International Master’s Degree in Sustainable Territorial Development:

Climate Change, Diversity and Cooperation / Maestría en Cambio Climático, Sustentabilidad y Desarrollo

Drivers of Forest Fires: Identification and Strategies in the Colombian Amazon

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Academic Year 2022/2023

Convenio de cooperación para la implementación de la maestría internacional, STeDe, entre la Università Degli Studi Di Padova y la Universidad Andina Simón Bolívar, Sede Ecuador, firmado el 24 de enero de 2017.

University of Padova

Department of Civil, Environmental and Architectural Engineering ICEA

Master Thesis in Sustainable Territorial Development – Climate Change Diversity Cooperation

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Para María, la abuela invencible.

Abstract

Recent times have witnessed wildfires causing harm to both ecological communities and urban-rural regions, underscoring the necessity to comprehend wildfire triggers and assess measures for mitigation. This research hones in on Cartagena del Chaira, delving into the interplay between meteorological conditions and land cover/use that cultivate a conducive environment for wildfires. Meteorologically, the prevalence of wildfires is concentrated during boreal-winter, characterized by warm and dry air, strong winds, and negligible precipitation. Additionally, wildfires gravitate toward river-adjacent locales housing agriculture-linked shrubs, notably in the northern part of the zone, where a confluence of land attributes and meteorological factors synergize to promote fire incidents. Employing climate scenarios, we deduced that elevated temperature and reduced humidity augment wildfire susceptibility, while wind speed and precipitation discourage their propagation across most scenarios. The trajectory toward a warmer climate could instigate fire-friendly conditions in boreal-summer, indicating the potential for year-round fire susceptibility. Subsequently, via Machine-Learning-driven sensitivity analysis, we discerned that among the scrutinized socio-economic variables, GINI, low educational attainment, and displacement by armed groups wield the most substantial influence on wildfire occurrence. Ultimately, these findings converge to shape proposed wildfire mitigation strategies that amalgamate existing practices with enhancements or supplementary approaches.

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Listing of acronyms

IPCC .... The Intergovernmental Panel on Climate Change

MASL .... Meters Above Sea Level

ITCZ .... Intertropical Convergence Zone

FARC-EP ...... Fuerzas Armadas Revolucionarias de Colombia Ejercito del Pueblo

GDP .... Gross Domestic Product

DANE .... National Administrative Department of Statistics

MPI .... Multidimensional Poverty Index

OMC .... Observatory of Memory and Conflict

CEDE .... Center for Economic Development Studies

OCHA .... Coordination of Humanitarian Affairs

GHG .... Greenhouse Gas

UNFCCC ...... United Nations Framework Convention on Climate Change

CMWG .... Coupled Modeling Working Group

CMIP .... Coupled Modeling Working Group

CCCma .... Canadian Centre for Climate Modelling and Analysis

CNRM .... Centre National de Recherches Météorologiques

ENSO .... El Niño-Southern Oscillation

AMOC .... Atlantic Meridional Overturning Circulation

IPSL .... Institut Pierre-Simon Laplace

SSP .... Shared Socioeconomic Pathway

TCWV .... Total Column Water Vapor

ML .... Machine Learning

IDEAM .... Institute of Hydrology, Meteorology and Environmental Studies

USGS .... United States Geological Survey

GEE .... Google Earth Engine

NDVI .... Normalized Difference Vegetation Index

NIR .... Near Infrared

SWIR .... Shortwave Infrared

PBLCC .... Phenology-based Land Cover Classification

ECMWF .... European Centre for Medium-Range Weather Forecasts

FIRMS .... Fire Information for Resource Management System

MODIS .... Moderate Resolution Imaging Spectroradiometer

VIIRS .... Visible Infrared Imaging Radiometer Suite

ANOVA .... Analysis Of Variances

CDS .... Climate Data Store

RMSE .... Root Mean Square Error

MBE .... Mean Bias Error

1
Introduction

The Amazon Basin holds immense significance on a global scale due to its exceptional biodiversity, vital role as a carbon sink, and its contribution to climate regulation (James et al., 2023). The Intergovernmental Panel on Climate Change (IPCC) has projected that temperatures in Tropical Forests could potentially rise by up to 4.8°C by the end of this century (Ometto et al., 2022), a change exacerbated by both direct and indirect drivers of deforestation influenced by a complex interplay of factors, including land use, demographics, economics, politics, and institutions (Armenteras et al., 2019). In Colombia, approximately 40% of the land is covered by Amazonian rainforest, spanning an area of roughly 48,3164 km^2 and divided into three subregions with distinct relief patterns (SINCHI, 2023). The ecosystems and environment of the Colombian Amazon encompass various biomes, with the tropical rainforest biome being dominant at 64.9% (Carolsfeld et al., 2003), followed by Litobiomas at 14.5%, Helobiomas at 12%, and Peinobiomas at 12% (SINCHI, 2023). The Peinobiomas cover an additional 3.4%, while the Orobiomas cover 4.7% across the low, medium, and high mountain areas of the three subregions (SINCHI, 2023).

The climate of the Colombian Amazon is shaped by the Intertropical Convergence Zone (ITCZ), as pointed out by Carolsfeld et al. (2003). Within this region, the typical temperature ranges between approximately 24°C to 29°C, accompanied by a relative humidity surpassing 85%. Sunlight exposure lasts around 4 hours per day (IDEAM, 2023). While the government has monitored the Amazon area as a protective buffer to safeguard national sovereignty, as highlighted by Roca et al. (2013), challenges have arisen due to the considerable geographical separation between the central governing body and the obstructive mountainous terrain, resulting in an inadvertent neglect of the zone in terms of governance. The aforementioned meteorological factors play a pivotal role in comprehending the underlying forces behind forest fires, which lead to enhanced policy-making and planning strategies. However, in isolation, they fall short of fully elucidating the genesis of wildfires. Their interpretation necessitates a synergistic consideration alongside land cover, land use, and notably, socioeconomic factors, as emphasized by Dávalos et al. (2011). The occurrence of fires is predominantly contingent upon the intricate interplay of these four dimensions, which is why wildfires should be studied in a framework that includes these four dimensions.

Understanding the meteorological factors that drive forest fires is of utmost importance for comprehending the origins, patterns, and dynamics of these catastrophic incidents. A myriad of factors can initiate forest fires, spanning from natural occurrences like lightning strikes to human actions including negligence, deliberate ignition, and industrial operations. Meteorology plays a central role in shaping the behavior, progression, and intensity of forest fires. Weather elements like temperature, humidity, wind velocity, and atmospheric stability exert a direct influence on fire conduct, ignition potential, and the extent of fire spread (Jain et al., 2021). The nature of the land's covering significantly guides the course of forest fires by directly molding the conditions and mechanics of fire propagation. Certain attributes of land covering, such as thick vegetation, desiccated fuel loads, and proximity to human habitations, frequently exacerbate forest fires (Armenteras Pascual et al. 2011; Casallas et al. 2022). Regions with copious fuel sources like fallen leaves, branches, and dense undergrowth supply ample material for fires to ignite and rapidly extend (Kosovíc et al., 2023).

Furthermore, socioeconomic aspects, encompassing population growth and Gross Domestic Product (GDP), are critical to incorporate, as they contribute to the expansion of human settlements into fire-prone areas, leading to what is termed the wildland-urban interface. This juncture amplifies the fire potential, as human structures intermingle with flammable vegetation. Additionally, economic incentives like timber demand, agricultural yields, and land requisition for diverse purposes can drive practices that escalate fire susceptibility, including subpar forest management and unsustainable land utilization (Gobierno-Colombia 2020; Agudelo-Hz et al. 2023). Factors like colonization trends, drug-related influences, and the aftermath of peace agreements also warrant consideration (Dávalos et al. 2011; Armenteras et al. 2020). All these facets assume significance because forest fires in the Amazon rainforest predominantly stem from both natural and human causes, forming a multi-layered process. The emergence and progression of uncontrollable fires disrupt the ecosystem (Armenteras et al., 2020), with far-reaching consequences for both the ecosystem and global climate. In general, although natural forces, such as lightning strikes, can initiate fires in dense vegetation during arid periods, the majority of Amazon forest fires are a consequence of human activities, particularly deforestation and the expansion of agriculture and livestock grazing (highlighting the importance of land cover). Practices like slash-and-burn land clearance, coupled with extended droughts and the use of fire for pasture management, intensify the susceptibility and dissemination of fires (Morton et al., 2008).

These factors would become more pronounced in a climate change context, as changes in atmospheric conditions might create a more conducive environment for the initiation and propagation of fires. This underscores the importance of comprehending the current triggers of wildfires to establish effective policies, develop strategies, and mitigate the occurrence of fires. Employing Machine Learning (ML) models offers a method to assess the significance of these triggers and appraise policy effectiveness. Agudelo-Hz et al. (2023), designed three distinct land cover scenarios to gauge potential impacts on the Amazon forest. These endeavors lay a foundation not only for evaluating diverse scenarios that encompass socio-economic factors, land cover characteristics, and meteorological conditions but also for discerning the potency of each variable in influencing the likelihood of wildfire ignition. On the other hand, Armenteras-Pascual et al. (2011) evaluated the incidence of spatial and temporal patterns of vegetation burning in Colombia with regional and climatic variation. The results indicated a strong climatic and fire seasonality, as well as a marked regional difference. In Amazonia they established a high impact of small fires in the tropical rainforest present in this transition zone and the Amazon rainforest deserves more attention in Colombia due to its lack of attention prior to its contribution to climate change.

Taking into account all the significant factors discussed earlier, our primary focus shifts towards (i) identifying the specific meteorological and land cover/use conditions prevailing during the onset of wildfires in Cartagena del Chaira which is located in the Amazon, and has one of the largest number of fires in the region. (ii) Recognizing the pivotal role of meteorology, it is imperative to assess its potential alterations in a warmer climate. This has driven us to undertake a climate change analysis, aimed at quantifying the extent of meteorological deviations projected for 2049. This endeavor aims to provide a foundational understanding for governmental actions to mitigate fire-related risks. (iii) In tandem with the preceding analysis, we ascertain the most influential socio-economic variables (among those examined) that contribute to the propensity for fire ignition. By grasping the intricate interplay between meteorology, land cover/use, socio-economic factors, and climate dynamics, we then (iv) propose strategies that align with governmental plans. These strategies are designed either to enhance existing plans or to be synergistically combined with already established approaches.

The general aim of this study is to design informed mitigation strategies by comprehensively understanding the complex interplay of meteorological, climatological, and socio-economic factors that influence wildfire dynamics in Cartagena del Chaira. This involves specific goals, (i) identifying the precise meteorological and land cover/use conditions that prevail during the onset of wildfires in the region. (ii) Recognizing the pivotal role of meteorology in shaping wildfire patterns and assessing potential alterations in a warmer climate scenario projected for the year 2049. (iii) Determining the most influential socio-economic variables, among those examined, that contribute to the propensity for fire ignition. This will aid in understanding the socio-economic context's impact on wildfire occurrence and guide mitigation strategies.

2
Theoretical Framework

This section explained the state of the art regarding drivers to forest fires on the Colombian Amazon and encompasses a comprehensive examination of past and present debates, theoretical approaches, and methodological perspectives. For this, is presents a concise overview of its key elements, tools, and methodologies showing the work done and aspects has not been adequately developed or explored to its fullest extent.

2.1 Amazon Basin

The Amazon Basin comprises areas of Colombia, Venezuela, Guyana, French Guyana, Suriname, Ecuador, Perú, Bolivia, and Brazil representing one of the most important regions on Earth in terms of biodiversity, carbon sink, and climate regulation (James et al., 2023). The Amazon rainforest covers approximately 6.7 million square kilometers contributing about 16% of the global photosynthetic production (Nobre et al., 2021) and containing around 10% of the world's known species. Many of these Amazonian species are relevant for biodiversity conservation as they are endemic: around 34% mammals and 20% of birds are only found in this region (Nobre et al., 2021). The exceptional multiple-scale of Amazonian biodiversity (species, genes, and ecological functions), is the result of the complex spatio-temporal evolution of ecosystems, and natural processes coupled with environmental heterogeneity, climate, and unique biotic interactions (Nobre et al., 2021). The distribution of diversity is uneven across the Amazon due to differences in pedology, climate gradients, and biological and ecological interactions that coexist in these ecosystems, which is why studying specific parts of the Amazon and also the Amazon as a whole is important.

This environmental heterogeneity is important to maintain the ecological balance of the region. Amazonian vegetation act as a biotic pump, capturing water from the soil and releasing it into the atmosphere through evapotranspiration processes, which means that the Amazon plays a crucial role in the global climate system (Nobre et al., 2021) due to its interactions with the hydrological cycle and also with the global radiative budget. For example, some consequences of high evapotranspiration rates are: removing latent heat, decreasing drought risk, and improving the hydrologic cycle. Moreover, amazonian vegetation plays an important role in the carbon cycle, accounting for 16% of terrestrial productivity, in fact, between 150 and 200 billion tons of carbon are stored in its soils (le Polain de Waroux et al., 2019).

On the other hand, the Amazon include also bio-cultural diversity related to the presence of many indigenous populations who have lived in the region for thousands of years have developed lifestyles that are based on their interaction with the rainforest, their cosmovision, hereditary values and beliefs which are connected to the Amazon (Moran, 1983). In this sense, indigenous communities possess unique knowledge that leads to the conservation and preservation of the ecosystem. Furthermore, they represent a movement-force against climate change. Despite this, the Amazon basin is under threat due to imminent deforestation. By 2019, due to legal and illegal activities such as agriculture, logging, road building, burning, dams and mining, about 14% of the Amazon's land cover is converted by land use changes, resulting in drastic ecosystem degradation (Albert et al. 2023, le Polain de Waroux et al. 2019).

According to the IPCC, Tropical Forests temperature could increase up to 4.8°C at the end of this century (Ometto et al., 2022) due to and intensify by direct and indirect deforestation drivers influenced by forces, such as land use and those related to demographic, economic, political and institutional approaches (Armenteras et al., 2019), that have complex interactions and act at multiple scales. This drivers lead to changes in ecosystem balance (e.g. ecological disturbances) that would affect species richness, approaching or exceeding the extinction value of taxa over this period, as well as a major threat to entire communities and even entire ecoregions of tropical forests (Ometto et al., 2022).

2.1.1 Colombian Amazon: a geographical framework

About 40% of the Colombian territory is considered Amazonian rainforest, covering 61 municipalities in the departments of Meta, Guainía, Guaviare, Vaupés, Amazonas, Putumayo, Caquetá, Cauca and Nariño Figure 2.1. The Colombian Amazon has an extension of 483,164 km^2 with three sub-regions divided into types of relief (SINCHI, 2023). The Amazon floodplain has maximum altitude of 300 meters above sea level (MASL) where the great plains and lowlands are flooded in rainy seasons due to the proximity of Amazonian rivers (i.e., Caquetá, Inírida, Guaviare, Putumayo, and Amazon) that cross the sub-region and acts as modeling agents of the landscape (Roca et al., 2013). On the other hand, the Andean-Amazonian piedmont relief is located at the confluence of the Amazon basin with the Andes mountain range and is characterized by its slightly undulating relief with gentle slopes (Roca et al., 2013). Its formation is mainly due to a large amount of alluvial materials coming from the interior of the Andes that deposit sediments. Finally, the Serranías is the high jungle formed by mountainous areas and rocky plateaus that make up the mountainous system (Roca et al., 2013).

Based on this orography, the Annual Balance on the State of the Ecosystems and Environment of the Colombian Amazon identifies biomes present in the Colombian Amazon (SINCHI, 2023). The climate of the Colombian Amazon is influenced by the Intertropical Convergence Zone (ITCZ) (Carolsfeld et al., 2003), presenting unimodal regime with a peak on May-June-July, but the rain intensity varies depending on the geographical location (Guzman et al., 2014). Near the Eastern Cordillera, at the Piedemonte Amazonico, the humid air parcel rises, saturates and produces heavy precipitation amounts (Guzman et al., 2014). More to the south (in Guaviare) the precipitation is less strong since the parcels are not as humid as at the South of the Amazon, and there are no branches to lift the parcel and rise the rain saturation ratio. At the south Amazonian the rain is significant (4,000 mm year^{-1}) since the parcels tend to be very humid and buoyant (Hernandez-Deckers, 2022) due to the amount of evapotranspiration produced in that zone. In more general terms, precipitation values range between 2,500 mm year^{-1} in the lowlands and up to 5000 mm year^{-1} in the Andean foothills (Carolsfeld et al., 2003). The evapotranspiration capacity is 1447 mm year^{-1} which means that precipitation exceeds the drainage capacity resulting in a constant excess of water in the soil. The average temperature is around 24-29°C and the relative humidity is larger than 85%, and the solar brightness is 4 h day^{-1} (IDEAM, 2023). One difficulty that arise to categorize in detail the climatological and meteorological conditions of the Colombian Amazon is the mountain ranges that split the

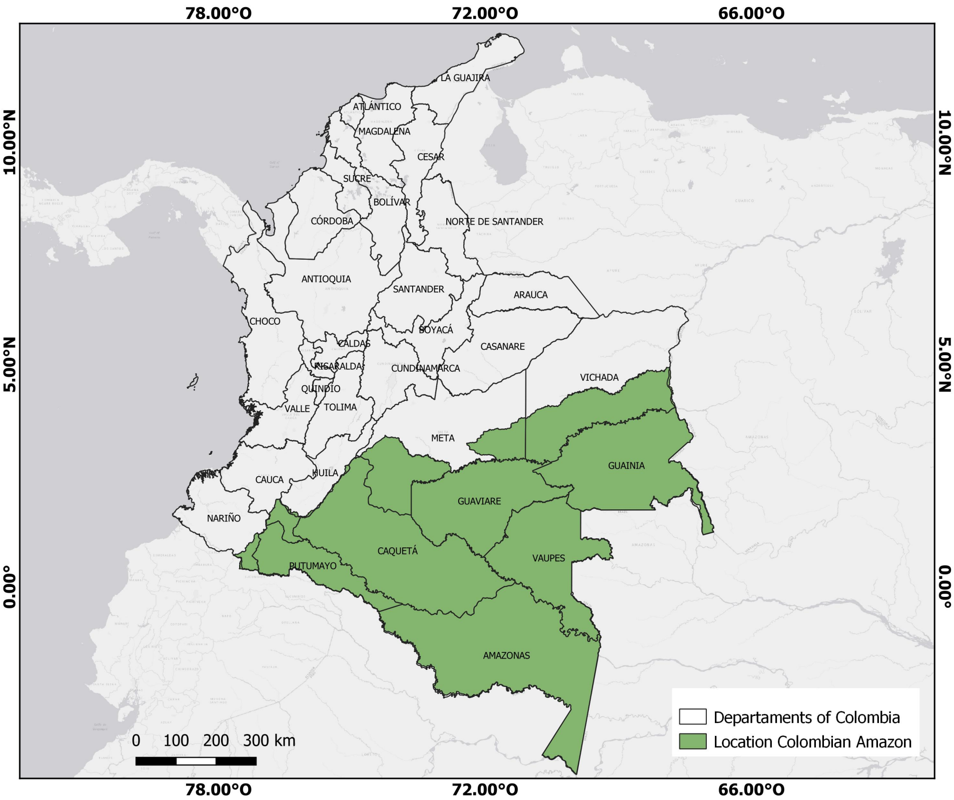

Figure 2.1: Colombian Amazon location.

country into different zones.

Due to the fact that Colombia is not fully connected, the Amazon region has been monitored by the government as a buffer zone to protect the country's sovereignty (Roca et al., 2013), nevertheless, the physical distance between the central state, and the mountainous obstacle, have produced an unwanted abandonment of the zone in terms of governmentality. In order to understand the socioeconomic and political processes in the Colombian Amazon, it is important to understand the identity of the inhabitants due to their colonization processes, the influence of drugs, and the subsequent repercussions of the peace agreement. Colonization began in the 19th century and has continued since then from the Andes mountain range in response to social, economic, and political problems. In the 1930s, peasants began to seek a more stable livelihood in marginal areas outside the agrarian frontier dominated by large landowners, this migration accelerated in the 1950s due to political confrontations (Ramírez, 2011).

In order to formalize these settlements, the government issued Law 2 of 1959, which, for reasons of public, economic and social interest, allows the removal of forests and promotes the change of land use under the sustenance of forest reserve areas (Instituto Nacional de los Recursos Naturales Renovables y del Ambiente, 1985). From its beginnings, the eastern Amazon region (departments of Amazonas, Vaupés and Guainía) has mainly indigenous populations. In contrast, the western Colombian Amazon (departments of Putumayo, Caquetá and Guaviare) has the majority of the contingent population, that is, people who arrive and leave throughout an evolutionary cycle of commodity booms (coca, gold, rubber, among others depending on the Amazonian area) and the portion of permanent population establishes small crops. Nevertheless, the presence of big companies in zones with the presence of guerrilla groups, extortions and kidnappings increased the costs of entering the Colombian Amazon (Ramírez 2011, Roca et al. 2013).

These illegal activities boomed one after the other in a context where the population of this region began to form a *cocalero* social movement, understood as the identity around illicit cultivation of coca and its economic benefits, which according to Ramírez (2011) was motivated by the abandonment and stigmatization by the central Colombian state. It was becoming an area with high drug trafficking and disputes between Armed Forces and illegal groups "owners" of the coca-growing areas, processing laboratories and access roads getting the control of the main municipalities of the Western Amazon developing special socioenvironmental circumstances

(Roca et al., 2013). Before the Colombian peace agreement between the Colombian government and the biggest guerrilla; by substituting the role of the State, the Fuerzas Armadas Revolucionarias de Colombia-Ejercito del Pueblo (FARC-EP), an armed guerrilla organization, was the authority in these regions, restricting mobility in and out of the area as well as the activities in this area (Armenteras et al., 2019).

2.2 Forest fires on Colombian Amazon

Forest fires in the Amazon rainforest are mainly caused by natural and human factors as a multi-scale process where the occurrence and spread of uncontrolled fires disrupt the ecosystems (Armenteras et al., 2020) has significant consequences for the ecosystem and global climate. Natural causes, such as lightning strikes, can ignite fires in dense vegetation during dry seasons. However, the majority of Amazon forest fires are a result of human activities, particularly deforestation and the expansion of agriculture and livestock grazing. The clearing of land through slash-and-burn practices, combined with prolonged droughts and the use of fire to manage pastures, intensifies the risk and spread of fires (Morton et al., 2008). The consequences of these fires are far-reaching and devastating. They lead to the loss of valuable biodiversity, destruction of habitat for countless plant and animal species, and the release of enormous amounts of carbon dioxide into the atmosphere, exacerbating global climate change.

According to Eva and Lambin (2000) before 2000 in the Colombian Amazon, the land-cover conversion in natural savannas has no significant relationship with fire activity, nevertheless in the areas where agriculture is expanding into the forested areas (i.e., frontier zone) where the armed conflict was more controlled has a positive relationship (R = 0.6) with forest fires. This suggests that land ownership and traditional practices like slash-and-burn may be an important factor in the type of land conversion due to the management techniques differing depending on the types of land use (Eva and Lambin, 2000; Morton et al., 2008). Although generally low deforestation rates in Colombia have been increasing in the first 2000's decade, Armenteras et al. (2009) determinate that forest fires are present in all Colombian territory especially in the Caquetá and Putumayo piedmont (5000 hotspots) finding that 10% of them are in the protected areas, 3.3% in indigenous reserves, and 6.1% in forest reserves (Armenteras et al., 2009). In this period, the most affected vegetation cover was grasslands, which are twice more affected than pastures and forests, these three being the most affected coverage (Armenteras et al., 2006).

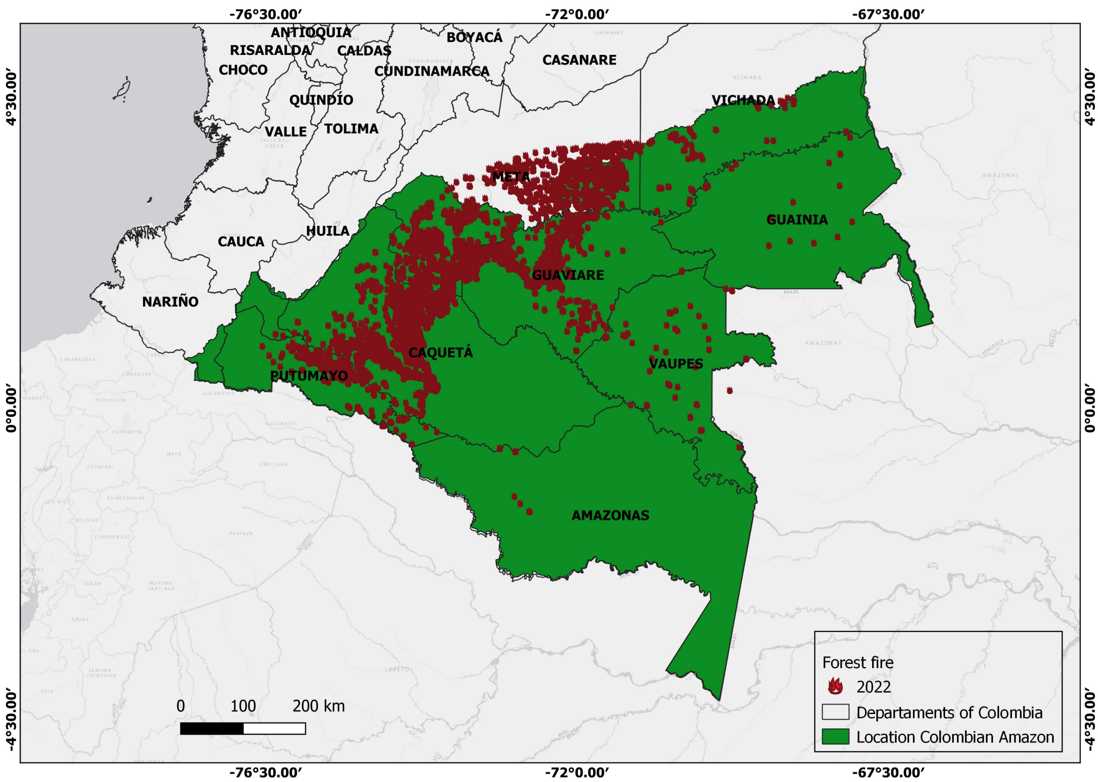

Figure 2.2: Forest fires in the Colombian Amazon in 2010-2022 with 80% of confidence

In the first half of the 2010s, the forest fires have the same tendency where forest loss since then has been concentrated along the dynamic agricultural frontiers (Figure 2.2) (Armenteras et al., 2019) and in remote areas where settlements have not yet been established and a floating colonist population moves around, creating new colonization hotspots mainly using rivers networks (Armenteras et al., 2013a). Nonetheless, since the Colombian peace agreement in 2016 and its implementation in 2018, the forest fire dynamic has been increasing (see details in Chapter 4) due to the absence of territorial control and increased accessibility to land for cultivation and grazing by both former combatants familiar with the region, as well as newcomers waiting to get large concentrations of land mainly in agricultural areas causing an intensification of deforestation (Armenteras et al., 2019; Bautista-Cespedes et al., 2021).

In addition to the coexistence of diverse land cover and land use types within a spatial context, they also exhibit a temporal interdependence, creating intricate land-use/land-cover trajectories, with certain trajectories specifically oriented towards agriculture and pastures (Eva and

Lambin, 2000). For example, forest conversion to pastures occurs through widespread fire. The forest is cut, left to dry, and burn. In the majority of cases is necessary to burn periodically the land to maintain the pasture and avoid pioneer species. On the other hand, the conversion of savannas to agriculture depends on the type of agriculture in the area. Mechanized agriculture does not use fires in its normal cycle; however, as with small and medium-scale agriculture, depending on the spatial and temporal patterns, burn patterns may occur (Eva and Lambin, 2000). On the contrary, the conversion of forest to agriculture through the use of fires is done to clear the area to facilitate the establishment of crops, especially those that use techniques such as slash and burn. However, the use of fire after land preparation depends on the cropping system and the amount of residues.

Besides the fire used in land cover/change trajectories, forest fires in the Amazon have become increasingly prevalent due to the changing weather patterns. Over the past few years, the region has experienced a rise in temperatures and a decrease in rainfall (Jain et al., 2021), creating drier and more combustible conditions, especially on December-January-February -DJF- (see details in Chapter 4) where the temperature are above the mean and the humidity is below the average. These climatic shifts, attributed to factors such as deforestation, global warming, and El Niño events, have contributed to the escalation of devastating forest fires (Albert et al., 2023). The combination of higher temperatures, reduced moisture levels, and an abundance of dry vegetation has transformed the Amazon rainforest into a tinderbox waiting to ignite. As fires spread rapidly across vast expanses of land (as trajectories mentioned before).

