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

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ABSTRACT. In recent years, there is growing 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 analyze variations in climatic and spectral indices over a 29-year period (1995–2023) to identify patterns that enhance the understanding of the fire regime in xerophytic shrublands. Additionally, trends in climatic variables were evaluated within the framework of global climate change. Meteorological data and records of burned area were analyzed. The Standardized Precipitation and Evapotranspiration Index (SPEI) was calculated at four-time scales, and monthly Normalized Difference Vegetation Index (NDVI) data for shrubs and grasslands were obtained. Trend detection and correlation analysis between variables were performed using the Theil-Sen estimator and the non-parametric Mann-Kendall test. A SARIMA model was used to explore lagged correlations between selected variables. SPEI values typically ranged between -2 to 2, with SPEI-12 showing the highest correlation with large, severe fire events. 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 fire regime understanding and management 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

Fire has captured human's interest since ancient times, whether to understand it or to manage it. Naturally, this element is part of many ecosystems and represents one of the main agents 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). On the other hand, 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, there is 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 is enhanced by a higher frequency of extreme weather events generally characterized by intense droughts and high temperatures in a context of climate change (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 are 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). As a broader scale, these elements are embedded within the larger drivers of global climate change (Obando Cabrera *et al.*, 2022).

In this regard, the study of weather patterns in order to understand the different natural phenomena has become increasingly relevant due to its implication in risk management and in mitigation or adaptation actions facing uncertain climate scenarios (Ferrelli *et al.*, 2020; Ertugrul *et al.*, 2021; Pausas and Keeley, 2021). In this sense, and particularly concerning wildfires, other studies show that climatic variables -such as precipitation and mean temperature- directly influence their ignition and spread, becoming an interesting tool in fire management (Reyes Bueno and Balcázar Gallegos, 2021; Chen *et al.*, 2024).

Although most studies analyzing 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 represent a major disturbance in natural ecosystems. This highlights the importance of studying climatic variability in relation to fire dynamics in these environments. Nationwide, during the period 2001 and 2016, 18 million hectares were burned, of which approximately 60% correspond to wildfires in La Pampa province, mainly in natural systems (SAyDS, 2018; Estelrich *et al.*, 2022). Of the total affected area, 30% corresponds to shrubland physiognomies in the Monte Ecoregion (de Titto and Savino, 2021; Mosiejchuk and Mazzola, 2025). In this context, La Pampa was the most affected province, 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 at the level of community structure and functioning, wildlife and domestic livestock (Cangiano *et al.*, 2021), infrastructure, human lives, and also with implications for the loss of carbon stocks (Ricard *et al.*, 2022; Aryal *et al.*, 2022; Utello, 2024).

When delving into the regional fire ecology, drought and humidity events become relevant. These spatio-temporal phenomena are dynamic, which makes quantifying their duration, frequency, periodicity, and intensity complex (Ferrelli *et al.*, 2020). Therefore, the design of indices that include, combine or weight different weather variables in their formulation has made it possible to estimate the duration of drought and moist spells, characterize them and monitor their behavior over time (Masanta and Srinivas, 2022; Gebrechorkos *et al.*, 2023). In turn, the incorporation of vegetation spectral indices in the comprehensive analysis allows for an improved interpretation of vegetation dynamics and its recovery rate in response to drought-humidity events (Gebrechorkos *et al.*, 2023; Arroyo-Ramírez, 2024).

The study aimed to analyze the variations in the climatic (SPEI) and vegetation spectral indices (NDVI) over a multi-year time series to identify patterns that enhance the understanding of the fire regime in xerophytic shrublands of La Pampa province, Argentina. Additionally, within the context of global climate change, the trends of the variables involved in the study were analyzed. Implementing this methodology to monitor vegetation responses and fire events in relation to climatic dynamics in xerophytic systems provides a significant contribution to the prevention of natural disasters and the development of effective management strategies. At the ecosystem level, it serves as a valuable tool for reinterpreting potential successional trajectories of these systems within the context of the climate crisis.

