DELIMITATION OF MANAGEMENT ZONES IN AGROFORESTRY COFFEE SYSTEMS

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Abstract.
The search for more sustainable agricultural production systems is a common goal for both agroforestry systems and precision agriculture. Integrating precision agriculture technologies into coffee cultivation within agroforestry systems has the potential to make these systems more efficient, productive, and sustainable. Thus, this study aims to test the effect of different variables on the delimitation of management zones (MZs) in agroforestry systems. The study was conducted on two coffee-producing farms that maintain their crops in shaded environments in the municipality of Coimbra, Minas Gerais, Brazil. To generate the management zones using the Smart Map plugin, four combinations of three variables (apparent soil electrical conductivity - ECa, normalized difference vegetation index - NDVI, and altitude/digital elevation model - DEM) were tested: 1 (NDVI + DEM + ECa), 2 (ECa + DEM), 3 (ECa + NDVI), and 4 (DEM + NDVI). The optimal number of zones was determined based on the Fuzzy Performance Index (FPI) and Normalized Classification Entropy (NCE). To evaluate the delimited zones, soil samples were collected in each zone for subsequent analysis, and the means of the physical and chemical attributes were compared using Student's t-test at a 5% significance level to verify if the zones represented distinct environments. The results demonstrated that NDVI exerted a strong influence on spatial segmentation, mainly highlighting areas with greater vegetation cover. Combinations that included ECa allowed for the identification of zones with significant differences in soil attributes, especially for potassium, magnesium, organic matter, and texture. Altitude showed a secondary influence on zone delimitation. Among those evaluated, the combination of ECa and NDVI showed the best performance by generating statistically different zones without excessive field fragmentation, presenting significant differences for essential nutrients (potassium, magnesium, calcium, and manganese), as well as soil quality indicators (organic matter and cation exchange capacity - CEC). Therefore, it is concluded that the delimitation of management zones based on ECa and NDVI in agroforestry systems presents high potential for better resource allocation and reduction of input use.

Keywords.
Decision-making; variability; Mmapping; Precision agriculture.

Introduction

Agroforestry systems (AFS) integrate agricultural crops with tree and forest species, aiming for sustainable production (Bene et al., 1977). Precision agriculture (PA), in turn, utilizes technologies to manage the spatial and temporal variability of the crop, enabling greater productivity and environmental efficiency (Pierce & Nowak, 1999). The integration of PA into coffee cultivation within AFS presents high potential, as it can allow for the stratification of areas with different productive potentials, optimizing input use and contributing to the system's sustainability.

In these systems, the delimitation of management zones, which are homogeneous areas regarding soil, relief, and vegetation attributes (Schepers et al., 2004), has the potential to increase system efficiency and aid in the optimization of input application. In this context, the present study aimed to evaluate the effect of different variables on the delimitation of management zones in coffee cultivation conducted under an agroforestry system.

Material and Methods

The study was conducted during the 2024/25 crop season on two neighboring Arabica coffee farms located in the municipality of Coimbra, MG, Brazil. The study area comprised the union of four continuous fields, totaling approximately 1.4 ha, with predominantly flat terrain.

The delimitation of management zones was performed based on the combination of three variables: apparent soil electrical conductivity (ECa), Normalized Difference Vegetation Index (NDVI), and Digital Elevation Model (DEM). The NDVI and DEM were obtained through aerial imagery captured by an unmanned aerial vehicle (UAV). The ECa was measured in the field using a portable sensor**.**

Management zones were generated using the Smart Map plugin, with four combinations of variables: 1 (NDVI + Altitude + ECa), 2 (ECa + Altitude), 3 (ECa + NDVI), and 4 (Altitude + NDVI). The optimal number of zones was determined based on the Fuzzy Performance Index (FPI) and Normalized Classification Entropy (NCE), with adjustments made where necessary to ensure no continuous areas were smaller than 0.1 ha.

To evaluate the delimited zones, soil samples were collected in each zone to analyze physical and chemical attributes. Attribute means were compared using Student's t-test at a 5% significance level to verify if the zones represented truly distinct environments.

Results and Discussion

The combinations of variables resulted in distinct patterns for the delimitation of management zones. It was observed that NDVI exerted a strong influence on spatial segmentation when used alone or combined with only one additional variable, highlighting areas with higher vegetation cover. In agroforestry systems, this sensitivity of NDVI is particularly relevant due to the increased heterogeneity of the vegetation cover.

Combinations that included ECa allowed for the identification of zones with significant differences in soil physical and chemical attributes, especially potassium, magnesium, organic matter, and texture, confirming its potential to characterize the spatial variability of soil physicochemical attributes (Silva et al., 2022). Areas with higher ECa values showed better fertility conditions, reinforcing the hypothesis that areas with higher ECa tend to present superior soil fertility conditions (Bottega et al., 2022).

Altitude played a secondary role in the delimitation of management zones in this study; however, in other areas with different topography, it may be a significant variable. Among the evaluated combinations, the integration of ECa and NDVI showed the best performance, as it generated statistically distinct zones without promoting excessive field fragmentation. Furthermore, it allowed for the identification of a more fertile zone associated with similar management practices, a relevant aspect for site-specific management in agroforestry systems (Ribeiro Filho et al., 2024).

Significant differences were observed for nutrients essential to coffee cultivation, such as potassium, magnesium, calcium, and manganese, as well as for soil quality indicators like organic matter and cation exchange capacity (CEC). These attributes are directly related to coffee productivity and sustainability (Sousa et al., 2018; Martinez et al., 2023). These results reinforce the importance of delimiting management zones for the adoption of site-specific management practices, with the potential to increase productive efficiency and sustainability.

Conclusion

Precision agriculture proved to be a strategic tool for coffee cultivation in agroforestry systems. The combination of apparent soil electrical conductivity (ECa) and NDVI was the most efficient in delimiting management zones with distinct soil chemical and physical attributes, without generating excessive field fragmentation. This approach shows high potential for better resource allocation, reduction of input use.

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