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Impact of variable-rate application of nitrogen on yield and profit: a case study from South Africa

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Abstract The response of maize (*Zea mays*) to banded variable-rate nitrogen (N) application over a period of 3 years (2002/3–2004/5) is analyzed. The experimental design alternated variable-rate (VR) and single-rate (SR) applications of N. The yield monitor data were spatially autocorrelated and therefore were analyzed with spatial regression methods. The baseline spatial regression model defined in this study showed that the VR treatment, treatment by year and treatment by management zone were statistically significant. Sensitivity tests were applied; the first showed that VR treatment had a yield advantage when soil depth was greater than the field average of 174 cm. The second test showed that the VR N rates applied were close to those that would maximize profit. Partial budgeting indicates that benefits from VR vary from year to year, but in this test VR was slightly more profitable than uniform rate application. Economic sensitivity testing indicates that farm size and the price of maize are the key factors in the profitability of VR N.

Keywords Precision agriculture · Variable-rate application · Spatial regression models · South Africa

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Introduction

Precision agriculture (PA) in the modern sense of the word is rarely practiced in Africa (Nell et al. 2006). It is only in South Africa that a substantial number of farmers are using this technology. Key issues concerning the profitability of PA technology remain largely unresolved (Weiss 1996; Lowenberg-DeBoer and Swinton 1997; Griffin and Lowenberg-DeBoer 2005). Several factors need to be considered in the formulation of a strategic approach to enhance the adoption of PA in South Africa, including balancing the potential economic returns with environmental impact and the degree of risk involved. Farmers have to be confident of the outcome of their decision to adopt PA as it is capital-intensive and requires significant capital outlay.

By reducing costs or increasing the value of production, PA has the potential to increase the profit of farming in South Africa. Agriculture is facing a cost-price squeeze, and PA could enhance its growth and sustainability. If PA can reduce costs and improve economic returns to producers in South Africa, which is classified as semi-arid to arid, it could help to increase farm productivity, enhance environmental quality and contribute to the growth of the country's economy.

This research involved collaboration between a farmer, researchers and extension services. This kind of cooperation between researchers and on-farm experimentation encourages learning about new technologies, facilitates the development of decision-making processes and establishes a basis for a low risk adoption of such approaches. Precision agriculture requires local information of the effects of seeding rates, fertilizers and other agro-chemicals on yields. The results from on-farm experiments can promote effective use of this new technology (Napier 2001). The experiment conducted for this study endeavoured to establish the relationship between yield as a dependent variable and different rates of nitrogen (N, the explanatory variable) under South African conditions. The study also used the effective rooting depth of soil to delineate management zones. The effective soil depth is the total thickness of the A- and B-horizons (Le Roux et al. 1999). The study area (Bothaville) is generally known as the maize capital of South Africa as it produces 60% of the country's maize. The soil at the study site is regarded as generally homogeneous with 10–15% clay in the A horizon and has a depth of 1.2–2 m. The soil is categorized as Eutric Arenosol under the World Reference Base (Food and Agricultural Organisation 1998), whereas it is categorized as Quartzipsament in the USDA classification system (Soil Survey Staff 1999).

The overall objective of this analysis was to determine the profitability of variable-rate (VR) N application on maize in the Free State Province of South Africa. Specific objectives included testing the impact of soil depth on yield, determining if the rates of N applied by VR approximated optimal rates and identifying the major economic factors in the profitability of VR N in South Africa. Statistical analyses with regression models were used to analyze the data from the comparison of VR and single-rate (SR) applications of N. The results of ordinary least squares (OLS) regression and the spatial autoregressive (SAR) methods are presented and compared. Partial budgets are used to determine the profitability of the two treatments by testing the financial effect that the use of PA will have on the maize-production part of the farming business.

The profitability of PA is the single most important consideration with regard to this technology, and often determines whether it will be adopted or not. In South Africa, profitability of PA supersedes environmental benefits. The adoption of PA solely for environmental benefits increases the likelihood of financial unsustainability. Lowenberg-DeBoer and Swinton (1997) summarized the results of 17 field crop PA profitability analyses. Five showed PA to be unprofitable, six produced mixed or inconclusive results and the other six indicated potential profitability. Lambert and Lowenberg-DeBoer (2000) also reviewed and summarized 133 publicly available studies on the profitability of PA. Of these, 108 papers reported on the economics associated with the technology: 63% indicated positive net returns, 11% indicated negative returns for a specific technology and the remainder reported inconclusive results. Griffin et al. (2004) later reviewed 243 papers, and of the 210 that reported benefits or losses 68% reported benefits from the given PA technology. Economic returns on maize (*Zea mays*) alone featured in 37% of the papers reviewed, with 73% reporting some benefits associated with PA. Bullock and Lowenberg-DeBoer (2007) reviewed studies that used spatial econometric methods on yield monitor data to determine the profitability of VR application. They concluded that because yield monitor data are inherently spatially correlated, spatial statistical methods that take this into account must be used to obtain reliable estimates of economic returns.