2. Study area

The study was conducted in Lihué Calel National Park (LCNP) located in the east-central region of La Pampa province, Argentina, within the Monte Ecoregion (Cabrera, 1976). The park encompasses 32514 hectares and exclusively harbors representative plant communities of the ecoregion with a high 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 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 grasslands with scattered shrubs are characterized by grasses of the genus *Nassella* (Oyarzabal *et al.*, 2018). The vegetation exhibits morphological and physiological traits typical of xerophilous communities, including small and 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 minimizing evapotranspiration loss (Gibson, 2012).

Additionally, this 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 ignitions, and burned area. Over this period, 25 wildfire events have been recorded. These events have occurred within a context that underscores the significance of such natural phenomena at both regional and national scales. The xerophytic vegetation of this region, combined with its historical management, has created ideal conditions for fires to develop, often with devastating consequences. Consequently, plant communities are frequently subjected to fire events of varying characteristics and recurrence. Within this context of wildfires, four significant events stand out due to their intensity and the 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).

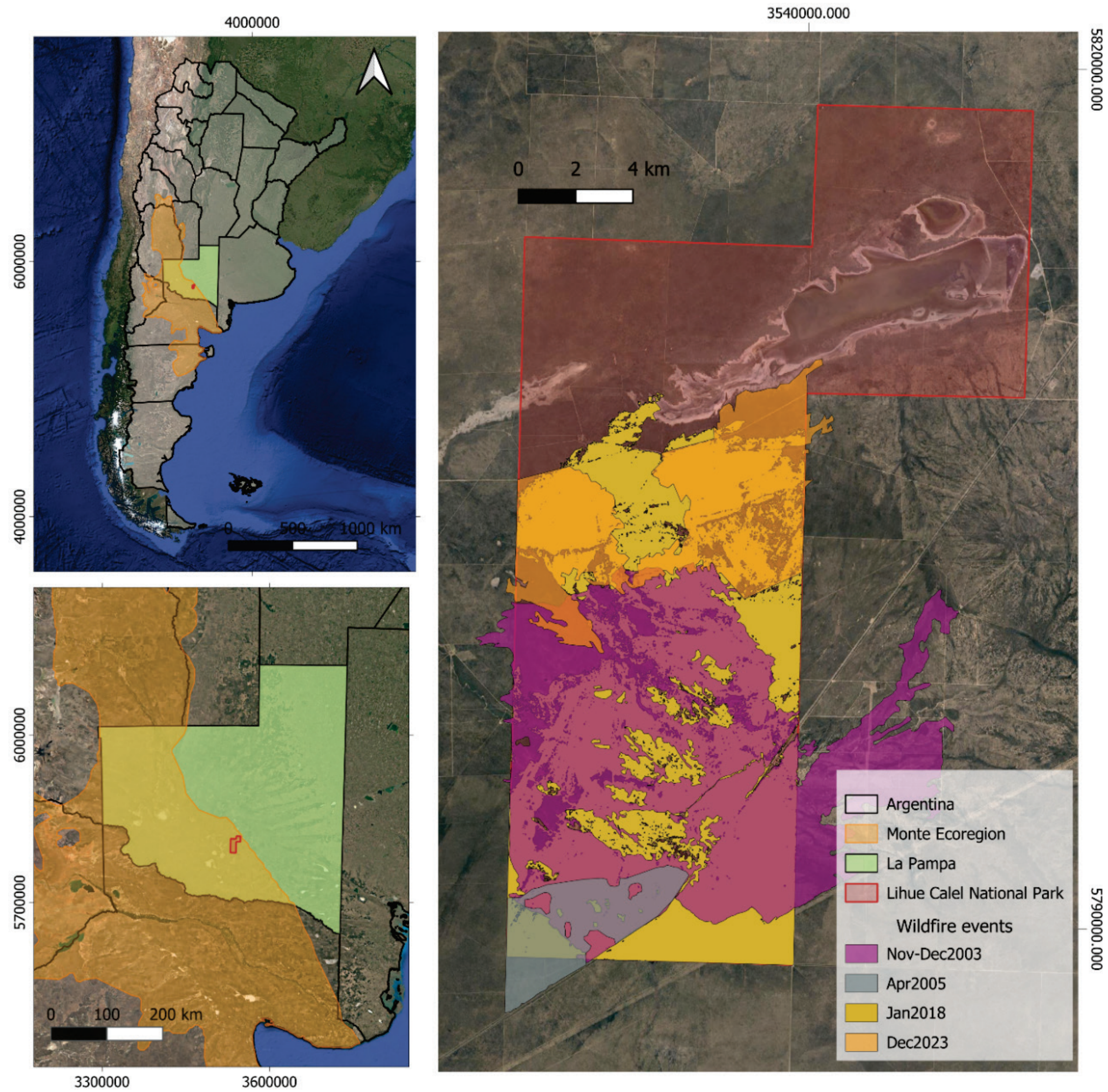

Figure 1. Location of the study area: Lihué Calel National Park, La Pampa, Argentina, the Monte Ecoregion and the spatial extent of major wildfire events recorded in the park over the past 29 years.

3. Methods and materials

3.1. General description of data sources

The climatic and wildfire dataset includes monthly averages of precipitation (pp), minimum temperature (Tmin), maximum temperature (Tmax), mean temperature (Tmed), and burned area size (APN, 2021). Climate data were sourced from the Automated Meteorological Station of LCNP 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 utilized, 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. Standardized Precipitation Evapotranspiration Index (SPEI)

The SPEI is a climate index based on the monthly water balance $D = P - PET$, where P is precipitation and PET in potential evapotranspiration. The resulting D values were fitted to a probability distribution and standardized to obtain the SPEI values. In this way, a climatic water balance is obtained and it can be calculated at different time scales (Vicente-Serrano *et al.*, 2010).

