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Original Article

Soil physical attributes for discriminating soybean yield-based management zones[1]

Atributos físicos do solo que discriminam zonas de manejo associadas à produtividade da soja

Lourenço Q. Scalon[2], Diandra P. D. Flora[2], Jorge W. Cortez[2*], Michely Tomazi[3], Dario A. Schwambach[2]

[1] Research developed at Universidade Federal da Grande Dourados, Dourados, MS, Brazil
[2] Universidade Federal da Grande Dourados, Dourados, MS, Brazil
[3] Embrapa Agropecuária Oeste, Dourados, MS, Brazil

HIGHLIGHTS:

Clay, silt, organic matter, water-dispersible clay, and microporosity define high-yield zones.
Sand content, bulk density, and depth to maximum penetration resistance define low-yield zones.
Multivariate analysis and fuzzy indices delineate two management zones.

ABSTRACT: This study aimed to identify soil physical attributes most effective in discriminating management zones associated with soybean yield across three consecutive growing seasons. The research was conducted on a commercial farm managed under a long-term no-tillage system for more than 30 years, using a 73-point georeferenced sampling grid. Soil attributes analyzed included clay, silt, sand, microporosity, aggregate stability index, organic matter, bulk density, degree of flocculation, mean weight diameter of aggregates, depth to maximum penetration resistance, and water-dispersible clay. Soybean yield data were obtained from a calibrated yield monitor installed on a combine harvester. Data analysis involved geostatistical procedures and spatial interpolation using ordinary kriging, followed by delineation of two management zones based on the Fuzzy performance index and Normalized classification entropy. Integration of soil physical attributes with multi-season yield data proved effective and reliable for defining management zones. The high-yield zone was characterized by higher clay and silt contents, organic matter, water-dispersible clay, and microporosity, which showed positive correlations with yield. In contrast, higher sand content and greater depth to maximum penetration resistance were associated with the low-yield zone and exhibited negative correlations with soybean yield. These results indicate that combining soil physical properties with multitemporal yield data enables identification of consistent spatial patterns, supporting development of site-specific management strategies in soybean production systems.

Key words: *Glycine max*, precision agriculture, site-specific management, geostatistics

RESUMO: Este estudo objetivou avaliar os atributos físicos do solo mais eficazes para discriminar zonas de manejo associadas à produtividade da soja ao longo de três safras consecutivas. A pesquisa foi conduzida em uma fazenda comercial sob sistema de plantio direto por aproximadamente 30 anos, utilizando uma malha amostral de 73 pontos. Os atributos analisados incluíram argila, silte, areia, microporosidade, índice de estabilidade de agregados, matéria orgânica, densidade do solo, grau de floculação, diâmetro médio ponderado dos agregados, profundidade de máxima resistência à penetração e argila dispersa em água. Os dados de produtividade foram obtidos por meio de um monitor de colheita calibrado instalado em colhedora. A análise envolveu geoestatística e interpolação espacial por krigagem ordinária, seguida da delimitação de zonas de manejo com base no Índice de desempenho fuzzy e na Entropia de classificação normalizada. A integração entre atributos do solo e produtividade multissazonal mostrou-se eficaz e consistente na definição de zonas de manejo. A zona de alta produtividade foi caracterizada por maiores teores de argila e silte, matéria orgânica, argila dispersa em água e microporosidade, os quais apresentaram correlações positivas com a produtividade. Em contraste, areia e profundidade da resistência à penetração foram associados à zona de baixa produtividade, exibindo correlações negativas com a produtividade da soja. Esses resultados indicam que a integração entre propriedades físicas do solo e dados multitemporais de produtividade contribui para a identificação de padrões espaciais consistentes, auxiliando a definição de estratégias de manejo localizado em sistemas de produção de soja.

Palavras-chave: *Glycine max*, agricultura de precisão, manejo localizado, geoestatística

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* Corresponding author - E-mail: jorgewcortez@gmail.com
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Introduction

Soybean (*Glycine max* L. Merr.) is one of the most important crops in global agribusiness, with Brazil ranking among the world's leading producers and exporters. In the 2023–2024 growing season, Brazilian production exceeded 150 million tons, underscoring economic and strategic importance of this legume to the country (CONAB, 2024). Despite this impressive performance, soybean yield remains constrained by spatial variability of soil and climatic factors, which highlights need for more efficient and sustainable management practices (Moraes et al., 2020; Crespo et al., 2021).

