Management zone delineation for the optimization of nitrogen use efficiency in Arabica coffee crops

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Abstract.

Efficient management of nitrogen fertilization in mountain coffee farming requires advanced tools that identify the ideal scale of field intervention. This study evaluated and compared different dimensionality reduction models for agricultural management zone (MZ) delineation, based mainly on remote sensing data, aiming to maximize nitrogen fertilizer use efficiency in Arabica coffee plantations. Operating in the Zona da Mata Mineira region, we contrasted the traditional spatial statistical technique MULTISPATI-PCA against a deep learning architecture based on 3D Convolutional Autoencoders (AEC-3L). The AEC-3L model successfully filtered out high-frequency spatial noise, establishing cohesive and operationally viable MZs with a superior Davies-Bouldin index of 0.2729. Agronomic validation confirmed that this zone-based approach accurately segregated areas with distinct yield potentials (81.3 vs. 64.9 bags ha^{-1}), justifying tailored variable-rate nitrogen prescriptions (272 vs. 330 kg ha^{-1}) and validating the proposed decision framework.

Keywords.

Precision Agriculture; Convolutional autoencoders; Remote sensing.

INTRODUCTION

Coffee production in rugged terrains, such as the Zona da Mata region, at Minas Gerais state, faces notable yield constraints due to steep topography and traditional, uniform crop management. Among primary macronutrients, Nitrogen (N) plays a critical role in vegetative growth and yield potential; however, its homogeneous application across variable landscapes regularly leads to low fertilizer use efficiency, economic losses, and environmental risks like leaching and volatilization (Pham et al., 2019). Precision Agriculture (PA) practices address this issue by partitioning fields into site-specific Management Zones (MZs) or Differentiated Management Units (UGDs) that share similar soil, terrain, and vigor characteristics.

In recent years, the availability of high-resolution satellite constellations has made multi-temporal remote sensing a cornerstone for tracking crop canopy dynamics and nutritional status over time (Li, S. et al., 2021). Nevertheless, utilizing dense time-series data creates a "dimensionality curse", yielding vast datasets filled with atmospheric noise and redundant information. This data abundance presents a crucial operational dilemma for coffee growers: should the crop be managed at a highly fragmented pixel/cell scale, or consolidated into macroscopic, continuous management zones? To address this challenge, this study evaluated and compared different dimensionality reduction models for agricultural management zone (MZ) delineation, based mainly on remote sensing data, aiming to maximize nitrogen fertilizer use efficiency in Arabica coffee plantations.

METHODOLOGY

The study was conducted across commercial Arabica coffee fields in Coimbra-MG and São Geraldo-MG. To capture spatial and temporal variability, multi-layer data cubes were built using spatio-temporal data, which included Sentinel-2 imagery time-series (including NDVI, NDRE, and GNDVI indices) processed with the HANTS (Harmonic Analysis of Time Series) algorithm to remove cloud noise. Topographic data was integrated via Digital Elevation Models (DEM), yielding altitude, slope, and aspect (north and east-facing slopes).

Two distinct workflows were tested prior to clustering via the Fuzzy c-means algorithm: the spatial statistical algorithm MULTISPATI-PCA and a Deep Learning 3D Convolutional Autoencoder (AEC-3L) featuring residual connections and spatial attention gates (Li, Z. et al., 2021). The choice of strategy was guided by a structured operational decision model: the cell-based approach (MULTISPATI-PCA) extracts high-frequency spatial variations, capturing abrupt pixel-to-pixel anomalies, making it suitable only for farms equipped with high-end, real-time automated variable-rate machinery. Conversely, the zone-based approach (AEC-3L) extracts low-frequency, semantic structural features governed by macro-topography, grouping fields into smooth, continuous polygons, making it ideal for conventional manual or mechanical fertilization logistics.

RESULTS:

The algorithms displayed markedly different spatial structures during field partition. As shown in Figure 1, MULTISPATI-PCA produced highly fragmented zones. In contrast, the AEC-3L model successfully leveraged its convolutional layers to filter out short-term vegetative noise, aligning the zones with perennial terrain features and yielding continuous, operationally practical polygons (Zhang et al., 2022). The quantitative evaluation metrics confirmed the structural advantages of the deep learning approach, where AEC-3L dramatically lowered the Davies-Bouldin index to 0.2729 compared to 0.6070 observed in the cell-based method (MULTISPATI-PCA), proving that convolutional feature extraction creates far more cohesive clusters with well-defined boundaries (Zheng et al., 2024).

