Economic Analysis of Phosphorus Applications under Variable and Single-Rate Applications in the Bothaville District

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Abstract

Variable-rate (VR) application of inputs in South African cash crop production is mainly concerned with fertilizer and lime, and this indicates the importance of these inputs in cash crop production. However, the profitability of VR application of inputs has not yet been investigated under South African conditions. This paper studies the maize yield response to variable-rate application of phosphorus (P) and the profitability thereof in South Africa, on the basis of data collected on a 104-hectare experimental field on a farm in the Bothaville district. The strip-plot design of 180 strips was used for this on-farm research experiment. This design involved treatments that run in the same direction across the field as planting and harvesting. The objective is to determine the maize crop response functions under different P rates and to estimate the profitability of VR relative to the single-rate (SR) application of P. The methodology involves modelling maize yield response functions for P under VR and SR treatments, and for different management zones. A spatial quadratic regression model is developed, according to which yield is estimated as a function of applied P, the treatment and management zones. The results indicate that yield response to P varies between VR and the SR application methods, as well as between management zones. Variable-rate treatment results in higher profits than the SR treatment.

Keywords: Precision agriculture, precision farming, site-specific phosphorus management, variable-rate application, fertilizer, yield response, South Africa

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1. Introduction

Simpson (1986) reports a substantial annual increase in the use of NPK fertilizers all over the world, especially nitrogenous fertilizers in areas with more developed agricultural systems**.** This is the result of efforts to intensify production to achieve maximum profits. As a result of the inability of producers/farmers to identify the profit-maximising input level and the expected yields, inefficient and uneconomic use of fertilizer occurs. This results in the contamination of watercourses by leached nutrients, especially nitrates.

The price control on fertilizer that was lifted in 1984 had serious financial consequences for farmers and the fertilizer industry in South Africa. Prior to 1984, all prices and imports of fertilizer were controlled (Fertilizer Society of South Africa, 1986). The fertilizer price per unit has increased tremendously in recent years, forcing farmers to find means of utilising fertilizer more efficiently. Currently, the availability of new technologies such as variable-rate (VR) technologies increases the scope of techniques that can aid in reducing fertilizer costs or making fertilizer use more efficient. Variable-rate fertilizer application involves radical changes and/or substantial investment in the technology, as well as additional management capacity. Although this technology is more expensive, its technical efficiency makes it a better choice for increasing profitability despite the rise in fertilizer costs.

Precision agriculture advice based on the soil mineral nitrate (N) and phosphorus (P) is gradually replacing the standard rates of fertilizer application for individual cropping systems in South Africa. Variable-rate (VR) technology, the aspect of precision agriculture that is the focus of this study, entails the precision application of inputs. Inputs are varied throughout the field according to pre-determined yield potentials or other guidelines. According to Matela (2001), VR application of inputs in South African cash crop production is mainly concerned with fertilizer and lime, and this indicates the importance of these inputs in cash crop production. Burt, Heathwaite and Trudgill (1993) argue that adjustments in the form and application method of fertilizer (especially N) are mainly in response to changing price per unit of N, rather than considerations regarding the likely efficiency of use. In contrast, Matela (2001) found that farmers in South Africa adopt VR technologies to improve efficiency, which leads to reduced per unit cost of production and ultimately a probable increase in profit.

Malzer *et al.* (1999) identify the real challenge to precision agriculture as determining the factors or items that influence crop production for a given field, and developing an appropriate strategy to maximise profitability for the producer. In a study carried out by Matela (2001), farmers cited the potential increase in profitability that can be attained with precision agriculture as one of their main considerations in adopting the technology in South Africa. However, the profitability of the technology has not yet been investigated under South African conditions, and this study is aimed at analysing the profitability of VR application of P (kg/ha) in a spatial setting. The hypothesis is that VR application of P results in higher yields compared to the SR application, and that the ensuing profit is higher for the VR.

2. Literature

Godwin *et al.* (2002) describe precision agriculture as a name given to a method of crop management that entails managing areas within a crop field that require different levels of inputs. Lowenberg-DeBoer and Boehlje (1996) define precision agriculture as monitoring and control applied to agriculture, including the site-specific application of inputs, timing of operations and monitoring of crops and employees. Although precision agriculture is not a new concept, recent interest has been fuelled by advances in computer technologies that allow capture and analysis of spatial variability in fields, as well as in application technologies that allow VR application of nutrients (Schnitkey, Hopkins, & Tweeten., 1996). Modern technology in agriculture is one of the important keys to success. As technology is rapidly evolving, farmers must keep up with the changes that may be of benefit to their farming operations (Roberson, 2000).

