Impact of Climate Variability on Rangelands: Evaluation of Adaptive Management Strategies from Extended Time Series and Local Practices

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Abstract

Grasslands are among the most climate-sensitive ecosystems, particularly in arid and semi-arid regions where interannual climate variability strongly constrains primary productivity. In Mexico, grassland-based livestock systems are highly exposed to fluctuations in precipitation and increasing temperatures, posing significant challenges for sustainability. This study evaluated the impact of climate variability on grassland productivity in Mexico and assessed the effectiveness of adaptive management strategies by integrating extended time series and local management practices.

A mixed-methods approach was applied, combining a longitudinal quantitative analysis of climate and vegetation time series (1990–2022) with qualitative information derived from local livestock management practices. Climate variability was characterized using precipitation and temperature records, while grassland productivity was assessed through satellite-derived NDVI indicators. Adaptive management strategies were identified through semi-structured interviews and categorized using thematic analysis. Statistical analyses included trend detection, correlation, and regression models linking climate variables with vegetation dynamics.

Results showed high interannual variability in precipitation across all regions, which explained a substantial proportion of NDVI variability. Temperature exhibited a moderate but significant negative effect on grassland productivity, particularly during dry years. Grasslands managed under adaptive strategies displayed higher productivity stability and reduced NDVI declines during drought events compared to conventionally managed systems. Qualitative findings revealed that flexible stocking rates, rotational grazing, strategic resting periods, and conservation of native species were key practices enhancing resilience.

The integration of quantitative and qualitative results highlights the critical role of adaptive management in buffering the impacts of climate variability on Mexican grasslands. These findings underscore the importance of promoting flexible, knowledge-based management strategies supported by long-term climate and vegetation monitoring to enhance the resilience of grassland-based livestock systems under increasing climatic uncertainty.
Keywords: Climate variability; Grasslands; Adaptive management; NDVI; Livestock systems; Mexico

1. INTRODUCTION

1.1 General context

Grasslands constitute one of the largest and most strategic terrestrial ecosystems on the planet, playing a fundamental role in the provision of ecosystem services such as forage production, carbon sequestration, hydrological regulation and the sustenance of extensive livestock systems. Globally, these ecosystems are among the most vulnerable to climate variability, understood as the interannual and multi-decadal fluctuations of key climate variables, particularly precipitation and temperature.

In Mexico, natural and semi-natural grasslands cover approximately 12–15% of the national territory and are mainly concentrated in arid and semi-arid regions of the north and central highlands, where extensive livestock farming represents one of the main rural economic activities. These regions have a high exposure to recurrent droughts, heat waves and changes in precipitation patterns, which increases the sensitivity of pastoral systems to climate change.

1.2 Climate variability and grassland dynamics in Mexico

Several studies have documented that the primary productivity of Mexican grasslands is closely linked to the interannual variability of precipitation, particularly during the rainy season (June–September). Extreme weather events, such as prolonged droughts associated with ENSO phenomena, have caused significant reductions in forage biomass, soil degradation and loss of vegetation cover, compromising the productive and ecological sustainability of these systems.

In addition, the sustained increase in average temperature and the greater frequency of extreme events have altered the phenological cycles of forage species, favoring in some cases the invasion of less palatable species or the reduction of native perennial species. These processes, when combined with anthropogenic pressures such as overgrazing, can accelerate the degradation of grasslands and reduce their resilience to future climate shocks.

1.3 Adaptive management strategies in pastoral systems

Faced with this scenario, **adaptive management** has been proposed as a key strategy to increase the resilience of grasslands to climate variability. In the Mexican context, producers have historically developed local practices based on empirical knowledge of climate and vegetation, such as dynamic adjustment of animal stocking, the use of resting periods, pasture rotation, and the conservation of drought-tolerant native species.