Although current developments in application technologies allow VR application of all inputs, much of the interest has focused on fertilizer application, possibly because of the knowledge available on fertilizer-crop nutrient-yield relationships. The relative importance of fertilizer among other crop production expenses adds to this interest in VR fertilizer application (Schnitkey et al. 1996).

The study of VR application of N by Babcock and Pautsch (1998) showed that changing to VR technology increased gross returns over fertilizer costs over the entire study area. Most of this increase (86%) resulted from reducing fertilizer application. Godwin et al. (2002) indicated that seven out of eight treatment zones showed positive economic returns to VR N application. By contrast, Anselin et al. (2004) showed modest profits from variable-rate N in Argentina. Kahabka et al. (2004) concluded that their results indicated a low potential for increasing profits from VR N application in their particular study field where the drainage was variable. This indicates that the profitability of VR technology is site-specific, and what is profitable in one area may not necessarily be profitable elsewhere.

Materials and methods

The study area

The farm used for the study is Rietgat in the Bothaville district, which is about 145 km southwest of Johannesburg. A 104 ha field was used for the study located at Latitude −27°35′ 57.6′ and −27°36′ 11.0′, Longitude 26°33′ 30.4′ and 26°32′ 38.0′ and 27 35′52.75″S and 26 32′54.32″E at the centre. The monoculture of white maize is practiced in this region as the production of other crops in rotation is limited by the small clay content of the soil.

Experimental design

A strip-plot design (Brouder and Nielsen 2000) was used for the field experiment; the design involved interchanging treatments that ran forwards and backwards across the field, corresponding to planting and harvesting passes. Two treatments were investigated, VR and SR applications of N. The field was divided into 8 m strips of six rows. The design comprised six rows for VR application of N that alternated with six rows for SR treatment. Each treatment strip in the field crossed different management zones (described below). As the planting was done back and forth across the field, there were multiple random side-by-side replicates. It should be noted that this experimental design was created with the baseline model (see below) in mind.

The identification of management zones entailed overlaying yield maps for the previous 3 years (1998/9–2000/1) with the John Deere Office Software System. Four management zones were identified. Zone 1 was one of low yield potential, with a potential yield of <3 t ha^{-1}. Zone 2, the medium potential yield zone, had a potential yield of 3–4 t ha^{-1}. The high potential zone, zone 3, had a historical yield of between 4 and 5 t ha^{-1}, and zone 4 was the very high potential yield zone with a potential yield of >5 t ha^{-1}. The relation between management zones and the soil's effective rooting depth was determined by sampling the soil with a hydraulic soil drill (auger) on a 50 × 50 m grid. The effective rooting depth was determined at each grid node. Although the depth limit of diagnostic horizons in the South African Soil Classification is 1.5 m, the maximum depth of coring was extended to 3 m to measure the deepest parts of the field. Zones 3 and 4 had the greatest mean effective rooting soil depths of 197 and 178 cm, respectively. The average effective depth of zone 2 was 164 cm, whereas zone 1 had a mean effective depth of 173 cm.

Each year, constant rates of N fertilizer mixture were banded over the entire field before planting as a uniform application. In the first year, a constant rate of 30 kg N ha^{-1} was applied over the field 4 weeks before planting. The second uniform application of N was a rate of 30 kg N ha^{-1} during planting. For the second and third years, a constant rate of 36 kg N ha^{-1} was applied on the entire field before planting and another 24 kg N ha^{-1} was applied during planting. During each growing season (November to February), N in the form of Urea was applied to the strips by either VR or SR to compare the two treatments. The total quantities applied are given in Table 1.

Data collection

Yield data were recorded by a combine harvester fitted with a yield monitor at georeferenced points. Before the yield data were analyzed, they were edited, filtered and cleaned using Yield Editor Software (Sudduth and Drummond 2007). Observations likely to be erroneous were identified by examining harvester velocity (minimum and maximum), changes in velocity, start- and end-pass delay, maximum and minimum yield, flow delay and the standard deviation, and then removed. Dummy variables representing the two treatments (VR and SR) were allocated to the yield data. As the soil data were the least dense, a circle of 7 m diameter, a notional sample support, was created around each soil sampling position, and the yield data within this support were averaged and assigned to the soil sampling position. On average, there were two yield values in each circle. The

Table 1 Applications of nitrogen

Potential yield zones	Nitrogen (kg ha^{-1})					
	2002–2003		2003–2004		2004–2005	
	VR	SR	VR	SR	VR	SR
Zone 1	84	105	69	102	69	102
Zone 2	92	105	85	102	85	102
Zone 3	100	105	110	102	114	102
Zone 4	110	105	123	102	127	102

diameter of the circle was based on the width of the treatment strip of 8 m; the smaller diameter ensured that yield data from adjacent treatments were not averaged together.

