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Review Article

Remote sensing applications for effective fire disaster management plans: A review

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ABSTRACT: The current context of climate change and imminent global warming is leading to changes in temperature and rainfall patterns worldwide that affect soil moisture, vegetation, and soil conditions, the incidence of dry and wet events, and consequently, the occurrence, intensity, and magnitude of fires. Fires harm people's quality of life as they can disrupt economic activities and affect public health. Additionally, fires damage the environment, accelerating water and wind erosion processes, altering air quality, and contributing to ecosystem degradation. Pampas in Argentina was selected as an example to study fires at a regional scale using remote sensing techniques due to its status as one of the most fertile plains in the world and the country's most densely populated area. The fires are carefully analyzed and described considering three stages: i) pre-fires, ii) fires, and iii) post-fires. Afterwards, fire disaster management plans are described to assess these events, reduce their impacts on society and biodiversity, and minimize the ecosystems' recovery time. In this sense, this manuscript aims to review the relationships between climate change, global warming, and the occurrence of fires. Additionally, it proposes to analyze the potential of remote sensing in analyzing these events at a regional scale to provide the mechanisms and tools necessary for formulating fire disaster management plans.

KEYWORDS: fires; climate change; global warming; remote sensing; disaster management

1. Introduction

Climate change and global warming alter thermal and rainfall patterns worldwide, thereby impacting extreme events, intensifying droughts, floods, heatwaves, cold spells, and sea-level rise. The environmental effects caused by these phenomena are manifold. However, the changes they induce in land cover, particularly vegetation, increase the availability of fuel. Additionally, the development of storms with greater electrical activity creates a context where fires are more frequent and intense. It is important to consider these phenomena as part of the planet's natural climate variability and common agricultural practices in some parts of the world. Therefore, they could be intensified due to the greater energy available in the atmosphere.

In this context, remote sensing emerges as an indispensable tool for studying, monitoring, and assessing the impacts of fires on the environment, especially at regional scales. This knowledge is crucial for contextualizing and designing fire management plans in different parts of the world. These plans can be redesigned, rethought, or established as new methodologies and approaches for assessing their impacts in a scenario where fires are expected to become increasingly intense and severe. The following sections describe the relationships between fires, climate change, and global warming, the study of these relationships using satellite products, and the importance of processes for implementing spatial management plans.

1.1. Fires in the climate crisis context

The climate crisis is a concept related to the climate emergency and the global warming crisis. It is a term to describe the urgent and severe challenges generated by human-induced climate change. It refers to rising global temperatures' ongoing and projected impacts and associated environmental, social, and economic consequences[1,2]. In this context, fires represent a vital aspect of climate change's broader environmental and societal challenges.

Fires in the climate crisis have several impacts. For example, the amplification of fire risk is generated by the contribution of higher temperatures, heterogeneous rainfall patterns, and increased severe drought, making fires more likely to occur. Therefore, fires contribute to the climate crisis. They behave as part of a climate change loop as they introduce carbon dioxide into the atmosphere, exacerbating the increase in temperature[3,4].

Ecosystems and biodiversity are also at risk due to the relationship between fires and climate crises. The increase in the intensity and severity of fires profoundly impacts ecosystems. Likewise, the impacts on economic activities and human life are significant issues. Loss of lives, negative effects on infrastructure, and local and regional economies are linked to fires[2,4].

Therefore, when analyzing fires, it is essential to understand climatic and meteorological conditions in past, present, and future scenarios. This allows for establishing relationships between the current climate and future scenarios of greenhouse gas concentrations based on Shared Socioeconomic Pathways (SSPs) while considering short-term, medium-term, and long-term projections[5,6]. Furthermore, knowledge of the spatiotemporal dynamics of land cover and its relationship with soil moisture variations is crucial for understanding and predicting vegetation behavior regarding fuel availability[7]. Additionally, evaluating the effects on the environment, hydrographic basins, and the time required for ecosystem recovery are crucial elements for interpreting the significance of sustainable land management plans[8]. It is important to note that local stakeholders and decision-makers play a significant role in taking measures related to affected areas, as wildfires tend to impact public health adversely.

1.2. Fires and remote sensing

In the context of studying wildfires as a natural and anthropogenic disaster, a transdisciplinary approach is necessary. Geographic Information Systems (GIS) and Remote Sensing (RS) technology are important tools for studying these phenomena. In the literature, these tools have been widely used and have yielded good results in exploring different aspects of wildfires[9–14].

RS plays a crucial role in effective fire disaster management by providing valuable data for monitoring the surface in near-real-time and providing information for multispectral and Synthetic Aperture Radar (SAR)[15]. RS is essential for fire detection and monitoring, as thermal infrared sensors can detect temperature anomalies on the surface[16]. Satellite data allows for the design of detailed fire maps, which help understand fire extent, progression, and behavior[17].

