



Assessing seeding rate management strategies for maize production in South Africa: Insights from the Data Intensive Farm Management Project

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Abstract

Purpose Maize (*Zea mays* L.) is South Africa's most widely cultivated row crop, yet traditional flat-rate seeding practices often fail to account for spatial variability, potentially limiting yield and profitability. This study evaluated the agronomic and economic outcomes of three seeding rate strategies—producers' *status quo*, optimal flat rate, and optimal variable rate, where "optimal" refers to profit-maximizing rates—across nineteen site-years in four major maize-producing regions of South Africa.

Methods Trials were conducted in the 2020/2021 to 2023/2024 seasons under diverse climatic and soil conditions, capturing a range of yield potentials and environmental variability. Data from planters with precision agriculture technology and yield monitors were processed into subplots to account for intra-field heterogeneity, and linear mixed-effects models were used to quantify yield responses.

Results Both profit-maximizing flat and variable rate approaches increased yield relative to producers' *status quo*, with mean yield gains of 1.05 and 1.57 t ha⁻¹, respectively. Yield responses were strongly influenced by site- and season-specific factors, particularly rainfall and baseline productivity. Variable rate seeding provided yield advantages in fields with pronounced spatial heterogeneity, though gains were often marginal in uniform fields or under constrained yield potential. Across all site-years, 79% of site-years performed better under optimal flat rates, and 89% of site-years under optimal variable rates, compared to the producers' *status quo* seeding rates.

Conclusion These findings demonstrate that both flat- and variable-rate optimization can enhance productivity, however the relative benefits of variable-rate seeding depend on site-specific conditions, such as baseline yield potential and spatial variability. Environments exhibiting substantial within-field variability in yield response to inputs offer the greatest potential for optimization, whereas fields that are spatially uniform or consistently yield-limited show limited additional benefit from variable rate strategies. Future research should focus on integrating multi-source datasets, hybrid-specific responses, and long-term, multi-season trials to refine site-specific recommendations and improve decision-making for sustainable maize production under precision agriculture.

Keywords Precision Agriculture · Variable rates · Seeding rates · Maize

Introduction

As the country's most widely grown grain crop, maize (*Zea mays* L.) is cultivated over 2.5 million hectares annually and contributes significantly to both human food and livestock feed (CEC, 2025). Given its economic and social importance, improving the efficiency and profitability of maize production is important. Precision agriculture practices offer a valuable opportunity to enhance productivity while addressing the challenges of rising input costs, erratic climatic conditions, and the need for more sustainable agricultural practices (Erickson & Fausti, 2021). On a global scale, precision agriculture offers the potential to transform modern crop production by enabling site-specific management, particularly when supported by on-farm experimentation that generates field-scale data to inform input optimization. Unlike traditional uniform applications, technologies such as GPS-guidance, remote sensing, yield monitors, and data analytics are used to support data-driven decisions addressing the inherent spatial variability of soil and crop performance within fields (Kharel et al., 2019; Getahun et al., 2024; Tantalaki et al., 2019; Bongiovanni and Lowenberg-Deboer, 2004). Variable rate application is a key operational component of precision agriculture, allowing site-specific adjustment of inputs based on spatial data such as soil properties, nutrient levels, yield history, and delineated management zones (Heege, 2013; Truter et al., 2025). In maize production systems, both seed and fertilization input rates are important management decisions that significantly influence yield and profitability. However, traditional flat-rate management does not account for intra-field variability in yield response to inputs, which can lead to inefficiencies when a uniform rate deviates from locally optimal rates across different parts of a field (Munnaf et al., 2022). Variable rate applications potentially offer a targeted solution by tailoring input rates to specific field conditions, improving input-use efficiency, economic returns, and environmental outcomes.

The Data Intensive Farm Management (DIFM) project was established to respond to these on-farm input rate uncertainties (Hegedus et al., 2023). The project employs on-farm precision experimentation techniques to evaluate the economic and agronomic value of variable rate input management across large-scale agricultural environments (Bullock et al., 2019). The project uses commercial on-farm trials and advanced data analytics to shift decision-making from intuition to evidence, with an emphasis on optimizing profitability. Analyses identify profit-maximizing flat and variable input rates using algorithms on on-farm technology, standard agronomic practices, and input rates as a baseline. This article presents findings from nineteen site-years of maize trials conducted across five different maize-producing regions in South Africa. The key objectives of this study were to (1) quantify the profit-maximizing yield response of maize to producers' *status quo*, flat-rate, and variable-rate seeding approaches under diverse seasonal and site-specific conditions, and (2) provide practical insights and evidence-based recommendations for the adoption of variable-rate strategies in maize production systems.

Materials and methods

Site description

Trials were conducted in four provinces of South Africa that coincide with the main maize production regions (Fig. 1). Reported data are from nineteen site-year trials planted between the 2020/2021 and 2023/2024 seasons, near the towns of Bothaville and Hennenman in the Free State province (fields FS1, FS2, and FS3), Ottosdal in North West (field NW1), Paulpietersburg in KwaZulu-Natal (fields KZN1 and KZN2), and Wonderfontein in Mpumalanga (fields MP1, MP2, and MP3). Similar trials in these regions are still ongoing despite data not included in this manuscript. These provinces account for 87% of national maize production and 91% of maize area planted in South Africa (CEC, 2024). The selected sites represent key agroecological zones, encompassing variation in rainfall, soil types, and production risks, capturing much of the environmental and management diversity present in regions where large-scale commercial maize farming predominates. Participating producers are typical of the commercial producers in these regions in terms of farm size, production systems, and management practices, thus supporting the representativeness of the sample.

Trial sites were selected based on the willingness of local producers to participate, ensuring practical relevance to local production systems. While the voluntary nature of participation introduces some selection bias, the spread across the four provinces and multiple seasons strengthens the generalizability of the results. Field sizes ranged from 35 to 123 hectares, representing commercial production fields in each region. The scale allowed for

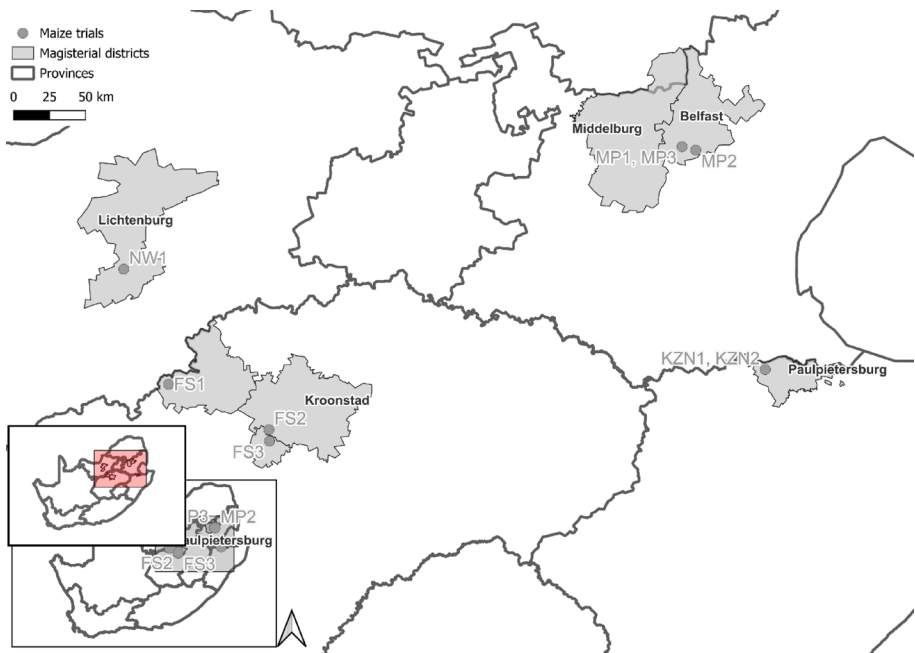


Fig. 1 Map of the provincial borders indicating locations for the maize fields used for trials between the 2020/2021 and 2023/2024 production seasons

adequate spatial replication and robust data collection. After data processing, approximately 3300 observational units were analysed per trial site, depending on the size of the field.

General annual climatic conditions for the four provinces are shown in Table 1, with rainfall (mm rain season⁻¹) for each site indicated in Fig. 2. From the 2020/2021 to the 2022/2023 seasons, La Niña conditions dominated the maize production areas of South Africa, resulting in above-average rainfall that facilitated increased yields in multiple field crops. In the 2023/2024 season, a significant El Niño event occurred, resulting in drier conditions across the primary maize-producing areas of South Africa. Supplementary Figures S-1 to S-5 present rainfall data (mm day⁻¹) and cumulative rainfall per season (CHIRPS, 2024). In-season rainfall in Fig. 2 and Supplementary Figures is indicated as rainfall received from 14 days before planting up to the harvest date.