Model specifications

The baseline model developed in this study analyzes the statistical significance of PA as a package by assessing the estimated model coefficients. In this study, the PA package included investment in GPS survey of the field, harnessing the tractor to put the necessary wiring in place, purchasing the VR applicator, GPS satellite receiver, a computer display, the necessary software and soil sampling. Baseline model is a generic term used in econometric studies for the core statistical model. Variants of this baseline model are the object of sensitivity testing. Two sensitivity test models were used to determine the methodological robustness of the results. Sensitivity test one included soil depth to determine whether the response to VR N application varied with soil depth. Sensitivity test two determined whether the N rates applied were close to the optimal rates required by the maize crop. To test the response of yield to N, linear and quadratic N rate variables were included in the statistical model. The data were adequate, but not ideal, for the sensitivity tests. This was because the yield zones and soil depth are somewhat correlated and also, in any given year, there were only two rates of N in each yield zone (i.e. the VR rate and SR). However, over the 3 year period there were five rates of N in each zone. From a mathematical perspective the model can be estimated, but it would have been better to have data on more levels of N. The sensitivity tests were done to help identify factors that affect the impact of VR on yield and subsequently on profits.

Both OLS and SAR models were used for regression analyses of the three years' data by a single regression analysis, followed by individual analyses for each year. The GeoDa$^{\text{TM}}$ statistical package for spatial data analysis was used for all regression analyses.

The experimental design was developed assuming the baseline model, and data for the 3 years aggregated together was estimated with the following baseline model:

$$\begin{aligned} Y = {} & \alpha_0 + \alpha_i TRT + \alpha_{ii} Z_i + \alpha_{iii} Z_{ii} + \alpha_{iv} Z_{iii} + \alpha_v TRT(Z_i) + \alpha_{vi} TRT(Z_{ii}) + \alpha_{vii} TRT(Z_{iii}) \\ & + \alpha_{viii} D_{ii} + \alpha_{ix} D_{iii} + \alpha_x D_{ii}(TRT) + \alpha_{xi} D_{iii}(TRT) + \alpha_{xii} Z_i D_{ii} + \alpha_{xiii} Z_i D_{iii} \\ & + \alpha_{xiv} Z_{ii} D_{ii} + \alpha_{xv} Z_{ii} D_{iii} + \alpha_{xvi} Z_{iii} D_{ii} + \alpha_{xvii} Z_{iii} D_{iii} + \upsilon, \end{aligned} \tag{1}$$

where *TRT* is treatment with VR = 1 and SR is zero, $Z_i = 1$, $i = 1, 2, 3$, and zero otherwise (zone 4 is a base zone), Z_{i}, Z_{ii}, Z_{iii} and zone 4 are zones 1, 2, 3 and 4, respectively, $D_i = 1$, $i = 2, 3$ and zero otherwise (Year 1 is the base year), D_1, D_2, D_3 and D_4 are Years 1, 2, 3 and 4, respectively, α are coefficients to be estimated and υ is *the* error term. For the spatial error model, the error term is assumed to be spatially correlated such that $\upsilon = \lambda\upsilon + u$, where λ is the spatial error term and u is the uncorrelated, random error term.

(i) *The model for Sensitivity Test 1 is*:

$$\begin{aligned} Y = {} & \alpha_0 + \alpha_i TRT + \alpha_{ii} ED + \alpha_{iii} ED^2 + \alpha_{iv} TRT(ED) + \alpha_v D_2 + \alpha_{vi} D_{iii} + \alpha_{vii} D_{ii}(TRT) \\ & + \alpha_{vii} D_{iii}(TRT) + \alpha_{ix} D_{ii}(ED) + \alpha_x D_{iii}(ED) + \alpha_{xi} D_2(ED^2) + \alpha_{xii} D_{iii} ED^2 + \upsilon, \end{aligned} \tag{2}$$

where *ED* is the effective rooting depth and υ is an error term.

