What 255 sugarcane farms and 15,000 ha reveal about sustainable nutrient management

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Abstract.

Considering spatial variability is a key pathway toward improving sustainability in broadacre agricultural systems. However, despite decades of technological development in precision agriculture, fertilizer management in commercial sugarcane production remains largely based on uniform management assumptions, particularly under replacement-based fertilization strategies. This study evaluated the implications of spatial variability for nutrient allocation using a large-scale dataset comprising soil, terrain, and yield information from 255 commercial sugarcane farms in southeastern Brazil, covering approximately 15,000 ha. Yield maps from the 2023 and 2024 seasons, digital elevation models, and soil information were integrated to delineate management zones (MZs), which were subsequently used to compare nutrient recommendations generated under uniform and spatially differentiated management strategies. Elevation emerged as an important explanatory variable, with 81.1% of the evaluated farms exhibiting strong yield–elevation relationships ($|r| \geq 0.5$), although both positive and negative associations were observed across the dataset. Nutrient recommendations based on management zones revealed substantial spatial heterogeneity, with localized misallocation exceeding 45% in some portions of the landscape. Nevertheless, more than half of the analyzed area exhibited recommendation differences below 5% relative to uniform management, indicating that not all observed variability is necessarily operationally relevant. Cumulative analyses further demonstrated that nutrient misallocation rarely followed an extreme Pareto distribution, with approximately 70–80% of the delineated management zones required to capture 80% of the total misallocation observed within fields. These findings suggest that while high-misallocation hotspots exist, meaningful improvements in nutrient allocation frequently require interventions across a substantial proportion of the production landscape. Overall, the results indicate that the value of management zones lies not in attempting to manage every detectable source of variability, but in providing an operational framework for identifying where variability becomes sufficiently relevant to justify intervention. Management zones therefore represent a practical pathway for transitioning from uniform management toward more advanced site-specific nutrient management strategies in commercial sugarcane systems.

Keywords

Fertilizer efficiency; Management zones; On-farm data; Yield variability; Zone-based analysis

1. INTRODUCTION

Spatial and temporal variability are inherent characteristics of agricultural systems, emerging from the interaction of multiple production factors that ultimately shape crop performance. Recognizing this variability is essential for improving resource-use efficiency and advancing the ecological, economic, and environmental sustainability of agricultural production systems (Gebbers and Adamchuk, 2010). Conversely, management strategies that disregard spatial heterogeneity tend to reduce system efficiency by treating inherently distinct portions of the landscape as functionally equivalent.

Precision agriculture has emerged precisely to address this challenge, particularly in broadacre production systems where management decisions are still frequently based on field-average conditions (Mulla and Khosla, 2016). Under uniform management assumptions, a single representative value is often used to guide decisions across highly heterogeneous production environments, regardless of whether the managed area encompasses a few hectares or thousands. Such an approach implicitly neglects the spatial variability that characterizes key agronomic attributes within agricultural fields.

Among the production factors affected by this simplification, nutrient allocation represents one of the most critical (Mirzaee and Nafchi, 2025). Fertilizer recommendations derived from field-average conditions may simultaneously under-supply portions of the field with greater nutrient demand while over-supplying others with lower productive potential. As a result, uniform nutrient management may contribute not only to reduced agronomic efficiency, but also to unnecessary economic costs and environmental impacts associated with nutrient excesses and deficits (Ali and Salem, 2024).

Sugarcane represents a particularly relevant example within this context. In Brazil alone, the crop occupies approximately 9 million hectares and plays a central role in the bioenergy sector, contributing to one of the world's largest renewable energy matrices (Cherubin et al., 2021). Due to its extensive territorial coverage and strategic importance for energy production, sugarcane management has direct implications not only for agricultural productivity, but also for broader sustainability goals associated with resource-use efficiency and environmental performance.

Like most high-yielding cropping systems, sugarcane production is strongly dependent on fertilizer inputs. Nutrient management is commonly based on expected yield potential or replacement fertilization strategies, in which nitrogen (N), phosphorus (P), and potassium (K) recommendations are estimated as a function of projected or previously harvested yield. In practice, however, these recommendations are frequently established using field-average productivity values, despite the substantial spatial variability that characterizes commercial production environments.

This creates an important operational contradiction. Although sugarcane production is closely associated with sustainability-oriented agendas due to its relevance for renewable energy systems, fertilizer allocation within commercial fields often remains based on simplified uniform management assumptions. Consequently, nutrient application may fail to adequately match the heterogeneous productive potential observed within agricultural landscapes, limiting both agronomic efficiency and the environmental benefits expected from more sustainable production systems.

Within commercial sugarcane systems, the existence of spatial variability is already well established. Advances in sensing technologies, vegetation indices, digital terrain analysis, and, more recently, yield mapping have substantially increased the capacity to characterize field heterogeneity under operational conditions (Longchamps et al., 2022). At the same time, precision agriculture has accumulated decades of methodological and operational experience, particularly in grain production systems, resulting in highly developed approaches for detecting and describing spatial variability in agricultural fields.

Despite this technological evolution, uniform management strategies still dominate commercial production systems. This raises an important question: if variability is widely recognized and increasingly measurable, why does uniform management remain the prevailing operational paradigm? Part of this resistance may be associated with the difficulty of consistently demonstrating when spatially explicit management effectively translates into practical agronomic, economic, or environmental benefits under commercial conditions.

Recent approaches such as on-farm experimentation attempt to address this challenge by generating knowledge directly within production environments, facilitating the interpretation of variability and its management implications under real operational scenarios (Lacoste et al., 2022). However, an important conceptual distinction remains necessary: the existence of variability alone does not necessarily justify intervention. Some portions of agricultural fields may remain sufficiently close to average conditions such that uniform management provides an operationally acceptable solution. In these situations, the complexity and cost associated with site-specific management may not be justified by the magnitude of the expected gain.