Experimental design

The DIFM field trials are designed to generate data for localized crop responses to site-specific input factors (Bullock et al., 2019; Hegedus et al., 2023). Trials followed a Latin Square Design with seeding rate and nitrogen fertilizer rate as treatment factors (Fig. 3A–B), tailored to each field's equipment and operational requirements. Across all site-years, between five and nine seeding rates were evaluated per field, spanning minimum rates of

Table 1 General annual climatic conditions for the town nearest to the trial sites

Province	Town	General annual climatic conditions
Free State	Bothaville	• Köppen BSk: Semi-Arid Climate • Average temperature range: 16–22 °C • ~401–600 mm year⁻¹ • Hot summers with low rainfall and dry winters
	Hennenman	
KwaZulu-Natal	Paulpietersburg	• Köppen Cfa/Cwb: Humid Subtropical and Subtropical Highland Climates (varies with altitude) • Average temperature range: 17–26 °C • ~800–1200 mm year⁻¹ • Hot, humid summers with high rainfall and mild, dry winters
Mpumalanga	Wonderfontein	• Köppen Cwb: Subtropical Highland Climate • Average temperature range: 20–25 °C • ~601–800 mm year⁻¹ • Hot and humid summers with mild winters
North West	Ottosdal	• Köppen BSk: Semi-Arid Climate • Average temperature range: 16–22 °C • ~410–600 mm year⁻¹ • Hot summers with low rainfall and dry winters

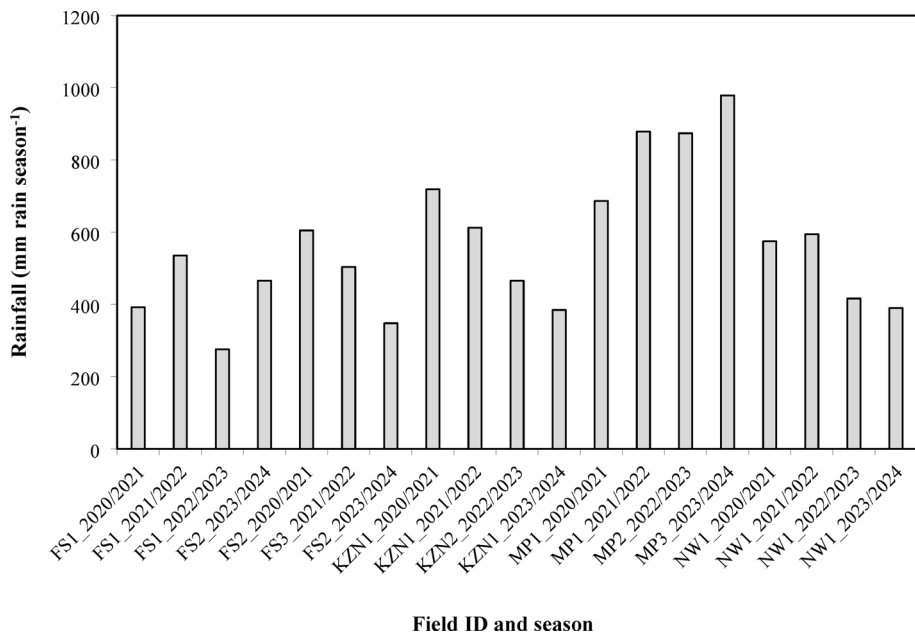


Fig. 2 Cumulative rainfall (mm rain season⁻¹) per province, field, and season, calculated from 14 days prior to planting until the harvest date for each field

approximately 10 000–30 000 seeds ha⁻¹ and maximum rates of approximately 50 000–82 000 seeds ha⁻¹, depending on region and season. Trials were designed using the open-source web application developed by the DIFM project collaborators (<https://difm.farm>, accessed on 31 December 2025). Fertilizer rates were varied at planting, using commonly applied fertilizer products representative of regional commercial practice. All other fertilizer applications during the growing season were applied uniformly across each field according to the producer's standard management practices. Each seeding rate × fertilizer rate combination was spatially replicated within fields, with a minimum of three replications per treatment combination, depending on field size.

Because trial designs were tailored to local conditions, treatment and trial setups varied across seasons and regions rather than being fully standardized across trials. The approach prioritized practical over experimental uniformity. Accordingly, the objective of this study was not to compare specific cultivars or fertilizer products across sites but to evaluate the relative agronomic and economic performance of three seeding rate approaches: the producers' standard *status quo*, an optimal flat rate, and an optimal variable rate. Fields were managed according to regionally appropriate agronomic practices, and cultivars represented commonly planted commercial hybrids selected based on producer preference, planting date, and local suitability rather than experimental control. Included cultivars ranged from medium- to long-season classes (Supplementary Tables S-1). Field characteristics, planting dates, cultivars, producers' *status quo* rates, and minimum and maximum seeding and fertilizer rates are summarized in Table 2, with full treatment details provided in Supplementary Table S-2.

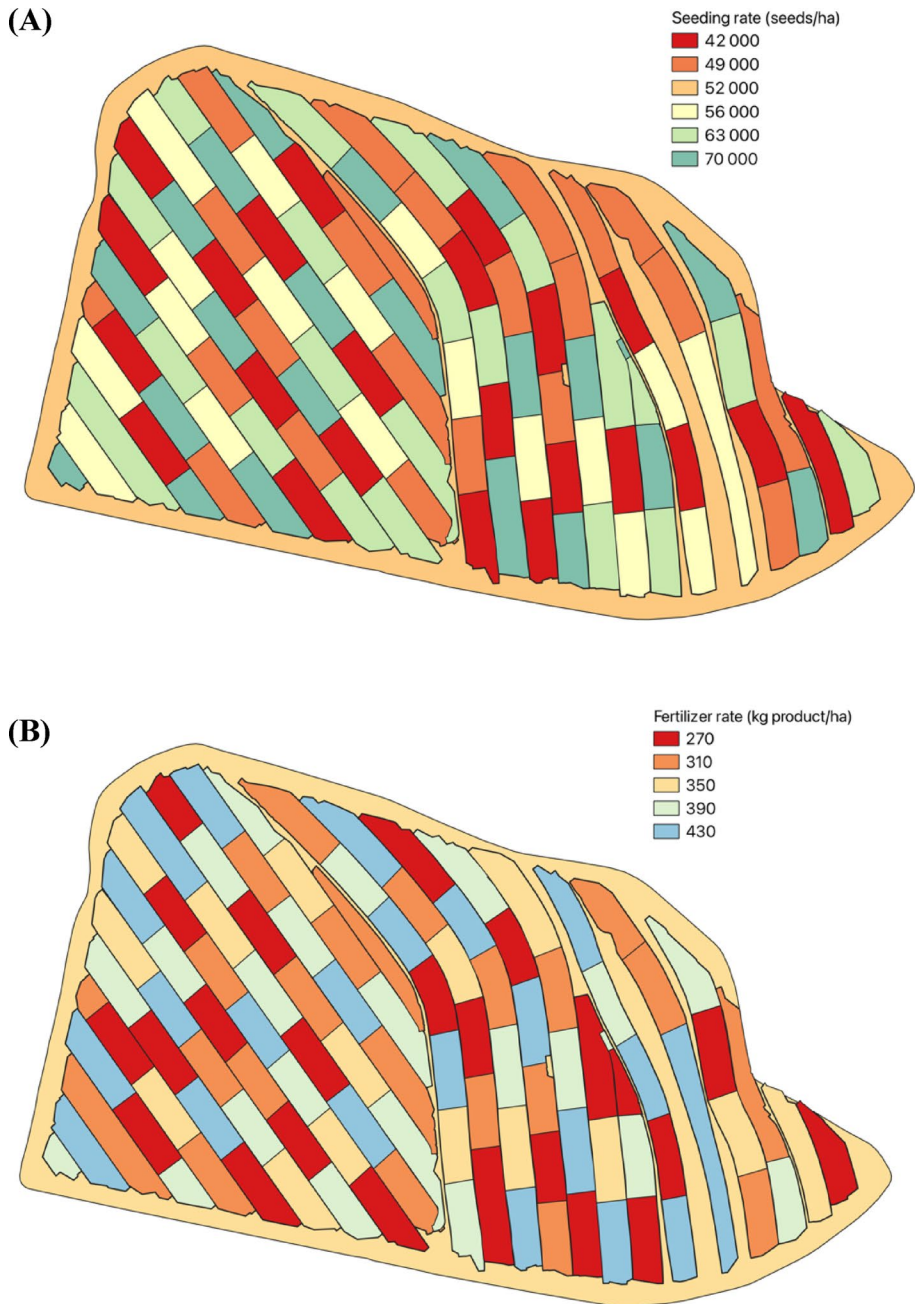


Fig. 3 Experimental layout of a trial in the Data Intensive Farm Management (DIFM) project, examples of maize seeding rate (A) and 3:0:1(33) fertilizer rate (B) trial plans for field MP2 in the Mpumalanga province for the 2022/2023 production season

