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CERTAIN ECONOMIC ASPECTS OF PHOSPHORUS FERTILISING OF MAIZE*

by

T.F. Nienaber, Maize Board

and

J.A. Groenewald, University of Pretoria**

1. INTRODUCTION

Phosphorus is an essential plant nutrient. Although the phosphorus content of most plants, including maize, is considerably lower than the nitrogen, potassium and calcium contents, some experts consider phosphorus to be a more important yield limiting factor¹.

Phosphorus is present in all cells and is essential for various elements of plant growth, such as the use of sugars and starches, photosynthesis, nucleus formation and cell division, fat and albumen formation, cellular organisation and heredity². Phosphorus has a number of unique characteristics. It is the only element that can effectively be accumulated in the soil³. The main reasons for this are that phosphorus is stable in the form of orthophosphates under conditions of oxidation and normal pH values of soil, and that no volatilisation or significant leaching loss occurs. Moreover, phosphorus is relatively immobile in soil. Even in relatively sandy soils under high rainfall conditions, where a degree of movement does occur, the distance moved is small in comparison with that of, for example, nitrogen.

Black⁴ mentions experiments in which the equivalent of 3 372 kg of phosphorus per hectare was applied over a period of 11 years. In these experiments an annual loss of only 0,1 kg of phosphorus was found through the entire soil depth of 46 cm. Phosphorus is also a plant nutrient that does not become toxic to commercial crops, such as maize, when present in large quantities in the soil.

Phosphorus reduces hardness of soil⁵ and therefore improves tilth. It also increases the moisture retention ability of soil⁶.

The interaction between phosphorus and certain other plant nutrients, especially nitrogen and certain micro-elements such as aluminium and zinc, is well-known^{7 8 9}. Phosphorus often increases plant resistance to certain root diseases¹⁰ and it has been found that high phosphorus levels in the soil have the following practical advantages^{1 1}:

- (1) Better standing ability.
- (2) Greater drought resistance in that higher phosphorus levels bring about a deeper root system and subsoil moisture can therefore be better utilised.
- (3) Increased effectiveness of nitrogen fertilising.

Economically optimum fertiliser quantities can be determined under specific conditions by using statistically suitable production functions and ratios between prices of products and inputs. Fariña and Mapham¹² point out that an economic optimum may mean one of two things: A farmer with an adequate capital but limited land may endeavour to maximise profit per hectare. On the other hand a farmer may have such a limited amount of capital that he will try to realise the highest return per rand spent on fertiliser. The writers feel that the latter approach may possibly be the more rational approach for many farmers in the Black homelands.¹³

The possibility of phosphorus accumulation in the soil, together with the fact that phosphorus is not toxic to plants, means that two possible fertiliser strategies may be followed in attempts to maximise profits.

The one strategy involves applying phosphorus annually, along with the other plant nutrients, in quantities that will be economically optimal according to the average annual production function and current or expected price ratios.

An alternative strategy involves the accumulation of phosphorus in the soil to a high level — one approaching the biological optimum — and then basing annual phosphorus applications on the withdrawal of phosphorus from the soil by the previous crop. This amounts to replenishment of withdrawn phosphorus at high soil phosphorus levels. With this strategy, nitrogen applications will be adapted to current climatological

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and other conditions.

If there were no variation in growth conditions from year to year, there would be little justification for using the latter strategy. However, fluctuations in growth conditions from year to year mean that, since such growth conditions are unpredictable, the second strategy merits consideration.

The first strategy — annual applications according to average growth conditions — will, during a year with considerably above-average growth conditions cause the fertiliser level and consequently yields to be sub-optimal, with resultant sub-optimal incomes. The strategy of phosphorus accumulation, on the other hand, requires considerable expenditure during the accumulation phase. The accumulation of phosphorus may therefore be regarded as an investment, which subsequently entails an interest cost. During years of poor growth a low return might be realised on this capital. In economic terms, the interest on this capital should be seen as a fixed cost.

