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WILDFIRES IN THE XEROPHYTIC SHRUBLANDS OF LIHUÉ CALEL NATIONAL PARK, LA PAMPA, ARGENTINA: A TEMPORAL ANALYSIS BASED ON CLIMATIC AND SPECTRAL INDICES

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ABSTRACT. In recent years, there has been increasing evidence of changes in fire frequency, with varying intensities and magnitudes across ecosystems worldwide. La Pampa, located in central Argentina, is affected by significant annual wildfire activity. This study aimed to analyse variations in climatic and spectral indices over a 29-year period (1995–2023) to identify patterns that might enhance our understanding of the fire regime in xerophytic shrublands. Additionally, it evaluated trends in climatic variables within the context of global climate change. Meteorological data and records of burned area were analysed; the Standardised Precipitation and Evapotranspiration Index (SPEI) was calculated at four timescales; and monthly Normalised Difference Vegetation Index (NDVI) data for shrubs and grasslands were obtained. The Theil-Sen estimator and the non-parametric Mann-Kendall test were used to detect any trends or correlations between variables, and a SARIMA model was used to explore lagged correlations between selected variables. The SPEI values typically ranged between -2 and 2, with SPEI-12 showing the highest correlation with large, severe fire events. The NDVI for shrubland and grassland exhibited positive correlations with SPEI-24 and SPEI-6/SPEI-12, respectively. SPEI-12 and burned area displayed a significant negative correlation. Monitoring climatic and spectral indices over time helps identify periods of phytomass accumulation and ignition thresholds. In the context of climate change, the observed increasing trends in precipitation, mean temperature, and maximum temperature suggest a future with heightened fire frequency in xerophytic shrublands. This study underscores the importance of integrating climatic and vegetation indices to improve our understanding and management of fire regimes in fire-prone ecosystems.

Incendios forestales en matorrales xerófitos del Parque Nacional Lihué Calel, La Pampa, Argentina: análisis temporal basado en índices climáticos y espectrales

RESUMEN. En los últimos años, existe una creciente evidencia de cambios en la frecuencia de incendios, con intensidades y magnitudes variables en ecosistemas de todo el mundo. La Pampa, ubicada en el centro de Argentina, experimenta anualmente una significativa actividad de incendios forestales. Este estudio tuvo como objetivo analizar las variaciones en índices climáticos y espectrales durante un período de 29 años (1995–2023) para identificar patrones que permitan mejorar la comprensión del régimen de incendios en los matorrales xerófitos. Además, se evaluaron las tendencias en las variables climáticas en un contexto de cambio climático global. Se analizaron datos meteorológicos y áreas afectadas por incendios. Se calculó el Índice Estandarizado de Precipitación y Evapotranspiración (SPEI) a cuatro escalas temporales, y se obtuvieron datos mensuales del Índice de Vegetación de Diferencia Normalizada (NDVI) para matorrales y pastizales. El análisis de tendencias, las pruebas de significancia y las correlaciones entre variables se realizaron utilizando el estimador de Theil-Sen y la prueba no paramétrica de Mann-Kendall. Se utilizó un modelo SARIMA para explorar correlaciones entre las variables seleccionadas. Los valores de SPEI oscilaron entre -2 y 2, siendo el SPEI-12 el que mostró la mayor correlación con eventos de incendios grandes y severos. El NDVI para matorrales y pastizales presentó correlaciones positivas con SPEI-24 y SPEI-6/SPEI-12, respectivamente. SPEI-12 y el área quemada mostraron una correlación negativa significativa. El seguimiento de índices climáticos y espectrales a lo largo del tiempo permite identificar períodos de acumulación de fitomasa y umbrales de ignición. En el contexto del cambio climático, las tendencias crecientes observadas en la precipitación, la temperatura media y la temperatura máxima sugieren un futuro con mayor frecuencia de incendios en los matorrales xerofíticos. Este estudio destaca la importancia de integrar índices climáticos y de vegetación para mejorar la comprensión y gestión del régimen de incendios en ecosistemas propensos a estos eventos.

Key words: Climate crisis, natural disasters, NDVI, SPEI, wildfire risk.

Palabras clave: Crisis climática, desastres naturales, NDVI, SPEI, riesgo de incendios.

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1. Introduction

Since ancient times, humans have been fascinated by fire, seeking to understand and control it. Naturally, it is an element that forms part of many ecosystems, playing a key role in shaping their structure and functioning (Luo *et al.*, 2020; Rogers *et al.*, 2020). In ecosystems more vulnerable to environmental stressors -such as drought, high temperatures, or soil degradation typical of semiarid regions- wildfires can severely affect their functioning and biodiversity (Harrison *et al.*, 2021; Vidal-Riveros *et al.*, 2023). Wildfires are also considered a threat to urban-rural interface systems, where the overlap between natural and human environments often leads to severe socioeconomic and health consequences (Vega and Fernández, 2020; Xu *et al.*, 2020; Kala, 2023).

In recent years, we have seen growing evidence of changes in fire frequency, with varying intensities and magnitudes across ecosystems worldwide (Zamora-Fernández *et al.*, 2022; Armenteras and González, 2024). This situation is being exacerbated by the increasing frequency of extreme weather events driven by climate change, such as intense droughts and high temperatures (Shao *et al.*, 2023). From a fire-risk perspective, drought events reduce the moisture content of fine aerial biomass, making it more flammable and thus increasing its availability as fuel. Under these conditions, and the presence of ignition sources, the probability of ignition and spread rises significantly (Chen *et al.*, 2024).

At the regional level, fire triggers are multi-causal and related to aspects of ecosystem structure, current management and land-use legacies, fire use or suppression and variations in weather over time (Santacruz-García *et al.*, 2019; Giorgis *et al.*, 2021; Kirkland *et al.*, 2024). On a broader scale, these elements are embedded within the larger drivers of global climate change (Obando Cabrera *et al.*, 2022).