In this context, monitoring vegetation health is essential since it can fuel wildfires[18]. RS enables the assessment of fuel characteristics such as vegetation density, moisture content, and flammability[19]. Moreover, satellite imagery can map vegetation types and monitor changes over time[20]. During fires, smoke affects air quality. RS can monitor smoke plumes and evaluate air quality impacts during such events[21]. Satellite products are applied to measure and track smoke plumes and the concentration of pollutants. RS can also be used for post-fire damage assessment[22,23]. After a fire event, RS can assess the severity and extent of damage. High-resolution imagery and aerial photography provide information about the impact on land covers and cities[22,24].

By utilizing information from RS and applying GIS, it is possible to construct fire risk maps considering vegetation types, fuel load, topography, weather conditions, and historical fire patterns[22]. Moreover, integrating RS data into early warning systems for fire disasters can establish an early warning system that continuously observes environmental conditions and detects areas with high fire risk[25]. This enables the timely issuance of alerts and warnings to authorities and local communities, facilitating preventive and evacuation measures[26].

When studying fires, it is advisable to include three steps or phases[27]. The pre-fire phase involves assessing fuels, meteorological conditions, soil conditions, thermal anomalies, and air quality. During the fire phase, the impacts and effects of fires are studied, including their extent, duration, intensity, and implications for the environment and the population. This phase also includes the study of air quality and smoke plumes. The post-fire phase focuses on the recovery time for different ecosystems, infrastructure damage, relocation of people, and measurement of impacts[28–30].

Understanding these phases, it is crucial to incorporate detailed knowledge about the context of climate change and global warming. These processes can intensify fire seasons and their severity. For these reasons, the study and assessment of fires is a multidisciplinary and transdisciplinary topic that needs to be carefully analyzed[31].

1.3. Disaster management process

Disaster management is a process that involves systematic planning, organizing, coordinating, and implementing measures to mitigate, prepare for, respond to, adapt to, or recover from disasters such as fires[32,33]. This topic encompasses a wide range of activities and strategies to minimize the negative impacts of disasters on human lives, infrastructure, the environment, and the economy[34]. It involves four essential phases, as described below:

1) Mitigation: This phase focuses on reducing the risk and vulnerability to disasters. It includes identifying potential hazards, evaluating their impact, and implementing measures to minimize their occurrence or mitigate their negative effects[35,36].
2) Preparedness: It involves the development of plans, procedures, and capacities to respond to disasters effectively. It includes training emergency responders, conducting public awareness campaigns, and developing evacuation plans[37,38].
3) Response: It includes the immediate actions taken during a disaster to save lives, reduce suffering, and mitigate negative environmental effects. It is related to providing medical care, temporary shelters, distributing supplies, and other emergency measures[39,40].
4) Recovery: This focuses on restoring affected communities, infrastructure, ecosystems, and the environment to pre-disaster conditions or better. It involves providing psychological support to individuals, implementing economic recovery measures, and planning long- and mid-term rehabilitation and reconstruction efforts[41,42].

The study of disaster management is a multidisciplinary and transdisciplinary field that requires collaboration among scientists, government agencies, non-governmental organizations, emergency responders, community groups, and other stakeholders. The main objective of disaster management is to reduce the vulnerability of communities, increase their resilience, and minimize the impacts of disasters through proactive measures and efficient response strategies[43,44].

1.4. Objectives and study area

Based on the abovementioned factors, this manuscript aims to assess the relationship between climate change and global warming with fire occurrences. Furthermore, it focuses on analyzing the significance of remote sensing techniques in studying fires at regional scales. The stages of pre-fire, fire, and post-fire conditions were thoroughly examined. Finally, it was crucial to determine how the scientific community, decision-makers, and stakeholders can act to mitigate and adapt to the negative effects of fires, climate change, and global warming. In this context, studying fire disaster management plans has become crucial to developing actions to address these issues.

The study area selected for this research was Pampas in Argentina. This region was chosen as a key area where the primary economic activities depend on climate variability due to its agricultural and livestock sectors. It is worth mentioning that fires have significant consequences for local and regional populations, including habitat loss, displacement, and changes in species composition. Studying fires in this region allows scientists to identify the vulnerability of animal species and assess population risks. This information is vital for developing effective disaster management plans to safeguard biodiversity. Since agricultural activities and livestock production are key economic drivers in Pampas, farming fires and wildfires cause substantial risks. These fires can damage grazing lands, impact livestock health, and lead to soil erosion, further highlighting the need for comprehensive fire management and mitigation strategies. Therefore, researching fires is crucial for understanding the ecological role of fires, their effects on biodiversity, and the resilience of ecosystems. This knowledge provides a solid foundation for developing strategies to protect and restore the natural balance worldwide.