In this article an attempt will be made to give certain guidelines in this connection.

2. RESEARCH PROCEDURE

In an investigation into the relationship between soil phosphorus and maize yields the following functions were fitted and compared:

- (i) Linear production functions with $Y = a + bX$
- (ii) Quadratic functions with $Y = a + bX + cX^2$. Theoretically c is expected to be negative
- (iii) Square root functions with $Y = a + bX + c\sqrt{X}$. Theoretically b is expected to be negative
- (iv) Cobb-Douglas type functions with $Y = aX^b$.

The functions were fitted to fertiliser trials conducted by researchers of the Fertilizer Society of South Africa at various places in the maize triangle, as reported by Möhr¹⁴. In these trials only P levels were varied. P applications varied between 10 kg and 300 kg per hectare, depending on the initial soil P value and soil series. Nitrogen, potassium and trace element applications were standard. The quantities were determined as the optimum required for the yield potential of the experimental plot concerned according to the maize calculator¹⁵.

Since, according to theoretical expectations, an actual maximum point on a total yield curve cannot be achieved with soil phosphorus as independent variable, and the determination of a biological optimum is important for this purpose, another procedure was followed to measure yield following the analysis of Fariña and Maphan¹⁶.

The dependent variable in the functions is "relative yield" of maize (Y). In order to render the results of various trials comparable, the maximum yield achieved in a trial was set at 100 and all the other yields in the trial were expressed as percentages of this maximum yield.

The independent (X) variable in the production function is the tested P content of the soil expressed in parts per million, as extracted with Bray II solution.

In the experimental data the following classification is used:

- (i) Poorly leached Avalon and Hutton soils (S/100 g clay > 15)
- (ii) Medium leached Avalon and Hutton soils (S/100 g clay 5 - 15)
- (iii) Well leached Avalon and Hutton soils (S/100 g clay < 5)

In the case of medium and well leached Hutton soils many observations for classification purposes were found to be borderline cases which fell either just within or just outside the specific group. For this reason, and because of the possibility of errors, which often occur in soil analyses, it was decided to combine the data pertaining to medium and well leached Hutton soils for purposes of analysis.

Eventually functions were fitted for five different soil types to describe the response of maize production to soil phosphorus content, namely:

- (i) Poorly leached Avalon (S/100 g clay > 15)
- (ii) Medium leached Avalon (S/100 g clay 5 - 15)
- (iii) Well leached Avalon (S/100 g clay < 5)
- (iv) Poorly leached Hutton (S/100 g clay > 15)
- (v) Medium and well-leached Hutton (S/100 g clay 0 - 15)

After fitting the functions the economic optimum level, defined as the phosphorus level giving the highest margin per hectare, was first determined.

In order to compare the two aforementioned strategies with one another, two areas were subsequently chosen, one with a considerably more stable rainfall pattern than the other. With the aid of actual rainfall figures and fitted functions the potential margins above fertilising costs that would be achieved in the two areas over a period of 10 years were determined. In this way the two strategies could be compared with one another.

3. EMPIRICAL RESULTS : PRODUCTION FUNCTIONS

Results obtained by fitting production functions statistically appear in Table 1.

All the functions give satisfactory fits on both poorly and well leached Avalon soil and also on poorly as well as medium and well leached Hutton soil. The R^2 and r^2 values were consistently 0,66 or higher; 66 per cent or more of the variance in Y is thus explained by the independent variable(s). In the case of medium leached Avalon soil the R^2 and r^2 values vary from 0,44 to 0,47.

The quadratic and square root functions consistently gave higher coefficients of determination than the Cobb-Douglas and linear functions. Except in the case of medium leached Avalon soil better fits were obtained

with the Cobb-Douglas function than with the linear function. With both the Cobb-Douglas and the linear functions significant t values for coefficients of P were obtained throughout.