Consequently, the critical question is not simply whether variability exists, but rather whether its magnitude is operationally relevant. Understanding where uniform management remains adequate and where spatially explicit intervention becomes justified is essential for improving the practical adoption of precision agriculture strategies. Without this distinction, the potential benefits of precision agriculture may become diluted across areas where management adjustments provide limited practical advantage, making it more difficult to identify where operational changes truly generate meaningful returns.

In this context, an important gap remains within the precision agriculture literature. Over recent years, increasing attention has been directed toward the use of data derived from real field operations, particularly under commercial production conditions. This movement represents an important step forward, since highly controlled small-scale experimental studies, while essential for isolating specific mechanisms and testing methodological advances, do not always capture the operational complexity of large agricultural systems. As a result, conclusions derived under experimental conditions may not fully represent the constraints, variability, and decision-making dynamics observed in commercial farming environments.

This limitation also affects the practical translation and adoption of precision agriculture strategies within the productive sector. One of the major contemporary challenges of precision agriculture is no longer simply detecting variability, but demonstrating where and when spatially explicit management produces sufficiently relevant benefits to justify operational changes under real-world conditions.

Despite the growing availability of large-scale operational datasets, relatively few studies have quantified the practical implications of spatial variability across multiple commercial farms managed under routine production conditions. Consequently, the observational understanding of how precision agriculture principles translate into operationally relevant outcomes at large scales remains limited. Expanding this type of evidence is therefore essential for improving both the scientific understanding and the practical implementation of site-specific management strategies.

To address these questions, this study assembled one of the largest operational sugarcane spatial datasets currently reported under commercial Brazilian production conditions, comprising nearly 15,000 ha distributed across more than 250 commercial farms. Using this large-scale dataset, the present study evaluated whether the adoption of management zones, as an initial step toward sugarcane spatial management, could improve the efficiency of nutrient allocation relative to conventional uniform management strategies.

Rather than focusing primarily on methodological novelty or on management zones delineation itself, this study aimed to quantify where, how frequently, and at what magnitude spatial variability translates into meaningful divergence between uniform and zone-based nutrient management approaches. In this context, management zones were treated not as an end in themselves, but as an operational framework for investigating the practical relevance of spatial variability under commercial production conditions.

By adopting a large-scale observational perspective, this work seeks to contribute to a broader understanding of how precision agriculture principles and variability-oriented management may translate into agronomic, economic, and environmental efficiency gains when evaluated under real-world operational scenarios.

2. MATERIAL AND METHODS

2.1 Study areas and operational dataset

This study used data derived from commercial sugarcane production systems. The dataset comprised 255 commercial farms covering a total monitored area of 14,991.5 ha. The study areas were distributed across the central and northeastern sugarcane-producing regions of São Paulo, southeastern Brazil, one of the country's most important regions for sugarcane production and bioenergy supply. The regional climate is predominantly tropical with dry winters and wet summers, characterized by marked seasonality in rainfall distribution and favorable thermal conditions for sugarcane development throughout most of the year.

All analyzed areas contained yield data for two consecutive growing seasons corresponding to the 2023 and 2024 harvests. Yield information represented the primary dataset used in this study and was obtained from commercial sugarcane yield monitoring systems recently introduced into the Brazilian production sector. The monitoring system employed a proprietary commercial sensor (Solinftec, Araçatuba, São Paulo, Brazil) capable of estimating sugarcane yield from variations in hydraulic oil pressure associated with the chopper system of mechanical harvesters. The operational principles and validation of this sensing approach were previously described by Maldaner et al. (2022). Data acquisition was performed at a temporal resolution of 0.2 Hz, and yield values were provided by the commercial platform after the proprietary conversion of sensor signals into estimated productivity values.

To support spatial analyses, field boundaries provided by the surveying departments of the partner mills were subdivided into regular 10 × 10 m cells. Rather than generating interpolated yield surfaces, the study adopted a valid-cell approach in which only cells containing yield observations for both analyzed seasons (2023 and 2024) were retained for subsequent analyses. This strategy allowed analyses to be conducted directly from observed field measurements while maintaining temporal consistency between seasons across the entire dataset.

In addition to yield information, auxiliary spatial datasets were also systematized when available. Soil information derived from pedological surveys was available for part of the study areas, depending on data availability from the partner mills. Digital elevation information, however, was available for the entire dataset as it was derived from Sentinel-based remote sensing products from the Copernicus Open Access Hub (https://scihub.copernicus.eu/).

All datasets were obtained through research partnerships established between the university and commercial sugarcane production stakeholders under public–private collaborative agreements. Due to commercial confidentiality clauses associated with these agreements, the exact geographic locations of the analyzed fields cannot be disclosed.

2.2 Yield data preprocessing and spatial consistency filtering

Yield datasets were received as individual geospatial files, each representing a commercial sugarcane field containing georeferenced yield observations associated with spatial coordinates and estimated productivity values. Initial preprocessing consisted of statistical and spatial filtering procedures adapted from the workflow proposed by Maldaner et al. (2021), which describes preprocessing strategies for commercial sugarcane yield monitoring datasets.

For each field/dataset, extreme yield values considered operationally implausible were removed using a fixed upper threshold of 200 Mg ha^{-1}. Subsequently, a global statistical filter based on the field median was applied. After global filtering, a local spatial filtering procedure was performed using neighboring observations within a 50 m search radius, retaining only points within ±25% of the local median. Median-based filtering approaches were adopted due to their robustness against outliers and operational noise commonly observed in commercial yield monitoring datasets.

