Cuadernos de Investigación Geográfica *Geographical Research Letters*	2024	Nº 50 (1)	pp. 41-57	EISSN 1697-9540

http://doi.org/10.18172/cig. 5774

INFLUENCE OF CLIMATE VARIABILITY ON FIRE GENERATION: MYTHS AND FACTS IN SOUTHERN PAMPAS (ARGENTINA)

FEDERICO FERRELLI[1]*, ANA CASADO[2]

[1]*Instituto Argentino de Oceanografía (IADO), Universidad Nacional del Sur (UNS)-CONICET, Bahía Blanca-Argentina.*

[2]*CEDETS, Universidad Provincial del Sudoeste (UPSO), Ciudad de Cali 320, 8000, Bahía Blanca, Argentina.*

ABSTRACT. This study evaluates the occurrence of dry and wet events and their relationship with fires in southern Pampas, Argentina. The intensity and magnitude of dry and wet events were determined based on the regional series of the Standardized Precipitation and Evapotranspiration Index (SPEI) for the 2000-2021 period. The data obtained were related to the El Niño Oceanic Index (ONI) to analyze the incidence of El Niño and La Niña events in generating them. Fires in the region were detected using remote sensing techniques, considering the number of events, their intensity, extent, and duration. The southern Pampas experiences marked rainfall variability, with 15 dry events, 11 wet years, and 2 standard years recorded for the period analyzed. Extreme dry years were, on average, more intense (SPEI = -2.14) and occurred mainly during the negative ONI phase. In contrast, extreme wet years exhibited lower intensity (SPEI = 1.98), and only the most intense ones were related to neutral ONI phases. We analyzed a representative extremely dry (ED) and an extremely wet events (EW) to interpret the relationship between climate variability and the spatiotemporal variability of fires in the region. It was observed that during the EW event (2014-2015, SPEI = 1.52, and El Niño event until 2015) the number of fires was higher compared to an ED event (2008-2009, SPEI = -2.22, and La Niña event during 2008), with 460 and 205 fires, respectively. The intensity was higher in the EW (302.6 and 31.5 MW), while the area presented considerable differences (1722 and 815.5 km^2, respectively). Finally, the duration of the fires was shorter in ED than in EW (6 and 8 months, respectively). These results were related to vegetation health (NDVI = 0.29 and 0.41 and EVI = 0.15 and 0.21 in ED and EW, respectively) and changes in land covers. This study provides a solid database for future research efforts and sustainable land management plans.

Influencia de la variabilidad climática en la generación de incendios: mitos y hechos en el sur de la Pampa (Argentina)

RESUMEN. Este estudio evalúa la ocurrencia de eventos secos y húmedos y su relación con los incendios en el sur de la Pampa, Argentina. La intensidad y magnitud de los eventos secos y húmedos se determinaron a partir de las series regionales del Índice Estandarizado de Precipitación y Evapotranspiración (SPEI) para el período 2000-2021. Los datos obtenidos se relacionaron con el Índice Oceánico El Niño (ONI) para analizar la incidencia de eventos de El Niño y La Niña. Los incendios en la región fueron detectados utilizando técnicas de teledetección, considerando el número de eventos, su intensidad, extensión y duración. El sur de la Pampa experimenta una marcada variabilidad de precipitaciones, con 15 eventos secos, 11 años húmedos y 2 años estándar registrados para el período analizado. Los años de sequía extrema fueron, en promedio, más intensos (SPEI = -2,14) y ocurrieron principalmente durante la fase ONI negativa. En contraste, los años húmedos extremos exhibieron menor intensidad (SPEI = 1,98), y solo los más intensos estuvieron relacionados con las fases ONI neutrales. Se analizó un evento representativo extremadamente seco (ED) y un evento extremadamente húmedo (EW) para interpretar la relación entre la variabilidad climática y la variabilidad espacio-temporal de los incendios en la región. Se observó que durante el evento EW (2014-2015, SPEI = 1,52 y El Niño hasta 2015) el número de incendios fue mayor en comparación con un evento ED (2008-2009, SPEI = -2,22 y La Niña durante 2008), con 460 y 205 incendios, respectivamente. La intensidad fue mayor en el EW (302,6 y 31,5 MW), mientras que el área presentó diferencias considerables (1722 y 815,5 km^2, respectivamente). Finalmente, la duración de los incendios fue más corta en ED que en EW (6 y 8 meses, respectivamente). Estos resultados se relacionaron con la salud de la vegetación (NDVI = 0,29 y 0,41 y EVI = 0,15 y 0,21 en ED y EW, respectivamente) y los cambios en la cobertura del suelo. Este estudio proporciona una base de datos sólida para futuras investigaciones y planes de gestión sostenible de la tierra.

Keywords: Climate variability, El Niño and La Niña events, fires, southern Pampas.

Palabras clave: Variabilidad climática, El Niño y La Niña, incendios, sur de la Pampa.

Received: 13 June 2023

Accepted: 7 November 2023

***Corresponding author:** Federico Ferrelli. Instituto Argentino de Oceanografía (IADO), Universidad Nacional del Sur (UNS)-CONICET, Bahía Blanca-Argentina. E-mail address: fferrelli@criba.edu.ar

1. Introduction

Climate variability results from the heat exchange between the oceans and the atmosphere (Wang *et al.*, 2004). The magnitude and persistence of climate fluctuations exhibit a scalar structure in space and time involving all climate variables. However, temperature and precipitation exhibit the most noticeable spatial manifestation (Franzke *et al.*, 2020). In South America, interannual precipitation variability is an essential modulator of synoptic and intra-seasonal variability and responds primarily to the effects of the El Niño-Southern Oscillation (ENSO) phenomenon (Grimm, 2011). ENSO influences the frequency of extreme events, resulting in a succession of dry and wet periods that affect soil moisture and vegetation health and, by extension, fires' occurrence, intensity, and magnitude (Xu *et al.*, 2020).

On the other hand, global warming results in greater atmospheric ignition power and promotes a higher frequency of fire events. Indeed, most literature documents that dry and warm conditions contribute to vegetation drying, leading to an increase in the number, intensity, and duration of fires on the global scale, regardless of the climate region (Wehner *et al.*, 2017 in the United States; Bowman *et al.*, 2020 in Australia; Zupichiatti *et al.*, 2022 in Argentina; among others).

Fires in Argentinean Pampas exhibit varying origin, intensity and extent yet high frequency and obey complex relationships between hydroclimatic variability, land cover changes, and agro-pastoral activities management (Delegido *et al.*, 2018; Ferrelli *et al.*, 2022). Most generally, the events of greater magnitude are related to long-standing drought conditions and affect mainly both natural and grazing grasslands (Bert *et al.*, 2021). From a climatic point of view, the arid and semiarid sectors in southern Pampas are exposed to greater risk, as dry events are the most intense and long-lasting in these areas (Aliaga *et al.*, 2017; Ferrelli *et al.*, 2021). However, there is evidence that fires in these sectors are mainly linked to agricultural activity and that their intensity may vary depending on the agroecosystems management (Pezzola and Winschel, 2004). In this regard, the origin of fires in southern Pampas is likely associated with hydrological conditions favouring such management practices.

This study evaluates the occurrence of dry and wet events and their relationship with fire dynamics in southern Pampas (Argentina). It seeks to determine the causal relationship between climate variability, vegetation status and health, and fire dynamics within a region where natural precipitation variability strongly intensifies arid and semiarid conditions. The analysis evaluates and combines (i) the intensity and duration of dry and wet events based on the regional series of the Standardized Precipitation and Evapotranspiration Index (SPEI), (ii) their associations to El Niño and La Niña events based on the Oceanic Niño Index (ONI), (iii) the vegetation response to such variability, and (iv) the resulting fire dynamics in terms of the number of events, intensity, extent, and duration, using remote sensing techniques. In addition to providing robust results based on the detailed analysis, two key events of contrasting hydroclimatic conditions were selected and compared to determine different scenarios. The results of this study provide a solid database to guide future research efforts and sustainable development land management plans.