The profitability of precision agriculture tools is an important consideration for farmers and the agri-business sector. They need to determine whether it is the new trend for the future or a technological dead end (Lowenberg-DeBoer & Swinton, 1997). The profitability of precision agriculture is the single most asked question regarding this technology, and determines whether it will be adopted or not. According to Schilfgaarde (1999), the expectation is that precision agriculture will increase crop yields and enhance net returns from farming and, at the same time, reduce environmental damage. Even though current developments in application technologies allow VR application of all inputs, much of the interest in South Africa has been focused on fertilizer application due to the knowledge available on the fertilizer-soil nutrient-yield relationships and the aggressive marketing of fertilizer companies. The relative importance of fertilizer among other crop production expenses adds to this interest in VR fertilizer application (Schnitkey *et al.*, 1996).

Moss and Schmitz (1999) measured the value of VR application of inputs by comparing the gross benefit from the application of inputs in the absence of precision information and technology, with the gross benefits from optimal application of inputs where precision information and technology were utilised. The analysis showed the value of spatially variable field operations, as inputs can be used more efficiently. In research conducted by Godwin *et al.* (2002) in eastern and southern England, seven out of eight treatment zones delivered positive economic returns to VR nitrogen application, with an average benefit of £22 per hectare.

In contrast, the study of Anselin, Bongiovanni and Lowenberg-DeBoer (2004), in which a comparison of the returns from different N application rates was made, indicated modest results for VR. Returns above fertilizer costs varied, with the N fertilizer rate recommended by agronomists having the lowest return at $415.35 per hectare, and the profit-maximising rate for the entire field the highest at $419.56 per hectare. VR returns for recommendations by agronomists were higher than the uniform recommended rate, but lower than the profit-maximising rate for the entire field at $417.00 per hectare. VR demonstrated lower returns as a result of the added costs incurred with this type of application.

In an experiment carried out by Welsh *et al.* (1999) in southern England, where VR strategies were tested, it was found that applying more N fertilizer to both the historically high- and low-yielding sections led to a significant increase in yield. A penalty of declining yield can occur if fertilizer rate (N, P, K) is reduced, particularly in high-yielding areas (Welsh *et al.*, 1999).

Lowenberg-DeBoer and Swinton (1997) summarised the results of 17 field crop precision agriculture studies. Overall, five studies found precision agriculture to be non-profitable, six produced mixed or inconclusive results, and six showed potential profitability. Lowenberg-DeBoer and Swinton (1997) concluded that, since yield and input use changes vary from farm to farm, it is difficult to make a general statement about the profitability or non-profitability of precision agriculture. The profitability of any given precision agriculture technology and the factors involved may be site-specific, and what works in one area may not necessarily work in another. As a result, precision agriculture should be evaluated on a farm-by-farm basis (Lowenberg-DeBoer & Swinton, 1997 and Malzer *et al.*, 1999). It is also important to evaluate the profitability of precision agriculture - mainly VR technology - in South Africa, which is a semi-arid country and therefore differs considerably from the USA, where most studies of the profitability of precision agriculture have been conducted. Anselin *et al.* (2004)

and Lambert, Lowenberg-DeBoer and Bongiovanni (2002) contend that the profitability assessment of VR crucially depends on the model specification used. All spatial models investigated by these authors consistently indicated the profitability of VR nitrogen application, while non-spatial models did not.

3. Objectives

The main objective of this paper is to evaluate the profitability of the VR application of phosphorus in a maize field in the Bothaville district of the Free State Province in South Africa.

- Determine crop response functions under different P rates.
- Compare the profitability of VR application of P with the profitability of SR application.

4. Methodology

4.1 Description of the study area

Data was collected from a 104-hectare field on a farm in the Bothaville district of the Free State Province. The spatial variability in the study field is mainly caused by the depth of the soil, as the soil survey revealed a one-metre variation in depth within a 100-metre distance. More than 70% of the soils in this field are classified as an Avalon soil form under the South African classification system (Soil Classification Working Group, 1991). Under the World Reference Base, they are categorised as Eutric Arenosol (FAO, 1998) while they are categorised as Quartzipsaments under the USDA classification system (Soil Survey Staff, 1999). The average annual rainfall of this region is 525 mm, which generally occurs during the summer months from November to February.