Table 2 Trial design information, including location, field sizes, seasons, planting and harvesting dates, and seeding rate, fertilization rates

Field ID ^a	Field	Season	Planting date	Harvest date	Cultivar	Status quo seeding rate	Minimum seeding rate	Maximum seeding rate	Fertilizer product varied	Minimum nitrogen rate	Maximum nitrogen rate
						seeds ha ⁻¹				kg ha ⁻¹	
FS1	41.50	2020/2021	17 Nov 2020	6 March 2021	DKC 77-77BR	18 000	15 000	60 000	Urea	46	161
FS1	41.50	2021/2022	29 Nov 2021	7 July 2022	DKC 77-77BR	18 000	15 000	60 000		46	161
FS1	41.50	2023/2024	14 Dec 2023	6 April 2024	DKC 77-77BR	25 000	10 000	50 000		41	143
FS2	57.80	2020/2021	14 Nov 2020	24 April 2021	DKC 77-77BR	18 000	10 000	50 000		44	124
FS2	57.80	2021/2022	1 Nov 2021	24 May 2022	DKC 78-83R	18 000	10 000	50 000		44	124
FS3	75.60	2022/2023	26 Oct 2022	18 May 2023	DKC 77-77BR	18 000	15 000	50 000		42	124
FS2	57.80	2023/2024	8 Nov 2023	22 April 2024	DKC 77-77 BR	22 000	10 000	50 000		42	124
KZN1	41.90	2020/2021	26 Oct 2020	22 April 2021	P1197	55 000	30 000	65 000	1:2:1(36)+0.2% Zn	9	32
KZN1	41.90	2021/2022	16 Oct 2021	24 May 2022	P1197R	55 000	40 000	75 000		9	32
KZN2	122.90	2022/2023	15 Nov 2022	17 May 2023	P1517W & PAN3A-173	65 000	55 000	82 000		5	32
KZN1	41.90	2023/2024	4 Nov 2023	28 May 2024	P1197R & PAN 3R-524R	65 000	55 000	82 000		9	22
MP1	46.50	2020/2021	1 Nov 2020	21 May 2021	DKC 72-74R	50 000	40 000	70 000	2:3:2(22)+0.2% Zn	9	22
MP1	46.50	2021/2022	18 Oct 2021	21 July 2022	DKC 72-74R	50 000	40 000	70 000	1:2:1(36)+0.2% Zn	16	32
MP2	35.00	2022/2023	11 Oct 2022	22 June 2023	PAN 4R-528R	52 000	42 000	70 000	3:0:1(33) & 11:7:4(28)	57	120
MP3	196.40	2023/2024	25 Oct 2023	3 July 2024	P1788R	52 000	42 000	70 000	6:1:1(33) & 11:7:4(28)	65	109
NW1	36.00	2020/2021	18 Nov 2020	13 July 2021	DKC 76-77BR	18 000	14 700	29 400	3:0:1(45) & MAP	21	70

Table 2 (continued)

Field ID ^a	Field	Season	Planting date	Harvest date	Cultivar	Status quo seeding rate	Minimum seeding rate	Maximum seeding rate	Fertilizer product varied	Minimum nitrogen rate	Maximum nitrogen rate
ha											
NW1	36.00	2021/2022	7 Dec 2021	1 Aug 2022	DKC 76-77BR	18 000	16 000	30 000	2:0:1(47) & MAP	21	65
NW1	36.00	2022/2023	19 Nov 2022	3 July 2023	DKC 76-77BR	25 000	20 000	30 000		56	96
NW1	36.00	2023/2024	21 Dec 2023	28 June 2024	DKC 76-77BR	22 000	18 000	24 000	3:2:1(36.5)	24	53

^a Field ID includes an abbreviation of the province with a field number (FS=Free State, KZN=KwaZulu-Natal, MP=Mpumalanga, NW=North West)

^b Refer to Sect. 2.2 of the Materials and Methods for the experimental design and the fertilizer rates used

^c The nitrogen units were combined where two products were varied together at fields MP2, MP3, and NW1

For the Free State province, trials were planted with a 2015 Equalizer SL 16/914 planter with 0.915 m row widths, while harvesting took place with a John Deere S760 combine equipped with a 35-foot John Deere Flex Draper header. At Paulpietersburg in the Kwa-Zulu-Natal province, trials were planted with a Monosem NXM 8-row trial, and the trials were harvested with a Case 6140 combine harvester. The Mpumalanga province trials were planted with a John Deere 1755 Seedstar2 with a Greenstar rate controller at row widths of 0.76 m, and the trials were harvested with a John Deere S760 harvester. The trials in the North West province were seeded with a 12-row no-till Equalizer SL2 planter at 0.913 m row widths and harvested with a Claas Lexion 7600 Terra Trac harvester.

Data collection, processing, and preparation for analysis

A standardized procedure for data collection, cleaning, and processing was applied across all DIFM trials, as outlined by Bullock et al. (2019), Edge et al. (2024), and Trevisan et al. (2021). Before planting, digital prescription maps with required seeding (Fig. 4A) and fertilization rates were provided to producers (Fig. 4A; Supplementary Table S-2). During the growing season, as-planted, as-applied, and yield monitor data were collected from the variable rate equipment and combine harvesters, generating spatially referenced observations with associated GPS coordinates (Fig. 4B–C).

Recorded as-planted seeding rate (seeds ha^{-1}), as-applied input rate (kg N ha^{-1}), and yield (t ha^{-1}) GeoJSON datasets were processed using a structured geometric and statistical workflow to generate analysis-ready observations. The process starts with spatial-temporal alignment, where spatial datasets were projected to a common UTM coordinate system; headland areas on the field edges and borders as well as transient mechanical noise from sharp turns were excluded. Data were cleaned by removing extreme values (records that fall outside four standard deviations of the mean) and erroneous observations (e.g., records that exhibit anomalous harvesting speed and widths). During the data cleaning algorithm, a buffer was applied at the end of each trial-design-plot to account for transitions between application rates. The size of the transition zone buffer is determined endogenously in the data cleaning algorithm based on the differences between as-applied, as-planted, and trial design target rates.

Yield records exceeding four standard deviations from the field mean were excluded, together with observations associated with implausible harvesting speeds or effective swath widths. This filtering ensured statistical integrity while retaining the underlying spatial variability of crop response. A key feature of the workflow was the transformation of discrete yield monitor point data into area-weighted yield polygons. Polygons were constructed using recorded swath width, point spacing, and machine heading, thereby representing the physical footprint of the harvesting operation. Overlapping harvest passes were identified and removed to prevent duplication of yield observations.

Cleaned yield polygons were spatially intersected with as-planted and as-applied datasets to ensure that each observation represented a consistent combination of yield and applied seeding rate. These intersected polygons were subsequently aggregated into standardized subplots of approximately 12–24 m in length, based on minimum machine travel distance and similarity in seeding or fertilizer rates.

Within each subplot, yield (t ha^{-1}) was calculated as the area-weighted mean of all intersected yield polygons, and seeding rate (seeds ha^{-1}) was calculated as the mean recorded