2. Materials and methods

2.1. Study Area

The southern Pampas comprise the Villarino and Patagones districts, both of which belong to Buenos Aires province, Argentina (Fig. 1). Primary land uses mix both livestock and rainfed agriculture, except for a central band irrigated by the Colorado River (Iurman, 2010). The total population is 61,221 inhabitants. The 79 % of the population concentrates in urban areas, being the city of Carmen de Patagones the most populated (20,533 inhabitants). The rural population density remains below unity over 94 % of the territory (INDEC, 2010). The absence of marked topographic gradients is in contrast to a marked decreasing rainfall gradient from 600 mm in the northeast to 360 mm in the southwest (Winschel, 2017; Ferrelli *et al.*, 2020), reaching arid conditions near Río Negro (Gabella *et al.*, 2013).

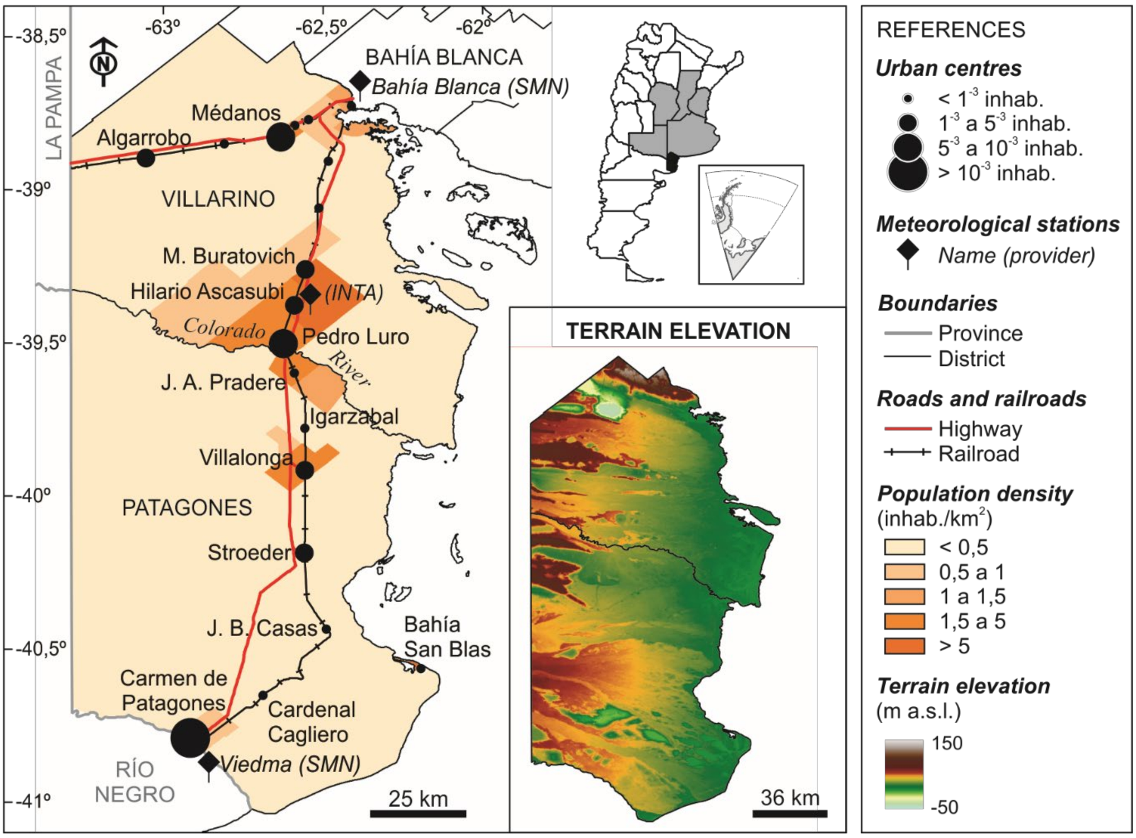

Figure 1. Location and configuration of the southern pampas (Argentina). Source: Own elaboration based on cartographic data from the National Geographic Institute (IGN, Argentina). Population data was extracted from the 2010 Census (National Institute of Statistics and Census, INDEC, Argentina). GMTED2010 Digital Elevation Model with a resolution of 7.5 arc seconds (U. S. Geological Survey).

Mean annual temperature ranges between 14 and 15 ºC, with a yearly amplitude of about 13 to 14 ºC (Campo de Ferreras *et al.*, 2004; Aliaga *et al.*, 2017). The natural vegetation integrates the Espinal and Monte ecoregions (Cabrera, 1976). The Espinal develops in the northern and eastern sectors, and exhibits low, xerophytic, dense to open forests dominated by *Prosopis caldenia* and grasslands of *Stipa sp*. in the lower strata. The Monte develops in the southwestern sector, and constitutes a shrub steppe of *Larrea sp.*, interspersed with *Geoffroea decorticans* and *Capparis sp*. in the most humid sites (Morello *et al.*, 2012). Grazing, tillage, and fires, originated by human activity, introduce profound changes in the landscape, with particularly noticeable impacts on the vegetation structure (Pezzola and Winschel, 2004).

2.2. Materials

This study combines gridded climate data series, global climate models, and environmental indices with global fire information (Table 1). The dataset is openly accessible and distributed as maps or spatially referenced data series. All data were processed to span a concurrent analysis period (2000-2021) and area of interest (southern Pampas). The geospatial information layers were projected following the national system of flat coordinates (POSGAR 07). Additionally, we used meteorological records from the National Institute of Agricultural Technology (INTA, Argentina) and the National Meteorological Service (SMN, Argentina).

Table 1. Summary of the dataset used for analysis.

Data type	**Serie**	**Resolution**		**Source**	**Reference**
		Spatial	**Temporal**		
Gridded climate series	Standardized Precipitation and Evapotranspiration Index (SPEI)	25 km	Monthly 2000-2021	Sistemas de Información sobre Sequías para el Sur de Sudamérica (SISSA)	https://sissa.crc-sas.org/
	Standardized Precipitation and Evapotranspiration Index (SPEI)	0,5°	Monthly 2000-2021	Consejo Superior de Investigaciones Científicas de España (CSIC)	Vicente Serrano *et al.* (2010)
Global climate indices	El Niño Oceanic Index (ONI)	---	Monthly 2000-2021	Climate Prediction Center (CPC), NOAA	NOAA (2022)
Global environmental indices and maps	Normalized Difference Vegetation Index (NDVI) and Enhanced Vegetation Index (EVI)	250 m	Monthly 2000-2021	Sistema de Análisis Temporal de Vegetación (Brazil)	https://www.satveg.cnptia.embrapa.br/satveg/login.html
	CCI Land Cover products v2.0.7	300 m	1992-2015	European Space Agency (ESA)	https://www.esa-landcover-cci.org/?q=node/164
Global information on fires	Fire Information for Resource Management Systems (FIRMS)	250 m	Daily 2000-2021	Earth Data, NASA	https://www.earthdata.nasa.gov/learn/find-data/near-real-time/firms

2.3. Methods

2.3.1. Climate analysis

The analysis of climate variability involved detecting dry and wet events based on gridded series of the Standardized Precipitation and Evapotranspiration Index (SPEI) using time scales of 3 and 12 months. Hereafter, these series are referred to as SPEI-3 and SPEI-12, respectively. Gridded SPEI series were provided by the CSIC and the SISSA (Table 1) and were used comparatively because of their global and regional relevance, respectively. Initially, SISSA and CSIC data sets were compared to inspect the degree of agreement between regional and international gridded SPEI series. In the second step, the quality of the regional SPEI series was evaluated based on *in-situ* observations. Meteorological data is available for three stations strategically located in the North (Bahía Blanca), the Centre (Hilario Ascasubi) and the South (Viedma) of the study area (Fig. 1). Irrespective of their reduced number, these stations provide a valuable set of records *in situ* to validate the accuracy of regional SPEI series. For each station, the SPEI was calculated following the equation of Vicente-Serrano *et al.* (2010) as follows:

$$\mathrm{SPEI} = \mathrm{W{-}C0{+}C1{+}C2W21{+}d1W{+}d2W2{+}d3W3'} \quad (1)$$

where W = -2ln (P), P is the probability of exceeding a specific D, and D is the difference between precipitation and potential evaporation. The constants C and d are: C0 = 2.515517, C1 = 0.802853, C2 = 0.010328, d1 = 1.432788, d2 = 0.189269, and d3 = 0.001308. The quality of the gridded SPEI series was evaluated using the Pearson and Spearman correlation coefficients, the Concordance index, and the determination coefficient R^2.