4.2 The experimental design

The data of a trial year (2002) was selected for this paper from the ongoing experiment of four years (2001/2 - 2004/5), with approximately 56 000 yield point observations. Data was collected by a combine harvester equipped with a yield monitor. The strip-plot design (illustrated in Figure 1) was used to compare the effect of fertilization on yield under SR and VR applications. This design involved treatments that run in the same direction across the field as planting and harvesting. Planting was done back and forth across the field, resulting in multiple random side-by-side replicates for each pass.

The treatments were randomly assigned by each pass of the planter across the field, with VR application followed by an SR application, which was followed by VR again, and so forth. The 8.5-metre widths of the strips were equal to the width of a planter, a fertilizer applicator and a combine harvester. The field was divided equally, with six alternating rows for VR and six rows for SR, resulting in 80 replicates of each treatment. Each set of six rows constituted a strip or a plot. The middle block highlighted in Figure 1 shows an area where the two strips meet. Each treatment strip in the field ran across the good, average and poor yield potential zones, i.e. crossed over different potential zones. In the SR application method, one application was carried out in different zones as the application rate was kept constant in each strip, while the rates changed as different areas warranting varying rates were reached when using the VR method.

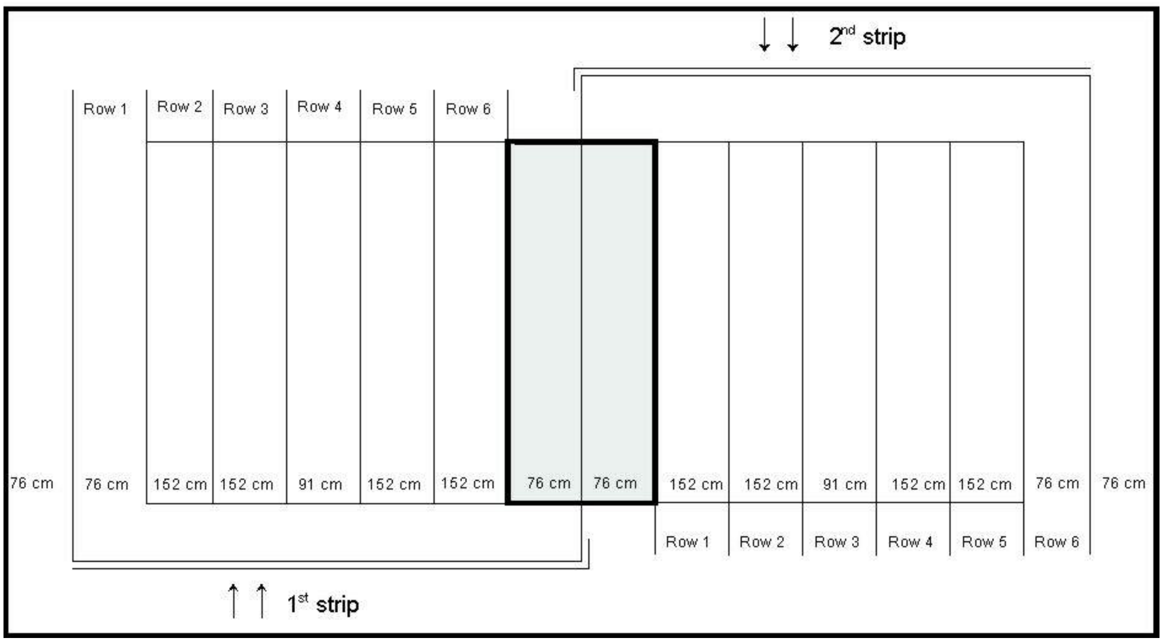

Figure1: Experimental Design: Strip-plot Design

For the VR application, different P rates (kg/ha) were determined for different zones and these were used as ranges within which fertilizer application was varied. The management zones were determined by layering yield maps of the past three years, and potential zones were established based on yield. Average yields were determined by means of this layering, and an average yield map was created. P was varied as superphosphate in winter after harvesting the proceeding crop. Variable rates were 6.79 kg/ha for the low-potential zone, 10.28 kg/ha for the medium-potential zone and 12.64 kg/ha for the high-potential zone. Low-potential zones received the total P rate of 14.79 kg/ha, while 18.28 kg/ha P was applied in the medium-potential zone. The high-potential zone received total P rates of 20.64 kg/ha. Under the SR application method, a total of 16 kg/ha hectare of P was applied. This includes the 8 kg/ha of superphosphate and 8 kg/ha of 4:2:1(28) fertilizer mix. The National Fertilizer Association of South Africa provides farmers with guidelines in the form of prescription rates for different potentials, and these were used as the basis for determining the ranges. These prescription rates were based on the soil P content and the soil yield potential.