2. Climate change and global warming context

Climate change refers to long-term shifts in global or regional climate patterns. It is primarily caused by human activities, particularly the emission of greenhouse gases into the atmosphere, such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). These gases trap heat from the sun, leading to an overall increase in the Earth’s average temperature, known as global warming. Climate change encompasses a range of effects beyond just temperature changes, including alterations in precipitation patterns, sea-level rise, melting glaciers and ice caps, shifts in ecosystems and biodiversity, and changes in the frequency and intensity of extreme weather events[45–47].

While natural factors can influence climate variations, such as volcanic eruptions and solar radiation, human activities have become the dominant driver of the recent and rapid changes observed in the Earth’s climate system. These activities include burning fossil fuels for energy production, industrial processes, deforestation, and land-use changes. The release of greenhouse gases from these activities has significantly increased their atmospheric concentrations, resulting in an enhanced greenhouse effect and subsequent climate change[48–50]. Besides, climate change has wide-ranging impacts on both natural and human systems. It risks food security, water resources, public health, infrastructure, and economies[51,52].

Efforts to address climate change involve mitigation and adaptation strategies. Mitigation aims to reduce greenhouse gas emissions by transitioning to renewable energy sources, improving energy efficiency, and implementing sustainable land-use practices. Adaptation involves adapting to the changing climate by enhancing resilience, developing robust infrastructure, implementing disaster risk reduction measures, and promoting climate-conscious policies[53,54].

Climate change has become one of the most pressing environmental challenges worldwide[55]. Global temperatures have risen significantly, warming 0.7 °C from 1906–2005 and 0.9 °C from 1880 to 2012. Since 1970, the rate of temperature increase has been 0.2 °C per decade[56]. This global warming phase has resulted in environmental changes that impact various economic activities, particularly agriculture and livestock, affecting people's quality of life[57]. The latest IPCC report (2021) predicts the possibility of surpassing the 1.5 °C global warming threshold in the coming decades, with uniform temperature increases worldwide. This would lead to more frequent temperature extremes that exceed critical tolerance thresholds for land cover and human health[5].

Global warming is closely linked to wildfires as it increases the potential for ignition and, consequently, the frequency of fire events. Most parts of the world have observed more intense and recurrent forest fires[5], and projections indicate a 74% increase in the risk of forest fires by the end of the century[7]. Besides the environmental and socioeconomic impacts of such events, wildfires directly affect public health, resulting in physical injuries (burns, injuries), mental health implications (post-traumatic stress), and even loss of life due to flame exposure. Moreover, significant medical assistance and public and private investments are required to repair property damage[36]. The effects on public health are also linked to the generation of wildfire smoke, which can cause eye irritation, chronic respiratory system effects, and increased traffic accidents[7].

Climate change and global warming profoundly impact fire seasons worldwide due to various interconnected factors[58]. The rising global temperatures and drier conditions associated with global warming contribute to more frequent and intense fires[59]. These conditions increase evapotranspiration, depleting moisture from vegetation and soil, making them more susceptible to ignition and contributing to spreading fires. Changes in temperature and precipitation patterns resulting from climate change also alter the timing and duration of seasons, leading to longer periods of dryness and an increased risk of fires. Furthermore, changes in fire frequency, intensity, and timing can disrupt the natural cycle of vegetation growth, recovery times, and nutrient cycles[60–64].

To summarize, hotter and drier conditions create a positive feedback loop, where fires generate weather conditions, such as fire-induced thunderstorms or fire whirls, which can intensify the fire and facilitate its rapid spread. Severe wildfires, including wild, bush, and agricultural fires, have significant ecological, economic, and societal impacts, including loss of life, property damage, and destruction of natural habitats[65–67]. It's important to note that the carbon dioxide emitted from wildfires contributes to the overall increase in greenhouse gas concentrations, further exacerbating global warming and perpetuating the cycle of climate change[68].