The quadratic and square root functions did not give significant t values for the fits on medium leached Avalon soil. In addition the wrong sign was obtained for X in the square root function, thus implying increasing marginal productivity. On medium leached Avalon soil the quadratic and square root functions could therefore not be used further.

For convenience's sake it was decided to use the same function on all the soils. The choice therefore fell on the Cobb-Douglas function which in this case is both logically and statistically a better function than the linear function. Heady and Dillon¹⁷ describe the usefulness of the Cobb-Douglas function as follows: "This algebraic model provides a compromise between (a) adequate fit of the data, (b) computational feasibility, and (c) sufficient degrees of freedom unused to allow for statistical testing."

TABLE 1 - Statistical functions of the relationship between soil P content (ppm) and relative maize yield

Soil type	Functions						
	Cobb-Douglas			Quadratic function			
	Equation	r^2	t	Equation	R^2	t(B ₁)	t(B ₂)
Avalon, poorly leached	$Y_1 = 65,46 X_1^{0,1259}$	0,77	9,7079***	$Y_1 = 71,24 + 1,80X_1 - 0,03X_1^2$	0,79	4,11***	2,888***
Avalon, medium leached	$Y_1 = 57,29 X_1^{0,1632}$	0,44	3,6768***	$Y_1 = 72,49 + 1,34X_1 - 0,01X_1^2$	0,47	0,80	0,37
Avalon, well leached	$Y_1 = 39,57 X_1^{0,2601}$	0,69	5,2042***	$Y_1 = 48,69 + 2,62X_1 - 0,03X_1^2$	0,75	2,85**	1,89
Hutton, poorly leached	$Y_1 = 62,58 X_1^{0,1320}$	0,81	10,3805***	$Y_1 = 71,02 + 1,48X_1 - 0,02X_1^2$	0,83	6,26***	4,28***
Hutton, medium and well leached	$Y_1 = 41,88 X_1^{0,2399}$	0,72	10,2129***	$Y_1 = 46,40 + 2,81X_1 - 0,04X_1^2$	0,79	6,71***	4,87***

Soil type	Functions						
	Square root function			Rectilinear function			
	Equation	R^2	t(B ₁)	t(B ₂)	Equation	r^2	t
Avalon, poorly leached	$Y_1 = 31,29 - 1,98X_1 + 23,33\sqrt{X_1}$	0,80	2,49***	3,19***	$Y_1 = 84,12 + 0,5509X_1$	0,72	8,48***
Avalon, medium leached	$Y_1 = 64,61 + 0,05X_1 + 6,20\sqrt{X_1}$	0,46	0,02	0,22	$Y_1 = 78,56 + 0,7283X_1$	0,46	3,82***
Avalon, well leached	$Y_1 = 13,91 - 2,69X_1 + 34,94\sqrt{X_1}$	0,76	1,59	2,13	$Y_1 = 67,23 + 0,9135X_1$	0,66	4,89***
Hutton, poorly leached	$Y_1 = 36,39 - 1,45X_1 + 19,25\sqrt{X_1}$	0,84	3,28***	4,41***	$Y_1 = 82,98 + 0,4883X_1$	0,71	8,01***
Hutton, medium and well leached	$Y_1 = 4,15 - 2,31X_1 + 31,00\sqrt{X_1}$	0,79	3,60***	4,88***	$Y_1 = 69,35 + 0,8029X_1$	0,66	8,97***

* = statistically significant at P = 0,05
 *** = statistically significant at P = 0,001

** = statistically significant at P = 0,01

One of the main reasons for the use of this function is still that few degrees of freedom are needed to satisfy the declining marginal yield concept¹⁸. The function allows for rising or declining marginal product, but not both in the same analysis¹⁹. The Cobb-Douglas curve never reaches a turning point – i.e. negative marginal product cannot follow positive marginal product. In the case of phosphorus fertilising this characteristic accords with theoretical expectations, because, according to existing literature, within practical limits, phosphorus never becomes toxic as a result of too high concentrations in the soil in the cultivation of maize under normal conditions. The marginal product can drop to

nil or almost nil, when practically speaking no additional measurable increase in yield is obtained by further increases in phosphorus fertilising. When using "relative yield" the maximum production is set at 100.