The regional series of the SPEI were averaged into one series accounting for mean regional SPEI values for each time scale (3 and 12 months) over the 22-yr analysis period (2000-2021). Dry and wet events were determined based on deviations of mean regional SPEI-3 and SPEI-12 values, as shown in Table 2. The characteristics of such events (intensity, duration and magnitude) were determined using the methodology described by Aliaga *et al.* (2017). SPEI-3 series allow evaluation of the succession of seasonal dry and wet events affecting the soil moisture content. They are beneficial for inspecting for associations between climate variability and vegetation states. SPEI-12 series aggregate the effects of seasonality on an annual scale, allowing determining key events exhibiting contrasting hydroclimatic conditions. For the study, key events are selected based on extreme hydroclimatic conditions, i.e., events showing the lowest and the highest values of the SPEI-12.

The relationship between climate variability and varying phases of ENSO was analyzed based on cross-correlations between the series of the SPEI and El Niño Oceanic Index (ONI). According to the ONI, a warm ENSO event (El Niño) occurs when the index remains above 0.5 for five consecutive months or more, while a cold ENSO event (La Niña) occurs when the index remains below -0.5 for the same period. The association between SPEI-based climate events and ONI-based ENSO phases was measured using tests on contingency tables (Chi-square). The frequency of months classing as a given event under Niño, Niña and neutral conditions allowed inspecting for the ENSO influence on the regional climate variability.

Table 2. Classification criteria for dry and wet climate events according to SPEI values

Type of event	**Intensity**	**SPEI value**	**Probability of occurrence**
Dry	Extreme drought (ED)	SPEI < -1.5	0.067
	Severe drought (SD).	-1.5 < SPEI < -1	0.092
	Moderate drought (MD)	-1.0 < SPEI < -0.5	0.18
Normal	Normal (N)	-0.5 < SPEI < 0.5	0.38
Wet	Moderate wet (MW)	0.5 < SPEI < 1.0	0.18
	Severe wet (SW)	1.0 < SPEI < 1.5	0.092
	Extreme wet (EW)	SPEI > 1.5	0.067

2.3.2. Environmental analysis

We inspected for variations in two spectral indices, the Normalized Difference Vegetation Index (NDVI) and the Enhanced Vegetation Index (EVI), to determine the association between vegetation status, health, and climate variability. NDVI and EVI series were aggregated at the regional scale to ensure compatibility with SPEI gridded series. Both NDVI and EVI series were classed into five status categories based on the mean (μ) and the standard deviation (σ). Vegetation status classes range from very low (μ-2 σ) to very high (μ+2 σ). Associations between vegetation classes and SPEI-based climate events were determined based on tests on contingency tables (Chi-square). In addition, we measured variations in the surface extent of land cover types for the key events determined by climate analysis.

2.3.3. Fire analysis

The nature of fires in southern Pampas (intensity, extent, and duration) was analyzed for two key events defining extreme dry and extreme wet scenarios. Active fire products provided by MODIS and VIIRS satellites were analyzed along with thermal anomaly products to detect fire events, their extent, and their duration. We used WorldView and FIRM's websites to perform these analyses. The latter allowed for the location of fires and the study of their spatiotemporal evolution.

The fires were studied considering i) the number of fires, determined by the number of fire spots identified throughout the events, ii) their intensity, represented by the average value of the fires measured in MW, iii) their extension, measured in km^2, determining the area affected by the fires, iv) the fire season, defined from the temporal extension in months with the presence of fires, and v) the brightness temperature (°K) indicating the average energy of the fire spots. Finally, the satellite products were analyzed to identify fire spots. They were located according to their intensity using ArcGIS 10.3 software.

3. Results

The following sections present the results from the spatiotemporal evolution of fires in the southern pampas. The effects of climatic variability on vegetation health and soil cover extent are analyzed, and the quantity, intensity, and size of fires during different climatic events are identified.

Before analysis, we inspected the quality of regional gridded SPEI series (SISSA) considering their agreement relative to global data sets (SCIC) and their accuracy relative to the SPEI calculated from meteorological records *in situ*. The spatiotemporal behaviour of regional and global SPEI series exhibited an excellent correlation, with Pearson and Spearman values of 0.91 and 0.89, respectively, a Concordance of 0.88, and an R^2 of 0.89, considering the SPEI-12 scale. Regional series from SISSA also exhibited a good correlation with *in-situ* data, although the SPEI-3 series showed lower adjustment than the SPEI-12 series. Pearson and Spearman's correlations were 0.79 and 0.81 for SPEI-3 and 0.93 and 0.95 for SPEI-12, respectively. The Concordance was 0.74 for SPEI-3 and 0.91 for SPEI-12, and the R^2 was 0.88 and 0.95, respectively. Irrespective of these differences, both SPEI-3 and SPEI-12 series exhibit reasonable adjustment.

3.1. Climate variability: extreme events and their relationship to the ENSO phenomenon

The marked climate variability characteristic of the southern Pampas is evidenced by both the SPEI-3 and the SPEI-12 series (Fig. 2). Note that an *event* begins when the SPEI value for a given month classifies under a given category that is different from the previous month and ends when that category changes in the subsequent month. It is also vital to notice that climate events may be referred to as individual events, defined by the intensity of the SPEI (Table 2) or as types of events, namely wet and dry, represented by the direction of the SPEI and its persistence above or below normal conditions, respectively. In this regard, *wet events* refer to a continuous succession of months classing as MW, SW and/or EW, whilst *dry events* refer to a constant sequence of months classing as MD, SD and/or ED.

The march of the SPEI-3 along the 22 years of analysis registers 27 wet events (from which 5 were extreme), 32 dry events (from which eight were extreme), and 53 normal events (Fig. 2). On average, wet events exhibited an intensity of 0.9 for a 2.6-month duration, reaching maximum period (12 months) and extreme values (2.2) in 2014-2015. Dry events were slightly longer (2.7 months, on average) and intense (-1.0, on average), although the driest events (2009 and 2014) exhibited smaller values (-2.0) and duration (4 months). Climate events defined by the SPEI-12 series were smaller in number than for SPEI-3 but notably greater in duration (Fig. 2). The series accounts for 11 wet events that average 5.8-month duration. From these, two events were classed as extreme, although the event of 2014-2015 exhibited the greatest duration (17 months) and the highest SPEI-12 value of the series. Dry events were greater in number (15 events) and longer in duration, persisting over 7.0 months, on average. Although the series registers two extreme dry events, the most marked drought occurred in 2008-2009, persisting over 23 consecutive months and reaching up to -2.5. This event and the extreme wet event of 2014-2015 define two key events of contrasting hydroclimatic conditions on which to base fire analyses.

Correlations between SPEI-based climate events and the ONI in southern Pampas are low yet statistically significant (for $\alpha = 0.05$), with the best Pearson coefficients obtained for a lagged ONI of -2 (0.22; SPEI-3) and -7 (0.30; SPEI-12). Table 3 summarizes the proportion of months under varying climate events and varying phases of the ENSO phenomenon, determined from deviations of lagged ONI series. Most dry events occur under La Niña and neutral conditions for both time scales of the SPEI, following a similar trend to that observed for Southeastern South America. In opposition to what was expected, wet events do not exhibit clear associations with El Niño phases, as most occur under neutral ENSO phases. This indicates the influence of other large-scale atmospheric phenomena on precipitation extremes whose analysis exceeds the scope of the present study. Irrespective of these broad associations, key dry conditions (2008-09) occurred under negative ONI conditions (La Niña event), while key wet conditions (2014-15) occurred under positive ONI conditions (El Niño event).