With the above in mind, studies of weather patterns have become increasingly important for understanding various natural phenomena, as they can provide valuable insight for risk management and the development of mitigation and adaptation strategies in response to uncertain climate scenarios (Ferrelli *et al.*, 2020; Ertugrul *et al.*, 2021; Pausas and Keeley, 2021). In this context, and particularly in terms of wildfires, other studies have shown that climatic variables -such as precipitation and mean temperature- directly influence both fire ignition and spread, which makes them an interesting tool for fire management (Reyes Bueno and Balcázar Gallegos, 2021; Chen *et al.*, 2024).

Although most studies analysing climatic variables in the central semiarid region of Argentina have focused on agricultural and livestock production systems (Ferrelli *et al.*, 2020; Méndez *et al.*, 2018;

Oruezabal *et al.*, 2022), wildfires can also cause significant disturbance in natural ecosystems. This highlights the importance of studying climatic variability in relation to fire dynamics in these environments. Nationwide, between 2001 and 2016, 18 million hectares were burned, with approximately 60% of this area being attributed to wildfires in the La Pampa province, mainly in natural ecosystems (SAyDS, 2018; Estelrich *et al.*, 2022). Of the total affected area, 30% corresponded to shrubland physiognomies in the Monte Ecoregion (de Titto and Savino, 2021; Mosiejchuk and Mazzola, 2025). In this context, the La Pampa province was the worst affected, with a total of 7.1 million hectares burned, accounting for 39.6% of the total area affected during that period (including natural woodlands and shrublands). These events represent significant losses for community structures and functioning, wildlife and domestic livestock (Cangiano *et al.*, 2021), infrastructure and human lives. They also have implications for the loss of carbon stocks (Ricard *et al.*, 2022; Aryal *et al.*, 2022; Utello, 2024).

Drought and humidity events are important factors in any study of regional fire ecology. However, the dynamic nature of these spatio-temporal phenomena makes them challenging to quantify in terms of their duration, frequency, periodicity, and intensity (Ferrelli *et al.*, 2020). As a result, indices that include, combine, and weight different weather variables have been designed to help scientists estimate the duration of and characterise droughts and moist spells, as well as to monitor their behaviour over time (Masanta and Srinivas, 2022; Gebrechorkos *et al.*, 2023). In turn, incorporating vegetation spectral indices into comprehensive analyses improves our understanding of vegetation dynamics and recovery rates after drought or humidity events (Gebrechorkos *et al.*, 2023; Arroyo-Ramírez, 2024).

This study aimed to analyse variations in climatic (SPEI) and vegetation spectral indices (NDVI) across a multi-year time series in order to identify patterns that could enhance our understanding of the fire regime in the xerophytic shrublands of Argentina's La Pampa province. Additionally, given the context of global climate change, it analysed trends in the variables included in the study. It is hoped that implementing this methodology to monitor vegetation responses and fire events in relation to climatic dynamics in xerophytic systems will make a significant contribution to efforts to prevent natural disasters and develop effective management strategies. At the ecosystem level, it will help reinterpret their potential successional trajectories within the context of the climate crisis.

2. Study area

The study was conducted in Lihué Calel National Park (LCNP), situated in the central-eastern region of the La Pampa province in Argentina, within the Monte Ecoregion (Cabrera, 1976). The Park encompasses 32,514 hectares and serves as an exclusive habitat for several of the ecoregion's characteristic plant communities, underscoring its significant conservation value.

The region has a temperate semiarid to arid climate with average temperatures ranging from 15°C to 20°C and a pronounced seasonal temperature range (Villagra *et al.*, 2021). The humidity regime is aridic, with average annual rainfall of between 200 and 400 mm, highly variable throughout the year, and predominantly occurring during the summer-autumn season (Villagra *et al.*, 2021). The vegetation is relatively uniform at both physiognomic and floristic levels. Its varied relief, primarily flat with interspersed low sierras and hills in La Pampa, forms a mosaic of diverse plant communities. High shrublands are dominated by species of the genus *Larrea*, while the grasslands feature scattered shrubs characterised by grasses of the genus *Nassella* (Oyarzabal *et al.*, 2018). The vegetation exhibits morphological and physiological traits typical of xerophilous communities, including small, resinous leaves, leaves with high lignin content, photosynthetic and aphyllous stems, and the presence of thorns, among other features (Gardón, 2014). These adaptations enable plants to withstand extreme local environmental conditions by reducing exposure to solar radiation and minimising evapotranspiration loss (Gibson, 2012).

Furthermore, the region is continuously exposed to severe wildfires. Since 1983, the LCNP has maintained daily records of both meteorological variables and wildfire events, including dates, number of fires ignited, and burned area. During this period, 25 wildfires have been recorded, occurring within a context that underscores the significance of these natural phenomena at both a regional and national scale. The xerophytic vegetation of this region, combined with its historical management practices, has created optimal environmental conditions for fires to ignite and spread, often with devastating consequences. Consequently, the plant communities are frequently subjected to fire events of varying characteristics and recurrence. Of the wildfires on record, four particularly significant events stand out for their intensity and extent of area affected within the LCNP. These occurred in November–December 2003 (8,226 ha), April 2005 (800 ha), January 2018 (16,873 ha), and December 2023 (4,570 ha) (Fig. 1). The fires in 2003 and 2018 had anthropogenic origins, while those in 2005 and 2023 were caused by natural events (dry thunderstorms).