3. The effect of fires on the environment: The case of Pampas (Argentina)

Pampas is located in the central-eastern part of Argentina and covers an area of 613,532 km^2 (**Figure 1**). Most of its surface consists of plains, but the altitude increases from east to west (**Figure 1**). The northeastern sector of the region is characterized by subtropical climates favored by the influence of maritime tropical air masses from the semi-permanent high-pressure system of the South Atlantic. In the southwest, arid temperate climates are prevalent, selected by the inflow of continental polar air masses from the semi-permanent high-pressure system of the South Pacific[69]. As a result, precipitation decreases towards the southwest, ranging from 1466 to less than 400 mm/year (**Figure 2**). Tropical and polar air mass convergence promotes frontal rain[70,71]. Pampas is characterized by annual maximum values ranging from 19–24 °C, minimums ranging between 7 °C and 14 °C, and mean temperatures between 13 °C and 18 °C[72]. The thermal gradient decreases from north to south, but the lowest temperature records are found in the highest areas (**Figure 2**). Additionally, the annual and daily temperature ranges in arid temperate sectors are smaller than other continental regions located at similar latitudes in the Northern Hemisphere due to the proximity to the Atlantic Ocean[73].

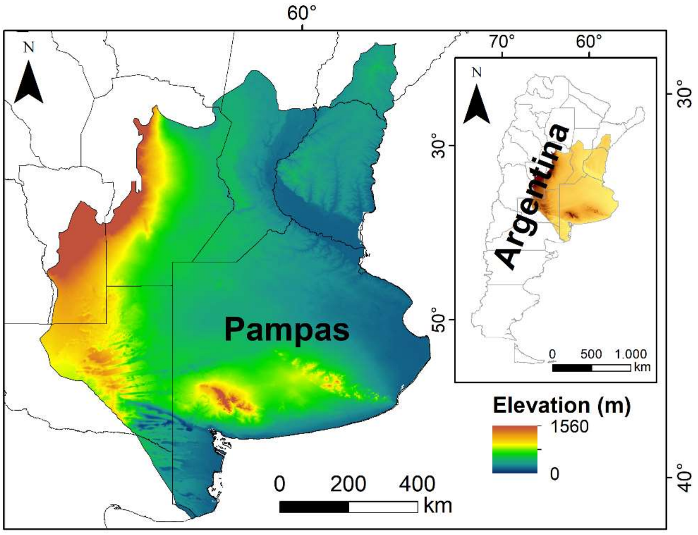

Figure 1. Location map.

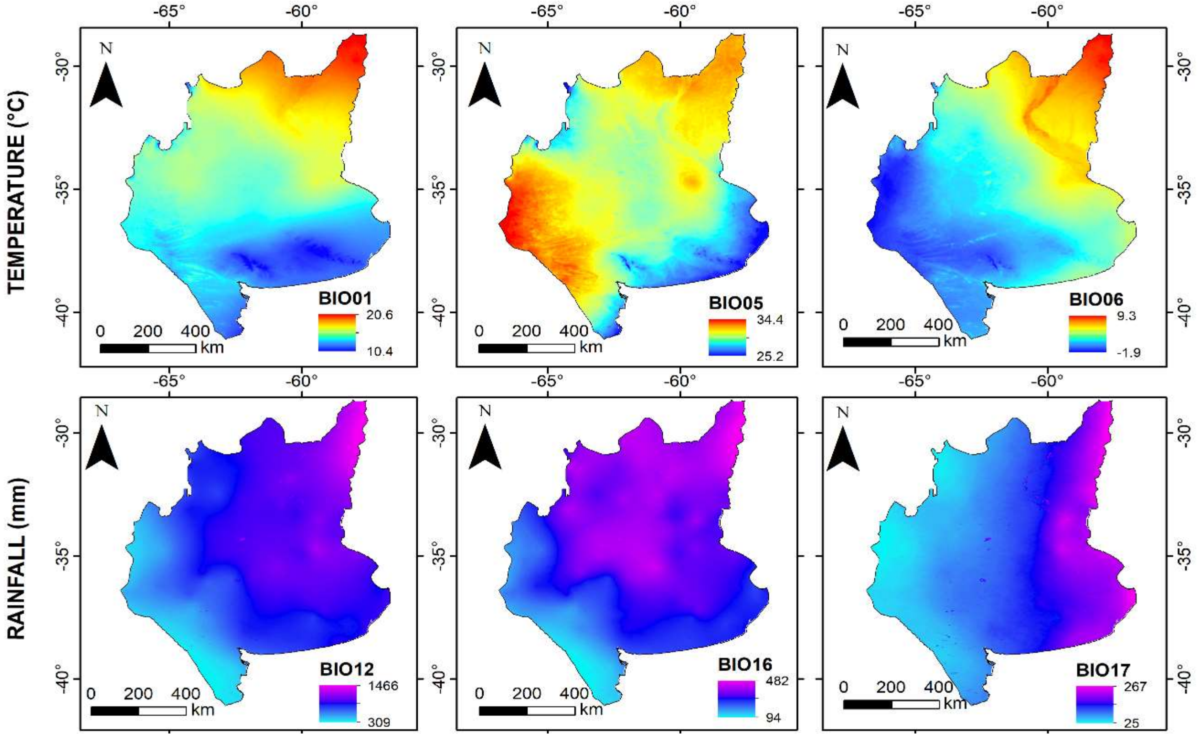

Figure 2. Spatial distribution of temperature (°C) and rainfall in Pampas. **(BIO01)** annual mean temperature; **(BIO05)** maximum temperature of the warmest month; **(BIO06)** minimum temperature of the coldest month; **(BIO12)** annual precipitation; **(BIO16)** precipitation of wetter quarter; and **(BIO17)** precipitation of drier quarter[78].