For each filtering stage, descriptive statistics including number of observations, minimum, maximum, mean, standard deviation, and coefficient of variation were recorded to ensure traceability and individual quality assessment for each field. Filtered datasets were then exported for subsequent analyses.

Following preprocessing, yield observations were associated with the 10 × 10 m valid-cell framework described in Section 2.1. Only cells containing yield observations for both analyzed seasons (2023 and 2024) were retained, ensuring temporal consistency throughout the analyses.

2.3 Management zone delineation

Management zone delineation was performed through a continuous and semi-automated workflow. For each field, spatial layers were organized into a composite dataset integrating data derived from the valid-cell framework described in Sections 2.1 and 2.2, digital elevation data, and soil classes when available from pedological surveys.

Two clustering approaches were evaluated for each field: K-means clustering and hierarchical agglomerative clustering. Prior to clustering, all numerical variables were standardized to avoid scale effects among features. Soil information, when available, was incorporated through categorical encoding procedures, while elevation data were conditionally included according to their spatial association with yield patterns evaluated using bivariate Moran's I statistics.

For the K-means approach, the optimal number of management zones was estimated using the optimization of the Fuzzy Performance Index (FPI) and the Normalized Classification Entropy (NCE). For hierarchical clustering, the number of zones was selected based on silhouette analysis. Both methods were automatically generated for each field, producing alternative delineation scenarios.

The final delineation method adopted for each field was selected individually through visual and operational comparison between clustering outputs and the original spatial layers, including yield patterns, elevation, and soil information when available. This continuous evaluation workflow was adopted to maintain consistency in management zone selection across the entire dataset while ensuring that the final zones adequately represented the observed spatial organization of each field.

The resulting management zones were subsequently used as the spatial basis for nutrient allocation and misallocation analyses described in the following sections.

2.4 Uniform and zone-based nutrient allocation framework

Nutrient allocation was estimated using a replacement fertilization strategy commonly adopted in commercial sugarcane production systems. This approach was selected because it allowed nutrient recommendations to be consistently estimated across all analyzed fields using the yield information available for the 2023 and 2024 harvest seasons. Under this strategy, fertilizer recommendation is based on nutrient replacement according to the productivity obtained in the previous harvest.

Nitrogen (N), phosphorus (P), and potassium (K) were considered as the primary macronutrients evaluated in this study. Nutrient replacement factors were defined according to recommendations adapted from Quaggio et al. (2022), assuming the application of 1.0 kg of N, 0.5 kg of P, and 1.5 kg of K per megagram (Mg ha^{-1}) of harvested sugarcane. Although changes in replacement coefficients would alter the absolute nutrient quantities estimated in this study, they would not affect the relative comparison between uniform and zone-based nutrient allocation strategies, since both management approaches were evaluated under the same replacement assumptions.

Uniform nutrient recommendation was estimated at the field level using the average field productivity according to Equation (1):

$$R_{UM} = \bar{Y}_f \times r_n \tag{1}$$

where R_{UM} is the uniform nutrient recommendation, $\bar{Y}_f$ is the mean productivity of the field, and r_n is the nutrient replacement factor for nutrient n.

Zone-based nutrient recommendation was estimated independently for each management zone according to Equation (2):

$$R_{MZ,i} = \bar{Y}_i \times r_n \tag{2}$$

where $R_{MZ,i}$ represents the nutrient recommendation for management zone i, and $\bar{Y}_i$ corresponds to the average productivity observed within that zone.

Nutrient misallocation under uniform management was then estimated as the divergence between uniform and zone-based nutrient recommendations (Equation 3):

$$M_i = R_{MZ,i} - R_{UM} \tag{3}$$

where $M_i$represents the signed nutrient misallocation for management zone i. Positive values indicated nutrient deficit under uniform management, i.e., situations where the zone-based recommendation exceeded the uniform recommendation. Negative values indicated nutrient excess under uniform management.

In addition to signed misallocation, absolute nutrient misallocation was also calculated as:

$$| M_i | \tag{4}$$

allowing the quantification of total nutrient divergence independently of whether the deviation represented deficit or excess. This distinction was considered relevant because nutrient deficits and excesses may lead to different agronomic and environmental implications under commercial production conditions.

2.5 Operational relevance and actionability analysis

To improve the practical interpretation of nutrient misallocation magnitudes, nutrient quantities were additionally converted into fertilizer-equivalent values using commonly adopted fertilizer sources in commercial sugarcane production systems. This conversion was intended exclusively as a communication strategy to facilitate the operational interpretation of nutrient quantities, without altering the proportional relationships between management strategies.

Nitrogen misallocation was expressed as urea equivalent assuming a nutrient concentration of 45% N. Phosphorus misallocation was expressed as simple superphosphate equivalent considering 18% P_2O_5, while potassium misallocation was expressed as potassium chloride equivalent assuming 60% K_2O content. Based on these conversion factors, total absolute fertilizer-equivalent misallocation, as well as deficit and excess quantities under uniform management, were estimated for each nutrient and season.

An operational relevance analysis was subsequently performed to evaluate the magnitude and spatial extent of nutrient divergence between uniform and zone-based management strategies. This analysis was based on the assumption that site-specific management should be prioritized in situations where the magnitude of nutrient divergence justifies the additional operational complexity associated with spatial management.

For this purpose, management zones were classified according to absolute percentage misallocation thresholds relative to uniform management recommendations. Thresholds of 5%, 10%, 15%, and 20% were evaluated. For each threshold, the number of management zones exceeding the defined divergence level, the corresponding proportion of zones and represented area, and the mean nutrient misallocation were calculated. Both arithmetic and area-weighted misallocation metrics were estimated to account for differences in management zone size across the dataset.