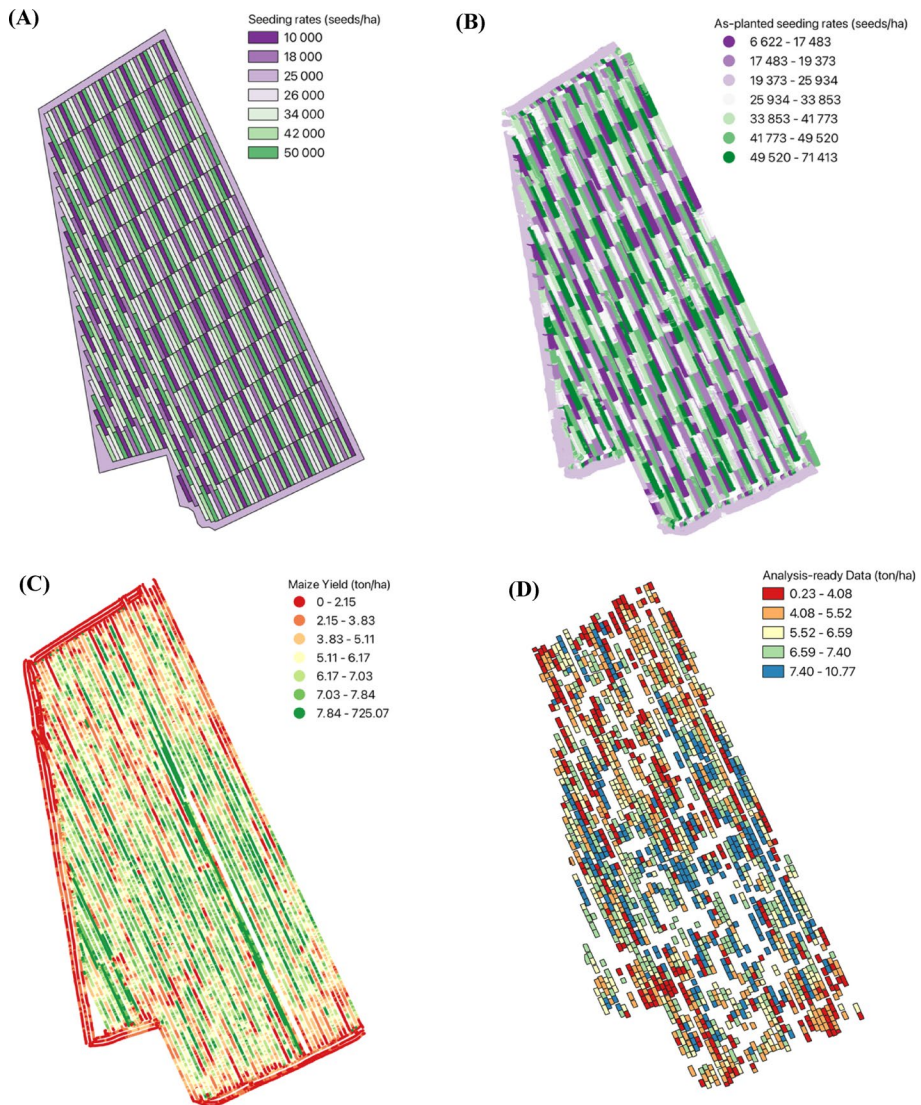


Fig. 4 Maize seeding rate trial plan of season 2023/2024 for field FS1 in the Free State province (10 to 50 thousand seeds ha^{-1}) (**A**), as-planted seeding rates (**B**), yield (t ha^{-1}) (**C**), and analysis-ready data (t ha^{-1}) (**D**)

as-planted rate across the same spatial footprint. These subplots constitute the analysis-ready data (Fig. 4D), representing internally consistent observational units suitable for high-resolution agronomic and economic analyses.

Management zones were delineated using a response-based, data-driven approach designed to capture spatial variation in the economic sensitivity of crop response to seeding rate (Fig. 5). Rather than grouping areas based on absolute yield or profit levels, zones were defined according to similarity in the marginal response of profit to changes in seeding



Fig. 5 Example of management zones delineated based on analysed data from the completely randomized trial data for seeding rates for field FS1 in the 2023/2024 production season

rate. The zoning procedure followed a two-step process. First, a Geographically Weighted Regression (GWR) model with an adaptive Gaussian kernel was fitted for each field to quantify spatial non-stationarity in the relationship between profit and seeding rate. The GWR framework estimates a local regression at each observation location, assigning greater weight to nearby observations, and produces spatially varying coefficients describing the local sensitivity of profit to seeding rate. Second, the resulting local GWR coefficients for seeding rate were classified into a predefined number of management zones using a quantile-based grouping approach. Zones were constructed to ensure a minimum number of observations per zone and to remain within a practical upper limit on the number of zones. This resulted in approximately equal-sized groups representing areas of relatively low,

medium, and high economic responsiveness to changes in seeding rate. Each management zone therefore represents a spatially contiguous area where the economic response of profit to seeding rate is similar. This approach generates response-based management zones that highlight differences in economic sensitivity to seeding decisions, rather than differences in mean yield or profit alone, thereby supporting spatially differentiated input optimization.

Optimal flat- and variable seeding rates were determined using an economic optimization framework based on estimated profit–seeding rate relationships (Baum et al., 2025). For each field and management zone, profit response to seeding rate was modeled using Generalized Additive Models (GAMs), which allow for flexible, potentially non-linear relationships without imposing a predefined functional form. The optimal seeding rate was identified as the rate that maximized predicted profit, corresponding to the peak of the estimated profit–seeding rate curve where the marginal changes in profit transition from positive to negative. A flat, uniform optimal seeding rate was calculated by fitting a single profit–seeding rate relationship using all analysis-ready observations within a field, representing the economically optimal rate under uniform management. In contrast, variable-rate seeding recommendations were derived by fitting separate profit–seeding rate relationships for each management zone, allowing for the calculation of zone-specific profit-maximizing seeding rates. This framework ensures that both flat and variable-rate recommendations are derived consistently from observed profit responses and reflect spatial differences in economic sensitivity to seeding rate, rather than yield alone.

Data are reported for three seeding rate approaches:

- **Status quo rate** defined as the producer’s typical seeding rate.
- **Optimal flat rate** a single profit-maximizing seeding rate calculated for the entire field, and.
- **Optimal variable rate** the average of three zone-specific profit-maximizing seeding rates.

To evaluate the effects of different seeding rate approaches on yield, linear mixed-effects models were used to account for the hierarchical structure of the data. Yield observations were nested within fields, towns, and years. Models were fitted using the *lmer()* function in the *lme4* package in RStudio (RStudio Team, 2023), with seeding rate strategy as a fixed effect and random intercepts for year, town, and field nested within town. Estimated marginal means were obtained using the *emmeans* package, and post-hoc pairwise comparisons were conducted using Tukey’s method at a 5% significance level. Model assumptions were assessed through inspection of residuals for normality and homoscedasticity.

This manuscript does not analyse fertilizer responses, even though fertilizer rates were a treatment factor in the experimental design. A linear mixed model, accounting for random effects of field and growing season, showed no significant interaction was found between seeding rate and fertilizer rate regarding yield outcomes ($p=0.214$). Seeding rate was a significant driver of yield ($p<0.001$), whereas fertilizer rate showed no main effect ($p=0.523$). Consequently, seeding rate and fertilizer rate were analysed independently, and all results presented here relate solely to seeding rate responses. This is consistent with findings from other DIFM datasets. Yield responses to seeding rate were estimated using observations pooled across the range of fertilizer rates applied within each field, representing average

seeding rate responses under prevailing soil fertility conditions rather than optimizing seeding rate at a specific nitrogen level.

Results and discussion

Results from the linear mixed-effects model indicate that the seeding rate management approach significantly influenced maize performance across sites and seasons when evaluated at profit-maximizing seeding rates. Both the profit-optimizing flat rate and variable rate approaches led to higher average yields compared to the *status quo* seeding rates ($P < 0.05$), reflecting outcomes achieved at economically optimum input levels rather than maximum agronomic yield. On average, the optimal variable rate approach increased yield by 1.57 t ha^{-1} relative to the *status quo*, while the optimal flat rate approach increased yield by 1.05 t ha^{-1} . Estimated marginal means revealed a consistent ranking of outcomes from *status quo* rate to optimal flat rates to optimal variable rates, with pairwise comparisons confirming differences among all three approaches ($P < 0.001$).

Despite the strong main effects captured through the model, interaction model comparisons indicated that the magnitude of treatment responses varied by location and season. This implies that while the general ranking of optimal variable rate > optimal flat rate > *status quo* was consistent, the economic and agronomic benefits of optimization are site-specific. Variability in response magnitude likely reflects differences in soil properties, rainfall amount and distribution, baseline seeding rates, and other management practices across regions. This site-specific dependence underscores a key principle of precision agriculture: optimal input decisions are context-dependent rather than transferable across environments (Bullock et al., 2002; Khan et al., 2023). Consequently, the results should not be interpreted as prescriptive recommendations for uniform seeding rates but rather as evidence of the potential performance gap between current management practices and economically optimized strategies when evaluated retrospectively under realized conditions.

Producers generally select seeding rates that perform acceptably across a wide range of possible outcomes, rather than optimizing for any single realized year. Empirical evidence further shows that seeding rate decisions are sensitive to economic, soil, and management conditions, with responses differing across crops, soil quality, tillage systems, and genetic traits (Che et al., 2025; Ruiz et al., 2026). However, the profit-optimization framework applied in this study evaluates seeding rate responses retrospectively for individual site-years. As such, the comparisons between producer *status quo* rates and optimized rates illustrate the direction and magnitude of potential deviations between current practices and profit-optimizing strategies, rather than implying producers should target year-specific optimums in advance.

Across sites and seasons, optimized flat rate recommendations typically suggested higher seeding rates than current practices, although several cases of recommended reductions were identified (Fig. 6). These yield-neutral or yield-positive reductions highlight that deviations from the *status quo* do not necessarily imply intensification but may also reveal opportunities to reduce input costs without sacrificing yield. This finding reinforces the importance of evaluating seeding rate decisions through an economic lens rather than focusing solely on yield outcomes (Lindsey et al., 2018).