As mentioned, Pampas holds global significance because its economy is closely tied to climate variability. The effects of climate change and global warming could result in severe future scenarios where fires become more frequent and intense, impacting not only the economy but also the health of the population, biodiversity, and ecosystem-recovery time after the occurrence of fires. Additionally, Pampas is known for being one of the most fertile plains in the world, making it globally relevant in food production, which ranks among the highest worldwide[8].

In that context, it is relevant to mention that Argentina's agricultural and forest fires are recurrent. For example, between 2016 and 2017, 30,000 km^2 of shrubs and grasslands were burned. In August and September of 2020, according to the Global Forest Watch, Argentina ranked second in the world for hotspots. The most affected areas correspond to the Paraná Delta, followed by the province of Córdoba and, to a lesser extent, the Central and Northern regions of the country[74]. These events are linked to extended periods of drought and subsequent thunderstorms that serve as ignition mechanisms. Controlled agricultural and intentional forest fires are also significant contributors[75].

Pampas is where fires occur periodically due to soil conditions, changes in soil moisture and land cover, and the management of grazing activities[75,76]. Generally, the most significant events are related to prolonged drought periods, with grassland cover being the most affected. However, there is evidence that in the southern sector of the region, fires are mostly agricultural and occur with higher intensity and frequency during wet periods[77]. It is worth noting that Pampas grasslands are adapted to these events. However, the intensity of fires has been modified due to introducing exotic plant species and managing agricultural systems.

The detection and assessment of fires in the Pampas region are particularly relevant in the context of climate change and global warming. There is evidence of a statistically significant increase in air temperature at a regional scale, which has led to alterations in the distribution patterns of atmospheric humidity. Over the past six decades, maximum temperature has increased by 1.8 °C, minimum temperature by 1.06 °C, and mean temperature by 1.2 °C. The rate of thermal increase has been 0.3 °C, 0.18 °C, and 0.2 °C per decade, respectively (**Figure 3**). As a result, precipitation regimes are changed, and the intensity of storms is modified (**Figure 4**). Strong and extreme storms are more frequent than in the past century. Simultaneously, the approach to addressing the issue of fires in this region is biased and localized in time and space. For example, previous studies conducted in different sectors of the mountainous region focused on producing spatial models for fire risk assessment and prevention or evaluating their effects on surface soil loss due to water erosion[79,80]. In their research, Delegido et al.[75] employed various geo-technologies to determine the severity level of fires in Pampas. Plenty of manuscripts apply remote sensing techniques and GIS software to analyze the impacts of fires on Pampas[81–84]. However, there is a lack of a homogeneous methodology for studying fires in different stages, including assessing the pre-fire conditions, identifying the ignition fuels, analyzing the effects of the fire event, and determining the recovery time for ecosystems and populations. For this reason, the following section describes a potential use of remote sensing for analyzing fires on a regional scale.