This approach allowed the identification of situations in which uniform management remained operationally adequate, as well as scenarios where the magnitude of divergence suggested a greater potential benefit from spatial nutrient allocation strategies.

3. RESULTS AND DISCUSSION

Yield patterns remained remarkably consistent across the two evaluated seasons (Figure 1). In 2023, mean yield across all fields was 105 Mg ha^{-1}, with a median of 102 Mg ha^{-1} and a coefficient of variation (CV) of 23.6%, indicating a slightly negatively skewed distribution. In 2024, mean yield decreased to 102.5 Mg ha^{-1}, while the distribution approached normality, with a median yield of 101 Mg ha^{-1} and a CV of 20.9%. Although these values represent aggregate statistics across the entire dataset, the observed trend is consistent with the well-documented phenomenon of sugarcane ratoon yield decline (Dlamini et al., 2024), as the 2023 and 2024 datasets corresponded to consecutive harvests from the same production areas.

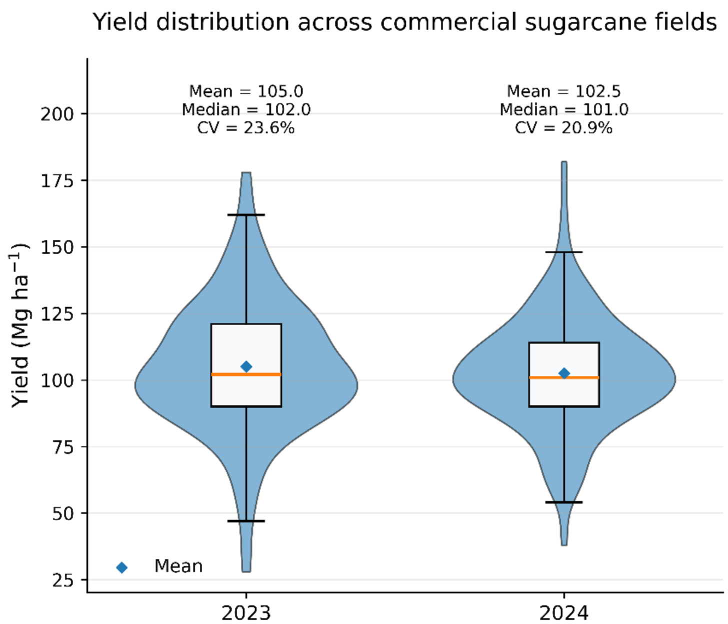

Fig. 1 Distribution of field-average sugarcane yield across the analyzed commercial dataset for the 2023 and 2024 harvest seasons.

Elevation data derived from Sentinel imagery were conditionally incorporated into the management zone (MZ) delineation process whenever a significant spatial association with yield was confirmed through bivariate Moran's I analysis. Across the 255 evaluated farms, elevation proved to be an important layer supporting spatial yield aggregation and management zone definition (Figure 2). Other authors reported topographic parameters as important variables driving sugarcane yield, such as slope and concavity of the field (Sanches et al., 2020). In our dataset, strong yield–elevation associations ($|r| \geq 0.5$) were observed in 81.1% of the fields. However, the direction of this relationship was not consistent throughout the dataset. Approximately 40% of the farms exhibited strong positive correlations ($r \geq 0.75$), whereas nearly 25% displayed similarly strong but negative correlations ($r \leq -0.75$).

The contrasting responses observed between yield and elevation likely reflect differences in soil properties, landscape position, and soil–water interactions. In coarse-textured soils, for example, lower landscape positions may accumulate water and nutrients, favoring crop growth and resulting in negative yield–elevation relationships. Conversely, in finer-textured soils with greater water-holding capacity, elevated portions of the landscape may benefit from improved drainage and reduced nutrient redistribution, leading to positive correlations. These examples are not intended to explain all observed patterns but rather to illustrate how the same environmental variable can be associated with yield through different mechanisms depending on local conditions (Sanches et al., 2019). More importantly, the coexistence of strong positive and negative relationships within a single large-scale dataset highlights the limitations of generalized assumptions regarding soil–plant–environment interactions and reinforces the need for field-specific evaluation when implementing precision agriculture strategies.

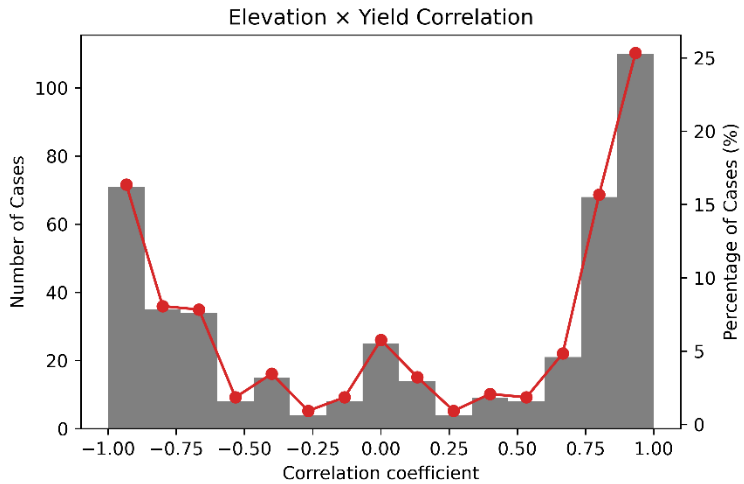

Fig. 2 Elevation–yield linear relationships across the farms analyzed in this study.