4.3 Data collection

Yield data was recorded on a yield monitor card and saved as a comma-delimited file that could be opened in Excel. The file contained different columns indicating latitude, longitude, height, yield, harvest rate and time in seconds. GeoDa™ spatial data analysis software (Spatial Analysis Laboratory, 2004) was used for spatial data analysis. The data set contained a total of about 56 000 yield point observations after removal of erroneous data. Yield editor software (Drummond, 2005) was used to remove erroneous data. The main variables used in cleaning data included velocity (km/hour); velocity change; end-pass and start-pass delay; flow delay; minimum and maximum yields, and the standard deviation. In appending input data to the yield data, guidelines provided by Griffin, Brown and Lowenberg-DeBoer (2005) were followed.

4.4 Description of the data

Yield was the dependent variable, and P (kg/ha), treatment (TRT) and management zones (Low, Medium and High) were used as explanatory variables. Treatment (TRT), Low, Medium and High are dummy explanatory variables. TRT is a dummy variable for the treatment, whether VR or SR application, with one for VR and zero otherwise. Low, Medium and High are management zones, with 'Low' indicating a low-potential zone with a potential yield of less than 3 ton/ha; 'Medium' indicating a medium-potential zone with a potential yield of between 3 and 5 ton/ha, and 'High' indicating a high-potential zone with a potential yield of more than 5 ton/ha. With regard to the proportions of different zones, the medium-potential management zone was the largest, constituting about 49% of the total field area. The high-potential management zone represented 31%, and the low-potential zone accounted for the remaining 20%. The low-potential zone was regarded as the base, and was therefore not included in the model. The dummy variables were constrained in such a way that they summed up to zero. For the continuous variable (P), it was anticipated that the linear terms would have positive signs and the quadratic terms would have negative signs. This would provide the expected concave production surface. Positive signs were anticipated for all the dummy variable coefficients.

4.5 The model used

Yield monitor data is inherently auto-correlated due to the coincidence of similarity in yield values and location between yield points. In the presence of spatial variability, that is, spatial auto-correlation and spatial heterogeneity, OLS and other traditional analysis methods are unreliable as the assumptions of normality, independence in observations, and identically and independently distributed errors are violated (Lambert & Lowenberg-DeBoer, 2000). With spatial regression analysis, these limitations can be overcome. Spatial regression analysis takes into account spatial auto-correlation, which is very important in spatial data such as yield data. A spatial error model was therefore used for analysis.

A quadratic spatial regression model was specified as follows:

$$Y = \alpha_0 + \alpha_1 P + \alpha_2 P^2 + \alpha_3 Z_2 + \alpha_4 Z_3 + \alpha_5 PZ_2 + \alpha_6 PZ_3 + \alpha_7 P^2 Z_2 + \alpha_8 P^2 Z_3 + \alpha_9 TRT + \alpha_{10} Z_2 TRT + \alpha_{11} Z_3 TRT + \upsilon$$

Where:

P:	Phosphorus (kg/ha)
Z2:	Management Zone 2 (Medium-potential zone)
Z3:	Management Zone 3 (High-potential zone)
TRT:	Treatment, with 1 for VR and zero otherwise

Yield was estimated as a function of applied P. Treatment (TRT), as well as Medium and High management zones, were used as other explanatory variables. Interaction terms of continuous variables were also included in the model. This quadratic function was preferred, as it fits what is known about maize response to fertilizer. It also allows for diminishing marginal returns and a maximum biological yield.

5. Results

5.1 Diagnostic tests

Diagnostic tests on the OLS residuals determine the presence of spatial effects and verify the optimal model. The specification tests on spatial auto-correlation and heteroscedasticity (structural change) are acquired by running the OLS model, which also suggests which model should be used - either the spatial error or spatial lag. Normality in the error terms is determined by the Jarque-Bera (JB) test, which evaluates the hypothesis that the residuals are normally distributed.