Precision agriculture has emerged as a strategic approach for characterizing spatial and temporal variability of soil, crop, and environmental attributes, thereby enabling definition of site-specific management units within agricultural fields (Molin & Gimenez, 2005; Delalibera et al., 2012; Pereira et al., 2022). Delineation of management zones (MZs) is based on the premise that different areas within a field respond unequally to agricultural inputs. Consequently, identification of soil attributes most strongly associated with yield variability becomes essential. Recent studies indicate that integrating geostatistical and multivariate analyses, such as principal component analysis (PCA) and ordinary kriging, enhances accuracy of MZ delineation (Oliveira et al., 2021; Silva Júnior et al., 2025).

Technological advances have further expanded scope of precision agriculture through incorporation of low-cost sensors, unmanned aerial vehicles (UAVs), multispectral imagery, machine-learning algorithms, and open-source geoprocessing platforms such as QGIS. For example, the Smart-Map plugin enables integration of spatial interpolation and multivariate statistics, contributing to more robust MZ delineation (Oliveira et al., 2021; Pereira et al., 2022). Digital tools have improved integration and analysis of agricultural datasets (Silva & Espejo, 2024; Carvalho et al., 2025); however, limitations related to data availability, cost, and operational feasibility still restrict their widespread adoption in commercial farming systems (Silveira et al., 2023). As a result, field-based soil measurements and yield data remain central to characterization of spatial variability and delineation of management zones.

Within this context, accurate identification of soil attributes that most influence soybean yield is fundamental for achieving consistent and effective MZ delineation (Faé et al., 2020; Bocuti et al., 2021; Silva Júnior et al., 2025). Nevertheless, few studies have evaluated this relationship through integration of soil physical attributes with multi-season yield data to generate stable management zones in long-term no-tillage systems, particularly under tropical soil conditions. Furthermore, application of objective criteria such as the Fuzzy Performance Index (FPI) and Normalized Classification Entropy (NCE) to support zone delineation remains limited. Therefore, this study aimed to determine which soil physical attributes are most effective in identifying management zones associated with soybean yield across three consecutive cropping seasons.

Material and Methods

The study was conducted on a commercial farm located in the municipality of Ponta Porã, Mato Grosso do Sul State, Brazil (Figure 1). The area has been managed under rainfed conditions using a no-tillage system for more than 30 years, with soybean as the main summer crop and maize cultivated as a second crop in most growing seasons. The site is located