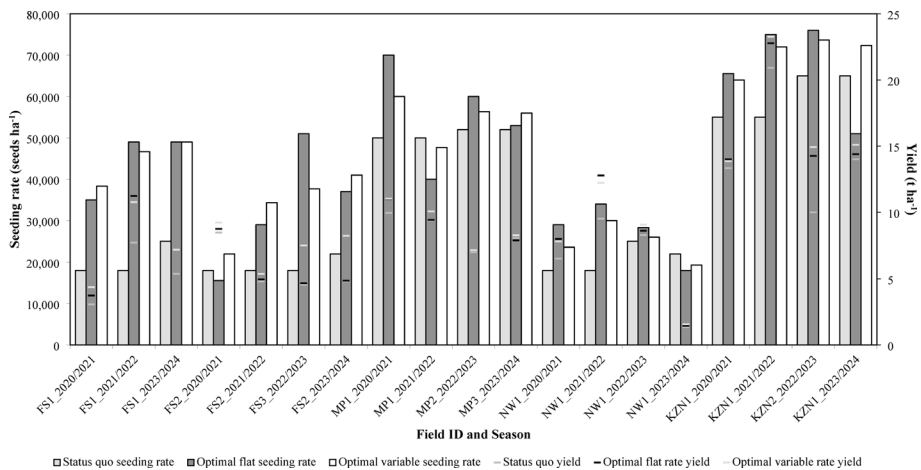


Fig. 6 Maize seeding rates (seeds ha^{-1}) for the *status quo*, optimal flat rate, and optimal variable rate with corresponding yields (t ha^{-1}) for each field located in four different provinces in South Africa from the 2020/2021 to 2023/2024 production seasons

A summary of the *status quo* rates, calculated profit-maximizing seeding rates for the optimal flat and optimal variable rates, and yield for all sites and seasons is presented in Fig. 6. The individual seeding rates per management zone per field that collectively contribute to the optimal variable rate are indicated in Tables 4, 5, 6 and 7. Only the average for all three management zones is indicated and discussed below. Yield response curves for the varied seeding rates are included in Figs. 7, 8, 9 and 10 with Standard Errors for the yields in Fig. 6 presented in Supplementary Table S-3.

Responses to profit-maximizing seeding rate adjustments varied among towns, provinces, and seasons, reflecting differences in yield potential, management practices, and climatic risk. Figures 7, 8, 9 and 10 show the results of the yield response curve for the *status quo* seeding rate and profit-optimizing seeding rate for each field. In Bothaville (Free State province), profit-maximizing recommendations consistently indicated increases in seeding rate relative to producers' *status quo* rates, translating into yield gains under favorable conditions. The effect was pronounced in 2022/2023 at field FS3, when the profit-maximizing flat- and variable strategies resulted in yield benefits exceeding 3 t ha^{-1} (Fig. 7G).

In contrast, Hennenman (Free State province) showed more variable profit-maximizing responses across seasons. For example, in 2020/2021 at field FS1, profit-maximizing strategies suggested reductions in seeding rate relative to the *status quo*, yet still resulted in yield increases of 0.28 and 0.76 t ha^{-1} for the optimal flat- and variable rate approaches, respectively (Fig. 7A). Illustrate that higher profitability can arise not only from increasing yields but also from reducing input costs where marginal yield responses to additional seed are limited.

Near Wonderfontein (Mpumalanga province), profit-maximizing recommendations generally involved smaller adjustments, reflecting already high baseline seeding rates ($50\,000$ – $52\,000 \text{ seeds ha}^{-1}$) used by producers in this region compared to the Free State and North West provinces. In a season like 2023/2024 at field MP3, profit-maximizing strategies suggested reductions of up to 20%, with negligible or even positive yield effects (Figure 8D).

Table 4 Average optimal seeding rate (seeds ha⁻¹) for each management zone with the average yield (t ha⁻¹) per zone for the fields FS1, FS2, and FS3 near Botahville and Hennenman in the Free State province for the 2020/2021 to 2023/2024 production seasons. Abbreviation: SE=Standard Error

Field ID	Season	Management Zone	Seeding rate (seeds ha ⁻¹)	Yield (t ha ⁻¹)	Yield SE (t ha ⁻¹)
FS1	2020/2021	1	14 000	4.88	0.16
		2	42 000	4.81	0.16
		3	59 000	3.72	0.15
FS1	2021/2022	1	42 000	9.51	0.24
		2	45 000	10.04	0.20
		3	52 000	12.70	1.15
FS1	2023/2024	1	49 000	6.60	0.18
		2	49 000	7.42	0.12
		3	49 000	7.60	0.17
FS2	2020/2021	1	15 000	10.10	0.15
		2	37 000	8.88	0.08
		3	42 000	9.23	0.12
FS2	2021/2022	1	21 000	5.50	0.11
		2	39 000	4.44	0.11
		3	50 000	6.40	0.19
FS3	2022/2023	1	49 000	6.42	0.07
		2	49 000	7.67	0.17
		3	49 000	8.60	0.21
FS2	2023/2024	1	31 467	7.12	0.09
		2	47 476	8.46	0.10
		3	49 000	9.27	0.16

Table 5 Average optimal seeding rate (seeds ha⁻¹) for each management zone with the average yield (t ha⁻¹) per zone for field NW1 near Ottosdal in the North West province from the 2020/2021 to 2023/2024 production seasons. Abbreviation: SE=Standard Error

Field ID	Year	Management Zone	Seeding rate (seeds ha ⁻¹)	Yield (t ha ⁻¹)	Yield SE (t ha ⁻¹)
NW1	2020/2021	1	14 000	8.07	0.49
		2	26 000	7.79	0.27
		3	30 000	7.80	0.21
	2021/2022	1	30 000	11.20	0.13
		2	30 000	12.62	0.13
		3	30 000	12.77	0.17
	2022/2023	1	20 000	9.50	0.14
		2	29 000	8.85	0.10
		3	30 000	8.92	0.16
	2023/2024	1	18 000	1.90	0.04
		2	18 000	1.52	0.03
		3	22 000	1.46	0.03

Highlighting opportunities to improve profitability through cost savings rather than yield enhancement when yield potential is constrained.

Similarly, in Ottosdal (North West province), profit-maximizing seeding rate responses varied strongly by season at field NW1. Large increases were proposed in 2021/2022, and reductions in 2023/2024 when yields were extremely low due to adverse climatic condi-

Table 6 Average optimal seeding rate (seeds ha⁻¹) for each management zone with the average yield (t ha⁻¹) per zone for fields MP1, MP2, and MP3 near Wonderfontein in the Mpumalanga province from the 2020/2021 to 2023/2024 production seasons. Abbreviation: SE=Standard Error

Field ID	Season	Management Zone	Seeding rate (seeds ha ⁻¹)	Yield (t ha ⁻¹)	Yield SE (t ha ⁻¹)
MP1	2020/2021	1	70 000	10.35	0.05
		2	70 000	11.01	0.06
		3	70 000	11.77	0.06
MP1	2021/2022	1	40 000	9.81	0.09
		2	62 215	9.63	0.05
		3	70 000	10.16	0.07
MP2	2022/2023	1	49 000	7.00	0.10
		2	55 000	7.09	0.12
		3	69 000	7.85	1.28
MP3	2023/2024	1	53 578	7.79	0.12
		2	64 387	8.66	1.67
		3	69 260	9.25	1.17

Table 7 Average optimal seeding rate (seeds ha⁻¹) for each management zone with the average yield (t ha⁻¹) per zone for fields KZN1 and KZN2 near Paulpietersburg in the KwaZulu-Natal province from the 2020/2021 to 2023/2024 production seasons. Abbreviation: Standard Error

Field ID	Season	Management Zone	Seeding rate (seeds ha ⁻¹)	Yield (t ha ⁻¹)	Yield SE (t ha ⁻¹)
KZN1	2020/2021	1	64 000	14.47	0.27
		2	64 333	13.39	0.28
		3	64 333	14.02	0.24
KZN1	2021/2022	1	74 000	21.75	0.18
		2	74 000	22.50	0.24
		3	74 000	23.50	0.23
KZN2	2022/2023	1	62 000	14.06	0.20
		2	76 000	14.95	0.19
		3	81 000	16.06	0.31
KZN1	2023/2024	1	55 000	14.76	0.07
		2	82 000	15.05	0.07
		3	82 000	15.89	0.07

tions. Yields of 1.35 t ha⁻¹ were reached in 2023/2024 compared to more than 6 t ha⁻¹ harvested in the previous three seasons on the same field (Figure 9). These contrasting outcomes underscore that profit-maximizing seeding rates are sensitive to seasonal risk and yield potential, particularly in semi-arid environments.