2.3 Drivers of forest fire dynamics

Identifying the drivers behind forest fires is paramount in understanding the causes, patterns, and trends of these devastating events. Forest fires can be triggered by a multitude of factors, ranging from natural phenomena like lightning strikes to human activities such as agricultural expansion and industrial operations, negligence, and arson. Pinpointing the drivers behind forest fires enables us to develop targeted prevention strategies, implement effective mitigation measures, and enforce appropriate regulations.

2.3.1 Meteorological Conditions

Meteorology plays a pivotal role in influencing the behavior, spread, and intensity of forest fires. Weather conditions such as temperature, humidity, wind speed, and atmospheric stability directly impact fire behavior and the potential for fire ignition and spread (Jain et al., 2021). Higher temperatures, low humidity levels, and strong winds can create an environment conducive to the rapid growth and spread of wildfires. Hot and dry weather conditions can quickly dry out vegetation, increasing its flammability and making it more susceptible to ignition. Additionally, wind plays a crucial role in determining the direction and speed of fire spread, allowing fires to move swiftly and potentially impacting larger areas. Atmospheric stability and the presence of inversions can also affect smoke dispersal, leading to health hazards and reduced visibility. Understanding meteorological factors is vital for fire prediction, prevention, and management.

The relationship between precipitation and forest fires is one of the most known even though it is complex and multifaceted. Precipitation plays a critical role in determining the fuel moisture content, which directly affects the flammability of vegetation. Generally, higher levels of precipitation can lead to increased fuel moisture, making it more difficult for fires to ignite and spread (Abatzoglou et al., 2018). Adequate rainfall can also promote the growth of vegetation, resulting in denser and more resilient forests that are less susceptible to fire. Conversely, prolonged periods of drought and insufficient precipitation create dry and highly combustible conditions, increasing the likelihood and intensity of forest fires. These dry spells can desiccate vegetation, creating abundant fuel sources for fires to rapidly propagate (Sombroek, 2001). However, it is essential to note that the relationship between precipitation and forest fires is not solely dependent on the amount of rainfall. The timing, duration, and distribution of precipitation throughout the year also play crucial roles in shaping fire regimes (Espinoza Villar et al. 2001; Abatzoglou et al. 2018).

Temperature also plays a significant role due to higher temperatures can create dry conditions, leading to increased evaporation and reduced moisture content in vegetation. This dryness raises the flammability of the forest ecosystem, making it more susceptible to fire ignition and rapid spread. As temperatures rise, the drying effect intensifies, creating a vicious cycle that further exacerbates fire risk (Jain et al., 2021). Extreme heatwaves and prolonged periods of high temperatures can desiccate vegetation, turning it into ready fuel for wildfires. Additionally, elevated temperatures can enhance the intensity of fires, making them more difficult to control and extinguish. Higher temperatures also contribute to increased evaporation rates, leading to decreased soil moisture and reduced water availability for firefighting efforts (Abatzoglou et al., 2018). As climate change continues to drive global temperature increases, the relationship between temperature and forest fires becomes even more critical.

On the other hand, humidity, the measure of moisture content in the air, is a crucial factor in the behavior and spread of forest fires. High humidity levels indicate a greater amount of moisture in the atmosphere, which helps to keep vegetation and fuels damp, reducing their flammability. In such conditions, the likelihood of fire ignition decreases, and the rate of fire spread slows down (Jain et al., 2021). Adequate humidity can also limit the availability of oxygen necessary for fire combustion. On the other hand, low humidity levels contribute to drier conditions, making the forest ecosystem more prone to fires. When humidity is low, vegetation and fuels become dry, increasing their susceptibility to ignition and facilitating the rapid spread of fires. Dry air also accelerates the evaporation of moisture from vegetation, further increasing their flammability.

2.3.2 Land Cover Conditions

Land cover plays a crucial role in driving forest fires, as it directly influences the conditions and dynamics of fire propagation. Forest fires are often exacerbated by certain land cover characteristics, such as dense vegetation, dry fuel loads, and proximity to human settlements. Forested areas with an abundance of fuel, such as dead leaves, fallen branches, and dense undergrowth, provide ample material for fires to ignite and spread rapidly. Additionally, areas with a high proportion of flammable tree species or vegetation types prone to drought and desiccation, like grasslands or shrublands, increase the likelihood and intensity of fires (Armenteras et al., 2013a). Human activities, including land fragmentation, and land-use change, can also contribute to the expansion of fire-prone land cover. These changes can disrupt natural fire regimes and lead to the accumulation of combustible materials, further fueling the risk of forest fires. Therefore, understanding and managing land cover patterns and their interactions with fire regimes are essential for effective fire prevention and mitigation strategies.

Vegetation susceptibility is a key factor in determining the vulnerability of an ecosystem to forest fires. Different types of vegetation exhibit varying levels of susceptibility based on their composition, structure, and adaptability to fire (Eva and Lambin, 2000). Some vegetation species have evolved to withstand and even benefit from periodic fires, while others are highly susceptible to ignition and rapid spread. Certain characteristics make vegetation more prone to fire. For instance, dry and dead vegetation, such as fallen leaves, dry grasses, and dead branches, can serve as readily available fuel sources. Additionally, vegetation with high resin or oil content, such as certain coniferous trees, can ignite easily and release highly combustible gases. On the other hand, moist vegetation, such as certain grasses and deciduous trees, tends to be less susceptible to ignition (Casallas et al., 2022). Moreover, the spatial arrangement and density of vegetation also influence susceptibility. Dense vegetation can create a continuous fuel ladder, allowing fires to climb from the ground to the forest canopy. Understanding the susceptibility of different vegetation types to fire is crucial for fire management and prevention efforts, including prescribed burning, fuel management, and the development of fire-resistant landscapes.

Armenteras Pascual et al. (2011) state that in the Colombian Amazon rainforest, fire-sensitive ecosystems prevail, defined as those ecosystems that do not have any natural fire intervention, in this sense they are not adapted to resist burning. Consequently, fires in these ecosystems cause enormous disturbances in the natural cycles that affect the flora and fauna. In spite of this, the predominant type of fuel in the Amazon rainforest (e.g., trees, shrubs) has a duration of up to 100 hours (Casallas et al., 2022) producing a rapid ignition due to the interstitial moisture of the tissues and the high leaf area (Armenteras Pascual et al., 2011). Apart from the Amazon forest vegetation susceptibility itself, land use transitions have been construed as constituting about a dozen processes, in the tropical zones the main processes are; Urbanization, conversion of forest/grassland to croplands, change of crops on existing cropland, incorporation of tress into cropland, conversion of cropland to forest/pasture, conversion of forest to pastures, incorporation of livestock into cropland, and, finally conversion of pastures to cropland (Figure 2.3). Transitions in land use are the result of a set of connected changes, which reinforce each but take place in several different components of the system creating multiple and reversible dynamics (Geist et al., 2006).

Some transformations in land use with high persistence of rainforest in the Colombian Amazon (99% of the cases) have transition matrices associated with forest fires (Armenteras et al., 2013b). The first significant transition, from forest to secondary vegetation is higher in fire mosaics than in the pasture mosaics, bedsides the transition from pastures to forest is higher

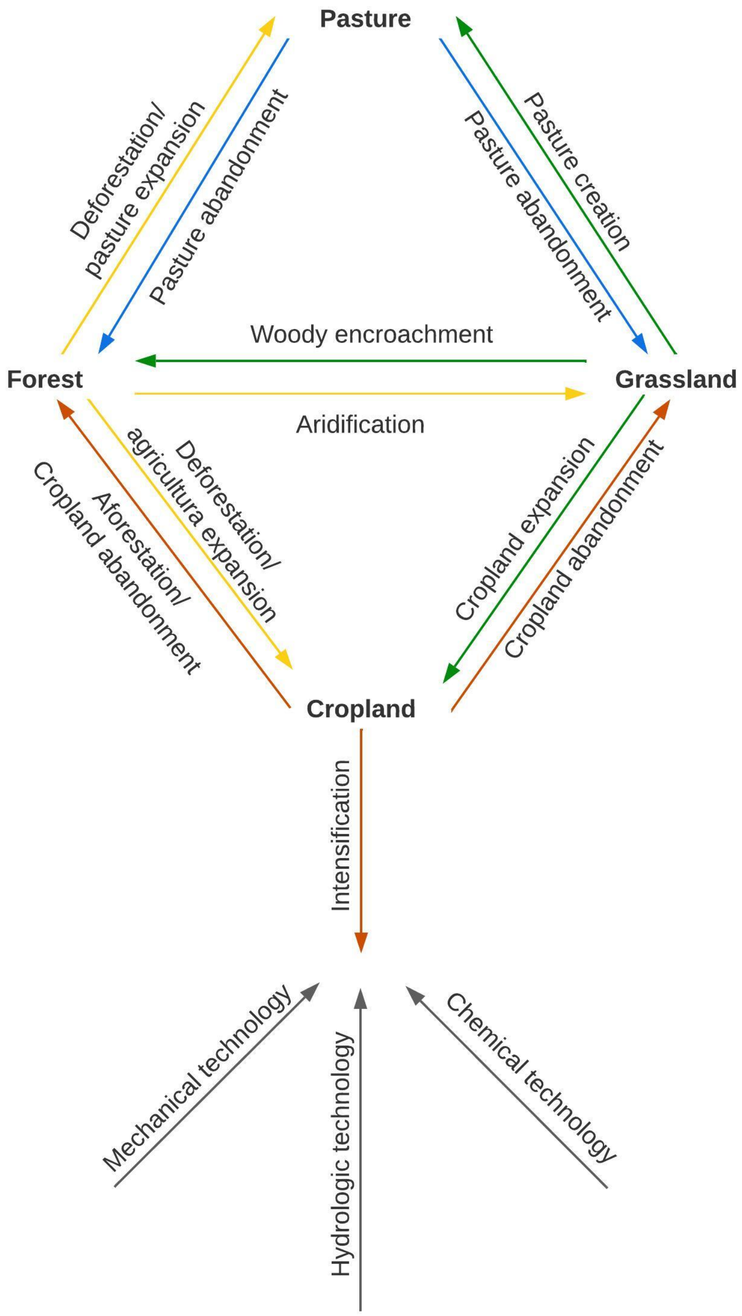

Figure 2.3: Potential transitions between two land-use/cover states. Adaptated from Geist et al. (2006)

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in the forest mosaic than in illicit crops mosaics. The transition from illegal crops to forest is significantly higher values for the forest mosaic than for the fire and especially the illicit crop mosaic (Armenteras et al., 2013b). Additionally, the pattern of fragmentation follows the colonization and development associated with the rivers (Armenteras et al., 2006) in majority of the cases, which could have a strong influence on fire development.

2.3.3 Socioeconomic conditions

Forest fires are influenced by a multitude of socioeconomic factors, such as population growth and Gross Domestic Product (GDP), which contribute to the expansion of human settlements into fire-prone regions, leading to the so-called wildland-urban interface (Casallas et al., 2022). This interface amplifies the potential for forest fires as human infrastructure intertwines with flammable vegetation. Additionally, economic factors, including demand for timber, agricultural products, and land for various purposes, can incentivize practices that heighten fire vulnerability, such as inadequate forest management and unsustainable land-use practices. Moreover, socioeconomic disparities can exacerbate fire risks, as marginalized communities may face challenges in accessing resources, education, and adequate firefighting infrastructure, leaving them more vulnerable to the impacts of forest fires.

In Colombia in the past years are being some efforts to try to establish the importance of socioeconomic variables in the Colombian Amazon deforestation. Armenteras et al. (2006) include some socioeconomic variables finding that the quality of life indicator and violence level has no significant relation with ecosystem degradation, however rural population density was the most significant determinant of ecosystem degradation. some scenarios of natural ecosystem degradation under three different projections of rural population density suggest that in 2040 between 85 and 100% of natural ecosystems will be lost (Armenteras et al., 2006). Other Socioeconomic variables are included in Armenteras et al. (2013a) where apart to contemplate urban and rural populations in deforestation analysis included unsatisfied basic needs, nevertheless, the latest in the general linear model made for deforestation at the national level has no significance, but the rural population as mentioned by Armenteras et al. (2006) has a positive relationship with the deforestation.

In addition to the variables mentioned above, Gomez et al. (2014) included the displacement to predict the influence of coca cultivation in forest fires in the Colombian Amazon. Three models where developed (Linear Probability Model, Logit and Probit) finding that displacement variable could be used by indicator of future coca increment in forest areas and, therefore, of the increase of fires to open areas for coca cultivation. The socioeconomic variables distance to the nearest navigable waterway and primary or secondary road were contemplated in Dávalos et al. (2011) finding a negative correlation between these two with the coca expansion indicating that coca does not expand in areas with high interconnectivity and tends to press the agricultural frontier leading to deforestation.

2.4 Climate Change Conditions

Climate change is a phenomenon generated by the increase of Greenhouse Gas (GHGs) emissions, these gases produce a radiative imbalance and thus generate a change in surface temperature, which modifies the energy balance and it can generate important impacts on climate extremes, e.g., heavy rains, floods and heat waves (IPCC, 2018). The Intergovernmental Panel on Climate Change (IPCC) defines climate change as a statistically significant variation in the mean state of the climate or its variability that persists for an extended period (Stocker et al., 2013). Thus, climate change is due to internal natural processes, external forcing changes, or anthropogenic changes in the composition of the atmosphere or land use. According to the United Nations Framework Convention on Climate Change (UNFCCC), Article 1 defines climate change as *a change of climate that is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods* (UN, 1992). The UNFCCC distinguishes between climate change attributed to human activities that alter atmospheric composition and "climate variability" attributed to natural causes (Stocker et al., 2013; IPCC, 2018).

Not all gases in the atmosphere have the property of functioning as greenhouse gases, the main ones being water vapor (H_2O_g), methane (CH_4), and carbon dioxide (CO_2) which are capable of absorbing large amounts of radiation and re-emitting it to the surface. Arrhenius and Holden (1897) and Manabe and Wetherald (1980) laid the foundation for understanding the importance of these gases and the role of humans in them. It is clear from this work that although CO_2 acts naturally and helps to maintain the planet at temperatures suitable for life. However, the accelerated growth of this gas, produced by humans, since the industrial revolution has considerably increased CO_2 concentrations. This growth in anthropogenic CO_2

emissions is so rapid that concentrations have increased sixfold since 1950 (Maslin, 2014).

The mechanism by which the surface heats up is associated with radiative forcing, given that under conditions without excess GHGs, two-thirds of the radiation reaching the atmosphere is absorbed by the oceans and the earth's surface in the form of shortwave radiation (Maslin, 2014). While the remainder may be returned to space in the form of long-wave (infrared) radiation emitted by the surface and clouds or absorbed by GHGs, which have the ability to (i) absorb the radiation, increase its temperature and return it to the surface, or (ii) reflect it directly back to the surface (Holton, 2004). When there is an excess of GHGs, radiative forcing increases, causing a greater amount of energy to be "trapped" in the earth and thus producing an increase in its temperature, causing a change in meteorological and climatic dynamics and all the phenomena and cycles associated with them.

This may lead to the intensification of extreme weather events such as cyclones, variations in precipitation and temperature, forest fires, natural disasters, coral bleaching, ocean acidification, loss of biodiversity (Maslin, 2014). Also to melting of polar ice caps, snow-capped mountains, permafrost ecosystems, food security, access to food and livelihood resources, where the most vulnerable populations such as indigenous communities, raizal, afro-descendants, women and poor people, will suffer with greater intensity the impacts (IPCC, 2018). Some efforts are being done with model ensemble to make projections of future meteorological conditions in the Amazon basin. Duffy et al. (2015) found that the western Amazon (location of the Colombian Amazon) will have a positive trend of precipitation, instead the eastern Amazon has the opposite trend. In this sense, seasonality projections indicate that the wettest months may become slightly wetter, and the driest months get drier. and the transition months will experiences strong drying trends.

2.4.1 Models for spatio-temporal analyses

In order to understand past, present, and future climate changes resulting from natural, unforced or in response to changes in radiative forcing, the Coupled Modeling Working Group (CMWG) created the Coupled Model Intercomparison Project (CMIP) as part of the Climate Model Diagnostics and Intercomparison Program (PCMDI) (IPCC, 2018). The new CMIP is CMIP Phase 6 (CMIP6), which has significant advances in a broader and more uneven range of climate sensitivity values contained in a large set of models run under different scenarios

(Colón-González et al., 2021) that could help understand what drives climate change, how and why it changed in the past, and what the climate may look like in the future for policymakers to make decisions around emissions mitigation and adaptation plans (IPCC, 2018). The results of the CMIP6 model ensemble are used by national and international climate organizations, including the IPCC due to its high rate of confidence and success. One of the most important features of the ensemble is associated with the different scales, variables, initial conditions, and parametrizations between models.

CANESM5-CANOE is an acronym that represents the specific configuration of the CanESM5 model used in CMIP6 project. CanESM5 (Canadian Earth System Model version 5) is developed by the Canadian Centre for Climate Modelling and Analysis (CCCma). It is a comprehensive Earth system model that simulates various components of the Earth's climate system, including the atmosphere, ocean, land surface, and sea ice (Christian et al., 2022). The "CANOE" component within CANESM5 stands for the Canadian Ocean-Sea Ice Model. It represents the specific ocean and sea ice model used in the CanESM5 configuration (Christian et al., 2022). Overall, the CANESM5-CANOE model is a sophisticated climate model that aims to simulate and project future climate conditions by incorporating various components of the Earth's system, including the atmosphere, ocean, land, and sea ice forecasting different variables in the surface. As one of the participating models in CMIP6 contributes to the broader understanding of climate change and its impacts (Christian et al., 2022).

Another model that forecast variables in surface is CNRM-ESM2-1 stands for Centre National de Recherches Météorologiques Earth System Model version 2.1. It is developed by the Centre National de Recherches Météorologiques (CNRM) in France (Voldoire et al., 2019). The model combines various components of the Earth's system, including the atmosphere, ocean, land surface, and sea ice, to simulate the interactions and dynamics that govern the Earth's climate system (Voldoire et al., 2019). This model incorporates advanced physical parameterizations, numerical techniques, and data assimilation methods to represent the processes and feedbacks within the climate system. It aims to simulate the past, present, and future climate conditions and provide insights into the response of the Earth's climate to changes in greenhouse gas concentrations, aerosols, and other external forcings (Voldoire et al., 2019).

By participating in CMIP6, the CNRM-ESM2-1 model contributes to the collective efforts of the climate science community to better understand climate change and its impacts. The model's simulations and projections can be used to study a wide range of climate-related phenomena, including temperature patterns, precipitation changes, sea level rise, and the behavior of large-scale climate modes like El Niño-Southern Oscillation (ENSO) and the Atlantic Meridional Overturning Circulation (AMOC).

IPSL-CMGA-LR is a climate model and the three one that predict variables on surface, it stands for Institut Pierre-Simon Laplace Climate Model, Global Atmosphere version - Low Resolution. It is developed by the Institut Pierre-Simon Laplace (IPSL) in France (Bonnet et al., 2021). The model combines different components of the Earth system, including the atmosphere, ocean, land surface, and sea ice, to simulate the interactions and processes that drive the Earth's climate system (Bonnet et al., 2021). The model incorporates advanced physical parameterizations, numerical techniques, and data assimilation methods to represent the complex behavior of the climate system. It aims to simulate the past, present, and future climate conditions and provide insights into the response of the Earth's climate to various factors such as greenhouse gas concentrations, aerosols, and other external forcings (Bonnet et al., 2021). By participating in CMIP6, the IPSL-CMGA-LR model contributes to the collective efforts of the scientific community to better understand climate change and its impacts. The model's simulations and projections can be used to study a wide range of climate-related phenomena, including temperature patterns, precipitation changes, sea level rise, and the behavior of large-scale climate modes such as El Niño-Southern Oscillation (ENSO) and the Atlantic Meridional Overturning Circulation (AMOC).

For this reason, for this research, an ensemble was used that included the models that have all the variables studied at the surface. Those models provided on the CMIP6 results have provided valuable insights into the potential impacts of climate change on the Amazon rainforest, which is a crucial ecosystem of global significance. CMIP6 projections indicate that the Amazon region is expected to experience significant warming under different emission scenarios. Higher temperatures can have detrimental effects on the rainforest, leading to increased stress on plant and animal species, changes in ecosystem dynamics, and increased risks of wildfires. In this sense, CMIP6 simulations suggest that the Amazon region may experience changes in precipitation patterns, including shifts in the timing, intensity, and distribution of rainfall. These changes can have profound impacts on the hydrological cycle, water availability, and ecosystem functioning within the rainforest.

2.4.2 Climate Scenarios for trends and trajectories

SSP1-RCP2.6

The Shared Socioeconomic Pathway (SSP) 1- Representative Concentration Pathways (RCP) 2.6 (SSP1-RCP2.6) is one of the scenarios used in the Coupled Model Intercomparison Project Phase 6 (CMIP6) to explore future socioeconomic and climate conditions. SSPs are narrative representations of plausible future socioeconomic developments and their associated greenhouse gas emissions. SSP1-RCP2.6 represents a world where strong climate mitigation efforts are implemented, resulting in low greenhouse gas emissions. Here are some key characteristics and features of the SSP1-RCP2.6 scenario:

- Mitigation Efforts: SSP1-RCP2.6 assumes that ambitious and effective climate mitigation policies and measures are implemented globally. These efforts lead to significant reductions in greenhouse gas emissions, including carbon dioxide (CO2), methane (CH4), and other greenhouse gases.

- Radiative Forcing: The SSP1-RCP2.6 scenario aims to achieve a radiative forcing level of 2.6 Watts per square meter (W/m^2) by the year 2100. Radiative forcing is a measure of the imbalance between incoming and outgoing energy in the Earth's atmosphere and is closely related to global temperature change.

- Socioeconomic Development: SSP1-RCP2.6 assumes a future characterized by sustainable development, with a focus on environmental conservation, energy efficiency, and renewable energy sources. It includes measures to promote social equity, reduce poverty, and enhance global cooperation on climate change mitigation.

- Energy Sources: In SSP1-RCP2.6, the energy system undergoes a substantial transformation, with a shift towards low-carbon and renewable energy sources. Fossil fuel consumption and greenhouse gas emissions decline significantly compared to baseline scenarios.

- Population and Land Use: SSP1-RCP2.6 assumes a moderate global population growth rate and a balanced distribution of urban and rural populations. It also considers sustainable land-use practices, including reforestation and afforestation efforts, to mitigate greenhouse gas emissions and enhance carbon sequestration.

Overall, the SSP1-RCP2.6 scenario represents a future world where strong climate mitigation measures are implemented, leading to low greenhouse gas emissions and a focus on sustainable development. It is one of several scenarios used in CMIP6 to explore different pathways and their implications for future climate change and associated impacts.

SSP2-RCP4.5

The Shared Socioeconomic Pathway (SSP) 2- Representative Concentration Pathways (RCP) 4.5 (SSP2-RCP4.5) is one of the scenarios used in the Coupled Model Intercomparison Project Phase 6 (CMIP6) to explore future socioeconomic and climate conditions. SSPs are narrative representations of plausible future socioeconomic developments and their associated greenhouse gas emissions. SSP2-RCP4.5 represents a world where moderate efforts are made to reduce greenhouse gas emissions. Here are some key characteristics and features of the Representative Concentration Pathways scenario:

- Moderate Mitigation Efforts: SSP2-RCP4.5 assumes that moderate climate mitigation policies and measures are implemented globally. These efforts result in some reduction in greenhouse gas emissions, although they are not as ambitious as those in more stringent scenarios.

- Radiative Forcing: The SSP2-RCP4.5 scenario aims to achieve a radiative forcing level of 4.5 Watts per square meter (W/m^2) by the year 2100. Radiative forcing is a measure of the imbalance between incoming and outgoing energy in the Earth's atmosphere and is closely related to global temperature change.

- Socioeconomic Development: SSP2-RCP4.5 assumes a future characterized by a mix of economic development pathways. It includes a range of societal, technological, and economic factors that lead to a moderate increase in greenhouse gas emissions compared to more stringent scenarios.

- Energy Sources: In SSP2-RCP4.5, the energy system sees a combination of fossil fuel use and a gradual increase in the deployment of renewable energy sources. While efforts are made to reduce emissions, fossil fuels continue to play a significant role in the energy mix, albeit with some level of decarbonization.

- Population and Land Use: SSP2-RCP4.5 assumes a moderate global population growth rate and a mix of urban and rural population distribution. Land use practices may vary, with some regions undergoing deforestation or land conversion, while others prioritize sustainable land management and conservation efforts.

Overall, the SSP2-RCP4.5 scenario represents a future world where moderate climate mitigation efforts are made, resulting in some reduction in greenhouse gas emissions compared to business-as-usual scenarios. However, the level of emissions reductions is not as ambitious as in more stringent scenarios. It is one of several scenarios used in CMIP6 to explore different pathways and their implications for future climate change and associated impacts.

SSP3-RCP7.0

The Shared Socioeconomic Pathway (SSP) 3- Representative Concentration Pathways (RCP) 7.0 (SSP3-RCP7.0) is one of the scenarios used in the Coupled Model Intercomparison Project Phase 6 (CMIP6) to explore future socioeconomic and climate conditions. SSPs are narrative representations of plausible future socioeconomic developments and their associated greenhouse gas emissions. SSP3-RCP7.0 represents a world with high greenhouse gas emissions and limited climate mitigation efforts.

Here are some key characteristics and features of the SSP3-RCP7.0 scenario:

- Limited Mitigation Efforts: SSP3-RCP7.0 assumes that limited climate mitigation policies and measures are implemented globally. These efforts result in higher greenhouse gas emissions compared to more ambitious scenarios, reflecting a continuation of current trends and practices.

- Radiative Forcing: The SSP3-RCP7.0 scenario aims to achieve a radiative forcing level of 7.0 Watts per square meter (W/m^2) by the year 2100. Radiative forcing is a measure of the imbalance between incoming and outgoing energy in the Earth's atmosphere and is closely related to global temperature change.

- Socioeconomic Development: SSP3-RCP7.0 assumes a future characterized by a fragmented global society with slow economic growth and limited international cooperation. It reflects a world where challenges such as poverty reduction, social equity, and economic development take precedence over aggressive climate mitigation efforts.

- Energy Sources: In SSP3-RCP7.0, the energy system relies heavily on fossil fuels, leading to substantial greenhouse gas emissions. Renewable energy deployment is limited, and there is a continued reliance on traditional energy sources such as coal, oil, and natural gas.

- Population and Land Use: SSP3-RCP7.0 assumes a high global population growth rate and rapid urbanization. Land use practices may vary, with some regions experiencing deforestation and land conversion for agriculture or other purposes, leading to increased greenhouse gas emissions from land-use change.

Overall, the SSP3-RCP7.0 scenario represents a future world with limited climate mitigation efforts, resulting in high greenhouse gas emissions and a continuation of current socioeconomic trends. It is one of several scenarios used in CMIP6 to explore different pathways and their implications for future climate change and associated impacts.

SSP5-RCP8.5

The Shared Socioeconomic Pathway (SSP) 5- Representative Concentration Pathways (RCP) 8.5 (SSP5-RCP8.5) is one of the scenarios used in the Coupled Model Intercomparison Project Phase 6 (CMIP6) to explore future socioeconomic and climate conditions. SSPs are narrative representations of plausible future socioeconomic developments and their associated greenhouse gas emissions. SSP5-RCP8.5 represents a world with high greenhouse gas emissions and limited climate mitigation efforts.

Here are some key characteristics and features of the SSP5-RCP8.5 scenario:

- Limited Mitigation Efforts: SSP5-RCP8.5 assumes that limited climate mitigation policies and measures are implemented globally. These efforts result in high greenhouse gas emissions, reflecting a continuation of current trends and practices without significant efforts to reduce emissions.

- Radiative Forcing: The SSP5-RCP8.5 scenario aims to achieve a radiative forcing level of 8.5 Watts per square meter (W/m^2) by the year 2100. Radiative forcing is a measure of the imbalance between incoming and outgoing energy in the Earth's atmosphere and is closely related to global temperature change.

- Socioeconomic Development: SSP5-RCP8.5 assumes a future characterized by strong economic growth, rapid population growth, and high energy demand. It represents a world where challenges such as poverty reduction, economic development, and lifestyle aspirations take precedence over aggressive climate mitigation efforts.

- Energy Sources: In SSP5-RCP8.5, the energy system heavily relies on fossil fuels, including coal, oil, and natural gas, leading to substantial greenhouse gas emissions. Renewable energy deployment is limited, and there is a continued dependence on conventional energy sources without significant decarbonization.

- Population and Land Use: SSP5-RCP8.5 assumes a high global population growth rate and continued urbanization. Land use practices may vary, with increased agricultural expansion, deforestation, and land-use change, contributing to higher greenhouse gas emissions.

Overall, the SSP5-RCP8.5 scenario represents a future world with limited climate mitigation efforts, resulting in high greenhouse gas emissions and a continuation of current socioeconomic trends. It is one of several scenarios used in CMIP6 to explore different pathways and their implications for future climate change and associated impacts.

