Evaluating Response-Based Management Units for Variable-Rate Nitrogen Application Using On-Farm Experiments

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Abstract.

Variable-rate nitrogen (N) application in precision agriculture is commonly based on management zones derived from soil properties and vegetation indices, implicitly assuming that spatial patterns in yield potential correspond to spatial patterns in crop response to N. However, yield level and marginal yield response represent distinct agronomic characteristics and may not coincide. This study evaluated whether productivity-based zones adequately capture spatial variability in N response and assessed the potential of response-based management units grounded in marginal yield response and economic optimality. Two years of on-farm N trials were conducted in Brandenburg, Germany, with six N rates applied across a field in silage maize (2024) and rye (2025). Plot-level yield data were combined with soil texture and historical Enhanced Vegetation Index (EVI) data. Quadratic N response models with covariate interactions were fitted to identify factors associated with spatial variability in yield level and N response. Economic optimum nitrogen rates (EONR) were estimated and used to delineate response-based management units. Correspondence between conventional productivity-based zones and response-based management units was weak. Historical EVI was consistently associated with yield variability, explaining approximately 50% of yield variation in 2024 and more than 70% in 2025. In contrast, significant interactions between N rate and soil texture were observed only in 2024, indicating spatial variability in N response that was not captured by conventional productivity zones. The medium-productivity zone exhibited the highest estimated EONR (132 kg N ha^{-1}), whereas the high-productivity zone showed the lowest EONR (54 kg N ha^{-1}), demonstrating that productivity level and N requirement were not directly related. Economic analyses showed that response-based strategies reduced average N application rates from 116 kg N ha^{-1} under uniform management to approximately 63–66 kg N ha^{-1} while maintaining comparable yield levels and increasing profitability. These results demonstrate that zoning based solely on yield potential is insufficient for guiding economically efficient variable-rate N application. Response-based management units derived from crop response functions and EONR estimates provide a more meaningful basis for variable-rate N recommendations and a practical framework for integrating on-farm experimentation, sensing data, and economic criteria into precision fertilization strategies.

Keywords.

Site-specific nitrogen management, Remote sensing, Soil properties, Nitrogen response modeling, Management zones.

Introduction

Variable-rate application (VRA) of nitrogen is a central component of precision agriculture and aims to improve input use efficiency by accounting for spatial variability within agricultural fields. VRA strategies commonly rely on management zones delineated from soil properties, topographic variables, historical yield maps, or vegetation indices, under the assumption that these variables adequately represent differences in crop productivity and management requirements (Bönecke et al., 2021; Longchamps et al., 2022; Reyes et al., 2019). These zones are frequently used to guide spatially variable nitrogen (N) fertilization and other site-specific management decisions.

Despite their widespread use, conventional management zones are generally designed to represent yield potential rather than crop responsiveness to inputs. Yield levels are influenced by both manageable factors, such as fertilization, and less controllable factors, including weather, pest pressure, soil constraints, and other environmental conditions (Bullock and Bullock, 2000; Bullock et al., 2009). Consequently, areas exhibiting similar yield levels may differ substantially in their response to additional nitrogen, while areas with contrasting productivity may exhibit comparable marginal responses. This distinction raises questions regarding the suitability of productivity-based zones for economically efficient nitrogen management.

Several studies have reported limited or inconsistent economic benefits from site-specific management despite substantial within-field variability (Liu et al., 2006; Wang et al., 2023; Weber et al., 2025). Evidence from different cropping systems and environments indicates that zones with high yield potential do not necessarily correspond to zones with high marginal responsiveness to nitrogen (Bachmaier and Gandorfer, 2009; Rodriguez et al., 2019; Trevisan et al., 2021). Since economically optimal nitrogen management depends on marginal yield response rather than yield level alone, reliance on productivity-based zoning may lead to inefficient fertilizer allocation and suboptimal economic returns.

Historical vegetation indices such as the Enhanced Vegetation Index (EVI) have been widely used to delineate management zones because of their ability to capture stable spatial patterns in crop productivity. However, variables that explain spatial variation in yield level are not necessarily the same variables that explain spatial variation in crop response to nitrogen. Soil properties, topography, and vegetation indicators may contribute differently to productivity and responsiveness, yet empirical evidence comparing productivity-based and response-based zoning approaches remains limited, particularly under practical on-farm experimentation conditions.