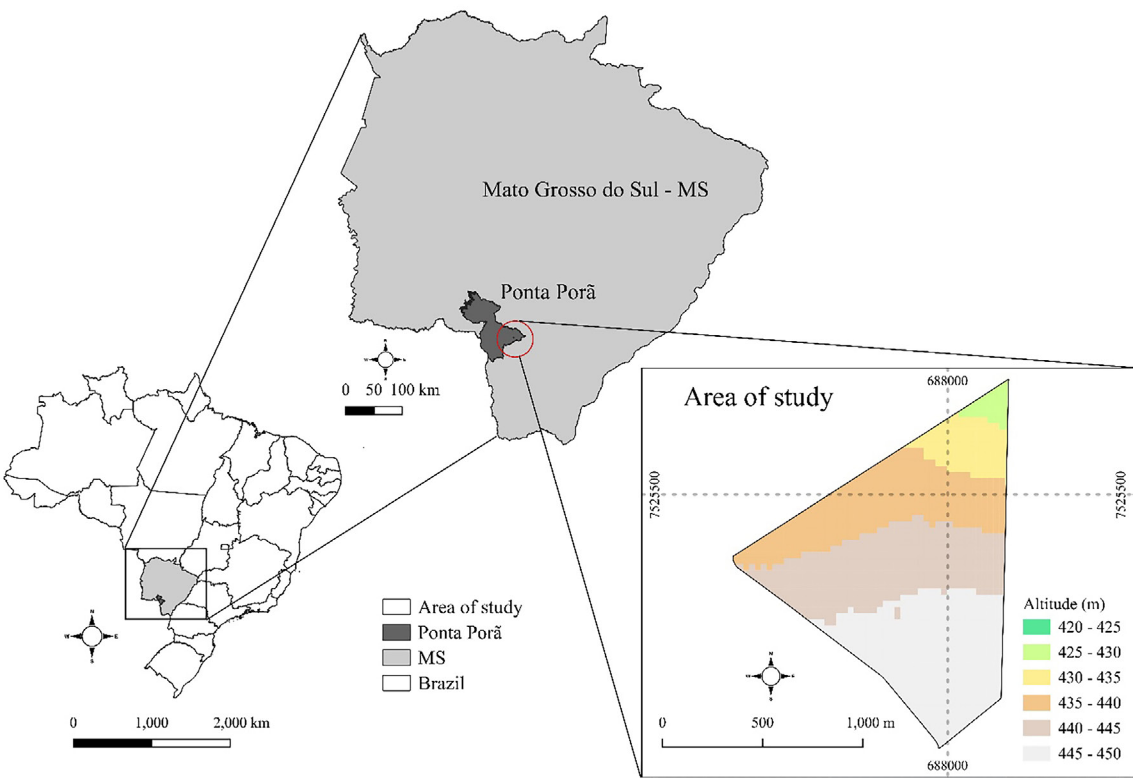


Figure 1. Location map and elevation distribution of the study area

at 22° 22′ S latitude and 55° 10′ W longitude, covering 131.32 ha, with a mean altitude of 440 m (ranging from 424 to 446 m) and an average slope of 1.34%.

Climate is classified as Cwa (humid subtropical with dry winters), according to the Köppen classification. Cumulative precipitation recorded on-site during November, December, January, and February totaled 665 mm in the 2019–2020 season, 600 mm in 2020–2021, and 220 mm in 2021–2022. The soil is classified as a dystrophic Red Latosol according to the Brazilian Soil Classification System - SiBCS (Santos et al., 2025), with a clayey texture and an average clay content of 43%.

For spatial characterization of soil physical attributes, a sampling grid consisting of 60 regularly spaced points was established, with one sampling point allocated every 2.0 ha (143.61 × 143.61 m). In addition, 13 supplementary points, representing approximately 20% of the original grid (Comparin & Cortez, 2023), were randomly distributed based on spatial variability observed in maize and soybean yield maps from the 2018 and 2019 growing seasons. As a result, the final sampling grid comprised 73 points, corresponding to a sampling density of one point per 1.8 ha (Figure 2).

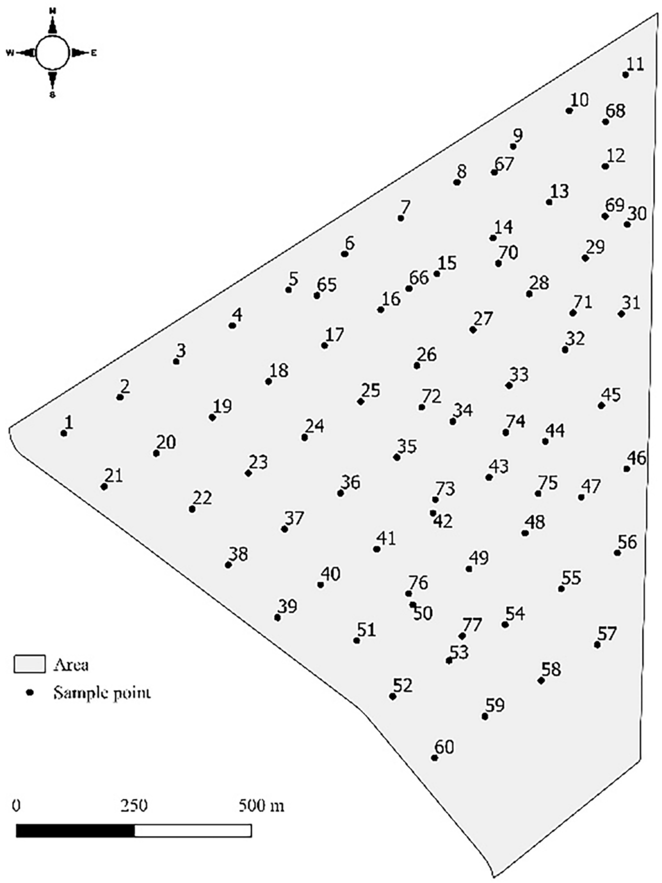


Figure 2. Spatial distribution of the soil sampling grid

Soil samples were collected in 2019 from the 0–0.20 m soil layer to determine particle-size distribution (sand, silt, and clay), aggregate stability index (ASI), degree of flocculation (DF), mean weight diameter of aggregates (MWD), water-dispersible clay (WDC), and organic matter (OM). For these attributes, five subsamples were collected at each sampling point. Bulk density (Bd) and microporosity (Mi) were determined by using three subsamples per point. All soil samples were air-dried and analyzed following procedures described by Teixeira et al. (2017).

Depth to maximum penetration resistance (PRD) was measured in the 0–0.40 m soil layer using five subsamples per sampling point. Measurements were obtained with an electronic penetrometer (SoloStar, Falker, Brazil; model PLG5500) mounted on an all-terrain vehicle (ATV) and equipped with a type-2 rod and type-2 cone (30° cone angle), operating at a constant penetration rate of approximately 30 mm s^{-1}. At the time of measurement, gravimetric soil moisture averaged 269.8 g kg^{-1}.