(ii) *The model for Sensitivity Test 2 is:*

$$
\begin{aligned}
Y = {} & \alpha_0 + \alpha_i\mathrm{N} + \alpha_{ii}\mathrm{N}^2 + \alpha_{iii}Z_1 + \alpha_{iv}Z_2 + \alpha_v Z_3 + \alpha_{vi}\mathrm{N}Z_1 + \alpha_{vii}\mathrm{N}Z_2 \\
& + \alpha_{viii}\mathrm{N}Z_3 + \alpha_{ix}\mathrm{N}^n Z_i + \alpha_x\mathrm{N}^n Z_{ii} + \alpha_{xi}\mathrm{N}^n Z_3 + \alpha_{xii}D_{ii} + \alpha_{xiii}D_{iii} \\
& + \alpha_{xiv}D_{ii}\mathrm{N} + \alpha_{xv}D_{iii}\mathrm{N} + \alpha_{xvi}D_{ii}\mathrm{N}^2 + \alpha_{xvii}D_{iii}\mathrm{N}^2 + \alpha_{xviii}Z_iD_{ii} + \alpha_{xix}Z_iD_{iii} \\
& + \alpha_{xx}Z_{ii}D_{ii} + \alpha_{xxi}Z_{ii}D_{iii} + \alpha_{xxii}Z_{iii}D_{ii} + \alpha_{xxiii}Z_{iii}D_{iii} + \upsilon,
\end{aligned}
\tag{3}
$$

where N is nitrogen.

Euclidean distance-based matrices were calculated in GeoDa$^{\mathrm{TM}}$ using minimum distances for each year to ensure that each observation had at least one neighbor. In this case each observation had more than one neighbor. Using baseline models, both the SAR and OLS regression analyses were computed; the former accounted for the spatial autocorrelation. The spatial error model selected was based on Griffin et al. (2005) who stated that the spatial error model is usually most suitable for yield data as the spatial structure is often generated by variables not included in the analysis (e.g. subsoil, microclimate). Dummy variables were used for the years in the model ($D_2 = 1$ for 2003/2004 and zero otherwise, $D_3 = 1$ for 2004/2005 and zero otherwise) because the 3 years of data were aggregated together in a single regression. The first year (2002/2003) served as a base year.

An area of 1000 ha was used for the economic analysis divided equally between VR and SR. This area is regarded as representative of the study region as more than 50% of the farmers in this region allocate an area >1000 ha to maize (C. F. Le Clus, personal communication, 2007). A more detailed description of the experimental design, statistical analysis and economic methods is available in Maine (2007).

Profit estimation

Using a partial budget, the baseline model (Eq. 1) was used to calculate the profitability of a package of technologies (described earlier) used by the farmer to implement VR compared with that of SR application. Partial budgets are used to compare alternatives. Only costs that change are deducted from revenue. In this case the costs that change are precision agriculture equipment and nitrogen fertilizer. Seed, weed control, other fertilizer, conventional equipment and land costs are assumed to remain the same. The first approximation of the objective of most commercial producers is to maximize farm profit (profit).

The yields that maximized profit and the average N rates applied at the trials were used to calculate profit in the baseline model. Separate calculations were done for VR and SR applications by Eqs. 4 and 6, respectively:

$$\pi = P\bar{Y}_{\mathrm{VR}} - A - r\bar{X}_{\mathrm{VR}} - O, \tag{4}$$

where π represents net returns to N, P is the price of maize in yield t^{-1}, r is the price of nitrogen fertilizer in Rands kg^{-1} (R1 = US\$0.15), O represents other fixed and variable costs incurred in the production of maize and A the fixed costs associated with the VR application, and is calculated as follows:

$$A = I^{*}i/[1 - (1 + i)^{-n}], \tag{5}$$

where I is the investment cost of VR technology and i is the discount rate. A discount rate is a rate used to discount future cash flows to their present values thus reflecting the time value or opportunity cost of money.

Investment in VR technology (described earlier) is a cost incurred in the first year and the interest payable over 3 years is discounted to the present. The total cost was R 326 190 (2005). Training costs and the farmer's management time to learn how to use the equipment and time spent analyzing data were not accounted for, although they are an essential component. With an estimated lifetime of 6 years and a discount rate of 10%, the annual VR costs amount to R74 896 for a 500 ha field of maize or R150 ha^{-1}.

Profit for the SR treatment is computed by Eq. 2 as follows:

$$\pi = P\bar{Y}_{\mathrm{SR}} - r\bar{X}_{\mathrm{SR}} - O \tag{6}$$

In Eqs. 4 and 6 X is calculated as follows

$$\bar{X} = \sum ijX_{ij} \big/ \mathrm{ha}, \tag{7}$$

where X is the input applied (N), and i and j apply to VR only and refer to locations of individual observations.

The calculations were based on a maize price of R1001 t^{-1} and a nitrogen price of R2.37 kg^{-1}, both of which are 3-year averages. The other production costs (seed, fertilizer, chemicals, fuel, repair, maintenance, etc.) were based on the enterprise budgets for the Bothaville region. Enterprise budgets show transaction flows of a particular enterprise within a farming business. These budgets can be used when planning a new enterprise or determining the profitability of an existing enterprise.