The objective of this study was to evaluate whether conventional management zones adequately capture spatial variability in crop response to nitrogen and to assess the potential of response-based management units derived from marginal yield response and economic optimum nitrogen rates. Using two years of on-farm nitrogen strip trials, productivity-based and response-based zoning approaches were compared, and the relative roles of historical EVI and soil texture in explaining yield potential and nitrogen responsiveness were investigated.

Materials and Methods

Study Site and Experimental Design

The study was conducted within the DigiMix-PA project in Brandenburg, Germany. Two years of on-farm nitrogen (N) strip experiments were used to evaluate spatial variability in crop response to N. In 2024, the experiment was established in silage maize (Zea mays L.), while winter rye (Secale cereale L.) was evaluated in 2025.

The experimental field was divided into management zones based on historical vegetation indices and soil information. Six nitrogen application rates (0, 80, 110, 150, 170, and 200 kg N ha^{-1}) were assigned to experimental plots using a randomized design constrained by management zones. Plot dimensions were approximately 15 × 25 m. Yield data were collected using a combine harvester equipped with a yield monitoring system and aggregated to the plot level.

Spatial and Environmental Data

Yield observations were combined with environmental covariates derived from soil sensing, topographic information, and remote sensing products. Soil variables included sand, silt, clay, pH, and humus content. Historical productivity was characterized using multi-year Enhanced Vegetation Index (EVI) data derived from satellite imagery.

To capture long-term productivity patterns, historical EVI values from previous growing seasons were aggregated into a mean EVI indicator for each plot. Soil and vegetation data were spatially linked to the experimental plots using geographic information system (GIS) procedures. The variables considered in the analysis are summarized in Table 1.

Table 1: Variables used for response modeling and zoning analysis

Variable	Description	Source
Yield	Plot yield	Yield monitor
Nrate	Applied nitrogen rate (kg N ha^{-1})	Experimental treatment
Sand	Sand content (%)	Soil sensing
Silt	Silt content (%)	Soil sensing
Clay	Clay content (%)	Soil sensing
pH	Soil pH	Soil sensing
Humus	Soil organic matter indicator	Soil sensing
TWI	Topographic Wetness Index	Digital elevation model
EVI_hist_mean	Multi-year average EVI	Satellite imagery

Statistical Analysis

Nitrogen response was modeled using quadratic response functions. For each explanatory variable, the following model was fitted:

$$Y = \beta_0 + \beta_1 N + \beta_2 N^2 + \beta_3 X + \beta_4 pH + \beta_5 (N \times X) + \varepsilon \tag{1}$$

where X represents either historical EVI, sand content, or clay content.

where Y is plot yield, N is the nitrogen application rate (kg N ha^{-1}), X represents either historical EVI, sand content, or clay content, and ε is the residual error term.

To evaluate the ability of conventional productivity zones to capture nitrogen response variability, an additional model including management zone effects and management zone × nitrogen interactions was fitted:

$$Y = \beta_0 + \beta_1 N + \beta_2 N^2 + \beta_3 Z + \beta_4 (N \times X) + \varepsilon \tag{2}$$

where Z denotes the predefined management zone classification.

Economic Optimum Nitrogen Rate and Response-Based Management Units

Economic optimum nitrogen rates (EONR) were derived from the fitted response functions. Profit was calculated as:

$$\Pi = P_Y Y - P_N N \tag{3}$$

where Π is profit per hectare, P_Y is crop price, Y is predicted yield, P_N is nitrogen fertilizer price, and (N) is the applied nitrogen rate.

The EONR was defined as the nitrogen rate that maximized expected profit. Plot-specific EONR values were calculated using the fitted response models for sand and clay. Response-based management units were subsequently delineated by classifying EONR values into low-, medium-, and high-response categories using k-means clustering. The resulting response-based management units were compared with conventional management zones to evaluate their ability to represent spatial variability in economically optimal nitrogen requirements.

