for different types of land use and cover (2001–2022), for Rio Branco, Acre, Brazil. AG = agriculture; FOAA = alluvial open rainforest; FOATB = lowland dense rainforest.

The kernel density for fire foci in the municipality of Rio Branco is presented in Figure 5, showing a higher concentration during the dry season than in the rainy season. It was possible to observe a distribution closer to the center of the capital of these foci in both periods.

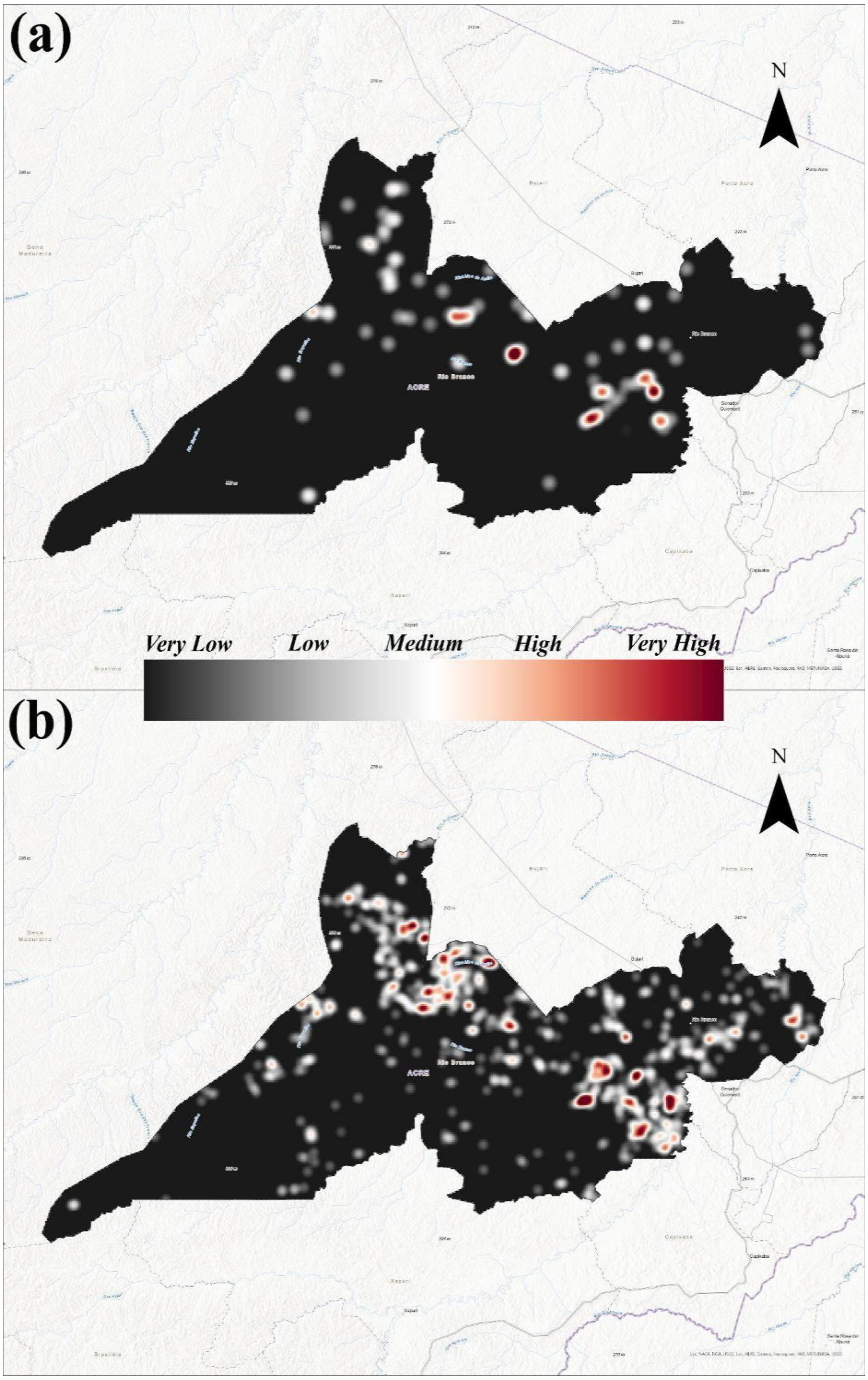

Figure 5. Kernel density for the year 2007, using the Pettit test, in Rio Branco, Acre, Brazil: (a) rainy season; (b) dry season.

DEFORESTATION AND AGRICULTURAL CROPS

During the time series analyzed, the years 2003, 2022, and 2002 ranked as the top three years with the largest deforested areas in Acre, as shown in Figure 6. The behavior of permanent crops evaluated during the period did not show much variation, with banana being the crop that presented higher harvested area values, exceeding 5000 hectares in 2022. On the other hand, regarding temporary crops, the harvested area of soybeans increased in the last five years of the series (2018, 2019, 2020, 2021, and 2022), jumping from 480 to 6570. The maize crop, which had dropped to the level of 30,000 hectares harvested in 2018, increased again, with more than 40,000 hectares of maize harvest recorded in 2022.

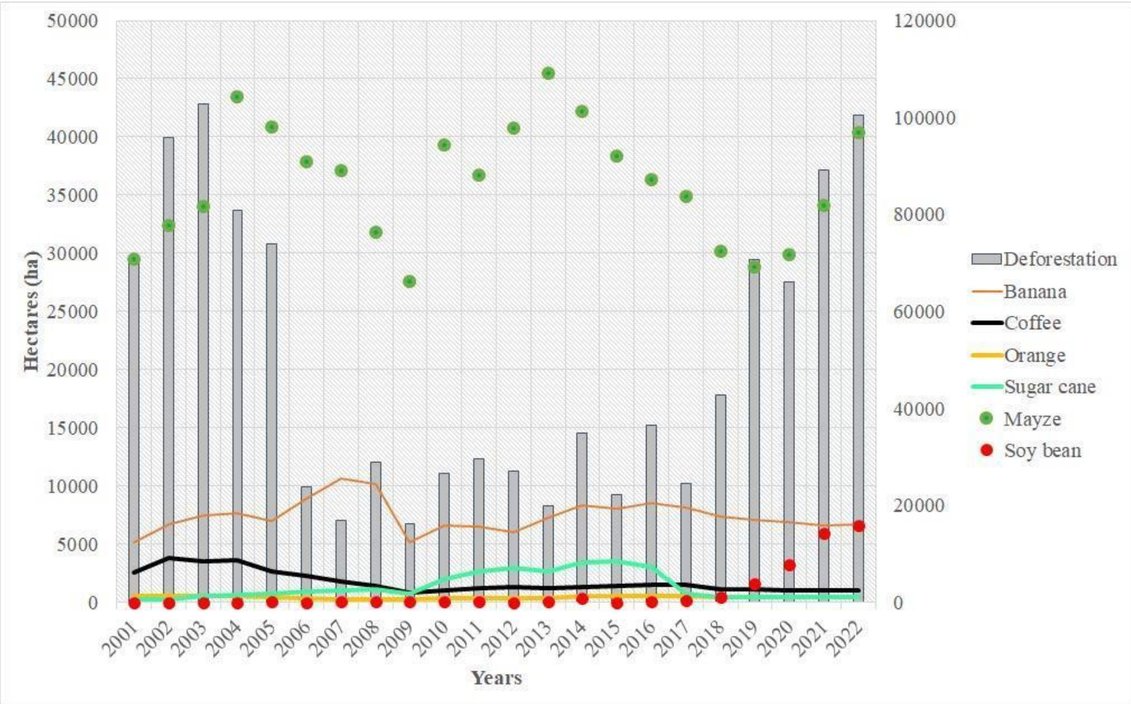

Figure 6. Deforestation and harvested area of agricultural crops in Acre, Brazil.

FIRERBR AND FUTURE

The fire risk for Rio Branco during the period from 1961 to 2020 can be seen in Figure 7, which shows the months with the highest concentration using the new proposed FIRERBR model. The analysis shows a higher concentration of risk in the months of June, July, and August, a period corresponding to drought, with many fire foci. In the other months, most of which correspond to the rainy season, the concentration was low.

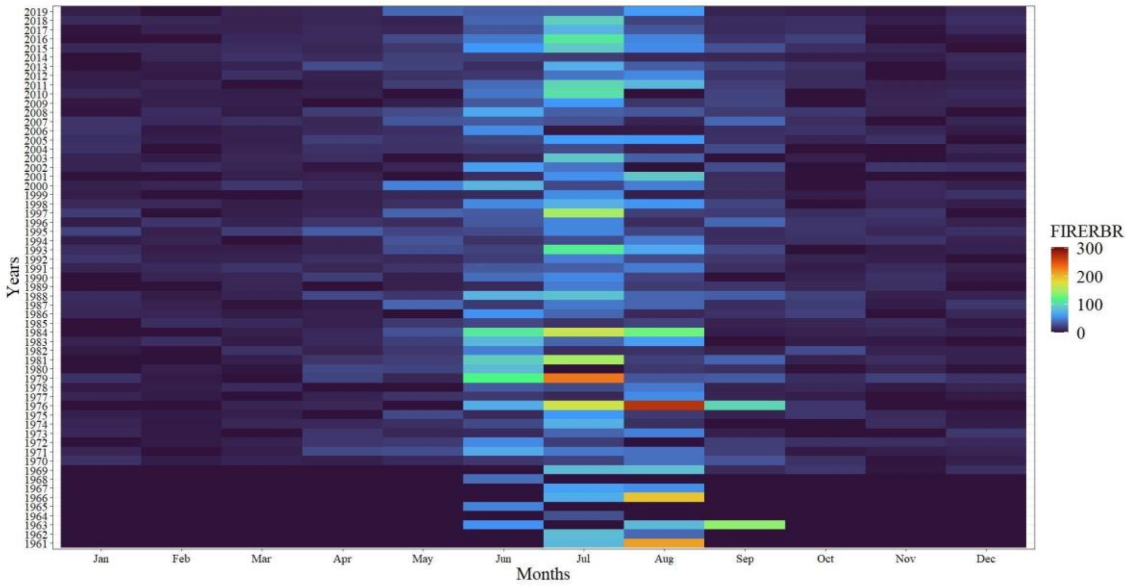

Figure 7. Monthly temporal analysis of FIRERBR (1961–2020) in Rio Branco, Acre, Brazil.