Results

Diagnostic tests for the baseline model

Breusch–Pagan (BP) and Koenker–Bassett (KB) tests are diagnostic tests of a regression to determine whether heteroscedasticity is present in the error terms. The larger the BP and KB test values, the greater is the evidence against homoscedasticity. Five diagnostic tests for spatial dependence reported with the OLS model include Moran's I for the spatial error model, the Lagrange Multiplier (LM) and its robust term, for both the lag and error spatial models. Diagnostic tests for heteroscedasticity are given in Table 2.

Table 2 shows that the error terms are heteroscedastic as all the BP and KB tests are significant at 1%. The five diagnostic tests for spatial dependence reported with the OLS regression output confirm the presence of spatial autocorrelation (Table 2). The model with the largest value for the Lagrange Multiplier and its robust counterpart, i.e. the spatial error model, is the most appropriate.

Baseline model regression results

The regression results of the 3 years' data estimated with the baseline model for the OLS and SAR models are given in Table 3.

The F test/likelihood ratio test is larger for the SAR model than the OLS one, indicating a better model fit. The information criteria, the Akaike Information Criterion (AIC) and the

Table 2 Diagnostic tests for heteroscedasticity

Breusch–Pegan test	Pooled data baseline model	Year 1 data baseline model	Year 2 data baseline model	Year 3 data baseline model
OLS	202	81	48	33
SAR	254	41	43	32
Koenker–Bassett	81	50	30	
Moran's I (error)	46	17	36	36
Lagrange multiplier (LM lag)	1292	326	1206	883
Robust LM (lag)	3	43	9	*0.08*[a]
Lagrange multiplier (error)	1580	284	1213	1267
Robust LM (error)	291	*0.48*	16	383

[a] Coefficient estimates in italics are not statistically significant at the 5% level

Table 3 Measures of model fit and estimated coefficients for the pooled data baseline model

Variable	OLS coefficients	SAR coefficients
Constant	4.6139	4.5011
TRT	0.3864	0.3193
Z_1	0.3395	0.4007
Z_2	*0.1218*[a]	0.2899
Z_3	*0.1810*	0.2686
TRT_Z_1	−0.4130	−0.3763
TRT_Z_2	−0.4382	−0.3633
TRT_Z_3	−0.3053	−0.2467
D_2	*0.0794*	*0.0089*
D_3	0.4337	0.3772
D_2_TRT	0.7692	0.7956
D_3_TRT	*0.0605*	*0.0569*
$Z_1\_D_2$	*−0.0949*	*−0.0406*
$Z_1\_D_3$	1.1555	1.2471
$Z_2\_D_2$	*−0.0680*	*−0.0223*
$Z_2\_D_3$	1.2416	1.3043
$Z_3\_D_2$	*0.0482*	*0.1116*
$Z_3\_D_3$	1.5740	1.6468
λ	–	0.6260
Measures of fit	OLS	SAR
F-statistic (OLS)/likelihood ratio test (SAR)	183	846
Log-likelihood	−2153	−1729
Akaike information criterion	4341	3495
Schwartz criterion	4443	3597

[a] Coefficient estimates in italics are not statistically significant at the 5% level

Table 4 The variable-rate treatment effect on maize yield, t ha^{-1}

	Zone 1		Zone 2		Zone 3		Zone 4	
	SR yield	VR yield advantage	SR yield	VR yield advantage	SR yield	VR yield advantage	SR yield	VR yield advantage
Year 1	4.90	−0.06	4.79	−0.04	4.77	0.07	4.50	0.32
Year 2	4.87	0.74	4.78	0.75	4.89	0.87	4.51	1.11
Year 3	6.53	−0.0001	6.47	0.01	6.79	0.013	4.88	0.38

Schwartz Criterion (SC) also show a better fit for the SAR model; the smaller AIC and SC values imply a better fit of the model.

The variation in yield according to management zone is determined by the significance test on the coefficients of Z_1, Z_2 and Z_3. Zone 4 (Z_4), which is the very high potential yield zone, serves as the base with the others deviating from this. As Table 3 shows, the differences between the coefficients of the SAR and OLS models are small. The coefficients for all zones are statistically significant at the 1% level for the SAR model, and they differ between the zones. Since λ (spatial error coefficient) is significant for the SAR model, the model fit should be improved by incorporating the correlated spatial error explicitly. The coefficients for the year dummy variable for the second year (D_2) and its interaction with all zones ($Z_1\_D_2$, $Z_2\_D_2$, $Z_3\_D_2$), as well as the Year 3 and treatment interaction (D_3_TRT), are all statistically significant at the 1% level, indicating that yields in these zones are significantly different from those in Z_4. The effect of VR is substantial and positive in zone 4 for the 3 years (Table 4).