2.5 Machine Learning Model Description

Machine learning revolutionizes artificial intelligence, enabling computers to learn from data and enhance performance. It transforms industries, from healthcare to entertainment, by recognizing patterns, making decisions, and predicting outcomes. Through algorithms and data-driven adaptation, machines automate tasks, uncover insights, and elevate capabilities, driving modern technology forward. Here we use Artificial Neural Networks (ANN) represent interconnected neural units that collectively learn from input data, optimizing their output (O'Shea and Nash, 2015), with Long-Short Term Memory and Convolutional layers. These neural units, akin to neurons in the human brain, compute when stimulus reaches a threshold. They combine input data with weighted coefficients to amplify or dampen the input (Khalil et al., 2019). The ANN architecture, encompasses input, hidden, and output layers. Activation functions introduce nonlinearity, preventing divergence (Wang, 2003). Wu et al. (2020) outline neural networks' key attributes: non-linearity, enhancing performance and fault tolerance; scalability, determined by interconnections; adaptability, self-learning and organization; dynamic, guided by state functions. Beyond pattern recognition, neural networks find utility in signal processing and optimization.

2.5.1 Convolutional

To streamline ANN complexity, Convolutional Neural Networks (CNNs) are employed, addressing intricate tasks beyond traditional ANNs' scope (Albawi et al., 2017). As Goodfellow et al. (2016) explain, CNN applies convolution—a mathematical operation—to real-valued functions with two arguments: input and kernel. The output, termed a feature map, can emerge from flipped-kernel convolution (commutative) or non-flipped (cross-correlation). CNNs combine convolution with other functions, enabling the algorithm to adapt kernel values, including flipping.

Discrete convolution mirrors matrix multiplication. In discrete univariate 1-D convolution, each row sequentially replicates the previous row, shifted by one element. 1-D CNNs suit cases with limited training data and cost-effective real-time implementation. They offer manageable training and low computational complexity while upholding performance (Kiranyaz et al., 2021). For 2-D scenarios, analogous to double-block multiplication, the matrix corresponds to 2-D CNN. Primarily used in image classification or spatially linked data, 2-D CNNs entail higher computational complexity during training, necessitate substantial datasets (Kiranyaz et al., 2021).

2.5.2 Recurrent Neural Networks - Long-Short Term Memory

The Recurrent Neural Network (RNN) employs looped networks to retain information for subsequent iterations. However, this can lead to substantial long-term learning delays (Kumar et al., 2018). Overcoming this, the Long Short-Term Memory (LSTM), a variant of RNN, mitigates such limitations by integrating multiple intermediate steps, curbing computational overhead. Detailed by Sundermeyer et al. (2012), this involves applying an activation function to 'a' followed by multiplication with factor 'b' and other adjustments.

LSTM's memory cell architecture enables prolonged information storage. The formulation employs the sigmoid function to establish three gates within the memory cell (Shewalkar et al., 2019). To simplify, a standard neural network unit 'i' encompasses activation input 'ai' and output activation 'bi', interconnected through a hyperbolic tangent (tanh) activation function Sundermeyer et al. (2012).

2.5.3 Dense Neural Network

A Dense Neural Network, also known as a Fully Connected Neural Network, features interconnected nodes between adjacent layers. Unlike specialized architectures like CNNs or RNNs tailored for tasks like image recognition or sequence processing (Casallas et al., 2022), dense connections characterize this network. Information flows from the input through hidden layers to the output, with associated weights determining connection strength (Sundermeyer et al., 2012). Non-linear transformations via activation functions shape data as it traverses these layers, facilitating intricate pattern learning (Sundermeyer et al., 2012).

Neurons in a layer receive inputs from all prior-layer neurons and employ activation functions, like sigmoid, hyperbolic tangent (tanh), or rectified linear unit (ReLU). Dense neural networks serve diverse machine learning tasks, including classification, regression, and feature extraction. However, excessive parameters with increasing connections can lead to computational burden and overfitting if not properly regularized. In essence, a dense neural network forms a foundational architecture, fully connecting neurons across layers to capture complex data relationships and patterns (Sundermeyer et al., 2012; Shewalkar et al., 2019).

3
Data and Methodology

This chapter explains the processing of the socioeconomic, meteorological, climatic and land use variables, as well as the description of the model used to identify the factors that trigger forest fires in Cartagena del Chaira. The first section describes the study area in terms of location, socioeconomic and climatic conditions, and also explains the importance of studying this area. The second section is related to the land cover analysis, explaining the selection criteria for the annual satellite images. In addition, it explains the PBCLL methodology used to classify the land cover by year and was used to determine the land cover in the study area between 2013-2021. The next section focuses on identifying the behavior and anomalies of humidity, temperature, precipitation, Total Column Water Vapor (TCWV), and wind speed, by season between 2013-2021 and their relationship with forest fires.

To contemplate the impact of climate change on the behavior of meteorological variables, the fourth section describes the models, scenarios and historical data (1984-2014) selected to predict different scenarios until 2049 in order to identify anomalies with current meteorological data and their potential impact on forest fires under climate change. The identification of drivers was done through the model description section where the Machine Learning (ML) tool is explained in terms of input data, structure, training process and validation. Subsequently, the selection of scenarios is determined to analyze the influence of each variable on forest fires. These scenarios and the climate analysis were used to develop the proposed strategies using a methodology that takes into account already design strategies, policies and plans by the government explained in depth in section 3.7. Finally, the delimitation, limitations and assumptions necessary to develop the methodology are explained in section 3.8.

3.1 Study Area

Cartagena del Chaira (1.336111, -74.846667) is a municipality of the Department of Caquetá, located in southern Colombia within the Colombian Amazon (Figure 3.1). The region has 32000 inhabitants in 12826 km^2 where the Caquetá River runs through the municipality and the Caguán River surrounds it on the east side. There are three morphological units present: the eastern flank of the Eastern mountain range, the foothills, and the Amazon plain (Murad and Pearse, 2018), where wetlands and tropical rainforest are the main ecosystems allowing a high rate of biodiversity and endemism (Peel et al., 2007). Likewise, according to the Institute of Hydrology, Meteorology and Environmental Studies (IDEAM, Spanish acronym), the average temperature is 25°C, while annual precipitation is 2500 mm, with a unimodal regime due to the ITCZ and biological factors that cause high evaporation and humidity rates, with the driest season being December, January and February and the wettest April, May and June (Guzman et al., 2014).

Serranía del Chiribiquete National Natural Park is one of the most important protected areas on the Colombian Amazon, Cartagena del Chaira has 303981 ha (10% of the total area), as well as areas of ecological importance giving particular significance to this zone (UNESCO, 2017). Despite this, there is a subtraction area in the municipality where the settlement was legalized in 16200000 ha of forest reserve, a zone in which, in principle, an adequate, harmonious and respectful intervention of the natural environment would be carried out, allowing acceptable productivity for human settlements, for which the land use of the forest reserve could be changed for reasons of public utility, social or economic interest (Instituto Nacional de los Recursos Naturales Renovables y del Ambiente, 1985).

This particular legal status allowed human colonization and the expansion of licit and illicit agricultural areas, making it an important zone in the context of the armed conflict and its subsequent termination after the peace agreement. According to the DANE, Cartagena del Chaira is the second largest contributor to the department's economy, basing its economy mainly on the primary economy (i.e., agriculture, hunting, silvicurture, fishing and mining) and the tertiary economy (i.e., generation of gas, electricity, water and services) contributing 6% of the

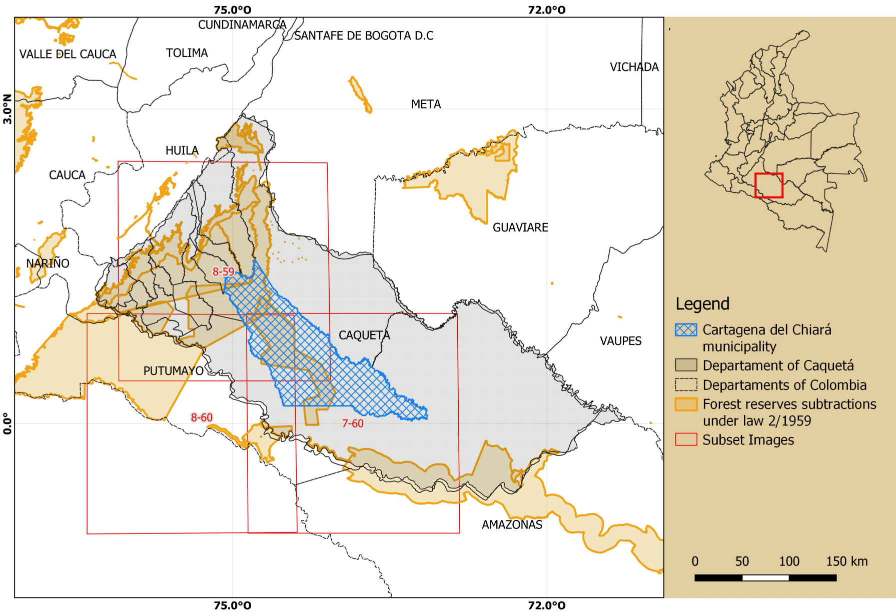

Figure 3.1: Cartagena del Chaira location.

national GDP (DANE, 2021). All these factors allow for interesting socioeconomic, land use and forest fire dynamics in this municipality that may be crucial in determining the fire drivers in this zone.

3.2 Land Cover and Land Use Analysis

The prevalence of clouds in the tropics makes challenging data selection regardless of satellite data resolution (Murad and Pearse, 2018). However being able to study the change in Land Cover is determining to establish a relationship with forest fires drivers, hence here used Landsat 8 Level 2, Collection 2, Tier 1 images provided by United States Geological Survey (USGS). This images contains atmospherically corrected surface reflectance and land surface temperature derived from the data produced by the Landsat 8 OLI/TIRS sensors (USGS, 2023) to reduce the cloud interference.

Cartagena del Chaira Landsat 8 images were downloaded using Python3 through Google Earth Engine (GEE) API. Multi-scene ensemble (see red rectangles of Figure 3.1 for spatial location) per year in the period 2013-2021 with less than 20% cloud cover was used (Table 3.1). Visible bands: Blue (B2), Green (B3), Red (B4), Near Infrared -NIR- (B5) band, Shortwave

Infrared bands -SWIR 1- (B6), -SWIR 2- (B7) and Normalized Difference Vegetation Index (NDVI) were downloaded with 30 meters resolution to be processed and find land cover classification in Cartagena del Chaira.

Year	Path/Row	Date (dd/mm)
2013	7/60	23/11
	8/60	11/09
	8/59	11/09
2014	7/60	31/03
	8/60	19/12
	8/59	19/12
2015	7/60	26/09
	8/60	20/11
	8/59	20/11
2016	7/60	01/02
	8/60	11/03
	8/59	11/03
2017	7/60	19/02
	8/60	25/01
	8/59	25/01
2018	7/60	18/09
	8/60	09/09
	8/59	24/08
2019	7/60	25/02
	8/60	10/07
	8/59	04/05
2020	7/60	27/01
	8/60	22/03
	8/59	22/03
2021	7/60	29/01
	8/60	17/09
	8/59	28/05

Table 3.1: Satellite data specifications used in Cartagena del Chaira, Caquetá-Colombia.

3.2.1 Land Cover Classification

The mosaic classification was applied to the subset images for each year using the Phenology-based Land Cover Classification (PBLCC) (Simonetti, E and Simonetti, D and Preatoni D, 2014). The PBLCC approach was applied because it has been successfully used for previous Landsat classification in tropical regions and specifically in Colombia, because it accounts for seasonality (Casallas et al. 2022,Muñoz-Brenes et al. 2018, Simonetti, E and Simonetti, D and Preatoni D 2014) and provides an accurate analysis that allows the correct identification of drivers. The PBLCC has thirteen (13) classes (Table 3.2) that are used to classify pixel by pixel each mosaic by an algorithm that uses the aforementioned bands. Comparison of the PBLCC maps produces a cross-tabulation analysis to show quantitative "from-to" percentage and area changes by category was done annually on a pixel-by-pixel basis as well. Although Land cover is of high importance for forest fires, it is not the only variable, meteorology, climatological, and socio-economical variables can be essential to understand wildfire dynamics, which is why they are centered in the next three sections.

Class ID	PBLCC Class	Description
WAT	Water	Deep Water bodies/Rivers (DWAT/SWAT)
SI	Snow	Snow / Ice
DWAT	Water	Deep Water bodies/Rivers (DWAT/SWAT)
CL	Clouds	Clouds
SV	Shadowed Vegetation	Shadowed / Low Illuminated Vegetation
SS	Shadowed Soil	Shadowed Soil / Burnt Areas
SPV	Sparse vegetation	Sparse Grassland/Sparse Shrub
OLD	Other Land Dark	Dark soil/rocks/sand
OLL	Other Land Light	Light soil/rocks/sand
TCD	Tree Cover Dark	Dense Forest/Dense Shrub
TCL	Tree Cover Light	Open Forest/Shrub
SHR	Shrub	Dense Shrub
GRS	Grassland	Dense Grassland/ Open Shrub

Table 3.2: PBLCC classification.

3.3 Meteorological Analysis

Meteorology is very important to study the development of forest fires (e.g., Jain et al. 2021). This is why, first, data from the European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis (Hersbach et al., 2020) is downloaded with an hourly time resolution, and a spatial resolution of 0.25x0.25 degrees ($\approx$22.5km^2) for the air temperature, wind speed, relative humidity and TCWV for the period between 2010 to 2022. Hotspots information is used from the Fire Information for Resource Management System (FIRMS), measured with the Moderate Resolution Imaging Spectroradiometer (MODIS) (NASA, 2023), and with the Visible Infrared Imaging Radiometer Suite (VIIRS), for a period between 2002 to 2022. After downloading the data, it is pre-processed the hotspots data, by removing the data points with less than 80% of confidence in the measurement (Casallas et al., 2023) and with temperatures > 400 K (Kaufman et al., 1998), in order to identify those hotspot that are forest fires. Then the data is split into days with (hereafter fire days) and without (hereafter non-fire days) hotspots, since hotspots serve as a proxy to forest fires. These two data batches are then divided depending on their seasonality, producing a data batch per season (i.e., DJF, MAM, JJA and SON) and also per type of event (i.e., with and without fires). Using these separated data we perform two analyses, which are described below.

1. Having the data separated into seasons and events, we proceed to calculate composite means of air temperature, wind speed, relative humidity and TCWV, for each season and event. This produces 8 maps per variable, 4 of them related to fire events and 4 related to non-fire days. Then from each fire day composite, the non-fire day composite is substracted, producing an anomaly per variable and per season. In terms of precipitation, the composites are the seasonal sum of the fire and non-fire days. Then the precipitation anomaly is calculated following the procedure of the other variables. This method allows us to determine the atmospheric characteristics when a fire event is developing, also accounting for seasonal changes.

2. Boxplots are plotted for each variable and season, accounting for the fire and non-fire days. This procedure would complement the anomalies and would also show the significance of the atmospheric characteristics between both events. To complement this boxplot analysis an Analysis Of Variances (ANOVA) is implemented to calculate if the mean difference between the two events is statistically significant.

These analyses are then complemented with climate change scenarios (section 3.4), to help describe the possible risk that would develop in the future.

3.4 Climate Change Analysis

The database was downloaded from the CMIP6 project explained in chapter 2 using an ensemble constructed with three (3) models (CANESM5-CANOE, CNRM-ESM2-1, and IPSL-CMGA-LR) for four (4) different climate change scenarios (SSP1.26, SSP2.45, SSP3.70, and SSP5.85, see section 2 for details of the scenarios and models) in the period 2015-2049. The models and scenarios were carefully selected, considering the surface data availability of the study variables and the possibility of comparing the scenarios to analyze how future climates would impact the development of forest fires. The ensemble reduces the uncertainty related to the models' initial conditions, resolution and parameterizations. Simulation outputs are available on the servers of ECMWF, through the Climate Data Store (CDS) platform. This center provides access to model outputs according to the selected climate change scenarios. There are two ways to access the servers: (i) manually or (ii) using an Application Programming Interface (API). For this research, the API was used because it allows downloading data in an efficient way. To access the API, the Python3 library *cdsapi* was used, which allows requests to be made to CDS for variables, periods, models and areas of interest. For this research, (5) meteorological variables (i.e., precipitation, temperature at 2m, relative humidity, total column water, and wind speed) were downloaded.

The data were downloaded for two time periods, the historical (1984-2014), and the simulated future (2015-2049) with a monthly temporal resolution and a spatial resolution of 0.5x0.5 degrees, for the department of Caquetá (Lon: -74.8831, -72.7652; Lat: -1.1016, 2.9873). This, in order to calculate the differences of the selected variables between the historical period and the simulated future period, something that hereafter is called anomalies. The anomalies are defined as the subtraction between the climatology of the historical period and the climatology of the future period. In other words, the temperature anomaly is calculated by subtracting the average temperature of each pixel in the historical period from the average temperature of each (same) pixel in the simulated period. The same procedure is used for relative humidity, wind speed, and TCWV but not for precipitation. In the case of precipitation, it is first accumulated annually, and then averaged for each period, in order to be subtracted (Casallas et al., 2023). The anomalies serve as input to produce maps that allow analyzing spatial differences and also magnitudes of changes that can be compared with the atmospheric conditions when a wildfire is developing, giving an idea of the future behavior of the wildfires in the region of interest.

3.5 Socio-economic and Territorial Data

Taking into account the variables mentioned in the previous chapter including in a socioeconomic drivers analysis and in order to improve and make a more complete socioeconomic driver selection, here were used twelve socioeconomic variables. For this reason, the following paragraphs explain why variables were chosen, their definition and where were obtained.

Demographic information (Urban and Rural Population) was obtained from the municipalities' population census made by National Administrative Department of Statistics (DANE, Spanish acronym) and its projections to avoid gaps in the data, defined as the number of people in Cartagena del Chairá (DANE, 2023c). The economic data was also obtained from DANE and are three variables. First, GDP was taken from the quarterly financial reports of the municipality by percentage, represents the combined value generated by all domestic producers in an economy, including product taxes and excluding subsidies that are not accounted for in the product value. The calculation does not include deductions for the wear and tear of manufactured assets or the depletion and deterioration of natural resources (The Word Bank, 2023a).

Second, Informal Work is described as the Percentage of the total population that fill in one or more of the following categories (i) Private employees and laborers working in establishments, businesses or enterprises that employ up to five persons in all their agencies and branches, including the partner, (ii) unpaid family workers, (iii) unpaid workers in enterprises or businesses of other households, (iv) domestic employees, (v) day laborers or laborers, and (vi) self-employed workers working in establishments up to five persons, except independent professionals, employers in enterprises of five workers or less, Government workers or employees are excluded (DANE, 2023a). Finally, the third economic variable obtained as well from DANE is Long Term Unemployment refers to people who have been unemployed for 12 months or more (DANE, 2023b). Informal Work and Long Term Unemployment are part of the indicators of the Multidimensional Poverty Index (MPI) by DANE, for this reason, they are in percentages, and were taken separately for the rural and urban populations in order to make a more specific analysis into Cartagena del Chairá (DANE, 2023a).

In order to contemplate Educational variables that could be related to forest fires Low Educational level indicator from MPI was taken. It is defined as the percentage of the population with less than 9 years of education (DANE, 2023a). For the Poverty category two variables were included, the GINI coefficient taken by DANE every month was included to contemplate monetary poverty as a measure of the distribution of income among households (in this case) within the economy. Thus a GINI index of 0 represents perfect equality, while an index of 1 implies perfect inequality (The Word Bank, 2023b). The other variable in the poverty category is a MPI, this is an integrated index that allows the analysis of multiple dimensions of poverty that are experienced simultaneously by households, grouping 15 indicators in 5 categories: educational conditions of the household; conditions of children and youth; work; health and access to public utilities and housing conditions. Each dimension has the same weight (20%) in the index and each indicator has the same weight within each dimension (Oviedo et al., 2021). Thus, when a household, and all the people who compose it, present deprivations in at least 5 of the 15 indicators (33.3% of the MPI) according to the cut-off point defined for each indicator, it is considered multidimensionally poor (Angulo et al., 2020).

Finally, the variables associated with victims of armed conflict were obtained from the Observatory of Memory and Conflict (OMC). The first variable, related to Massacres, is understood as the intentional homicide of four (4) or more people in a state of defenselessness and in equal circumstances of mode, time and place, and which is distinguished by the asymmetrical relationship between the armed actor and the civilian population, without interaction between armed actors (CMO, 2023). Forced Disappearance is the deprivation of the freedom, against the will (arrest, detention, kidnapping or hostage-taking) by agents of the State, members of illegal armed groups that take part in the armed conflict, or with their authorization, support or acquiescence, followed by their concealment and/or refusal to acknowledge such deprivation or to provide information on their whereabouts, removing them from the protection of the law (Congreso de Colombia, 2000).

Recruitment of Children and Adolescents is understood as when minors under 18 years of age are forced to participate directly or indirectly in hostilities or armed actions for the purpose of armed conflict (Congreso de Colombia, 2000). While, displacement, was obtained from the Center for Economic Development Studies (CEDE, Spanish acronym) for the period 2013-2017 and from the United Nations Office for the Coordination of Humanitarian Affairs (OCHA) for the period 2018-2021. It is defined as a situation where a person has been forced to migrate within the national territory, abandoning their home or usual economic activities, because their life, physical integrity, personal safety or freedom have been violated or are directly threatened by any of the following situations: internal armed conflict; internal disturbances and tensions, generalized violence, massive violations of Human Rights, violations of International Humanitarian Law or other circumstances arising from the above situations that may drastically alter public order (Congreso de Colombia, 1997).

3.6 Drivers Identification: Model Description

3.6.1 Feature Selection

Forest fires are difficult to simulate due to the large number of variables that are related to them. Several studies (e.g., Jain et al. 2021, Casallas et al. 2022) have shown that fires are highly affected by meteorological conditions such as air temperature, humidity and wind speed. Being the former two the most important since the amount of water and the temperature can produce favorable conditions for a fire to develop and start. In fact, in Colombia, seasonal changes are the ones that produce the largest modification to the number and location of wildfires, since the humidity and temperature change depending on the ITCZ. This means, that places far from the ITCZ develop a larger number of fires, since there are not many moisture sources, the temperature is stronger and not many convective events develop, leading to small amounts of precipitation (Guzman et al., 2014). This is the reason were included the wind speed, air temperature, relative humidity and total column water vapor. These last two, are included to account for the amount of moisture but also its relative value. The fires, not only depend on meteorology, they also depend on the fuel (land cover) and the socioeconomic variables.

On one hand, the land cover is important since the type of vegetation can be favorable to the development of forest fires (e.g., Murad and Pearse 2018, Albert et al. 2023), which is why we include the land cover categories in the model. On the other hand, fires in Colombia are highly related to socioeconomic variables since the socioeconomic dynamic could produce enormous changes in the dynamics of the fire (Bautista-Cespedes et al. 2021, Quan et al. 2022, Gomez et al. 2014). Socioeconomic data were carefully selected based on the monthly available data and representative ones for 2013-2021 from governmental agencies, taking into account those variables studied in previous studies related to land changes and forest fires (Bautista-Cespedes et al. 2021, Quan et al. 2022, Gomez et al. 2014), as well as considering those that were never studied and could have incidence in forest fires drivers. Also those without gaps in the study period at the municipality level in order to be able to analyze which high accuracy of the relationship with Forest Fires in Cartagena del Chaira. For this reason, some variables that could have incidence in forest fires were not considered.

Table3.3 shows the twelve (12) studies of socioeconomic variables (see chapter 2 for the definition of each one) in Cartagena del Chaira and their source. It is important to mention that the author created her own database with all the variables between 2013-2021 by month to be used in the model.

Category	Variable	Expression	Source
Demographic	Urban Population Rural Population	Number of people	Population and back projections
Economic	GDP Informal work Long-Term Unemployment	- Percentage Percentage	Trimester GDP Informal Work Indicator Long Term Unemploymeny Indicator
Education	Low Educational Level	Percentage	Low Educational Level Indicator
Poverty	GINI Multidimensional poverty	- -	Monetary poverty MPI
Victims Armed Conflict	Massacres Forced Disappearance Child and Adolescent Recruitment Displacement	Number of people	Victims Database CEDE Database and OCHA Database

Table 3.3: Socioeconomic variables studied between 2013-2021 in Cartagena del Chaira, Caquetá associated with forest fires drivers.

3.6.2 Input/output matrix description

After the VIF method is performed, five meteorological variables (i.e., Air temperature, Relative humidity, Precipitation, TCWV and wind speed), eight socioeconomic variables (i.e., Population, GDP, Informal work, Long-Term Unemployment, low Educational Level, GINI, Displacement, Victims Armed Conflict) and the land cover are selected as inputs for the ML technique designed. The meteorological variables have an hourly resolution, different from the socioeconomic ones that are collected monthly, which means that for the model the variables are hourly static but change dynamically every month. The same is true for the land cover, which has a yearly resolution, so its input is static but changes monthly. All the variables are integrated into the ERA5 data spatial resolution before entering to the model. The X-Tensor (input) includes the aforementioned variables with their related temporal and spatial resolution. The Y-matrix (output) is created by the air temperature from the ERA5 data but includes the brightness temperature from the hotspots of the MODIS dataset. In other words, we took the brightness temperature from hotspot, and its position and replaced it into the same position as the ERA5 data, to be sure that the output include forest fire values for detection.

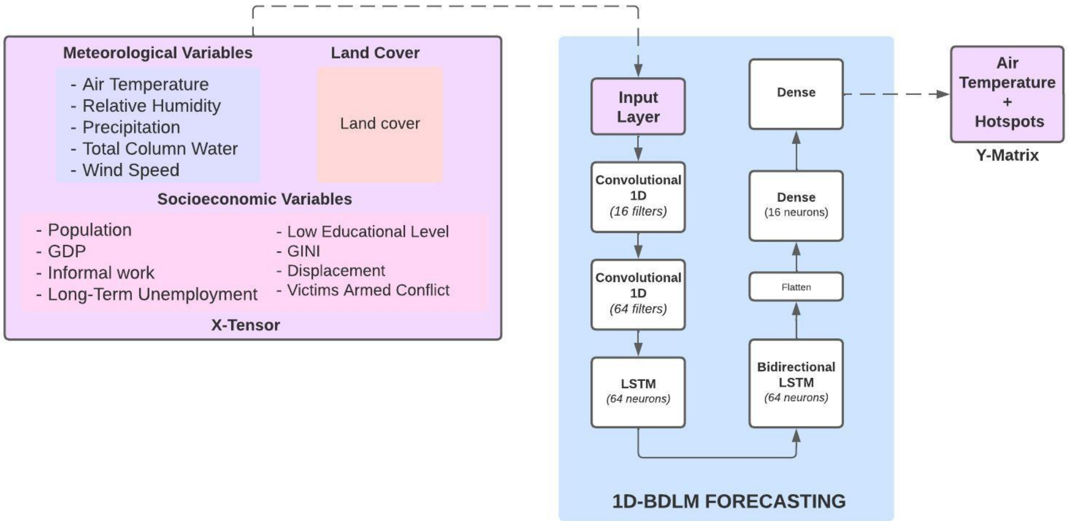

Figure 3.2: Neural network structure. Notice that every box has the number of neurons/filters in the layer and that the dropout percentage of a layer is also indicated.

3.6.3 Structure, training and validation

The Neural Network model structure is shown in Figure 3.2 with its inputs and output. The model is constructed using Tensorflow-2.4.1 (Abadi et al., 2015) and Keras-2.4.3 (Chollet et al., 2015) libraries from Python-3.9. Its structure and type of networks are shown in Figure 3.2 and were identified by using grid-search and it is based on Celis et al. (2022) convolutional network structure. The loss selected is the Mean Square Error (RMSE), Adam (Kingman and Ba, 2014) is used as an optimizer and for the activation, the dense layer used ReLu (Fukushima, 1975), meanwhile the LSTM layers (Hochreiter and Schmidhuber, 1997) used sigmoidal (Cybenko, 1989).

For the training we use 50 epochs, and it is declare if the variables are static or dynamic in order for the training to produce the best results, as was previously done by Agudelo-Hz et al. (2023). The training set consist on 80% of the data and the remaining 20% is used for validation. From this 20% we make sure to include days with and without wildfires, and at least 5 days per month, with emphasis on days from DJF and MAM season. To prevent overfitting we include dropouts but also an Early stopping method (Ndiaye et al., 2019).

To validate the model we calculate RMSE – equation 3.1, the Mean Bias Error (MBE) – equation 3.2, and the Pearson Correlation (r) – equation 3.3, from the domain mean, so that we only have a time series of data, in which the wildfires can be identified.

$$RMSE(x,y) = \sqrt{\frac{\sum_{i=0}^{N-1}(x_i - y_i)^2}{N}} \tag{3.1}$$

where, x represents the prediction, y is the observation, i is each of the data points in the calculation, and N is the total number of data points.

$$MBE(x,y) = \frac{1}{n}\sum_{i=0}^{N}(x_i - y_i) \tag{3.2}$$

The variables here are the same as in equation 3.1

$$r(x,y) = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2 \sum_{i=1}^{n}(y_i - \bar{y})^2}} \tag{3.3}$$

The variables of this equation are the same as equations 3.1 and 3.2 but with the addition of $\bar{y}$ and $\bar{x}$ that represent the mean of the observations and the predictions, respectively.