Soybean sowing during the 2019–2020, 2020–2021, and 2021–2022 growing seasons followed seeding rates and input management practices described in Table 1. Although cultivar and planting density varied among growing seasons, management practices were uniform within each season across the entire study area. Consequently, their influence on within-field yield variability was minimized, and observed spatial patterns were primarily associated with soil physical attributes and their interaction with seasonal conditions.

Yield data were collected over three consecutive growing seasons (2019–2020, 2020–2021, and 2021–2022) using combine harvesters equipped with mass-flow sensors, yield monitors, and GPS receivers operating at a 1 s logging interval. Raw yield data were initially filtered to remove outliers, such as zero values and unrealistically high observations. This filtering procedure also excluded non-representative data associated with harvester maneuvering, sensor instability, and field border effects. In addition, spatially isolated yield values inconsistent with neighboring observations were removed prior to geostatistical analysis.

Geostatistical analyses of soil physical attributes and soybean yield were performed exclusively to support the delineation of management zones (MZs). For each variable, semivariograms were computed and fitted to theoretical models, including spherical, exponential, and Gaussian models. Model selection was based on the lowest residual sum of squares and the highest coefficient of determination (R^2), followed by validation through cross-validation. Model adequacy was assessed using the slope of the cross-validation regression, seeking values closest to 1, along with the lowest root mean square error (RMSE). Ordinary kriging was

Table 1. Agricultural inputs used for soybean sowing during the 2019–2020, 2020–2021, and 2021–2022 growing seasons

Growing season	Soybean cultivar	Seeding density (seeds m^{-1})	Fertilization	Fertilization Fertilizer dose (kg ha^{-1})	Application method
2019-2020	Bmx Potência	14.3	NPK 02-23-23	300	In-row
2020-2021	Bmx Fibra	14.5	NPK 02-23-23	320	In-row
2021-2022	Bmx Fibra	15.8	NPK 02-23-23	310	In-row

applied using selected model parameters, including nugget effect, sill, and range. Spatial interpolation was performed on a regular grid with a 10 × 10 m cell size using the WGS 84 / UTM zone 21S coordinate reference system (EPSG:32721).

Management zones (MZs) were delineated using a clustering approach based on soil physical attributes and multi-season soybean yield data. Yield data from each growing season were incorporated individually into the analysis, with each season treated as an independent variable. Thus, MZ delineation considered yield information from the three growing seasons in combination with soil physical attributes. Clustering was performed using a fuzzy classification algorithm implemented in the Smart-Map plugin (Pereira et al., 2022) within the QGIS environment. Interpolated datasets were processed using the MZs module, which applies multivariate statistics to identify spatial clusters. The number of clusters was evaluated across a predefined range, and the optimal number of MZs was determined primarily based on combined analysis of the Fuzzy performance index (FPI) and Normalized classification entropy (NCE), seeking minimum values for both indices while ensuring practical interpretability of the resulting zones. The delineation process was conducted using 100 iterations and a fuzzy exponent of 1.25, as recommended in the plugin documentation. Both geostatistical modeling and spatial interpolation by ordinary kriging were performed using the Smart-Map plugin (Pereira et al., 2022) within the open-source QGIS platform, version 3.34 (QGIS, 2024).

After MZ delineation, soil physical attributes, and soybean yield from the three growing seasons were analyzed within each zone to compute mean, standard deviation, and coefficient of variation. Differences in soil attributes and yield between management zones were evaluated using one-way analysis of variance (ANOVA), with MZs considered the independent factor and soil attributes and soybean yield as dependent variables. When significant differences were detected, mean comparisons were performed using Tukey's test at $p \leq 0.05$.

Principal component analysis (PCA) was applied to investigate relationships among soil physical attributes and soybean yield by summarizing the variance–covariance structure of the original variables into a reduced set of orthogonal components (Hair, 2005). Prior to PCA, all variables were standardized to zero mean and unit variance. Components with eigenvalues greater than 1 were retained, and the first two principal components were selected for interpretation based on their proportion of explained variance. A two-dimensional biplot was generated to visualize relationships among variables and clustering patterns.

Pearson correlation analysis was conducted to quantify relationships between soil physical attributes and soybean yield for each growing season (2019–2020, 2020–2021, and 2021–2022). Correlation strength and direction were evaluated using the Pearson correlation coefficient (r), and results were subsequently used to support interpretation of management zone delineation and to complement multivariate analyses.

The adopted methodology is consistent with recent national and international studies that integrate multivariate statistical approaches with precision agriculture techniques for MZ delineation (Oliveira et al., 2021; Torres et al., 2022; Carvalho et al., 2025).