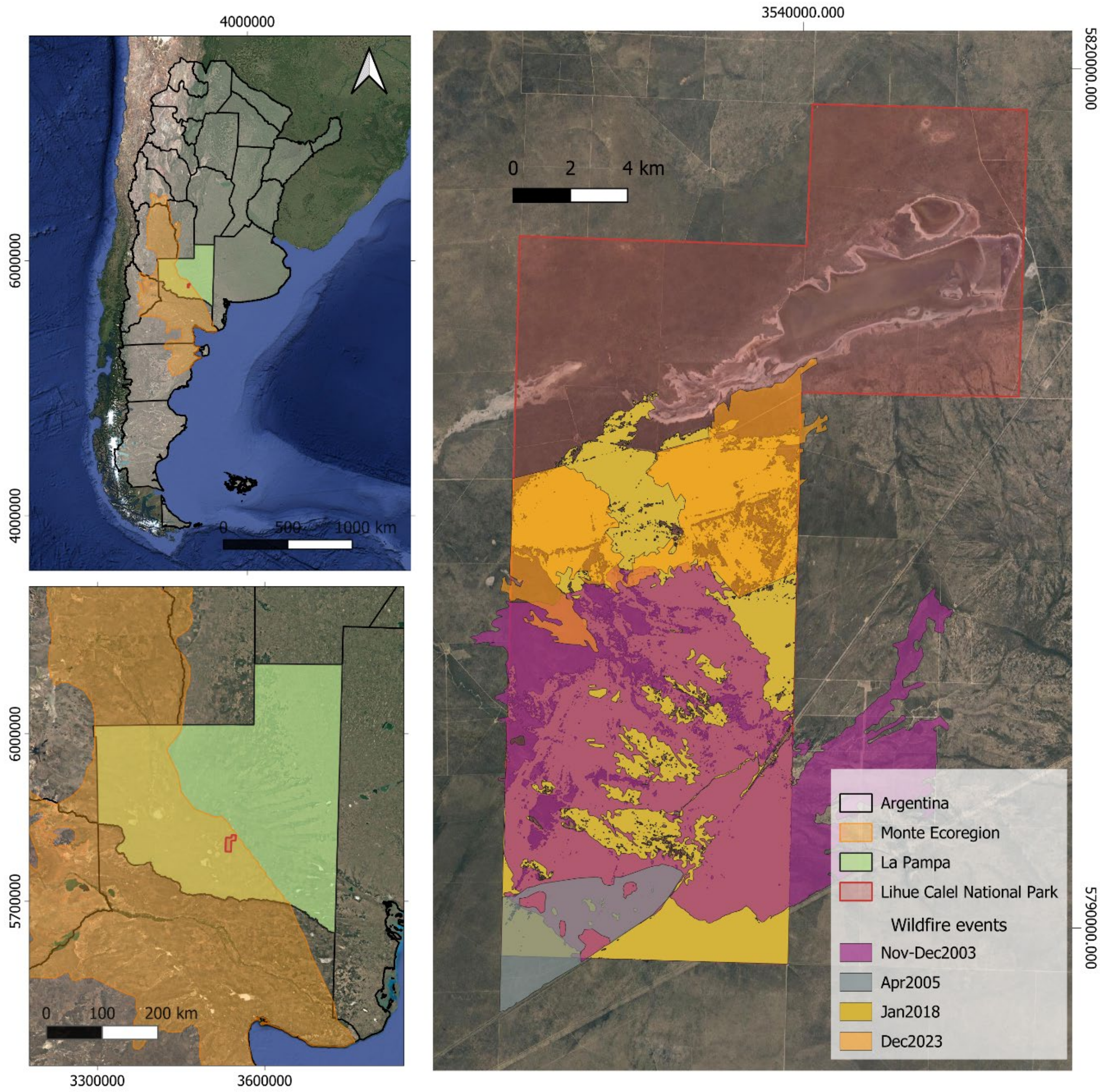

Figure 1. Location of the study area: Lihué Calel National Park, La Pampa, Argentina, the Monte Ecoregion and the spatial extent of major wildfire events recorded in the park over the past 29 years.

3. Methods and materials

3.1. General description of data sources

The climatic and wildfire dataset includes monthly averages for precipitation (pp), minimum temperature (Tmin), maximum temperature (Tmax), mean temperature (Tmed), and burned area size (APN, 2021). Climate data were sourced from the LCNP Automated Meteorological Station for a 29-year period (1995–2023), while fire information was retrieved from the LCNP Fire Management Plan (APN, 2021). Additionally, annual averages of the climatic variables were computed for subsequent analyses. Furthermore, monthly NDVI data were utilised, derived from the database available at SATVeg (https://www.satveg.cnptia.embrapa.br), covering a 23-year time series starting in 2000, the earliest record available.

3.2. Standardised Precipitation Evapotranspiration Index (SPEI)

The SPEI is a climate index that measures monthly water balance, calculated as $D = P - PET$, where P is precipitation, and PET is potential evapotranspiration. The resulting D values are fitted to a probability distribution and standardised to obtain the SPEI values. This process enabled the assessment of the climatic water balance, which can be calculated over various timescales (Vicente-Serrano *et al.*, 2010).

The SPEI is a multiscale index that can be calculated over different timescales depending on the objective of the study. For this project, the estimated monthly indexes were obtained for multiple scales: 3, 6, 12 and 24 months, being defined as SPEI-3; SPEI-6; SPEI-12 and SPEI-24, respectively. The monthly mean precipitation and temperature data described in section 3.1 were used. Table 1 outlines the index's value ranges along with their corresponding categories. Extended periods with values below -0.5 were classified as "drought events", indicating dry conditions. Conversely, "humidity events" were identified as prolonged periods with values exceeding 0.5. Both event types were further characterised by their duration, intensity, and severity.

Table 1. Categories assigned to each value range obtained using the Standardised Precipitation and Evapotranspiration Index (SPEI). Source: Drought Information System for Southern South America (SISSA) https://sissa.crc-sas.org.

Category	Value range
Extremely wet	≥ 1.5
Severely wet	1.5 ; 1.0
Moderately wet	1.0 ; 0.5
Near normal	0.5 ; -0.5
Moderately dry	-0.5 ; -1.0
Severely dry	-1 ; -1.5
Extremely dry	≤ -1.5

3.3. Normalised Difference Vegetation Index (NDVI)

The NDVI is calculated using two bands of the electromagnetic spectrum, expressed as NDVI = (NIR – Red) / (NIR + Red), where *NIR* is the near-infrared band and *Red* is the visible red band. Healthy or photosynthetically active vegetation strongly reflects NIR light due to cell structure while absorbing most red light for photosynthesis (Lacouture *et al.*, 2020). In this study, NDVI was used to assess the photosynthetic activity of various shrubland and grassland physiognomies following drought periods. NDVI values range from -1 to 1, with higher values indicating a greater density of live vegetation.

