Soil Structural Gradients as Drivers of Multiyear Spectral Variability: A Robust Framework for Management Zone Delineation in Heterogeneous Sugarcane Systems

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Abstract.

Persistent soil structural gradients are widely recognized as key drivers of spatial heterogeneity in perennial cropping systems. In the heterogeneous sugarcane production environments of northwestern Argentina (Salta and Jujuy provinces), contrasting sandy and clay-rich sectors generate long-term differences in crop growth potential and resource-use efficiency. Distinguishing stable edaphic influences from transient seasonal variability is essential for reliable precision management. This study evaluated whether multiyear spectral variability is primarily associated with underlying soil structural contrasts and assessed its potential for robust management zone delineation.

A total of 47 georeferenced sampling points distributed across five representative production areas were analyzed. Soil properties included texture fractions (sand, silt, clay), saturation water capacity, organic matter, total nitrogen, pH, and electrical conductivity. Multiyear Sentinel-2 imagery (2018–2025) was processed in Google Earth Engine to derive NDVI, EVI2, GNDVI, NDRE, NDWI, and SAVI indices. Spectral values were extracted during peak vegetative growth using cloud-masked seasonal composites to enhance cross-year comparability and minimize short-term atmospheric variability. Statistical analyses included Pearson correlation analysis ($p < 0.05$), Principal Component Analysis (PCA), and unsupervised k-means clustering ($k = 3$), with silhouette coefficients used to quantitatively validate management zone separability.

Persistent edaphic heterogeneity emerged as the dominant source of multiyear spectral variability. Significant positive correlations were observed between clay content, saturation water capacity, organic matter, and total nitrogen and vigor-related spectral indices ($r = 0.55–0.78$), whereas sand content showed consistent negative associations. PCA explained 80.4% of total variance within the first two components. The first component (64.0%) represented a structural soil gradient separating sandy environments from clay-rich, higher fertility zones and exhibited strong associations with EVI2 and NDRE, while the second component (16.4%) was primarily associated with NDWI, reflecting canopy water status dynamics.

Clustering analysis demonstrated clear environment separability, with NDRE presenting the *highest silhouette coefficient (0.63), followed by NDVI (0.60) and EVI2 (0.56). NDRE proved particularly robust for discriminating high-biomass environments, while EVI2 showed greater sensitivity to fertility-related soil attributes.*

These findings indicate that multiyear spectral variability in heterogeneous sugarcane systems is strongly associated with persistent soil structural gradients. The integration of soil attributes, multiyear satellite time series, and quantitative clustering validation provides a robust and operational framework for stable management zone delineation. This approach supports zone-specific soil sampling and more efficient fertilizer and irrigation allocation strategies in heterogeneous perennial cropping systems.

Keywords.
sugarcane, soil structural gradients, multiyear remote sensing, NDRE, management zones

Introduction

Sugarcane (Saccharum spp.) is one of the most important agroindustrial crops worldwide and represents a strategic component of the agricultural economy in northwestern Argentina, particularly in the provinces of Salta and Jujuy. Despite its economic relevance, sugarcane production systems in this region are characterized by pronounced environmental heterogeneity resulting from variations in soil texture, water retention capacity, organic matter content, nutrient availability, and landscape position. These factors generate persistent spatial differences in crop growth, resource-use efficiency, and productivity potential, even within relatively small geographic areas (Kitchen et al., 2003; Mulla, 2013).

In perennial and semi-perennial crops such as sugarcane, the identification of stable production environments is particularly important because management decisions often affect multiple ratoon cycles and may have long-term agronomic and economic consequences. However, conventional uniform management practices frequently overlook the intrinsic variability of production fields, leading to inefficient allocation of inputs, reduced profitability, and increased environmental risks. Consequently, the delineation of management zones has become a central component of precision agriculture strategies aimed at improving resource-use efficiency and supporting site-specific crop management (Doerge, 1999; Molin et al., 2015; Ali et al., 2024).

Management zones are commonly defined as relatively homogeneous areas that exhibit similar yield potential, soil characteristics, or crop responses through time. Their effectiveness depends largely on the temporal stability of the environmental factors controlling crop performance. Consequently, identifying persistent environmental gradients is essential to ensure that delineated zones remain operationally relevant and agronomically meaningful (Kitchen et al., 2003). Among these factors, soil structural attributes such as texture, saturation water capacity, and organic matter are particularly important because they are relatively stable over time and strongly influence crop water and nutrient dynamics (Webster and Oliver, 2007; Bramley et al., 2019).