However, the effectiveness of these strategies has been evaluated in a fragmented manner and, in many cases, without integrating long-term quantitative analyses that allow directly relating climate variability with the productive response of rangelands. The absence of studies that combine extensive climate time series with detailed information on management practices limits the ability to formulate public policies and technical recommendations based on solid scientific evidence.

1.4 Knowledge gap

Despite the growing literature on climate change and pastoral ecosystems, an important gap persists in the Mexican context: (i) there is a lack of studies that analyze multidecadal climate variability and grassland dynamics in an integrated manner; (ii) there is limited incorporation of local knowledge and adaptive management strategies in quantitative analyses; and (iii) there are few studies that evaluate the effectiveness of these strategies using objective indicators derived from remote sensing and historical records.

1.5 Rationale for the study

This study is justified by the need to generate robust scientific evidence to understand how climate variability has influenced the productivity and stability of grasslands in Mexico, and to what extent the adaptive management strategies implemented by producers have contributed to mitigating these impacts. The integration of extended time series with local practices offers an innovative and relevant approach to strengthen decision-making in the livestock sector and the sustainable management of natural resources.

1.6 Objectives of the study

General objectiveTo evaluate the impact of climate variability on grassland dynamics in Mexico and to analyze the effectiveness of adaptive management strategies through the use of extended time series and local management practices.

Specific objectives

1. To analyze trends and patterns of climate variability (precipitation and temperature) in representative regions of Mexican grasslands during the last decades.
2. Assess the relationship between climate variability and rangeland productivity using indicators derived from vegetation time series.
3. Identify and categorize the main adaptive management strategies implemented by local livestock producers.
4. Integrate quantitative and qualitative results to determine the effectiveness of adaptive management strategies in the face of climate variability.

1.7 Research hypothesis

H1: Interannual variability in precipitation and temperature has a significant effect on pasture productivity in Mexico.H2: Pastures managed with adaptive strategies have greater productive stability in the face of climatic variability compared to those under conventional management. H3: The integration of local management practices contributes to increasing the resilience of pastoral systems to extreme weather events.

2. THEORETICAL FRAMEWORK AND LITERATURE REVIEW

2.1 Climate variability and climate change: conceptual foundations

Climate variability refers to natural fluctuations in climate on interannual, decadal and multi-decadal timescales, while climate change involves persistent modifications in long-term climate averages. In arid and semi-arid regions, such as much of Mexico, climate variability represents a determining factor of ecological productivity, even in the absence of clear climate change trends.

In Mexico, the interannual variability of precipitation is strongly influenced by large-scale phenomena such as the El Niño–Southern Oscillation (ENSO), the Pacific Decadal

Oscillation and the atmospheric circulation of the tropical Atlantic. These fluctuations directly affect the duration and intensity of the rainy season, conditioning the availability of water for vegetation and the stability of pastoral systems.

2.2 Mexican grasslands: ecological and functional characteristics

Grasslands in Mexico include a diversity of plant communities dominated by perennial and annual grasses, adapted to conditions of water stress and high environmental variability. They are mainly located in the north of the country (Chihuahua, Coahuila, Durango, Zacatecas and San Luis Potosí) and in the central highlands, where semi-arid and arid climates predominate.

From a functional perspective, rangeland productivity is determined by the interaction between climatic, edaphic, and management factors. Seasonal precipitation, rather than total annual precipitation, has been identified as the main driver of aboveground biomass, while temperature regulates phenological processes and water use efficiency.

Studies based on remote sensing have shown that the temporal dynamics of the normalized difference vegetation index (NDVI) is a robust indicator of primary productivity and the response of Mexican grasslands to climate variability, allowing to evaluate spatial and temporal changes at regional scales.

2.3 Impacts of climate variability on rangeland productivity and stability

Recent literature agrees that grasslands in semi-arid areas are highly sensitive to climate variability, particularly to the occurrence of prolonged droughts. In Mexico, severe droughts have been associated with significant decreases in forage biomass, reduction of vegetation cover and increased vulnerability to desertification processes.