The spatial layers organized under the valid-cell framework were subsequently used to evaluate both k-means and hierarchical clustering approaches for management zone delineation. For each field, the clustering method that produced the most coherent representation of the observed spatial patterns was selected, considering yield, elevation, and soil information when available. This procedure ensured that the resulting zones provided a meaningful spatial basis for comparing nutrient allocation under uniform and zone-based management strategies.

Figure 3 presents a representative example of the delineation workflow and its implications for nutrient allocation. In the illustrated field, average yield ranged from 79 to 148 Mg ha^{-1}, while the whole-field average yield was 111 Mg ha^{-1}. The resulting management zones exhibited average yields of 101, 103, and 125 Mg ha^{-1}, respectively. By replacing a single field-average value with zone-specific productivity estimates, nutrient recommendations become spatially differentiated and more closely aligned with the productive potential of each portion of the field.

This example also highlights an important characteristic of zone-based management: it represents a compromise between operational simplicity and spatial specificity. Although substantial within-field variability existed, the adoption of three management zones intentionally simplified the production environment into a limited number of actionable management units. Compared with pixel-level management, this approach sacrifices fine-scale variability in exchange for greater operational feasibility. Such simplification may be particularly relevant during the early stages of precision agriculture adoption, as managers often perceive management zones as a more realistic transition from uniform management than highly granular prescription strategies. Furthermore, it acknowledges practical constraints frequently encountered in commercial operations, including positioning uncertainty, data quality concerns, and machinery limitations regarding the application of inputs at very fine spatial resolutions.

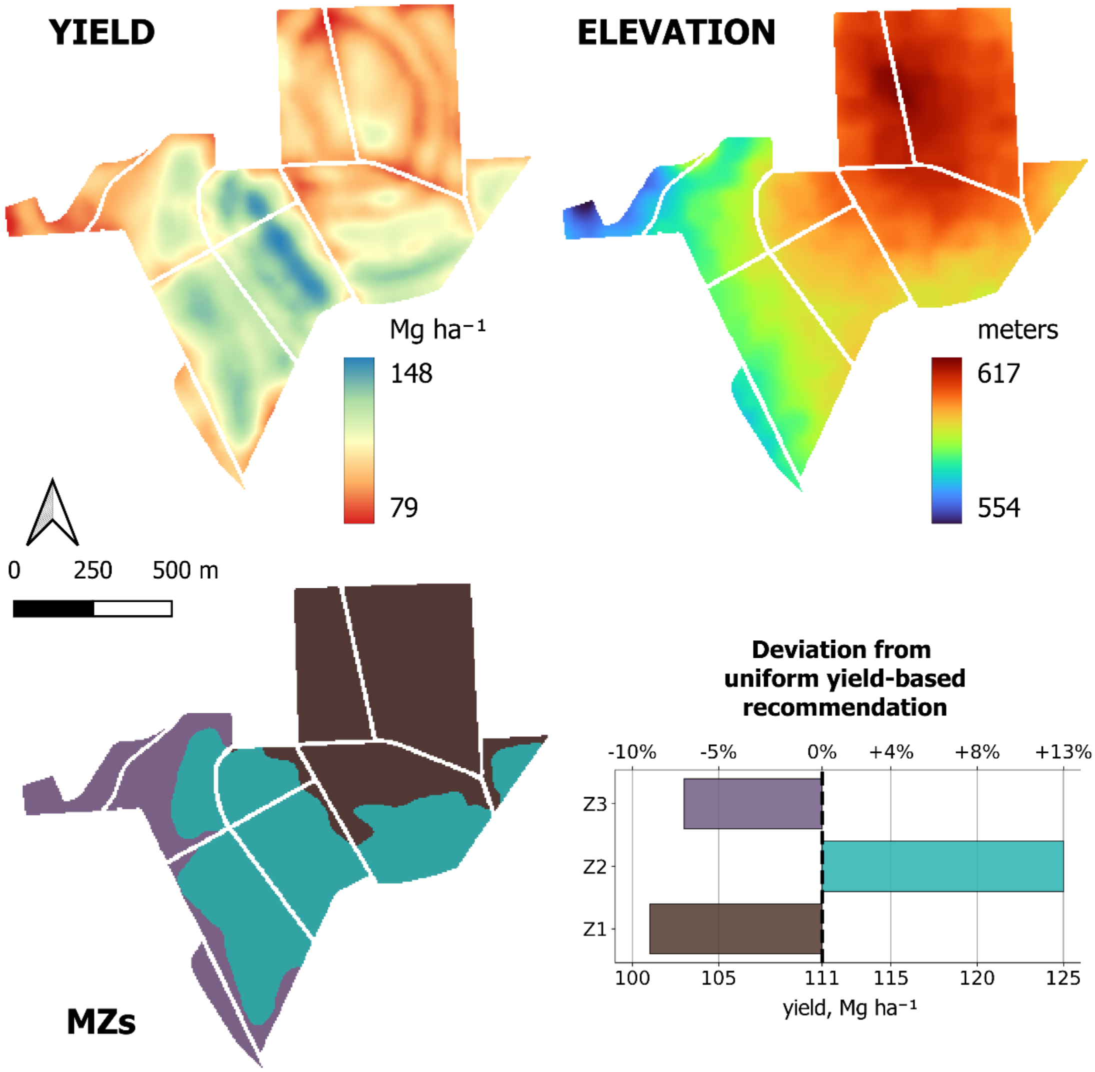

Fig. 3 Representative example of the management zone delineation and nutrient allocation framework adopted in this study. Spatial patterns of sugarcane yield and elevation were integrated to generate management zones under commercial production conditions. The deviation plot illustrates how zone-specific yield levels diverged from the field-average yield assumed under uniform management, resulting in differentiated nutrient recommendations across management zones. This field is presented solely as an illustrative example of the analytical workflow applied across the entire multi-farm dataset.

