Evaluation of variable and uniform rate prescriptions of potassium fertilizing for small plots in family-run coffee farms

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A paper from the Proceedings of the
17th International Conference on Precision Agriculture and 11th Brazilian Congress on Precision and Digital Agriculture
13-15 July 2026
Porto Alegre, Brazil

Abstract.

Brazil plays a central role in the global coffee supply as one of the primary providers for strategic international markets. As extreme weather threats, prolonged droughts, and international agricultural commodity price volatility increase, enhancing economic efficiency in input use has become fundamental for the sustainability and resilience of coffee production systems. Thus, efficiency in the use of agricultural inputs transcends economic concerns, becoming part of the broader discussion on food security and productive resilience. In this context, nutritional management strategies that incorporate spatial heterogeneity can increase allocative efficiency and improve input performance. This study aimed to construct and compare two contrasting potassium fertilization scenarios in coffee crops: a conventional uniform rate strategy and variable rate application among plots. The analysis focused on differences in input allocation and economic outcomes under each management regime. Soil analyses from a family-run coffee farm located in the state of Minas Gerais, comprising six plots totaling 14.43 ha, with data available for 2012, 2013, 2015, 2019, and 2020. A simulation-based approach was adopted to evaluate the allocative inefficiency associated with uniform rate fertilization along the farm compared to a spatially differentiated recommendation derived from real inter-plot variability data. Uniform application prescriptions were compared with those derived from variable rates, both developed according to the guidelines of the Minas Gerais State recommendation manual. The results indicate that the variable rate strategy increased both agronomic and economic allocation efficiency throughout the analyzed years, with differences reaching up to 3.6 Mg ha^{-1} of KCl and US$ 1,928 ha^{-1} in a single production cycle. It was also observed that, in all evaluated years, the variable rate demanded a higher total amount of fertilizer than uniform management, thus, the temporal and spatial variability of the soil determines the magnitude of the economic results. This approach showed that farm-level averages, even the very small ones, mask the actual variability within plots, causing inefficiencies when uniform input recommendations are used. Although PA

does not guarantee systematic cost reductions in every production cycle, it reduces spatial allocation inefficiency by avoiding both waste and localized undernutrition, which are not captured by uniform management.

Keywords.

Soil fertility management, allocation efficiency, smallholder farming

Introduction

Coffee (*Coffea arabica* L.) is one of the most widely traded agricultural commodities in the world and plays a critical role in the livelihoods of millions of producers and in the economies of several producing countries (Silva et al., 2025). Brazil is currently the world's largest coffee producer, accounting for approximately 35% of global coffee production and 63 million 60-kg bags in the 2025/26 season (USDA-FAS, 2025).

As climate change intensifies the frequency of extreme weather events, droughts, and production uncertainties, improving the efficiency of agricultural systems has become a central challenge for both producers and policymakers. Sustainable intensification is increasingly recognized as a necessary pathway to simultaneously increase productivity, improve resource-use efficiency, and contribute to global commitments associated with the United Nations Sustainable Development Goals (SDGs), particularly those related to food security, responsible consumption and production, and climate action (United Nations, 2015).

The urgency of this challenge has become increasingly evident as climate-related disruptions have begun to affect not only agricultural production but also commodity markets. Recent evidence indicates that extreme weather events in major coffee-producing regions, including Brazil and Vietnam, contributed to substantial increases in international coffee prices during 2024 (Kotz et al., 2025). Although higher commodity prices may temporarily improve farm revenues, they also increase uncertainty regarding production decisions and investment strategies.

At the same time, fertilizer markets have experienced significant price fluctuations over the last decade, particularly for imported nutrients such as potassium. As a result, coffee growers are increasingly exposed to simultaneous uncertainty in both output and input markets, making efficient resource allocation a critical component of economic resilience and long-term sustainability.