Results and Discussion

Yield variability among management zones

Conventional management zones successfully captured spatial variation in crop productivity. Yield distributions differed among management zones, with high-productivity zones generally exhibiting higher yields than medium- and low-productivity zones (Fig. 1). This result is consistent with the rationale underlying management-zone delineation, which seeks to identify relatively homogeneous areas based on soil, topographic, and vegetation characteristics (Bönecke et al., 2021; Reyes et al., 2019). However, differences in yield level do not necessarily imply differences in crop responsiveness to nitrogen. Yield is influenced by multiple environmental and management factors, including weather, soil constraints, and biotic stresses, many of which are only partially controllable through fertilization (Bullock and Bullock, 2000; Bullock et al., 2009). Therefore, zones that differ in productivity may not necessarily differ in their economically optimal nitrogen requirements.

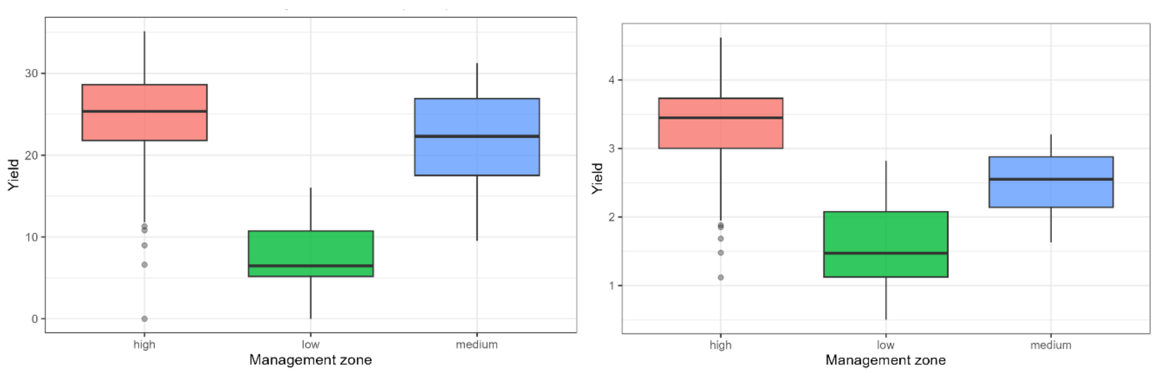

Fig 1: Yield distribution across low-, medium-, and high-productivity management zones for silage maize (2024) and rye (2025)

Factors explaining yield level and nitrogen response

The response models revealed clear differences between variables associated with yield level and variables associated with nitrogen responsiveness (Table 2). Historical EVI was the strongest predictor of yield, explaining approximately 50% of the observed yield variability in 2024 and more than 70% in 2025. Models including EVI consistently exhibited substantially greater explanatory power than models based solely on soil texture variables. In contrast, both sand and clay content exhibited significant interactions with nitrogen rate when analysed individually in 2024. The positive interaction between sand content and nitrogen rate indicated stronger responses to nitrogen in sandier areas, whereas the negative interaction observed for clay suggested lower marginal responses at higher clay contents. These results indicate that soil texture can contribute to explaining spatial variability in crop response to nitrogen under certain environmental conditions.

Table 2: Estimated effects of historical EVI and soil texture on yield level and nitrogen response. The "Estimate" column represents the main effect of each variable on yield, whereas "N × Variable" represents its interaction with nitrogen rate and therefore it

Year	Variable	Estimate	N × Variable
2024	EVI	459.85***	-1.156.
2024	Sand	-1.316***	0.0066**
2024	Clay	3.467**	-0.0223*
2025	EVI	45.45***	-0.0068 ns
2025	Sand	-0.116***	0.0002 ns
2025	Clay	0.224**	-0.0006 ns

However, no significant interaction effects were detected in 2025. Furthermore, when EVI and texture variables were included simultaneously, the texture interactions became non-significant. The moderate correlation between EVI and soil texture suggests that historical vegetation patterns captured part of the same spatial variability represented by soil properties. This finding highlights an important distinction: variables that explain yield potential are not necessarily the same variables that explain nitrogen response. While EVI was highly effective at explaining productivity, soil texture provided a more mechanistic explanation of response heterogeneity when analysed independently.

The absence of consistent interaction effects across years suggests that spatial variation in nitrogen response may be influenced by year-specific environmental conditions and cannot be inferred solely from historical productivity patterns. These findings are consistent with previous studies showing that yield level alone is a poor predictor of crop nitrogen requirements (Rodriguez et al., 2019; Thorburn et al., 2024). They also support the argument that economically optimal nitrogen management should be based on crop response functions rather than productivity indicators alone (Dhakal and Lange, 2021; Miguez and Poffenbarger, 2022).