To quantify the practical implications of these differences, each management zone was classified according to its degree of nutrient misallocation relative to uniform management assumptions (Figure 4). This analysis recognizes that uniform management is not necessarily inappropriate throughout the entire field and that the benefits of spatial management depend on the magnitude of the divergence between recommendations. In 2023, 59.3% of the evaluated area (approximately 8,900 ha) exhibited nutrient recommendations differing by less than 5% from those generated under uniform management. A similar pattern was observed in 2024, when 53.7% of the area fell within this same range. Consequently, approximately 40.7% and 46.3% of the total area in 2023 and 2024, respectively, displayed deviations exceeding 5%, representing more than 6,100 and 6,900 ha of commercial sugarcane production. At the most extreme cases, nutrient misallocation exceeded 45% in individual management zones.

The average magnitude of misallocation was further evaluated under progressively stricter intervention thresholds. When considering only zones with deviations greater than 5%, average nutrient misallocation was approximately 10% in both seasons. As intervention thresholds increased, the average divergence between uniform and zone-based recommendations increased almost linearly, reaching approximately 15%, 20–24%, and 25–35% for thresholds of 10%, 15%, and 20%, respectively.

From a practical perspective, these results suggest that the perceived benefits of precision agriculture depend strongly on the level of spatial variability considered operationally relevant. If every detectable deviation from uniform management is interpreted as actionable, average recommendation differences remain relatively small. However, when attention is directed toward portions of the landscape exhibiting stronger divergences, substantially larger recommendation differences emerge, revealing zones where the potential benefits of spatial management are likely to be greater.

This observation raises an important discussion regarding actionability in precision agriculture. Modern yield monitoring systems, remote sensing products, and machine-learning-based prediction frameworks are all subject to measurement uncertainty. Likewise, agricultural machinery operates within finite limits of positioning accuracy and application precision. Consequently, not every observed source of spatial variability can be effectively translated into management actions. Within this context, the indiscriminate pursuit of increasingly detailed spatial management may dilute the practical benefits of precision agriculture by emphasizing variability that falls within the operational uncertainty of the production system itself.

In contrast, prioritizing management interventions in areas exhibiting larger and more consistent deviations may provide a more transparent and realistic pathway for precision agriculture adoption. The results obtained from nearly 15,000 ha of commercial sugarcane production suggest that the value of spatial management lies not in addressing every detectable source of variability, but rather in identifying where variability is sufficiently large to justify additional management complexity. Under this perspective, actionability thresholds emerge as a useful framework for translating spatial variability into operationally meaningful decisions and for communicating the benefits of precision agriculture more effectively across the research–consultant–farmer continuum.

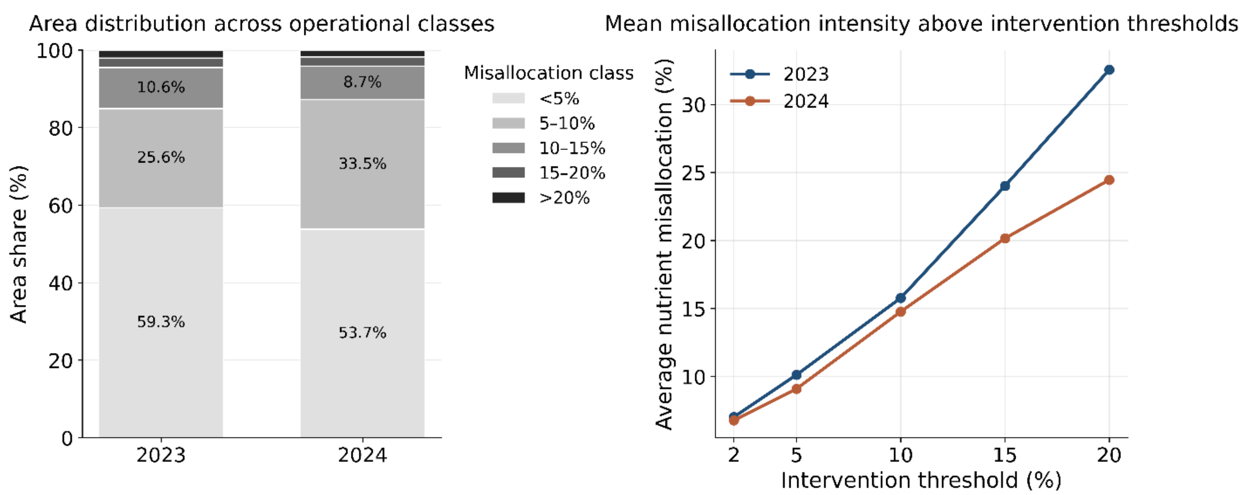

Fig. 4 Operational relevance of nutrient misallocation under uniform nutrient management assumptions. (A) Distribution of the production area across nutrient misallocation classes relative to zone-based recommendations. (B) Area-weighted mean nutrient misallocation observed in zones exceeding progressively stricter intervention thresholds. Although highly divergent zones occupied a smaller fraction of the landscape, their average misallocation intensity increased substantially, indicating spatially concentrated hotspots with greater operational relevance.

The delineation of management zones represents an inherent trade-off between operational simplicity and spatial specificity. While zone-based management substantially reduces the complexity associated with pixel-level approaches, it still requires the redesign of management practices across large portions of the field (Heidari et al., 2026). Given that the previous analysis introduced the concept of actionability thresholds and demonstrated that not all observed variability necessarily justifies intervention, an additional question emerges: should spatial management focus on redesigning the entire field, or should it prioritize the zones responsible for the largest share of nutrient misallocation?