The increasing availability of satellite remote sensing data has considerably expanded the capacity to characterize crop spatial variability at field and regional scales. Multispectral sensors such as Sentinel-2 provide repeated observations that enable the assessment of vegetation vigor, chlorophyll concentration, canopy function, and crop water status through spectral indices (Bégué et al., 2010; Miphokasap et al., 2012; Mulla, 2013). Among the most widely used indices, the Normalized Difference Vegetation Index (NDVI) has been extensively adopted as a general indicator of crop vigor and biomass accumulation. However, under high biomass conditions such as those commonly found in sugarcane, NDVI may exhibit saturation effects that reduce its sensitivity to differences among highly productive environments (Huete et al., 2002; Jiang et al., 2008). In contrast, red-edge-based indices such as the Normalized Difference Red Edge Index

(NDRE) and enhanced vegetation metrics such as the Enhanced Vegetation Index 2 (EVI2) have demonstrated greater sensitivity to chlorophyll concentration, nitrogen status, and canopy functioning under dense crop canopies (Jiang et al., 2008; Clevers and Gitelson, 2013; Li et al., 2022).

Although remote sensing has become increasingly integrated into precision agriculture workflows, relatively few studies have explicitly evaluated the extent to which persistent soil structural gradients control multiyear spectral variability in sugarcane production systems. Most previous research has focused on yield prediction, crop monitoring, or single-season analyses, limiting the ability to distinguish transient environmental effects from persistent soil-driven patterns. Consequently, the relationship between stable soil attributes and long-term spectral responses remains comparatively underexplored, particularly in subtropical sugarcane environments (Canata et al., 2021; De Oliveira Maia et al., 2023; De França e Silva et al., 2024). Furthermore, evidence linking detailed soil characterization with multiyear satellite-derived responses for operational management zone delineation remains limited. To our knowledge, no studies have integrated detailed soil characterization with multiyear Sentinel-2 time series to support management zone delineation across the heterogeneous sugarcane production systems of northwestern Argentina.

We hypothesized that persistent soil structural gradients constitute the primary drivers of multiyear spectral variability and that these stable soil–crop relationships can be translated into robust management zones for precision sugarcane management. Therefore, the objectives of this study were to (i) quantify the relationships between key soil properties and multiyear Sentinel-2 spectral indices, (ii) identify the dominant environmental gradients controlling crop spectral responses, and (iii) assess the potential of multiyear spectral information for management zone delineation in heterogeneous sugarcane systems. By integrating detailed soil characterization with multiyear satellite observations, this study proposes a robust and operational framework for transforming persistent environmental variability into actionable decision-support information for precision sugarcane management.

Materials and methods

The study was conducted across five representative sugarcane production areas located in the provinces of Salta and Jujuy, northwestern Argentina: Colonia Santa Rosa, El Tabacal, Urundel, Rodeito, and Los Manantiales (Figure 1). These locations encompass a broad range of environmental conditions representative of the principal sugarcane-producing regions of the Argentine subtropics.

The study area is characterized by marked environmental heterogeneity associated with variations in soil texture, organic matter content, water retention capacity, and nutrient availability. The regional climate is subtropical with a pronounced summer rainfall regime and a dry winter season, generating strong interactions between soil properties and crop water dynamics. Sugarcane production is concentrated in piedmont and transitional landscapes where sandy and clay-rich soils coexist over relatively short spatial distances, resulting in substantial variability in crop performance and productivity potential.

The selected sites were chosen to capture the dominant edaphic gradients present across the regional sugarcane production systems and to evaluate their influence on multiyear crop spectral responses.