The FIRERBR model can also be observed in Figure 8, which shows the behavior of the new proposed model in different ENSO events from 1961 to 2020, always considering the type of land use and coverage that presented the highest average index values as the reference. Thus, the AG use was the one that stood out the most, which was found to be related to strong El Niño (SE), strong La Niña (SL), very strong El Niño (VSE), weak El Niño (WE), weak La Niña (WL) and moderate La Niña (ML).

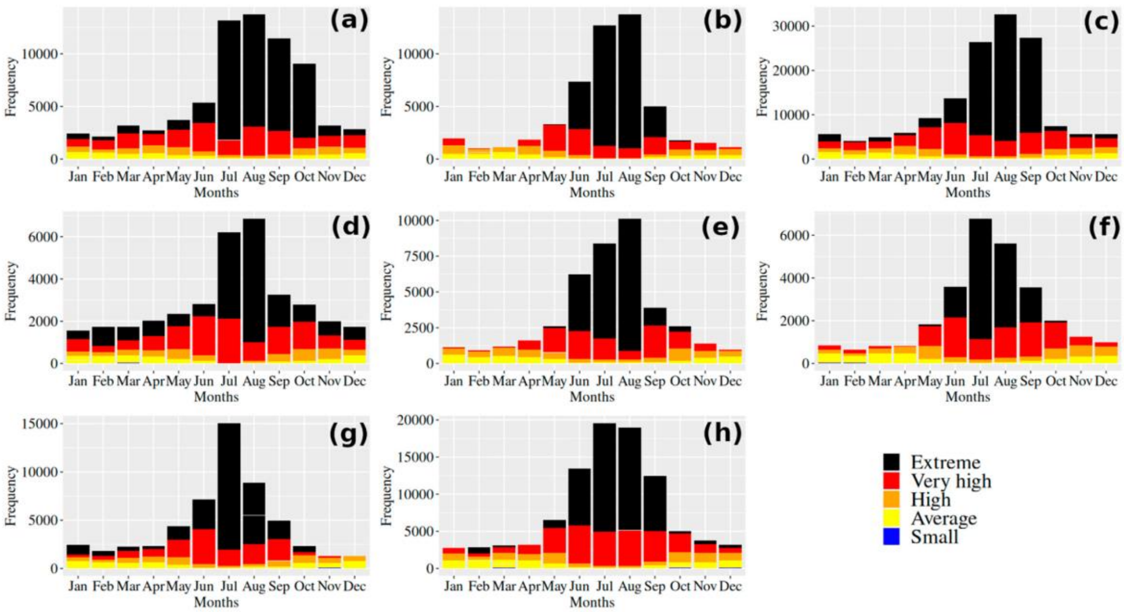

Figure 8. FIRERBR degree of danger for different ENSO events across land use and cover types: (a) moderate El Niño; (b) moderate La Niña; (c) neutral; (d) strong El Niño; (e) strong La Niña; (f) very strong El Niño; (g) weak El Niño; (h) weak La Niña.

In all the events evaluated, the degree of extreme danger was most present in the months of July, August, and September (dry season). In the other months, the model presented lower rates, meaning a lower degree of danger.

In the SL and ML events, both related to AG, none of the months of the rainy season, presented a degree of extreme danger, except for October. In contrast to this behavior, in the SE event, also related to AG, all months of the year presented this degree of danger, regardless of the intensity.

A monthly analysis of the FIRERBR input variables in different ENSO events can be seen in Figure 9. Rainfall presented a pattern of behavior across the analyzed events, with June, July, August, and September (dry season) determined as the months with the lowest values. Likewise, the relative air humidity at 13:00 presented the lowest values in this season, with emphasis on the months of June, August, and September. The wind speed presented a similar distribution of values over the months.

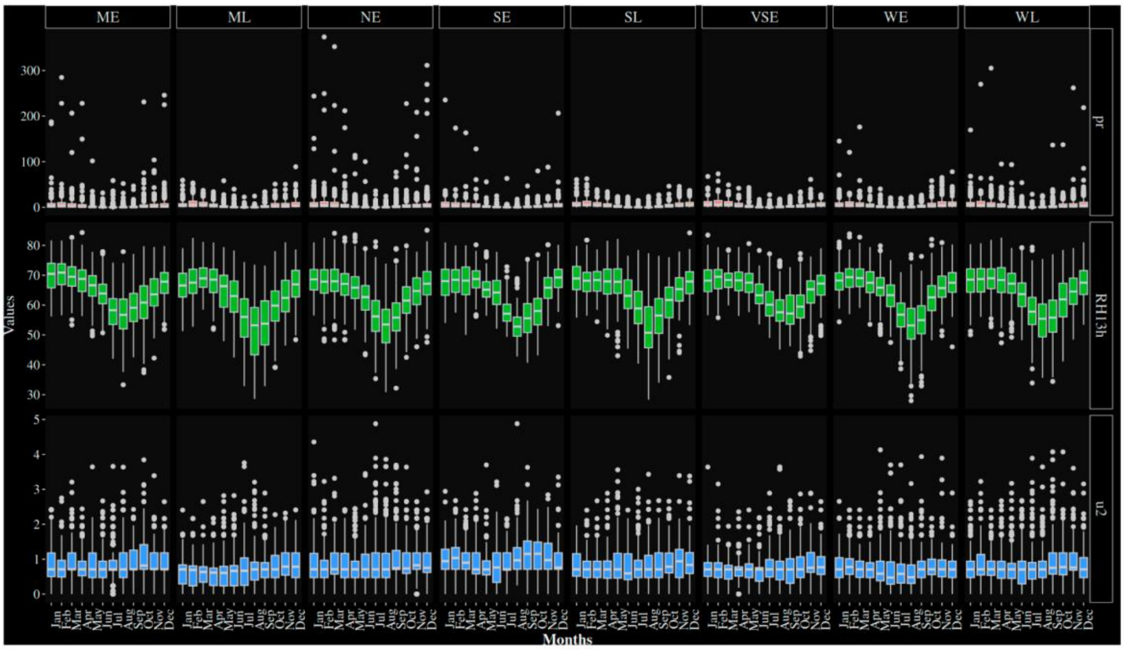

Figure 9. Monthly temporal analysis of variables associated with the FIRERBR (1961–2020), for different ENSO events in Rio Branco, Acre, Brazil.

In Figure 10, it is possible to see a comparison between these same variables in the two IPCC scenarios considering the three types of land use and cover analyzed. In

AG, all variables presented lower values in the SSP5-8.5 scenario than in the SSP2-4.5 scenario. The variable that showed the greatest reduction was the relative air humidity. In FOAA and FOATB, lower values were also observed in the SSP5-8.5 scenario, but no variable showed a discrepancy.

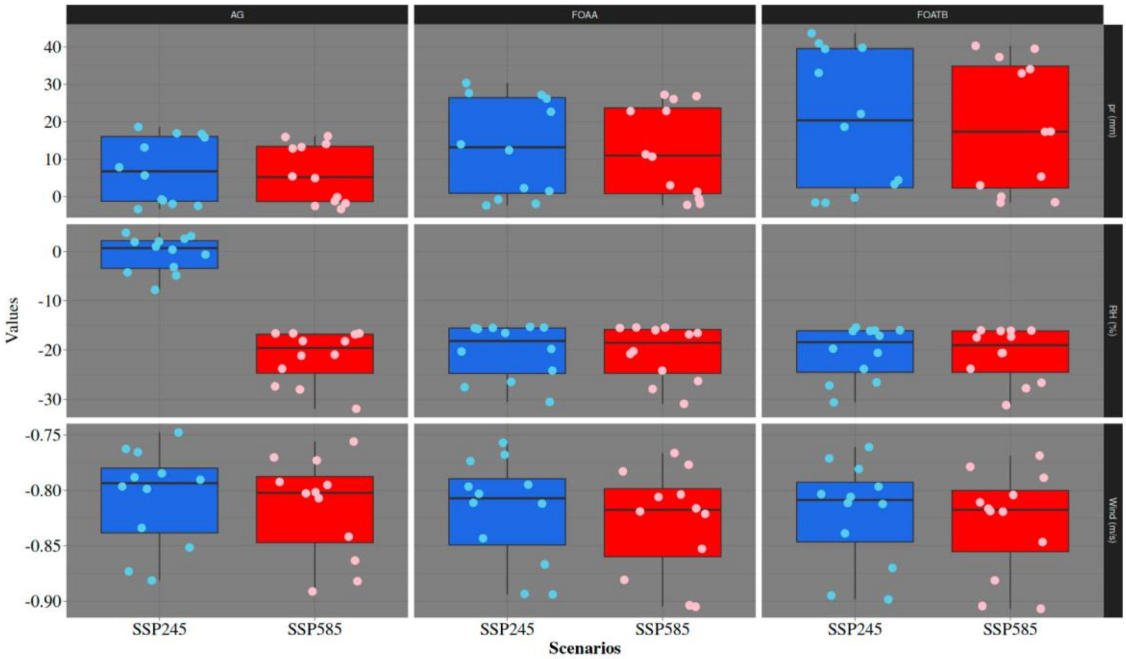

Figure 10. Comparison of fire risk index variables between different IPCC scenarios, by different types of land cover in Rio Branco, Acre, Brazil: blue = SSP2-4.5 scenario; red = SSP5-8.5 scenario.

The FIRERBR in the period from 1961 to 2020 (baseline) and the IPCC scenarios (future) relative to the types of land use and cover can be seen in Figure 11. Our results show that the fire risk in the future (scenario SSP2-4.5 and scenario SSP5-8.5) will be higher, increasing from values close to 50 to values close to or greater than 100 in all uses.