To address this question, a cumulative misallocation analysis was performed by ranking management zones within each field according to their contribution to total fertilizer misallocation and computing cumulative distributions (Figure 5). This approach evaluates the degree to which nutrient misallocation is concentrated within a small subset of management zones and provides insight into the potential effectiveness of targeted interventions.

The median cumulative curve revealed an initial steep increase, indicating that the largest management zones often accounted for a disproportionate share of total misallocation. However, this concentration was less pronounced than would be expected under a classical Pareto (80/20) behavior. On average, approximately 40–50% of the management zones were required to account for 50% of the total misallocation, while 70–80% of the zones were needed to capture 80% of cumulative misallocation. These results indicate that nutrient misallocation is partially concentrated but remains distributed across a substantial fraction of the production landscape.

Considerable variability was observed among fields, as evidenced by both the spread of individual curves and the interquartile range surrounding the median trend. In some cases, a small fraction of management zones concentrated most of the total misallocation, suggesting strong opportunities for targeted intervention. In other fields, misallocation was more evenly distributed, requiring a much larger proportion of the management zones to achieve equivalent reductions. This variability reinforces the importance of field-specific assessment and suggests that no universal intervention strategy can be applied across all production scenarios.

From a management perspective, these findings provide an important complement to the actionability framework discussed previously. The existence of high-misallocation hotspots does not necessarily imply that correcting only a few zones will resolve most inefficiencies. While some fields exhibited strongly concentrated patterns, the median behavior suggests that meaningful reductions in nutrient misallocation generally require management actions across a substantial proportion of the delineated zones. Therefore, the benefits of spatial management should not be evaluated solely based on the magnitude of individual hotspots but also on the extent to which misallocation is distributed throughout the field.

Overall, the results indicate that nutrient misallocation in commercial sugarcane production rarely follows an extreme Pareto-type distribution. Instead, most fields exhibit intermediate levels of concentration, where a limited number of zones contribute disproportionately to total misallocation, yet a broader portion of the landscape remains relevant for achieving substantial improvements in nutrient allocation efficiency.

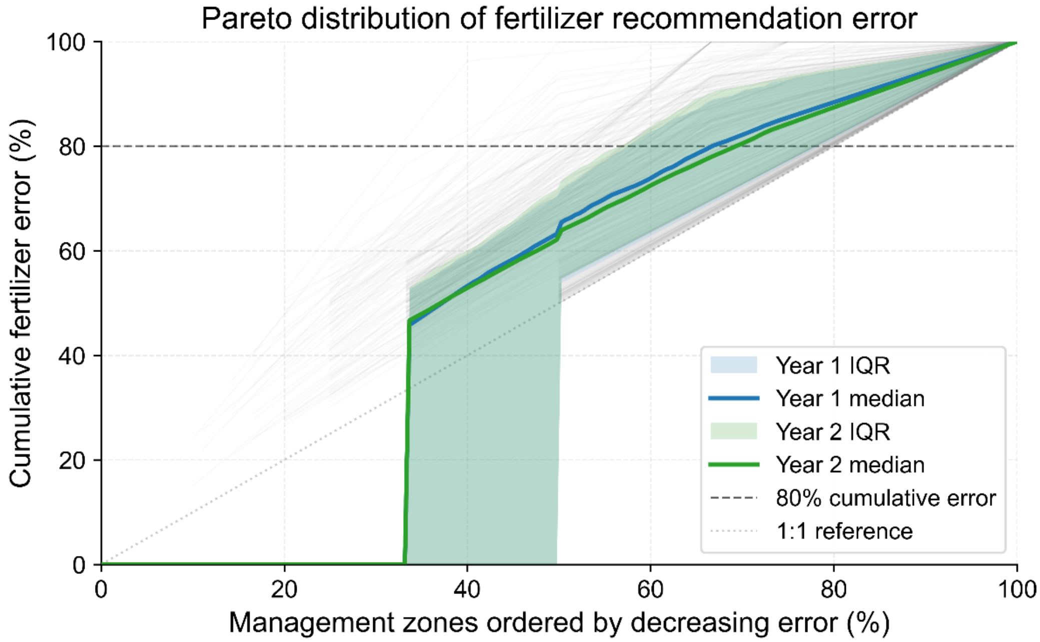

Fig. 5 Cumulative distribution of fertilizer misallocation across management zones. Management zones were ranked from highest to lowest contribution to total fertilizer misallocation within each field. Thin gray lines represent individual fields, whereas colored lines and shaded regions indicate the median and interquartile range across all fields.

Finally, the practical implications of nutrient redistribution were evaluated by expressing misallocation in terms of fertilizer-equivalent quantities rather than nutrient mass alone (Figure 6). This transformation was adopted to facilitate communication and practical interpretation, as fertilizer products represent the operational units used by growers and managers. Across both seasons, urea-equivalent misallocation exceeded 150 Mg, corresponding to approximately 75 Mg of deficit and 75 Mg of excess in 2023, and 79 Mg of both deficit and excess in 2024. For single superphosphate (SSP), total fertilizer-equivalent misallocation reached 188 Mg in 2023 and 196 Mg in 2024, while potassium chloride (KCl) exhibited values of 170 Mg and 176 Mg for the first and second seasons, respectively.

The concepts of deficit and excess, as well as the near symmetry observed between them, illustrate an important characteristic of management zone implementation. As a first step, zone-based nutrient management does not necessarily imply an increase or reduction in fertilizer consumption. Rather, its primary objective is to improve the spatial allocation of inputs by replacing a single field-average recommendation with recommendations that better reflect the productive potential of different portions of the field. In this context, management zones act as a mechanism for redistributing nutrients within the production system rather than altering the overall fertilizer budget.