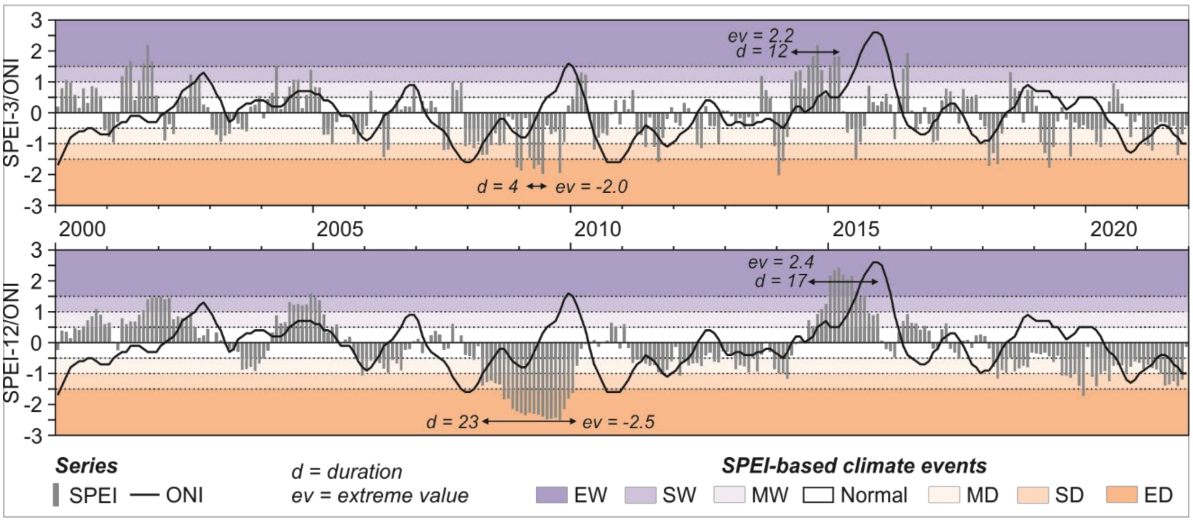

Figure 2. Distribution of the SPEI for two temporal scales (3 and 12 months) in the southern pampas and series of ONI over 2000-2021.

Table 3. Frequency of months (%) classing under varying SPEI-based climate events by ONI-BASED ENSO phases in the southern Pampas (2000-2021 period)

	ENSO phase				ENSO phase		
SPEI-3	Niña	Neutral	Niño	***SPEI-12***	Niña	Neutral	Niño
EW	0.0	**76.9**	23.1	EW	0.0	**55.6**	44.4
SW	10.5	42.1	**47.4**	SW	11.1	**77.8**	11.1
MW	31.6	**42.1**	26.3	MW	35.1	**35.1**	29.7
Normal	31.8	**48.6**	19.6	Normal	21.6	**44.3**	34.0
MD	36.2	**38.3**	25.5	MD	**49.2**	44.4	6.3
SD	**55.6**	37.0	7.4	SD	**50.0**	29.2	20.8
ED	**46.2**	30.8	23.1	ED	**56.3**	37.5	6.3

3.2. Environmental impacts

The EVI and NDVI series trend exhibits the seasonality characteristic of temperate climates. However, the intensity of the peaks is closely related to the interannual climate variability of the region (Fig. 3). Pearson correlation coefficients of EVI and NDVI series to SPEI-3 series were significant (for $\alpha = 0.05$), reaching 0.58 and 0.50, respectively. The lowest values occurred in 2008-2009 for both series, according to the most intense drought recorded along the analysis period (key dry conditions), while the highest peaks matched the maximum positive deviations of the SPEI-3 in 2014-2015 (key wet conditions).

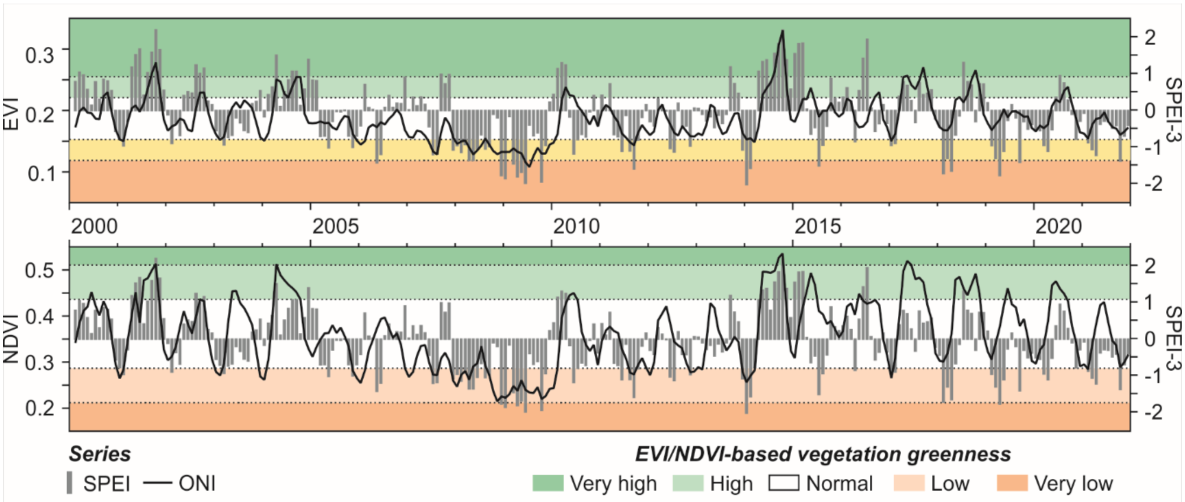

Figure 3. Distribution of NDVI and EVI for the 2000-2021 period for the southern pampas.

The behaviour of both spectral indices, EVI and NDVI, strongly correlates to the succession of wet and dry events (Table 4). For example, vegetation greenness above normal conditions matches wet climate conditions for most cases and for both indices, with the strongest associations occurring for very high greenness and extremely wet climate. On the other side of the scale, most cases where vegetation greenness is below normal conditions occur under dry climate conditions. However, vegetation-climate associations for dryness are less clear than those for wetness. Very low EVI values match extreme dry events by 50 % of cases, whilst the remaining proportion occurs under normal climate. Regarding the NDVI, the series does not account for very low values so that interpretations may be awkward.

Changes in land cover were analyzed considering the two key events defined by climate variability analysis. The most remarkable differences between extreme dry and extreme wet conditions were observed in the central and western regions, where scrublands contracted in extent against the expansion of croplands (Fig. 4). The importance of land cover areas showed remarkable differences. For example, shrublands covered a much larger size during the dry period (14,087 km^2) and contracted by 11,8 % under extreme wet conditions. In opposition, cropland and mosaic cropland cover was lower under extremely dry conditions, increasing by 19,6 % under wetter climates (8,268 and 9,890 km^2, respectively).

Table 4. Monthly frequency (%) by the value of (a) EVI and (b) NDVI, according to climatic events based on SPEI-3 series for the southern pampas (2000-2021 period)

(a) EVI	EW	SW	MW	Normal	MD	SD	ED
Very high	**62.5**	0.0	12.5	25.0	0.0	0.0	0.0
High	5.9	26.5	**32.4**	26.5	5.9	2.9	0.0
Normal	3.3	5.4	13.6	**46.7**	17.9	9.8	3.3
Low	0.0	0.0	2.9	22.9	**34.3**	22.9	17.1
Very low	0.0	0.0	0.0	**50.0**	0.0	0.0	**50.0**

(b) NDVI	EW	SW	MW	Normal	MD	SD	ED
Very high	**66.7**	0.0	16.7	16.7	0.0	0.0	0.0
High	7.5	17.5	27.5	**35.0**	10.0	2.5	0.0
Normal	3.6	7.1	13.7	**46.4**	16.7	10.1	2.4
Low	0.0	0.0	6.1	26.5	**30.6**	18.4	18.4