3.7 Propose Strategies

ML have been used for a large number of applications, some of which have focused on the prediction of meteorological variables (Tompkins and Semie, 2021), air quality (Celis et al., 2022) and wildfires (e.g., Coughlan et al. 2021), producing reliable forecasts and showing their potential to be used to understand the importance of several variables (McGovern et al., 2019), and also to create sensitivity experiments that could be used to evaluate strategies or scenarios (Casallas et al., 2023; Agudelo-Hz et al., 2023). Casallas et al. (2023) performed sensitivity analyses to understand the tropospheric ozone variations due to the COVID-19 lockdowns, showing the potential of ML to process understanding. Following this research road, Agudelo-Hz et al. (2023) use a ML model to create scenarios of land cover change depending on possible future conditions and evaluate their possible impacts on the Amazon. Here we use a hybrid of these two approaches to determine which meteorological and socio-economic variables must be measured, evaluated and in the case of the socio-economic variables improved by, for example, enacting policies, or creating employment.

In this sense, we modify all the input variables of the ML model (Figure 2) except the air temperature. To do this, we increase/decrease each variable by 30%, to then quantify the change between the control prediction and the experiments, using Bland-Altman plots (Altman and Bland, 1983; Bland and Altman, 1986). This, with the idea of identifying the variables that produce the largest sensitivities to the wildfires and also in order to create strategies that could help to efficiently mitigate the number of wildfires. Regarding the aforementioned strategies, they are developed based on the already existing policies and plans of the study region (e.g., Vargas-Correa 2019), but they are also designed to complement them.

3.8 Delimitation, Limitation and Assumptions

The methodology is focused on an Amazonian municipality in Colombia, taking into account the data available and relevant to this specific context. However, it may be replicated in other municipalities even at the national and/or regional level. Nonetheless, it is important to take into account some limitations and assumptions that must be made to achieve the development of this research. In order to prioritize high-quality satellite images, the image taken from path/row 7/60 was taken on another date to achieve a cloud cover less than 20%.

On the other hand, the main limitations are related to the socioeconomic data, due to the need to have monthly data for each variable, for this reason, some variables such as; Population, Informal Work, Long Term Unemployment, Low Educational Level it was necessary to assume that through the months those values do not change. In the case of GDP, the trimester GDP was the most specific value obtained by DANE, for this reason, this value was divided into three and put for the months of the trimesters as appropriate. For the controller experiments in the ML model when land cover is changed it was assumed that all pixels in the mosaic are transformed into the same category to make possible a good performance of the model and to make a selection a number of experiments to work with, otherwise, each pixel would have 12 possible categories each year.

4

Results and Discussion

This chapter commences with an account of the progression of wildfires in Cartagena del Chairá. Subsequently, our focus shifts to illustrating the prevalent meteorological conditions during wildfires occurrences in the region, aimed at comprehending the driving factors behind these incidents. We proceed to elucidate the vegetation cover that exhibits a stronger correlation with fire development in the region, as well as the interplay between vegetation and human practices. Following this, a climatological analysis is performed for the near future (up to 2049) to discern potentially heightened wildfire risks arising from atmospheric conditions. Concluding this section, we subject a ML model to assessment and subsequently employ it to appraise strategies. These strategies illuminate potential avenues for mitigating the risk associated with fires in the region.

4.1 Forest Fires temporal behavior and meteorological conditions

Forest fires in Cartagena del Chairá through the years have been rising significantly (Figure 4.1), showing a positive tendency. In 2018 there are a peak (+1000 hotspots), coinciding with the FARC-EP demobilization as a result of the peace agreement signed in 2016. In the following years number of forest fires decreased but still are higher than in previous years, in 2022 was present another peak in the first quarter of the year that could be attributed to different

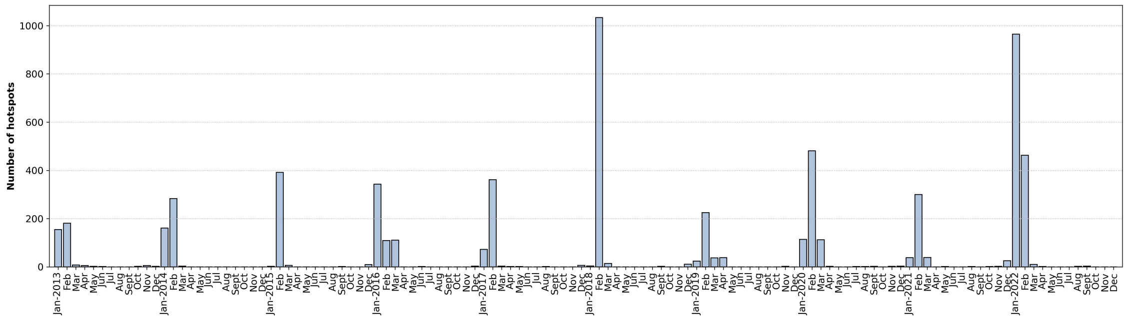

Figure 4.1: Cartagena del Chairá forest fires behavior.

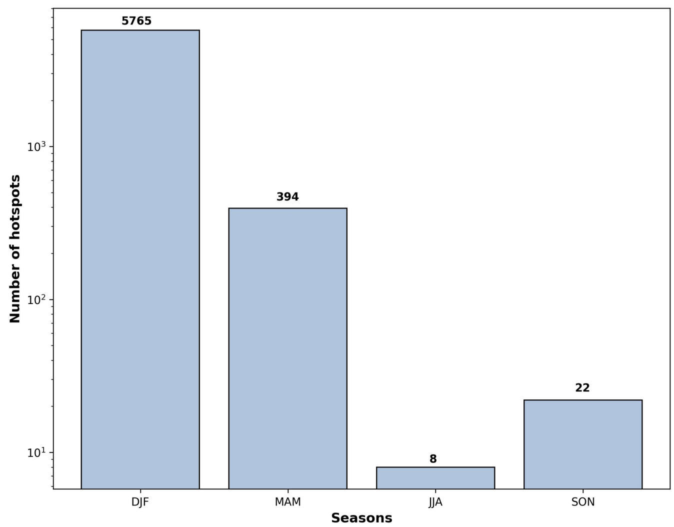

Figure 4.2: Cartagena del Chairá forest fires behavior by seasons.

socio-environmental causes. In thi sense, there is a clear behavior over the years in Cartagena's del Chairá Amazon forest (Figure 4.2), where DJF and MAM are the seasons with the largest number of hotspots, whereas the seasons with fewer fire days are JJA and SON during the studied period, suggesting that different behavior between seasons could be promoted in part for some meteorological variables that are changing over the year.

Forest fires' spatial location (Figure 4.3) since 2010 follows a tendency, there are located northwest of Cartagena del Chairá and surrounding the river Caquetá. This behavior is influenced by the subtraction zone (see Figure 3.1 for spatial location) due to it allows landcover change from native forest to agricultural and cattle practices, principally. Those practices are being expanded and being more intense through the years and the farmers, peasants even large

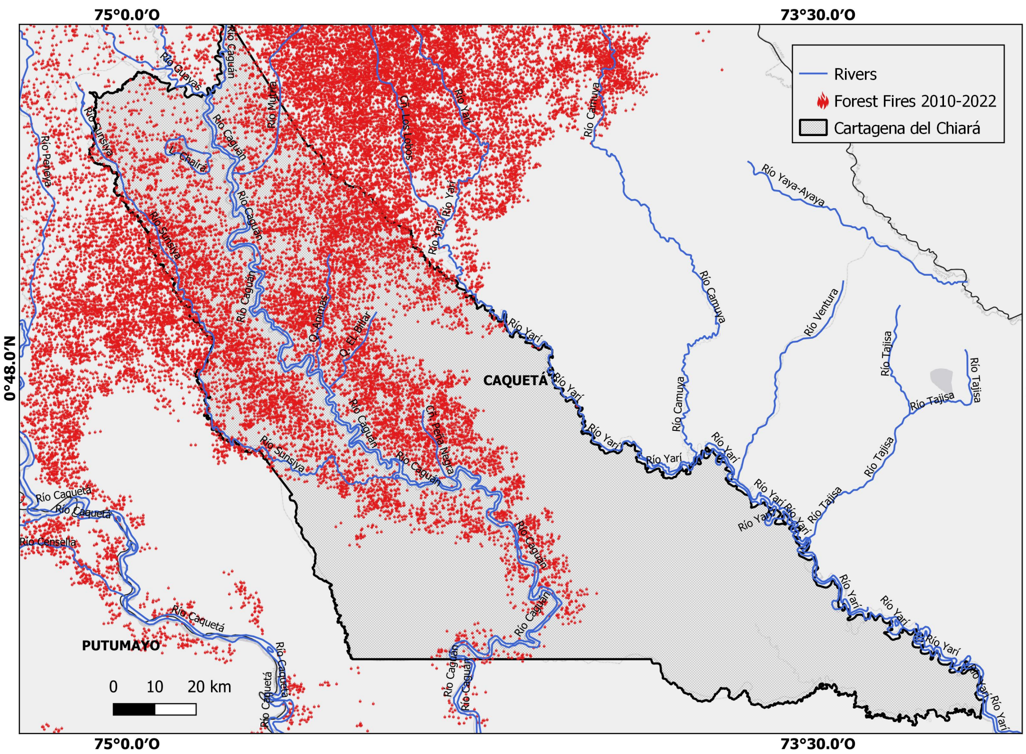

Figure 4.3: Forest Fires Spatial location on Cartagena del Chairá.

industries used fires as slash and burn technique as the fastest and cheapest way to clear the terrain to plant new crops, expand existing ones, and/or introduce new activities in the area (Armenteras et al., 2019). Despite these practices being legally constituted by the subtraction law (Instituto Nacional de los Recursos Naturales Renovables y del Ambiente, 1985), over the years, especially on the boreal winter (DJF and MAM) are rising forest fires due to a set of circumstances that affects the communities and the Amazon.

For this reason, meteorological variables were analyzed for Cartagena del Chairá in order to determine the differences between seasons and non-fire and fire days on the forest fires development. The first variable analyzed was the temperature, showing that fire days have a higher yearly maximum (310 K) and the median (298 K) is up to quartile Q3 of non-fire days (Figure 4.4a). Regarding seasonal analysis especially those with the highest number of forest fires (DJF and MAM), was found that they have similar behavior, on fire days have the shortest maximums and highest minimums, also the median in both seasons is 300 K, while the quartile Q1 is

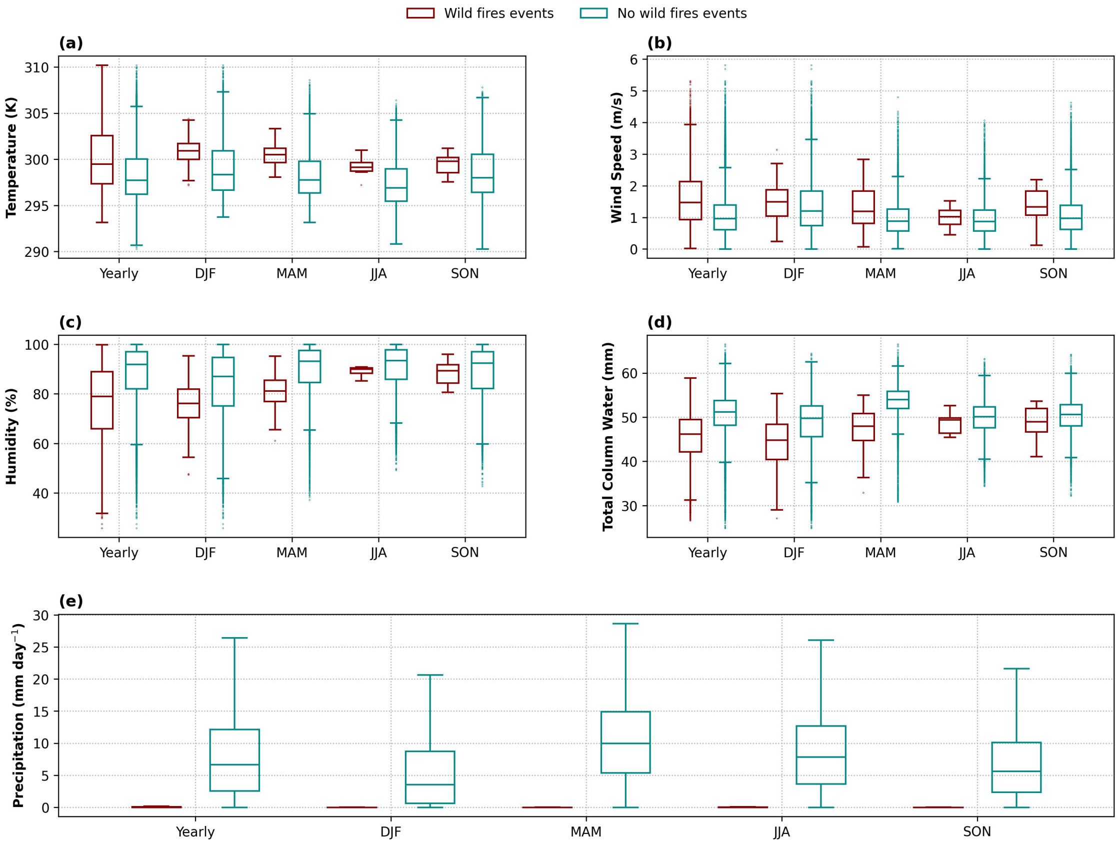

Figure 4.4: Boxplot to meteorological variables in Cartagena del Chairá split by non-fire days and fire-days.

up to non-fire days Q3. Those seasons present a positive anomaly (Figure 4.5a and Figure 4.5b) showing values up to 5 K with the maximum on the northwest, especially in MAM where the hotspots are mostly concentrated in this zone and season. In contrast, JJA (Figure 4.5c) and SON (Figure 4.5d) presents a mild positive anomaly with values around 2 to 0 K, which suggests that in those seasons the temperature does not increase too much and for this reason, forest fires occur in a lower quantity and magnitude.

The wind speed on fire days has a higher yearly median compared to non-fire days (Figure 4.4b). In relation to the seasonal behavior, DJF on fire days has a median above non-fire days, while MAM and SON have a fire days median above the quartile Q3 of non-fire days. On the contrary, in JJA the behavior is similar in non-fire days and fire days (Figure 4.4b) this could be important taking into account this is the season with fewer forest fires events. The anomaly has positive values (up to 3 m/s) in DJF, MAM, and SON (Figure 4.6a, Figure 4.6b,

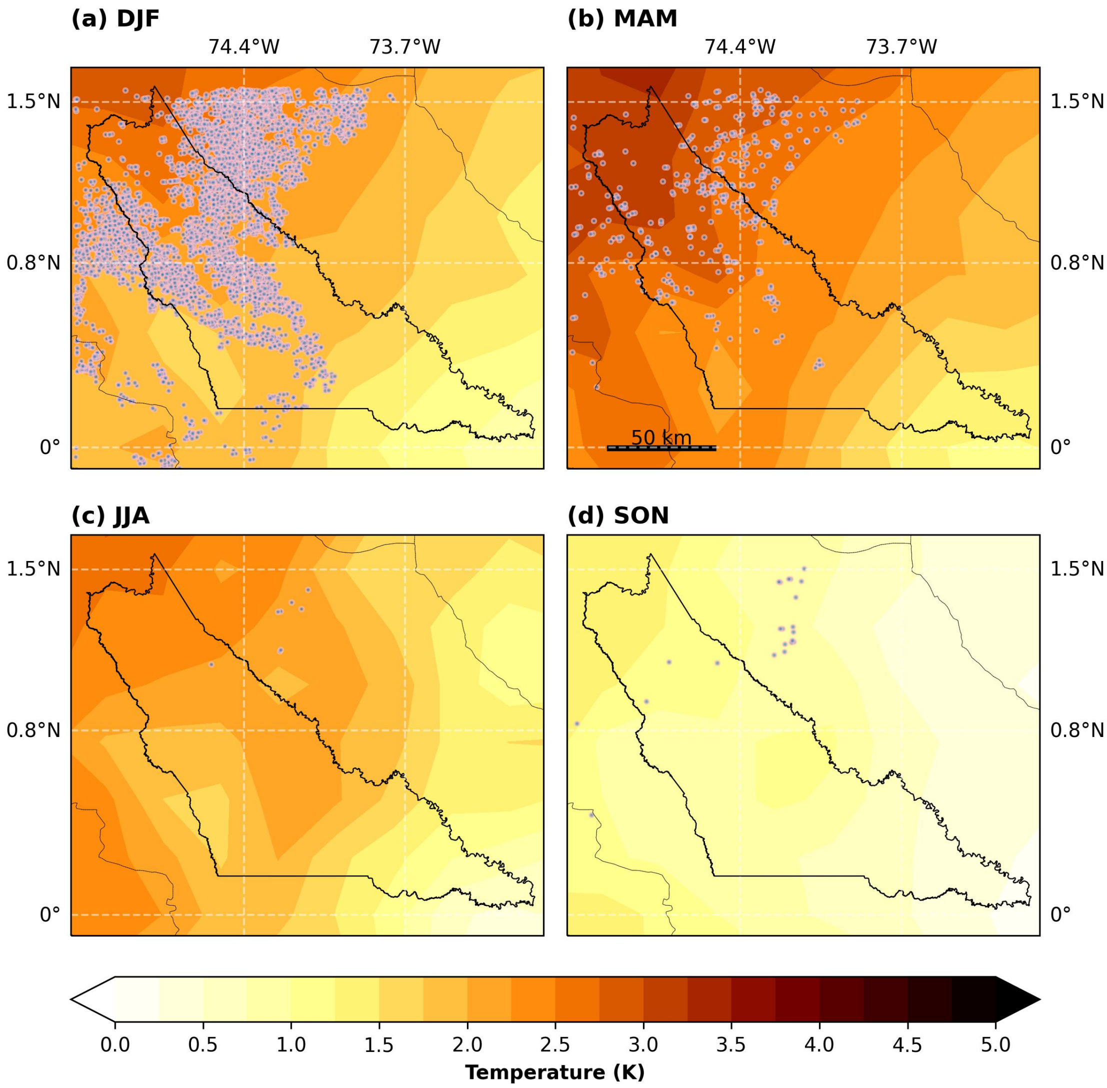

Figure 4.5: Temperature anomaly in Cartagena del Chairá between non-fire days and fire-days. Where the pink dots were the forest fires in 2013-2022

and Figure 4.6d, respectively) located in the North of the municipality, where are located most of the forest fires. Nevertheless, in JJA there are negative anomalies up to -3 m/s that could have an incidence in the few number of hotspots in this season.

On the other hand, humidity in DJF and MAM is lower on fire days, having its Q3 quartile below the Q1 quartile of non-fire days Figure 4.4c. Furthermore, humidity values in JJA have the interquartile range between Q1 and the median of the non-fire days boxplot. In contrast, SON has similar behavior between fire and non-fire days, and maximums in non-fire days without season distinctions are 100%. The anomaly of humidity was also evaluated (Figure 4.7) finding that DFJ and MAM can decrease up to -30% when a forest fire is present, especially in the north of the department. However, in the second half of the year JJA (Figure 4.7c) did not show changes in the humidity between fire and non-fire days, SON for its part (Figure 4.7d), has an anomaly up to 10% promoting a more humidity atmosphere associated to more favorable conditions to decrease the risk associated to ignition of forest fires (Jain et al., 2021).

TCCWV yearly behavior has on fire days the interquartile range below the non-fire days quartile Q1, moreover, fire days have a lower minimum and maximum in comparison to non-fire days Figure 4.4d. Seasonal analysis shows that DJF and MAM have lower interquartile range values than non-fire days. In the seasons with fewer hotspots (JJA and SON) the values are similar between fire and non-fire days, the median in both cases is near 50 mm. However, the maximum values in these seasons on non-fire days are lower in comparison to fire days. The TCWV anomaly shows two highlights, as well. DFJ and MAM (Figure 4.8a and Figure 4.8b, respectively) present a negative anomaly with values around -12mm, especially in the north of Cartagena del Chairá, that is more evident in the second quarter. JJA and SON (Figure 4.8c and Figure 4.8d, respectively) have a positive anomaly up to 4mm with the opposite spatial behavior, the highest values are on the southeast part of the municipality.

Regarding precipitation behavior, is significantly lower in all seasons on fire days (Figure 4.4e) having the Q3 quartile and the maximum near 0 mm. On non-fire days, the maximum is between 0.75 mm and a maximum 1.50 mm in MAM, Q3 quartile in all the season are around 0.60, while the minimum is near 0 mm in all the season and on the yearly values. The anomaly has an interesting behavior, according to the Figure 4.9 in DJF the difference between fire days and non-fire days is not up to -3mm. Meanwhile, in MAM the precipitation in fire days has the highest values (up to -15mm) in the north of Cartagena del Chairá. JJA and SON have

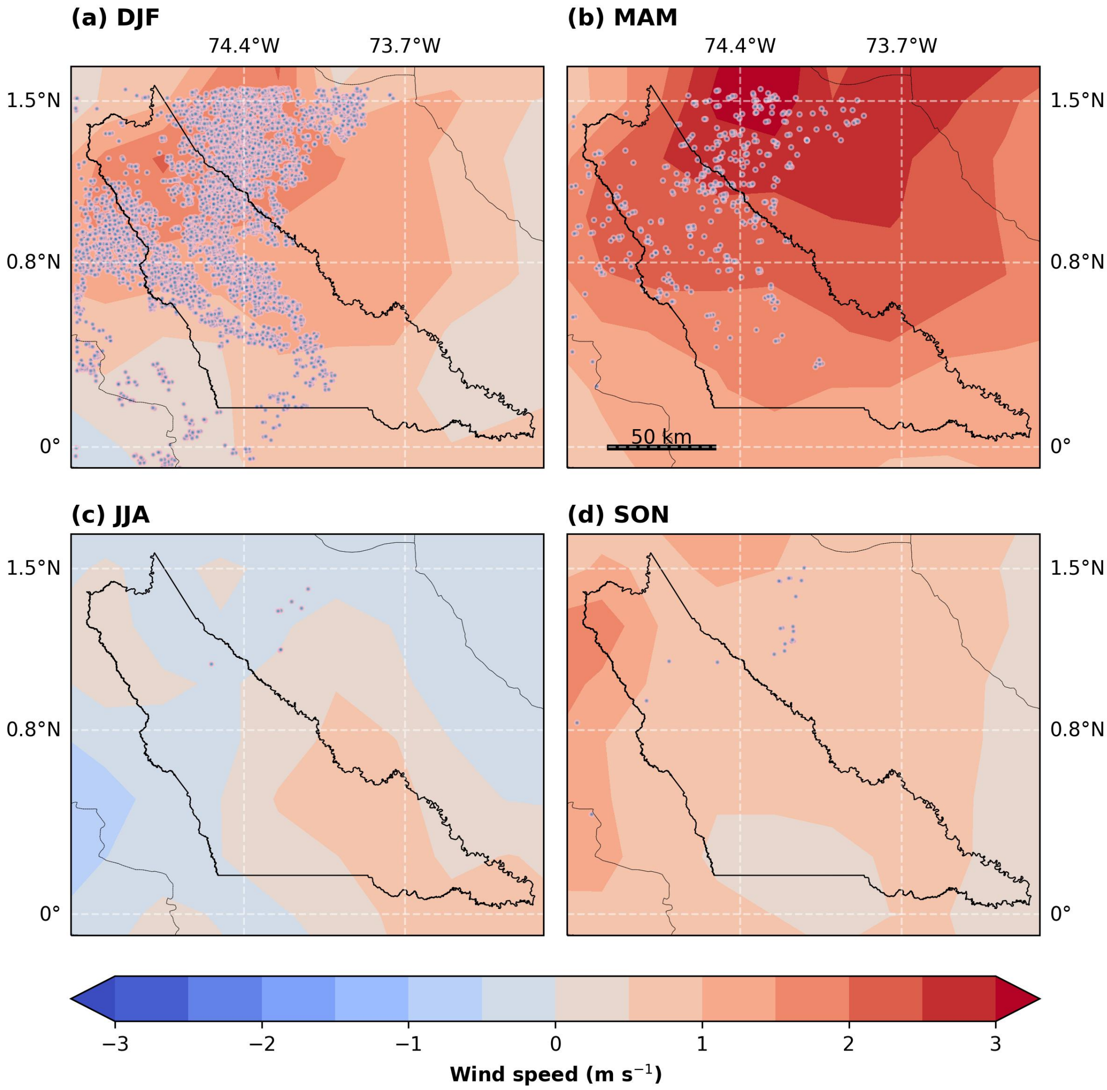

Figure 4.6: Wind speed anomaly in Cartagena del Chairá. Where the pink dots are the forest fires between 2013-2022

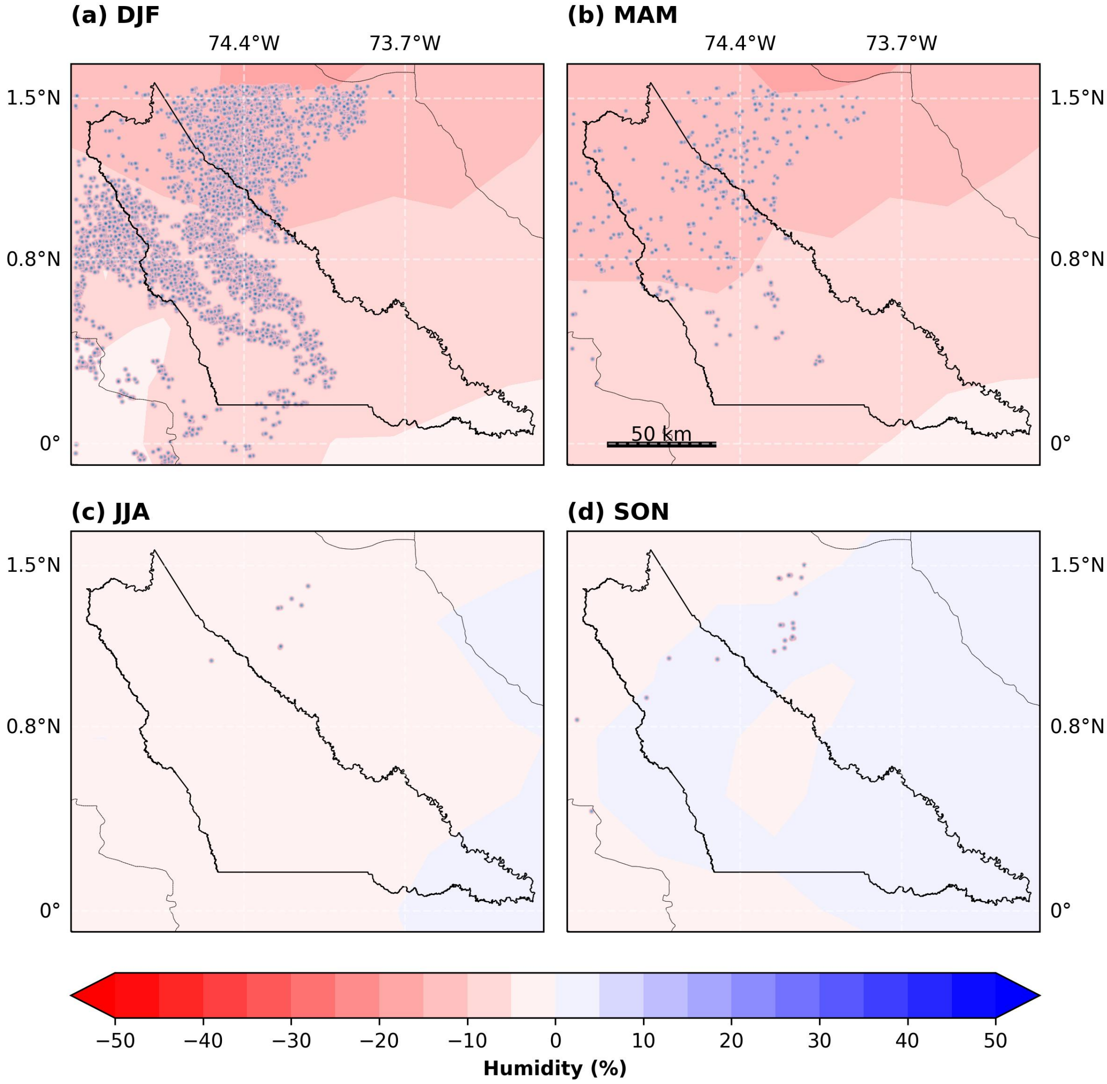

Figure 4.7: Humidity anomaly in Cartagena del Chairá. Where the pink dots are the forest fires between 2013-2022

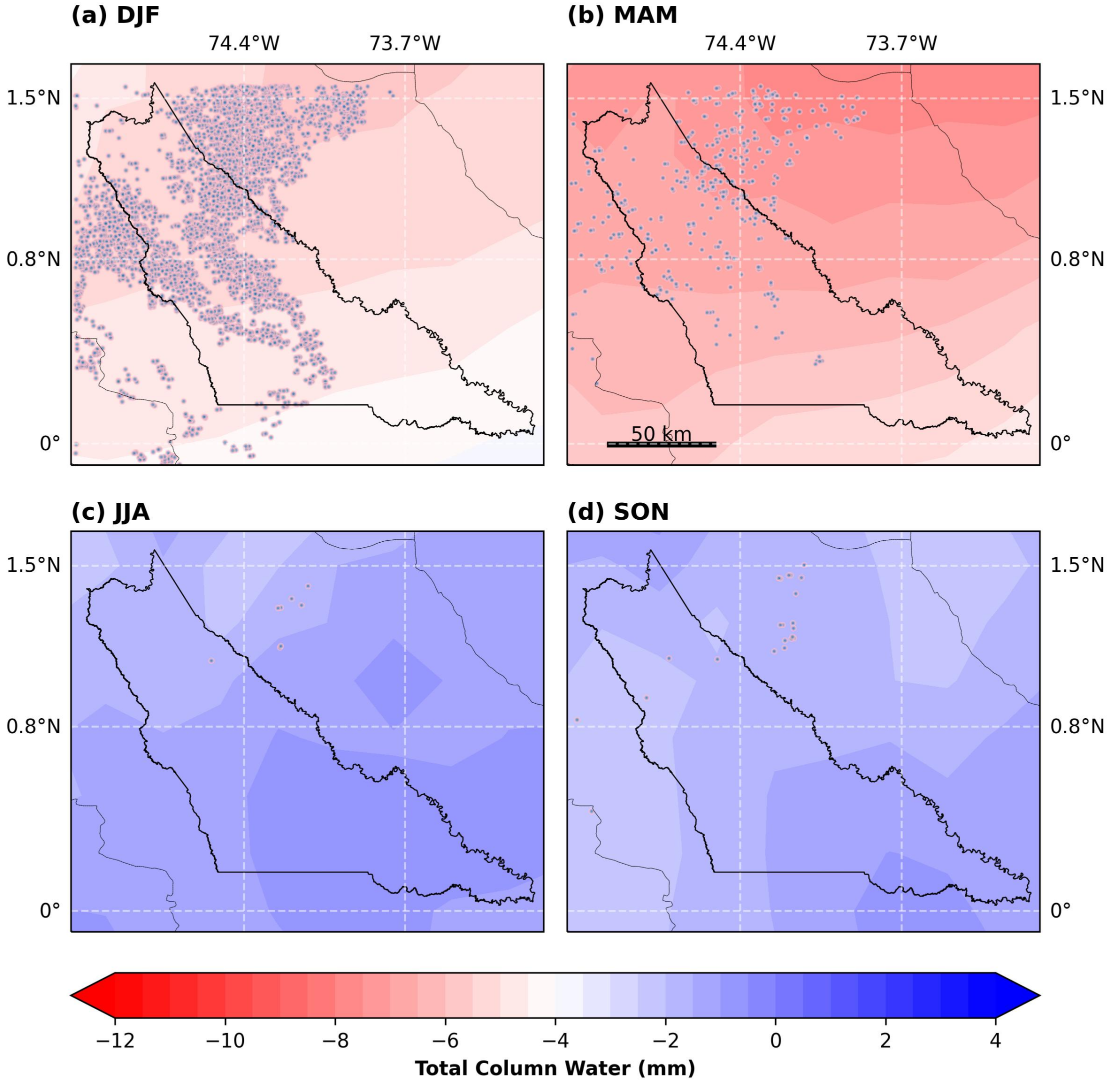

Figure 4.8: TCWV anomaly in Cartagena del Chairá. Where the pink dots are the forest fires between 2013-2022

negative anomalies as well with similar values as MAM specially JJA, suggesting this variable could not be a determinant factor.