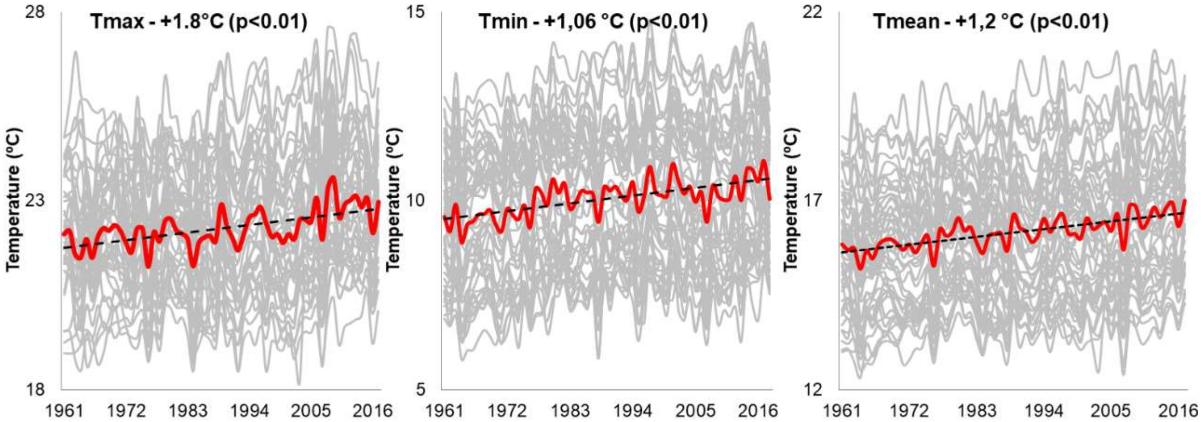

Figure 3. Evidence of global warming in Pampas. Tmax: maximum temperature; Tmin: minimum temperature; and Tmean: mean temperature. Bold lines indicate regional trends[8].

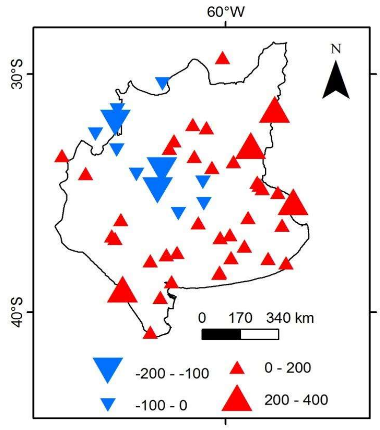

Figure 4. Annual precipitation trends (mm/1960–2018) in Pampas[72].

4. Remote Sensing techniques for studying fires at a regional scale

In the literature, there are various ways to study fires. However, it is important to highlight that the most common way to identify these events is based on the knowledge of three interconnected phases: the pre-fire stage, the fire stage, and the post-fire stage[76,84,85]. The first phase allows studying critical conditions or eventualities that lead to an event. The second one is closely related to the effects of the event while it is ongoing. Finally, the last one is connected to all the processes that occur until the system is restored.

On the other hand, it is important to note that there is scientific evidence that the frequency, spatial extent, and temporal variation of fires show a close relationship with daily, seasonal, annual, and decadal climate variability, as well as with climate change scenarios (e.g., the study of Abatzoglou et al.[86], Shen et al.[87], Cardil et al.[88]). Furthermore, the study of climate change in different scenarios and under different Shared Socioeconomic Pathways (SSPs) can be carried out based on the advances made by the IPCC. These scenarios allow for the consideration of short, medium, and long-term future scenarios under the constraints of SSP1, SSP2, SSP3, SSP4, and SSP5, which indicate the different degrees of societal development to address greenhouse gas emissions and thereby reduce the impact of climate change and global warming[5].

4.1. Pre-fires stage

The temperature increases and resulting drought conditions influence fire activity[89,90]. Drought conditions are analyzed considering different indices. One of the most commonly used is the Standardized Precipitation Index (SPI) and the Standardized Precipitation and Evapotranspiration Index (SPEI). It has been demonstrated that both indices yield good results when applied to the study of dry and wet cycles in different parts of the world[80,91]. The SPEI provides information for different periods and at a spatial scale of 0.5° of longitude and latitude[92]. This index considers accumulated precipitation and potential evapotranspiration, making it a good indicator to study the effects of wet and dry periods on land cover. Its application is recommended at three temporal scales: monthly, seasonal, and annual, as it allows for the understanding of interannual and inter-seasonal variations.

Remote sensing is an essential tool for fire studies. It enables the analysis of meteorological conditions, soil moisture, and atmospheric conditions in near-real-time to assess the environmental needs before the occurrence of fires. The literature's most cited providers and software are SMAP data (AρρEEARS, Giovanni, and Global Modelling and Assimilation System). Processing optical and radar satellite images allows for mapping and evaluating vegetation behavior and evolution. It also aids in understanding the type of fuel present, that is, the characteristics of live and dead biomass that could contribute to the spread and intensity of fires. For this purpose, the Global Wildfire Information System (GWIS) is utilized, a virtual Geographic Information System providing access to information about landscape characteristics, land cover, and more. It enables the identification of phenological phases and vegetation health. To achieve this, applying spectral indices is necessary to assess vegetation status and health evolution. Examples include the Normalized Difference Vegetation Index (NDVI), Enhanced Vegetation Index (EVI), and Soil-Adjusted Vegetation Index (SAVI).

Vegetation moisture is another essential factor in understanding pre-fire conditions and the potential of said vegetation as fuel. Vegetation with lower moisture content is more prone to ignition, facilitating fire spread. In this context, multitemporal studies and mean anomalies of the Normalized Difference Water Index (NDWI), Normalized Drought Index (NDMI), and Evaporative Stress Index (ESI) are crucial. The state of vegetation can be evaluated at a regional scale using satellite images and satellite-derived products from MODIS and VIIRS satellites.