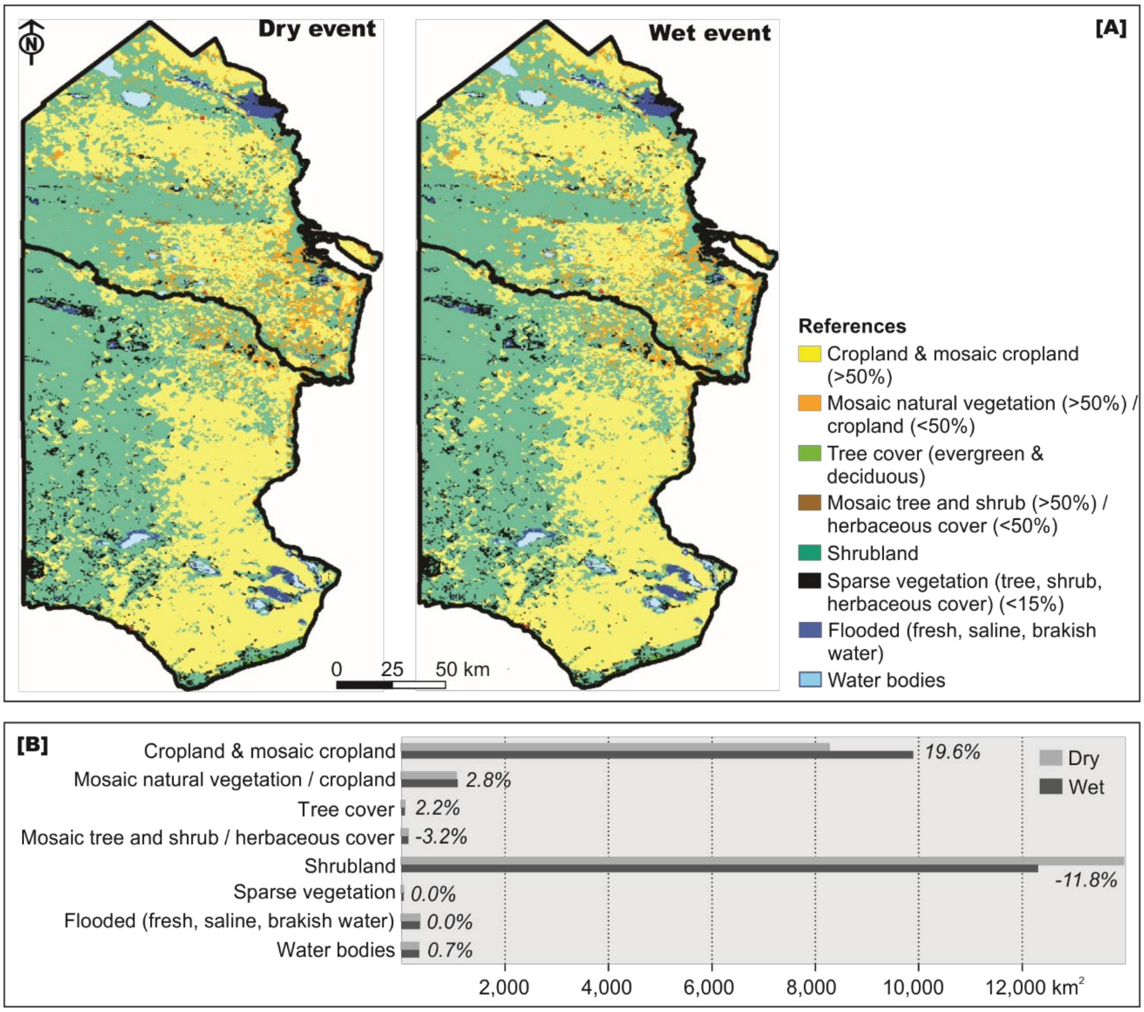

Figure 4. [A] Land cover maps for key dry and wet events, and [B] surface extent by land cover class and percent variation between events. Land cover classes were modified from those provided on the ESA/CCI.

3.3. Characterization of fires

Fire analysis was performed for the two key events defined from climate variability analysis, 2008-09 (key dry year) and 2014-2015 (key wet year). It is noticeable that climate fluctuations along with the changes in vegetation and land cover, generate different scenarios where fires have very different impacts (Table 5). During the 2014-2015 event, there were twice as many fires as in 2008-2009 (460 and 206, respectively). The intensity of the fires was ten times higher in the wet event than in the dry one, while the affected area was doubled on the surface. In addition, the fire season was two months longer under extreme wetness than under extreme dryness. All these results are related to the agricultural activities in the study area. As a semiarid and subhumid area, wet events create favourable environmental conditions for crop planting. These results suggest that the area could be affected by a complex combination of wildfires and agricultural fires, including controlled and uncontrolled burns.

Table 5. Characteristics of fires, vegetation, and rainfall events in extreme dry period (2008-2009) and extreme wet period (2014-2015). Results are the addition or the average of each period

Characteristics	2008-2009 (ED)	2014-2015 (EW)
Number of fires	205	460
Intensity (MW)	31.5	302.6
The extension (km^2)	815.5	1722
Fire season (months)	6	8
Brightness temperature (°K)	302.3	336.2
NDVI	0.29	0.41
EVI	0.15	0.21
ONI	-0.24	0.78
SPEI-12	-2.22	1.52

The frequency of fires, their location, and their relationship with the SPEI during extreme wet and dry events were analyzed. Marked differences were observed. The extreme wet event (EW) was characterized by presenting higher values of SPEI > 1.5 all over the study area. The fires were more intense and were mainly located in the west and south of the study area, coinciding with shrub cover. Similarly, the centre of the study area presented fires of great intensity. That is because the irrigated crop areas are located in that region (Fig. 5). On the other hand, in the extreme dry event (ED), the SPEI values were consistently below -1.5. The most extreme values were located in the centre of the study area, marking an event of great intensity, with areas where the SPEI was less than -2.5. In this scenario, vegetation presented minimum values of NDVI and EVI, and the environmental conditions of drought generated the occurrence of fires but of low intensity. Most of the fires had an intensity of 3.3 to 55 MW and were scattered in location. As in the EW period, the highest-intensity fires were located west and south of the study area (Fig. 5).

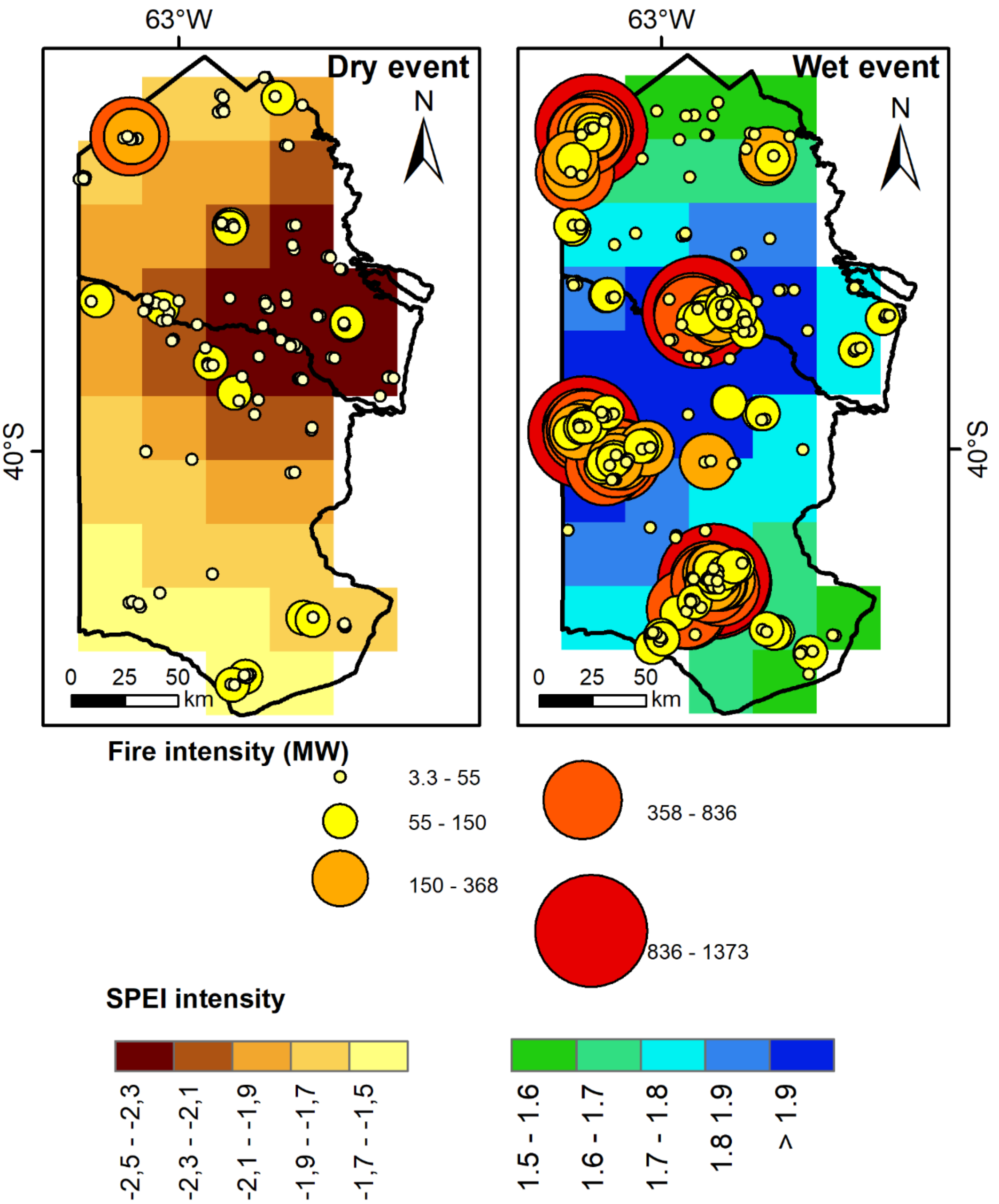

Figure 5. Fire intensity and rainfall events in the southern pampas during dry (2008-2009) and wet (2014-2015) events.