Researchers are finding positive relationships between meteorological conditions and forest fires (e.g., Casallas et al. 2022; Jain et al. 2021; Kosovíc et al. 2023). Three main components of fire (heat source, fuel and oxygen) are influenced by atmospheric conditions. According to Kosovíc et al. (2023) fire behavior and spread in forest fires is a result of a coupled system influenced by atmospheric conditions, so interactions between weather and forest fires are characterized by complex feedbacks (Kosovíc et al., 2023) that can intervene in the development of fires. Despite that, the research on the relationship between meteorology and forest fires in the Amazon is not widely studied. Authors such as Ma et al. (2022) claim that in the south Amazon (Brazil), most meteorological variables were not statistically significant to the forest fires occurrences based on a global model, and on the contrary, directly related to human activities exhibiting close spatial relations with deforestation (Ma et al., 2022). However, Cavalcante et al. (2021) mentioned that in the Brazilian Amazon, most hotspots occurred in deforested areas and native forests, in this sense, is important to study the complex dynamic of forest fires in each specific spatial, social, economic, and environmental context.

Authors such as Casallas et al. (2022) did the first efforts to try to understand the role of meteorology on the Colombian Amazon, finding a relationship between different meteorological variables and fires in the area. Seasonality shows how DJF and MAM are the months with the characteristics that lead to improved conditions of ignition and the forest fire spreads. The combination of meteorological conditions such as the increase in temperature in the northwestern area of the municipality, as well as the increase in wind speed in the same subzone raises the rate of fire spread (Kosovíc et al., 2023) (especially on MAM). At the same time, winds also affect the rate of fire spread indirectly by enhancing the drying of dead and live fuels that are also affected by precipitation which, in turn, acts on humidity, and the TCWV especially on MAM decreases in general on fire days but decreases even more on the seasons with the highest number of fires (DJF and MAM), affecting the chance to interrupt the forest fires spreads.

In these conditions, the heat released by fires results in local circulation potentially igniting new forest fires or resulting in the formation of pyrocumulus modifying the weather (Kosovíc et al., 2023). This cyclical behavior could be presented more frequently and more pronounced due to weather extremes resulting from climate change, affecting in the short term the health,

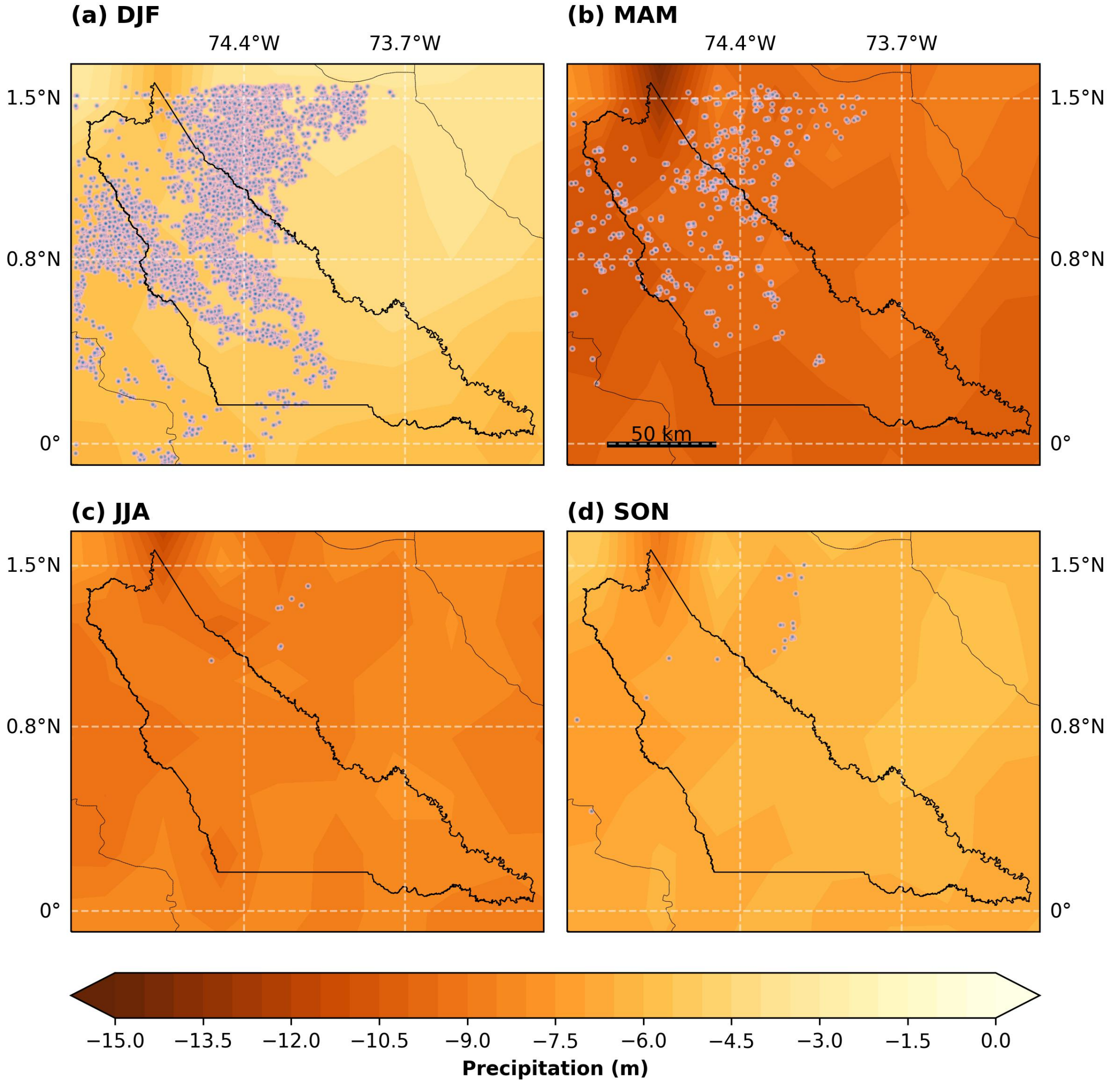

Figure 4.9: Precipitation anomaly in Cartagena del Chairá. Where the pink dots are the forest fires between 2013-2022

housing, job, and food the Cartagena's del Chairá communities, an important zone with an exceptional social, economic, and political dynamic.

In summary, wildfire occurrences are concentrated in the northern and central sectors of the region, closely tied to positive anomalies in temperature and wind speed, along with negative anomalies in RH, TCWV, and precipitation during boreal winter. Conversely, boreal summer experiences fewer wildfires in the northern region, linked to elevated air temperatures, a dry environment characterized by reduced RH and TCWV levels, and a shortage of rainfall. The fact that wildfires emerge in specific zones within our study area suggests that the type of land cover may significantly influence wildfire development. This drives our focus in the subsequent section on analyzing the land cover characteristics of the region.

4.2 Climatic Change conditions

The climatic condition has particular importance in forest fires on the Colombian Amazon due to the now well-known importance of meteorological conditions for the development and ignition of forest fires, as well as the susceptibility of this zone to changing climate combined with the intensification, expansion, and replication of the socioeconomic practices that could trigger a tipping point. For this reason, temperature, wind, humidity, and precipitation were evaluated climatologically and by season in the short term (up to 2049) in four different climate change scenarios (SSP1.26, SSP1.24, SSP3.70, and SSP585) with 3 coupled models (see § 3.4 for details) to establish the implications of changes in climatological variables on forest fires in Cartagena del Chairá.

The first variable analyzed is the temperature, the climatological behavior (Figure 4.10) indicates in all the scenarios there is an increment. SSP126 scenario shows an increase between 0.5 and 1.5 K. This behavior prevails in the other 3 scenarios, nonetheless, on the SSP245 the increment is between 1.5 to 2.0 K, SSP370 has values between 2.5-3.0 K, and SSP585 has the largest increment between 3.0 to 3.5 K. The subzone with the highest increment is southeast of Cartagena del Chairá, the area with the lowest temperature increase so far, suggesting that this could promote the ignition and spread of forest fires, affecting part of the Chiribiquete National Natural Park, a protected area declared by UNESCO as a cultural heritage site, Caguán fluvial river roads and unexplored rainforest.

The analysis by season for each variable establishes interesting findings. Taking into that

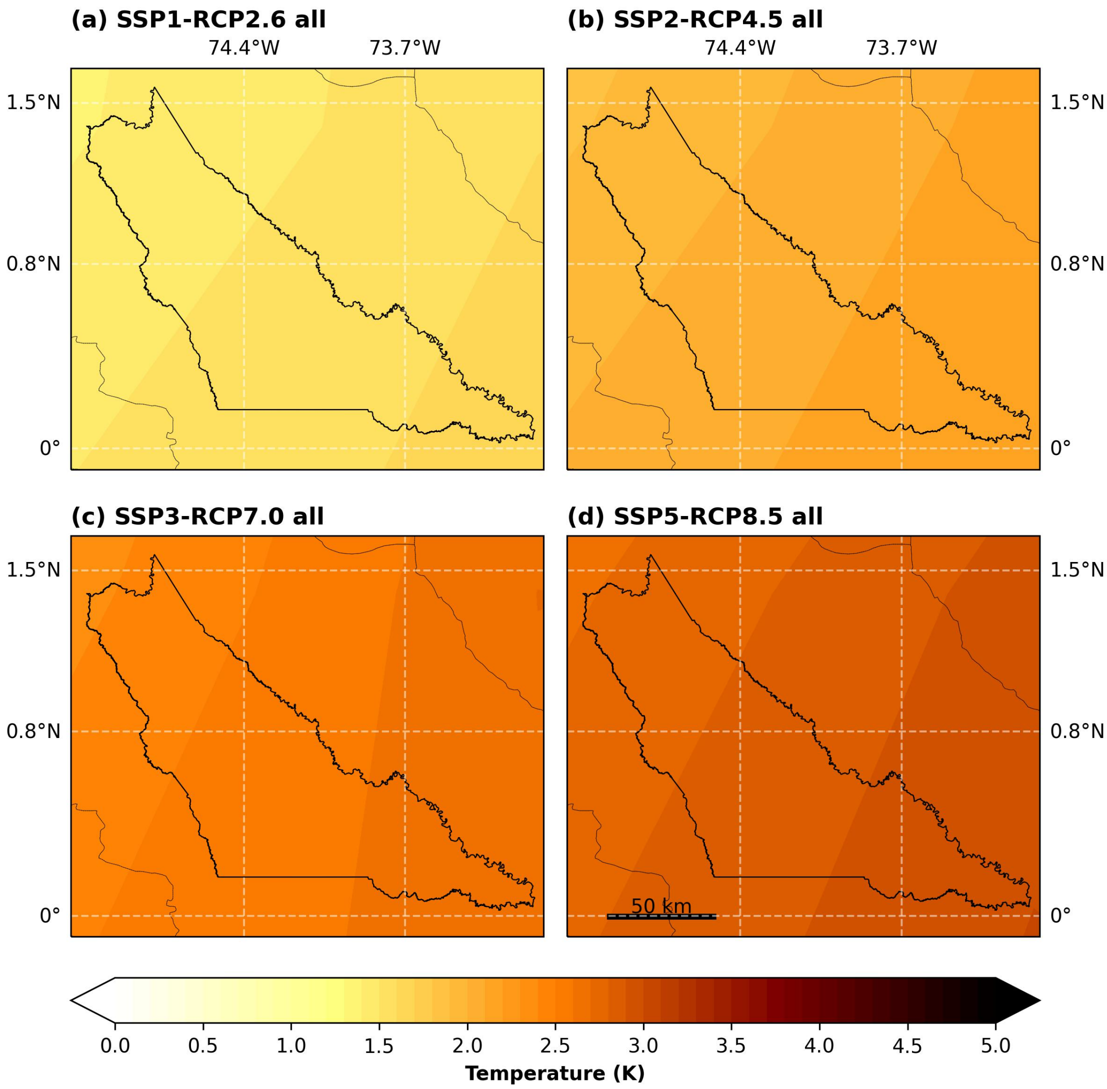

Figure 4.10: Climate change scenarios for temperature up to 2049

the biggest forest fires in number and magnitude are in DFJ and MAM, these two seasons are shown in the present chapter in order to analyze the predicted changes in different meteorological variables. The temperature in DJF (Figure 4.11) for SSP126 has a small increment of around 0.5 K, on SSP245 is higher (2.0 K), nonetheless on SSP370 and SSP585 the temperature could increase up to 3.5 K. This season has the same spatial behavior on Figure 4.10 indicating that the probability of increasing fires is higher as the scenarios change, being the highest in SSP858 especially on the southeast part of the municipality.

According to the models, the temperature on the scenarios on MAM (Figure 4.12) is similar in magnitude to DJF, especially on SSP126 which has values near to 0.5-0.75 K. The temperature in this season on SSP245 and SSP370 could increase around 1.25 to 1.75 K, respectively. These values are lower in comparison to the previous season. On SSP585 the temperature is lower than SSP370 and SSP585 in DJF with 1-1.25 K. In this season, the highest increases are in the southwest part where the subtraction zone has allowed colonization, land clearing and the entry of new agro-commercial practices to begin in recent years at the mouth of the Caquetá River. The intensification of these practices and the increase in temperature in the coming years will increase the probability of a greater number of forest fires of high duration and magnitude.

Wind speed climatology (Figure 4.13) shows a small increment in the first scenario SSP126 whit a reduction of -10 m/s uniformly throughout the municipality. Whereas SSP245 has not a significative change, even so at the north has a smooth increment (0.05 m/s). On the other hand, the SSP370 scenario (Figure 4.13c) shows an increment of up to 0.05 m/s, while the SSP585 has an increment of up to 0.15 with the highest wind speed north of Cartagena del Chairá.

Some authors suggest that the increment in the wind speed could increase the probability of ignition and spread of forest fires (Kosovíc et al., 2023 and Brando et al., 2020). For this reason, was analyzed the seasons (boreal winter) with the highest relevance in relation to the number and magnitude of forest fires. DJF's first scenario SSP126 (Figure 4.14a) shows a different behavior in comparison to the other three evaluated. The wind speed according to this scenario could decrease up to -0.20 m/s, however, could have an increment in the north of the municipality near to 0.10 m/s. SSP245 (Figure 4.14b) scenario has not shown significant changes in most of the municipality despite a subzone in the north with values up to 0.10 m/s. The behavior of SSP370 (Figure 4.14c) and SSP585 (Figure 4.14d) is similar to each other apart from

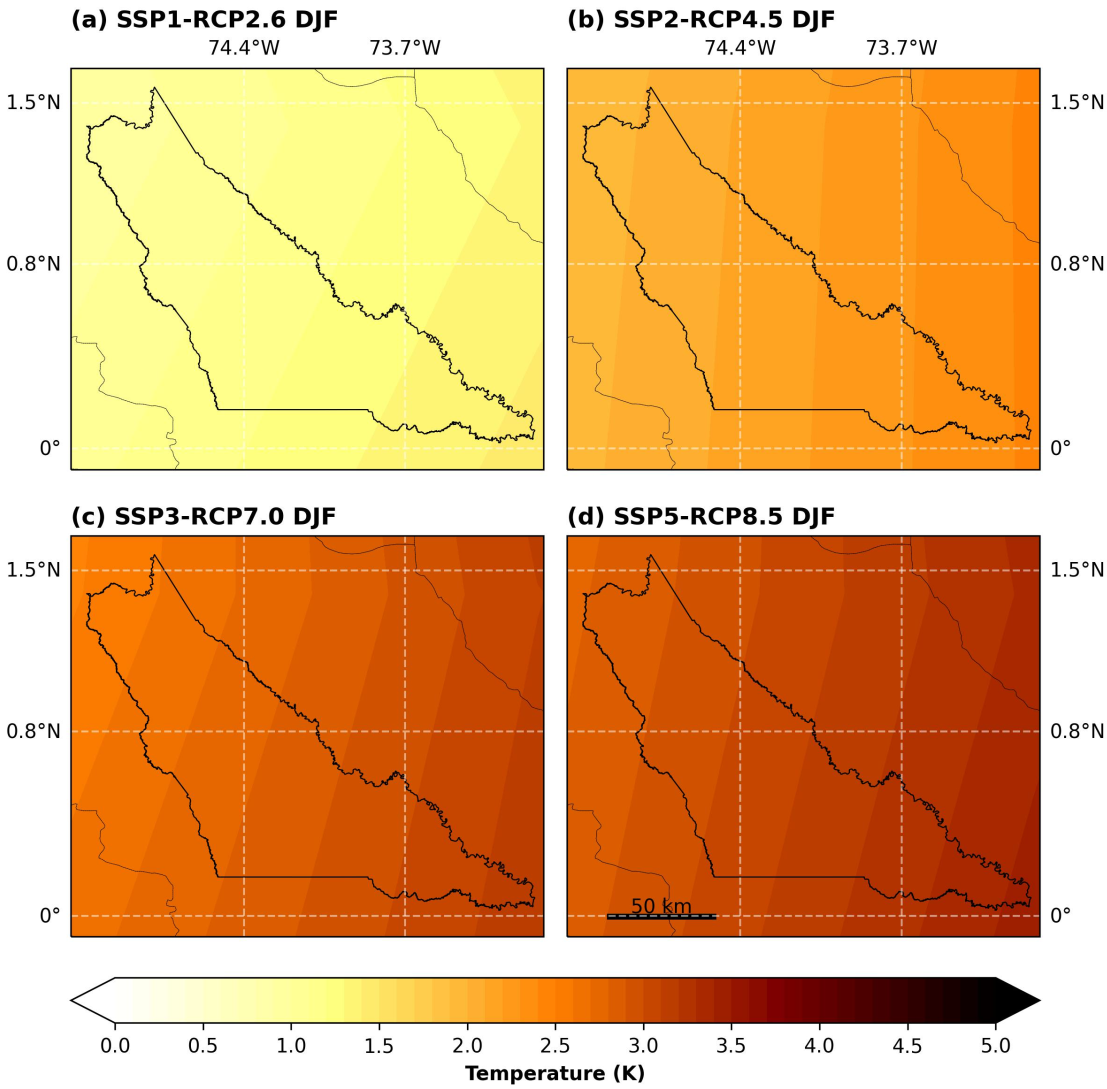

Figure 4.11: Climate change scenarios for temperature scenarios in DJF up to 2049

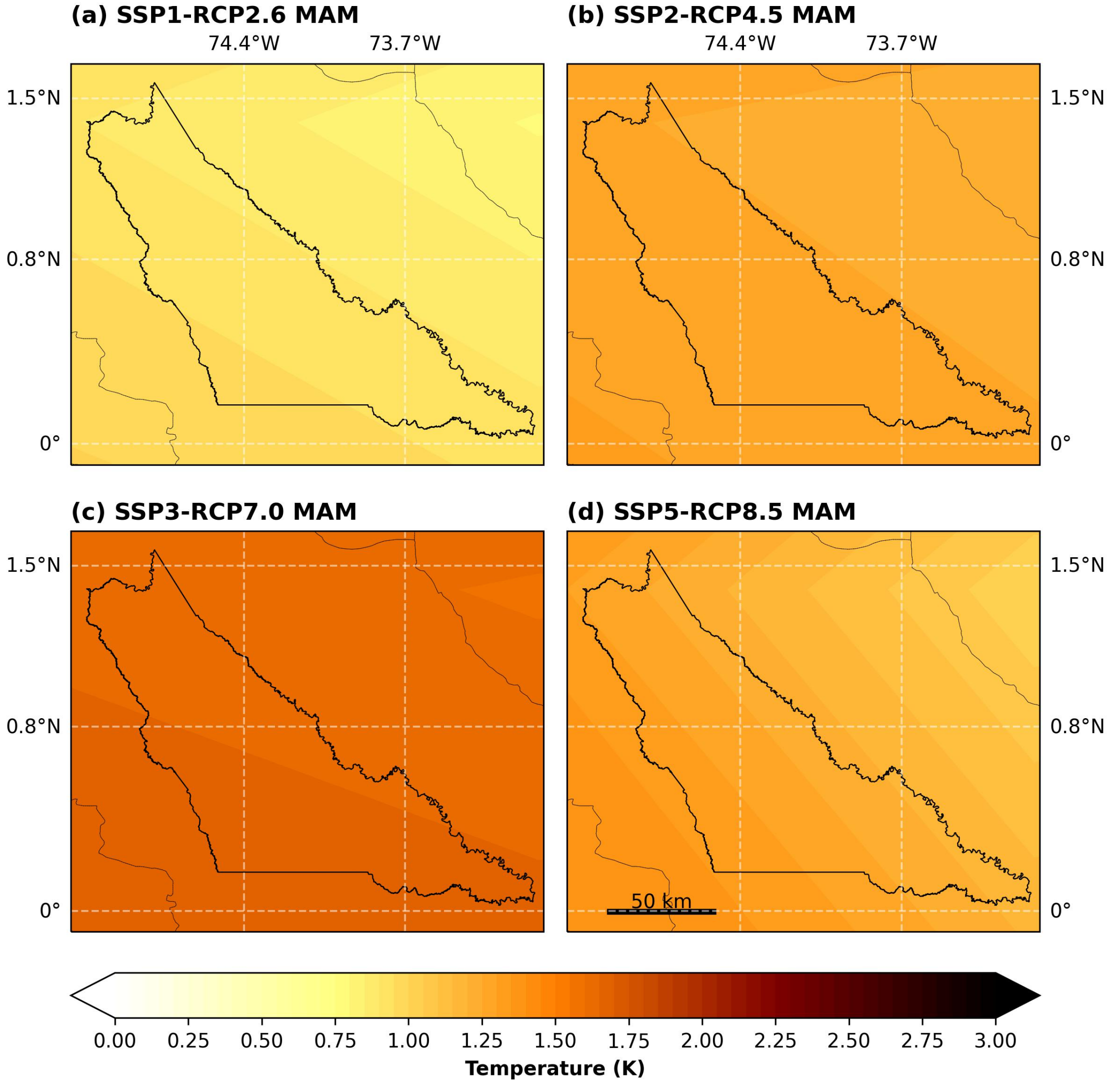

Figure 4.12: Climate change scenarios for temperature scenarios in MAM up to 2049

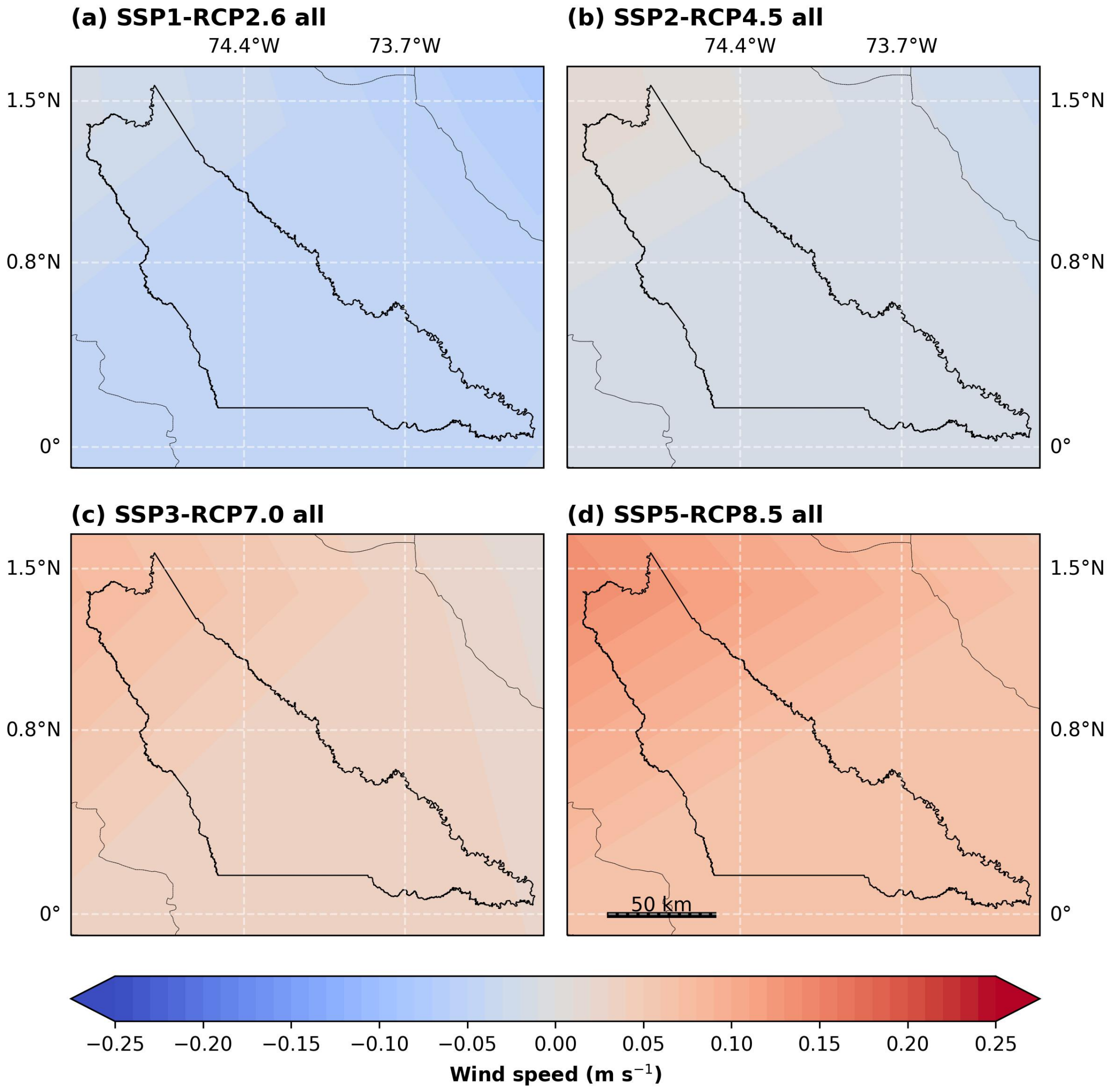

Figure 4.13: Climate change scenarios for wind speed scenarios up to 2049

the fact that SSP585 has a higher increase in the north (0.30 m/s). The rest of the municipality in both scenarios was values between 0.10-0.15 m/s.