The study area displayed a gradient of structural and floristic complexity, ranging from grasslands with sparse shrubs to dense, tall shrublands. This complexity necessitated a differentiated analysis due to distinct spectral signatures. Consequently, separate NDVI datasets were created for shrublands and grasslands, referred to as NDVIs and NDVIg, respectively.

NDVIs and NDVIg values were derived from the SATVeg database, developed by Embrapa Digital Agriculture (https://www.satveg.cnptia.embrapa.br), spanning a 23-year time series starting in 2000, the oldest available record. The satellite imagery utilised in SATVeg was acquired from the MODIS sensor aboard NASA's Terra mission, with a temporal resolution of 16 days and a spatial resolution of 250 metres. Within the SATVeg platform, missing data and atmospheric corrections were applied before data extraction. Monthly NDVI values were calculated as averages from 10 geographic points dominated exclusively by tall shrublands (NDVIs) and 10 geographic points representing grassland physiognomies (NDVIg). The number of sampling points was considered representative due to the physiognomic homogeneity of the area. These points were selected based on field surveys, during which each location was georeferenced and classified according to its physiognomy to ensure an accurate representation of shrubland or grassland vegetation. This approach ensured a precise representation of the study area's vegetation dynamics.

3.4. Data analysis

3.4.1. Trends and linear inflexion points

The Theil-Sen estimator was used to estimate the trends in pp, Tmed, Tmax, Tmin, and SPEI (Sen, 1968; Fernandes and Leblanc, 2005). The significance of these trends was evaluated using the non-parametric Mann-Kendall test (Kamruzzaman *et al.*, 2018), with a significance level of p=0.05. The null hypothesis assumed no linear trend in the series, while the alternative hypothesis indicated the presence of a linear trend. This analysis was performed using the *Trend* statistical package in RStudio (RStudio Team, 2020).

Additionally, to detect fluctuations in the mean and variance of the climatic variables, linear inflexion points were identified through segmented regression. This method allows the time series to be divided into segments with distinct linear trends and identifies breakpoints at which the statistical properties change. Previously, the number of inflexion points was predefined to ensure that their confidence intervals did not overlap (Ferrelli *et al.*, 2020). The s*trucchange* statistical package in RStudio was employed to perform the segmented regression and detect structural changes (RStudio Team, 2020).

3.4.2. Pearson’s Correlation Coefficient

Pearson's correlation coefficient was estimated to quantify the strength and direction of the linear relationship between SPEI and NDVI. The significance levels for each correlation were also obtained. This process identified the SPEI calculation timescale that best explained the NDVI behaviour of the shrublands and grasslands. Prior to conducting the correlation analysis, the data normality assumptions were verified using the Shapiro-Wilk test at a significance level of p=0.05. A coefficient value close to 1 was interpreted as a strong positive correlation. The *cor.test* function in the RStudio statistical software was used (RStudio Team, 2020).

3.4.3. Seasonal Modelling and Cross-Correlation Insights

Indices showing a strong linear correlation, as determined by Pearson's correlation coefficient, were fitted to SARIMA models, followed by a cross-correlation analysis. In this context, burned area size was considered as the response variable with climatic (SPEI) and spectral vegetation (NDVI) indices as predictors. All computations were performed using the RStudio software (RStudio Team, 2020).

Initially, the data series were transformed into time series objects with a monthly frequency using the *ts()* function. The Augmented Dickey-Fuller (ADF) test was then applied to assess stationarity, evaluating the associated p-value and t-statistic. The SPEI-24 and NDVIs series showed insufficient evidence of stationarity, necessitating differentiation via the *diff()* function to meet this requirement before proceeding with modelling. The *auto.arima()* function was employed to automatically determine the optimal model order for each series (Hyndman and Khandakar, 2008). A SARIMA model (p, d, q) $(P, D, Q)\ s$ consists of seven parameters; it is an extension of the ARIMA model with additional terms to handle the seasonality of the data series. Once the model order was established, the models were fitted, and the residuals were examined using the *checkresiduals()* function and the Ljung-Box test. A p-value > 0.05 in the Ljung-Box test indicated no significant autocorrelation in the residuals, confirming an adequate model fit.

Subsequently, an exploratory cross-correlation analysis was performed on the residuals to eliminate variable-specific trends and mitigate autocorrelation issues. This analysis was conducted using the *ccf()* function, which calculates the linear relationship between two time series across various positive and negative lags. The objective was to identify patterns, trends, and significant relationships between the analysed variables within the context of the time series.

In this approach, SARIMA residuals were interpreted as the stochastic or 'random' component of each time series, after accounting for trend and seasonality. Cross-correlation between residuals thus focuses on short-term deviations -often associated with anomalous or extreme events- that are not explained by regular temporal patterns. This strategy facilitates the identification of inter-variable associations that may otherwise remain hidden due to autocorrelation in the raw series.

4. Results

4.1. Trends and inflexion points of climatic variables

The trends for pp, Tmed, and Tmax were positive and significant (pp z=2.3072, *p*=0.02104; Tmed z=3.692, *p*=0.00022; Tmax z=1.9941, *p*=0.04614) (Fig. 2a and b). All variables showed increases within the period analysed: pp= 217.5 mm (Theil-Sen estimator=7.51), Tmed= 1.24°C (Theil-Sen estimator=0.04285) and Tmax= 1.4°C (Theil-Sen estimator=0.048). For Tmin, the trend was positive but not significant (z=1.184; *p*=0.2364), with an increase of 0.97°C for the entire period (Theil-Sen estimator=0.033) (Fig. 2b). Mean precipitation over the study period was 433 mm (Fig. 2a). The estimated inflexion points for the variables with a significant trend occurred in 2013, 2007 and 2008 for pp, Tmed and Tmax, respectively.