4. Discussion

4.1. Climate variability and its effects on soil, water and vegetation

This study has investigated the influence of climate variability on fire generation in southern Pampas. The area is not only in transition, but is also affected by marked climate variability, with conditions ranging from arid to humid. There may be 300 mm of rainfall in one year, while the following year could bring 1000 mm (Aliaga *et al.*, 2017; Ferrelli *et al.*, 2021). As a result, the vegetation varies between very low vigour and very high vigour. An interesting factor is the changes in land use: during wet periods, agriculture expands over natural vegetation, while during dry periods, agriculture contracts, and shrublands thrive. This creates two complex scenarios for the occurrence of fires. It is evident that during dry periods, the number of fires is lower (perhaps due to fewer controlled burns related to agriculture activities), and the intensity is also lower (possibly due to less combustible material). In wet periods, the number of fires increases (because of increased agriculture) as well as their intensity (more considerable amount of vegetation available to burn) (Pezzola and Winschel, 2004).

Results suggest that the spatial and temporal fire dynamics within this complex environment are also complex, and different from what is observed on a global, national, and regional scale. In these arid and semiarid ecosystems, fires are primarily agricultural and caused by complex interactions between climate variability, soil moisture content, vegetation cover and greenness, meteorological conditions, and crop and grazing management practices (Bran *et al.*, 2007; Delegido *et al.*, 2018). Climate variability is marked and evidenced both in space and in time. Spatial climate variability is given by the transition from humid and warm northeastern pampas to arid and cold southwestern Patagonian features (Aliaga *et al.*, 2016), with differences of up to 400 mm in mean annual rainfall and up to 1.7 ºC in mean annual temperature (Aliaga *et al.*, 2017; Ferrelli *et al.*, 2019). Time climate variability responds to the complex influence of regional and global atmospheric phenomena (Wu *et al.*, 2022), resulting in rainfall and temperature variations that occur at nested seasonal, annual, and interannual scales (Ferrelli *et al.*, 2021). Whilst vegetation cover types express regional climate and soil features, the extent and greenness of vegetation cover are an expression of climate variability affecting the soil moisture content within a season, within a year, or between seasons and years. In this point, it is interesting to highlight the difference between meteorological drought, involving rainfall shortfalls that affect the soil moisture content, and hydrological drought, involving a long-standing water deficit that affects not only the soil moisture, but also the sources of freshwater (Andrade *et al.*, 2015; Brendel *et al.*, 2019). In this regard, a meteorological drought will result in a drying of vegetation that grows under normal or wet conditions.

In contrast, a hydrological drought will prevent vegetation growth and spread. Finally, irrigation plays a fundamental role in areas affected by climate variability. It provides a vital solution to ensure a consistent water supply to crops, especially in regions with insufficient or irregular precipitation. In non-irrigated areas, adaptation to this climate variability is achieved through a combination of grazing and cultivation practices. In southern Pampas, for example, grazing becomes a primary strategy during dry periods. Animals feed on natural vegetation, making the most of any available resources. This adaptation allows for maintaining a certain level of livestock production even in adverse climatic conditions (Foucher *et al.*, 2023).

On the other hand, during wet periods, the increased water availability is utilized for cultivation. Farmers use soil fertility and favourable conditions to grow crops such as cereals, oilseeds, and forages. This helps diversify production and make the most of available resources during these periods (Scherger *et al.*, 2022). However, it is essential to note that exclusive reliance on climate variability can have limitations. Controlled and planned irrigation remains an efficient and reliable solution to ensure agricultural production in areas affected by extreme climate variability. It allows for proper water distribution, maximizes crop yields, and reduces risks associated with climate fluctuations.

4.2. Fires generation – Myths and Facts

Both wild and agricultural fires occur periodically and model the regional landscape by affecting the balance between crops, pastures, natural grasslands, and shrublands (Pezzola and Winschel, 2004; Delegido *et al.*, 2018). This study suggests, however, the coexistence of two contrasting scenarios for fire generation, intensity and extent that result from varying land cover and land use dynamics as a consequence of a variable climate. Fires are more significant in number, size and intensity under wet climate conditions, as rainfed croplands and grasslands mosaics expand over much of the natural shrublands, exhibiting their highest vigour even if reduced in extent. For example, in addition to the 460 fire events detected during the key wet period selected for this study (2014-2015), a series of thunderstorms that took place in the context of a meteorological drought resulted in a large-scale fire that affected more than 30,000 km^2 between December 2016 and January 2017 (Delegido *et al.*, 2018). The magnitude of most fire effects is related to the prior land use condition of the plot (for example, whether the land was used for grazing or for extracting firewood as fuel), the accumulation of dry matter, density and size of woody species, the proliferation of refined fuel before the fire, as well as the environmental conditions at the time of the incident (Vanzolini *et al.*, 2017). In much of the region, the high density of shrubs makes it difficult for livestock to access and consume the forage provided by the natural grassland (Kröpfl *et al.*, 2007), increasing combustible material. In opposition, the water stress caused by long-standing drought conditions prevents rainfed agricultural practices and vegetation development other than natural shrublands, which in turn lose their vigour. Consequently, fire generation under such conditions is less likely to occur because the fuel material is reduced relative to wetter periods.

In southern Pampas, legislation regarding fire prevention is based on meteorological indices that consider short-term drought conditions. However, this study has shown that initial drought conditions do not increase the number and intensity of fires. For such an increase, sustained periods of normal or wet weather conditions are required. In this scenario, vegetation can thrive, and the environmental conditions favour intensive farming and grazing activities in dryland areas.

Therefore, this study has demonstrated the importance of considering climate variability beyond just meteorological conditions and anticipating the occurrence of these periods to develop effective land management plans. Resource managers and fire experts are facing new challenges when effectively applying current climate science and fire ecology to adapt their day-to-day practices. To address these challenges, the Adaptation Strategies and Approaches for Managing Fire in a Changing Climate (Sample *et al.*, 2022) offers a comprehensive fire menu encompassing the concepts of resistance, resilience, and transition. It establishes clear connections between these concepts and actionable steps, identified as strengths by workshop participants during the workshop's reflection phase. Additionally, the group expressed a keen interest in ongoing collaboration as part of the Kaibab Climate Workgroup, ensuring continued regional discussions, scientific advancements, and management efforts related to fire and climate adaptation. This includes sharing the Fire Menu and Adaptation Workbook process with other audiences to further progress in the field (Sample *et al.*, 2022).

In Argentina, the National Forest and Rural Fires Law 26815 in the 2nd Article Scope consider the actions and operations related to prevention, pre-suppression, and firefighting of forest and rural fires that burn live or dead vegetation in native and planted forests, protected natural areas, agricultural zones, meadows, grasslands, shrublands, wetlands, and areas where building structures are intermingled with vegetation outside strictly urban or structural environments. It also covers planned fires that can burn under previously established environmental conditions, aiming to achieve management objectives for a territorial unit.

Is in this context where Fire Hazard Assessment and Early Warning Plans are crucial components of effective fire management strategies. These plans assess the potential risk and danger of fires in specific areas and provide timely warnings to minimize the impact and damage (Lestienne *et al.*, 2022). Fire Hazard Assessment involves evaluating various factors such as weather conditions, fuel availability, topography, and historical fire data to determine the likelihood and severity of fire incidents. It identifies high-risk areas and prioritises resources for prevention, preparedness, and response efforts (Ribeiro *et al.*, 2022).