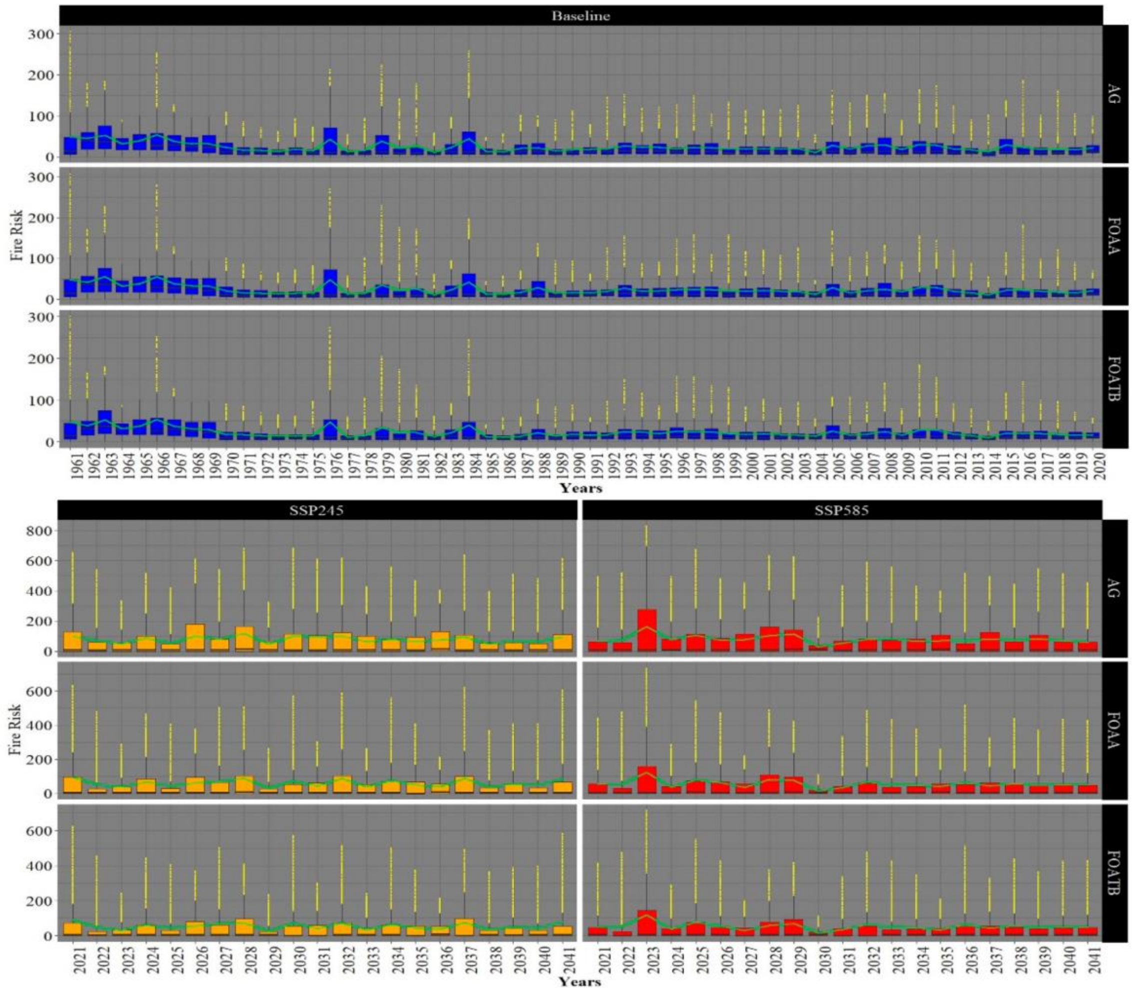

Figure 11. Comparison of fire risk between the baseline and different IPCC scenarios relative to different types of use and land cover in Rio Branco, Acre, Brazil.

In the SSP5-8.5 scenario, AG was the use that presented the highest fire risk, registering an index close to 300 in 2023. This year also registered a high index in FOAA and FOATB uses. In the SSP2-4.5 scenario, AG also presented a higher risk, recording an index close to 200 in 2026.

STATISTICAL ANALYSIS

The result of the Mann–Kendall test for the observed meteorological data (baseline) can be seen in Table 2, with a significance interval of 5% and 10%. The relative air humidity showed significant decreasing trends in almost all months, while solar radiation showed a significant increasing trend only in April. The analysis of the other input data of the fire risk model revealed that rainfall exhibited the greatest reduction in December (rainy season), and wind speed exhibited the greatest reduction in May (dry season).

Table 2. Z index (Zmk) of the Mann-Kendall test for the observed data (baseline) in Rio Branco, Acre, Brazil.

MONTHS	ETO	PR	RH	RS	TMAX	TMIN	TAVG	U2
JANUARY	*	*	-2.61	*	*	*	*	*
FEBRUARY	*	-1.84	-2.33	*	*	*	*	*
MARCH	1.74	*	-2.72	*	1.70	*	*	-2.60
APRIL	3.06	*	-3.20	1.80	2.25	*	*	-3.25
MAY	*	*	-2.26	*	*	2.26	2.39	-3.34
JUNE	*	*	*	*	*	2.02	2.34	*
JULY	-1.67	*	*	*	2.16	2.62	1.83	*
AUGUST	*	2.91	-3.03	*	3.14	2.42	*	-2.95
SEPTEMBER	*	*	-3.48	*	*	*	3.55	-2.44
OCTOBER	*	*	-3.41	*	3.11	*	*	-1.69
NOVEMBER	*	*	-3.27	*	3.03	*	*	*
DECEMBER	*	-2.20	-3.73	*	*	*	*	*

*NOT SIGNIFICANT.

The results of the Mann–Kendall test for deforestation and agricultural crop data, soybean crops had the highest Z index (4.43), showing an increasing trend in the region. Deforestation had a Z index of 0.45, also indicating an increase.

For fire foci data, the Z index was higher for FOAA with 2.42, showing an increasing trend in this type of forest. FOATB was found to have a Z index of 2.2, and AG had a Z index of 1.87 (Figure 12).

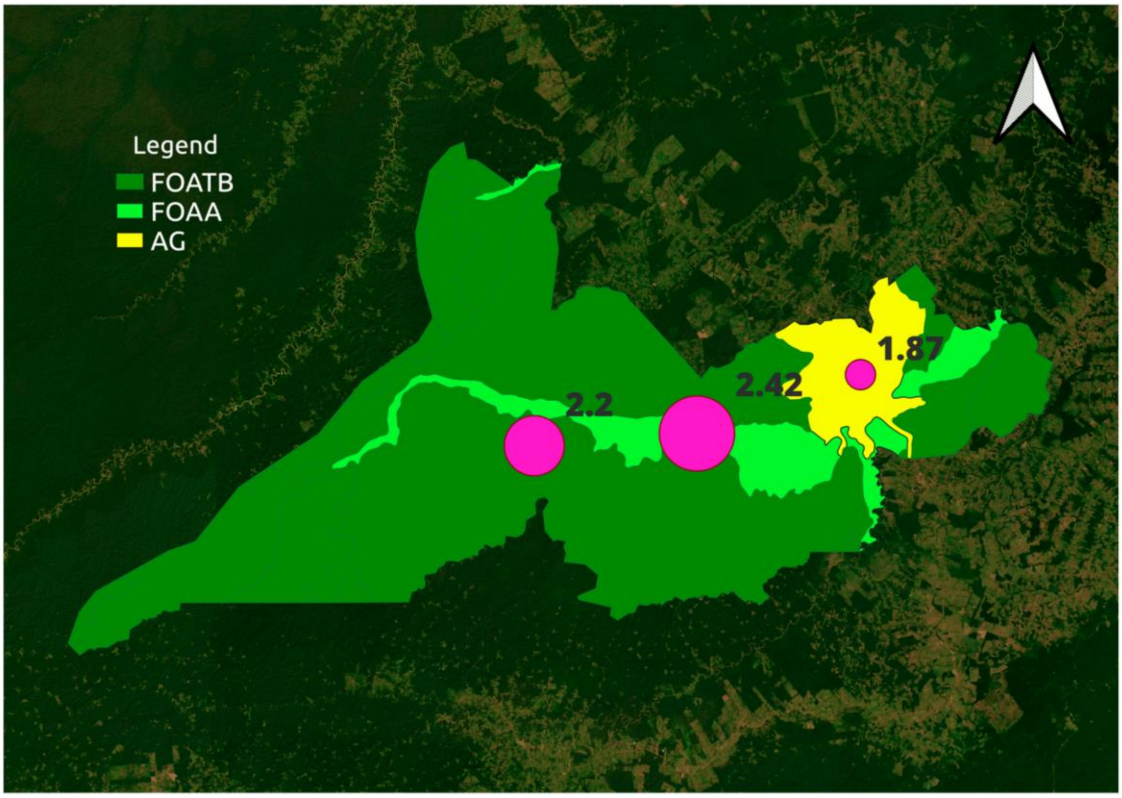

Figure 12. Z index (Z_{mk}) of the Mann–Kendall test for fire foci by different types of land use and land cover in Rio Branco, Acre, Brazil.

The results of the Spearman correlation can be seen in Figure 13, which shows the power of the relationships and their direction. Regarding rainfall, stronger relationships were found with evapotranspiration (−0.99), solar radiation (−0.93), and temporary crops (−0.71). These values show that an increase in rainfall is associated with a reduction in other variables, with the opposite also being true. Wind speed showed a moderate relationship with the average temperature of −0.54, indicating that the increase in the average temperature negatively affects wind speed.

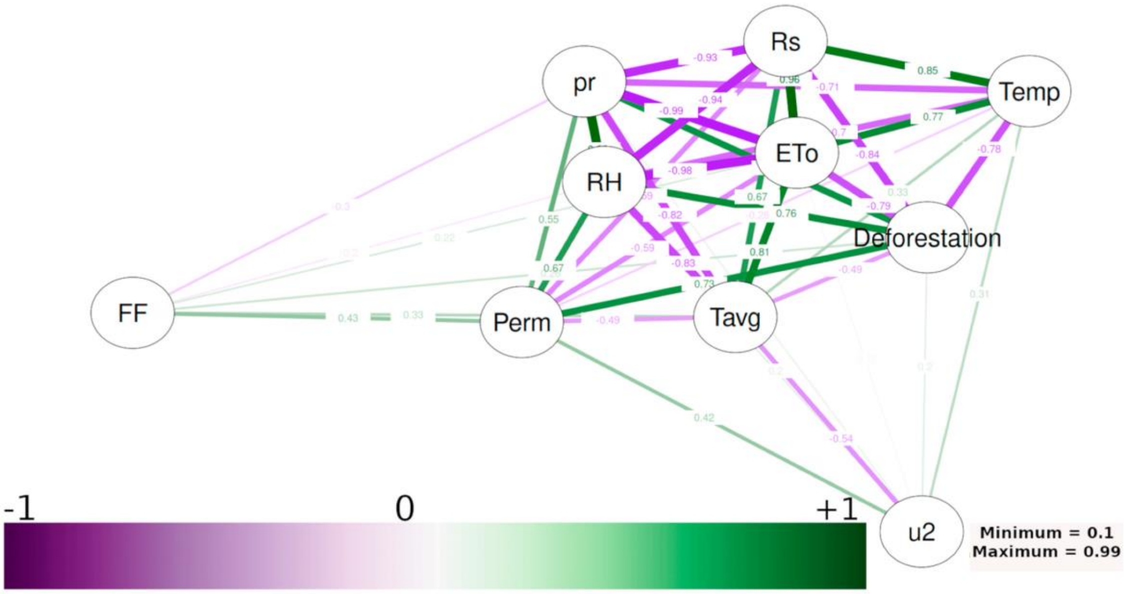

Figure 13. Spearman correlation analysis. FF = Fire foci (number); pr = Rainfall (mm); RH = Relative air humidity (%); Perm = Permanent crops (hectares); Temp = Temporary crops (hectares); RS = Solar radiation (MJ m^{-2} day^{-1}); ETo = Reference evapotranspiration (mm day^{-1}); Tavg = Average air temperature (°C); Deforestation (hectares); u2 = Wind speed (m s^{-1}).