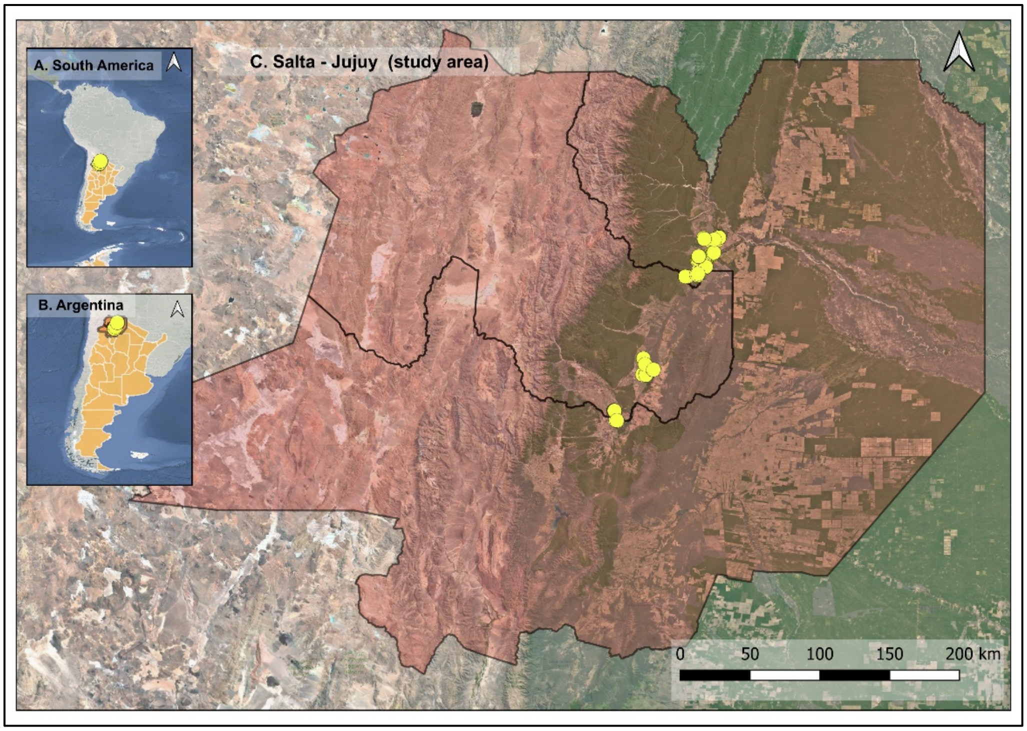

Figure 1. Geographic location of the study area and distribution of the 47 georeferenced sampling points across Salta and Jujuy provinces, northwestern Argentina.

Soil samples were collected using a helical auger at a depth of 0–40 cm, corresponding to the soil layer with the highest root activity and the greatest influence on water and nutrient availability for the crop. At each sampling point, the following soil physicochemical properties were determined: sand, silt, and clay content; saturation water capacity (SWC); pH; electrical conductivity (EC); organic matter (OM); total nitrogen (TN); C/N ratio; extractable phosphorus (P); and exchangeable potassium (K). These variables were selected due to their relevance for soil characterization, their influence on crop growth, and their relative temporal stability.

Spectral information was obtained from Sentinel-2 imagery processed using the Google Earth Engine (GEE) cloud-computing platform. Images acquired between 2018 and 2025 were analyzed to capture interannual variability and minimize the influence of conditions associated with any single growing season. The following spectral indices were calculated (Table 1): Normalized Difference Vegetation Index (NDVI), Enhanced Vegetation Index 2 (EVI2), Green Normalized Difference Vegetation Index (GNDVI), Normalized Difference Red Edge Index (NDRE), Normalized Difference Water Index (NDWI), and Soil Adjusted Vegetation Index (SAVI). These indices were selected because of their widespread use as indicators of vegetation vigor, chlorophyll concentration, nutritional status, and canopy water dynamics (Huete et al., 2002; Jiang et al., 2008; Clevers and Gitelson, 2013; Ali et al., 2024).

For each year, cloud-masked Sentinel-2 observations acquired during the main crop growth period (January–June) were used to generate seasonal median composites. The median statistic was selected to reduce the influence of residual cloud contamination, atmospheric noise, and anomalous observations while preserving representative spectral conditions for each growing season. Subsequently, annual composites were averaged across the 2018–2025 period to obtain multiyear spectral representations for each sampling location.

For each sampling point, multiyear spectral values were extracted from the resulting composites and used for subsequent statistical analyses.

Table 1. Spectral indices used in the study and their mathematical formulations.