The SPEI is a multiscale index that can be calculated at different time scales depending on the interest of the study. For the development of this work, the estimation of the monthly index was obtained from multiple scales: 3, 6, 12 and 24 months, being defined as SPEI-3; SPEI-6; SPEI-12 and SPEI-24 respectively. Monthly mean precipitation and temperature data described in section 3.1 were used. Table 1 outlines the value ranges of the index 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 characterized by their duration, intensity, and severity.

Table 1. Categories assigned to each range of values taken by the Standardized 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. Normalized Difference Vegetation Index (NDVI)

The NDVI is calculated using two bands of the electromagnetic spectrum, expressed as NDVI = (NIR – Red) / (NIR + Red), where *NIR* represents the near-infrared band and *Red* represents 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 utilized to assess the photosynthetic activity of various shrubland and grassland physiognomies in response to drought periods. NDVI values range from -1 to 1, with higher values indicating 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 utilized 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 meters. 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 where 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 inflection points

To estimate the trends in pp, Tmed, Tmax, Tmin, and SPEI, the Theil-Sen estimator was applied (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 inflection points were identified through segmented regression. This method allows the time series to be divided into segments with distinct linear trends and identifies breakpoints where the statistical properties change. Previously, the number of inflection 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 level of significance for each correlation was also obtained. In this way, the SPEI calculation time scale that best explained the behavior of the NDVI of shrubs and grasslands was detected. Prior to the correlation analysis, the assumptions of normality of the data were verified from the Shapiro-Wilk test with a significance level of p=0.05. A coefficient value close to 1 was interpreted as a strong positive correlation. The *cor.test* function of the RStudio statistical software was used (RStudio Team, 2020).

3.4.3. Seasonal Modeling 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 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 modeling. 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, 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 analyzed 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 accounted 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 inflection 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. 2 a and b). All variables showed increases within the period analyzed: 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 inflection points for the variables with a significant trend occurred in 2013, 2007 and 2008 for pp, Tmed and Tmax, respectively.