The JB statistic is significant at 1% level, implying that the errors are not normally distributed. The Breusch-Pagan (BP) test is a diagnostic test of a regression to determine the presence of heteroscedasticity in the error terms. The larger the BP test, the greater the evidence against homoscedasticity. The Koenker-Bassett (KB) test in the OLS model also confirms the presence of heteroscedasticity in the data. Diagnostic tests are presented in Table 1.

Table 1: Diagnostic tests for normality and heteroscedasticity

	Test statistic	Probability
Jarque-Bera	31392	0.00
Breusch-Pagan	4421	0.00
Koenker-Bassett	1809	0.00

Due to the presence of spatial variability in the data set and the diagnosis of non-normality and spatial heteroscedasticity, the spatial model is more appropriate for analysis so that the spatial effects can be taken into account. The presence of spatial auto-correlation was reported by five diagnostic tests for spatial dependence with the OLS regression output. The spatial error model is more appropriate when the spatial structure is captured in the residuals of the regression, or all the omitted variables are taken care of in the residual. Many factors affect yield variability at field level, and it is not possible to include all the variables in the model. The variables that cannot be included in the model are captured in the residual, making the spatial error model the most suitable model (Griffin *et al.*, 2005).

5.2 Regression analysis

GeoDa™ spatial data analysis software provided diagnosis and estimation of parameters for this spatial regression model. The regression properly accounted for the spatial structure in the model. Spatial econometric models require specification of the weights matrix. In this study, the definition of neighbours is based on the geographic criteria, in terms of the distance between yield points, using the Cartesian space (longitude and latitude). The Euclidean distance-based matrices were calculated in GeoDa™ using the threshold (minimum) distances for each year, which ensures that each observation has at least one neighbour. The regression output results from GeoDa™ are presented in Table 2.

Table 2: Summary of the regression output: Spatial error model

Dependent Variable	Yield (tons/ha)			
Mean dependent variable	4.60088		Number of observations	57377
Weight~14.GWT			Number of variables	12
S.D. dependent variable	1.19		Degrees of freedom	57365
Lag coeff. (Lambda)	0.73			
R-squared	0.71		R-squared (BUSE)	
Sq. Correlation			Log Likelihood	-61138
Sigma-squared	0.41		Akaike info criterion	122300
S.E of regression	0.64		Schwarz criterion	122408

Variable	Coefficient	Std.Error	z-value	Probability
CONSTANT	-21.46079	2.39910	-8.94537	0.00000
TRT	-1.77371	0.12709	-13.95602	0.00000
P	2.57786	0.24506	10.51940	0.00000
P_2	-0.05886	0.00595	-9.88988	0.00000
Z2	18.58848	2.39593	7.75835	0.00000
Z3	-41.43420	4.76622	-8.69331	0.00000
TRT_Z2	1.61003	0.12839	12.54017	0.00000
TRT_Z3	-3.28365	0.25651	-12.80126	0.00000
Z2_P	-1.79333	0.24490	-7.32261	0.00000
Z3_P	4.18260	0.48627	8.60139	0.00000
Z2_P2	0.03922	0.00596	6.58220	0.00000
Z3_P2	-0.09688	0.01179	-8.21957	0.00000
LAMBDA	0.72931	0.00210	346.71710	0.00000

The P coefficient of 2.58 has the expected positive sign and a significant z-statistic (10.51) at 1% probability level. The quadratic P coefficient (-0.06) has a negative sign, upholding the law of diminishing marginal returns and indicating the marginal physical productivity of inputs. If everything is kept constant, a onekilogram (kg) increase in P leads to a yield increase of about 2.519 tons/ha (taking P and P^2 into account).

The zone dummy variable was defined as Zi = 1, i = 2, 3 and zero otherwise, with Zone 1 used as the base. The two zones Zone 2 (Z2) and Zone 3 (Z3) are both significant, indicating that maize response to P varies throughout the field, and this difference is captured according to management zones. Zones 1 and 3 display the concave production functions, while Zone 2 exhibits the convex production function.

The treatment (TRT) coefficient has a negative sign for Zones 1 and 3, suggesting that SR results in a yield increase of about 1.77 tons/ha relative to the VR application treatment in the base zone (Zone 1). In Zone 3, the difference between the two treatments is greater (3.28 tons/ha). This is consistent with the descriptive statistics results (not reported in this paper), in which average yields for SR are statistically higher than average yields under the VR treatment. Average yields are 4.57 for the VR and 4.62 for SR; the difference is statistically significant in the t-test. The VR treatment has a positive effect in Zone 3 only.