Among production inputs, mineral fertilizers represent one of the most important and volatile cost components in coffee farming. Potassium (K) is particularly relevant because of its high extraction by the crop and its direct involvement in physiological processes related to photosynthesis, carbohydrate transport, water-use efficiency, grain filling, and crop productivity (Guimarães et al., 1999; Matiello et al., 2015). Consequently, decisions regarding potassium fertilization have direct implications for both agronomic performance and economic outcomes.

Under increasingly volatile fertilizer and commodity price scenarios, improving allocative efficiency becomes especially important because profitability depends not only on crop productivity but also on the producer's ability to allocate inputs efficiently under uncertain economic conditions.

Precision Agriculture (PA) has emerged as a promising approach to improve resource-use efficiency by measuring and managing spatial variability within agricultural fields. The fundamental premise of PA is that agricultural systems are inherently heterogeneous and that management decisions should account for this variability rather than relying on uniform interventions. Previous studies have demonstrated that site-specific management can improve input allocation, optimize fertilizer use, and enhance the sustainability of agricultural production systems (van Evert et al., 2017; Silva et al., 2025).

Despite these advances, a critical knowledge gap remains. While the agronomic potential of variable-rate fertilization has been extensively discussed, decision-makers still lack a clear answer to a simple but fundamental question: what is the cost of ignoring spatial variability when fertilizer recommendations are based on area-average soil information? This question is particularly relevant because uniform recommendations remain the dominant management strategy in many coffee-producing regions, especially among small and medium-sized farms. Under this approach, a single fertilizer recommendation is derived from an average soil fertility

value and applied uniformly across the entire production area, implicitly assuming that all plots have similar nutrient requirements. However, if substantial variability exists within the farm, this simplification may generate allocative inefficiencies that remain largely unquantified.

Therefore, the objective of this study was to construct and compare two contrasting potassium fertilization scenarios in coffee production: a conventional uniform-rate strategy based on area-average soil fertility and a variable-rate strategy based on plot-specific soil information. By quantifying the agronomic and economic inefficiencies associated with uniform fertilization, this study seeks to estimate the cost of replacing site-specific nutrient information with area-average recommendations and to provide evidence supporting more efficient and resilient nutrient management strategies in agronomic production systems.

Material and methods

Study site and dataset description

This study was conducted using a historical dataset of soil analyses collected from a coffee farm associated with the Regional Coffee Growers Cooperative in Guaxupé (i.e.,Cooxupé), located in the state of Minas Gerais, Southeast Brazil. The farm comprises six production plots totaling 14.43 ha and is representative of the smallholder coffee production systems that predominate in the region. Soil fertility data were available for the 2012, 2013, 2015, 2019, and 2020 growing seasons, allowing the evaluation of fertilization recommendations under different soil fertility and fertilizer price conditions over time. For each year, plot-level soil potassium (K) concentrations were obtained from routine soil analyses used by the producer for nutrient management decisions.

Minas Gerais was selected as the study region because it is the main coffee-producing state in Brazil and accounts for most of the country's Arabica coffee production. In addition to its economic relevance, the region provides a suitable environment for evaluating the implications of spatial variability on nutrient management, as coffee production is frequently characterized by heterogeneous soil fertility conditions resulting from differences in soil properties, topography, management history, and fertilizer application practices. Therefore, although the analysis was conducted in a single coffee farm, the study was designed to investigate a broader question relevant to precision agriculture: the consequences of replacing site-specific management information with area-average values in fertilizer recommendation systems

Fertilizer price data and inflation adjustment

Annual fertilizer prices were obtained from the Brazilian National Fertilizer Association (ANDA) annual reports (2012–2020) and expressed as annual averages. Original values were reported in nominal U.S. dollars (USD) and included freight and applicable taxes. To enable interannual comparisons, all prices were adjusted for inflation using the Consumer Price Index for All Urban Consumers (CPI-U), published by the U.S. Bureau of Labor Statistics (BLS). The CPI-U was selected because it is the most widely used measure of inflation for values expressed in U.S. dollars and provides a consistent basis for converting nominal prices into constant monetary values over time. All prices were converted to constant 2020 U.S. dollars, which was adopted as the base year corresponding to the final year of the study period.