DISCUSSION

FOREST FIRES AND ANTHROPIC ADVANCE IN THE WESTERN AMAZON

The fire foci found in Rio Branco were concentrated in September, during the dry season, a result similar to that observed in similar studies carried out in the same region [23,26,36]. The results also showed that the land use most susceptible to fire was the lowland dense ombrophilous forest, a result similar to that found by [23]. Our results showed a high number of fire foci in September 2022, a behavior that was also observed for the Brazilian Amazon in a study that identified more than 74,000 active fires in the period of August and September of the same year, characterizing it as the year with the highest number of fires since 2010. The study also highlighted that 62% of fires occurred in deforested areas [37].

The kernel density is a methodology that provides greater reliability for analyzing fire behavior, as it transforms fire foci (points) into surface data [38]. In this aspect, our results showed a higher concentration of fire foci in Rio Branco during the dry season, following the pattern found by other studies [23,36,37].

The greater susceptibility of FOATB to fire found in our study, especially in the dry season, may be associated with the effects of climate change on forests, considering that a drier climate, with low humidity in the soil and vegetation, and a warmer climate constitute a favorable scenario for burning and spreading fire, increasing the likelihood of fires [39]. According to a report from the World Meteorological Organization (WMO), 2022 was one of the eight hottest years on record [40], which may have influenced the high value found in our study for September of that same year.

Our results showed an increase in deforestation and temporary crops, mainly maize and soybeans. According to the Institute of Economic Research (IPEA) [41], the advance in grain planting, mainly maize and soybeans, consolidates Acre as a new and promising agricultural frontier in the country. The institute reports that harvests of these crops are currently the highest in the last 30 years, which reinforces the results of our study.

Although the increase in deforestation recorded for the year 2022 was not statistically significant in this study, monitoring is necessary, given the increase in the production of the aforementioned agricultural crops in the Acre territory. Soybean farming alone grew 7000% between 2012 and 2022 [41]. Monitoring is also necessary due to the extensive livestock farming that is also advancing in the state, which requires the incorporation of new land for production and has converted forest into pasture [42].

FIRERBR for baseline and the future in the Western Amazon

Our FIRERBR model, based on the FIAF model, showed good results with meteorological data from Rio Branco. The FIAF model can be applied in regions with conditions similar to the Atlantic Forest, which is characterized by a large volume of rain during the rainy season and little precipitation during the dry season [13].

FIRERBR, using baseline data, indicated a greater risk of fire when associated with AG. However, the new model did not show major differences when using ENSO events to compare the degree of danger, which, according to [23], are important events for understanding the occurrence of fires in the state. This may indicate that the risk of fire in the region is not directly associated with ENSO events, as also found in a similar study [23] with fire foci in Acre.

Analyzing the variables used in the new model in future scenarios, it is possible to notice a reduction in all of them, associated with AG, indicating an influence of crop cultivation. A study conducted in South America using the SSP5-8.5 scenario also found a significant reduction in rainfall (−110 mm) in the north and northeast, during the months of September, October, and November [19]. An environment with low humidity and precipitation conditions facilitates the spread of fire. Therefore, arboreal individuals inserted in this context are more exposed to fires, normally caused by the management of the area before agricultural activities [43].

In the SSP2-4.5 scenario, our study showed a higher fire risk in the year 2026, associated with AG use. A similar study carried out in the Atlantic Forest using another fire risk model and the same scenario concluded that the rainy season will undergo more extreme fire conditions from the same year onward [13], indicating a greater distribution of fire over several months and no longer concentrated in the dry season. For the SSP5-8.5 scenario, our model showed that 2023 was the year with the highest fire risk in all uses, showing the effectiveness of the new index in practice. According to the WMO, the year 2023 is considered the hottest in 174 years of meteorological measurements. In Brazil, the year also stands out as being the hottest since the 1960s [44].

The projections of our study indicate that new fire events will likely occur in the coming years in the region, especially for the year 2026. The effects of these events can include the intensification of various economic, environmental, and mainly social impacts, making the population more vulnerable [45]. Our results are an important contribution, as they generate knowledge about the relationship between climate change and fire risk and land use and cover in the westernmost state of the Amazon.

CONCLUSIONS

The FIRERBR model that was developed in this work showed that, in the future, Acre may be subject to fires mainly in regions targeted by agricultural activities. Years like 2028 and 2029 could witness great fire activity, according to projections in an intermediate climate change scenario.

Given the advancement in the deforestation arc and the reduction in rainfall and the relative air humidity in the region, our study highlights the potential of the new model to combat possible fire events not only in the municipality of Rio Branco but also in other regions of the Western Amazon that are close to each other and have similar climatic characteristics.

Furthermore, it is important to highlight that the preservation of these areas and monitoring them with the proposal of a new fire model can serve as an aid to civil defense and contribute to not only short- and long-term actions for decision makers but also global actions to reduce greenhouse gas emissions.

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CHAPTER II - ARTICLE II

RAINFALL DYNAMICS IN THE ACRE RIVER BASIN AND ANDEAN SNOW COVER: CLIMATE INTERACTIONS IN WESTERN AMAZONIA

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ABSTRACT

The state of Acre, located in the Western Amazon, has been more intensely affected in recent years by extreme weather events, especially those of a hydrological nature. These are rainy seasons with major floods and record water levels and, later in the same year, severe droughts that last for more months than normal for the dry season. In this sense, remote sensing acts as an important tool for monitoring the meteorological variables involved in this dynamic and for predicting future climate trends. Our research used data on rainfall (1982-2023), air temperature (2001-2020), fire foci, vegetation and snow cover (2001-2023) for these purposes. The MOD10CM product was used to quantify snow cover in an area close to the state, connected to one of the main river basins in Acre. The results showed an increase in the amount of rainfall for the month of February and a reduction in the amount for months of the dry season, as well as an extension of the same. A reduction in the percentage of snow cover was also observed in the region, which may have a direct impact on water availability for several populations, including Rio Branco. The Mann-Kendall test reinforced this reduction, with a Z index of -1.98 for the month of June. The Principal Component Analysis (PCA) indicated a strong relationship between the variables rainfall and minimum temperature. Between rainfall and minimum temperature, this relationship was negative, showing that the higher the minimum temperature, the lower the amount of rainfall in the region. On the other hand, the same analysis showed a strong relationship between the variables fire outbreaks and maximum temperature. This strong relationship was positive, showing that the higher the maximum temperature, the greater the number of fire foci. The level of statistical significance (p-value) adopted for the data was up to 0.10.

KEYWORDS: water; CHIRPS; Andes; Acre River; influence.

INTRODUCTION

The world has suffered more frequently from extreme weather events, affecting humans in terms of food, economy, culture and health [1]. In the Amazon, these events are usually major floods and droughts [2].

The state of Acre, located in the Brazilian Amazon, is one of the states most affected by extreme weather events. Until 2004, there were records of one extreme event per year in Acre's municipalities, on average. After 2010, two or more events were frequently identified in the same year and in the same municipality, showing the difficulty of regenerating the environment [3].

A notable episode of this change in pattern occurred in 2015, when the state capital (Rio Branco) suffered its largest flood in history, with estimated damages of up to 200 million US dollars. That year, the Acre River remained above flood level for 32 consecutive days and reached 18.4 m in depth [4].

An analysis of the hydrological behavior in the municipality of Rio Branco showed that in the last decade there was a greater concentration of flows with values above the average for the period from 1968 to 2017 [5]. The authors of this study emphasize that this behavior may be related to changes in the hydrological conditions of the river basin in question, or of adjacent regions. Several global climate models indicate more rain in the western part of the Amazon, resulting in flooding [6].

Given this scenario, studying the hydrological behavior of the region becomes essential, especially rainfall. According to [7], rainfall is the primary element of the hydrological system, being the starting point for several other processes that impact human activities since the first civilizations. Given its importance, the need to quantify and predict its occurrences has become essential for human development [8].

The Climate Hazards Infrared Precipitation with Stations (CHIRPS) dataset provides combined satellite precipitation estimates covering most global land regions. This dataset can be used in conjunction with land surface models to make effective drought predictions or to analyze recent changes in decadal precipitation in data-sparse regions [9]. Several studies carried out in different parts of the world, such as the Philippines [10], Turkey [11], Argentina [12] and Colombia [13], validate this data set as an accurate way of estimating rainfall, highlighting that this estimate is conditioned by the geographic and climatic characteristics of the region of interest.

In addition to precipitation, it is important to check the vegetation cover status of the region, since part of the rainfall is intercepted by vegetation and is retained above the soil surface [14]. In a study conducted by [15] in the Alto Juruá river basin, located in Acre, it was observed that interception has a strong relationship with vegetation cover. It was found that the replacement of forest cover by urbanized areas increased the annual rainwater that reaches the soil of the hydrographic basin by more than 1,000 $m^3 h^{-1}$.

Finally, given Acre's proximity to the Peru portion of the Andes Mountains, it is important to check the snow cover situation in this region, given that it can directly impact the Acre River basin. A study on all areas with frozen water on Earth estimated a shrinkage of approximately 87,000 km^2 per year on average between 1979 and 2016, as a result of climate change [16]. Records from sensors show an accelerated decrease in the Andean cryosphere [17], but most studies focus on latitudes above 10º S of the Cordillera [18, 19]. Therefore, a study aimed at discovering whether snow near the Amazon region is following global behavior and the influence of climate variables in this process becomes pertinent.

In this sense, the MODIS sensor offers products that assist in this monitoring, such as the MOD10CM, which provides the percentage of snow cover in the region of interest [20]. Therefore, the objective of this work was to investigate the behavior of rainfall and other climate variables along the Acre River basin and to verify whether the behavior of Andean snow has an influence on the region, through remote sensing tools.