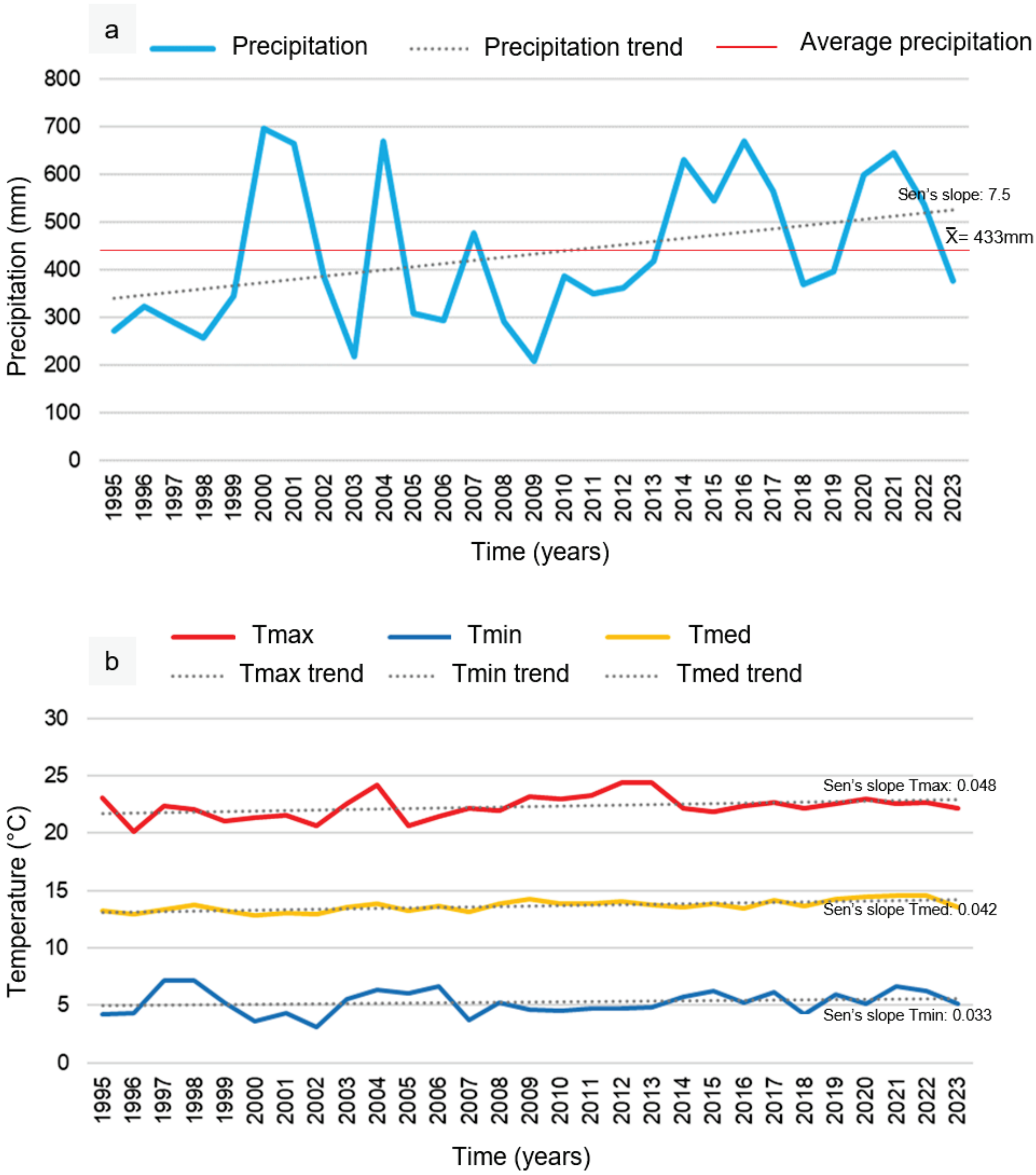

Figure 2. a. Trend and average value of precipitation (pp) and b. Trend of mean temperature (Tmed), maximum temperature (Tmax) and minimum temperature (Tmin) for the period between 1995-2023.