Sensitivity test 1 model: the TRT effective rooting depth model

Even though the baseline model is superior to sensitivity test 1, the latter is used to establish whether the treatment varies with effective rooting depth and whether it differs between the management zones. In the sensitivity test 1 model (Table 5), the treatment and effective depth are explanatory variables.

The results of this model are consistent with those of the baseline model. As for the latter, the fit of the SAR model is better than that for OLS. The log-likelihood value increases from −2121 for the OLS model to −1844 for the SAR one. The AIC and SC also indicate this improvement in the fit of the model. The AIC and SC values decline from 4269 and 4342, respectively, for OLS to 3715 and 3789, respectively, for the SAR model.

Coefficients for the effective depth (ED and ED^2) have the expected positive signs, and are significant. Effective depth conforms to the expectation of a positive effect on yield. The combined effects of the *TRT* and *ED_TRT* variables indicate that the treatment effect in Year 1 was positive for soil depths >173 cm. As the average soil depth in the field is 174 cm, this means that in Year 1 VR had a positive effect on yield in this field for soil depths greater than the average. The statistical significance of the soil depth and soil depth interaction variables shows that the management zones, based in part on soil depth, reflect important information on spatial variation.

The coefficients of sensitivity test 1 were used to estimate yields, and the expected yields with VR and SR treatments, Table 6.

Table 5 Coefficients for sensitivity test 1

Variable	OLS coefficient	SAR coefficient
Constant	1.4257	1.4785
TRT	*−0.2499*[a]	−0.2809
ED (cm)	0.0361	0.0400
ED^2	−0.0001	−0.0001
ED_TRT	0.0014	0.0020
D_2	*0.0806*	*−0.3777*
D_3	4.0343	3.6696
D_2_TRT	0.7888	0.8010
D_3_TRT	*0.0790*	*0.0753*
D_2_ED	*−0.0019*	*0.0032*
D_3_ED	−0.0290	−0.0252
$D_2\_ED^2$	*0.0000*	*−0.0000*
$D_3\_ED^2$	0.0001	0.0001
λ	–	0.5410
Measures of fit	**OLS**	**SER**
Adjusted R^2	0.60	0.76
F-statistic (OLS)/likelihood ratio test (SAR)	272	554
Log-likelihood	−2121	−1844
Akaike Information Criterion	4269	3715
Schwartz Criterion	4342	3789

[a] Coefficient estimates in italics are not statistically significant at the 5% level

Table 6 Expected yields[a] with VR and SR treatments using sensitivity test 1 model, t h^{-1}

	Zone 1		Zone 2		Zone 3		Zone 4	
	Expected SR yield	VR advan-tage	Expected SR yield	VR Advan-tage	Expected SR yield	VR Advan-tage	Expected SR yield	VR Advan-tage
Year 1	4.93	−0.01	4.88	−0.02	4.95	0.03	4.93	0.01
Year 2	4.94	0.80	4.87	0.79	4.99	0.83	4.95	0.81
Year 3	6.45	0.07	6.40	0.06	6.53	0.11	6.46	0.08

[a] Yields estimated at the average soil depth for the zone

The VR treatment had a yield advantage at the average soil depth for all the zones in Years 2 and 3. That advantage was about 0.8 t ha^{-1} in all zones in Year 2. Therefore, analysis indicates that the effectiveness of VR fertilizer application does vary with soil depth and the effective soil rooting depth can be used as one of the determinants of management zones in this field, but not necessarily as the main criterion. Other variables such as the spatial distribution in yield across the field over time should also be taken into account.

Sensitivity test 2 model: the nitrogen-zone model

Sensitivity test 2 is the model that includes N and the three zones as the explanatory variables. The baseline model is statistically better than sensitivity test 2 model, as the AIC and SC values are still the smallest for the baseline. Sensitivity test 2 was estimated to determine whether N response varies by zone; Table 7 gives the results.

Given the definitions of the dummy variables, the linear and quadratic terms for N in Table 7 represent the response in zone 4 in Year 1. This is because estimation of the dummy

Table 7 Coefficients for sensitivity test 2

Variable	OLS coefficients	SAR coefficients
Constant	*−0.4732*[a]	*−0.2218*
N (kg ha^{-1})	*−0.0099*	*−0.0109*
N^2	0.0006	0.0006
Z_1	12.0131	11.2593
Z_2	6.9536	8.7513
Z_3	−35.9452	−22.6161
N_Z_1	−0.1331	−0.1236
N_Z_2	−0.0394	−0.0724
N_Z_3	0.8302	0.5676
N^2_Z_1	0.0002	*0.0001*
N^2_Z_2	−0.0003	−0.0001
N^2_Z_3	−0.0047	−0.0034
D_2	−10.860	−9.2179
D_3	−4.5582	−4.5846
D_2_N	0.2917	0.2504
D_3_N	0.0936	0.1002
D_2_N^2	−0.0018	−0.0015
D_3_N^2	−0.0005	−0.0005
Z_1_D_2	−0.4123	−0.3733
Z_1_D_3	1.4935	1.4598
Z_2_D_2	−0.3415	−0.3710
Z_2_D_3	1.4038	1.4877
Z_3_D_2	*−0.1838*	*−0.1050*
Z_3_D_3	1.8417	1.8026
λ	–	0.5939
Measures of fit	OLS	SER
Adjusted R^2	0.60	0.79
F-statistic (OLS)/ likelihood ratio test (SAR)	145	−1758
Log-likelihood	−2105	692
Akaike information criterion	4258	3565
Schwartz criterion	4394	3702