Likewise, it has been documented that climate variability not only affects the amount of forage available, but also its nutritional quality, altering the floristic composition and favoring less palatable species or with lower forage value. These changes have direct implications on the carrying capacity and sustainability of extensive livestock systems.

From a time series approach, pastoral systems have been observed to exhibit nonlinear responses to climate variability, with critical thresholds beyond which vegetation recovery becomes slow or incomplete, especially under inadequate management conditions.

2.4 Grazing management and pasture degradation

Grazing management is a key factor in modulating climate impacts on rangelands. In Mexico, historical overgrazing has been identified as one of the main drivers of degradation, amplifying the negative effects of climate variability and reducing ecosystem resilience.

The literature distinguishes between conventional management, characterized by fixed animal loads and poor spatial and temporal planning, and more flexible approaches that adjust grazing intensity according to environmental conditions. Empirical evidence suggests that systems with greater flexibility in management have a better capacity to cushion the impacts of recurrent droughts.

2.5 Adaptive management approach in pastoral systems

Adaptive management is based on the premise that socio-ecological systems are dynamic and uncertain, so management decisions must be continuously adjusted based on monitoring and learning. In the context of rangelands, this approach involves modifying grazing practices in response to climate variability and vegetation condition.

In Mexico, adaptive management strategies include practices such as seasonal adjustment of animal load, rotation of pastures, use of strategic breaks, conservation of patches of native vegetation, and diversification of forage sources. These practices are usually based on the local knowledge accumulated by generations of producers.

Recent studies have shown that the implementation of adaptive strategies can reduce the interannual variability of forage productivity and improve the stability of the system in the face of extreme weather events. However, the effectiveness of these strategies depends on their adequate integration with local ecological conditions and their evaluation through reliable quantitative indicators.

2.6 Integration of time series and local knowledge

An emerging trend in the literature is the integration of data derived from remote sensing and historical climate records with qualitative information on local management practices. This approach allows capturing both the biophysical dynamics of grasslands and the human decisions that influence their ecological trajectory.

In the case of Mexico, this integration is particularly relevant due to the country's climatic and socioeconomic heterogeneity. The combination of extended time series of NDVI, precipitation and temperature with interviews and records of livestock management offers a solid basis for assessing the resilience of pastoral systems and designing more effective adaptation strategies in the face of climate variability.

2.7 Conceptual framework of the study

Based on the literature review, this study is based on a conceptual framework that links climate variability with grassland dynamics, mediated by adaptive management practices. In this framework, the productivity and stability of pastures result from the interaction between climatic factors (precipitation and temperature), ecological characteristics of the system and management decisions, which can amplify or mitigate climatic impacts.

This integrative approach makes it possible to assess not only the direct effects of climate variability, but also the role of adaptive management as a resilience mechanism in Mexican grasslands.

3. METHODOLOGY

3.1 Research approach and design

The study adopted a mixed sequential explanatory approach, in which quantitative analysis of extended time series was complemented with qualitative information on local adaptive management practices. The quantitative design was longitudinal observational, based on climatic and vegetation data collected over a period of more than three decades, while the qualitative component had a descriptive-interpretive design.

The integration of both approaches made it possible to assess the impact of climate variability on grasslands and, simultaneously, to analyze the role of adaptive management as a mechanism of socio-ecological resilience.

3.2 Study Area

The study area included representative regions of natural and semi-natural grasslands of northern and central highlands of Mexico, including areas of the states of Chihuahua, Coahuila, Durango, Zacatecas and San Luis Potosí. These regions are characterized by arid and semi-arid climates, with an average annual rainfall between 250 and 500 mm and a marked seasonality of rainfall.

The predominant production systems correspond to extensive cattle farming, with different levels of management intensity and varying degrees of adoption of adaptive practices. The selection of these regions was based on their livestock importance, availability of long-term climate information and ecological representativeness.