4.2. Characteristics of drought and humidity events

The different SPEI time scale (SPEI-3, SPEI-6, SPEI-12 and SPEI-24) exhibited comparable general patterns over time. However, each timescale allowed for a distinct characterization 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 related to the intensity of the events. These indices reached values above the range of 2 to -2 (Fig. 3 a and b). The SPEI-12 and SPEI-24 indices, on the other hand, provided information regarding the duration and severity of the events, while masking the seasonal oscillations characteristic of these systems (Fig. 3 c and d).

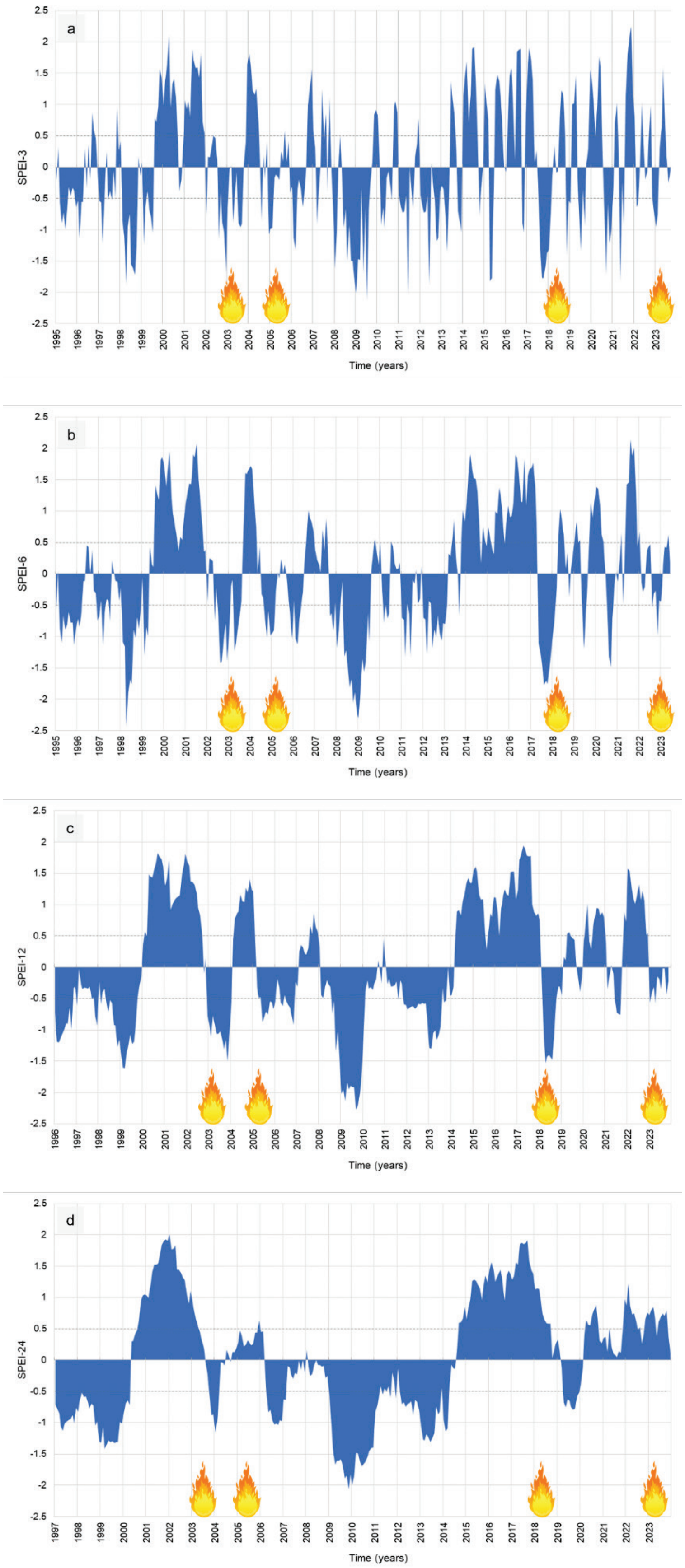

Figure 3. Standardized Precipitation and Evapotranspiration Index (SPEI), and fire events for the 1995-2023 time series, calculated for 3, 6, 12 and 24 months (a-SPEI-3, b-SPEI-6, c-SPEI-12 and d-SPEI-24 respectively).