Such redistribution represents the immediate consequence of incorporating spatial variability into the decision-making process. More sophisticated management frameworks may subsequently evolve toward zone-specific recommendation equations supported by on-farm experimentation, dose–response relationships, and localized agronomic objectives (Lacoste et al., 2022), potentially leading to changes in total fertilizer consumption. However, during the initial stages of precision agriculture adoption, maintaining a simplified decision structure may be advantageous. Transitioning from a single recommendation per field to a limited number of management zones represents a substantially smaller operational leap than moving directly toward highly detailed, fine-scale prescription systems (Tibbs et al., 2026).

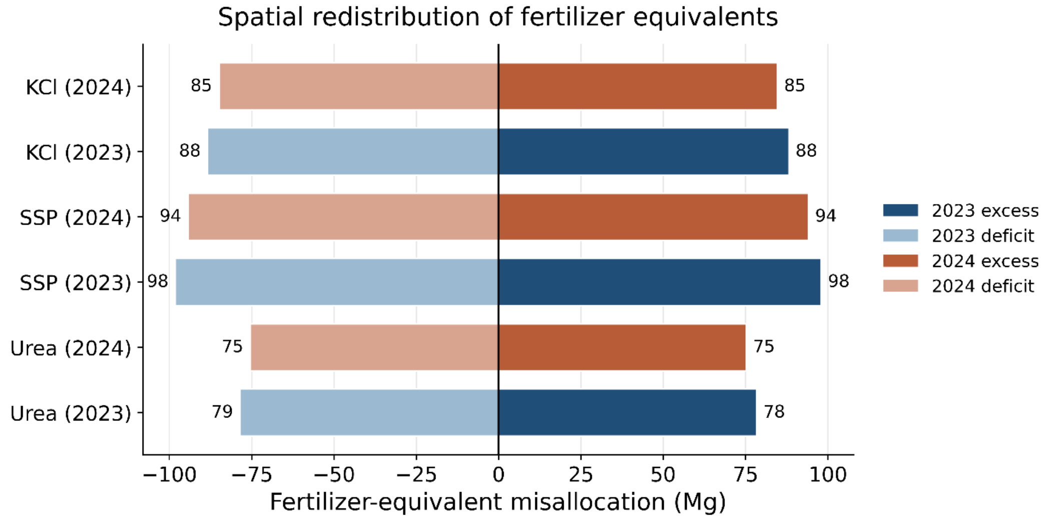

Fig. 6 Fertilizer-equivalent misallocation under uniform management assumptions relative to zone-based nutrient distribution. Total fertilizer-equivalent misallocation was calculated as the sum of deficit and excess quantities, emphasizing the magnitude of spatial redistribution rather than net nutrient imbalance

The fertilizer-equivalent analysis also reinforces the broader concepts of actionability and misallocation concentration discussed previously. Two complementary conclusions emerge from this large-scale dataset. First, not all observed spatial variability can necessarily be managed under current conditions of measurement accuracy, positioning precision, and field-level implementation. Second, meaningful improvements in nutrient allocation frequently require interventions across a substantial proportion of the delineated management zones. Although these conclusions may initially appear contradictory, they address different dimensions of the precision agriculture adoption process.

The first conclusion relates primarily to communication and expectation management. Precision agriculture may undermine its own credibility if it assumes that every detectable source of variability is actionable or that uniform management is inherently inefficient in all circumstances. The results presented here indicate that a considerable portion of the production landscape exhibits relatively small divergences from uniform recommendations, suggesting that not all variability is equally relevant from an operational perspective. Establishing realistic actionability thresholds may therefore be essential for aligning management expectations with the actual capabilities of current technologies.

The second conclusion relates to implementation. While some fields exhibited strongly concentrated hotspots of nutrient misallocation, the cumulative analyses demonstrated that many production areas required a relatively large proportion of management zones to capture most redistribution opportunities. Consequently, focusing exclusively on a few high-misallocation zones may not always provide substantial improvements. Instead, delineating management zones across the entire field appears to offer a more coherent framework for representing spatial variability, even when some zones ultimately receive recommendations that differ only marginally from field-average management.

Together, these findings suggest that the value of management zones extends beyond immediate gains in fertilizer allocation. The process of spatially reorganizing the field establishes a management framework that can gradually evolve toward more sophisticated forms of precision agriculture, including localized experimentation, zone-specific recommendations, and adaptive management strategies. Under this perspective, management zones should not be viewed solely as a tool for correcting current inefficiencies, but also as an operational foundation for future advances in site-specific crop management (Ali et al., 2024; Heidari et al., 2026).

CONCLUSIONS

This study evaluated the implications of spatial variability for nutrient management across 255 commercial sugarcane fields covering approximately 15,000 ha under real production conditions. Strong yield–elevation relationships were observed in most fields, although both positive and negative associations occurred, highlighting the complexity and site-specific nature of soil–plant–environment interactions. While management zones revealed substantial nutrient misallocation under uniform management assumptions, the results also demonstrated that not all observed variability is necessarily operationally relevant. More than half of the analyzed area exhibited recommendation differences below 5%, whereas a smaller proportion of the landscape concentrated substantially larger divergences. Cumulative analyses further showed that nutrient misallocation rarely followed an extreme Pareto distribution, indicating that meaningful improvements in nutrient allocation generally require interventions across a considerable proportion of the delineated management zones. Collectively, these findings suggest that the primary value of management zones lies not in attempting to manage every detectable source of variability, but in providing an operational framework capable of identifying where variability becomes sufficiently relevant to justify intervention. As a result, management zones represent a practical pathway for improving nutrient allocation while establishing the foundation for more advanced site-specific management strategies in commercial sugarcane systems.

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