3.3 Climate Data Sources

The climate data used included monthly time series of total precipitation and mean temperature, corresponding to the period 1990–2022. The information was obtained from official weather stations and climate databases of national coverage, previously validated and used in climatological studies in Mexico.

For each study region, continuous time series were constructed using quality control procedures, outlier detection, and interpolation of missing data. Likewise, indicators of climate variability were calculated, such as precipitation coefficient of variation, standardized anomalies, and frequency of dry and extremely dry years.

3.4 Vegetation and Grassland Productivity Data

Rangeland productivity was assessed using remote-sensing indicators, mainly the Normalized Difference Vegetation Index (NDVI), obtained from satellite time series with moderate spatial resolution. Monthly and seasonal compositions for the period 1990–2022 were used to capture the interannual dynamics of the vegetation.

NDVI was used as a proxy for primary airborne productivity and forage biomass availability. For each region, metrics such as annual average NDVI, maximum seasonal NDVI and year-on-year coefficient of variation were calculated, allowing both average productivity and system stability to be evaluated.

3.5 Identification of adaptive management strategies

The qualitative component of the study was based on the collection of information on local adaptive management practices implemented by livestock producers. Semi-structured interviews and reviews of local technical records were conducted, focused on identifying strategies such as:

- Dynamic adjustment of the animal load according to forage availability.
- Rotation of paddocks and rest periods.
- Conservation of drought-tolerant native forage species.
- Use of forage reserves and strategic supplementation during dry years.

The practices identified were systematized and categorized through a thematic coding process, allowing their subsequent integration with the quantitative results.

3.6 Quantitative Data Analysis

The quantitative analysis included descriptive and inferential statistical procedures. First, temporal trends in climate and NDVI variables were evaluated using non-parametric trend tests. Subsequently, the relationships between climate variability and pasture productivity were analyzed using correlation analysis and linear and nonlinear regression models.

Likewise, the stability of productivity was compared between systems with different degrees of adoption of adaptive management, using indicators of interannual variability and statistical tests to identify significant differences. The analyses were carried out at the regional and temporal levels, considering possible lagging effects between climate and vegetation response.

3.7 Qualitative Data Analysis

Qualitative information was analyzed using a thematic content analysis approach. The interviews were transcribed and coded in an iterative way, identifying main categories and subcategories related to the perception of climate variability, management decisions and the response of the production system.

The validity of the qualitative analysis was strengthened by triangulation of sources and comparison between regions with different climatic conditions and levels of adoption of adaptive practices.

3.8 Integration of results

The integration of the quantitative and qualitative results was carried out in the interpretation phase, linking the patterns observed in the NDVI and climate time series with the management strategies identified. This process made it possible to comprehensively evaluate the effectiveness of adaptive management as a mechanism for mitigating the impacts of climate variability on Mexican grasslands.

4. RESULTS

4.1 Climate variability in grassland regions of Mexico

The analysis of the climate time series (1990–2022) showed a marked interannual variability of precipitation in all the regions studied, with coefficients of variation ranging from 28% to 41%. Precipitation showed a high seasonal concentration, with more than 70% of the annual total occurring during the rainy season (June–September).

In contrast, the average annual temperature showed a moderate but consistent positive trend, with average increases of between 0.3 and 0.5 °C per decade, particularly pronounced from 2005 onwards.

Table 1. Descriptive statistics of climate variables (1990–2022)