Response-based management units and EONR variability

The spatial patterns of EONR differed substantially between conventional management zones and response-based management units (Fig. 2). Under the management-zone approach, EONR values were estimated at 63, 132, and 54 kg N ha^{-1} for the low-, medium-, and high-productivity zones, respectively. Notably, the medium-productivity zone exhibited the highest estimated EONR, illustrating that productivity level and nitrogen requirement were not directly related.

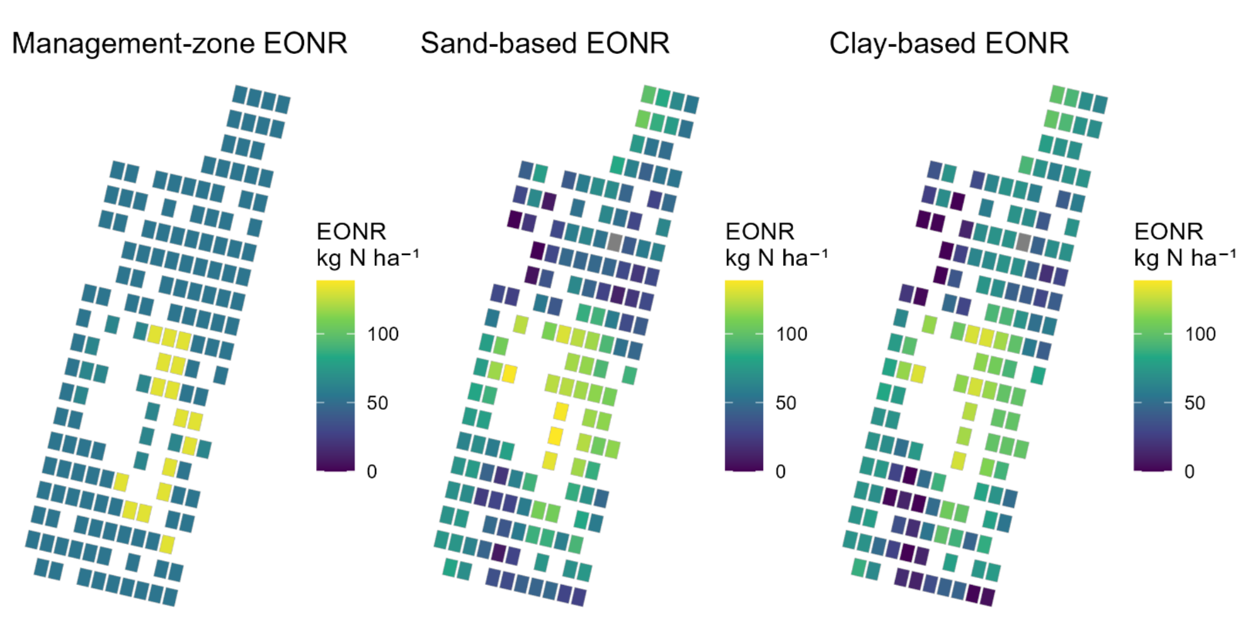

Fig 2: Spatial patterns of economic optimum nitrogen rates (EONR) estimated using conventional management zones (left), sand-based response zones (centre), and clay-based response zones (right) for the 2024 maize experiment.

The sand- and clay-based response models generated a broader range of EONR values. For the sand model, average EONRs ranged from approximately 33 kg N ha^{-1} in the low-response class to 118 kg N ha^{-1} in the high-response class. Similarly, the clay model produced average EONRs ranging from 16 to 105 kg N ha^{-1} across response classes.

These findings indicate weak correspondence between conventional productivity zones and economically meaningful response zones. Areas classified as high productivity frequently contained both low- and high-response locations, while some lower-productivity areas exhibited relatively high marginal responses to nitrogen. Similar observations have been reported by Bachmaier and Gandorfer (2009), Rodriguez et al. (2019), and Trevisan et al. (2021), who found that spatial variability in input response often differs from spatial variability in yield.