MATERIAL AND METHODS

STUDY AREA

The study area included 3 different river basins, namely: Acre River basin, Purus basin and Ucayali basin. Figure 1 shows the study area as a whole.

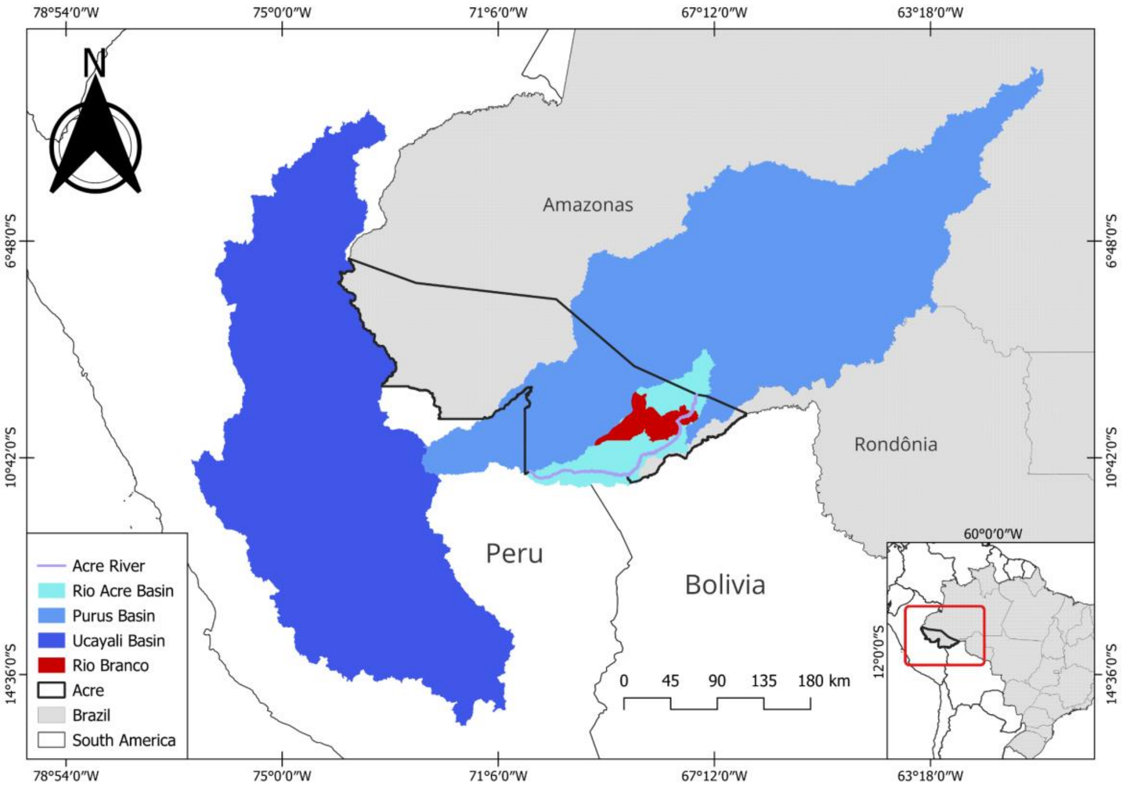

Figure 1. Geographic location of the study area as a whole, showing the Acre River basin, the Purus basin and the Ucayali basin.

The Acre River basin covers an area of approximately 35,000 km^2, with 23,000 km^2 located upstream of Rio Branco, the state capital. Several cities occupy the banks of the Acre River, which originates in Peru and has its mouth in the city of Boca do Acre, in the state of Amazonas [21]. According to [22], the Acre River is a source of capture for the water supply of both the capital Rio Branco and other municipalities. The basin in question is inserted within a larger basin (the Purus basin), according to the classification level adopted by NWA [23].

The Purus Basin covers approximately 368,000 km^2 and is distributed across the territories of Peru and Brazil, with more than 90% of its extension located in the states of Acre and Amazonas. The tributaries of the Purus River originate in central areas of tropical forests (in the Departments of Ucayali and Madre de Dios, in Peru) and have black or clear waters [24]. The Purus Basin is classified in the group of basins that are still in a high state of conservation in the Brazilian Amazon. However, in recent years, livestock farming, the advance of the agricultural frontier mainly for soybean production and associated deforestation have constituted a threat to aquatic ecosystems [25].

The Ucayali River basin is approximately 350,000 km^2 and is located entirely in Peru, with more than 90% of its area concentrated in Loreto, Ucayali and Cuzco. The Ucayali River stretches for approximately 2,670 km, starting in the Andes Mountains and joining the Marañón River to form the Amazon River [26].

The three basins were used as study areas, depending on the data to be processed. For data on rainfall, elevation, air temperature, fire foci and Enhanced Vegetation Index, the study area was the Acre River basin. For data on snow cover, the study area was an area covering part of the Purus basin and the entire Ucayali basin. The discrimination of the study area for each of the variables can be seen in Figure 2.

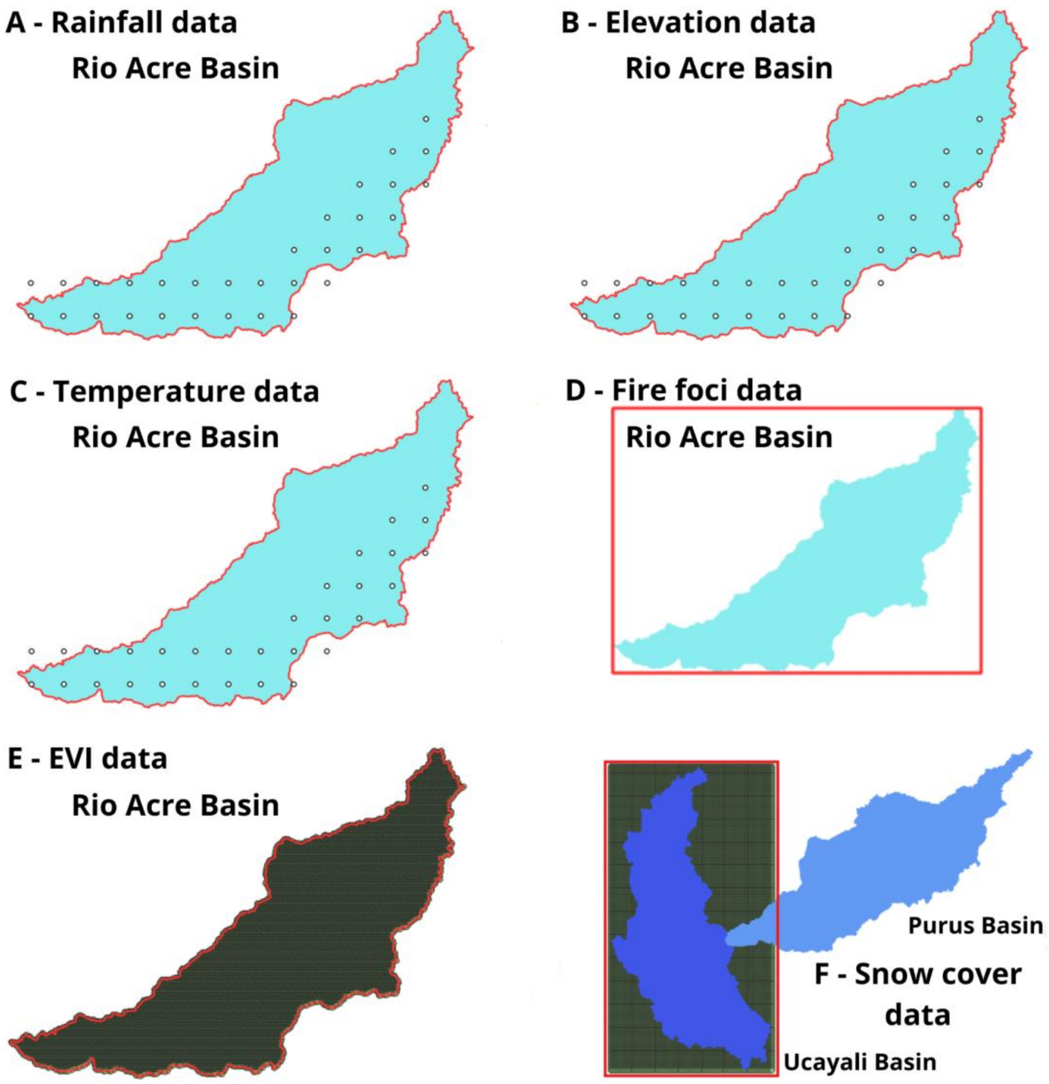

Figure 2. Limits (in red) of the study area for each of the variables worked on.

RAINFALL DATA AND DIGITAL ELEVATION MODEL

Rainfall data were obtained for the Acre River basin (Figure 2A). To do this, a 0.25º x 0.25º grid of points (approximately 25 km x 25 km) was generated within this basin. Then, 31 points close to the river course were selected (Figure 3). The points were later imported into R Studio for extraction of rainfall data.

The CHIRPS dataset was used for this extraction. This quasi-global dataset spans over 35 years and is based on precipitation estimates from rain gauges and satellite observations [9]. Monthly mean values from 1982 to 2023 were extracted for each of the 31 data points within R Studio using the "chirps" library.

The Digital Elevation Model (DEM) of the Acre River basin region (Figure 2B) was also obtained through Alos Palsar, a synthetic aperture radar that provides altimetric information for various applications free of charge and with global reach [27]. These altitude data were obtained for the 31 points along the Acre River basin for comparison purposes with the rainfall data, in order to understand the relationship between the variables. These points were classified according to altitude into: highest elevation portion, middle elevation portion and lowest elevation portion, as shown in Figure 3.