Index	Abbreviation	Formula	Sentinel-2 Formula	Reference
Normalized Difference Vegetation Index	NDVI	(NIR − Red) / (NIR + Red)	(B8 − B4) / (B8 + B4)	Tucker (1979)
Enhanced Vegetation Index 2	EVI2	2.5 × (NIR − Red) / (NIR + 2.4 × Red + 1)	2.5 × (B8 − B4) / (B8 + 2.4 × B4 + 1)	Jiang et al. (2008)
Green Normalized Difference Vegetation Index	GNDVI	(NIR − Green) / (NIR + Green)	(B8 − B3) / (B8 + B3)	Gitelson and Merzlyak (1996)
Normalized Difference Red Edge Index	NDRE	(NIR − Red Edge) / (NIR + Red Edge)	(B8 − B5) / (B8 + B5)	Barnes et al. (2000)
Normalized Difference Water Index	NDWI	(NIR − SWIR) / (NIR + SWIR)	(B8 − B11) / (B8 + B11)	Gao (1996)
Soil Adjusted Vegetation Index	SAVI	[(NIR − Red) / (NIR + Red + L)] × (1 + L), L = 0.5	1.5 × (B8 − B4) / (B8 + B4 + 0.5)	Huete (1988)

Descriptive statistics were calculated for all soil variables and spectral indices. Pearson correlation analysis ($p < 0.05$) was used to evaluate relationships between soil properties and multiyear spectral responses. Principal Component Analysis (PCA) was performed using standardized variables to identify dominant environmental gradients and quantify the relative contribution of soil and spectral attributes to overall system variability. PCA has been widely applied in precision agriculture to reduce data dimensionality and characterize spatial variability within agricultural systems (Molin et al., 2015).

Management zones were delineated using unsupervised k-means clustering applied to multiyear spectral information. Three management classes (k = 3) were defined to represent low-, medium-, and high-potential production environments. This classification was selected because it provides an operationally practical representation of spatial variability and is commonly adopted in precision agriculture applications to support differential management strategies. Cluster separability and robustness were evaluated using silhouette coefficients, allowing comparison of the performance of different spectral indices for management zone delineation (Molin et al., 2015; Ali et al., 2024). The overall methodological workflow adopted in this study is summarized in Figure 2. Soil attributes and multiyear spectral responses derived from Sentinel-2 imagery were integrated through a cloud-based processing framework, followed by soil–spectral analysis and management zone delineation