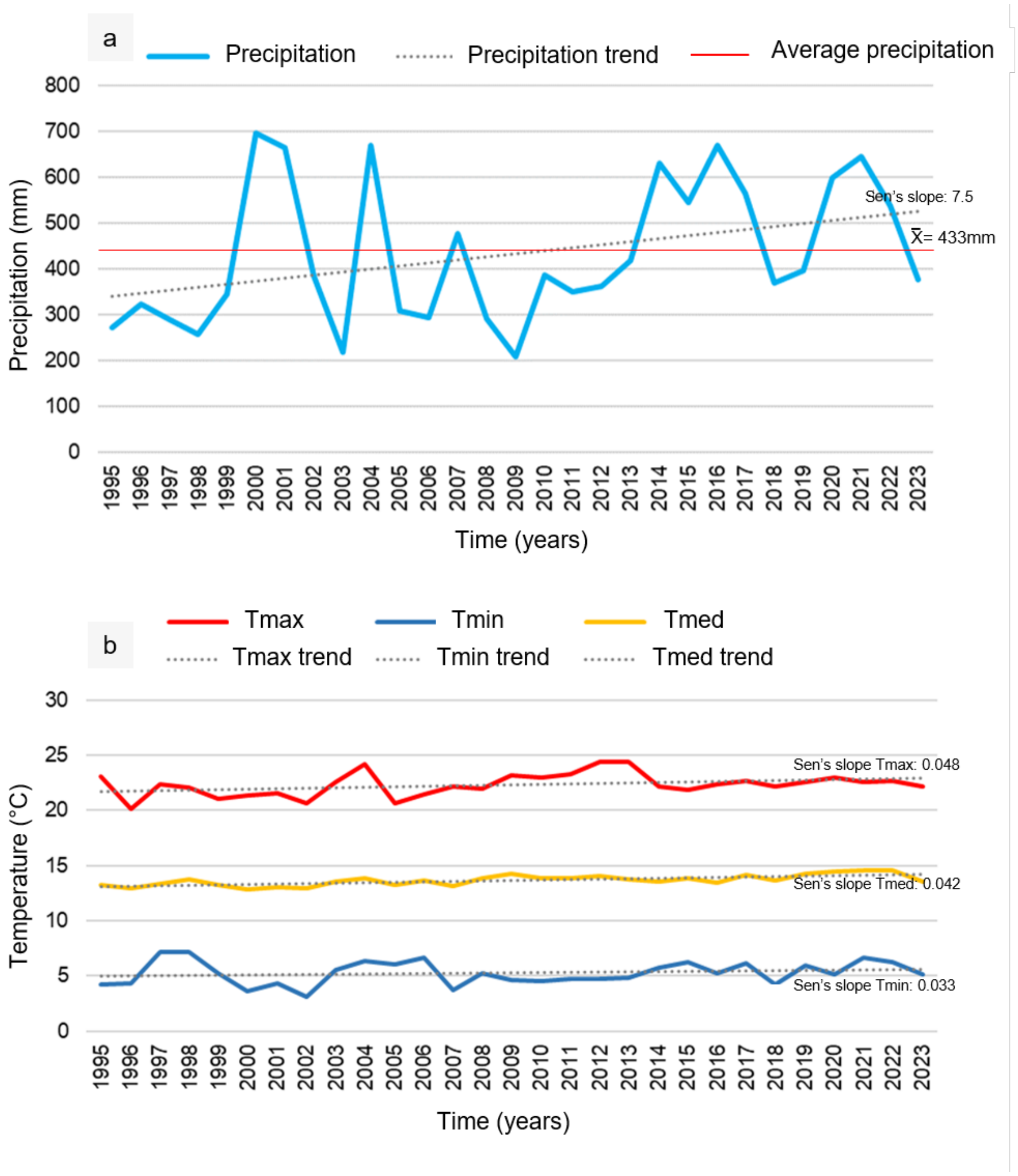

Figure 2. a. Trend and average value of precipitation (pp) and b. Trend of mean temperature (Tmed), maximum temperature (Tmax) and minimum temperature (Tmin) for the period 1995-2023.

4.2. Characteristics of drought and humidity events

The different SPEI timescales (SPEI-3, SPEI-6, SPEI-12 and SPEI-24) exhibited comparable general patterns over time. However, each timescale allowed for a distinct characterisation of attributes related to drought and humidity events, such as intensity, duration, and severity. On the one hand, SPEI-3 and SPEI-6 showed monthly and annual oscillations that correlated with the intensity of the events. These indices reached values outside the range of 2 to -2 (Fig. 3a and b). The SPEI-12 and SPEI-24 indices, on the other hand, provided information on the duration and severity of the events, while masking the seasonal oscillations characteristic of these systems (Fig. 3c and d).