The economic optimum on the production function is obtained where the marginal product, i.e. the first derivative of the production function, equals the inverse price ratio: where $dY/dX = PX/PY$.

In Table 2 a summary is given of the various optimum soil P contents for various soil types with a number of yield targets and the calculated biological optimum soil P contents for these soil types.

In the calculation of the economic optimums the

various yield targets are always equal to the relative yield of 100. From this the "price" of maize is determined.

Fariña and Mapham²⁰ as well as Möhr²¹ found that about 6.5 kg of phosphorus was needed to increase the soil P content by one part per million. Double supers

were used to satisfy this condition from which the "price" of P and then the price ratio was calculated.

Figures 1 and 2 graphically illustrate the relationship between relative yield of maize and soil P content for Avalon and Hutton soils with various degrees of leaching.

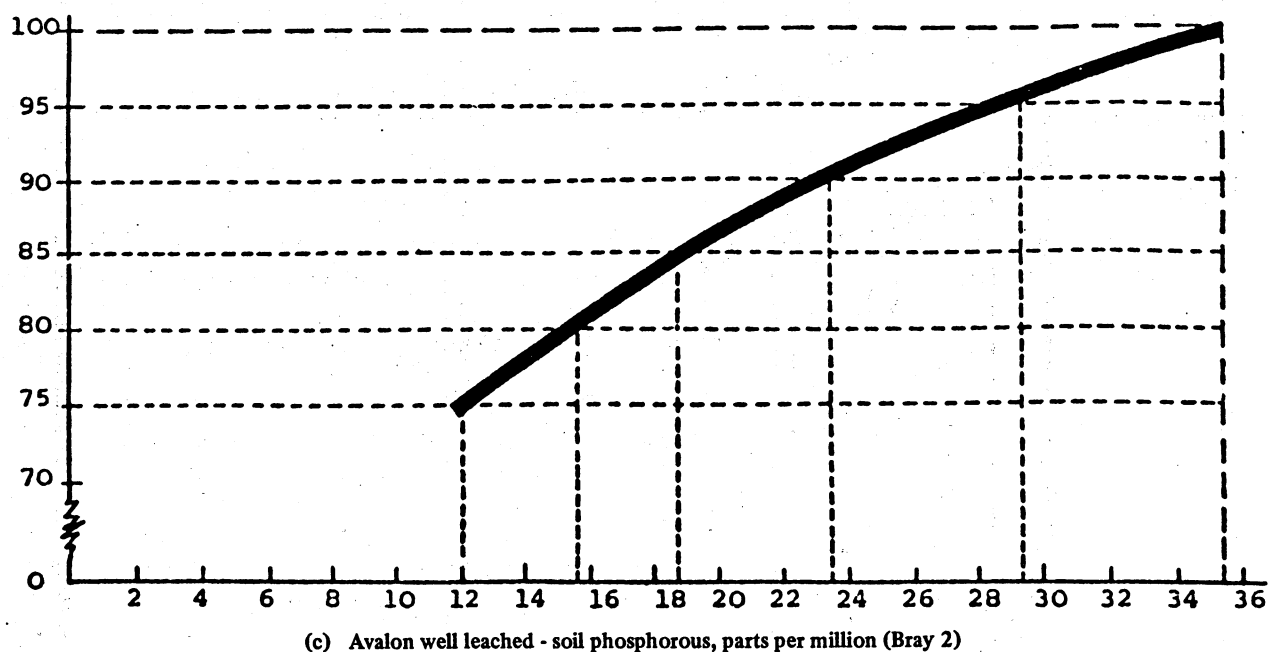
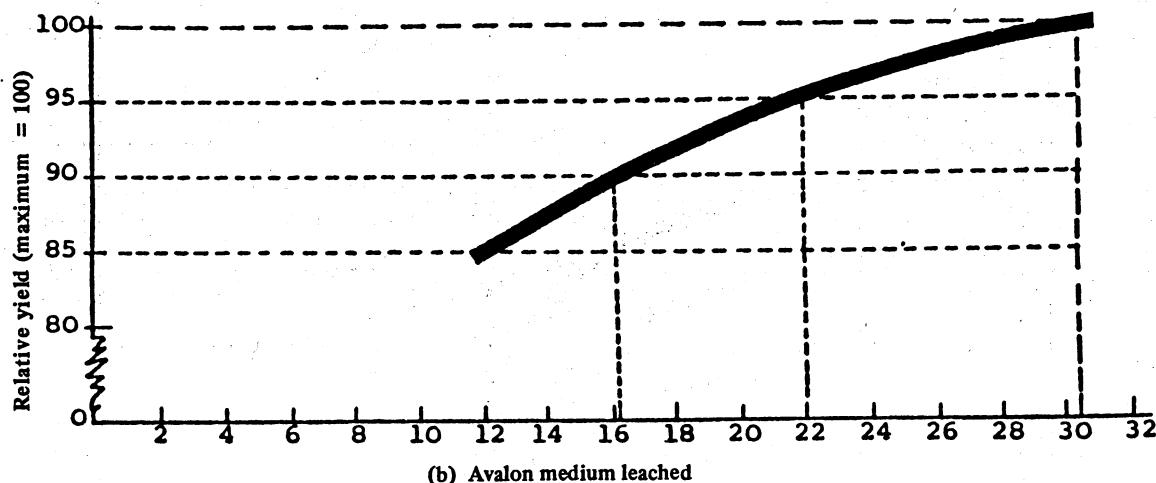
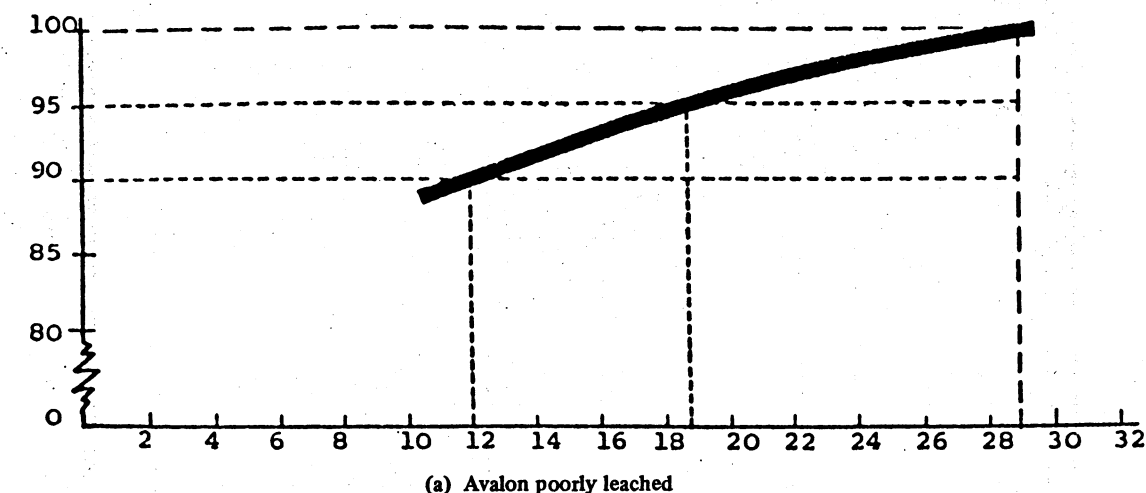