[a] Coefficient estimates in italics are not statistically significant at the 5% level

variable always requires one category to be dropped, which becomes the reference category. All non-dummy variable coefficients are then estimates of the effects on the reference category. Because the linear term is negative and the quadratic term is positive (Table 7), the function is convex for zone 4 in Year 1. Given the signs and magnitudes of the estimated interaction terms, the estimate is convex for zones 1, 2 and 4 in Years 1 and 3.

The rates of N required to maximize yield and profit for each zone and year computed from the coefficients of the sensitivity test 2 are summarized in Table 8. For zone 3 in all years and all zones in Year 2 the response is concave and the rates of N to maximize yield and profit occur at the point where the slope of the response curve equals the ratio of nitrogen price to maize price (internal solutions). In other cases, the rates of N to maximize yield and profit are at the minimum and maximum VR N rates in Table 1 (corner solutions).

The comparison of N rates should be done cautiously because the estimated response is convex at 6 of the 12 zone year combinations, but overall the N rates which maximize profit are close to those actually applied in the VR treatment. For zone 3 where the estimated response was concave in all years, actual rates of and those to maximize profit are almost identical in Year 1. The actual VR rates for zone 3 are 15–16 kg ha^{-1} larger than the profit maximizing rates in Years 2 and 3. In Year 2 where estimated responses are concave across all zones, the profit maximizing N rates are larger than those applied by VR in zones 1 and 4 by 2–9 kg ha^{-1}. Actual rates of N for VR are larger than the rates to maximize profit in zones 2 and 3 by 3–16 kg ha^{-1}.

Profitability analysis

The OLS model appears to overestimate profit for the VR treatment in all the study years, which is consistent with results reported by Florax et al. (2002); Lambert et al. (2004);

Table 8 Nitrogen rate alternatives by year and zone using the N-zones model

Crop season and N management alternatives	Zone 1	Zone 2	Zone 3	Zone 4
2002/2003				
Yield max N	84	84	99[a]	110
Profit max N	84	84	99[a]	110
SR N	105	105	105	105
VR N	84	92	100	110
2003/2004				
Yield max N	72[a]	84[a]	99[a]	133[a]
Profit max N	71[a]	82[a]	94[a]	132[a]
SR N	102	102	102	102
VR N	69	85	110	123
2004/2005				
Yield max N	69	127[a]	100[a]	127
Profit max N	69	127[a]	99[a]	127
SR N	102	102[a]	102	102
VR N	69	85[a]	114	127

[a] Indicates internal yield or profit maximizing solution. In other cases, yield and profit maximizing levels are corner solutions using the minimum and maximum N levels from Table 1

Anselin et al. (2004); Griffin (2006) and Griffin et al. (2006). This implies that an inaccurate conclusion would be reached about the profitability of PA when using the OLS model. The results of the baseline model only are reported in this paper because the experimental design assumed this model.

A comparison of the profit obtained from the two application strategies indicates which is the more profitable. For VR, it is essential to determine whether the *possible* benefits of an increase in yield and savings on inputs are greater than the quasi-fixed costs of the VR application equipment and the need for intensive data to be obtained (Lowenberg-DeBoer and Boehlje 1996). Quasi-fixed costs are those costs that are incurred if a certain technology or practice is used, but not necessarily incurred for other technologies or practices. For example, GPS is a cost if VR is used regardless of the fertilizer rate spread, but GPS is not a cost for uniform fertilizer application. As Fig. 1 indicates, estimated profit is greater for VR in some zones compared with SR.

With the exception of zone 4, the profit is greater from SR than VR treatment in Years 1 and 3. Statistically, this statement is based on the significance of the treatment and treatment by zone interactions (*TRT_Z*) in the baseline estimate (Table 3). In Year 2, estimated profit is greater for VR treatment in all the zones. Variable-rate application performs better than SR in all years for zone 4. On average, the profit is R100 ha^{-1} more for VR over the 3 year period.