5.3 Profit estimation

The coefficients estimated from the spatial regression models formed the basis for the economic analysis. Profit was estimated using Formulas 1 and 2.

$$\pi = P\overline{Y}_{VR} - A - r\overline{X}_{VR} - O \qquad (1)$$

Profit for the VR application was calculated using formula 1, where π symbolizes profit; *P* is the price of maize yield per ton; *r* represents the price of phosphorus fertilizer in kg/ha, *O* represents other fixed and variable costs incurred in the production of maize and *A* stands for fixed costs associated with the VR application, and is calculated as follows:

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

where *I* is the investment cost of VR equipment and *i* the discount rate.

For the SR treatment, Formula 2 was used:

$$\pi = P\overline{Y}_{SR} - r\overline{X}_{SR} - O \quad (2)$$

$\overline{X}$ in both formulas was calculated with the following formula:

$$\overline{X} = \sum ij \, X_{ij} / ha$$

where $\overline{X}$ is the input applied (P), and *i* and *j* apply for VR only.

Since profit can be maximised on the basis of both the inputs used and the output produced, the profit-maximising input and output levels are determined (Figures 2 and 3 respectively).

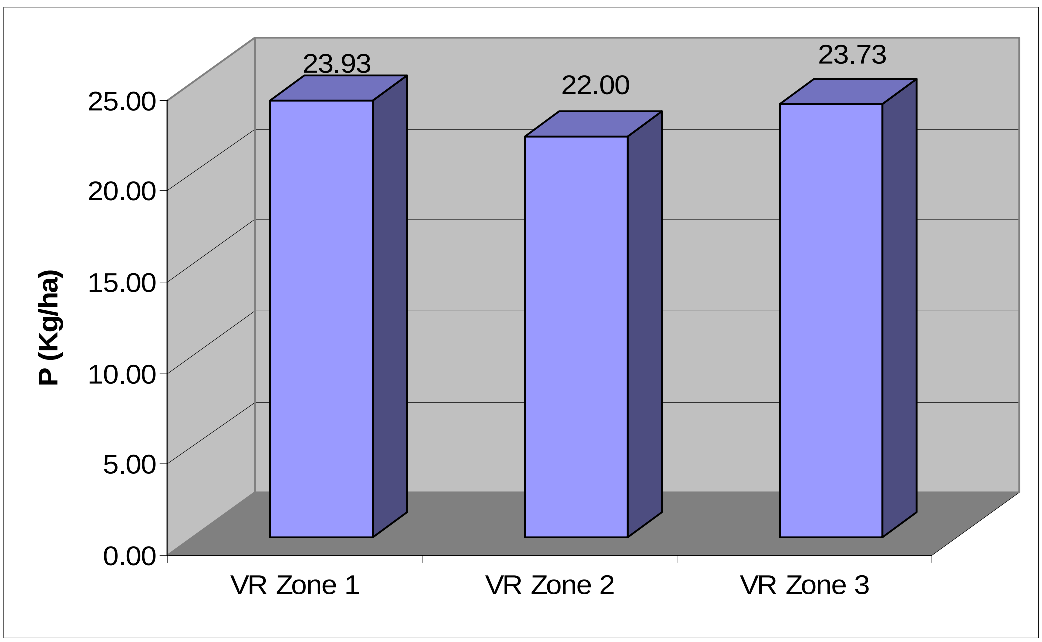

Figure 2: Profit-maximising P levels for VR application

The profit-maximizing P levels do not vary significantly between the zones, but differ from the rates used at the trials. The rates used at the trials were lower than the profit maximization rates, with only the rates in Zone 3 closer to the profit maximization rates. The SR rate of 16 kg/ha is far below the profit maximization rates. In addition to the profit-maximising P levels for each zone, the profit-maximising yield levels for each treatment were also estimated, as illustrated in Figure 2.