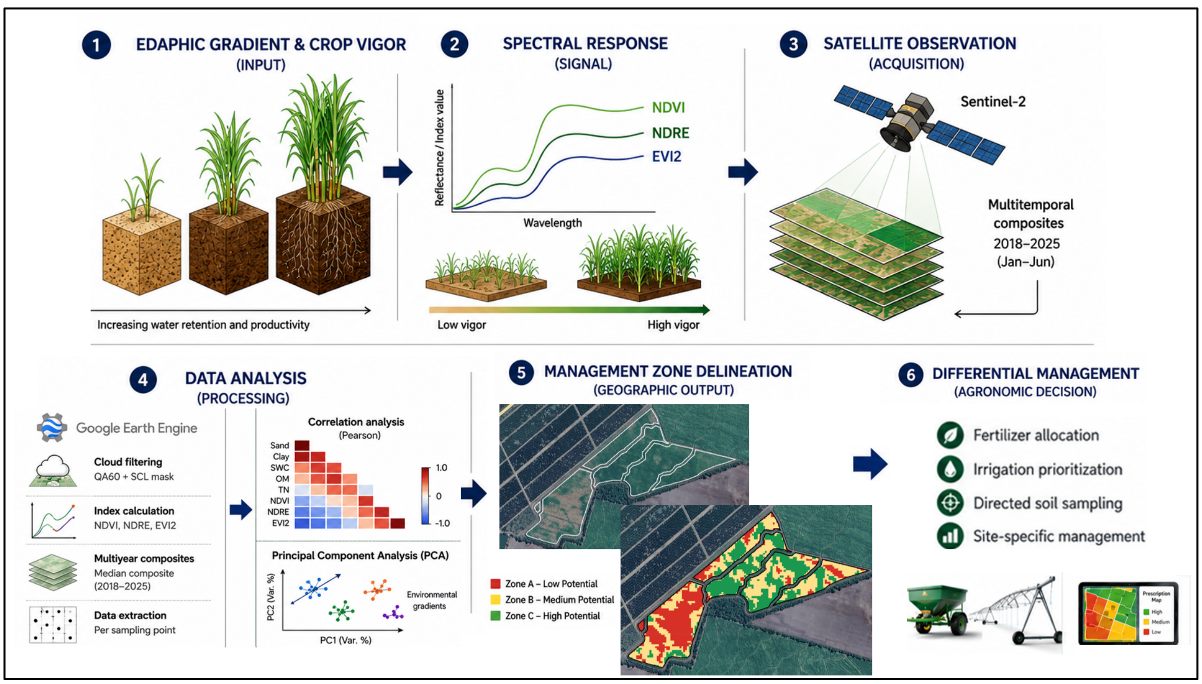

Figure 2. Operational framework linking soil structural variability, multiyear spectral responses, environmental characterization, and management zone delineation in heterogeneous sugarcane production systems.

Results

Soil and Spectral Variability

The analysis of soil properties revealed substantial environmental heterogeneity across the 47 sampling points (Table 2). Soil texture fractions exhibited the highest coefficients of variation, with values exceeding 50% for both sand (CV = 52.4%) and clay (CV = 52.6%), indicating the coexistence of environments with contrasting water-holding capacities. Similarly, organic matter (CV = 44.3%) and total nitrogen (CV = 42.3%) showed considerable variability, reflecting structural differences in nutrient availability among sites. Electrical conductivity showed the highest relative variability, suggesting the presence of localized salinity-related constraints.

In comparison, spectral indices displayed lower coefficients of variation (CV ranging from 12.4% to 17.4%), suggesting that multiyear satellite observations integrated environmental heterogeneity into a more stable representation of crop performance. Nevertheless, EVI2 and NDRE exhibited greater relative variability than NDVI, suggesting enhanced sensitivity to environmental differences under heterogeneous sugarcane conditions.

Table 2. Average, minimum, maximum values, and coefficient of variation (CV) of soil variables and spectral indices across 47 georeferenced sampling points

Variable	Average	Minimum	Maximum	CV (%)
Sand (%)	37.6	8.0	85.0	52.4
Silt (%)	39.2	12.0	61.0	29.3
Clay (%)	23.2	3.0	51.0	52.6
Saturation water capacity (SWC)	38.1	22.0	62.0	25.7
Organic matter (%)	1.89	0.64	4.35	44.3
Total Nitrogen (%)	0.11	0.03	0.26	42.3
Electrical conductivity (dS m^{-1})	0.56	0.16	1.18	46.0
NDVI	0.70	0.52	0.83	12.4
EVI2	0.47	0.33	0.62	17.4
NDRE	0.50	0.33	0.63	17.2
GNDVI	0.63	0.52	0.71	8.4

Relationships Between Soil Properties and Spectral Indices

Pearson correlation analysis revealed consistent relationships between soil properties and multiyear spectral responses (Table 3). Clay content, saturation water capacity, organic matter, and total nitrogen exhibited positive correlations with vegetation vigor indices, whereas sand content showed predominantly negative associations with most spectral variables. Among the evaluated soil properties, total nitrogen and organic matter displayed the strongest relationships with EVI2 (r = 0.59 and r = 0.57, respectively), while clay content and saturation water capacity were positively associated with NDVI, EVI2, and NDRE. These results indicate that environments characterized by greater water and nutrient retention capacity consistently exhibited stronger spectral responses and higher crop vigor. Electrical conductivity showed predominantly negative relationships with vegetation indices, suggesting potential constraints associated with soil salinity. Overall, the observed correlation patterns indicate that persistent soil structural and fertility-related properties exert a strong influence on multiyear crop spectral behavior and constitute important drivers of spatial variability within the evaluated sugarcane systems.