Results and Discussion

Management Zone delineation based on soil physical attributes and soybean yield resulted in the lowest values of the Fuzzy Performance Index (FPI) and Normalized Classification Entropy (NCE) when two zones were defined (0.087 and 0.110, respectively; Figure 3A). For configurations with a greater number of classes, both indices increased, indicating that the two-zone solution was the most appropriate for the study area. The resulting MZs were represented as polygons across the field (Figure 3B), revealing a clear spatial division, with Zone 1 (Z1) occupying the western portion and Zone 2 (Z2) covering the eastern portion. In terms of area, Z1 encompassed approximately 66.895 ha, whereas

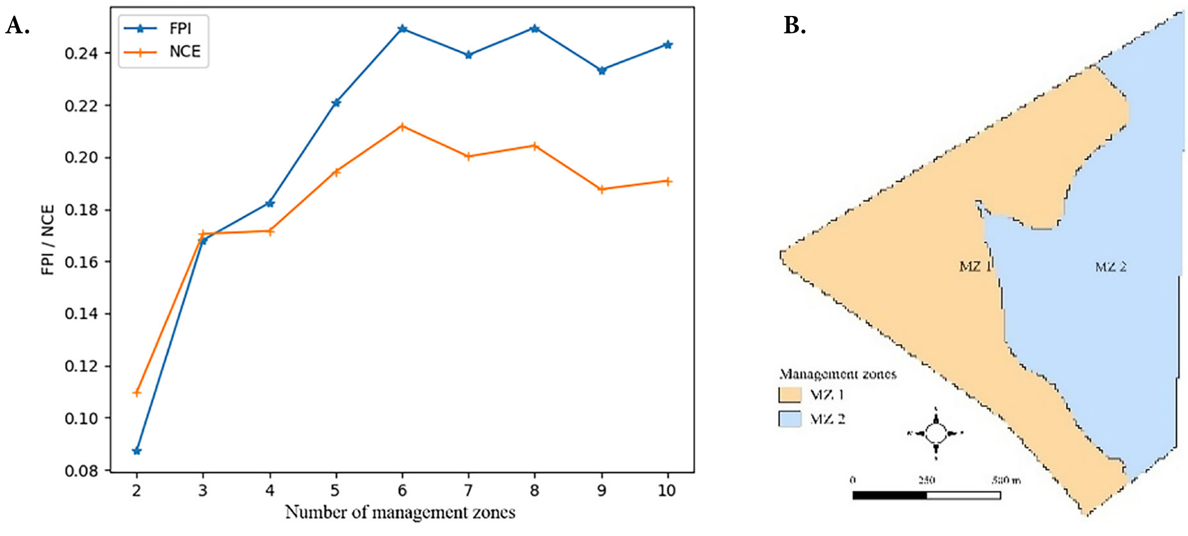


Figure 3. Fuzzy performance index (FPI) and Normalized classification entropy (NCE) values used to evaluate management zone delineation (A) and resulting management zones (B)

Z2 accounted for about 64.425 ha. Similar spatial patterns were reported by Guimarães et al. (2024) and Carvalho et al. (2025), who also observed marked contrasts in soybean yield and other crops associated with soil textural variation and compaction under long-term no-tillage systems.

Once MZs were defined, soil physical attributes were evaluated within each zone (Table 2). Descriptive analysis revealed clear contrasts among MZs that directly reflected observed yield patterns. Zone 1 (Z1), associated with higher soybean yields, exhibited greater clay (524.94 g kg^{-1}) and silt (143.53 g kg^{-1}) contents, as well as higher values of water-dispersible clay (WDC), organic matter (OM), and microporosity (Mi). These attributes indicate soils with greater water-holding capacity and structural stability, providing a physical environment more favorable for root development and microbial activity and, consequently, improved soybean agronomic performance (Moraes et al., 2020; Oliveira et al., 2021).

These findings are consistent with correlation analysis, which revealed negative associations between soybean yield and sand content, Bd, DF, and PRD. Conversely, clay, silt, organic matter, microporosity, and water-dispersible clay showed positive correlations with yield, confirming their relevance in defining productive soil environments favorable for soybean cultivation.

Higher aggregate stability index (ASI) values observed in Z1 indicate a greater degree of soil aggregate stability in this zone. According to Alho et al. (2014) and Ghosh et al. (2020), soils with higher aggregate stability are less susceptible to compaction and erosion and tend to exhibit improved infiltration and aeration. Microporosity, which is closely related to plant-available water retention, was among the attributes showing the strongest positive correlations with yield across all growing seasons, underscoring its importance in maintaining crop resilience under water-deficit conditions (Fu et al., 2019; Wulanningtyas et al., 2021). Comparable results were reported by Choudhary et al. (2018), who observed that increased microporosity is directly associated with improved soil moisture retention and enhanced gas exchange.