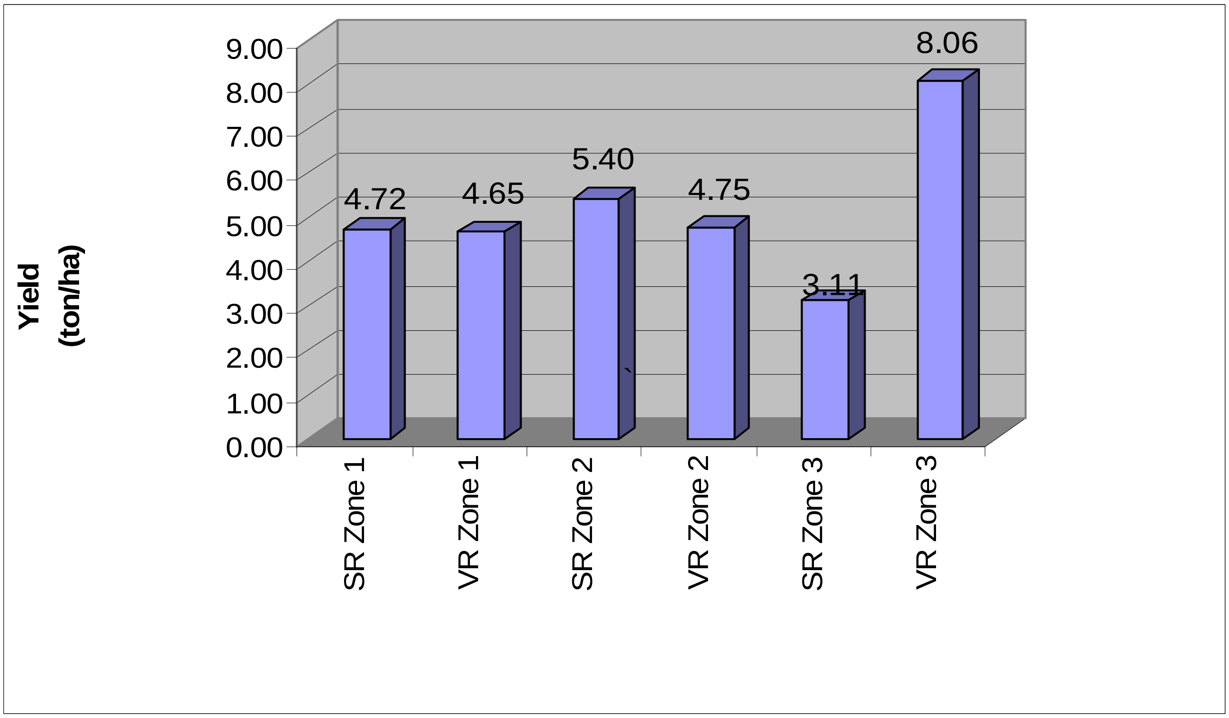

Figure 3: Profit-maximizing yield levels for VR and SR

The results indicate that there is variation in maize yield response to the applied P depending on the application method used - the VR treatment produced statistically higher yields than the SR treatment, mainly in Zone 3. The reason could be that trial rates in Zone 3 approximate the profit-maximizing rates. On average, yields are higher for the VR treatment. This supports the hypothesis that VR application of P results in higher average yields than the SR application.

When analyzing profit per management zones, the high-potential zone subjected to VR application resulted in the highest profit of R6 633.08/ha relative to the profit of R3 587.78/ha in the analogous zone, but under SR application. The other zones (medium-potential and low-potential) under SR application performed better than their counterparts under VR application, resulting in profits of R2 763.69/ha and R2 686.01/ha respectively in comparison to their equivalent zones under VR application. Profits were R2 663.05/ha and R697.94/ha for medium-potential and low-potential zones under the VR treatment.

However, the weighted profits for the two treatments were similar - despite statistically higher yields obtained in the high-potential zone for VR. The VR strategy was penalised by the low profit obtained in the medium-potential zone, which happens to contribute a greater share to the total size of the field. These calculations are based on a maize price of R1 200 per ton, total costs of R2 864 per hectare (variable and fixed costs, excluding P costs) and a P price of R2.03 per kg.

6. Conclusion

The results indicate that maize yield response to applied P varies depending on the application method used and among management zones. It has been shown that if the technology is used in such a way that P application for each zone approximates the profit maximising rate as shown by zone three, the VR application does not only produce higher yields than SR application, but the profit margin between the two application strategies is bigger as well. Even though the SR application produced higher average yields, the profit analysis resulting from the two application treatments indicates that VR resulted in higher unweighted profit than the SR application. These results are a building block based on a single year and single-site data, and temporal analysis is required to determine the profitability of VR technology over a period of time.

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