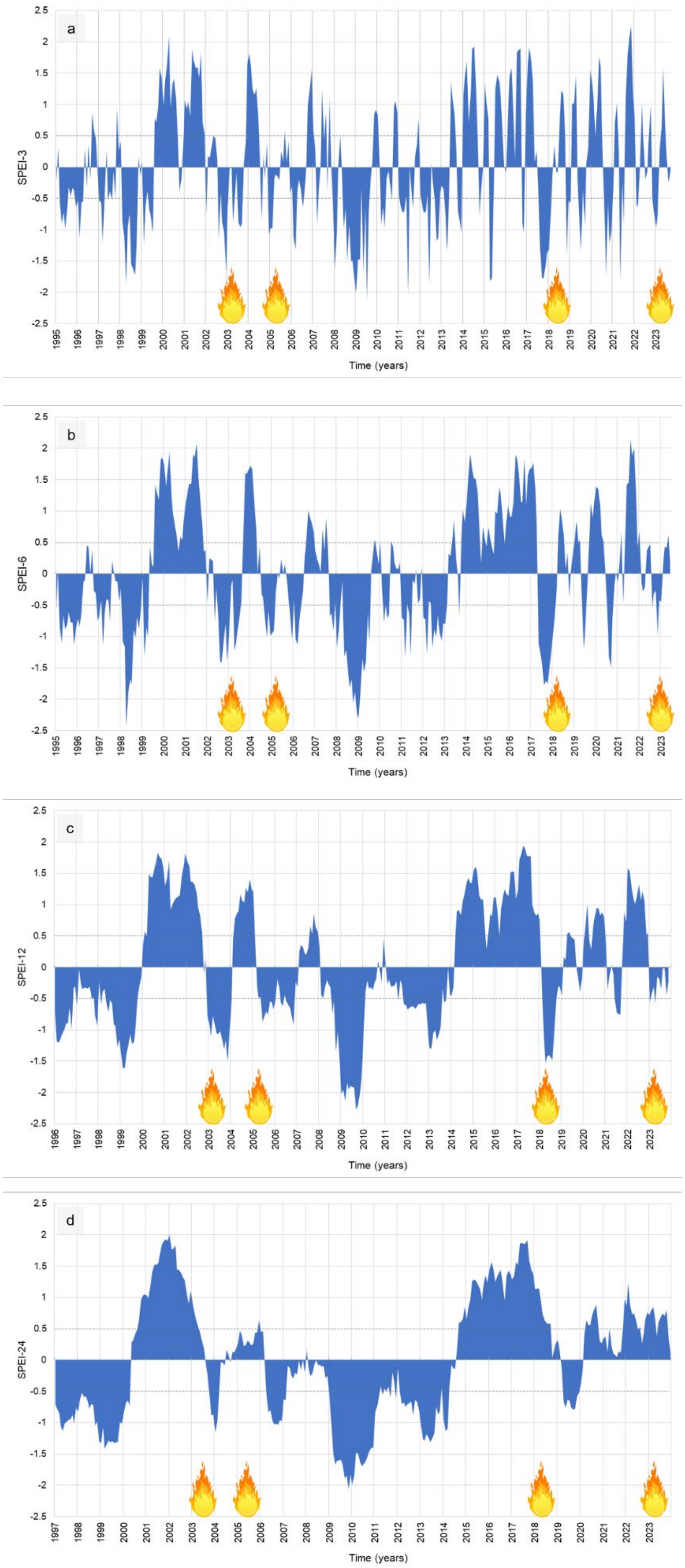

Figure 3. Standardised Precipitation and Evapotranspiration Index (SPEI), and fire events for the 1995-2023 time series, calculated for 3, 6, 12 and 24 months (a-SPEI-3, b-SPEI-6, c-SPEI-12 and d-SPEI-24, respectively).

SPEI-12 experienced the longest drought period (values below -0.5) from December 2011 to August 2013, in addition to a total of 21 months that fell into the "moderate drought" category. For SPEI-24, the longest dry period was recorded from January 2009 to March 2014, spanning a total of 63 months. For both SPEI, extreme drought events were identified with values close to -2. Conversely, the longest wet period for SPEI-12 was recorded from April 2014 to February 2018, comprising a total of 47 months of positive water balance with values between 1.5 and 2. For SPEI-24, the longest humid period lasted 49 months, from September 2014 to September 2018.

A positive and significant linear trend was observed for SPEI-6, SPEI-12, and SPEI-24, indicating a shift toward higher values. However, SPEI-3 did not display a significant linear trend (Table 2). Over the analysed period, SPEI-3 increased by 0.0299, SPEI-6 by 0.0574, SPEI-12 by 0.0638, and SPEI-24 by 0.0920 (Table 2).

Table 2. Values of z (trend indicator), p-value and the Theil-Sen estimator for each timescale of the Standardised Precipitation and Evapotranspiration Index (SPEI) index. The p-values>0.05 do not infer significant differences.

	z	p	Theil-Sen estimator
SPEI-3	1.835	0.0665	0.00103
SPEI-6	3.395	0.0007	0.00198
SPEI-12	4.140	0.00003	0.00225
SPEI-24	4.864	0.000001	0.00317

4.3. Spectral index insights from climatic dynamics

Both NDVIs and NDVIg showed a significant positive correlation with the 4 SPEI timescales (p-value<0.001 for all correlations) (Table 3). The strongest correlations were found between NDVIs with SPEI-24 (0.68) and between NDVIg with SPEI-6 and SPEI-12 (0.81 for both) (Table 3 and Fig. 4).

Table 3. Pearson's correlation coefficient between the Standardised Precipitation and Evapotranspiration Index (SPEI) and the Normalised Difference Vegetation Index (NDVI) at multiple timescales and physiognomies. References: SPEI 3, 6, 12 and 24; NDVIs - shrubland and NDVIg - grassland. The strongest linear correlations appear in bold.

	SPEI-3	SPEI-6	SPEI-12	SPEI-24
NDVI shrubland	0.61 (p=0.001)	0.63 (p=0.001)	0.65 (p=0.001)	**0.68** (p=0.0002)
NDVI grassland	0.74 (p=0.00004)	**0.81** (p=0.000001)	**0.81** (p=0.000001)	0.64 (p=0.001)

The climate index and the spectral index exhibited a similar dynamic throughout the time series, with the most extreme SPEI values followed, with delay, by the NDVI. The highest NDVIs value was 0.4654 in 2019, which corresponded to a continuum of four previous SPEI-24 years with annual averages above 0.5 (moderate/severely wet years). In the case of NDVIg, the highest value was 0.539 in 2004, related to three previous SPEI-6 and SPEI-12 years with values close to or greater than 1 (Fig. 4). At the other end of the scale, the lowest for NDVIs and NDVIg values (0.2542 and 0.2508, respectively) were recorded in 2009. For the first index, this value corresponded to four previous SPEI-24 years with negative values. In the case of the second index, the lowest NDVIg value corresponds to almost seven previous SPEI-6 and SPEI-12 years with negative values reaching close to -2 (Fig. 4).