In contrast, Zone 2 (Z2) exhibited higher sand content (561.38 g kg^{-1}), bulk density (Bd; 1.56 kg dm^{-3}), degree of flocculation (DF), and depth to maximum penetration resistance (PRD). These characteristics can restrict root development, reduce the effective soil volume explored by roots, and limit water and nutrient uptake. Elevated Bd and a deeper compacted layer indicate potential physical constraints to root system expansion, as also reported by Moraes et al. (2014) and Faé et al. (2020), which likely contributed to the lower yields observed in Z2.

Descriptive statistics of soybean yield within each MZ revealed a clear differentiation between production environments. Zone 1 (Z1) consistently exhibited higher productivity and was therefore classified as the high-yield zone, whereas Zone 2 (Z2) represented the low-yield zone (Table 3). Across the three evaluated growing seasons (2019–2020, 2020–2021, and 2021–2022), Z1 maintained

Table 2. Descriptive statistics and ANOVA results for soil physical attributes by soil layer within each management zone

Attribute	Zone 1	Zone 2	Zone 1	Zone 2	ANOVA	
	Mean ± Standard deviation		Coefficient of variation (%)		F	P
Sand (g kg^{-1})	331.53 ± 61.29 b	561.38 ± 95.75 a	18.49	17.06	141.97**	< 0.001
Clay (g kg^{-1})	524.94 ± 51.52 a	348.54 ± 68.77 b	9.82	19.73	148.29**	< 0.001
Silt (g kg^{-1})	143.53 ± 16.94 a	90.07 ± 29.94 b	11.81	33.24	83.09**	< 0.001
WDC (%)[1]	11.63 ± 3.16 a	6.23 ± 2.17 b	27.15	34.90	74.45**	< 0.001
Mi (%)[2]	38.69 ± 2.18 a	33.53 ± 2.73 b	5.64	8.15	77.01**	< 0.001
ASI (%)[3]	87.23 ± 2.87 a	80.44 ± 9.33 b	3.29	11.59	16.22**	< 0.001
OM (g kg^{-1})[4]	25.49 ± 2.57 a	19.70 ± 2.53 b	10.25	13.02	90.68**	< 0.001
PRD (cm)[5]	21.21 ± 3.58 b	24.74 ± 3.87 a	16.89	15.65	16.09**	< 0.001
Bd (kg dm^{-3})[6]	1.42 ± 0.07 b	1.56 ± 0.07 a	4.69	4.60	72.55**	< 0.001
DF (%)[7]	78.11 ± 4.64 b	82.36 ± 4.19 a	5.94	5.09	16.84**	< 0.001
MWD (mm)[8]	3.79 ± 0.32 a	3.44 ± 0.59 b	8.49	17.06	8.95**	0.004

Different letters indicate significant differences between management zones according to Tukey's test (p ≤ 0.05). [1]WDC - Water-dispersible clay; [2]Mi - Microporosity; [3]ASI - Aggregate stability index; [4]OM - Organic matter; [5]PRD - Depth to maximum penetration resistance; [6]Bd - Bulk density; [7]DF - Degree of flocculation; [8]MWD - Mean weight diameter of aggregates

Table 3. Soybean yield (kg ha^{-1}) descriptive statistics and ANOVA results for each growing season within management zones

Attribute	Mean	SD[1]	CV[2]	Mean	SD[1]	CV[2]	Anova	
Season		Zone 1			Zone 2		F	P
2019-2020	3185.83 a	375.81	11.79	2836.92 b	422.76	14.90	60.41**	< 0.001
2020-2021	4013.22 a	481.34	11.99	3450.70 b	543.69	15.76	129.99**	< 0.001
2021-2022	1233.41 a	365.33	29.62	781.05 b	323.44	41.41	25.29**	< 0.001

Different letters indicate significant differences between management zones according to Tukey's test (p ≤ 0.05). [1]SD - Standard deviation; [2]CV% - Coefficient of variation superior performance, with mean yields of 3185.83, 4013.22, and 1233.41 kg ha^{-1}, respectively. In contrast, Z2 exhibited lower mean yields of 2836.92, 3450.70, and 781.05 kg ha^{-1}, indicating substantial yield reductions relative to Z1. Analysis of variance (ANOVA) confirmed a significant difference between management zones ($p < 0.001$).