The SPEI-12 showed the longest period of drought (with values below -0.5) from December 2011 to August 2013, adding a total of 21 months that corresponded to the "moderate drought" category. For SPEI-24, the longest dry period was recorded from January 2009 to March 2014 with a total of 63 months. For both SPEI, extreme drought events were identified with values close to -2. On the other hand, from April 2014 to February 2018, the longest wet period was recorded for SPEI-12, comprising a total of 47 months of positive water balance, with values between 1.5 and 2. For the 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 analyzed 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 time scale of the Standardized 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 time scales (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 Standardized Precipitation and Evapotranspiration Index (SPEI) and Normalized Difference Vegetation Index (NDVI) at multiple time scales and physiognomies. References: SPEI 3, 6, 12 and 24; NDVIs - shrubland and NDVIg - grassland. In bold the strongest linear correlations.

	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 presented a similar dynamic throughout the time series, in which the most extreme values of the SPEI are followed with delay by the NDVI. The highest value of NDVIs was 0.4654 in 2019, which corresponded to a continuum of four previous years of SPEI-24 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 years of SPEI-6 and SPEI-12 with values close to or greater than 1 (Fig. 4). On the other hand, the lowest values for NDVIs and NDVIg (0.2542 and 0.2508, respectively) were recorded in 2009. For the first index, this value corresponded to four previous years of a SPEI-24 with negative values. In the case of the second index, the lowest NDVIg value corresponds to almost seven previous years of a SPEI-6 and SPEI-12 with negative values, reaching values close to -2 (Fig. 4).