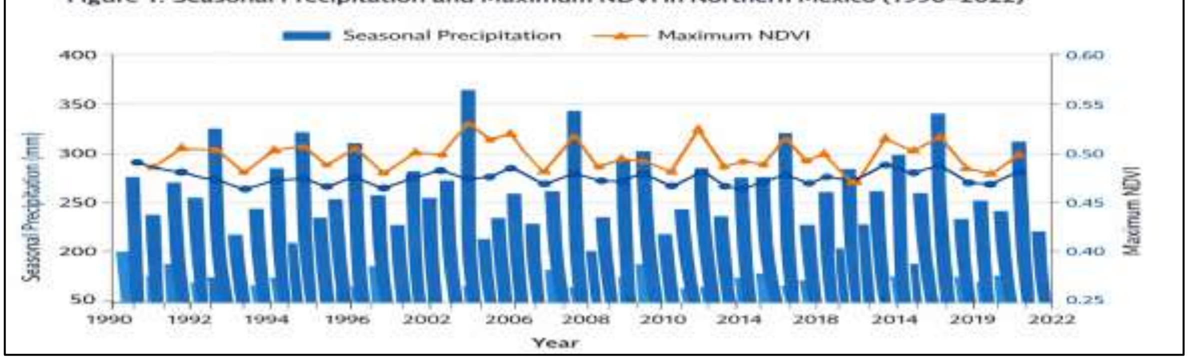
Region	**Average annual rainfall (mm)**	**CV precipitation (%)**	**Average temperature (°C)**	**Thermal trend (°C/decade)**
Chihuahua	312	41	17.8	+0.48
Coahuila	285	38	18.6	+0.44
Durango	410	31	16.9	+0.35
Zacatecas	360	34	17.2	+0.39
San Luis Potosí	455	28	18.1	+0.33

These results confirm that precipitation is the most variable and potentially limiting climatic factor for grassland productivity in Mexico.

4.2 Temporal dynamics of rangeland productivity

The NDVI time series showed a high correspondence with the variability of seasonal precipitation. In years with below-average rainfall, the seasonal maximum NDVI was reduced by 15% to 35%, depending on the region.

Figure 1. Seasonal Precipitation and Maximum NDVI in Northern Mexico (1990–2022)



(Line graph showing synchrony between dry years and steep declines in NDVI).

The average annual NDVI presented considerable interannual variability, with coefficients of variation between 18 % and 29 %, being higher in regions with lower average rainfall.

Table 2. Indicators of pasture productivity and stability

Region	Average annual NDVI	Seasonal Maximum NDVI	CV NDVI (%)
Chihuahua	0.29	0.42	29
Coahuila	0.27	0.40	27
Durango	0.35	0.48	22
Zacatecas	0.33	0.46	24
San Luis Potosí	0.38	0.51	18

4.3 Relationship between climate variability and pasture productivity

Correlation analyses revealed a positive and statistically significant relationship between seasonal precipitation and maximum NDVI ($r = 0.62–0.78$; $p < 0.01$). In contrast, mean temperature showed a moderate negative relationship with NDVI, particularly during dry years.

Regression models indicated that precipitation explained between 45% and 61% of the interannual variability of NDVI, while the inclusion of temperature marginally increased the explanatory power of the model.

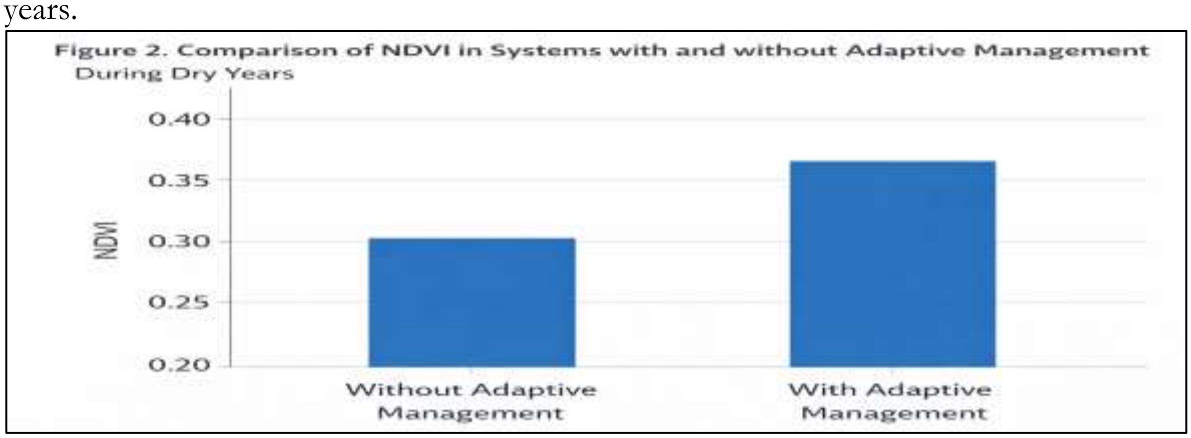
Table 3. Results of regression models between climate and NDVI