The highest soybean yields were recorded during the 2020–2021 growing season in both management zones (Table 3), likely reflecting more favorable climatic and phytosanitary conditions during that cycle, as well as possible genotype × environment interactions. Although cultivar and planting density varied among growing seasons, these practices were uniform within each season across the entire study area. Therefore, while management practices may have influenced overall yield levels between seasons, they do not explain the persistent yield differences observed between management zones, which were maintained across all evaluated seasons. This finding reinforces the role of soil physical attributes as primary drivers of spatial variability in soybean yield.

Notably, the 2021–2022 growing season exhibited a high coefficient of variation (CV), particularly in Z2, where CV reached 41.41%, indicating pronounced yield instability in this zone. Overall, CV values ranged from moderate to high across the evaluated seasons, reflecting substantial interannual yield variability, especially during the lowest-yielding season (2021–2022), even under consistent management conditions (Oliveira et al., 2024). This variability is likely associated with reduced water availability during that season and may be attributed to the combined effects of soil physical constraints and climatic stress during the cropping period. Similar responses were reported by Faé et al. (2020) and Silva Júnior et al. (2025), who observed that soils characterized by low porosity, high bulk density, and reduced organic matter content tend to exhibit greater yield variability under adverse environmental conditions.

Yield differences between MZ further confirm the effectiveness of classification based on soil physical attributes. These results suggest that adoption of site-specific management strategies, such as adjusting fertilizer application rates, mitigating soil compaction, and selecting cultivars better adapted to local soil conditions, may enhance productivity. This interpretation is consistent with findings reported by Obade (2019), who linked crop performance to soil quality and management practices tailored to spatial heterogeneity.

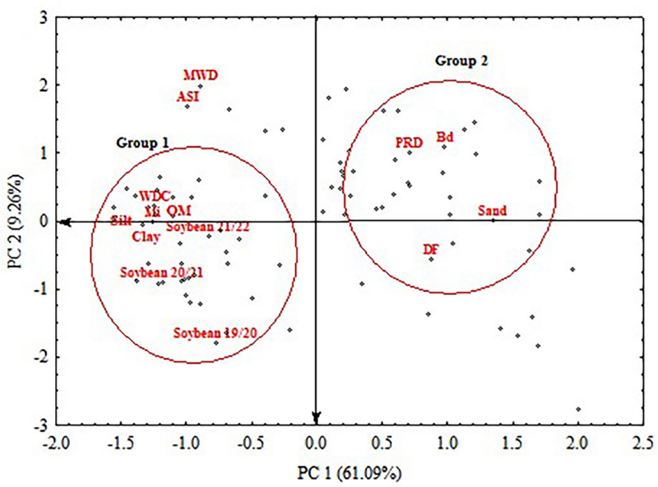
The first two principal components (PCs) accounted for approximately 70% of the total variance among the 14 analyzed variables (Table 4). This dimensionality reduction indicates that most information contained in the dataset can be represented by a limited number of independent factors, as also reported by Torres et al. (2022) and Pereira et al. (2022). Eigenvalues associated with PC3 and subsequent components were close to or below 1.0 (Table 4), and cumulative variance results confirmed that the first two PCs captured most of the relevant variability, whereas additional components contributed marginally to data interpretation.

The PCA biplot illustrates distribution and interrelationships among analyzed attributes within each MZ. In Z1, soybean yield across the three growing seasons was strongly associated with a cluster of five attributes: clay, silt, Mi, OM, and WDC. In contrast, Z2 was primarily influenced by sand, DF, Bd, and PRD. Both ASI and MWD appeared relatively isolated in the ordination space, suggesting limited contribution to management zone discrimination. This pattern is consistent with findings reported by Pereira et al. (2022) and Guimarães et al. (2024), who also identified well-defined spatial groupings resulting from integration of soil physical attributes and crop yield data.

The PCA biplot (Figure 4) revealed formation of two distinct groups, Group 1 and Group 2, corresponding to Z1 and Z2, respectively. Attributes that most strongly contributed to definition of Z1 included soybean yield and soil variables clay, silt, OM, Mi, and WDC. These variables showed consistent positive correlations with soybean yield across all evaluated seasons, with correlation coefficients predominantly classified as moderate to strong (Table 5).