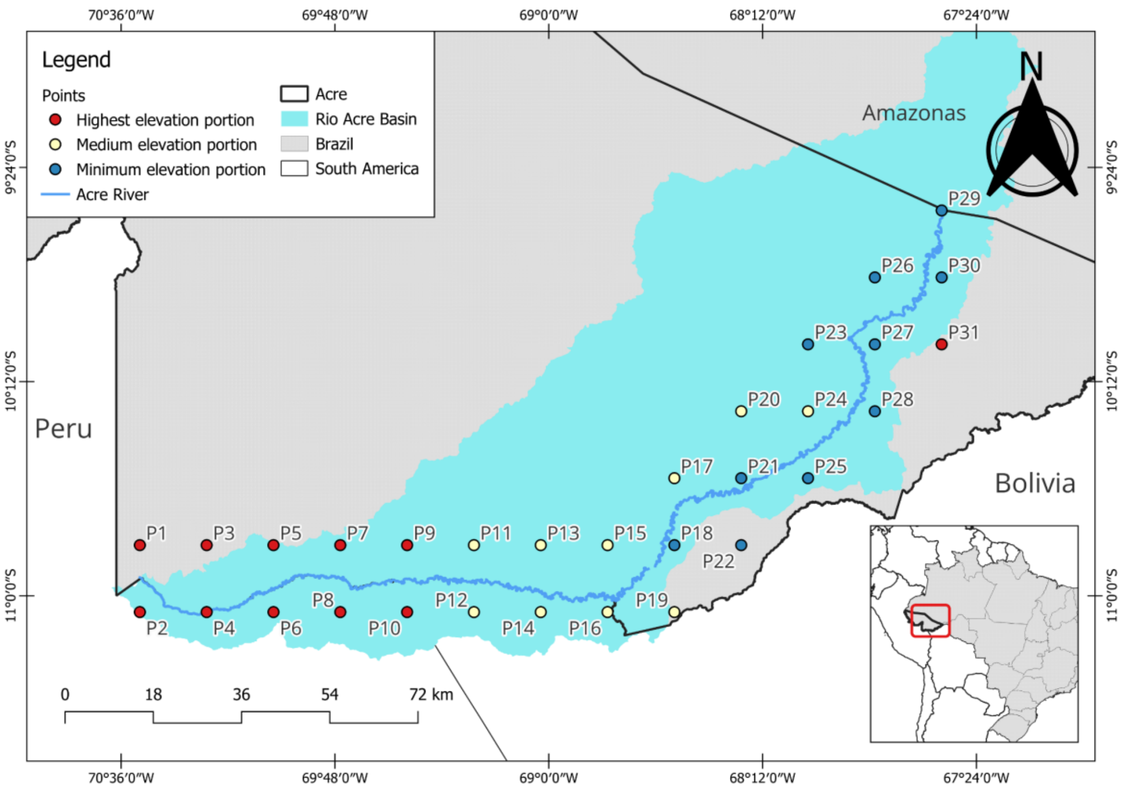

Figure 3. Distribution of the 31 data extraction points along the Acre River basin.

The air temperature data used were validated for the entire Brazilian territory and have a spatial resolution of 0.1º x 0.1º (approximately 10 km x 10 km) [28]. These are reanalysis data, which are being widely used in studies of climate trends in the Amazon [29]. For the present study, average values of maximum and minimum air temperature were extracted for the 31 points along the Acre River basin mentioned in the previous topic (Figure 3), within the period from January 2001 to July 2020.

The extraction was performed in R Studio, using the “ncdf4” library. After extraction, average temperature values were obtained using the average maximum and minimum temperature values obtained in the previous step.

Monthly fire foci from 2001 to 2023 were obtained through the Fire Information for Resource Management System (FIRMS) platform (https://firms.modaps.eosdis.nasa.gov/, accessed on August 11, 2024). The data are from the MCD14ML product of the MODIS sensor and have a spatial resolution of approximately 1 km x 1 km [30]. These foci were obtained for a rectangular polygon encompassing the Acre River basin (Figure 2D).

Enhanced Vegetation Index

The Enhanced Vegetation Index (EVI) was obtained through the MOD13C2 product of the MODIS sensor, coupled to the TERRA satellite. This product is monthly and provides a vegetation index value per pixel with a spatial resolution of 0.05º x 0.05º (approximately 5 km x 5 km) [31]. Monthly average values from 2001 to 2023 were extracted for points covering the entire Acre River basin (Figure 2E), within R Studio.

Snow cover data

Snow cover data were obtained from the MOD10CM product of the MODIS sensor, coupled to the TERRA satellite. This is a monthly product, in which snow cover is detected using the Normalized Difference Snow Index (NDSI) in a previous product (MOD10_L2). MOD10CM operates with a spatial resolution of 0.05º x 0.05º (approximately 5 km x 5 km) and its monthly data are generated by compositing 28 to 31 days of daily observations from MOD10C1 [20]. Table 1 presents the Scientific Data Sets (SDSs) included in the product.

Table 1. MOD10CM product details.

PARAMETER	DESCRIPTION	VALUES
SNOW_COVER_MONTHLY_ CMG	AVERAGE MONTHLY SNOW COVER	0-100: PERCENT OF SNOW IN CELL

Adapted from [20].

Monthly mean values from 2001 to 2023 were extracted for points encompassing the Ucayali basin and part of the Purus basin (Figure 2F), within R Studio. After extraction, a selection was made of only the values corresponding to the percentage of snow in the cell (Table 1). The years 2001, 2002, 2003, 2016 and 2022 did not present values for the month of December.

STATISTICAL ANALYSIS

In order to analyze the trend of the values, the non-parametric Mann-Kendall test was used [32,33]. For the rainfall data, it was applied to each of the 31 extraction points. For the Enhanced Vegetation Index and snow cover data, the test was applied to the entire time series, regardless of the extraction points. The aforementioned statistics were performed within R Studio, using the “kendall” library.

In order to examine the relationship between the variables rainfall and altitude (given by the DEM), an Exponential Nonlinear Regression Analysis was performed in each of the portions of the Acre River basin.

The data on rainfall, maximum temperature, average temperature, minimum temperature, fire foci, Enhanced Vegetation Index and snow cover were subjected to Principal Component Analysis (PCA) in each of the portions of the Acre River basin. PCA is a multivariate statistical technique that consists of transforming a set of original variables into another set of variables of the same dimension called principal components [29].

The Principal Component Analysis method used in the script is based on the prcomp() function in R studio. This method performs matrix decomposition using Singular Value Decomposition (SVD), a robust and widely used method for PCA. This approach is suitable for exploring the variance and correlation structure in the datasets (maximum, mean and minimum elevation), providing insights into which variables contribute most significantly to the observed patterns in the data.

RESULTS

RAIN IN THE ACRE RIVER BASIN

The results of the Mann-Kendall test for rainfall data show, in general, that P01, located in the highest elevation portion of the Acre River basin, presented a higher frequency of months with a significant increase in rainfall. These were: February (Z=2.49), March (Z=1.73), May (Z=1.82), June (Z=1.66), and August (Z=2.21). Up until P04, no significant reduction in rainfall (mm) was found, which was only observed from P05 onwards, with emphasis on the month of September at points in the highest elevation portion of the basin, for the month of November at points in the middle elevation portion, and for the months of July and September at points in the lowest elevation portion (Figure 4).

The month of February in P10 presented the highest value of significant increase in rainfall (mm) among all observed points (Z=2.60). February was also highlighted in the other points of the basin, since the 14 highest values of significant increase were recorded in that month. The highest values of significant reduction were recorded in the months of July, September and November (Figure 4).

The 5 highest average rainfall amounts (mm) were observed at points located in the highest elevation portion of the Acre River basin, with an altitude greater than 300 meters. The lowest average rainfall amount (mm) was observed at point 15, located in the lowest elevation portion of the basin, with an altitude of 264.75 meters and 134.24 mm, respectively (Table 2).

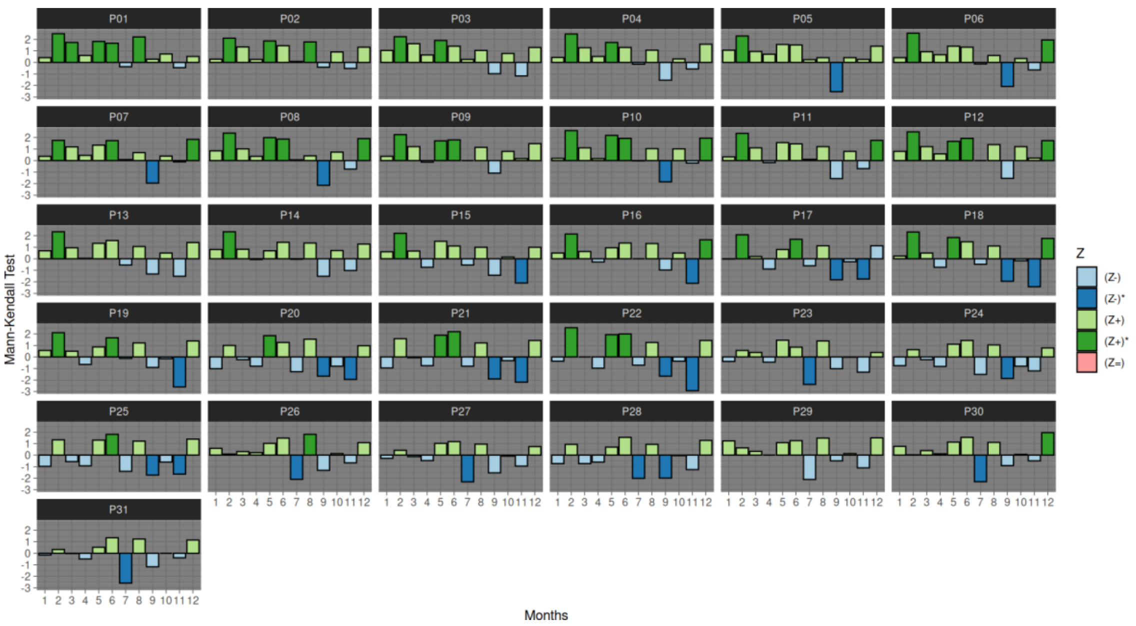

Figure 4. Mann-Kendall test values for rainfall data along the Acre River basin. In the legend, (Z-) indicates reduction, (Z-)* indicates statistically significant reduction, (Z+) indicates increase, (Z+)* indicates statistically significant increase and (Z=) indicates neutrality.

Table 2. Average altitude (DEM) and rainfall values for the 31 points along the Acre River basin.