Uniform and variable-rate fertilization scenarios

Potassium fertilizer recommendations were determined according to the guidelines proposed by Guimarães et al. (1999) for coffee production in Minas Gerais State. Two fertilization scenarios were constructed for each year and plot. In the variable-rate scenario, recommendations were calculated individually for each plot using its respective soil test result. In the uniform-rate

scenario, a single recommendation was generated from the area-weighted mean soil K concentration of all plots, representing the conventional approach in which management decisions are based on a single average soil fertility value for the entire farm. The difference between the two scenarios was then used to quantify allocative inefficiencies associated with the use of area-average recommendations allowing the estimation of the amount of KCl that would be misallocated under the uniform-rate strategy.

Results and discussion

Spatial variability and limitations of area-average recommendations

The spatial distribution of soil potassium (K) revealed substantial differences among plots and years, indicating that fertility conditions within the farm were far from homogeneous (Figure 1).

While area-average values suggested a single fertility condition, the spatial analysis revealed the simultaneous presence of contrasting nutrient levels within the same production system. Consequently, the use of a uniform recommendation based on average soil test values simplified a heterogeneous reality, obscuring differences that are agronomically relevant for fertilizer allocation.

These results indicate that average values may adequately describe the farm statistically, but not necessarily represent its nutritional requirements from a management perspective as evidenced by the variability in K concentrations among plots and by the coefficients of variation obtained for each year. As a result, recommendations based on a single area-average value were unable to adequately represent the nutritional conditions of all plots simultaneously, creating situations in which some areas would receive fertilizer above their estimated requirement while others would receive less than recommended.