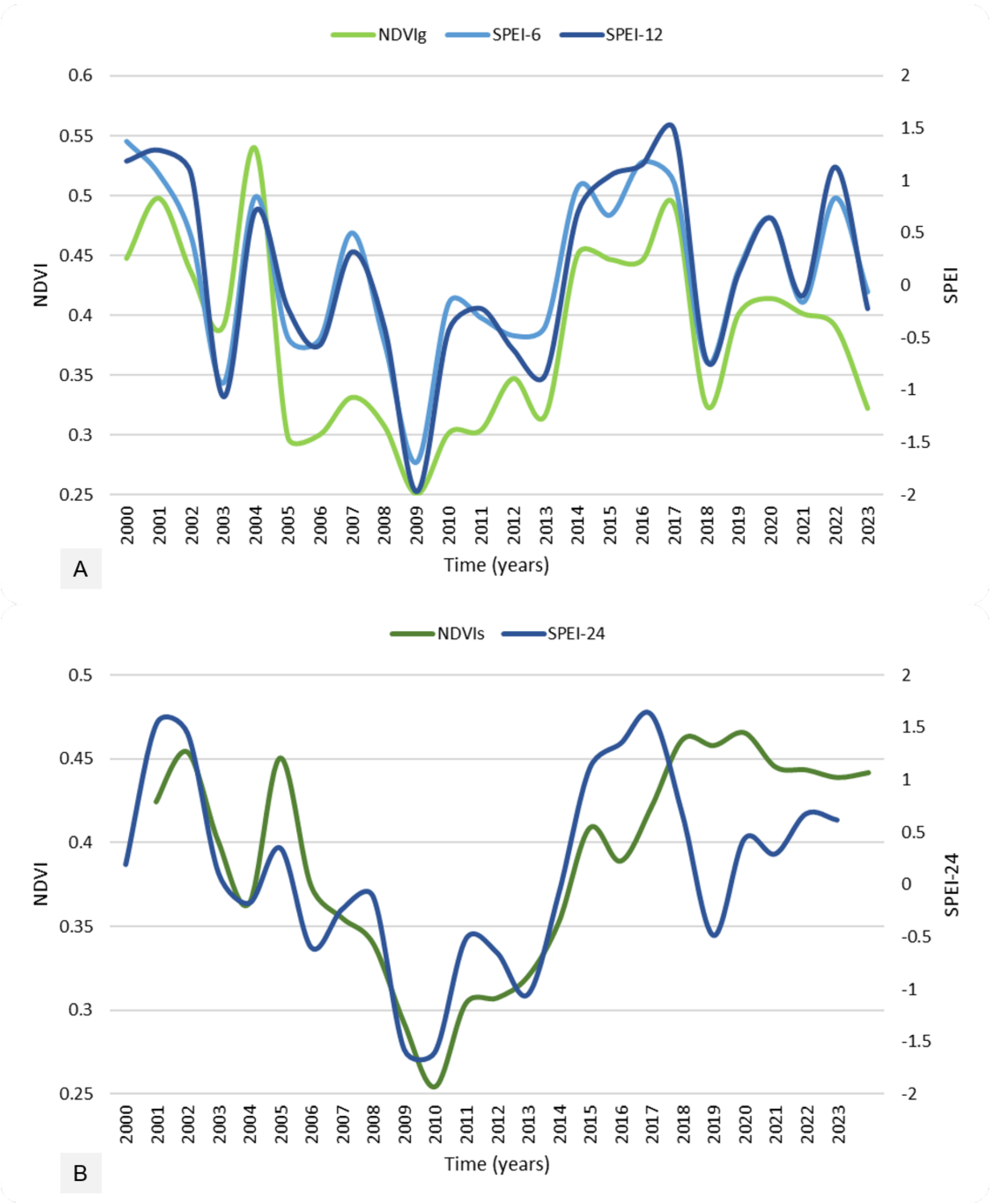

Figure 4. Dynamics of the grassland Normalised Difference Vegetation Index (NDVIg) and the Standardised Precipitation and Evapotranspiration Index (SPEI) timescales with the highest correlation (SPEI-6 and SPEI-12) (upper panel) and dynamics of shrubland Normalised Difference Vegetation Index (NDVIs) and the SPEI timescale with the highest correlation (SPEI-24) throughout the 2000-2023 time series (lower panel).

4.4. Cross-Correlation: climatic indices, vegetation, and fires

The cross-correlation analysis revealed synchronous relationships at lag 0 between SPEI and NDVI indices. Specifically, SPEI-12 and NDVIg showed the strongest association (r= 0.30; p< 0.001), while SPEI-24 and NDVIs also exhibited a significant but weaker correlation (r= 0.20; p= 0.0003) (Table 4). Although cross-correlation does not imply causality, it is worth noting that both SPEI-12 and SPEI-24 summarise the climatic water balance accumulated over the 12 and 24 months prior to each observation, respectively.

Finally, a weak but statistically significant negative correlation was found at lag 0 between SPEI-12 and the annual burned area (r-0.10; p= 0.0374). No significant correlations were detected at other lags for any of the variable pairs analysed.

Table 4. Summary of cross-correlation results between the residuals of SARIMA models for Standardised Precipitation and Evapotranspiration Index (SPEI), Normalised Difference Vegetation Index (NDVI) and burned area. The table includes the correlation coefficient (r), the associated Z-value, the p-value and an interpretation of the observed relationships.

Variable	Lag	Correlation (r)	Z-value	p-value	Interpretation
SPEI12 NDVIg	0	0.30	5.0218	< 0.001	Positive, gradual grassland response to cumulative 12-month moisture signal.
SPEI 24-NDVIs	0	0.20	3.5918	0.0003	Positive, long-term shrubland response to 24-month cumulative climate.
SPEI12-burned area	0	–0.10	-2.0818	0.0374	Inverse association: prolonged drought conditions associated with increased extent of burned area.

5. Discussion

The stochastic nature of wildfires, along with the numerous environmental and anthropogenic variables involved in their processes and development, makes it difficult to predict when such events will begin (Alvarado *et al.*, 2020; Reyes Bueno and Balcázar Gallegos, 2021; Conciani *et al.*, 2021). Therefore, the approach used in this study (a temporal analysis of climatic and spectral indices) could serve as a valuable methodological framework for gaining an in-depth understanding of the pre-ignition context (Ertugrul *et al.*, 2021). In this regard, the results obtained in this study enhance our understanding of how climate variables are interrelated and their potential to be considered as effective predictors of future fires (Reyes Bueno and Balcázar Gallegos, 2021; Chen *et al.*, 2024).

During the analysed period, major fire events were preceded by years in which precipitation exceeded the historical average for that period (433 mm). In contrast, the years in which these events occurred, recorded below-average precipitation. All significant wildfires during the study period (2003, 2005, 2018, 2023) took place at the beginning of or immediately following the summer season. A similar pattern was observed in the *caldén* forest areas of the central semiarid region of Argentina, with the most devastating events being preceded by years of above-average rainfall during the studied period (Estelrich *et al.*, 2022). In this context, additional findings from the region indicate that summer wildfires are positively associated with the average aridity index calculated over the two years preceding the events, reinforcing the role of multi-year climatic dynamics in shaping fire occurrence (Rodríguez, 2024).