Early Warning Plans are developed based on the fire hazard assessment results. They outline the procedures and protocols for detecting and monitoring fire activity and issuing timely warnings to relevant authorities, communities, and emergency responders. Early warning systems often incorporate various technologies, such as remote sensing, meteorological data, and fire behaviour modelling, to detect and predict fire incidents (Chen *et al.*, 2022).

4.3. A look beyond climate variability: fire generation and climate change

Climate change has become one of the world's most serious environmental problems (Wang *et al.*, 2013). Evidence of a progressive increase in air temperature affects mainly economic and agricultural activities, increasing negative impacts on the population's quality of life (Worku *et al.*, 2018; IPCC, 2021). In this context, it is essential to highlight that the increase in greenhouse gases released into the atmosphere due to anthropogenic activity has intensified the adverse effects related to climate change (IPCC, 2021). The temperature increase has been homogeneous worldwide. This warming is closely related to the occurrence of fires, given that the thermal expansion translates into a greater ignition power that increases the number and intensity of fires (Masson-Delmotte *et al.*, 2018). In this context, it is essential to note that the risk of fires will increase by 74 % by the end of this century (Xu *et al.*, 2020).

The study of these events is relevant because they directly impact the population's health. We highlight the affections of physical implications (burns, injuries), mental health (post-traumatic stress), and even loss of life resulting from flame exposure. Fires also require more significant planning of medical assistance services and public and private investments to repair, for example, property damage (Abatan *et al.*, 2016; Xu *et al.*, 2020). The effects on the population are also related to the generation and spread of smoke. That can affect people's health in areas far from the fires (Xu *et al.*, 2020).

In the literature, there is evidence that forest and agricultural fires are typical in Argentina. The generation of these events is directly related to prolonged droughts and the consequent succession of electrical storms that act as an ignition mechanism (Delegido *et al.*, 2018; Garay, 2020). Particularly in the Pampas region, fires are periodic and are generated due to soil conditions, changes in soil moisture, and changes in land cover (Ferrelli *et al.*, 2022). The events of greater magnitude occur during prolonged periods of drought in the grassland ecoregion (Bert *et al.*, 2021).

There is evidence that southern Pampas is subject to strong signals of global warming that will increase in future scenarios (Ferrelli *et al.*, 2021). Along with this, the change in the rainfall pattern will impact the current development of economic activities since a reduction in annual precipitation amounts and an increase in more severe and intense daily rainfall events (Ferrelli *et al.*, 2020). The fertile areas of southern Pampas are closely linked to rainfall variability. An increase in cultivated areas during wet periods has been recorded, drastically reducing pasture coverage (Ferrelli, 2017). In contrast, dry and extremely dry events have reduced crops affecting the region's economy and negatively impacting the population due to suspended dust from soil erosion processes.

5. Conclusion

Fires were studied in an area of high relevance due to their agricultural and livestock activities. Remote sensing techniques allowed us to identify and quantify fires' number, intensity, and magnitude in different rainfall periods. The SPEI proved to be a good indicator of these events because it considers precipitation and evapotranspiration. It is relevant to highlight that dry and wet events in southern Pampas are not linked with the fluctuation of the ONI index.

The land cover showed spatial and temporal variations related to different rainfall events generated in the study area. It was evident that crops occupy more in rainy periods, while shrubs cover the most extensive area during extreme droughts.

For those mentioned above, southern Pampa is an area that challenges the generalities established in the literature. In contrast to what happens in the rest of the world, this area has more fires of greater magnitude and intensity during severe rain events. They are closely related to increased agricultural and livestock activities and are generated by replacing grasslands with crop cover. In contrast, during drought events, shrubs occupy a more significant amount of surface area. However, the lack of combustible material, together with vegetation characteristics in Argentina's semiarid regions, means that fires are not as intense as those observed elsewhere in the world.

Acknowledgments

We duly acknowledge the National Council of Scientific and Technical Research and the FONCYT for funding this research through the projects PICT-2021-I-INVI-00580 and PIBAA 28720210100943CO. Additionally, we would like to express our gratitude to the various open databases that facilitated the development of this research - Sistemas de Información sobre Sequías para el Sur de Sudamérica (SISSA), Consejo Superior de Investigaciones Científicas de España (CSIC), Climate Prediction Center (CPC), NOAA, Sistema de Análisis Temporal de Vegetación (Brazil), European Space Agency (ESA, and Earth Data, NASA.

References

Abatan, A.A., Abiodun, B.J., Lawal, K.A., Gutowski Jr, W.J., 2016. Trends in extreme temperature over Nigeria from percentile-based threshold indices. *International Journal of Climatology* 36, 2527-2540. https://doi.org/10.1002/joc.4510

Aliaga, V.S., Ferrelli, F., Piccolo, M.C., 2017. Regionalization of climate over the Argentine Pampas. *International Journal of Climatology* 37, 1237-1247. https://doi.org/10.1002/joc.5079

Aliaga, V.S., Ferrelli, F., Alberdi Algarañaz, E.D., Bohn, V., Piccolo, M. C., 2016. Distribución y variabilidad de la precipitación en la región pampeana argentina. *Cuadernos de Investigación Geográfica* 42, 261-280. https://doi.org/10.18172/cig.2867

Andrade, B.O., Koch, C., Boldrini, I.I., Vélez-Martin, E., Hasenack, H., Hermann, J.M., Kollmann, J., Pillar, V. D., Overbeck, G.E., 2015. Grassland degradation and restoration: a conceptual framework of stages and thresholds illustrated by southern Brazilian grasslands. *Natureza Conservação* 13, 95-104. https://doi.org/10.1016/j.ncon.2015.08.002

Bert, F., de Estrada, M., Naumann, G., Negri, R., Podestá, G., de los Milagros Skansi, M., Spennemann, P., Quesada, M., 2021. *The 2017-18 drought in the Argentine Pampas–Impacts on Agriculture*. United Nations Office for Disaster Risk Reduction 2021. GAR Special Report on Drought.

Bowman, D., Williamson, G., Yebra, M., Lizundia-Loiola, J., Pettinari, M. L., Shah, S., Bradstock, R., Chuvieco, E., 2020. Wildfires: Australia needs national monitoring agency. *Nature* 584, 188-191. https://doi.org/10.1038/d41586-020-02306-4

Bran, D., Cecchi, G., Gaitan, J., Ayesa, J., Lopez, C., 2007. Efecto de la severidad de quemado sobre la regeneración de la vegetación en el Monte Austral. *Revista Ecología Austral* 17, 123-132.

Brendel, A.S., Ferrelli, F., Piccolo, M.C., Perillo, G.M.E., 2019. Assessment of the effectiveness of supervised and unsupervised methods: maximizing land-cover classification accuracy with spectral indices data. *Journal of Applied Remote Sensing* 13, 014503-014503. https://doi.org/10.1117/1.JRS.13.014503

Cabrera, M., 1976. Territorios fitogeográficos de la República Argentina. In: *Enciclopedia Argentina de Agricultura y Jardinería*. Editorial Acme SACI, 90 pp., Buenos Aires,

Campo de Ferreras, A.M., Capelli de Steffens, A.M., Diez, P.G., 2004. *El clima del suroeste bonaerense*. EdiUNS, Bahía Blanca, 99 pp.

Chen, F., Chen, J., Liu, J., 2022. Comprehensive evaluation and optimization model of regional fire protection planning of major hazard sources based on multiobjective fuzzy theory. *Computational Intelligence and Neuroscience* 2022. https://doi.org/10.1155/2022/3517836

Delegido, J., Pezzola, A., Casella, A., Winschel, C., Urrego, E.P., Jimenez, J.C., Sobrino, J.A., Soria, G., Moreno, J., 2018. Estimación del grado de severidad de incendios en el sur de la provincia de Buenos Aires, Argentina, usando Sentinel-2 y su comparación con Landsat-8. *Revista de Teledetección* 51, 47-60. https://doi.org/10.4995/raet.2018.8934

Ferrelli, F., 2017. Variabilidad pluviométrica y sus efectos sobre las coberturas del suelo al sur de la provincia de Buenos Aires, Argentina. *Revista Geográfica Venezolana* 58, 26-37.