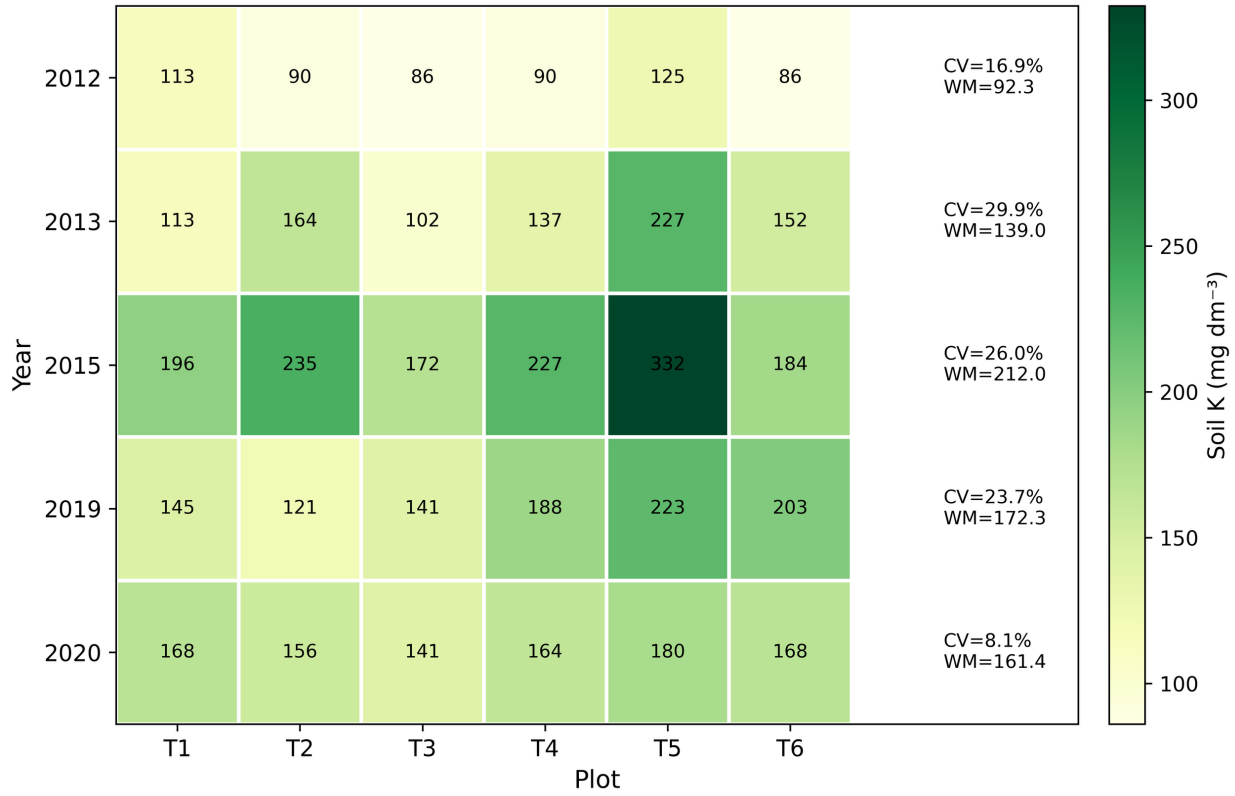
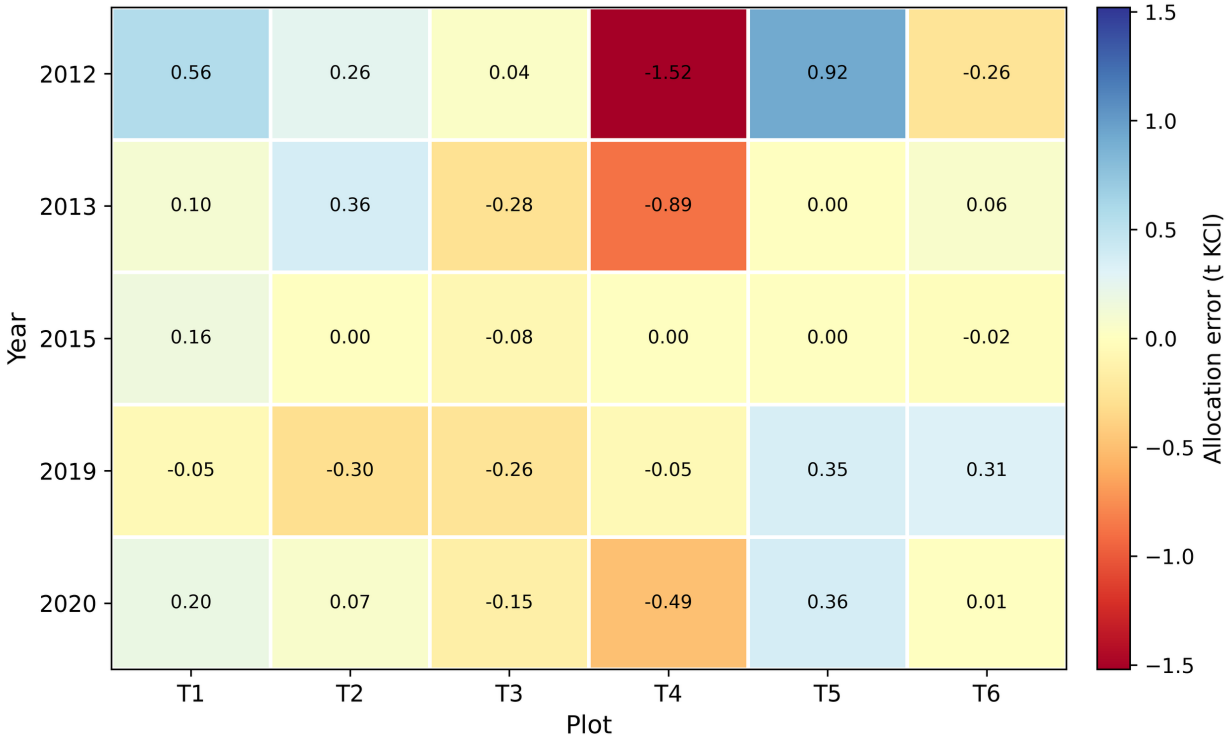


Fig 1. Area-average values mask substantial differences in soil potassium among coffee plots. CV, coefficient of variation;

WM, area-weighted mean.