Explanatory variable	b	Standard Error	p-value
Seasonal precipitation	0.0038	0.0005	<0.001
Average temperature	-0.021	0.008	0.012
Model R^2	0.58	—	—

These results confirm that the productivity of Mexican grasslands is strongly conditioned by climatic variability, especially by the availability of water during the growing season.

4.4 Effect of adaptive management on production stability

When comparing systems with high and low levels of adaptive management adoption, significant differences in productivity stability were observed. Grasslands under adaptive management had more stable NDVI values and a lower reduction during severe dry years.



(Bar graph showing a smaller drop in NDVI in adaptive systems).

Table 4. Comparison of production stability according to type of management

Type of handling	NDVI medium	CV NDVI (%)	NDVI reduction in dry years (%)
Conventional	0.30	26	32
Adaptive	0.34	18	19

These results indicate that adaptive management strategies contribute to buffering the impacts of climate variability on rangeland productivity.

4.5 Qualitative results: local adaptive management practices

The qualitative analysis allowed us to identify four **main categories** of adaptive management:

1. Flexible adjustment of animal load, based on early observation of forage availability.
2. Rotation and strategic breaks, aimed at the recovery of vegetation cover.
3. Conservation of native perennial species, considered more resistant to drought.
4. Use of forage reserves, as a preventive measure against adverse climatic years.

Producers in regions with greater adoption of these practices reported greater resilience after severe droughts:

"When the rains are delayed, we lower the number of animals and let the pastures rest; so the grass comes back faster when it rains."

4.6 Integration of quantitative and qualitative results

The triangulation of results showed a high coherence between the patterns observed in the time series and the management practices reported by the producers. Regions with higher adoption of adaptive strategies showed lower year-on-year variability of NDVI and faster recovery after extreme dry events.

These findings support the hypothesis that adaptive management plays a key role in the resilience of Mexican grasslands to climate variability.

5. DISCUSSION

5.1 Climate variability as a dominant factor in rangeland dynamics

The results of this study confirm that climate variability, particularly that associated with seasonal precipitation, is the main factor controlling grassland productivity in arid and semi-arid regions of Mexico. The high interannual variability observed is consistent with previous studies that document a strong dependence of forage biomass on water availability during the growing season.

The magnitude of the correlations between precipitation and NDVI found in this work is consistent with research carried out in grasslands of northern Mexico, where it has been shown that even small negative precipitation anomalies can translate into substantial reductions in primary productivity. These results reinforce the idea that the productive stability of Mexican grasslands is inherently limited by the climatic regime, rather than by long-term linear trends.

5.2 Combined Effects of Temperature and Precipitation

While precipitation emerged as the main determinant of productivity, the moderate negative effect of mean temperature on NDVI suggests complex climate interactions. Increasing temperatures can intensify water stress by increasing evapotranspiration, reducing the efficiency of water use by vegetation.

This finding is particularly relevant in the Mexican context, where the thermal increase observed in recent decades coincides with a greater frequency of severe droughts. The combination of higher temperatures and variable rainfall can displace grasslands towards less productive and more vulnerable states, especially in regions with shallow soils and limited moisture-holding capacity.

5.3 Adaptive management and resilience of pastoral systems

One of the central contributions of this study is the empirical evidence that demonstrates that adaptive management strategies can partially mitigate the negative impacts of climate variability on rangeland productivity. Systems that incorporated dynamic adjustments of animal load, pasture rotation and resting periods had lower interannual variability of NDVI and less pronounced reductions during dry years.