PORTION	POINTS	ALTITUDE[1]	RAINFALL[2]
HIGHEST ELEVATION	P31	595.25	156.72
	P2	390.00	174.45
	P5	354.50	159.04
	P6	343.75	163.41
	P9	326.25	162.39
	P8	324.25	163.79
	P3	323.25	160.73
	P1	315.50	306.61
	P7	313.50	159.94
	P4	306.50	174.17
	P10	301.75	164.42
AVERAGE ELEVATION	P12	299.75	159.35
	P11	291.00	155.13
	P14	271.00	160.76
	P15	264.75	134.24
	P20	253.50	149.89
	P17	247.50	144.01
	P19	243.50	139.36
	P13	236.25	154.68

	P24	230.00	154.90
	P16	228.25	160.58
LOWEST ELEVATION	P22	224.25	144.78
	P25	202.75	154.79
	P26	189.50	160.14
	P21	188.75	147.44
	P18	185.00	134.37
	P28	162.25	156.12
	P30	160.25	159.74
	P23	146.50	157.23
	P27	146.25	154.98
	P29	137.50	162.40

[1]Meters (m), [2]Millimeters (mm)

The models derived from the Regression Analysis for rainfall and altitude (DEM) are presented in Figure 5. The mid-elevation portion of the Acre River basin presented the highest Coefficient of Determination (R^2) value, being 0.39. The higher elevation portion, in turn, presented the lowest value, being 0.03.

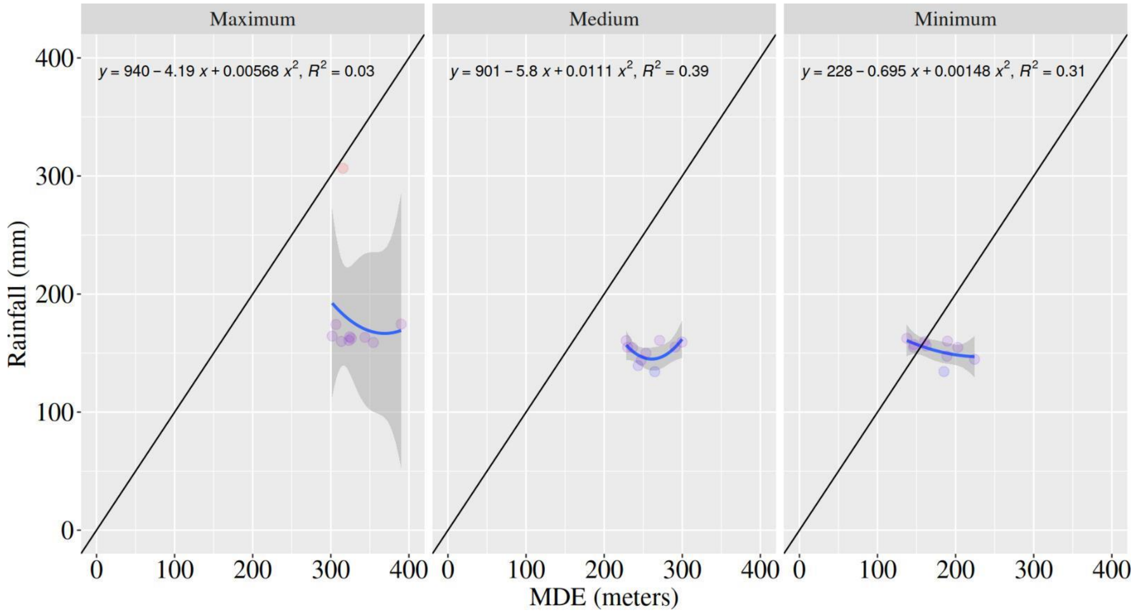

Figure 5. Regression analysis of data observed in the three portions of the Acre River basin.

AIR TEMPERATURE, FIRE AND ENHANCED VEGETATION INDEX IN THE ACRE RIVER BASIN

The results of the Mann-Kendall test for maximum temperature showed a significant increase for the months of April (Z=1.85) and September (Z=2.52). The highest significant value recorded in September indicates an intensification of maximum temperature in the future dry season. For minimum temperature, a significant increase was observed for the months of February (Z=1.72) and November (Z=1.68), indicating changes in the rainy season.

For fire, the test showed a significant increase for the months of January (Z=1.89), May (Z=1.72), June (Z=2.04), August (Z=1.69) and November (Z=1.66). These results indicate an intensification of fire foci for the dry and rainy seasons in the future. For the Enhanced Vegetation Index, the test showed a significant reduction for the month of August (dry season), with the value Z= -2.06.

SNOW COVER

The highest percentage of snow cover was observed in January 2001 (3.45%). The lowest percentage was observed in July 2020 (0.14%). In 2001, the lowest percentages were recorded in the months of August (0.49%), July (0.48%) and September (0.47%), that is, in the dry period of the year. In 2023, the lowest percentages were recorded in the months of April (0.38%), July (0.20%) and August (0.16%) (Figure 6).

Comparing the years 2001 and 2023 in relation to the highest percentages of snow cover, a decrease was observed. In 2001, the month of January had the highest coverage value with 3.45%. In 2023, the month of February had the highest coverage value with 1.52%. Since 2012, no month had a percentage higher than 2.00%, showing a reduction in snow cover over the years (Figure 6). The Mann-Kendall test applied to the time series showed a significant reduction for the month of June (Z= -1.98), indicating that snow will decrease in the dry season.

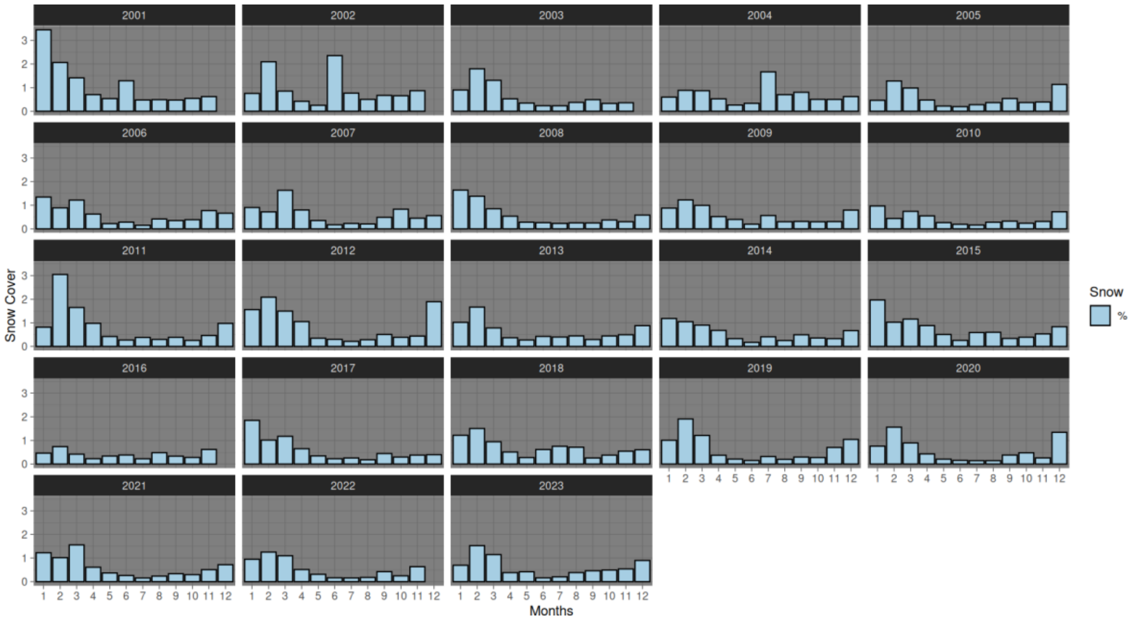

Figure 6. Snow cover percentages from 2001 to 2023 by months.

PCA IN THE ACRE RIVER BASIN

Principal Component Analysis for the study variables in the different portions of the Acre River basin showed similar results. In the highest part of the basin, the variables rainfall and minimum temperature showed a high relationship, which was negative, showing that the higher the minimum temperature, the lower the amount of rainfall in this portion. Fire foci and maximum temperature also showed a high relationship, which was positive, indicating that the higher the maximum temperature, the greater the number of fire foci (Figure 7).

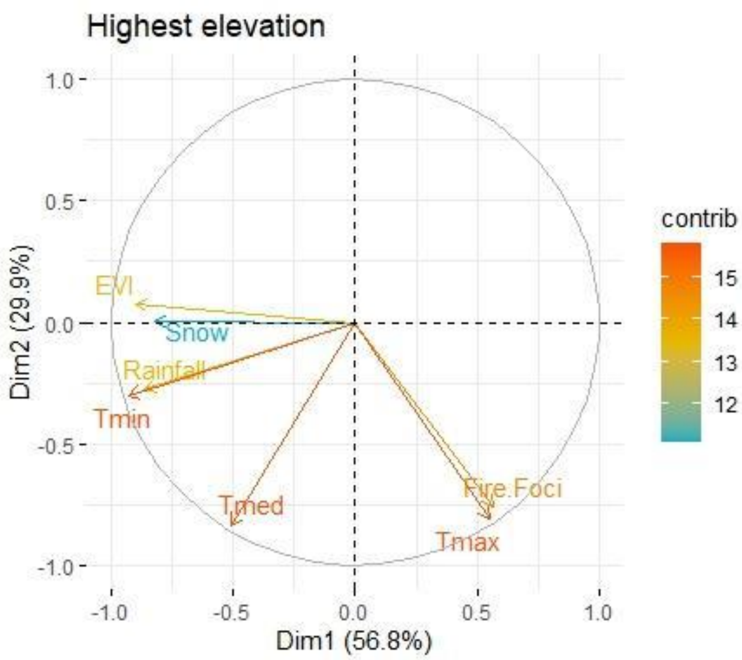

Figure 7. Principal Component Analysis in the highest portion of the Acre River basin.

In the middle part of the basin, the variables rainfall and minimum temperature showed a smaller relationship (Figure 8), when compared with the previous stratum, but they were still highly related. As in the previous stratum, the average temperature did not have a strong relationship with the remaining variables, most likely because it is an average between the maximum and minimum temperatures of the area.