In KwaZulu-Natal, near Paulpietersburg, producers applied the highest *status quo* rates of all sites (55 000–65 000 seeds ha⁻¹). Nevertheless, profit-maximizing strategies indicated further seeding rate increases in three out of four seasons, reflecting the higher and more stable yield potential of this region. In 2023/2024 (Fig. 10C), however, the optimal flat rate suggested a reduction without yield loss, while the variable approach still recommended localized increases, illustrating how variable rate seeding and reallocating seed spatially can maximize economic returns even when whole-field adjustments are not warranted (Schimelpennig, 2016).

Optimal plant population and row spacing will ultimately be a compromise between obtaining high yields and minimizing the potential for crop failure in semi-arid environments

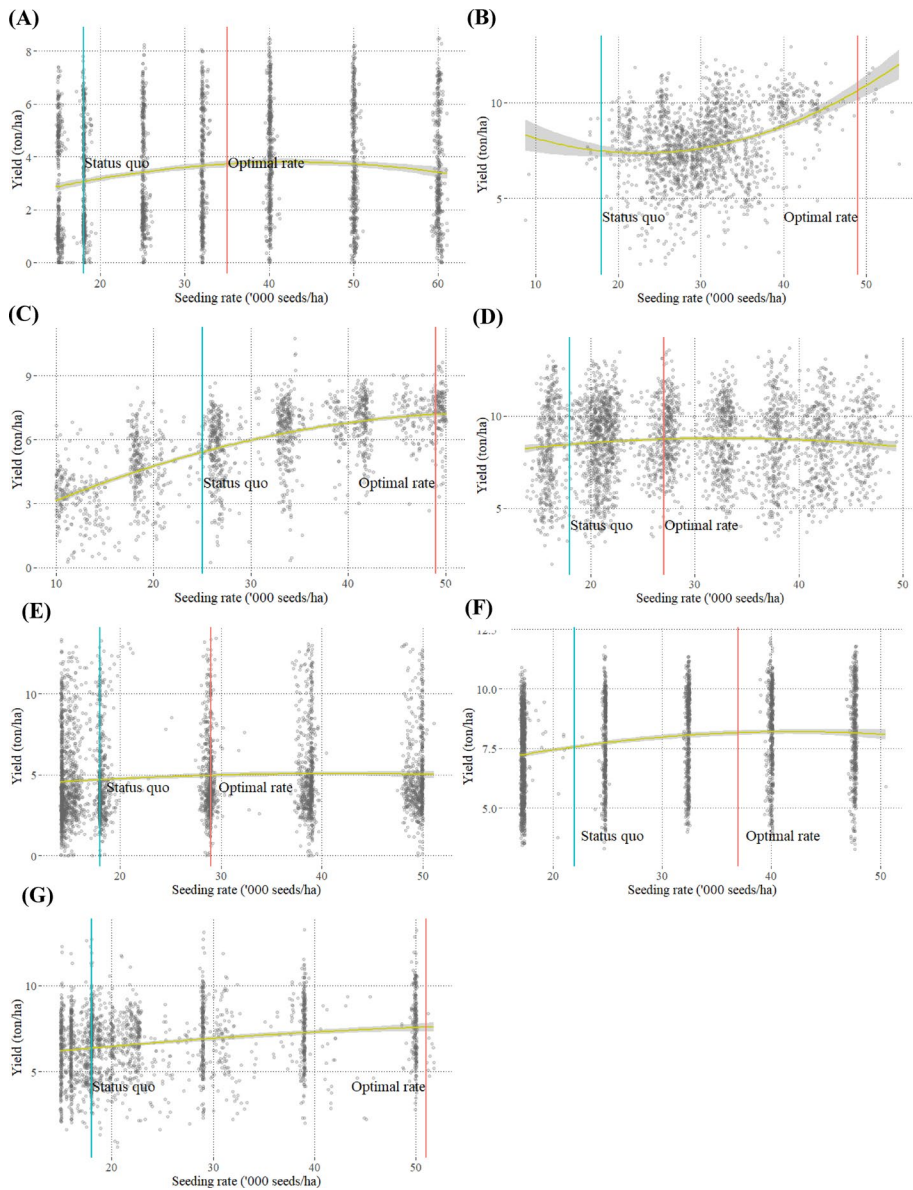


Fig. 7 Yield response (t ha^{-1}) curves based on varied seeding rates (seeds ha^{-1}) for fields in the Free State province, field FS1 in 2020/2021 (A), 2021/2022 (B), and 2023/2024 (C), field FS2 in 2020/2021 (D), 2021/2022 (E), and 2023/2024 (F), and field FS3 in 2022/2023 (G). Blue line indicates the producers usual seeding rate and the red line the determined profit-optimizing seeding rate

(Haarhoff & Swanepoel, 2022). Rainfall patterns across seasons and locations reflected both the inherent climatic differences between provinces and year-to-year variability (Fig. 2). The Free State and North West provinces generally received lower annual rainfall ($<600 \text{ mm year}^{-1}$), aligning with their semi-arid classification. These areas also showed large seasonal

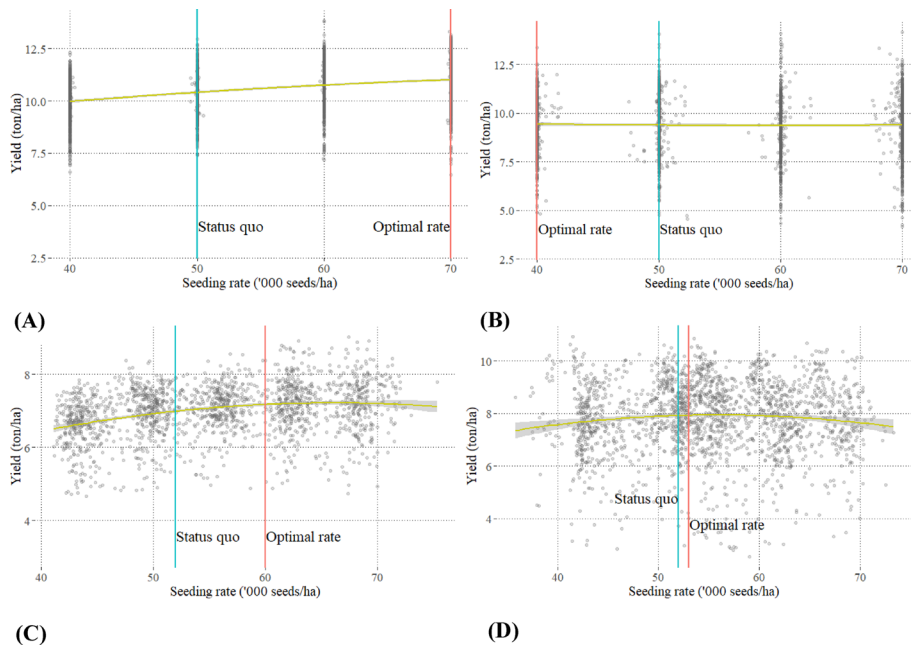


Fig. 8 Yield response (t ha^{-1}) curves based on varied seeding rates (seeds ha^{-1}) for fields in the Mpumalanga province, field MP1 in 2020/2021 (A) and 2021/2022 (B), field MP2 in 2022/2023 (C) and field MP3 in 2023/2024 (D). The blue line indicates the producers usual seeding rate and the red line indicates the determined profit-optimizing seeding rate

swings, with drier seasons such as 2020/2021 in Bothaville (~ 380 mm) and 2023/2024 in Ottosdal (~ 390 mm) likely imposing water stress during critical maize growth stages. In contrast, the Mpumalanga and KwaZulu-Natal provinces typically received higher rainfall, frequently exceeding 700 mm, with several seasons surpassing 900 mm year $^{-1}$. For example, 2020/2021 in KwaZulu-Natal and 2023/2024 in Mpumalanga. These wetter seasons in subhumid to humid zones would support higher yield potential and may permit higher optimum plant populations, though excessive rainfall in certain years could also increase disease pressure or lead to temporary waterlogging.

Seasonal conditions appeared to be a major driver of profit-maximizing seeding rate recommendations and yield outcomes. Seasons with higher rainfall and therefore increased yield potential, such as field FS1 in 2021/2022 and field KZN1 in 2021/2022, showed the largest yield benefits from increased seeding rates. Conversely, seasons with drier or other yield-limiting conditions, such as field NW1 in 2023/2024, saw smaller yield gains or no advantage from higher plant populations. In 2023/2024, field FS1 had contradictory results, which showed an increase in yield of 1.82 t ha^{-1} with an increase in seeding rate of 24 000 seeds ha^{-1} in a relatively dry season with less than 300 mm of rain. These patterns suggest that optimal seeding rates are not fixed but rather depend on site- and season-specific characteristics—such as soil water availability, soil water content at planting, and rainfall amount and distribution—and on the interaction of these environmental factors with management practices (Nielsen et al., 2009; Haarhoff & Swanepoel, 2022).