A sensitivity analysis was done on the net present value (NPV) to determine the viability of VR technology under different conditions. The net present value technique is a standard method of capital budgeting that uses the value of money at the time to appraise long-term projects or analyze the profitability of an investment. Assuming that the conditions in the 3 years investigated above have an equal chance of occurring in the future, the NPV was projected into a 6-year period. Possible N and maize prices, VR capital outlay, interest rates and land areas were varied to determine the effect of the variables on the NPV, and to ascertain which variable has the greatest effect on it. Table 9 gives the results of the sensitivity testing.

Of the variables investigated, maize prices and land area seem to be the most important. The higher the price of maize, the larger is the margin between the NPVs of the two

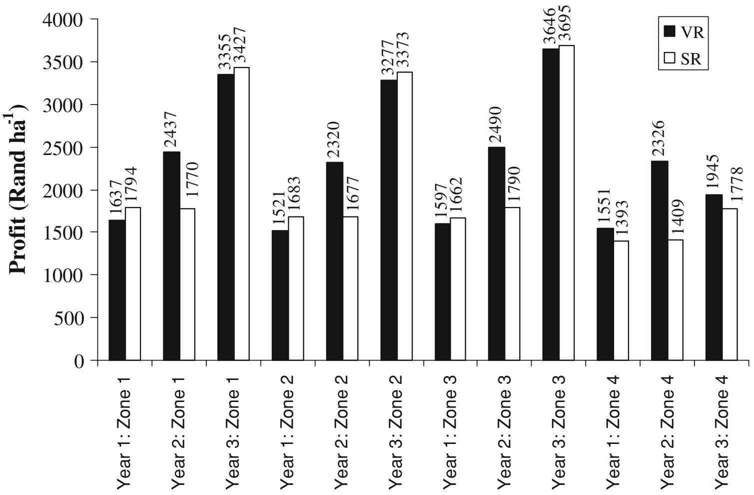

Fig. 1 Estimated profit: the baseline model

Table 9 Sensitivity testing on the NPV, Rand farm^{-1}

NPV	Scenarios			
	Baseline	1	2	3
N price (Rand kg^{-1})	2.37	3.56	5.33	8
VR	4 651 960	4 410 554	4 051 489	3 509 849
SR	4 211 513	3 968 637	3 607 386	3 062 448
Difference	440 447	441 917	444 103	447 401
Maize price (Rand t^{-1})	1001	500	1501	2001
VR	4 651 960	−889 732	10 183 682	15 735 343
SR	4 211 513	−968 749	9 382 455	14 572 036
Difference	440 447	79 017	801 227	1 163 307
VR capital outlay (Rands)	326 190	163 095	489 285	652 380
VR	4 651 960	4 800 228	4 503 692	4 355 423
SR	4 211 513	4 211 513	4 211 513	4 211 513
Difference	440 447	588 715	292 179	143 910
Interest rate (%)	10	8	12	15
VR	4 651 960	5 069 911	4 278 221	3 788 471
SR	4 211 513	4 573 326	3 887 792	3 463 253
Difference	440 447	496 585	390 429	325 218
Land size (ha)	500	250	750	1 000
VR	4 651 960	2 183 310	7 120 610	9 589 260
SR	4 211 513	2 105 756	6 317 260	8 423 025
Difference	440 447	77 554	803 350	1 166 235

treatments. If the price of maize is <R580 t^{-1}, the NPV for VR becomes negative. The area on which the equipment is used is also important; for <196 ha the NPV for SR treatment begins to be higher than for VR. However, as the land area increases, the difference in NPV between the two treatments increases with a larger NPV for VR, indicating economies of scale in the use of VR equipment.

As the N prices increase, the difference between the NPVs of the two treatments increases, implying that when N prices are high VR can make N application more efficient by cutting costs. However, N cost is a small fraction only of the total cost; the effect of the price of maize is more important. The cost of VR technology affects VR treatment only, therefore, an increase in these costs affects VR negatively. For a capital outlay of >R810 000, the NPV for SR exceeds that of VR.

Conclusion

Overall, VR N is modestly more profitable than uniform application, but the benefits of VR vary widely from year to year. In some years uniform rate N is more profitable than VR. The analysis confirmed that management zones based on soil depth were relevant in relation to the variation in yield within the field and that the N rates used approximated yield maximizing levels. In this case, the major factors determining the profitability of VR N are farm size and the price of maize.

This study indicates that on-farm trials, in conjunction with spatial econometrics, can be used successfully to analyze yield response to VR application of N. We have shown that the value of the results from spatially autocorrelated farm data can be increased when the spatial error structure is modeled explicitly. Spatial models take into account the spatial effects inherent in such data and generate smaller standard errors than OLS models. All the measures of goodness of fit indicated an increase in fit from the OLS to the SAR model, implying that the use of these models resulted in more accurate estimates.

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