Table 4. Eigenvalues obtained from principal component analysis (PCA)

PC	Eigenvalue	Total (%)	Cumulative	Cumulative (%)
1	8.55	61.09	8.55	61.09
2	1.30	9.26	9.85	70.35
3	1.07	7.66	10.92	78.02
4	0.74	5.26	11.66	83.28
5	0.63	4.46	12.28	87.74
6	0.53	3.79	12.81	91.53
7	0.44	3.14	13.25	94.67
8	0.25	1.80	13.51	96.47
9	0.18	1.31	13.69	97.78
10	0.14	1.00	13.83	98.78



WDC - Water-dispersible clay; Mi - Microporosity; ASI - Aggregate stability index; OM - Organic matter; PRD - Depth to maximum penetration resistance; Bd - Bulk density; DF - Degree of flocculation; MWD - Mean weight diameter

Figure 4. Principal component analysis (PCA) biplot showing grouping of soil physical attributes and soybean yield variables within management zones (Z1 and Z2)

Table 5. Pearson correlation matrix between soil physical attributes and soybean yield

Attribute	Soybean yield - Season					
	2019-2020	p-value	2020-2021	p-value	2021-2022	p-value
Sand (g kg^{-1})	-0.50	0.00**	-0.79	0.00**	-0.50	0.00**
Clay (g kg^{-1})	0.50	0.00**	0.80	0.00**	0.49	0.00**
Silt (g kg^{-1})	0.48	0.00**	0.73	0.00**	0.49	0.00**
WDC (%)[1]	0.43	0.00**	0.65	0.00**	0.42	0.00**
Mi (%)[2]	0.46	0.00**	0.76	0.00**	0.50	0.00**
ASI (%)[3]	0.22	0.07^{ns}	0.54	0.00**	0.42	0.00**
OM (g kg^{-1})[4]	0.47	0.00**	0.69	0.00**	0.49	0.00**
PRD (cm)[5]	-0.27	0.02*	-0.51	0.00**	-0.39	0.01**
Bd (kg dm^{-3})[6]	-0.46	0.00**	-0.62	0.00**	-0.40	0.01**
DF (%)[7]	-0.26	0.03*	-0.38	0.01**	-0.29	0.01**
MWD (mm)[8]	0.10	0.38^{ns}	0.43	0.00**	0.36	0.01**

*- Significant at $p \leq 0.05$; **, significant at $p < 0.01$; ns, not significant ($p \leq 0.05$). [1]WDC - Water-dispersible clay; [2]Mi - Microporosity; [3]ASI - Aggregate stability index; [4]OM - Organic matter; [5]PRD - Depth to maximum penetration resistance; [6]Bd - Bulk density; [7]DF - Degree of flocculation; [8]MWD - Mean weight diameter of aggregates

In contrast, sand content, DF, PRD, and Bd were associated with the low-yield zone (Z2), exhibiting stable negative correlations with yield across seasons. These results demonstrate a clear relationship between soil physical attributes and soybean yield, as well as their combined influence on MZ delineation, as further illustrated by the PCA biplot (Figure 4).

Pearson correlation analysis between soil physical attributes and soybean yield across the three growing seasons revealed consistent relationships with production environments defined by the MZs (Table 5). Sand content showed negative correlations with yield in all seasons, whereas clay and silt exhibited positive correlations, particularly during the 2020–2021 season. WDC, Mi, ASI, and OM were positively correlated with yield, indicating improved soil physical quality in higher-yield environments. In contrast, PRD, Bd, and DF showed negative correlations with soybean yield across seasons, highlighting the restrictive effects of soil compaction on crop performance. Mean weight diameter (MWD) exhibited positive correlations, especially during the last two seasons. Overall, strongest correlations were observed in the 2020–2021 season, which agrees with clearer separation of management zones indicated by FPI, NCE, and PCA results.

Recent studies have demonstrated feasibility and cost-effectiveness of integrating soil attributes and yield data for MZ delineation in commercial soybean fields (Pereira et al., 2022; Silva Júnior et al., 2025). Consistent with these findings, results of the present study indicate that combined use of soil physical attributes and multi-season soybean yield data effectively discriminated contrasting production environments. This distinction was evidenced by clear separation of high- and low-yield zones, performance of the FPI and NCE, and associations revealed by PCA. Together, these results reinforce robustness of this approach for supporting site-specific and sustainable management decisions in soybean production systems.

Conclusions

1. The integration of soil physical attributes with multi-season soybean yield data proved to be a robust and consistent approach for delineating management zones, with the two-zone solution supported by minimum Fuzzy performance index (FPI) and Normalized classification entropy (NCE) values and reinforced by Principal component analysis (PCA) and correlation analyses.

2. The high-yield zone was associated with greater clay and silt contents, organic matter, water-dispersible clay, and microporosity, indicating improved soil structure and water retention capacity, whereas the low-yield zone was characterized by higher sand content, bulk density, degree of flocculation, and deeper penetration resistance, reflecting physical constraints to root development.

3. These findings provide technical support for site-specific management strategies, including variable-dose fertilization and targeted soil compaction mitigation practices.

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