The behavior in MAM (Figure 4.15) is different from the previous season. The changes in this season are smoothies, not above 0.03 m/s and below -0.15 m/s. In the first scenario (SSP126) has the largest decrease in the entire municipality with values close to -0.12 m/s, SSP245 has a mean value of -0.06 m/s. Nonetheless, on SSP370 (Figure 4.15c) has an increment on the west part with values near 0 in the center, and on the east a decrement below -0.03 m/s. While the SSP585 scenario has a smooth increase in the north (0.03 m/s) and a decrease to -0.03 m/s in the rest of the municipality. The wind speed projections establish an intensity increment at the north part of Cartagena del Chiará in DJF, there is a subzone with the highest number of forest fires, the area with the greatest agricultural activity in the municipality and the main urban centers. Suggesting that an additional increase in wind speed, fires may spread at a higher speed and may have a greater magnitude. On the other hand, in MAM the wind speed decreases, this behavior may favor in climatological terms so that forest fires do not increase. However, there may be feedback that do not involve wind speed and promote the increase of fires in that season.

For this reason, humidity projections were made. The climatological behavior (Figure 4.16) for each scenario shows SSP126 values near 0 in the north of the municipality and decreases with values up to 1.5% in the south. While SSP245 indicates a decrease around -1 to -2 %. The SSP370 and SSP585 scenarios have the highest decreases principally in the southeast part of the municipality with values between -3 ad -6%, respectively. Noting that it could increase the probability and facilitate the ignition of forest fires due to the drying of the atmosphere and fuel and the relationship according to meteorological data between low humidity values and the activity of hotpots.

The analysis of DFJ (Figure 4.17) is different for the first scenario (SSP126), which presents an increase throughout the municipality, especially in the north. However, in SSP245, SSP370 and SSP585 the scenarios suggest a decrease in humidity more intense in each scenario for SSP245 near -1%, SSP370 and SSP585 with values from -1 to -6% with the lowest values in the south. Being DJF the most relevant season, the increase in humidity in the first scenario is favorable for not increasing forest fires; however, authors (Armenteras et al., 2006, 2020; Jain et al., 2021) suggest that this scenario is less and less likely to occur. Therefore, an additional

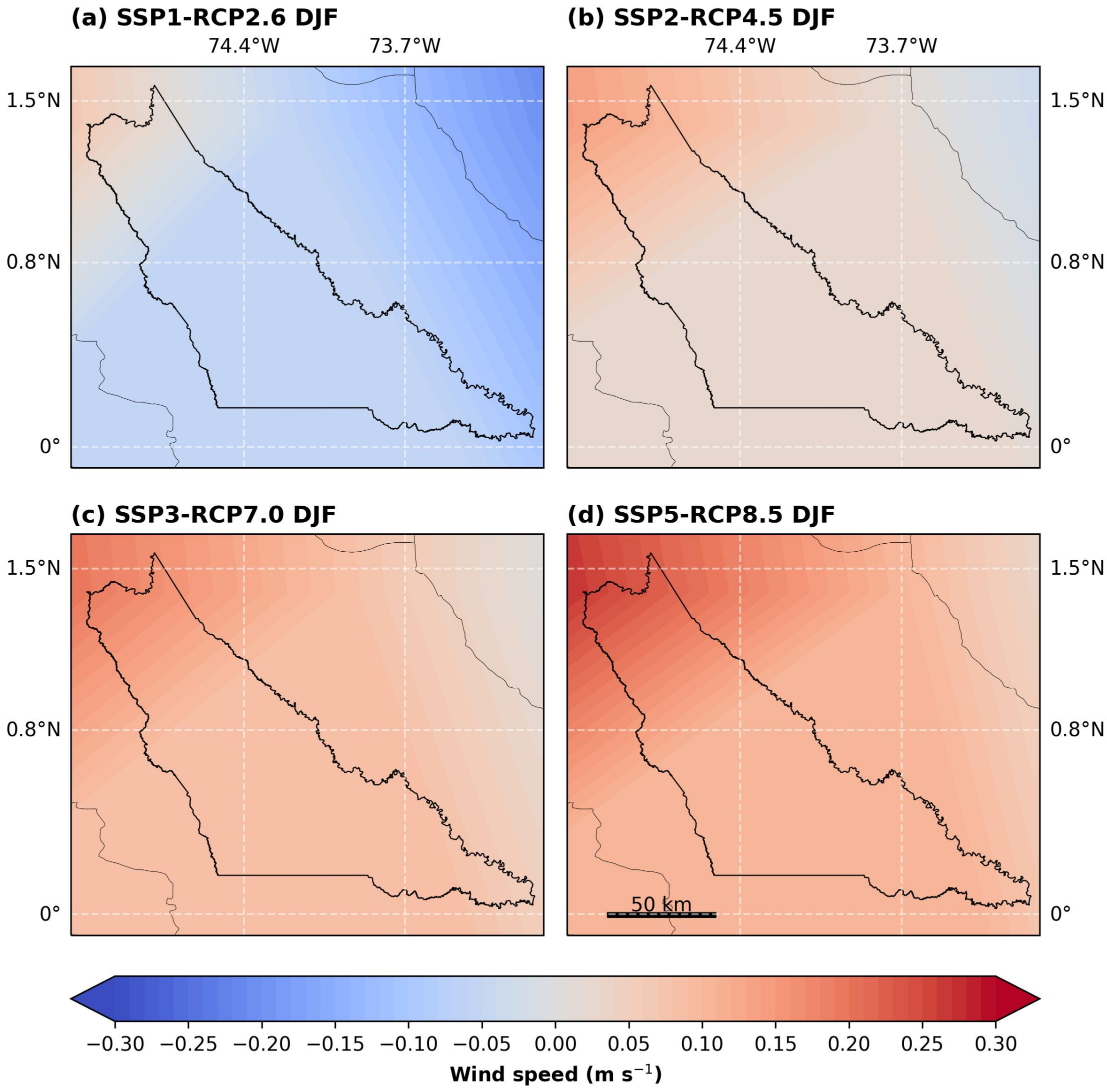

Figure 4.14: Climate change scenarios for wind speed scenarios in DJF up to 2049

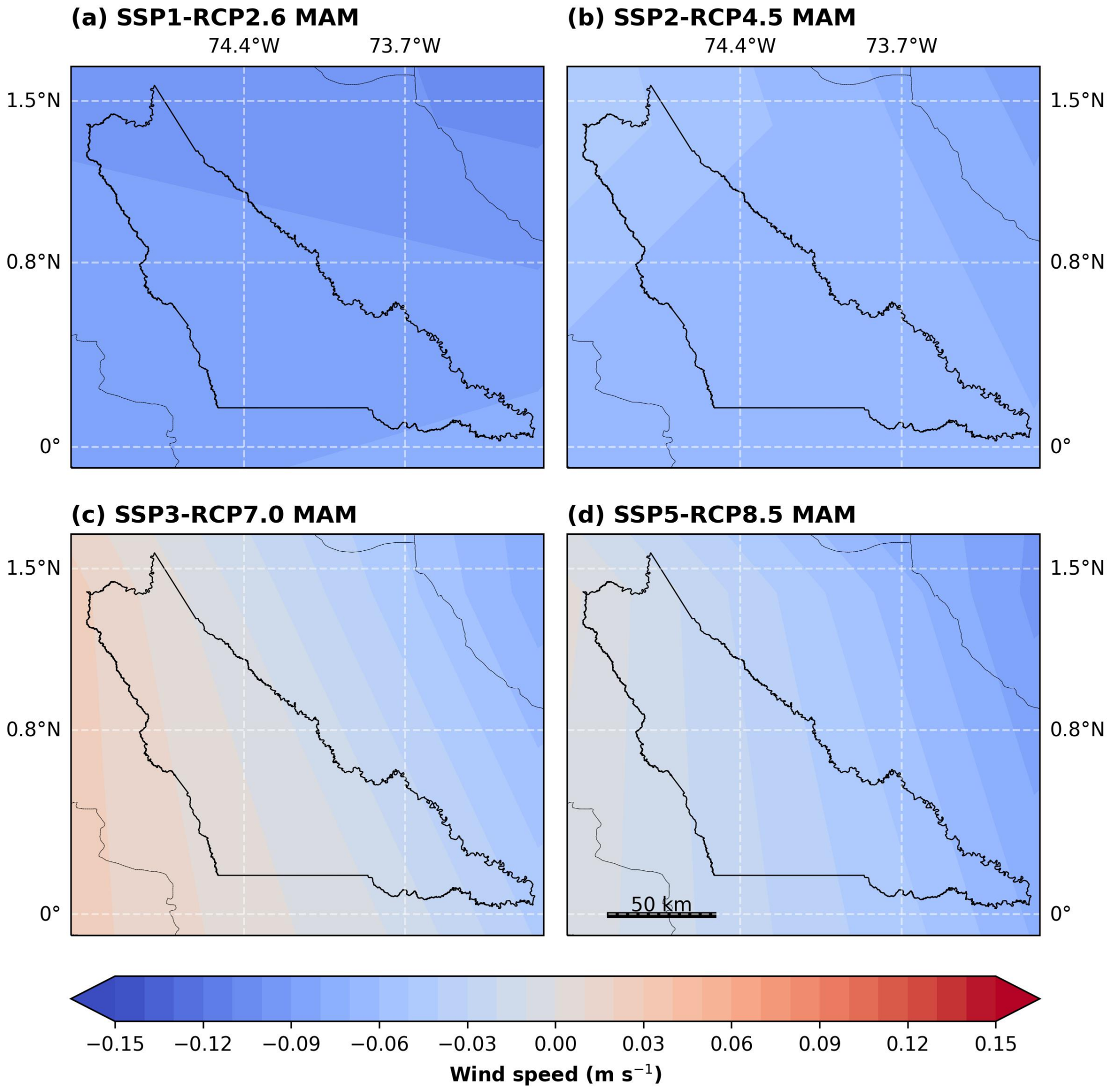

Figure 4.15: Climate change scenarios for wind speed scenarios in MAM up to 2049

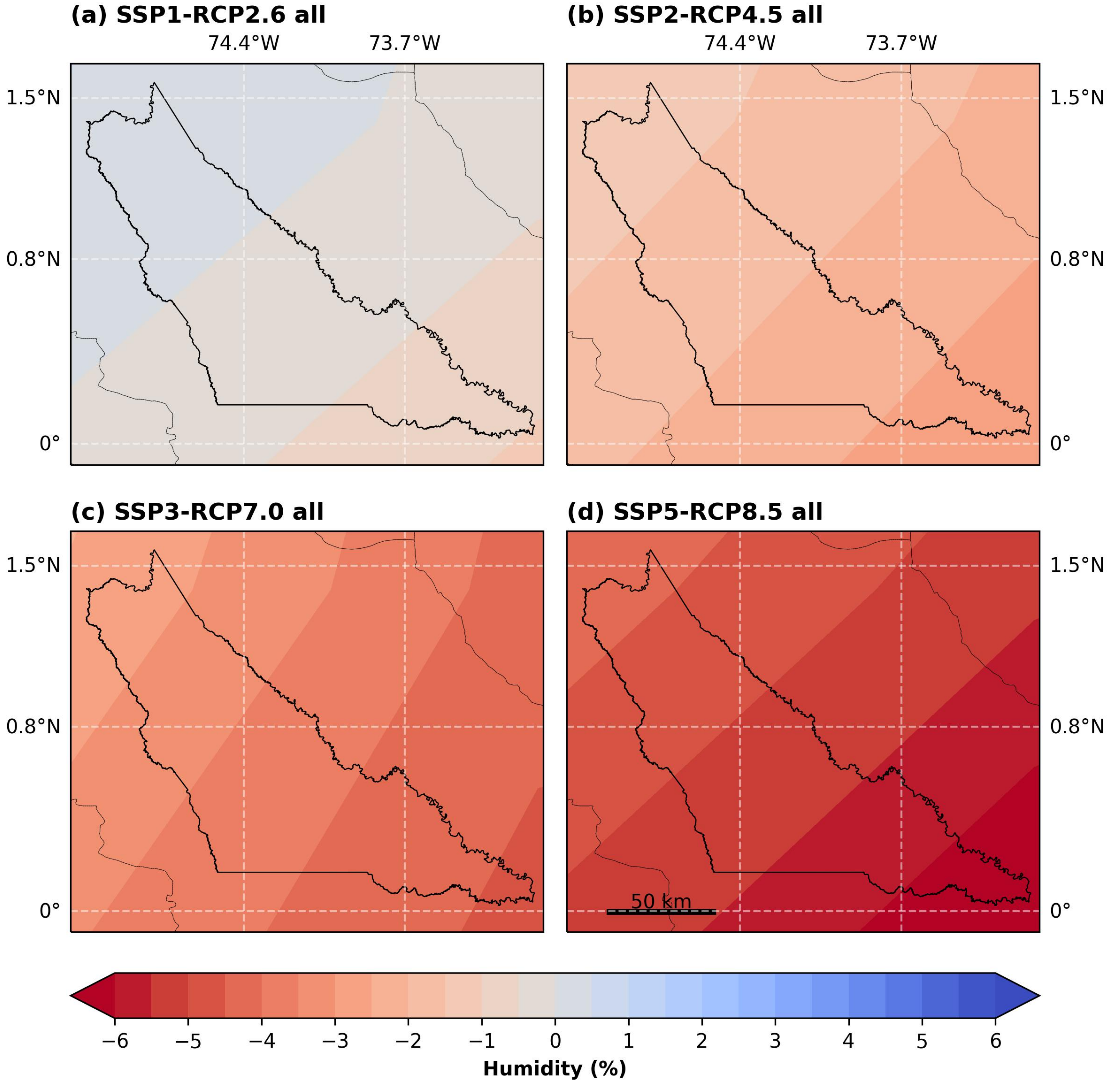

Figure 4.16: Climate change scenarios for relative humidity scenarios up to 2049

decrease in the number of fire days would help to prolong the events and the availability of fuel. Unlike the behavior shown in DFJ, in MAM (Figure 4.18) in all scenarios the humidity increased, with values of up to 6% in the municipalities near Cartagena del Chiara, and maximum values in this municipality around 4% (SSP585), the lowest increase is in SSP370 with minimum values around 0.5%, SSP245 and SSP126 have a similar behavior between them, with values between 1-1.5%. These projections would favor maintaining and increasing the percentage of humidity in this municipality avoiding the increase of forest fires.

Precipitation has an important role in the development of forest fires, absence of rainfall could increase forest fires and an increment of it can extinguish hot spots and control fires. In this sense, the evaluation of the precipitation in the climate change context is indispensable. The climatological analysis using the scenarios (Figure 4.19) presents an increment between 200 mm/year (SSP585) and 500 mm/year (SSP126), SSP245 and SSP370 have values around 300 - 400 mm/year. Suggesting the Amazon Rain Forest specifically in Cartagena del Chairá could increase the amount of precipitation that falls on the municipality decreasing in number and magnitude of the forest fires. Nonetheless, is important to take into account that the precipitation events could be more intense (more water falling in a fraction of time) and not more days with rain. In this case, the interaction with forest fires development could change.

For this reason, the precipitation in the season with special importance was analyzed. The rainfall on DJF (Figure 4.20) shows for SSP126 an increment over 135 mm/year describing an excellent scenario to decrease the number of forest fires, besides this scenario, the other three have less precipitation. For SSP245 on Cartagena del Chairá could increase up to 90 mm/year, SSP370 around 45 mm/year, however, could be zones where not increase the precipitation, especifically in the noth. SSP585 has an increase below 60 mm/year. The scenarios for MAM (Figure 4.21) present a higher increase compared to DJF. For SSP126 the increase is 220 mm/year, SSP245 has in the southeast maximum values of 300 mm/year and in the northwest the lowest values (240 mm/year). While SSP370 has in the northwest around 220 mm/year, however, in the rest of the municipality it has values close to 280 mm/year. SSP585, on the other hand, shows the greatest increase with a homogeneous behavior above 320 mm/year. In this sense, rainfall can preserve the amount of water in the fuel, soil and atmosphere to improve the environment and prevent the increase of forest fires.

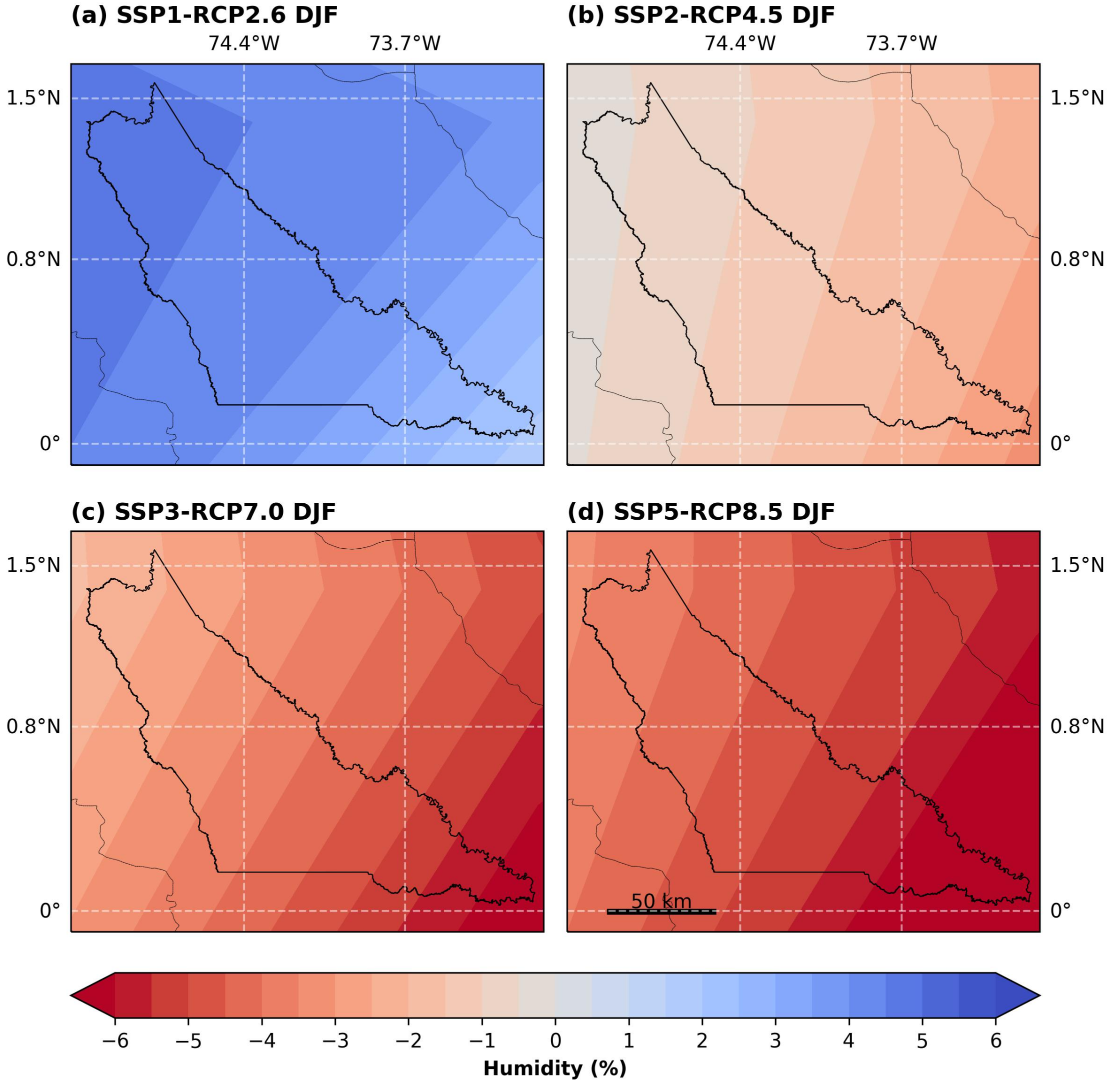

Figure 4.17: Climate change scenarios for relative humidity scenarios in DJF up to 2049

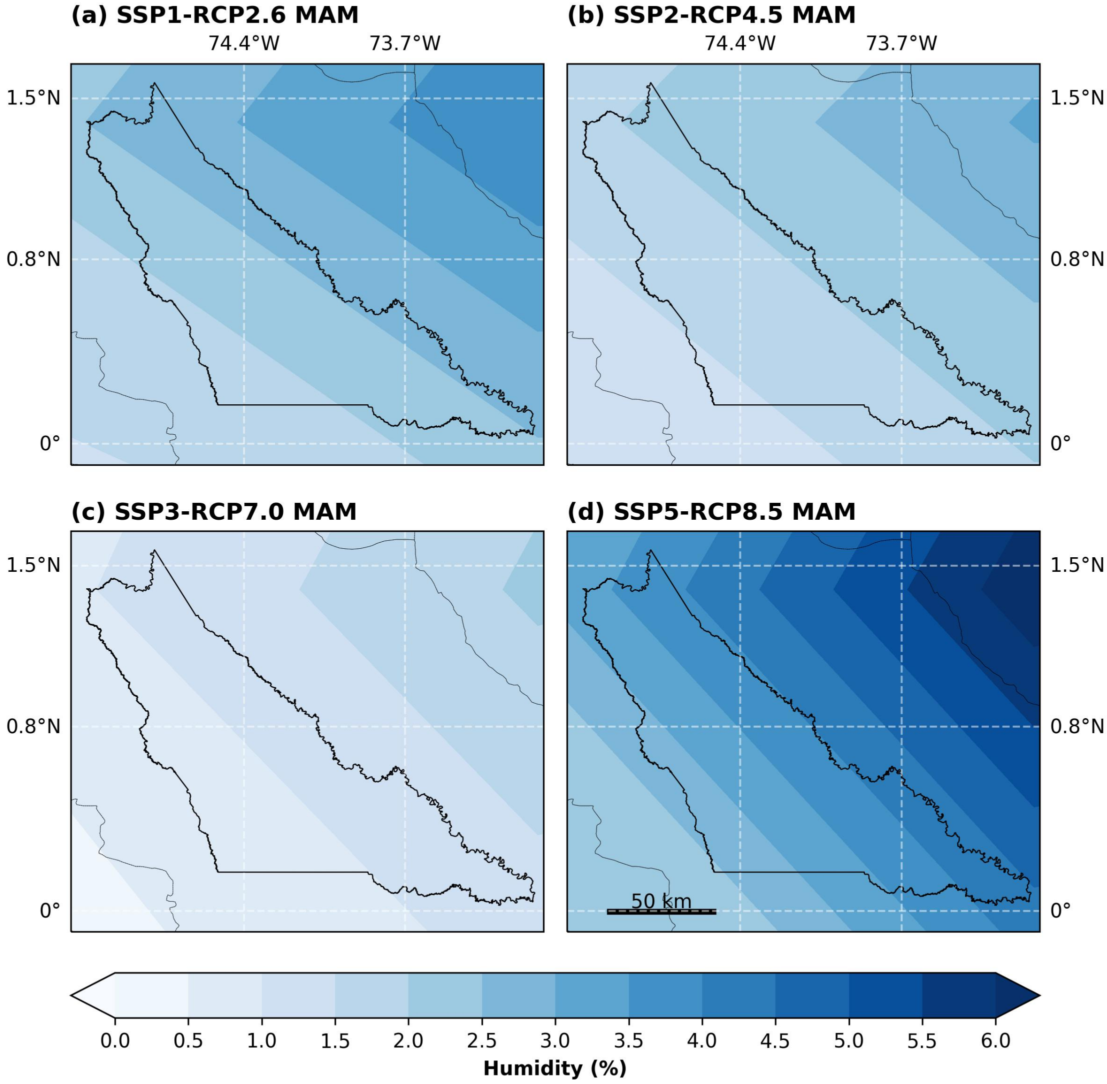

Figure 4.18: Climate change scenarios for relative humidity scenarios in MAM up to 2049