Table 3. Pearson correlation coefficients (r) describing the relationships among soil physical and chemical properties and spectral vegetation indices. Significance levels: * P < 0.05; ** P < 0.01

	Sand	Silt	Clay	SWC	pH	EC	OM	TN	NDVI	EVI2	GNDVI	NDWI	SAVI	NDRE
Sand	**1**													
Silt	-0.82**	1												
Clay	-0.84**	0.38**	1											
SWC	-0.85**	0.51**	0.90**	1										
pH	-0.61**	0.62**	0.39**	0.41**	1									
EC	-0.41**	0.30*	0.38**	0.43**	0.25	1								
OM	-0.54**	0.33*	0.55**	0.62**	0.01	0.11	1							
TN	-0.54**	0.35*	0.54**	0.61**	0.04	0.12	0.98**	1						
NDVI	-0.42**	0.14	0.55**	0.51**	0.20	0.27	0.54**	0.54**	1					
EVI2	-0.45**	0.23	0.52**	0.50**	0.23	0.31*	0.58**	0.59**	0.97**	1				
GNDVI	-0.42**	0.14	0.54**	0.52**	0.18	0.27	0.53**	0.52**	0.98**	0.92**	1			
NDWI	0.42**	-0.14	-0.54**	-0.52**	-0.18	-0.27	-0.53**	-0.52**	-0.98**	-0.92**	-1**	1		
SAVI	-0.45**	0.21	0.53**	0.51**	0.23	0.31*	0.57**	0.59**	0.98**	0.99**	0.93**	-0.93**	1	
NDRE	-0.41**	0.16	0.52**	0.48**	0.21	0.27	0.49**	0.50**	0.99**	0.95**	0.98**	-0.98**	0.96**	1

Principal Component Analysis

The Principal Component Analysis (Figure 3) explained 80.4% of the total variance within the first two components. The first principal component (PC1) accounted for 64.0% of the variance and showed positive loadings for sand (0.29) and negative loadings for clay (−0.32), SWC (−0.32), organic matter (−0.31), total nitrogen (−0.31), NDVI (−0.36), EVI2 (−0.35), NDRE (−0.35), and GNDVI (−0.35).

The second principal component (PC2) explained 16.4% of the variance and was associated with sand (0.43), clay (−0.34), SWC (−0.39), and the vegetation indices NDVI (0.34), EVI2 (0.31), and NDRE (0.37).

Overall, PC1 represented a persistent soil structural gradient separating sandy environments from clay-rich and more fertile areas, whereas PC2 captured secondary variability associated with crop functional responses.

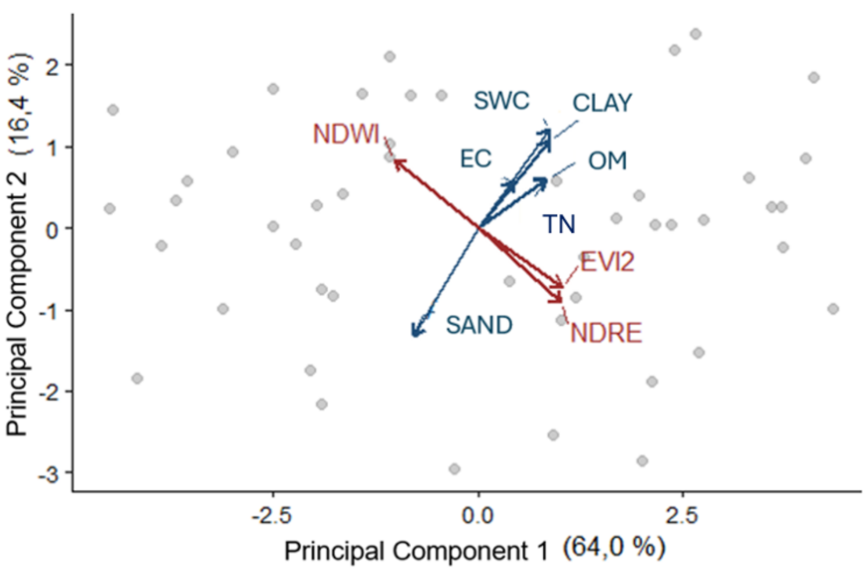

Figure 3. Principal component analysis of soil attributes and spectral indices used to identify dominant environmental gradients across the evaluated sugarcane production systems.

Management zones were delineated using k-means clustering (k = 3), and cluster separability was evaluated through the silhouette index. NDRE exhibited the highest separability value (0.63), followed by NDVI (0.60) and EVI2 (0.56).

Collectively, the statistical analyses revealed substantial regional soil variability, significant relationships between soil properties and spectral indices, differences in the explanatory power of the evaluated indices, the presence of dominant environmental gradients identified through multivariate analysis, and a high capacity of NDRE to discriminate management environments.