These results coincide with the literature that suggests that flexibility in management is a key component of socio-ecological resilience. In the case of Mexico, where climatic conditions are highly unpredictable, the ability to modify management decisions based on early weather signals becomes crucial to avoid irreversible degradation processes.

5.4 Local knowledge as a strategic component of adaptation

The qualitative analysis showed that many of the adaptive management strategies observed are based on the local knowledge of the producers, developed from direct experience with climate variability. The coherence between the patterns detected in the time series and the practices reported by producers highlights the value of integrating local empirical knowledge with modern quantitative tools, such as remote sensing.

This integrative approach makes it possible to overcome the dichotomy between scientific knowledge and local knowledge, generating more relevant information for the design of public policies and rural extension programs aimed at adaptation to climate change.

5.5 Implications for management and public policy

The findings of this study have direct implications for the sustainable management of grasslands in Mexico. Evidence suggests that livestock policies should actively promote adaptive management practices, rather than rigid approaches based on fixed animal loads. Likewise, the incorporation of climate and vegetation monitoring systems in near real time could strengthen decision-making at the local and regional levels.

The integration of long-term climate information with management practices provides a solid basis for the development of adaptation strategies that are both ecologically viable and socially acceptable.

5.6 Limitations of the study and future lines of research

Despite its contributions, this study has some limitations. The availability of detailed information on management at the farm scale varied between regions, which could influence the accuracy of the classification of adaptive systems. Likewise, the use of NDVI as a productivity proxy, although widely validated, does not directly capture the nutritional quality of forage.

Future research could integrate more detailed field measurements, incorporate other vegetation indices, and extend the analysis to climate projection scenarios, in order to assess the sustainability of adaptive management strategies under future climate conditions.

6. CONCLUSIONS

The present study evaluated the impact of climate variability on grassland dynamics in Mexico and analyzed the effectiveness of adaptive management strategies by integrating extended time series and local management practices. The results obtained allow us to draw relevant conclusions from an ecological, productive and management perspective.

First, it is concluded that the interannual variability of precipitation constitutes the main factor that controls the productivity and stability of Mexican grasslands. The fluctuations in water availability during the growing season are directly reflected in the dynamics of the NDVI, confirming the high sensitivity of these ecosystems to climatic conditions, particularly in arid and semi-arid regions of the country.

Second, although precipitation explains the largest proportion of productive variability, the sustained increase in average temperature emerges as an additional stress factor that can amplify the negative effects of dry years. This result suggests that the interaction between temperature and precipitation represents an increasing risk to the sustainability of pastoral systems under continuous warming scenarios.

A central conclusion of the study is that adaptive management strategies implemented by livestock producers contribute significantly to increasing the resilience of grasslands to climate variability. Systems that dynamically adjust the animal load, incorporate pasture rotation and apply rest periods show greater productive stability and a lower reduction in biomass during adverse climatic events, compared to conventional management systems.

Likewise, the integration of quantitative information derived from remote sensing with the local knowledge of the producers allowed to evidence a high coherence between the ecological responses of the pastures and the management decisions. This finding highlights the importance of recognizing and strengthening local knowledge as a key component of climate adaptation strategies in the Mexican livestock sector.

From an applied perspective, the results of the study suggest that public policies and rangeland management programs in Mexico should prioritize flexible and adaptive approaches, supported by long-term climate and vegetation monitoring systems. The promotion of adaptive management practices can not only reduce the vulnerability of grasslands to climate variability, but also contribute to the economic sustainability of rural communities.

Finally, this study provides scientific evidence that reinforces the need to address pastoral systems as dynamic socio-ecological systems, where the interaction between climate, vegetation and human management determines the future trajectories of grasslands. The continuity of integrative research will be essential to strengthen the adaptive capacity of Mexican grasslands in the face of an increasingly variable climate.

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