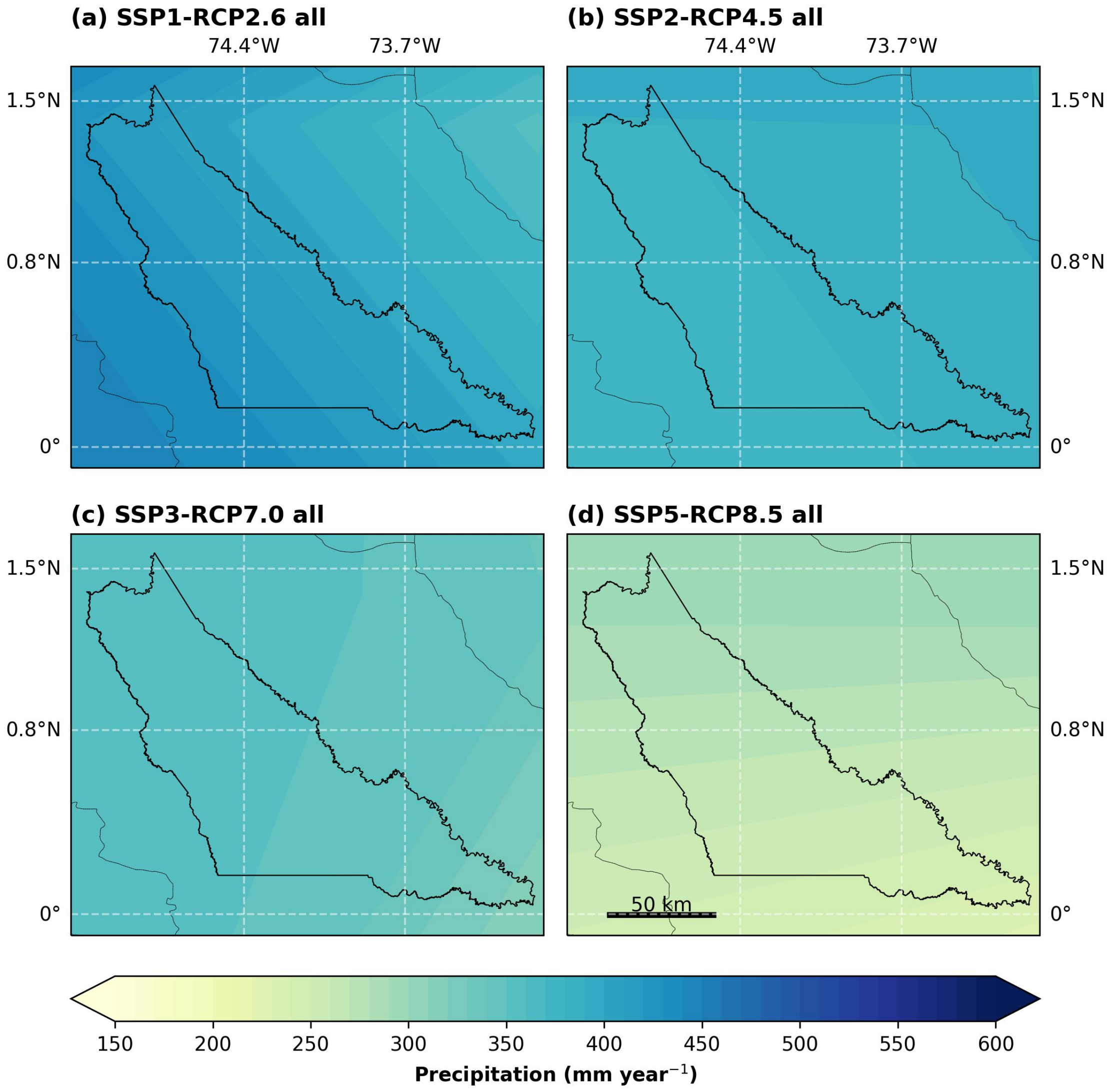

Figure 4.19: Climate change scenarios for precipitation scenarios up to 2049

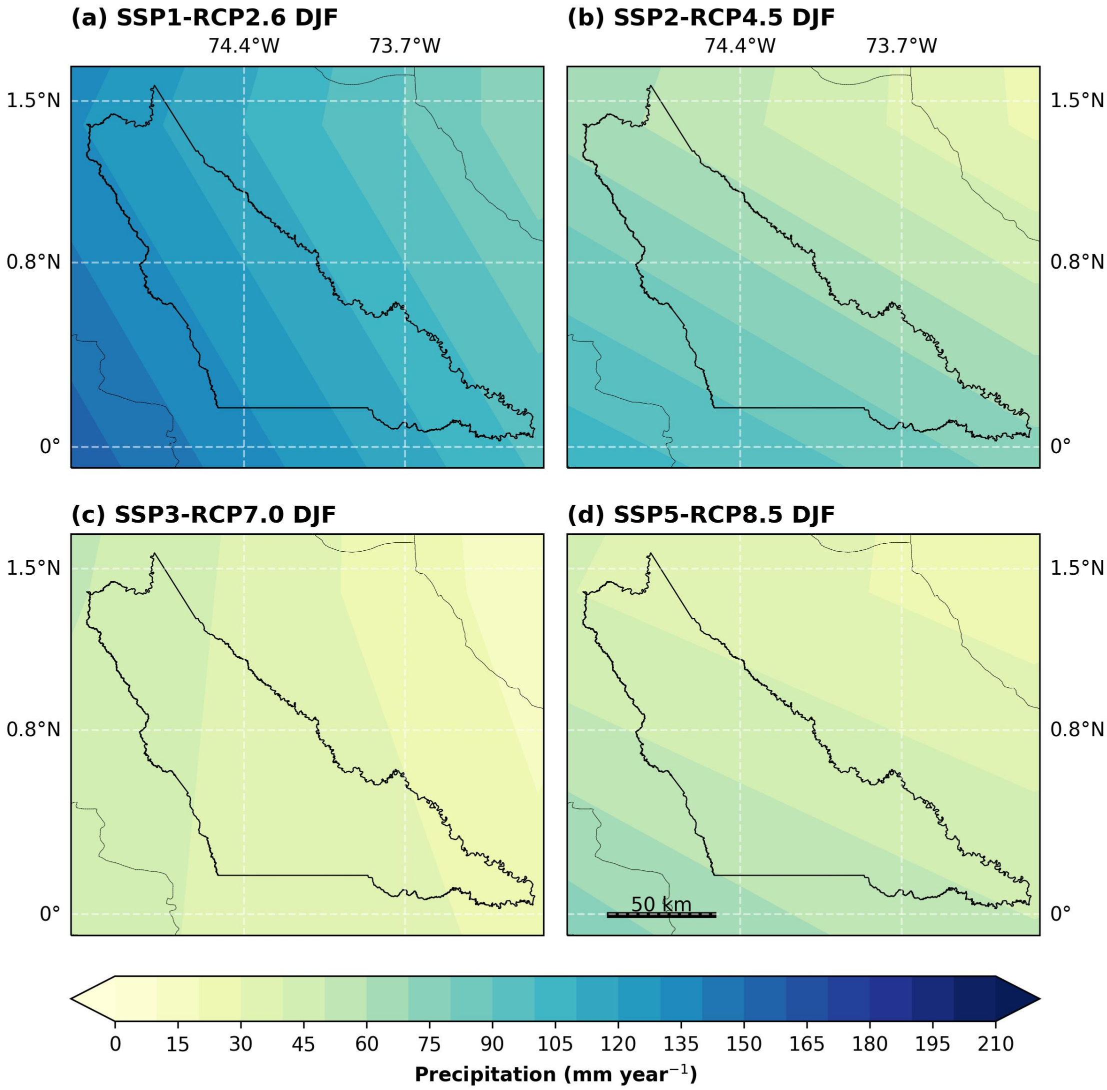

Figure 4.20: Climate change scenarios for precipitation in DJF up to 2049

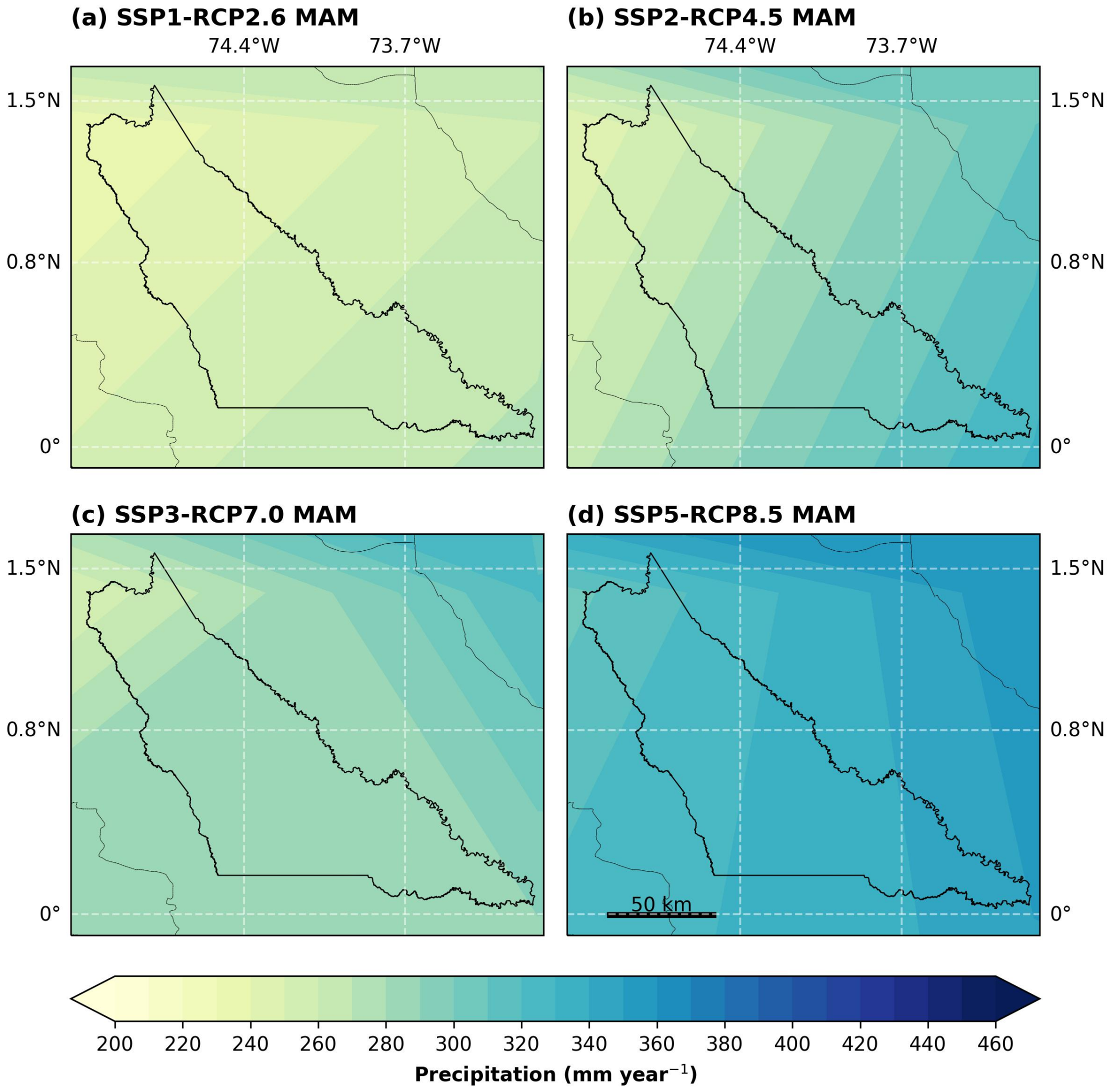

Figure 4.21: Climate change scenarios for precipitation in MAM up to 2049

Projections of climate change in the coming decades underscore the need to counteract the growing risk of fires in order to conserve the Amazon forests (Brando et al., 2020). Climatology in Cartagena del Chairá suggests that temperature, humidity and precipitation are the variables that most frequently influence the initiation and evolution of forest fires (Kosovíc et al., 2023). According to Cochrane and Barber (2009), if temperatures increase and precipitation decreases, potential fuels that are normally too wet to burn will dry out more quickly and more frequently, thus increasing the susceptibility of forests to burn. In Cartagena del Chairá, temperature increased, however, precipitation also increased, making conditions favorable for reducing the rate of drying. However, if deforestation increases simultaneously, the average precipitation level could be reduced, resulting in net desiccation (Cochrane and Barber 2009; Costa and Foley 2000).

The relationship between precipitation and fire potential is complex, even if the net precipitation rate is positive it cannot be argued that fire days will decrease, and there may be more intense rainfall events and drought seasons. According to Kosovíc et al. (2023) changes in weather patterns due to climate change can prolong the local hot season by decreasing humidity, as shown in the scenarios for this area of the Colombian Amazon, thus making droughts an explosive component for forest fires due to preconditioning and surface conditions. Finally, wind speed has relevance in DJF especially in the northeast of the municipality since it is the area where a significant increase in wind is presented. Its relevance is given mainly because it allows understanding the characteristics of wildfire spread, since it dictates how fast and where a fire will move (Schütze and Walz, 2021), however, this analysis should be combined with that of landcover given the importance of the fuel type and its spatial distribution due to its determining role as fuel (Armenteras-Pascual et al., 2011).

This section delineates how meteorological variables are projected to either favor or hinder wildfire development in 2050. A pivotal finding emerges: a radiative forcing increase beyond 2.6 Wm^{-2} could exert substantial impacts on the region, particularly evident during boreal summer, fostering favorable wildfire conditions year-round. While increased precipitation mitigates these impacts, rising temperatures and decreased RH in several scenarios underscore the urgency of acknowledging climate change and instigating strategies and policies for adaptation and mitigation. These measures are crucial, as urban centers, ecosystems, and vital economic activities are vulnerable to the cascading effects of climate change and wildfires.

4.3 Forest Fires Drivers

This section is focused on identifying and analyzing the principal socioenvironmental drivers on the Cartagena del Chairá in the Colombian Amazon rainforest. For this, was studied the land cover change from 2013 to 2022 and the influence of agriculture in the land cover change. On the other hand, socioeconomic variables were evaluated through the 1D-BDLM to identify the importance of each variable explained in section 3.6 in the following section to design and prioritize the strategies.

4.3.1 Landcover

The landcover classification area (Figure 4.22) has four main categories; Open Forest (TCL), shrubs (SHR), and grassland GRS, in less measurement fragmented forest (SPV), which are changing over the years. Open forests are decreasing three first years (2013-2015) and then increasing up to 800 km^2. The most interesting year for this category, in 2019 decreased by 1,610 km^2 ending the year with 609 km^2, however on the last 2 years the area was located up to 1,700 km^2. On the other hand, shrubs also were a sort of fluctuation behavior that could be strongly related to the changes in the other categories. The lowest area was in 2015 which may be connected to a landcover change on TCL. In the following years, the area was stable with around 10000 km^2 with a decrease in 2019 coinciding with the decrement of TCL and GRS, however in 2020-2021 SHR and TCL rises their area. Even though GRS and SVR have low values in comparison to the categories aforementioned have special importance in Cartagena's del Chairá context due to the deforestation land change incentive to categories where different and extensive activities could take part as cattle (e.g., Armenteras et al. 2013a,b, 2020; Nobre et al. 2021).

The percentage of each classification (Figure 4.23) allows for identifying the principal categories over the years and analysis of the land cover changes. SHR has the largest percentage of land cover in the analyzed period. In 2013, this category started with $\approx$ 70% fluctuating around this value and $\approx$ 80% until 2019 when it accomplish a percentage around $\approx$ 90% that ends with $\approx$ 79% in 2021. Regarding TCL classification has a percentage between $\approx$ 7 to 15 % over the years, getting the highest value in 2015 ($\approx$ 25%) and the second highest value in 2020 with near to 20% of the total area. GRS and SPV categories have fewer percentages but stills are important due to the characteristics for the context development has values that are mostly

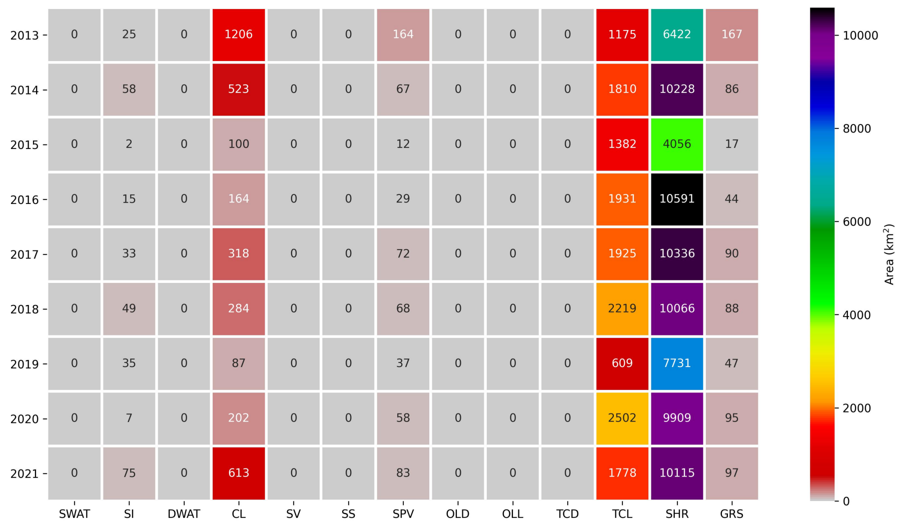

Figure 4.22: Landcover classification area in Cartagena del Chairá between 2013-2021

decreasing over the years up to 2021.

To identify the land cover categories transformation, a classification based on the delta transformation was carried out (Figure 4.24). There are three predominant behaviors of transformation, the first is shown in two years (2015 and 2019) where all categories are apparently decreasing, however, that means the categories with values rounded to 0 increased the area or are burned areas. 2016 is a unique year, showing the second behavior where all the principal categories (SHR, TCL, GRS, and SPV) are increasing which could be attributed to the reforestation and a natural regeneration cycle. The third is focused on one category decreasing and one and more increasing. There are four years that represent this, 2014 where decreased the area of SPV and transformed into SHR, principally. 2017 is an interesting year because it decreased two main categories (SHR and TCL) and increased GRS and SPV land cover used for cattle, principally. In 2018 the category objective was TCL, decreasing SHR and SPV. On the contrary, 2021 decreased TCL and increased SHR and SPV.

Even though the land cover transformation is established is essential to understand the change spatially. For this reason, the spatial location of each classification over the study period (2013-2021) was made. Two main categories (SHR and TCL) have over the years general development, SHR is principally surrounding the river, and TCL is at the south of Cartagena del Chairá. In 2013 (Figure 4.25a) is clear how coincides the subtraction area where the land cover

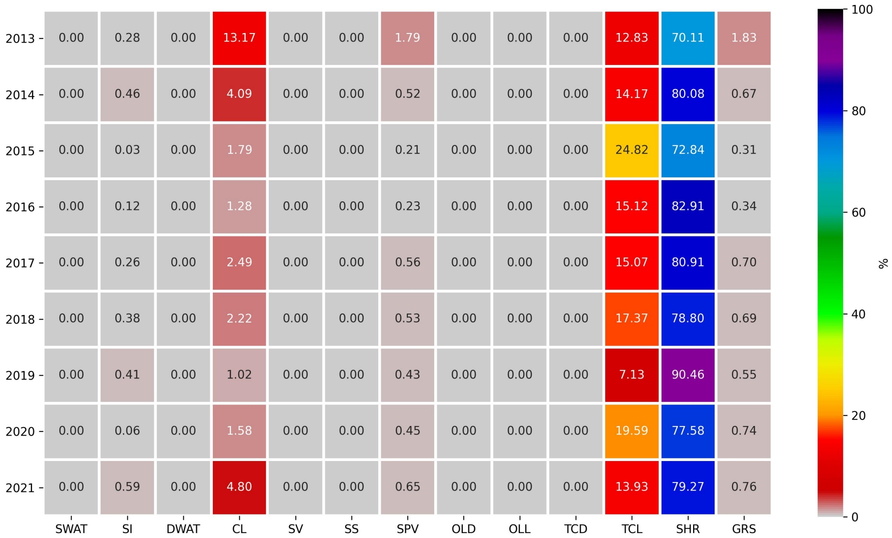

Figure 4.23: Landcover classification percentage in Cartagena del Chairá between 2013-2021

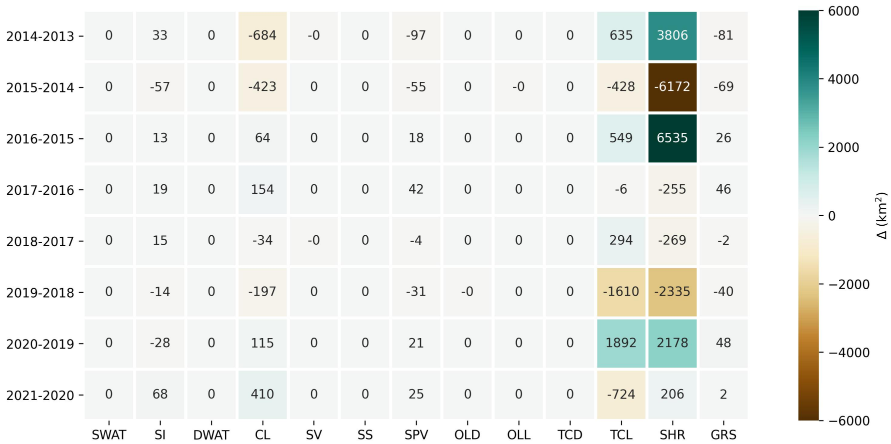

Figure 4.24: Landcover classification delta in Cartagena del Chairá between 2013-2021

change is allowed with the SHR class. In the following years (Figure 4.25b-c-d-e) SHR area starts to grow especially at the north reducing TCL in this zone. The have behavior but the SRH area in the center of Cartagena's del Chairá where is expanding the area. However, over the years, the area (lat: 1.2-1.0 long: 74.5-75) is changing SPV to SHR, and the area surrounding the river SHR is growing over the years in this zone. Nevertheless, the Figure 4.24 shows that in other zones are decreasing the Shurbs. Another interesting result is the area where is focus the TCL is on the southwest and despite decreasing not changing significantly throughout the years. On the other hand, GRS is located mixed with the shrubs, especially in the north.

Given the complex interplay between geography, socioeconomic variables, and SHR in Cartagena del Chairá, note the substantial link between SHR areas and agriculture (see Figure 4.26). Official SINCHI institute data confirms that expanding agriculture coincides with river courses, driving the concentration of SHR zones. In Figure 4.26(a) is able to identify the development of the change in 10 years on Cartagena's del Chairá agriculture that increases principally in the northwest of the municipality, the area where starts the Colombian Amazon and the subtraction area (Instituto Nacional de los Recursos Naturales Renovables y del Ambiente, 1985).

On the other hand, Figure 4.26(b) shows a different behavior, the expansion was at the border of the existing SHR zone in 2016, even though the difference compared to the last map is 4 years, it is visible in the increase of this zone. Figure 4.26(c) shows that in 2020 the expansion occurred mainly on the right edge of the SHR area, which could be attributed to slash-and-burn practices, crop expansion and crop intensification. The Figure 4.26 overlapping the 2002 and 2020 maps of agriculture, revealing the expansion in 18 years that developed more or less in the same measure around the Caquetá River, except in the mouth of the river south of the municipality where it can be seen that since 2002 there has been no significant expansion. It can suggest that colonization in the south of the municipality has occurred to a lesser extent and given the difficult conditions of road and river interconnection (Armenteras et al. 2020, Bautista-Cespedes et al. 2021), there is less interest in cultivation and logging for sale.

That could be attributed because some factors linked between them that involve lack of governance that causes grabbing land that caused big industries to use the land for extensive agriculture that is not the same to the small farmer that is located mostly in the nearest part to the river (Agudelo-Hz et al., 2023). In this area, despite the displacement has been a problem, especially in the first decade of the 2000s shown on the Figure 4.26

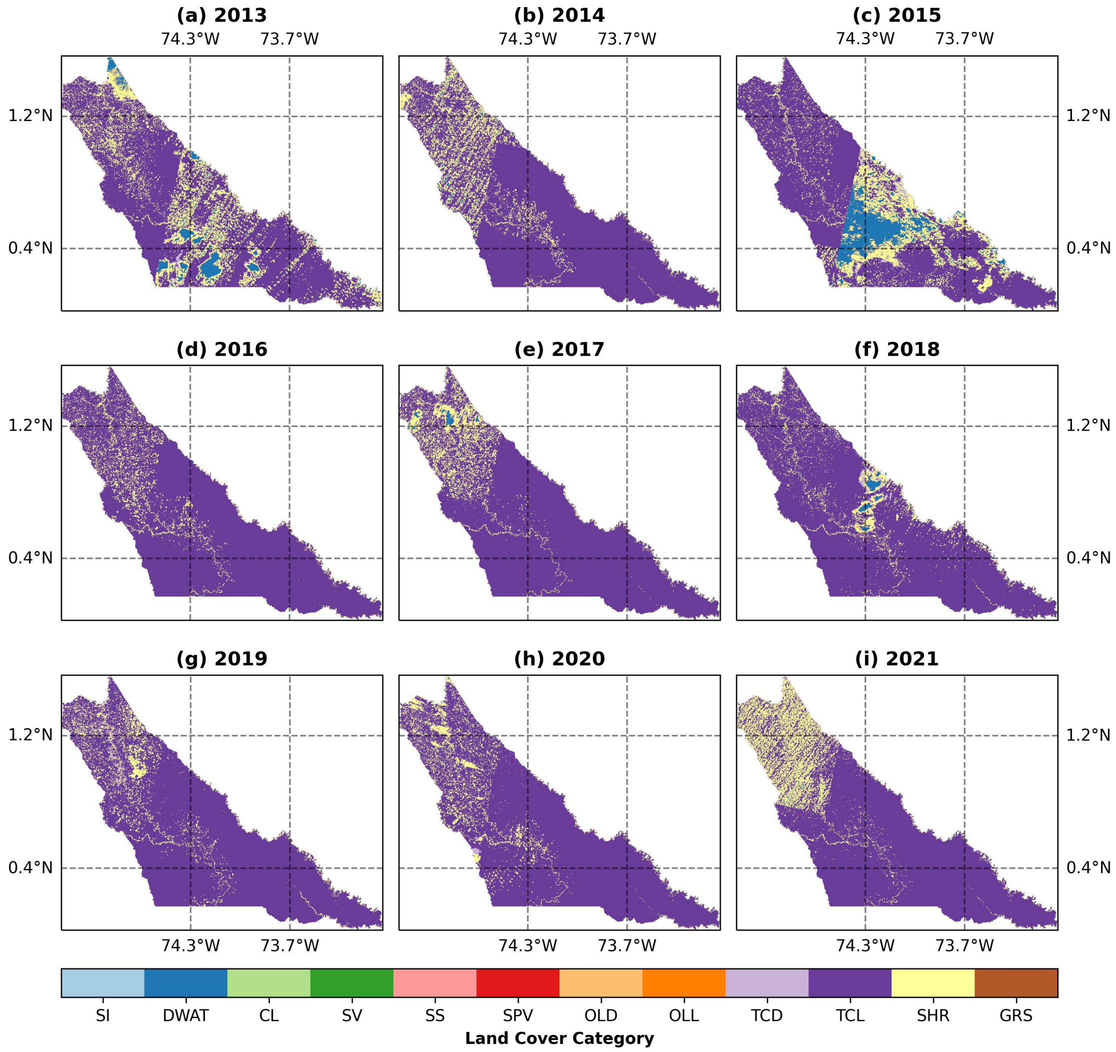

Figure 4.25: Spatial location over the years between 2013-2022

A transition away from fire-dependent to fire-free agriculture and agroforestry systems would reduce sources of ignition and ultimately wildfires —a trend that has already been reported in some tropical regions. Where there is a strong socioeconomic dependence on slash-and-burn systems, fire management techniques should be used to minimize the risk of agricultural fires escaping into neighboring forests while avoiding the negative socioeconomic effects of fire prevention to smallholders and traditional and indigenous peoples. Command-and-control operations against illegal agricultural fires are another important tool to prevent wildfires. Furthermore, expanding the existing network of well-trained and equipped fire brigades could enhance Brazil's ability to suppress unwanted fires. Last, specialized weather forecast systems and fire behavior models have effectively guided fire suppression efforts in many countries, often months before the fire season starts. These strategies could be readily adapted to and implemented in Brazil.

Over longer time scales, vegetation responses to climate change may drive changes in regional fire regimes. Forest dieback would likely result in periods of extensive and intense burning until reduction of forest fuels. Savanna (cerrado) vegetation would succeed forests when nearby but, throughout much of the basin, grass or scrub vegetation would dominate. These ecosystems would be characterized by frequent low intensity fires that would reinforce climate exclusion of mature forest species.

Smaller trees (30 cm in diameter) are at high risk of mortality because most Amazonian trees have very thin bark (Armenteras Pascual et al., 2011). However, bark thickness increases with tree diameter (Uhl and Kauffman, 1990). Typical fires may kill 40% of the trees (410 cm diameter), but reduce living biomass by as little as 10%, as few large trees are killed (Cochrane and Schulze, 1999). Fires spread slowly, on the order of 0.25 m min^{-1}, due to moist conditions under the forest canopy. Late in the day, as temperatures drop and relative humidity levels rise, fires often die out, residing only in a few smoldering logs. If weather conditions permit, the smoldering remains of the previous day's fires reignite by mid-tolate morning. Fire lines may move only 100–150 m a day but can keep burning this way for weeks or months, as weather permits (Cochrane and Schulze, 1999). The quantity, condition and distribution of large fuels (fallen boles, crowns and large branches) determine reignition probability because of their ability to shelter fires during periods when conditions are insufficient for flaming combustion and fire spread. Because of heavy slash loads, logged forests are more likely to sustain fires over

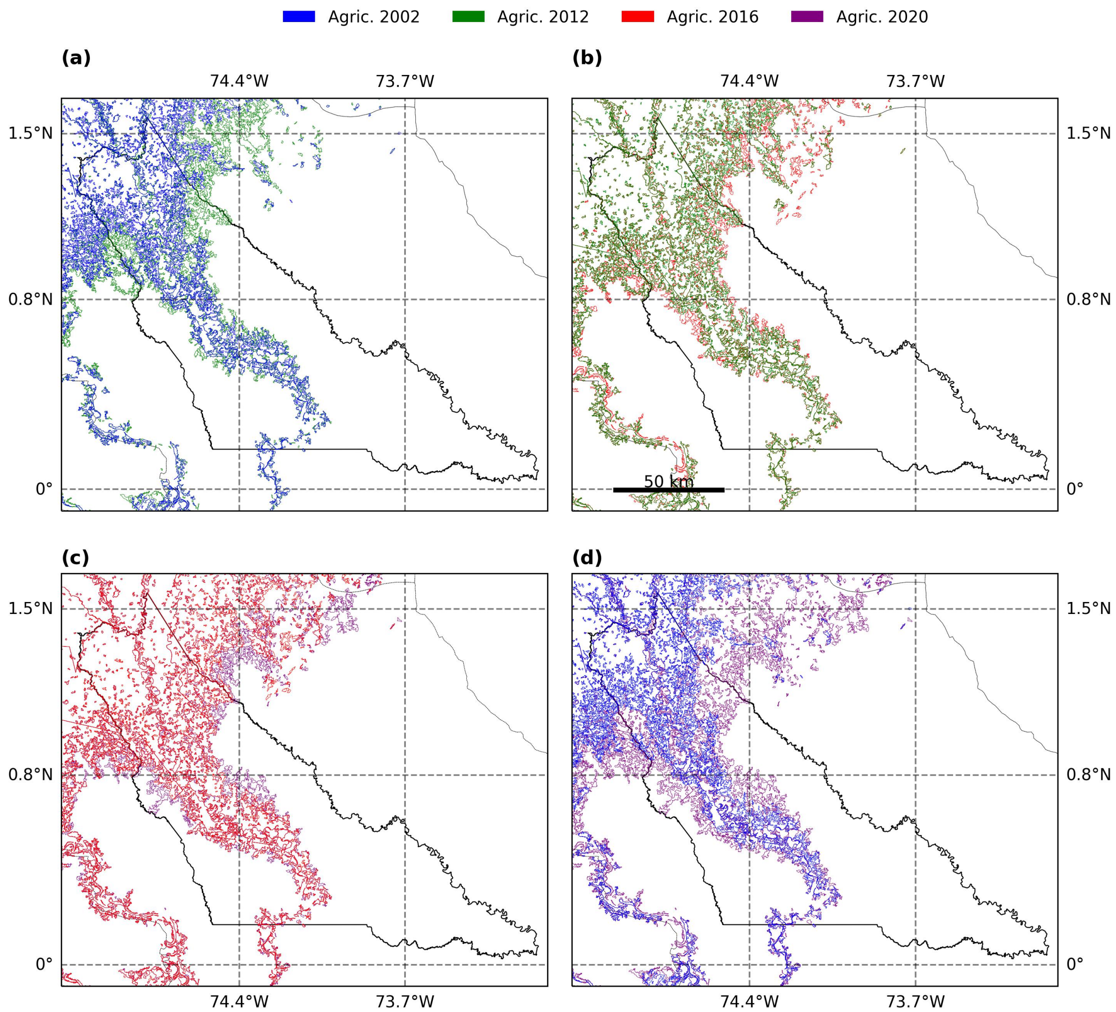

Figure 4.26: Agricultural maps overlapped in Cartagena del Chairá. (a) are 2002 (blue) and 2012 (green). (b) are 2012 (green) and 2016 (red). (c) are 2020 (purple) and 2016 (red) and (d) are 2020 (purple) and 2002 (blue).

extended time periods (Cochrane and Schulze, 1999).