Another relevant aspect to study at this stage is topography. The study area exhibits diverse topography, ranging from plains to hilly regions. Hence, the impacts of fires will vary. It is noteworthy that steep slopes act as a mechanism for fire propagation. In this context, slopes and terrain will be studied using Synthetic Aperture Radar (SAR) data. Data generated by the Advanced Spaceborne Thermal Emission and Reflection Radiometer ASTER Global Digital Elevation Map is employed to address it.

4.2. Fires stage

The second stage includes fire events when they are active. It represents one of the most important scientific activities, allowing for near-real-time monitoring. In the literature, smoke emissions, temperature anomalies, and spatial changes in nighttime luminosity patterns are studied, enabling more precise identification of fires. Smoke can be detected using different RGB combinations to differentiate it from clouds. These results must then be correlated with fire emission data sources from the Global Fire Emissions Database. Active fire products are available from the MODIS and VIIRS satellites, along with thermal anomaly data. They can detect fires and determine their quantity, extent, and duration.

Furthermore, the number of fires occurring in the study area, their intensity, duration, and frequency can be assessed. This requires using the EOSDIS Worldview and the Fire Information for Resource Management System Fire Information for Resource Management System (FIRMS). The latter allows for monitoring three hours after the satellite passes over the area of interest. It also facilitates global fire location and the acquisition of historical data series.

Additionally, analyzing aerosols, smoke forecasts, and air quality is essential. In this regard, mentioning the satellite products available in the JSTAR Mapper (noaa.gov) is important. This platform utilizes spectral information to calculate aerosol indices, differentiate between smoke and dust, and aid cloud discrimination. Alongside this, the study of aerosols can be complemented with atmospheric products derived from the MODIS and VIIRS satellites, available on the LAADS DAAC (nasa.gov). Finally, fire hazards, location, and intensity are studied using FIRECAST Firecast: DataMaps: LiveView and GWIS.

4.3. Post-fires stage

After a fire occurs in a specific area, evaluating the land surface temperature, burned areas, and vegetation recovery time is essential. Generally, post-fire conditions create an environment highly susceptible to wind and water erosion. After fires, intense storms can carry ashes into nearby watersheds, contaminating water sources.

Climatic conditions during fire events are studied using daily meteorological data, which can be measured in situ or modelled through validated reanalysis. For example, using downscaling techniques, NCEP/NCAR reanalysis data have been validated at different spatiotemporal scales worldwide. It is necessary to know the wind direction, heatwave events, consecutive dry days, and other indices defined by the Expert Team on Climate Change Detection and Indices (ETCCDI) that relate to the magnitude of the fire. To assess impacts on vegetation, spectral indices mentioned earlier should be applied again to determine the vigor of vegetation at the time the fires occurred.

To estimate the damage and burned areas and their temporal extent and identify the impacts of fires, satellite products of burned areas from MODIS and VIIRS are available in GWIS and FIRMS. The climate and satellite data analysis and their impacts on the environment can be complemented with Climate Engine—Democratizing Spaceborne Data and Analytics. It allows for the assessment of precipitation anomalies derived from the CHIRPS Pentad series from 2000, soil moisture at the root depth, rasterizing the Standardized Precipitation Index, identifying rainfall deficits, studying land surface temperature anomalies, temporal differences in NDVI, evaluating burned area products, and variation in surface runoff. Together with the analysis of land cover changes, these tools will provide detailed information on post-fire conditions, such as burn severity, ecosystem impacts, and identifying vegetation recovery (or regrowth) periods.

5. Fire disaster management plans

After understanding the impacts of climate change and global warming on wildfire seasons, intensity, and frequency, as well as the potential for studying them on a regional scale using satellite data, it is important to consider the opportunities for creating, rethinking, or establishing fire disaster management plans (FDMP) aimed at mitigating and adapting to climate change while reducing CO_2 emissions from fires. Assessing the global carbon cycle in specific regions is crucial for understanding the contribution of gas emitted by fires[93]. Furthermore, these management plans should incorporate community resilience and public health, as the study of these events encompasses social and human dimensions[94].

Understanding the effects of fires in the social and human dimensions is a key strategy for developing effective FDMPs[7]. Analyzing the impacts on local communities, livelihoods, and public health is essential for devising strategies to enhance community resilience, promote fire safety, and protect vulnerable populations from the health risks associated with wildfires and smoke exposure[95].

In this context, FDMP refers to the systematic planning, coordination, and implementation of measures to prevent, prepare for, respond to, and recover from fire-related emergencies and disasters. It involves various strategies, policies, and actions to minimize the loss of life, property, and environmental damage caused by fires[96,97].