Differences between uniform and variable-rate recommendations translated into measurable allocation errors throughout the study period (Figure 2). While some plots received fertilizer in excess of their estimated requirement, others received less than recommended, revealing a redistribution of KCl among management units. Therefore, the main consequence of adopting a uniform recommendation was not a change in the total fertilizer requirement of the farm, but a mismatch between fertilizer allocation and local demand.



Red = over-application under uniform rate | Blue = under-application under uniform rate

Fig 2. Spatial distribution of potassium allocation errors associated with uniform fertilization recommendations.

Quantifying the cost of ignoring spatial variability

The allocation errors identified in the previous section translated into substantial economic inefficiencies (Figure 3). Depending on the year, the monetary value associated with the mismatch between uniform and variable-rate recommendations ranged from US$124 to US$1,928, demonstrating that the consequences of using area-average values extend beyond theoretical allocation distortions and may affect farm-level resource use decisions.

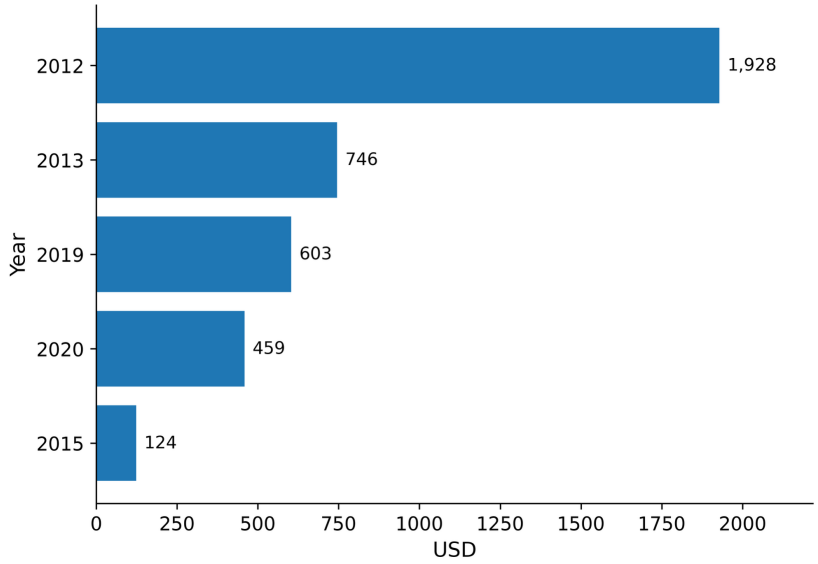


Fig 3. Economic inefficiency associated with uniform potassium fertilization recommendations relative to the variable-rate scenario.

The magnitude of the economic inefficiency was influenced not only by the spatial distribution of soil K, but also by fertilizer prices. Although spatial variability is a prerequisite for allocation errors, the economic consequences of those errors depend on the market value of the fertilizer at the time of recommendation. In addition, the coefficient of variation alone did not explain the observed pattern, suggesting that the interaction between soil test values, recommendation classes, and fertilizer prices ultimately determined the economic impact of uniform fertilization. In class-based recommendation systems, relatively small differences in soil K can lead to substantial changes in prescribed rates when values cross critical thresholds, amplifying the economic consequences of using area-average values.

Conclusion

The magnitude of allocative inefficiency varied substantially among the evaluated years. Nevertheless, in all scenarios, uniform fertilization recommendations failed to adequately represent the spatial heterogeneity of soil potassium across the farm. These findings indicate that the economic efficiency of fertilization depends not only on the average recommended rate, but also on how well nutrient allocation reflects the underlying variability of the production system. Therefore, precision agriculture should not be evaluated solely by its ability to reduce fertilizer use, but by its capacity to reduce allocative inefficiencies arising from the spatial simplification inherent to uniform recommendations

Acknowledgments

The authors thank the Coffee Producers Cooperative in Guaxupé LTDA – Cooxupé for data availability.

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