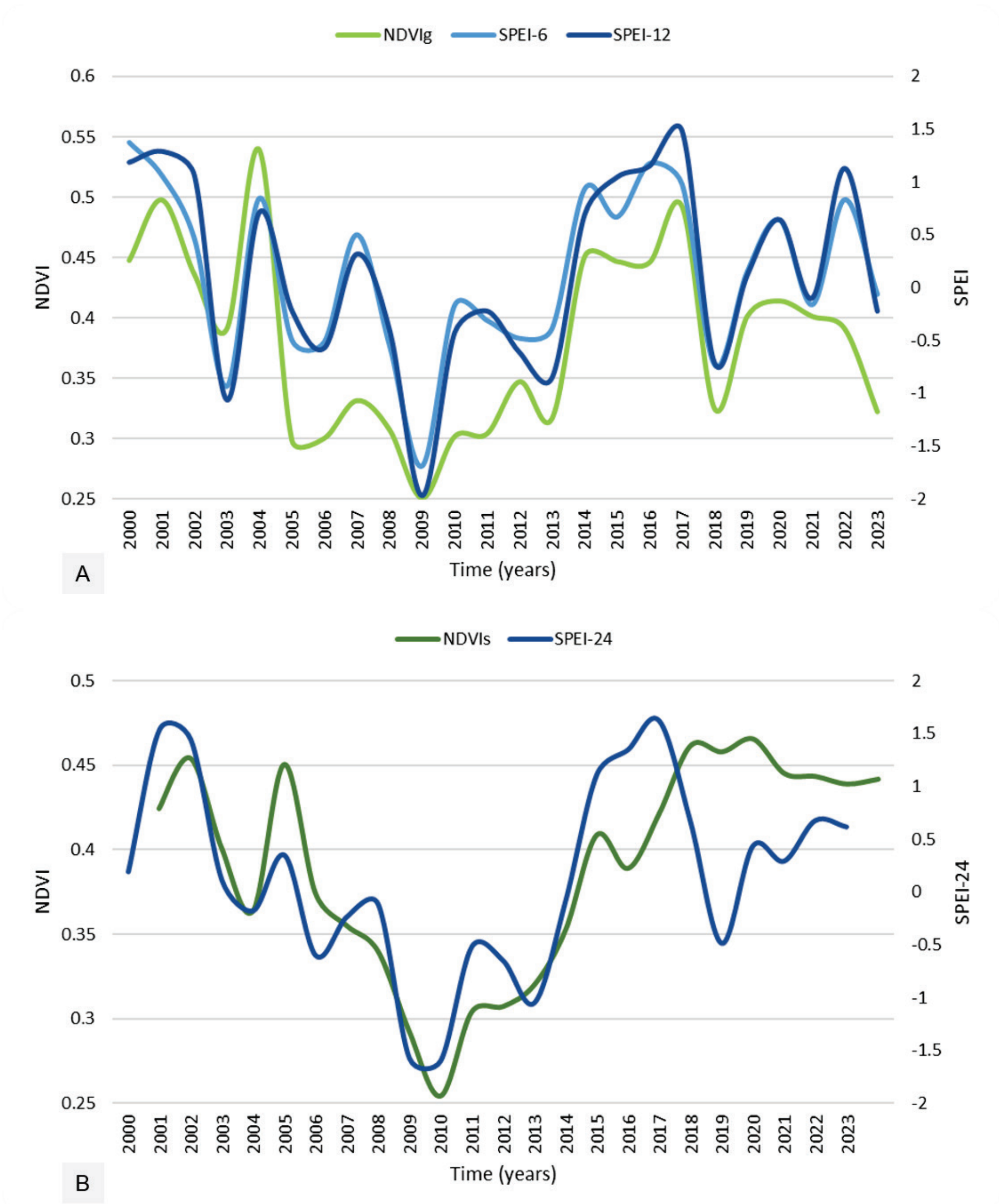

Figure 4. Dynamics of grassland Normalized Difference Vegetation Index (NDVIg) and the Standardized Precipitation and Evapotranspiration Index (SPEI) time scale with the highest correlation (SPEI-6 and SPEI-12) (upper panel) and dynamics of shrubland Normalized Difference Vegetation Index (NDVIs) and the SPEI time scale 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 summarize 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 analyzed.

Table 4. Summary of cross-correlation results between the residuals of SARIMA models for Standardized Precipitation and Evapotranspiration Index (SPEI), Normalized Difference Vegetation Index (NDVI) and burned area. The table includes the correlation coefficient (r), associated Z-value, 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 burned area extent.

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 offered by a temporal analysis of climatic and spectral indices could serve as a relevant tool 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 analyzed 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 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 SPEI facilitated the characterization 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. On the other hand, the SPEI at longer time scales smooths the dynamics of drought-moisture cycles, allowing us to analyze the characteristics of these cycles in terms of event duration and severity (Tirivarombo *et al.*, 2018; Musei *et al.*, 2021; Mousavi *et al.*, 2023).

In this way, the SPEI-12 (and partially the SPEI-24) was the time scale that most clearly indicated that during the years preceding a fire, values above the normal range of the index were recorded, reaching close to 2, while 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 the year of any of these wildfires, 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 favored 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 response of vegetation 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 of NDVIg with smaller-scale SPEI and NDVIs with larger-scale SPEI, the latter exhibiting a delayed response of the spectral index compared to the climatic index.

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). Then, pronounced droughts accelerate the moisture loss from the accumulated fine phytomass, transforming it into plant biomass fire-prone due to storms or high summer temperatures (Shao *et al.*, 2023; Chen *et al.*, 2024; Mosiejchuk and Mazzola, 2025). The integration of NDVI and SPEI in this study revealed synchronized patterns between vegetation activity and cumulative moisture conditions, particularly at 12- and 24- month timescales. These results underscore the value of combining multiscale climate indices with spectral vegetation indices to better characterize 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 analyzed 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 time scales were useful in characterizing event intensity, while those at longer time scales 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 through SPEI-12 or SPEI-24, combined with reductions in vegetation greenness, enables the anticipation of periods with 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. Thus, the findings of this study provide potential tools to connect ecological research with land management strategies and public policy for wildfire prevention in semiarid regions.

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