Considering the context of global warming and climate change, FDMP needs to account for the increased risks and challenges posed by the ever-changing environmental conditions[98]. Therefore, it is crucial to update these plans continuously. FDMPs should comprehensively assess the heightened fire risks associated with climate change. This includes analyzing historical fire data, projected temperature and precipitation patterns changes, and the vulnerability of ecosystems and communities to fires.

Identifying and mapping high-risk and vulnerable areas is important to prioritize resources and efforts accordingly[99].

An essential component related to fires is the establishment of early warning systems. While they exist in many regions of the world, enhancing and expanding them is crucial for detecting and monitoring fire risks in real time. This involves using advanced technologies, Remote Sensing, and weather forecasting to provide timely and accurate information on fire danger levels, fire behavior, and potential spread. Additionally, improving communication channels to ensure the prompt dissemination of warnings to relevant authorities and communities is essential.

Evidence highlights the importance of education in implementing disaster management plans[100]. Community engagement and education play a significant role in raising awareness about fire risks, prevention strategies, and evacuation procedures in the context of climate change. Encouraging community participation in fire management activities, such as fuel reduction efforts, controlled burning, and community fire planning, is of the utmost importance[101]. A sustainable management plan must foster a culture of fire safety and community resilience. In this context, it is important to include climate change mitigation measures, such as reducing greenhouse gas emissions, transitioning to renewable energy sources, and promoting sustainable land management practices[102].

Moreover, FDMPs must ensure firefighting agencies have adequate resources, equipment, and infrastructure to respond effectively to increased fire risks. Firefighting resources and infrastructure include investments in suppression technologies, equipment, and training for firefighters. It is crucial to guarantee accessibility to water sources, establish firebreaks, and maintain a well-coordinated network of fire stations and emergency response centers[103,104].

Specifically, in the case of fires, vegetation management and fuel reduction are of paramount importance. Implementing proactive vegetation management strategies to reduce fuel loads and minimize fire intensity is necessary. This includes prescribed burning, selective thinning, and strategic fuel breaks to create defensive spaces[105,106]. Consideration should also be given to using fire-resistant landscaping techniques and promoting fire-adaptive ecosystems that are resilient to fires. Therefore, fostering collaboration among relevant stakeholders, local and regional governments, communities, and researchers is critical. Coordinate response plans and protocols to ensure the efficient and effective allocation of resources during fire incidents. In this context, supporting research initiatives to understand better the linkages between climate change, global warming, and fire behavior is essential. Investing in monitoring systems that track fire activity, smoke dispersion, and environmental impacts is crucial for creating effective FDMPs[107,108].

Finally, regarding the population, FDMPs must develop strategies to enhance community resilience and reduce vulnerability to fire-related disasters. This includes land-use planning that takes fire risk into account, resilient building design, the development of evacuation plans, and the diversification of local economies to reduce dependence on fire-prone industries[109–111].

6. Conclusion

Climate change and global warming are impacting thermal and rainfall patterns worldwide. One of the most severe and significant consequences is the increasing intensity, severity, and extent of wildfires in recent years. Therefore, it is crucial to study and invest in fire research to reduce economic losses, prevent loss of life and population exposure to smoke, preserve environmental quality, and protect species diversity.

In this context, remote sensing techniques play a vital role in monitoring and assessing fire events on a regional scale with high accuracy and near-real-time capability. These tools are being implemented in various stages of fire study. During the pre-fire phase, it is essential to analyze vegetation health and vigor, determine fuel load levels, and understand the environmental conditions that can contribute to fires. During the fire phase, it is key to identify vulnerable areas, evaluate smoke plumes, and estimate changes in air quality. Finally, the post-fire stage allows for understanding recovery time, environmental changes following a fire, and the extent of burnt areas.

Regions such as Pampas are particularly relevant due to their dependence on agricultural and livestock activities, which make them more vulnerable to fires. Therefore, it is crucial to diversify economic activities to reduce vulnerability to these events. In this context, fire disaster management plans (FDMPs) are essential to address these environmental implications.

Addressing climate change and global warming can significantly benefit the implementation of effective wildfire management strategies, essential for mitigating the negative impacts of fires. These strategies should focus on improving forest management practices, implementing controlled burns, enhancing early warning systems, promoting community preparedness, and reducing greenhouse gas emissions. By integrating climate change considerations into FDMPs, communities can better prepare for and respond to fire emergencies in a warming world. The ultimate goal is to build resilience, protect lives and property, and mitigate the impacts of fires exacerbated by climate change.

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Conflict of interest

The author declares no conflict of interest.

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