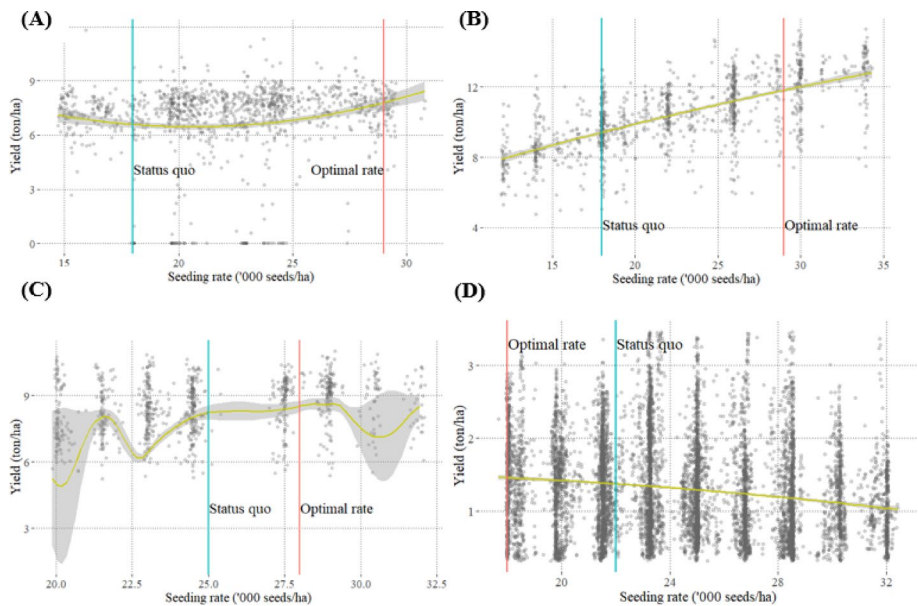


Fig. 9 Yield response (t ha^{-1}) curves based on varied seeding rates (seeds ha^{-1}) for fields in the North West province, field NW1 in 2020/2021 (A), 2021/2022 (B), 2022/2023 (C), and 2023/2024 (D). The blue line indicates the producer's usual seeding rate and the red line indicates the determined profit-optimizing seeding rate

Promoting more efficient uptake and use of available soil water and nutrients using greater plant densities is critical in semi-arid environments for achieving sustainable yields under rainfed conditions (Haarhoff & Swanepoel, 2018). Despite these benefits, producers in South Africa's semi-arid environments still opt for low plant populations ($< 30\,000$ plants ha^{-1}) established at a wide row spacing (> 0.91 m) to minimize the risk of crop failure. In a systematic review on maize plant population studies across different climatic zones by Haarhoff and Swanepoel (2018), a large variation in optimum densities was reported. In arid environments, yields remained low across all populations, with no clear response. Plant population explained little variation in yield in subhumid environments, while yields peaked at 9 tons ha^{-1} in semiarid environments, with an estimated optimum of $140\,000$ plants ha^{-1} . In humid environments, yields increased up to 11 t ha^{-1} at $120\,000$ plants ha^{-1} before declining (Haarhoff & Swanepoel, 2018). Highlighting that plant population–yield relationships are strongly environment-dependent, with higher optimum densities more likely in higher-potential environments. Lower populations reduce the risk of crop failure in dry years, although they may result in yield penalties in seasons with favorable rainfall (Birch et al., 2008).

While both seeding rate approaches often suggested similar directions of change in seeding rate, variable rate recommendations tended to be slightly higher than the flat rate suggestions and often resulted in larger yield differences. The largest advantages of variable rates occurred in fields with strong spatial heterogeneity, where adjusting seeding rates to in-field yield potential could better exploit favorable zones without over-seeding less productive

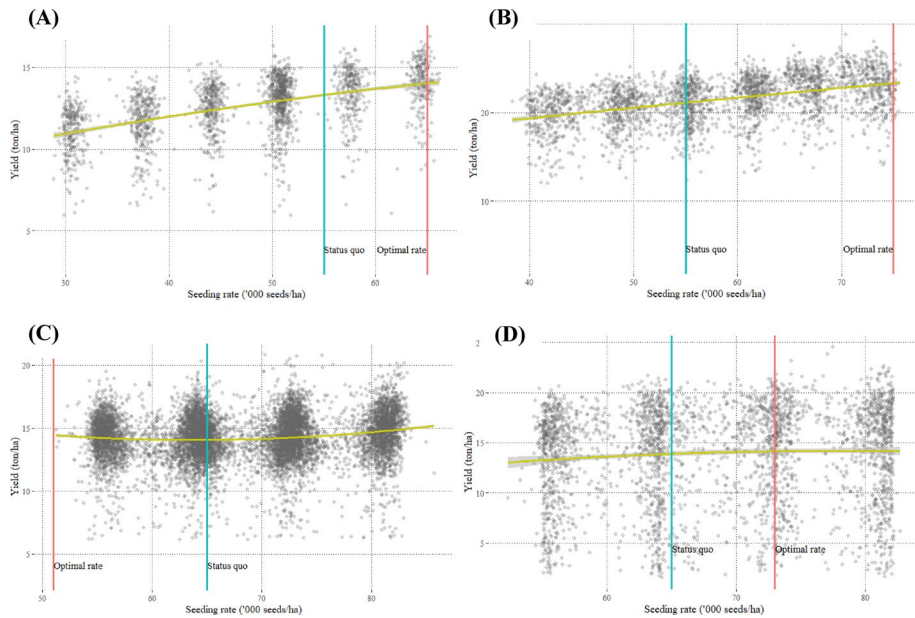


Fig. 10 Yield response (t ha^{-1}) curves based on varied seeding rates (seeds ha^{-1}) for fields in the Kwa-Zulu-Natal province, field KZN1 in 2020/2021 (A), 2021/2022 (B), and 2023/2024 (C), and field KZN2 in 2022/2023 (D). The blue line indicates the producer's usual seeding rate and the red line indicates the determined profit-optimizing seeding rate

areas. In more uniform fields or in seasons where overall yield potential was constrained, the benefits of variable rates over flat rates were smaller or negligible.

Across all sites and seasons, profit-maximizing flat rate recommendations mostly proposed increasing seeding rates compared to current practices, with only four cases recommending reductions. The suggested increases varied from modest ($<10\%$ at field MP2 in 2022/2023) to large ($>100\%$ at field FS3 in 2022/2023 and field FS1 in 2021/2022). Yield improvements matched these changes, with larger seeding rate increases leading to more significant yield gains—at field FS1, yield increases of 3.53 t ha^{-1} (up from 7.71 to 11.24 t ha^{-1}) were seen in 2021/2022, and at field NW1 in 2021/2022, yield increased by 3.27 t ha^{-1} (up from 9.52 to 12.79 t ha^{-1}). Conversely, in seasons with lower yield potential or where current seeding rates were already high, yield gains were small or even negative. Such as a 0.19 t ha^{-1} reduction from 8.07 t ha^{-1} at field MP3 in 2023/2024 with an increase of $1\,000$ seeds ha^{-1} from the *status quo* rate of $52\,000$ seeds ha^{-1} .

In arid and semi-arid environments, where rainfed maize production is limited by low and highly variable rainfall, grain yield responses to plant populations are often nullified within a limited range of densities. They become strongly negative when populations exceed the water-limited carrying capacity of the production system. Under such conditions, both under- and over-seeding can result in yield penalties, particularly in seasons where drought stress develops during the critical growth stages of the crop. Haarhoff and Swanepoel (2018) reported that maize grain yield in South African dryland systems was relatively insensitive to plant population within a moderate range but declined sharply at

excessive densities, emphasizing the need for environment-specific optimization rather than uniform recommendations.

In contrast, studies from higher-yielding, more stable environments demonstrate stronger and more consistent yield responses to seeding rate. In central Iowa, Licht et al. (2017) observed pronounced seasonal variability in optimal seeding rates, ranging from 61 750 to 111 150 seeds ha⁻¹, with an average optimum of 86 450 seeds ha⁻¹. Similarly, Kruger et al. (2018) reported lower optimal seeding rates in water-limited Western Nebraska (approximately 20 000 seeds ha⁻¹) to maximize grain yield and ear number per unit area. Highlighting the role of regional climate and resource availability. In north-eastern Hungary, Bűdi et al. (2025) identified profit-maximizing seeding rates of 67 000 seeds ha⁻¹ and 72 000 seeds ha⁻¹ for different hybrids across consecutive seasons. This reinforces earlier findings by Miao et al. (2006) that optimal plant populations are strongly influenced by hybrid characteristics, management practices, and environmental conditions. These findings underscore that optimal plant population is not fixed but must be aligned with expected water availability and seasonal risk.