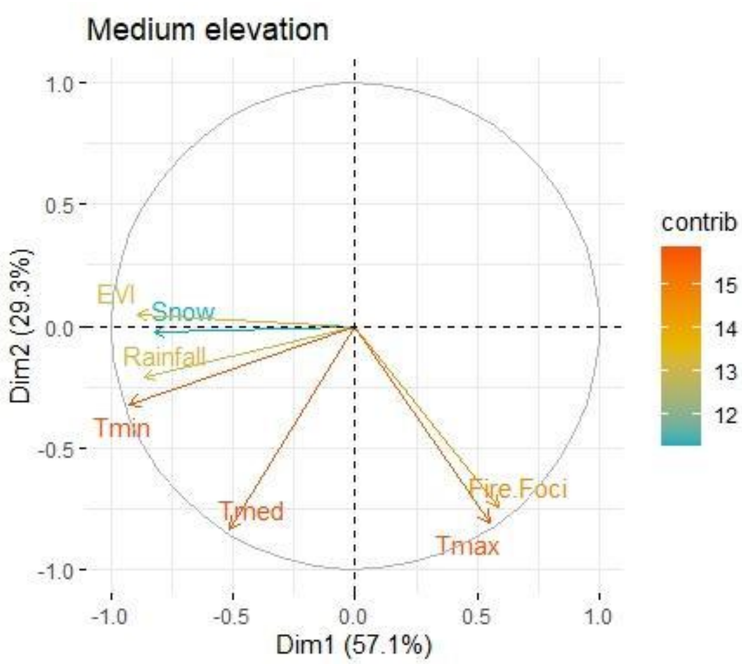

Figure 8. Principal Component Analysis in the middle portion of the Acre River basin.

In the lowest part of the basin (Figure 9), the behavior of the PCA was similar to that of the middle part. In the lowest part, the variables fire foci and maximum temperature showed a greater relationship when compared to the upper strata. In the three strata of the basin evaluated, snow cover showed the smallest contribution in the statistical analysis and temperatures (maximum, average and minimum) showed the highest.

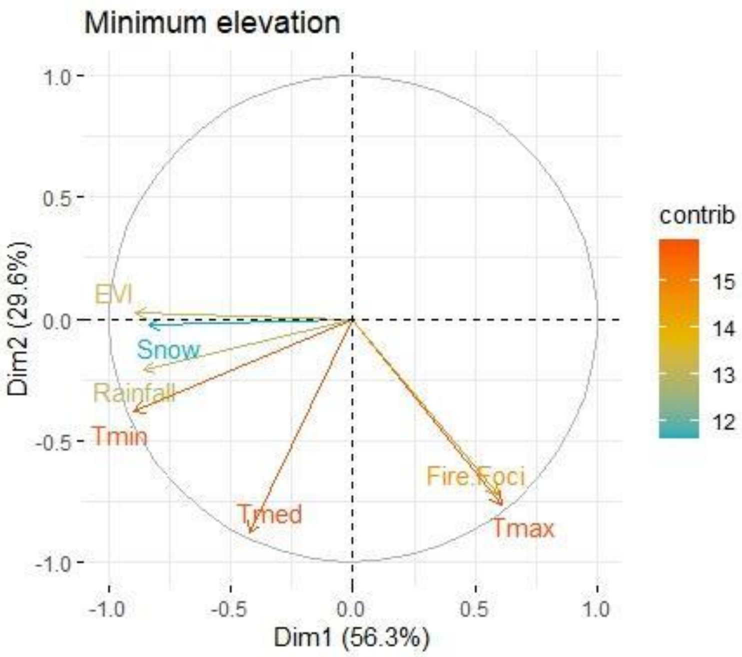

Figure 9. Principal Component Analysis in the lower portion of the Acre River basin.

DISCUSSION

RAINFALL BEHAVIOR IN THE ACRE RIVER BASIN

The results of this study show an increase in rainfall (mm) for the Acre River basin, mainly during the rainy season in the region. Conversely, the results show a reduction in rainfall (mm) for the same region during the dry season. A similar rainfall distribution pattern was observed in a study carried out by [35] in the city of Rio Branco (located within the same basin), which evaluated a historical series from 1970 to 2021, finding higher rainfall from November to March and lower rainfall from June to August.

The existence of significant rainfall reduction values (mm) for the month of November suggests an extension of the dry season in the Acre River basin region, given that this month marks the beginning of the rainy season, as shown in a study carried out by [36] in the Juruá basin, also located in the state of Acre. In it, the period from July to September presented the lowest rainfall records, evidencing a shorter dry season.

The extension of the dry season suggested above would directly affect the climate in other countries that have the Amazon biome, given that Brazil is the largest supplier of rainfall to them. Up to a third of the total annual precipitation in the Amazon territories of Bolivia, Peru, Colombia and Ecuador depends on water originating from the Brazilian portion of the Amazon rainforest [37].

Our results showed that February had an increase in rainfall (mm) compared to other months, suggesting an intensification of the rainy season and, consequently, of events such as floods. The rainy season, which includes the month in question, is considered the most likely to cause extreme flooding in other basins in the state [7].

In this decade alone, the Acre River has already recorded its second (2024) and third (2023) highest levels in history in the capital of the state of Acre, according to the Woodwell Climate Research Center (https://www.woodwellclimate.org/acres-communities-face-drinking-water-shortage-amid-amazon-drought/, accessed on September 9, 2024). Between 1987 and 2023, 254 extreme events were identified in the federative unit, 33% of which were flood events [3].

A study conducted by [38] on the Juruá River, in another region of Acre, showed that extreme floods occur approximately every decade, more precisely during La Niña events in February. With the intensification of rainfall in this month evidenced by our study, it is possible that there will be a greater frequency of floods in the region in the future. Furthermore, a study carried out on a global scale highlighted that precipitation extremes are more likely to increase than decrease in humid regions [39], as is the case in the region surrounding the study area.

AIR TEMPERATURE, FIRE AND VEGETATION TRENDS IN THE ACRE RIVER BASIN

Our results, evaluating the time series from January 2001 to July 2020, show an increase in maximum temperature in the dry season and an increase in minimum temperature in the rainy season. [36] found a significant positive trend for average air temperature during the dry season in the Juruá basin. Several climate models indicate more consecutive dry days and an increase in annual maximum temperatures of 2 to 4ºC in the Amazon region [40]. The PCA showed a strong relationship between maximum temperature and fire foci, especially in the lower part of the basin, which did not record high average rainfall values when compared to the higher part. Therefore, the increase in temperatures observed in our study will make the region more susceptible to forest fires.

Our results show an intensification of fire foci during the dry and rainy seasons, a behavior similar to that found by [29] in a study carried out in Rio Branco. These authors proposed a fire risk model for the capital and verified projections for the future, finding that there will be an increase in fire activity within the next 20 years in the region. In addition, they observed a greater significant increase (Z=2.42) in fire foci in the formation of the Alluvial Open Ombrophilous Forest type, which is present on the banks of the Amazon rivers [41], indicating a greater susceptibility of the basin to fire in the future.

Regarding the composition of the landscape, our results indicate a reduction in vegetation for the month of August. This behavior is expected, given the dry season, but it may also be associated with the advance of deforestation in the region, as observed in another study [29]. The dry season is more prone to fires, given the greater accumulation of combustible material in the soil, low humidity and high temperatures [42].

The trends of prolonging this season (with rising temperatures and reduced rainfall) observed in our study suggest a worsening of the climate situation in the Acre River basin region. In the southwestern Amazon, there is evidence that high temperatures and high percentages of deforested areas are some of the main factors in the occurrence of fires [43].

Reduction of Andean snow and impact on the Acre River basin

The snow cover percentages we found did not exceed 3.5% during the entire period analyzed, which is an expected result, considering that in the tropics Andean snow is restricted to high elevations (>5,000 meters) [44]. Our results show a reduction in snow cover in the last decade. A study investigated the same variable using MODIS data in the Andean region, between 2000 and 2016, also finding a reduction [18].

The aforementioned study found significant decreasing trends in snow cover, with results of 2 to 5 fewer days of snow each year. Another study conducted in the Andes region of Chile [45], between 2001 and 2021, found an average of 3.6 fewer days of snow cover per year.

The reduction in snow activity in the tropical Andean region may impact not only the glacial river basins present in Peru and Bolivia, but also downstream basins that are fed by them, leading to a long-term reduction in river discharge. This decrease in snow is related to the high air temperatures observed in the region [46].

This relationship is reinforced by the results of our study, which indicate a trend of significant reduction in snowfall, especially in June, a dry month characterized by high temperatures and low humidity. A study on snow cover in the dry season carried out by [47], between latitudes 18º and 40º S of the Andes, showed a decreasing trend in the most tropical stratum of the region (between 18º and 23º), with a reduction of approximately -16% in coverage per decade.

[18] found a high correlation between the variable snow persistence and the variables air temperature and precipitation in the Andes. For air temperature, the relationship with snow persistence was inverse. Precipitation, in turn, had a direct relationship with the variable. Our results show a similar pattern, with the variables snow cover, minimum temperature and rainfall showing a high relationship by PCA.

The reduction of tropical Andean ice is a concern for the Acre basins that are connected to the glacial basins of neighboring countries, such as the Purus basin (which is composed of the Acre River basin), due to the potential impacts on the economy and the environment. The reduction of snow can cause harm to the use of water resources, impacting both those living in the tropical Andes and those living downstream, at lower altitudes [48].

Understanding the factors that affect changes in snow cover is important for developing strategies to reduce the impacts of climate change. Thus, remote sensing products, such as those from the MODIS sensor, provide valuable data for monitoring snow cover [49]. Our study area showed climate trends that are favorable for the worsening of the situation, such as the extension of the dry season with high temperatures and decreased rainfall and a more concentrated rainy season, possibly indicating the occurrence of more extreme events for the Acre region in the future.

CONCLUSIONS

The dynamics of rainfall in the Acre River basin presented by our study show a greater intensity and concentration of this phenomenon in the month of February, suggesting a greater frequency of floods in the future for this month. The reduction in rainfall (mm) observed in months after the dry season proves an extension of this period, a situation aggravated by the high temperatures, the high number of fires and the reduction of vegetation, also observed for this period. Given this situation of climate extremes being intensified each year in the Amazon biome and the existence of several studies that monitor and project climate changes for the region, it is essential to apply the methodologies present in these studies in actions that in fact mitigate the effects of floods, droughts, forest fires and deforestation.

With regard to the Andean snow cover observed in our study, it was possible to observe a reduction over the last decade, an effect associated mainly with rainfall and temperatures. The percentages below 2% in the time series and the reduction projected for the dry season demonstrate this relationship. The use of the MODIS coverage product showed expected results for the region, considering that the data collection area does not represent the largest snow cover in the Andes.

The adoption of other MODIS sensor products that measure snow, in addition to the MOD10CM, in regions that impact not only the Acre River basin, but other important basins in the state, is essential to better investigate the effects of the reduction of Andean snow in Western Amazonia, and is a recommendation for similar studies carried out in the region in the future. The limitations of our study are mainly focused on the lack of a specific methodology that allows us to verify the direct impact of the reduction in snow cover in the Acre River basin.

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