In this context, the SPEI showed a sequence of dry-wet cycles generally interrupted by a fire event associated with the onset of the next dry cycle. The smaller-scale SPEIs facilitated the characterisation of event intensity (drought and humidity peaks) based on monthly and annual oscillations (Musei *et al.*, 2021), reflecting the extreme weather changes typical of these systems without providing relevant information at the ecosystem scale. By contrast, the SPEIs at longer timescales smooth the dynamics of drought-moisture cycles, allowing us to analyse their characteristics in terms of event duration and severity (Tirivarombo *et al.*, 2018; Musei *et al.*, 2021; Mousavi *et al.*, 2023).

Consequently, SPEI-12 (and partially SPEI-24) was the timescale that most clearly indicated values above the index's normal range (reaching close to 2) during the years preceding a fire, whereas in the year of the fire, the values turned negative. The highest index values were associated with the 2003 and 2018 fire events, which corresponded to a prolonged period of severe humidity. However, during all the wildfire years, the SPEI dropped below the normal range, reaching values as low as -1.5. Similarly, a recent study in the Central Monte region reported that the occurrence of large wildfires was strongly favoured by the combination of a spring-summer season with abundant precipitation followed by a year with low precipitation during the same period. Furthermore, precipitation and burned area showed a marked 6-7-year cycle, suggesting a dominant climatic control over wildfire occurrence

(Villagra *et al.*, 2024). This finding reinforces the potential applicability of an early warning system based on the identification of multi-year moisture and drought patterns.

In arid or semiarid environments, the ability of vegetation to respond to humidity and drought events is closely linked to its adaptive strategies (Gibson, 2012). In this regard, functional groups of herbaceous plants and grasses respond more quickly to short pulses of soil moisture from incident precipitation than shrubs, as they are more closely tied to groundwater dynamics (phreatophytes) (Giordano *et al.*, 2011). This relationship is reflected in the strong correlation between NDVIg and the smaller-scale SPEIs and between NDVIs and the larger-scale SPEIs, the latter exhibiting a spectral index response that follows the climatic index with delay.

Related to the dynamics previously described for grasses and herbaceous plants, the increase in available soil water during wet periods creates the necessary conditions for the accumulation of fine aerial phytomass (Del Valle Ledesma, 2020). Subsequently, pronounced droughts accelerate moisture loss from the accumulated fine phytomass, transforming it into plant biomass that becomes highly fire-prone during storms or high summer temperatures (Shao *et al.*, 2023; Chen *et al.*, 2024; Mosiejchuk and Mazzola, 2025). The integration of the NDVI and SPEI in this study revealed synchronised patterns between vegetation activity and cumulative moisture conditions, particularly at the 12- and 24-month timescales. These results underscore the value of combining multiscale climate indices with spectral vegetation indices to better characterise the timing and intensity of drought-humidity cycles and their influence on vegetation dynamics (Vicente-Serrano *et al.*, 2010; Conciani *et al.*, 2021; Arroyo-Ramírez, 2024; Cisneros-Vaca *et al.*, 2024).

The observed upward trends in both average temperature and total annual precipitation in the study area align with regional and national patterns reported for the Patagonian and central regions of Argentina (Oruezabal *et al.*, 2022). These trends are consistent with the broader impacts of climate change, which have already altered weather patterns globally and regionally (Pausas and Keeley, 2021; IPCC, 2023). Such changes influence key fire-related drivers, including drought frequency, temperature extremes, and vegetation flammability (Shi *et al.*, 2021; Singh, 2022), potentially leading to increased fire occurrence and intensity, as projected in multiple future scenarios (Pausas and Keeley, 2021; Naval-Fernández *et al.*, 2023).

Understanding fire dynamics through indices that provide insights into the environmental and climatic contexts in which they occur is a crucial contribution to management efforts. This knowledge supports the development of effective fire management and prevention strategies aimed at preserving these systems in the face of climate change. The application of these indices in fire-prone natural systems is particularly valuable, as it allows for the identification of scenarios with a high probability of ignition events.

6. Conclusions

Precipitation alternated between years with values above and below the average for the time series analysed in this study. Wet periods were followed by fire events occurring during drier periods. In this context, the SPEI indicated a sequence of dry-wet cycles, generally interrupted by wildfires coinciding with the onset of the next dry cycle. SPEI values calculated at shorter timescales were useful in characterising event intensity, while those at longer timescales provided insight into event duration and severity.

The NDVI for both grasslands and shrublands exhibited similar dynamics and a positive correlation with SPEI-12 and SPEI-24, respectively. Although some correlations, such as those involving fire occurrence, were relatively weak, the combined use of SPEI and NDVI remains a useful approach for detecting fuel accumulation periods and identifying climatic patterns potentially associated with fire events.

In the context of climate change, the observed upward trends in precipitation, mean, and maximum temperature suggest possible futures with increased fire frequency. Therefore, the continued monitoring of climatic and vegetation indices, even when associations are moderate, represents a valuable contribution to fire risk assessment. Promoting the integration of these tools into disaster risk management frameworks could benefit both productive systems and biodiversity conservation, especially when approached from an interdisciplinary perspective that includes climate science, plant community dynamics and fire ecology.

From an applied perspective, the patterns identified between climatic indices (SPEI), vegetation response (NDVI), and fire occurrence can support the development and strengthening of early warning systems. The detection of prolonged drought conditions, such as those identified in SPEI-12 and SPEI-24, combined with reductions in vegetation greenness, enables the anticipation of periods of increased fire susceptibility. Incorporating these signals into operational monitoring frameworks may support timely preventive actions, including prescribed burning, fuel load management, and the activation of local alerts. Therefore, the findings of this study provide potential tools that may serve to connect ecological research with land management strategies and public policies for wildfire prevention in semiarid regions.

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