Profit-maximizing variable rate recommendations also mostly suggested increases over producers' *status quo* rates, except for reductions at field MP1 in 2021/2022 and field NW1 in 2023/2024. Often, these optimal variable rates were slightly higher than optimal flat rates for the same season, reflecting a tendency to increase seeding rates more in high-yielding zones (Tables 4, 5, 6 and 7). Two management zones usually suggested a seeding rate towards the higher end of the spectrum, while one suggested a much lower rate.

Apparent inconsistencies between yield potential and profit-maximizing seeding rate among management zones highlight the distinction between absolute yield and yield response to seeding rate. Yield potential reflects the combined effects of multiple limiting factors (van Ittersum et al., 2013), whereas the economically optimal seeding rate is determined by the marginal yield response to additional maize plants. Consequently, zones with lower realized yields may still respond positively to increased seeding rates if plant density is limiting, while higher-yielding zones may exhibit limited response to further increases in population.

In some fields, management zones converged on similar optimal seeding rates or exhibited comparable yields. For example, this indicates that spatial yield variability does not always translate into economically meaningful differences in seeding rate response. In such cases, variable-rate seeding offers a limited advantage over flat-rate management, and this outcome is itself informative for guiding management decisions. Fields FS1 (2023/2024) and FS3 (2022/2023) resulted in management zones where 49 000 seeds ha⁻¹ were identified as optimal rates (Table 4). The difference between the lowest and highest yield between the management zones was 1 t ha⁻¹ at FS1 and 2.18 t ha⁻¹ at FS3. Results for field NW1 in 2021/2022 showed that 30 000 seeds ha⁻¹ is the optimal rate for all three management zones, with a difference of 1.57 t ha⁻¹ between the lowest and highest yield (Table 5). In 2023/2024, the same field had slight differences between the rates for the management zones, with two zones indicating 18 000 seeds ha⁻¹ and one zone 22 000 seeds ha⁻¹ as optimal rates. Yield differences were approximately 0.5 t ha⁻¹ between the lowest and the highest rate. At field MP1 in 2020/2021, the same rate of 70 000 seeds ha⁻¹ was determined for all three management zones, with a yield difference of 1.42 t ha⁻¹ (Table 6). In KwaZulu-Natal, at field KZN1 in 2020/2021, a small difference of 333 seeds ha⁻¹ was determined between the management zones (from 64 000 to 64 333 seeds ha⁻¹), together with a small

yield difference of 0.5 t ha^{-1} (Table 7). The same field in 2021/2022 resulted in the same optimal seeding rate of $74\,000 \text{ seeds ha}^{-1}$ for all the management zones, with a yield difference of 1.75 t ha^{-1} .

The greatest yield gains from variable rate seeding were in high-rainfall, high-yield seasons, such as at field KZN2 in 2022/2023 with a 4.93 t ha^{-1} increase from 10 t ha^{-1} and field FS2 in 2023/2024 with 3.43 t ha^{-1} from 4.80 t ha^{-1} . In some cases, variable rates outperformed flat rates (field FS3 in 2022/2023 and field FS2 in 2023/2024, field FS1 in 2020/2021, and KZN2 in 2022/2023). In other cases, yield gains were similar for both management approaches (field FS1 in 2023/2024).

Yield response to seeding rate depends on productivity level, with higher-yielding environments requiring higher populations. Pioneer trials showed the economic optimum seeding rate increased from approximately $76\,600 \text{ seeds ha}^{-1}$ at 9.4 t ha^{-1} to over $96\,400 \text{ seeds ha}^{-1}$ at 15.1 t ha^{-1} (Pioneer, 2025). Li Yang et al. (2022) showed that maize yield responded parabolically to seeding rate, with an agronomic optimal seeding rate identified for each soil organic matter level. The agronomic optimum seeding rate increased stepwise with higher soil organic matter, suggesting that seeding rate decisions can be guided by soil organic matter content (Li Yang et al., 2022). Beyond organic matter, other soil factors such as texture, compaction, pH, and nutrient availability may further influence optimal populations (Šarauskis et al., 2022; Truter et al., 2025).

Contradicting findings have also been reported. Munna et al. (2022) found that site-specific seeding did not result in statistically significant yield differences when compared to flat-rate seeding. The role of in-season climatic conditions should always be considered in terms of these seeding rate recommendations (McNunn et al., 2019). High rainfall and favorable temperatures amplify the benefits of increased populations, while dry or variable seasons may reduce differences between flat and variable rate strategies. Producers adopting precision seeding management strategies should focus on integrating in-season data, for example, early-season climatic conditions and cultivar choice, with historic performance trends to fine-tune recommendations. Long-term, multi-season trials will be critical to refining these recommendations and improving confidence in decision-making for both flat and variable rate strategies. Validatory work is still to be done for different decision-making factors to base variable rate inputs on (Licht et al., 2017; Truter et al., 2025).

Practical implications and future research recommendations for variable rate applications

The findings of this study provide practical guidance for adopting variable-rate seeding in South African maize production. While both profit-maximizing flat-rate and variable-rate approaches increased yields relative to producers' *status quo* practices, the greatest benefits of variable-rate seeding were observed in fields with high spatial heterogeneity and during seasons with high-yield potentials. This suggests that the suitability of variable rate seeding is strongly context-dependent, varying across environments, years, and management systems.

Producers should prioritize fields where within-field variability is evident from yield maps, soil properties, or other spatial datasets. In uniform fields, flat-rate seeding may remain sufficient, as the additional complexity and cost of variable-rate seeding may not be justified. Adoption decisions should emphasize economic return rather than yield maxi-

mization. Yield-neutral seeding rate reductions observed in some environments highlight opportunities to reduce input costs without compromising productivity, whereas in high-yielding conditions, increased seeding rates supported higher profitability. Integrating variable rate seeding with broader site-specific management strategies, such as variable-rate fertilizer application, may further enhance resource-use efficiency and on-farm sustainability. Optimized variable rate seeding demonstrates potential to increase maize yield across heterogeneous environments; however, site-specific calibration of yield response functions to different seeding rates and economic parameters is critical to realize these benefits. The observed spatial variability underscores the need for high-resolution, field-specific data in precision agriculture decision-making. Future research should aim to define the biophysical and management factors driving spatial differences in yield response, including soil properties, microclimate, and cultivar characteristics. Integrating multi-source datasets—comprising historic yield, soil fertility, remote sensing, and in-season weather—into predictive models may enhance the accuracy of variable rate recommendations. Further studies on cultivar-specific responses and environment-dependent optimization to enable genotype-tailored recommendations.

Identification of management zones with similar optimal seeding rates indicates situations where variable-rate seeding may not provide additional benefit over flat-rate management, underscoring the value of response-based zoning as a diagnostic tool rather than a prescriptive requirement.

Although nitrogen fertilization was included in the DIFM trials, interactions between seeding rate and nitrogen application were not discussed. Multiple previous DIFM analyses found limited or non-significant interactions between seeding and fertilizer rates at the field scale; however, finer spatial and temporal interactions likely exist. Future research should focus on analytical approaches, such as spatio-temporal modeling, joint response surface analysis, and machine learning, to capture these complex interactions and support integrated seeding-nitrogen recommendations.

Finally, long-term, multi-season trials are essential to quantify yield stability, profitability, and resource use efficiency, thereby providing robust evidence to support the adoption of site-specific seeding strategies. Continued validation across contrasting climatic conditions and production systems is necessary to strengthen confidence in site-specific seeding strategies and support their broader adoption in commercial maize production.

Conclusion

Overall, the results demonstrate that optimizing seeding rates using both flat-rate and variable-rate approaches can improve economic returns relative to producers' *status quo* practices, within the nitrogen range applied in each trial. Yield increases occur primarily in seasons with higher yield potential. Results indicated that 79% of site-years performed better with increased seeding rates under the optimal flat rate approach, and 89% of site-years performed better with increased seeding rates under the optimal variable rate approach. While optimal flat rate seeding offers a simpler, less management-intensive option, optimal variable rate seeding leverages within-field variability to improve profitability, either through yield increases, reductions in seeding rates, or a combination of both, depending on site-specific and seasonal conditions. However, the optimal variable rate approach's advan-

tage is not always guaranteed, and in some cases, its more aggressive seeding rate recommendations led to only marginal yield improvements. For some producers, this might not justify the added management complexity and cost of variable rate technologies. Nonetheless, these findings reinforce the need for site- and season-specific decision-making recommendations, supported by reliable yield potential estimates and variability assessments. This is done to determine when a variable rate strategy is likely to offer a clear economic advantage over a flat rate approach.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Competing interests The authors declare no competing interests.

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