The results therefore support the concept of Response-Based Management Units (RBMUs), where zones are defined according to expected economic response rather than productivity level. Such zones may provide a more direct basis for variable-rate nitrogen application because they explicitly target differences in marginal returns to fertilizer.

Economic implications of response-based zoning

The response-based approaches generated different spatial patterns of EONR compared with the conventional management-zone approach (Table 3; Fig. 2). Notably, higher EONR classes were associated with increasing sand content and decreasing clay content, indicating that soil texture influenced the economic response to nitrogen application.

Table 3: Economic optimum nitrogen rates (EONR) derived from alternative zoning approaches

Approach	Class	EONR (kg N ha^{-1})
Management zone	High	54
	Low	63
	Medium	132
Sand model	Low	32.9 (0–51.3)
	Medium	70.3 (51.8–93.2)
	High	118.2 (98.6–138.6)
Clay model	Low	16.3 (0–38.4)
	Medium	64.4 (40.8–82.8)
	High	105.1 (85.8–130.7)

The economic comparison demonstrated that response-based approaches substantially reduced nitrogen use relative to a uniform application strategy while maintaining comparable yield levels (Table 5). The uniform strategy applied 116 kg N ha^{-1} across the entire field, whereas the alternative strategies required approximately 63–66 kg N ha^{-1} on average, corresponding to a reduction of more than 50 kg N ha^{-1}.

Despite the lower fertilizer inputs, all zoning approaches achieved higher predicted profits than the uniform application strategy. Mean profit increased from 538 € ha^{-1} under uniform management to between 556 and 558 € ha^{-1} under the zoning approaches. Total profit increased by approximately 2,800–3,200 € across the study area while reducing nitrogen use by approximately 43–46%.

Table 4. Economic comparison of alternative nitrogen management strategies.

Strategy	Mean N (kg ha^{-1})	Mean yield	Mean profit (€ ha^{-1})	Total profit (€)
Uniform 116 kg N ha^{-1}	116.0	24.6	538	83,339
Management-zone EONR	62.8	22.9	558	86,550
Sand-based EONR	65.7	23.0	558	86,441
Clay-based EONR	64.9	22.9	556	86,150

These findings suggest that substantial opportunities exist to improve nitrogen-use efficiency without sacrificing economic performance. The results are consistent with previous studies reporting that the profitability of precision agriculture depends on accurately identifying spatial differences in crop response rather than merely describing yield variability (Liu et al., 2006; Bullock et al., 2009; Weber et al., 2025).

Overall, the results indicate that productivity-based management zones and response-based management units represent fundamentally different concepts. While conventional zones effectively describe yield variability, response-based zones appear more suitable for identifying economically optimal nitrogen management strategies.

Conclusion

This study evaluated whether conventional productivity-based management zones adequately capture spatial variability in crop response to nitrogen and assessed the potential of response-based management units derived from marginal yield response and economic optimum nitrogen rates (EONR).

Historical EVI was consistently associated with yield level and explained a substantial proportion of yield variability in both years. However, variables associated with yield potential were not necessarily the same variables associated with nitrogen responsiveness. In 2024, soil texture variables exhibited significant interactions with nitrogen rate, indicating spatial variation in crop response to nitrogen that was not captured by conventional productivity zones. In contrast, no significant interaction effects were observed in 2025, suggesting that nitrogen response patterns may vary across years and environmental conditions.

The comparison of zoning approaches revealed weak correspondence between conventional management zones and response-based management units. High-productivity areas did not consistently correspond to high nitrogen-response areas, and the highest EONR was observed in the medium-productivity zone. These findings demonstrate that yield potential and nitrogen requirement represent distinct agronomic characteristics and should not be assumed to coincide.

From an economic perspective, both management-zone and response-based EONR strategies reduced nitrogen use by more than 40% relative to a uniform application strategy while maintaining comparable yield levels and improving profitability. The results indicate that substantial gains in nitrogen-use efficiency can be achieved when fertilizer recommendations are based on crop response rather than productivity alone.

Overall, the findings support the concept of response-based management units as a promising framework for variable-rate nitrogen application. By integrating on-farm experimentation, economic analysis, and spatial covariates, response-based zoning provides a practical pathway toward more economically efficient and environmentally sustainable nitrogen management in precision agriculture.

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