Management zone delineation based on multiyear spectral information revealed clear differentiation among production environments. The comparison of silhouette coefficients showed that NDRE provided the highest cluster separability (0.63), followed by NDVI (0.60) and EVI2 (0.56), indicating superior performance for distinguishing relatively homogeneous management environments under dense sugarcane canopies. The greater separability achieved by NDRE likely reflects its enhanced sensitivity to chlorophyll concentration and nitrogen-related variability, whereas NDVI may be partially affected by saturation effects under high biomass conditions. Although EVI2 exhibited slightly lower silhouette values, it remained useful for characterizing functional crop responses and environmental contrasts. The resulting management zones identified low-, medium-, and high-potential production environments that were spatially associated with contrasting soil conditions, particularly differences in texture, saturation water capacity, and fertility attributes. The spatial consistency of these zones supports the use of multiyear spectral information as a practical tool for identifying relatively stable production environments and guiding site-specific management strategies within heterogeneous sugarcane production systems.

Discussion

The results demonstrate that spatial variability in sugarcane production systems of northwestern Argentina is primarily driven by persistent soil structural gradients, particularly those associated with soil texture, water-holding capacity, and organic fertility. This finding is consistent with previous studies conducted in sugarcane-growing regions of Brazil and Australia, where soil-related factors have been shown to explain a larger proportion of yield variability than short-term management practices (Kitchen et al., 2003; Bramley et al., 2019; Webster & Oliver, 2007).

The positive relationships observed between clay content, saturation water capacity, and vigor-related spectral indices indicate that long-term differences in water availability play a central role in determining crop performance. These results agree with previous research showing that multitemporal vegetation indices integrate the cumulative effects of soil and water limitations on crop growth and productivity (Canata et al., 2021; de França e Silva et al., 2024). Under heterogeneous production environments such as those found in Salta and Jujuy, areas with greater clay content and water storage capacity consistently exhibited higher spectral responses, reflecting superior crop development and resource-use efficiency.

Among the evaluated indices, EVI2 showed the strongest associations with organic matter and total nitrogen, suggesting a greater capacity to capture crop functional responses associated with soil fertility. This behavior is consistent with previous studies reporting that EVI2 is less prone to saturation and maintains higher sensitivity than NDVI under dense canopies and high biomass conditions, which are characteristic of commercial sugarcane production systems (Huete et al., 2002; Jiang et al., 2008; de Oliveira Maia et al., 2023).

NDRE, in contrast, exhibited the highest capacity to discriminate management environments, as indicated by the silhouette analysis. This result is supported by the physiological basis of red-edge vegetation indices, which are particularly sensitive to variations in chlorophyll concentration and crop nutritional status under high biomass conditions (Clevers and Gitelson, 2013). Similar findings have been reported in sugarcane and other perennial cropping systems, where NDRE consistently outperformed NDVI for distinguishing productivity gradients and identifying management zones (De Oliveira Maia et al., 2023; Li et al., 2022).

The PCA results further reinforce the hypothesis that multiyear spectral variability is largely controlled by persistent soil structural factors. The first principal component, which explained 64% of the total variance, represented a clear gradient from sandy environments with lower water and nutrient retention capacity to clay-rich environments characterized by higher fertility and stronger spectral responses. The dominance of this component suggests that stable edaphic conditions exert a greater influence on long-term crop performance than seasonal fluctuations, highlighting their importance for precision management strategies. Together, these results indicate that long-term crop spectral behavior is strongly conditioned by persistent edaphic variability.

Overall, the evidence supports a complementary use of spectral indices for site-specific management applications. NDRE appears to be the most suitable index for management zone delineation due to its superior discriminatory capacity, whereas EVI2 provides valuable information regarding crop functional performance and potential responsiveness to nutrient management. The integration of both indices with soil information offers a robust framework for precision agriculture and site-specific management in heterogeneous sugarcane production systems, contributing to more efficient allocation of inputs and improved resource-use efficiency (Mulla, 2013; Ali et al., 2024).