Fuel loading makes fires in these forests very intense (Uhl and Kauffman, 1990), highly degrading sites and making them more vulnerable to recurrent fires. Subsequent fires in previously burned forests are more ecologically severe. Forests lose much of their remaining canopy cover. An intact forest rarely exceeds 28 °C on the hottest days, but after fire or logging opens the canopy, temperatures may approach 38 °C under similar conditions (Uhl and Kauffman, 1990). Forest fuels dry quickly, making the forest susceptible to new fires. Mortality and treefall result in greater fuel loading after initial and subsequent fires. Flame lengths, flame depths, spread rates, residence times and fire line intensities are all significantly higher in recurrent fires (Cochrane and Schulze, 1999). A second fire can kill another 40% of the original trees, this time corresponding to 40% of the living biomass (Cochrane and Schulze, 1999). Canopy cover is further reduced and fuel loads increase again. Burning closed canopy evergreen forests creates a positive feedback in both fire susceptibility and fire severity. This process can continue until complete deforestation occurs and a grassland or scrub ecosystem replaces the forest (Cochrane and Schulze, 1999).

4.3.2 Meteorology assessment

Before delving into the details of the conducted sensitivity experiments, it is pivotal to assess the performance of the ML model to ascertain its capacity to accurately depict wildfire occurrences. Figure 4.28a illustrates the temporal progression of both observed data and ML model outcomes over a span of 10.5 consecutive days, while validation encompassed 20% of the dataset (refer to the Method section for comprehensive information). During periods devoid of active wildfires, the model exhibits exceptional precision; however, this precision diminishes during instances of fire occurrence (days 3 to 5). Nonetheless, the model is able to capture the upsurge in temperature and the associated peaks correlated with fires. Evidently, statistical metrics (depicted in Figure 12a) corroborate the model's robust performance in representing both the magnitude (RMSE = 0.47K and MSE = 0.22K) and temporal evolution (R = 0.85) of temperature.

Given the ML model's capacity to faithfully depict both temperature magnitude and evolution, including temperature peaks linked to wildfires, we leverage this capability to investigate the variables exerting the most substantial influence on temperature values during wildfire

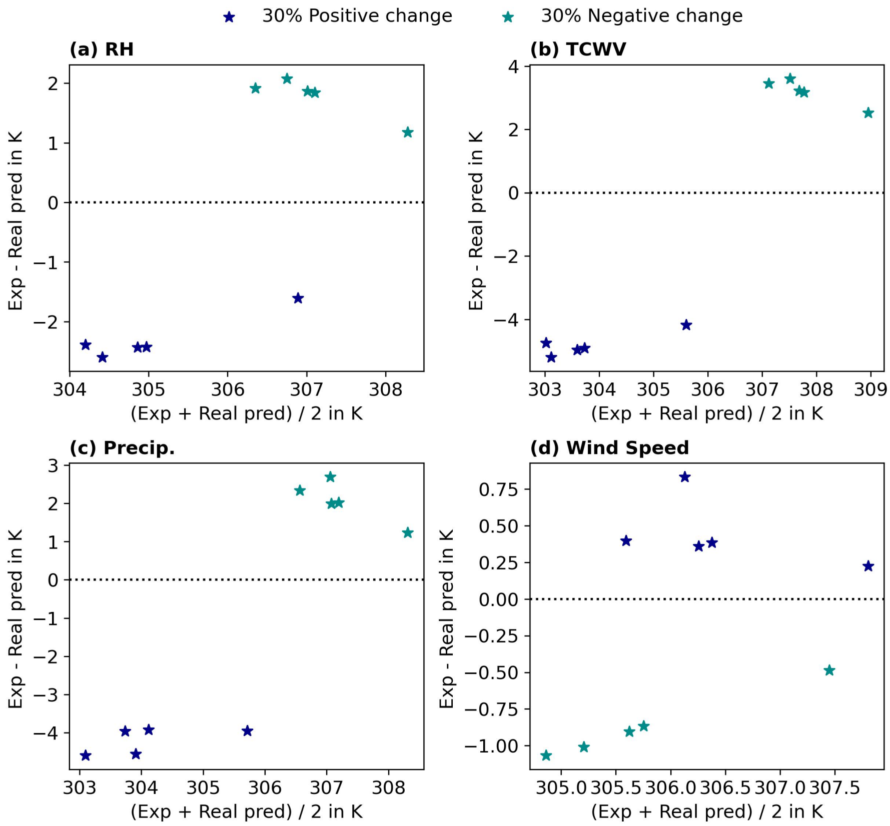

Figure 4.27: Experiments increasing (blue stars) and decreasing (green stars) by 30% the meteorological variables: (a) RH, (b) TCWV, (c) Precipitation, and (d) Wind Speed. For plotting purposes each star represents the mean of 10 wildfire events that present similar temperatures.

occurrences (temperature > 304, with consistent conclusions for alternative thresholds) when these variables are altered (refer to the Method section for details). In the realm of meteorology, RH, TCWV, and precipitation emerge as potent determinants of the model's output. Notably, an increase in these three parameters leads to temperature moderation, thereby diminishing the favorability of wildfire conditions (Figure 4.27). Moreover, wind speed influences temperature, causing a decrease when it diminishes, however, with a comparatively lesser impact relative to other meteorological variables (Figure 4.27). These findings align with theoretical expectations and the outcomes of prior sections, reinforcing the model's accurate representation of the interconnectedness between meteorology and fires. This suggests that the model could also aptly incorporate socio-economic variables, although this relationship might be less transparent.

4.3.3 Socio-economic assessment

Turning to the socio-economic experiments (Figure 4.28), the variables inducing the most substantial impacts on wildfires are GDP, GINI (of paramount significance), and Armed Conflict Victims, closely followed by displacement of people, unemployment, and lower education levels. Informal work and total population also generate changes in wildfire patterns, albeit with less pronounced effects. The salience of total population (Figure 4.28b) stems from the tendency of newcomers to colonize various areas, engaging in informal work and individual planting practices lacking in best practices. Elevating GDP (Figure 4.28c) tends to suppress wildfire incidents, as increased financial resources imply enhanced technologies and practices for soil protection and harvesting. This alignment with GINI outcomes (Figure 4.28d) underscores a decrease in wildfires with reduced inequality, as equity entails job creation, a decline in informal labor, and better agricultural practices and infrastructure.

The GINI experiment underscores that reducing unemployment (Figure 4.28h) and informal work (Figure 4.28e) diminishes wildfire favorability. This can be attributed to fewer potential ignition sources, decreased involvement in illegal activities like illegal crops (linked to fires, as per Dávalos et al. 2011), and improved conditions due to reduced inequality. Education's significance is also apparent in GINI results, where diminishing low-level education (Figure 4.28f) disfavors wildfires. Multiple factors contribute to this: (i) educated individuals are less prone to ignite forest or crops, (ii) they are less inclined towards illegal activities i.e. illegal crops, and (iii) enhanced agricultural knowledge fosters better practices, safeguarding soil and discouraging fires.

Conversely, displacement and armed conflict victimization are closely intertwined, with displacement primarily arising from Colombia's internal conflict. Interestingly, an increase in conflict victims and displacement leads to decreased fires. This is because heightened agricultural activity is curtailed, as people are reluctant to enter forests or agricultural areas due to the risk of encountering armed groups overseeing illegal crops (Dávalos et al., 2011). These findings emphasize the government's responsibility to not only conclude the conflict but also integrate displaced individuals into groups that contribute to CdC's educational, economic, and agricultural progress. Ceasing hostilities could yield unintended benefits, transforming challenges into opportunities to enrich lives, enhance agricultural practices, bolster connectivity, expand job opportunities, and develop technologies. Such growth would be personally and communally transformative, aiding CdC's advancement and concurrently diminishing GINI while bolstering GDP, thus reducing wildfire vulnerability from multifaceted angles.

4.4 Drawing Mitigation and Adaptation Strategies

Our approach begins with an exposition of the strategies that are currently in place, providing a contextual foundation for the subsequent presentation of the proposed strategies. This sequential arrangement serves to highlight the enhancements and linkages inherent in the new strategies, thereby ensuring transparency in their evolution. Considering the socioeconomic analysis and the latest governmental program by Cartagena del Chairá (Vargas-Correa, 2019), which is tailored to address forest fire concerns, we evaluated the proposed strategies as foundational for shaping the approaches discussed in this section. In the realm of education, the governmental plan underscores the significance of bolstering technical and non-formal education for adults engaged in non-formal occupations. It also advocates for the establishment of comprehensive farms within educational institutions to facilitate agricultural practices. In the domain of conservation and environment, the plan emphasizes the modernization of rural areas and the promotion of agricultural production to safeguard the food supply chain.

The primary arena aligned with fire-related issues within the plan is agriculture. To address this, the strategies concentrate on offering technical aid, training, and guidance in agricultural management practices. Furthermore, a mechanism for evaluating the potential impacts of new practices on the environment and society will be instituted. A dedicated focus is also placed on land tenure, aiming to optimize the procurement of arable land, enabling farmers to enhance their livelihoods through agriculture (Vargas-Correa, 2019). The financing for this endeavor will be derived from municipal, regional, and national budgets, alongside a portion of agricultural yield generated from the acquired land and both domestic and international funding. The strategies extend support to empower local farmer associations, fostering their self-management capabilities to enhance the well-being of farmers. Additionally, initiatives are targeted at restocking livestock and providing tools to augment the security of small livestock holders. To diversify the economic landscape, the municipality intends to allocate resources for the establishment of poultry and fish farms, managed by local producers (Vargas-Correa, 2019). Lastly, the municipality's agenda encompasses funding family farming programs to elevate the income of small-scale producers, ultimately improving their quality of life. Approaches with a social and post-conflict perspective encompass mechanisms for citizen engage-

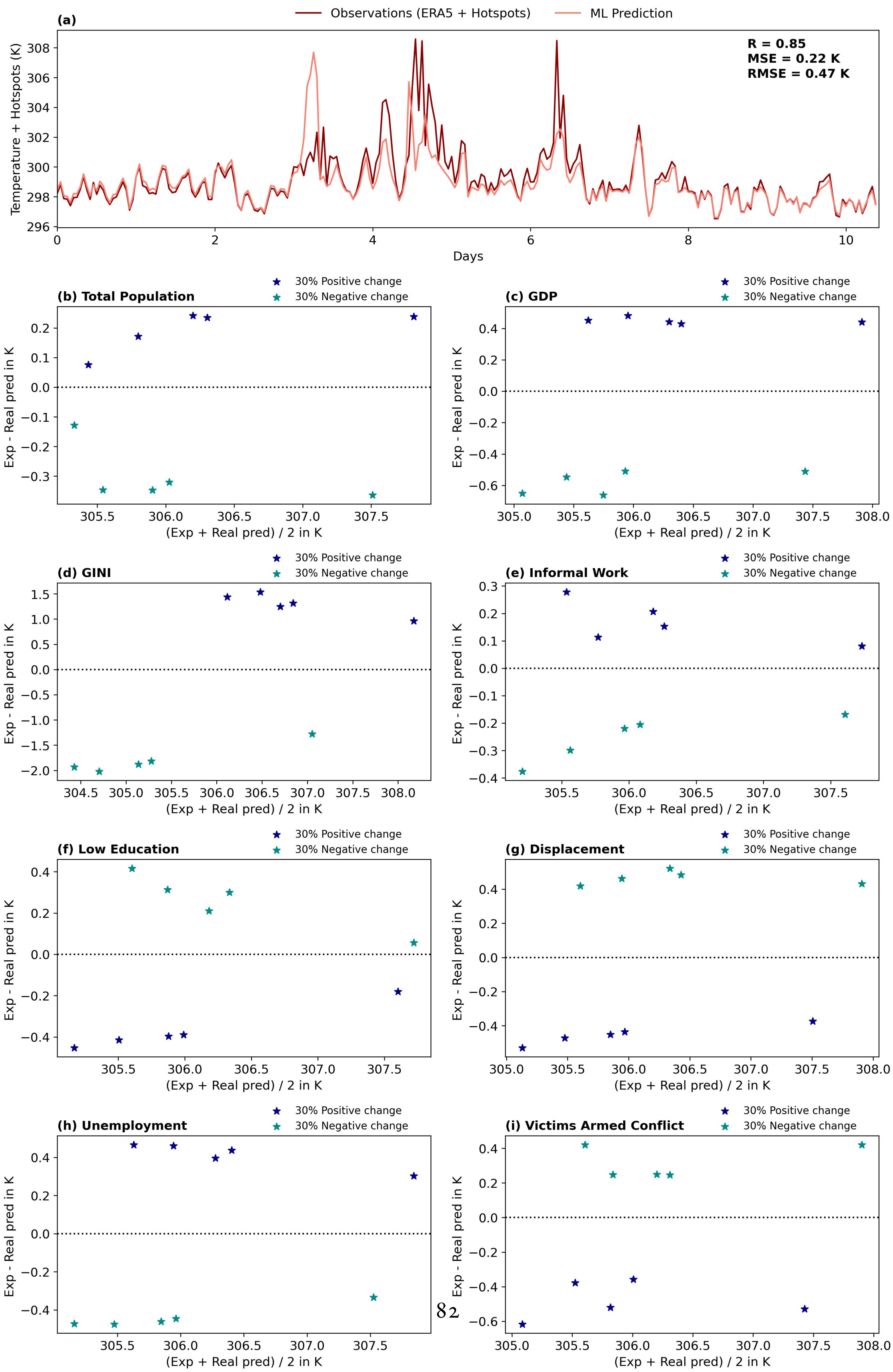

Figure 4.28: (a) ML model evaluation of three months of data, although here a subset of 10.5 days that include wildfires is plotted. Notice that the R, MSE and RMSE are also plotted in the figure, but are calculated for the three months and not only for the subset. Bland-Altman plots for experiments increasing (blue stars) and decreasing (green stars) by 30% the socio-economic variables: (b) Total Population, (c) GDP, (d) GINI, (e) Informal Work, (f) Low Education Level, (g) Displacement, (h) Unemployment, and (i) Victims Armed Conflict. For plotting purposes each star represents the mean of 10 wildfire events that present similar temperatures.

ment, pre-implementation consultation, employment creation funded through national post-conflict funds, and backing organizations dedicated to environmental preservation and safeguarding natural resources (Vargas-Correa, 2019).

The strategies formulated within the municipal government plan offer valuable insights into Cartagena del Chairá's political landscape and its prioritization and management approach. Strategies encompassing funding and technical support for family agriculture, economic diversification, and employment generation in alignment with post-conflict funds bear direct and indirect potential to alleviate forest fires in the Amazonian region. Nevertheless, certain strategies, such as cattle restocking, land tenure for municipal revenue, and agricultural technification, seem to diverge from the municipality's fire mitigation needs and the Sustainable Development Goals embraced for the Amazon by 2030 (Painter et al., 2023) and Amazonian panel recommendations (Nobre et al., 2021).

Guided by meteorological, vegetation coverage, and socio-economic findings, while considering near-term climate projections (2050), we propose preliminary measures that focus on three facets: land cover, economic, and social (inequality and displacement). These proposed strategies aim to sustainably mitigate forest fires in Cartagena del Chairá.

Land Cover Strategies

- Maintained a hydrated soil, using plants that retain moisture and evaporate slowly, so disfavor very dry conditions that could promote wildfires.

- To secure the border in the deforestation zone, a paramount focus should be on granting externally monitored concessions to small landowners whose plots contain substantial forest proportions. These concessions would be assigned within the deforested section of the plot and complemented by value-chain integration for endemic fruits and high-value agroforestry products (e.g., acai, camu-camu, buriti, etc.). The implementation of this controlled-support blend would resonate as a powerful shift in policy, transitioning from incentivizing deforestation to endorsing sustainable agroforestry and natural forests. Although unprecedented in Colombia, analogous bioeconomy approaches (Gobierno-Colombia, 2020) have been proposed in Brazil to tackle the same systemic flaw. It is through land market management that we can envisage the salvation of Amazonian forests and biodiversity.

- In line with this concept, the planning of areas, coverage change monitoring, and prevention of illegal settlements (Jara et al., 2016) contribute to mitigating the vulnerability to forest fires among the population (e.g., Galiana-Martin et al. 2011; Hernández 2016;

Miranda et al. 2020). These efforts involve integrating the identification of Wildland-Urban Interface (WUI) areas into planning instruments as a fire prevention guideline and risk reduction strategy (e.g., Calkin et al. 2014; Miranda et al. 2020; Moritz et al. 2014) in municipalities with medium, high, and very high socioeconomic vulnerability.

- Effective forest fire management encompasses all phases, from prevention to impact reduction. This begins with individual responsibility, community involvement, resident training, and provision of fire reduction equipment. It further involves implementing fire detection systems, communication networks, and safeguarding strategic ecosystems within the department (e.g., Calkin et al. 2021; Casallas et al. 2022). These actions collectively aim to prevent fire outbreaks and mitigate their adverse effects on both communities and ecosystems. It's a holistic strategy that involves situational awareness, long-term assessment, monitoring and control, as well as post-fire evaluation (Calkin et al., 2021).

- The synergy between community and ecological networks holds significant importance for driving (i) land management decisions, (ii) understanding the social, environmental, and economic context of an area, and (iii) developing a novel framework to link social and ecological systems (Windsor et al., 2022). To achieve this, the emphasis should be on practices that seamlessly integrate these two dimensions. Establishing agro ecological training partnerships among public, private, and non-profit organizations can facilitate education, implementation, support, and adaptation of such practices.

- Implementing a combination of positive and negative incentives policies is crucial. Prohibitive measures should be balanced with positive reinforcements. For instance, costly techniques like pasture rotation and trial verge management could be offset through social investment, aligning with the national development plan's commitment to rural sustainability. This approach could facilitate the adoption of agroecological methods.

- Government-led territorial consolidation efforts can be bolstered by addressing both infrastructural and cultural aspects. It's noteworthy that small-scale clearances by peasant families, often conducted in collaboration, accumulate into significant deforestation rates. These practices could be mitigated through a comprehensive approach that considers both environmental and social dimensions.

Economic Strategies

- Investing in research and securing funding often poses significant financial and operational challenges for institutions in the Global South (Coccia 2009; Clavijo 2016). Obtaining documentation for grant applications and managing subsidies can be convoluted and time-consuming, hindering timely completion of scientific projects, international collaborations with stringent project deadlines, and access to global research funding opportunities for researchers from the Global South (Merkle, 2016). Urgently, Global

South institutions must establish transparent funding management policies to ensure access to research funds, coupled with mechanisms to monitor fund utilization. These policies should streamline administrative burdens for researchers and ensure equitable benefits for both national and international researchers. However, implementing such standards often demands the establishment of entirely new administrative policies and teams, such as ethics committees, incurring both financial and time costs (Hyden 2016; van Helden 2012). Nonetheless, this endeavor offers the potential to raise awareness among administrative personnel regarding funding requirements and opportunities for research, promoting institutional growth (Ocampo-Ariza et al., 2023).

- Furthermore, certain funding opportunities are explicitly geared towards international collaborations, including provisions for exploratory visits to potential foreign partners and acceptance of proposals in multiple languages (e.g., WWF funding). Ecologists and conservationists from the Global South can harness these opportunities to spearhead research grant applications, ensuring direct access to funds and equitable benefits for national and international collaborators (Asase et al., 2022). Assuming leadership in funding applications may entail increased workloads, involving identifying funding avenues accessible to Global South researchers and aligning research proposals with specific standards. Beyond the additional workload, it can foster well-planned early collaborations with international researchers and expand funding alternatives for their promotion. Moreover, this approach facilitates funding agencies' understanding of the characteristics and needs of fund recipients in the Global South, ultimately enhancing grant application requirements with a broader diversity, equity, and inclusion perspective (Escobar-Alvarez et al., 2021). Currently, limited funding supports the development of participatory research collaborations and joint creation of research questions and methods between the Global South and international researchers, undermining collaborative research's potential based on shared interests. Augmenting research awards for early stages of international research agreements holds promise for fostering cross-cultural scientific collaboration (Ocampo-Ariza et al., 2023).

- In the realm of funding, it's important to highlight that private financing is absent. This is due to the voluntary nature of rainforest conservation and restoration initiatives, which lack attractiveness to financial institutions. However, livestock ownership could potentially align with the interests of financial institutions due to lending opportunities, as opposed to rainforest conservation initiatives that rely on volunteer efforts (private donations).

Social Strategies

- However, we must acknowledge that parachute research practices also exist within countries of the Global South, especially when access to higher education and capacity development is concentrated in large cities (e.g., de Vos and Schwartz 2022). Research and the practice of tropical ecology and conservation can greatly benefit from diverse teams, including local specialists, such as ”paraecologists,” who possess empirical knowledge of local ecosystems and biodiversity (Sheil and Lawrence 2004; Schmiedel et al. 2016). Collaborative project development and results discussion with local communities maximize applicability and impact, while respecting local communities' sovereignty over their territory and resources, and ensuring enduring trust-based relationships (Toomey et al. 2019; Ocampo-Ariza et al. 2023).

- Respectful engagement of local communities entails their active participation and input at multiple stages, securing permissions, co-developing research questions, collaborating with and hiring locals, and building capacities during data collection and processing. Open discussions of interim and final research findings and adaptive refinement of participatory research and practices are crucial (e.g., Toomey et al. 2019; Ramírez-Castañeda et al. 2022; Ocampo-Ariza et al. 2023).

- Interdisciplinary approaches in which ecological expertise engages in intercultural dialogue can support this objective and ensure the integration of traditional knowledge from local stakeholders.

- In the future, a significant challenge for integrating social and ecological networks revolves around appropriate data collection. Specifically, gathering and aligning data of the correct type (i.e., weighted links with comparable or interactable units) and at the correct resolution (e.g., seasonal management decisions and knowledge exchange by farmers) is vital. Many methods exist to generate social data for network construction; however, current methods are qualitative (i.e., using ecosystem service provision as a node linked to species without measuring the species' impact on service provision) and/or collect data at spatial or temporal resolutions inappropriate for integration with ecological networks (Windsor et al., 2022)

5

Conclusions

This study initially centers on an exhaustive spatio-temporal analyses of the meteorological conditions that instigate wildfires in Cartagena del Chaira, establishing that elevated temperatures, dry environments, strong winds, and absence of precipitation can trigger forest fires, particularly in the northern region and during the boreal winter season. Nevertheless, these conditions must coincide with areas hosting shrubbery tied to agricultural practices. Farmers employ ”controlled” fires for soil preparation, yet issues arise due to inadequate adherence to rigorous standards in many plantations. Moreover, the prevalence of illegal plantations using fires to supplant legal ones compounds the challenges.

Conversely, a thorough analysis of climate change in the study area is conducted by gauging the magnitude of meteorological variable anomalies for the year 2049 across four diverse scenarios encompassing different SSPs and RCPs. The findings reveal that during boreal winter, when wildfires typically emerge, temperature and RH primarily contribute to favorable wildfire conditions, whereas wind speed and precipitation hinder their development. It is crucial to highlight that certain scenarios depict conditions wherein both precipitation and wind speed at the south and southeast of CdC could foster fires, while temperature and RH in the same scenarios favor them more pronouncedly. This dual concern underscores the necessity for the government to not only mitigate existing fire-prone zones but also prevent new fire outbreaks in previously unaffected areas. Additionally, in boreal summer, temperature, RH, and wind speed promote wildfires, with precipitation offering a counteracting influence (albeit less potently than in boreal winter) across most scenarios. Nonetheless, at the south and southeast of CdC, all variables align to elevate the likelihood of wildfires, raising two alarming aspects: (i) regions previously untouched by fires could become susceptible, and (ii) boreal summer could evolve into a season conducive to wildfires, extending the fire-prone period beyond just the boreal winter.

Given the ominous climate change scenarios threatening the region, a ML model is devised to (i) discern the meteorological and socio-economic factors influencing fires and (ii) develop strategies to address the variables wielding the most significant impact on fire occurrences. The results underscore the significance of RH, TCWV, and precipitation in wildfire dynamics, emphasizing the importance of maintaining a moist environment and hydrated soil to curtail fires. On the socio-economic front, the GINI index and lower education levels exhibit potential to diminish wildfires, while heightened displacement trends could amplify fire risks. This underscores the government's imperative to not only resolve conflicts but also foster opportunities, employment, and education, with the overarching goal of reducing inequality (GINI) and thereby mitigating fire incidents.

Finally, we create strategies that combine all the results, and are based on already designed plans and policies. Our comprehensive approach encompasses land cover, economic, and social strategies to address the complex challenges posed by forest fires and sustainable land management in the Amazon region:

- **Land Cover Strategies:** To mitigate the risk of wildfires, we emphasize maintaining hydrated soil through the cultivation of moisture-retaining plants that discourage extremely dry conditions. Additionally, we propose granting monitored concessions to small landowners with significant forested areas in their plots, strategically positioned within deforested sections. These concessions would integrate value chains for endemic fruits and high-value agroforestry products, signifying a transformative policy shift towards sustainable agroforestry and natural forest preservation. This pioneering approach, although unprecedented in Colombia, mirrors successful bioeconomy strategies in Brazil, highlighting the potential of effective land market management for conserving Amazonian biodiversity.
- **Fire Vulnerability Reduction:** To minimize vulnerability to forest fires, we advocate for proactive measures such as proper area planning, continuous land cover monitoring, and the prevention of unauthorized settlements. Integrating WUI zones into planning tools is a strategic guideline for fire prevention in municipalities with varying socioeconomic vulnerabilities, safeguarding populations from fire-related hazards.

- **Holistic Fire Management:** Our approach to holistic forest fire management spans prevention to impact reduction, integrating individual and community responsibilities, training, and fire mitigation equipment provision. This strategy is underpinned by the deployment of fire detection systems, robust communication networks, and the protection of key ecosystems. By adopting a comprehensive approach that includes situational awareness, long-term evaluation, monitoring, control, and post-fire assessment, we aim to prevent fire incidents and mitigate their adverse effects on both communities and ecosystems.

- **Community-Ecological Synergy:** We recognize the significance of harmonizing community and ecological networks, essential for informed land management decisions, understanding local socio-environmental contexts, and establishing innovative connections between social and ecological systems. Prioritizing practices that seamlessly bridge these dimensions is crucial, and we propose forging agroecological training collaborations across public, private, and non-profit sectors to facilitate education, implementation, support, and adaptation of sustainable practices.

- **Balanced Incentive Policies:** Our approach emphasizes the importance of balancing positive and negative incentives. While prohibitions need to be balanced with rewards, we suggest that investments in social initiatives could offset costs associated with sustainable practices like pasture rotation and trial verge management. Aligning with the national development plan's goals for rural sustainability, this approach could foster the widespread adoption of agroecological methods.

- **Government-Led Territorial Consolidation:** To enhance government-led territorial consolidation, we recommend addressing both infrastructure and cultural factors. Collaborative small-scale clearances by local families significantly contribute to deforestation, and a comprehensive approach is essential to mitigate these practices, considering both environmental and social dimensions.

In conclusion, our multi-faceted approach, spanning land cover, economic, and social dimensions, underscores the importance of sustainable strategies for mitigating forest fires and promoting responsible land management in the Amazon region. Through a holistic framework that integrates diverse stakeholder perspectives and engages local communities, we aim to pave the way for a harmonious coexistence between people and the environment in this critical ecosystem.

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Acknowledgments

I wish to extend my heartfelt gratitude to the STeDe program for generously awarding me the mobility scholarship that played an important role in advancing this project. I also thank Prof. Salvatore Pappalardo for his guidance. My sincere appreciation knows no bounds as I acknowledge WWF Trieste and Sergio Arboleda University for their warm hospitality extended to me. Their invaluable contributions span from facilitating data collection to fostering enriching discussions. I would also like to express my regards to the Abdus Salam International Centre for Theoretical Physics (ICTP) for their gracious provision of essential computational resources.

I would also like to extend a heartfelt note of gratitude to my parents, whose unwavering trust in my abilities has been an incredible source of strength. Their unwavering belief in me, allowing me to flourish and love me above all else, is a treasure beyond measure. I am profoundly thankful for their sacrifices, which paved the way for me to stand here today. In addition, my appreciation extends to Alejandro Casallas for his unwavering support, love, and guidance throughout this journey. Lastly, I reserve a moment to acknowledge my own efforts in giving my utmost dedication to this endeavor.