Ferrelli, F., Brendel, A.S., Aliaga, V.S., Piccolo, M.C., Perillo, G.M.E., 2019. Climate regionalization and trends based on daily temperature and precipitation extremes in the south of the Pampas Argentina. *Cuadernos de Investigación Geográfica* 45, 393–416. http://doi.org/10.18172/cig.3707

Ferrelli, F., Brendel, A.S., Piccolo, M.C., Perillo, G.M.E., 2020. Tendencia actual y futura de la precipitación en el sur de la Región Pampeana Argentina. *Investigaciones Geográficas* 102. https://doi.org/10.14350/rig.59919

Ferrelli, F., Brendel, A.S., Perillo, G.M.E., Piccolo, M.C., 2021., Warming signals emerging from the analysis of daily changes in extreme temperature events over Pampas Argentina. *Environmental Earth Sciences* 80, 422. https://doi.org/10.1007/s12665-021-09721-4

Ferrelli, F. Brendel, A.S., Perillo, G.M.E., Piccolo, M.C., 2022. Determinación de coberturas del suelo en una región semiárida de Argentina mediante imágenes satelitales ópticas. *Revista Geográfica Venezolana* 63, 64-79.

Foucher, A., Tassano, M., Chaboche, P.A., Chalar, G., Cabrera, M., Gonzalez, J., Cabral, P., Simon, A.C., Agelou, M., Ramon, R., Tiecher, T., Evrard, O., 2023. Inexorable land degradation due to agriculture expansion in South American Pampa. *Nature Sustainability* 6, 662-670. https://doi.org/10.1038/s41893-023-01074-z

Franzke, C.L.E., Barbosa, S., Blender, R., Fredriksen, H.B., Laepple, T., Lambert, F., 2020. The structure of climate variability across scales. *Reviews of Geophysics*, 58, e2019RG000657. https://doi.org/10.1029/2019RG000657

Gabella, J.I., Iuorno, M.V., Campo, A.M., 2013. Análisis integral de un sistema territorial degradado: el caso del partido de Patagones. *Proyección* 8, 68-91

Garay, D.D., 2020. Incendios rurales y forestales: la importancia de la teledetección y los sistemas de información geográfica. *Revista TECNOÁRIDO* 2, 46-48.

Grimm, A.M. 2011. Interannual climate variability in South America: impacts on seasonal precipitation, extreme events, and possible effects of climate change. *Stochastic Environmental Research and Risk Assessment* 25, 537-554. https://doi.org/10.1007/s00477-010-0420-1

INDEC, 2010. Censo de Población, Hogares y Viviendas. Available at https://www.indec.gob.ar/ (last access: 14/04/2022)

Iurman, D., 2010. *Sistemas agropecuarios de Villarino y Patagones: análisis y propuestas*. Ediciones INTA, 32 pp., Buenos Aires,

Kröpfl, A.I., Deregibus, V.A., Cecchi, G.A., 2007. Disturbios en una estepa arbustiva del Monte: cambios en la vegetación. *Ecología austral* 17, 257-268.

Lestienne, M., Vannière, B., Curt, T., Jouffroy-Bapicot, I., Hély, C., 2022. Climate-driven Mediterranean fire hazard assessments for 2020–2100 on the light of past millennial variability. *Climatic Change* 170, 14. https://doi.org/10.1007/s10584-021-03258-y

Masson-Delmotte, V., Zhai, P., Pörtner, H. O., Roberts, D., Skea, J., Shukla, P.R., ... Waterfield, T., 2018. *Global warming of 1.5 ºC*. Intergovernmental Panel on Climate Change, Switzerland, 32 pp.

Morello, J., Matteucci, S.D., Rodriguez, A.F., Silva, M.E., Mesopotámica, P., Llana, P., 2012. *Ecorregiones y complejos Ecosistémicos de Argentina*. Orientación Gráfica Editora, 773 pp., Buenos Aires

NOAA, 2022. Cold and warm episodes by season. Available at https://origin.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ONI_v5.php (last access: 03/05/2022).

Pezzola, A., Winschel, C., 2004. Estudio espacio temporal de incendios rurales, utilizando percepción remota y SIG. *Boletín Técnico* 20, 12 pp.

Ribeiro, A.F., Brando, P.M., Santos, L., Rattis, L., Hirschi, M., Hauser, M., Seneviratne, S.I., Zscheischler, J., 2022. A compound event-oriented framework to tropical fire risk assessment in a changing climate. *Environmental Research Letters* 17, 065015. https://doi.org/10.1088/1748-9326/ac7342

Sample, M., Thode, A.E., Peterson, C., Gallagher, M.R., Flatley, W., Friggens, M., Evans, A., Loehman, R., Hedwall, S., Brandt, L., Janowiak, M., Swanston, C., 2022. Adaptation strategies and approaches for managing fire in a changing climate. *Climate* 10, 58. https://doi.org/10.3390/cli10040058

Scherger, L.E., Valdes-Abellan, J., Zanello, V., Lexow, C., 2022. Projecting climate change effect on soil water fluxes and urea fertilizer fate in the semiarid pampas of Argentina. *Earth Systems and Environment* 6, 745-758. https://doi.org/10.1007/s41748-021-00289-4

Vanzolini, J.I., Galantini, J.A., Martínez, J.M., Suñer, L., 2017. Changes in soil pH and phosphorus availability during decomposition of cover crop residues. *Archives of Agronomy and Soil Science* 63, 1864-1874. https://doi.org/10.1080/03650340.2017.1308493

Vicente-Serrano, S.M., Beguería, S., López-Moreno, J.I., Angulo, M., El Kenawy, A., 2010. A new global 0.5 gridded dataset 1901–2006 of a multiscalar drought index: comparison with current drought index datasets based on the Palmer Drought Severity Index. *Journal of Hydrometeorology* 11, 1033-1043. https://doi.org/10.1175/2010JHM1224.1

Wang, B., Zhang, M., Wei, J., Wang, S. J, Li, S.S., Ma, Q., Li, X.F., Pan, S.K., 2013.Changes in extreme events of temperature and precipitation over Xinjiang, Northwest China, during 1960–2009. *Quaternary International* 298, 141-151. https://doi.org/10.1016/j.quaint.2012.09.010

Wang, C., Xie, S.-P., Carton, J.A., 2004. A Global Survey of Ocean-Atmosphere Interaction and Climate Variability. *Earth Climate: The Ocean-Atmosphere Interaction* 147, 1-19. https://doi.org/10.1029/147GM01

Wehner, M.F., Arnold, J.R., Knutson, T., Kunkel, K.E., LeGrande A.N., 2017. Droughts, floods, and wildfires. In: D.J. Wuebbles, D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, T.K. Maycock (Eds.). *Climate Science Special Report: Fourth National Climate Assessment*, U.S. Global Change Research Program, pp. 231-256, Washington, https://doi.org/10.7930/J0CJ8BNN

Winschel, C.I., 2017. Integración por medio de geotecnologías de la información ambiental en estudios de degradación de los suelos para los partidos de Villarino y Patagones, provincia de Buenos Aires, Argentina (PhD Dissertation). Universidad Nacional del Sur, Bahía Blanca, 219 pp.

Worku, G., Teferi, E., Bantider, A., Dile, Y. T., 2018. Observed changes in extremes of daily rainfall and temperature in Jemma Sub-Basin, Upper Blue Nile Basin, Ethiopia. *Theoretical and Applied Climatology* 135, 839-854. https://doi.org/10.1007/s00704-018-2412-x

Wu, Q., Zuo, Q., Han, C., Ma, J., 2022. Integrated assessment of variation characteristics and driving forces in precipitation and temperature under climate change: A case study of Upper Yellow River basin, China. *Atmospheric Research* 272, 106156. https://doi.org/10.1016/j.atmosres.2022.106156

Xu, R., Yu, P., Abramson, M.J., Johnston, F.H., Samet, J.M., Bell, M.L., Haines, A., Li, S., Guo, Y., 2020. Wildfires, global climate change, and human health. *New England Journal of Medicine* 383, 2173-2181. https://doi.org/10.1056/NEJMsr2028985

Zupichiatti, V., Zeballos, S.R., Whitworth-Hulse, J.I., Gurvich, D.E., 2022. Survival and growth of cactus species after a wildfire in central Argentina: Differences among species and the effects of microenvironment characteristics. *Austral Ecology* 47, 482-490. https://doi.org/10.1111/aec.13102