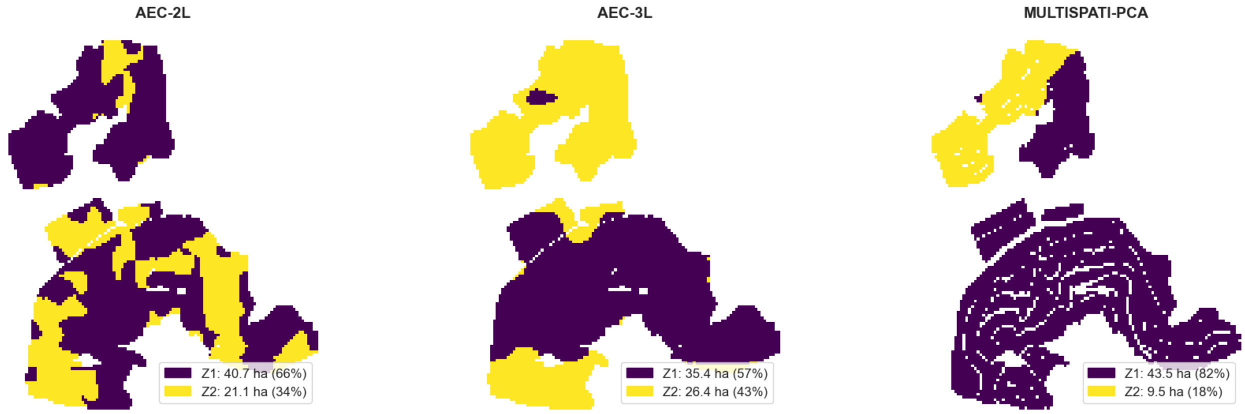

Fig 1. Spatial distribution and fragmentation comparison between MULTISPATI-PCA, AEC-2L, and AEC-3L management zones in Arabica coffee crops

This structural clarity justifies the higher computational cost of 152.83 seconds compared to 34.36 seconds required by the statistical alternative. Furthermore, the deep learning approach outperformed MULTISPATI-PCA across all mathematical partitioning scores, achieving a higher Fuzziness Performance Coefficient (FPC) of 0.9741 against 0.9655, and a superior Silhouette Index (SI) of 0.7925 against 0.7448, as compiled in Table 1. To verify the biological relevance of the zones, the MZs delineated by the AEC-3L model were cross-referenced with historic, multi-harvest field yield data.

Table 1. Quantitative partition and performance metrics for the tested algorithms.

Evaluation Metric	Zone-Based Approach (AEC-3L)	Cell-Based Approach (MULTISPATI-PCA)
Davies-Bouldin (DB)	0.2729	0.6070
Fuzziness Performance Coeff. (FPC)	0.9741	0.9655
Silhouette Index (SI)	0.7925	0.7448
Execution Time (seconds)	152.83	34.36

A Tukey test ($p < 0.05$) confirmed a statistically significant biological separation between the zones, demonstrating a substantial gap of 0.32σ in z-score. This clear division underpins the nitrogen decision model by segregating zones with distinct productive response potentials. Specifically, it demonstrated that in the High Yield Zone, the crop is highly efficient, achieving an expected maximum biennial average yield of 81.3 bags ha^{-1} requiring only 272 kg ha^{-1} of applied N. In contrast, the Low Yield Zone, constrained by permanent topographic features and lower nutrient use efficiency, required a higher application rate of 330 kg ha^{-1} of N to reach a lower expected yield ceiling of 64.9 bags ha^{-1}, as presented in Table 2. This localized adjustment prevents the uniform over-application of fertilizer in highly efficient areas and highlights the environmental and economic necessity of tailoring variable-rate fertilization to the actual biological ceiling of each management zone.

Table 2. crop yield and optimized Nitrogen prescription based on AEC-3L zones.

Delineated Management Zone (AEC-3L)	Maximum Biennial Average Yield (bags/ha)	Z-Score Difference	Optimized N Rate Prescription (kg ha^{-1})
High Yield Zone	81.30	0.32	272
Low Yield Zone	64.90	0.32	330

CONCLUSION:

The 3D Convolutional Autoencoder (AEC-3L) outperforms traditional spatial statistical methods in establishing stable, operational management zones for mountain coffee production. The decision model indicates that while cell-based methods support ultra-precise automated systems, consolidating data into semantic zones via AEC-3L offers a more practical and effective scale for variable-rate nitrogen fertilization under standard regional farming logistics.

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