An important contribution of this study is the use of multiyear satellite information rather than single-date imagery. Crop responses observed during a particular growing season are often influenced by short-term climatic conditions, management practices, and transient environmental factors. By integrating observations across multiple years, the influence of seasonal variability is reduced and persistent spatial patterns become more evident. This approach is particularly relevant for sugarcane because management decisions frequently affect several ratoon cycles and therefore require information that remains consistent through time. Recent precision agriculture studies have highlighted the importance of temporal stability for management zone delineation, emphasizing that spatial patterns must persist across years in order to support long-term site-specific management strategies (Ali et al., 2024).

From a precision agriculture perspective, the integration of soil characterization, multiyear Sentinel-2 imagery, and quantitative clustering validation provides a practical framework for management zone delineation in heterogeneous sugarcane systems. Unlike approaches based exclusively on yield maps or single-season imagery, the proposed methodology relies on environmental attributes and spectral responses that exhibit greater temporal persistence. This increases the likelihood that delineated zones remain relevant across multiple production cycles and can therefore support long-term management planning. Furthermore, the use of freely available satellite imagery and cloud-based processing platforms enhances the scalability and accessibility of the proposed framework, facilitating its implementation across a wide range of production environments.

The operational implications of these findings are particularly relevant in commercial sugarcane systems where environmental heterogeneity frequently limits the effectiveness of uniform management practices. The resulting management zones may support more efficient soil sampling strategies, improve fertilizer allocation, prioritize irrigation management, facilitate crop monitoring activities, and contribute to the gradual adoption of site-specific management practices. In this context, the proposed framework provides a mechanism for translating persistent soil variability into actionable spatial information capable of supporting agronomic decision-making at both field and regional scales.

Although the proposed methodology demonstrated strong potential for management zone delineation, some limitations should be acknowledged. The study focused primarily on relationships between soil properties and spectral responses and did not incorporate direct yield measurements or economic analyses. Future research should evaluate the temporal stability of the delineated zones under contrasting climatic conditions and assess their impact on productivity, resource-use efficiency, and economic returns under commercial production scenarios. Nevertheless, the results demonstrate that persistent soil variability can be effectively captured through multiyear spectral information and transformed into robust management zones, providing a valuable foundation for precision sugarcane management.

Conclusions

1. Persistent soil structural gradients were identified as the dominant drivers of multiyear spectral variability in the evaluated sugarcane production systems.
2. NDRE showed the highest management zone separability and therefore the greatest potential for delineating relatively homogeneous production environments under dense sugarcane canopies.
3. EVI2 provided complementary information associated with soil fertility and crop functional performance, improving environmental characterization.
4. The integration of soil properties, multiyear Sentinel-2 imagery, and clustering analysis enabled the delineation of robust management zones suitable for site-specific management.
5. The proposed framework represents a scalable and operational approach for translating persistent soil variability into decision-support information for precision sugarcane management.

Practical Implications

Operational Management Zone Delineation

The results suggest that multitemporal spectral indices, particularly NDRE, can be used to identify relatively stable management zones within sugarcane fields and farms. Such zonation may serve as a preliminary framework for organizing spatial variability, prioritizing intervention areas, and guiding targeted soil and crop sampling efforts, thereby improving diagnostic efficiency while reducing monitoring costs.

Prioritization of Nitrogen Management Strategies

The observed relationships between EVI2 and soil fertility attributes indicate that this index may provide useful information for ranking production environments according to their functional performance. Following further validation, EVI2-based assessments could support the development of differential nitrogen management strategies aimed at improving nitrogen-use efficiency and reducing unnecessary fertilizer applications in low-response environments.

Supporting the Adoption of Site-Specific Management

The proposed methodology, based on freely available satellite imagery, cloud-based geospatial processing, and soil validation, offers an accessible technical framework for advancing site-specific management in the sugarcane-producing regions of northwestern Argentina. Its gradual implementation, combined with local validation trials and economic assessments, could facilitate adoption by growers and sugar mills while supporting evidence-based decision-making and more sustainable resource management.

Integration into Commercial Decision-Making

The proposed workflow can be integrated into commercial sugarcane management through GIS layers, directed sampling schemes, and prescription maps for fertilization and irrigation. Because it relies on freely available Sentinel-2 imagery and cloud-based processing platforms, the methodology represents a scalable and cost-effective approach that can be adopted by growers, sugar mills, and technical advisory services. Consequently, the framework provides a practical pathway for transforming environmental variability into actionable decision-support information within precision sugarcane production systems.

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