FIG. 1 - Relationship between soil phosphorous and relative yield, Avalon soils

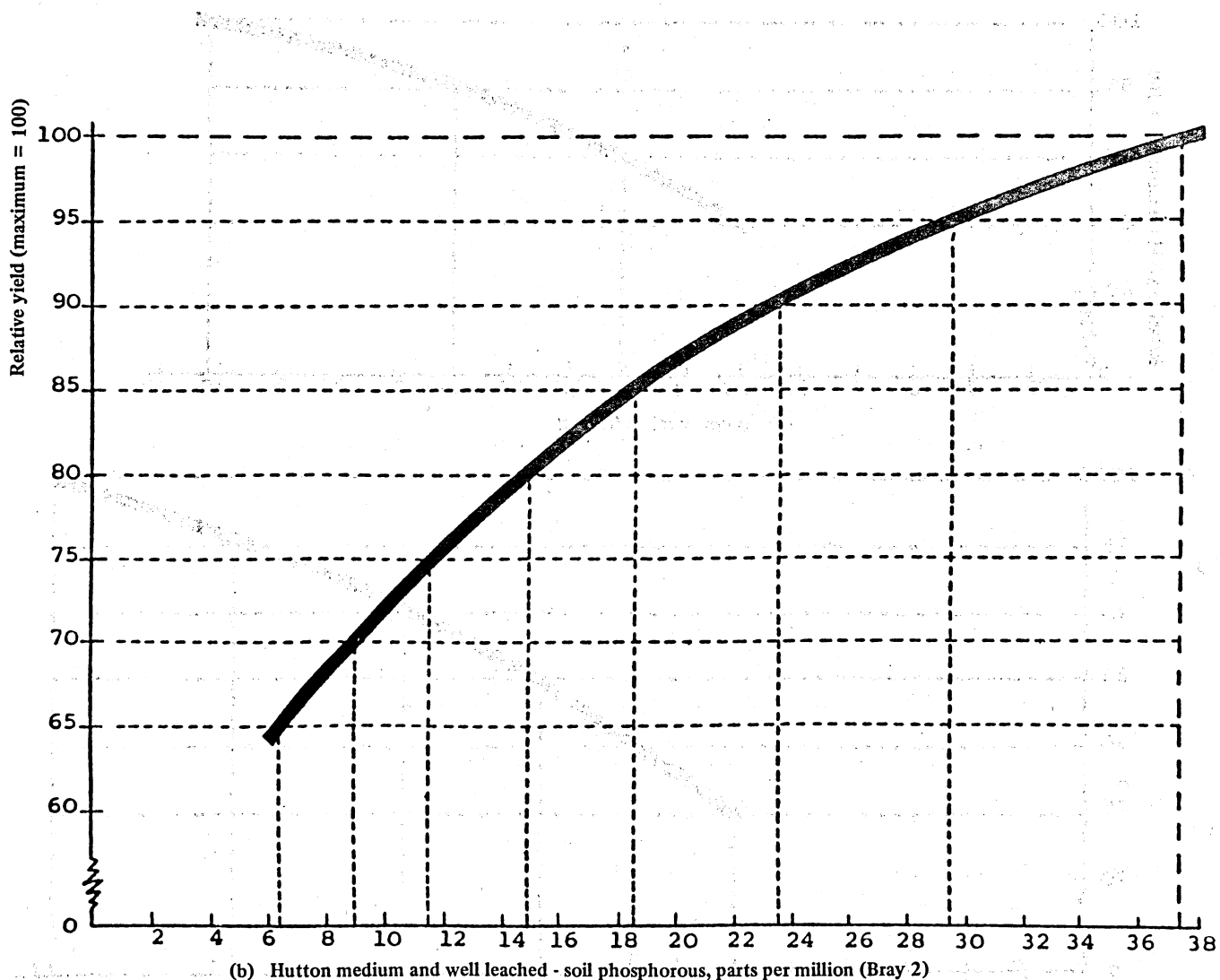
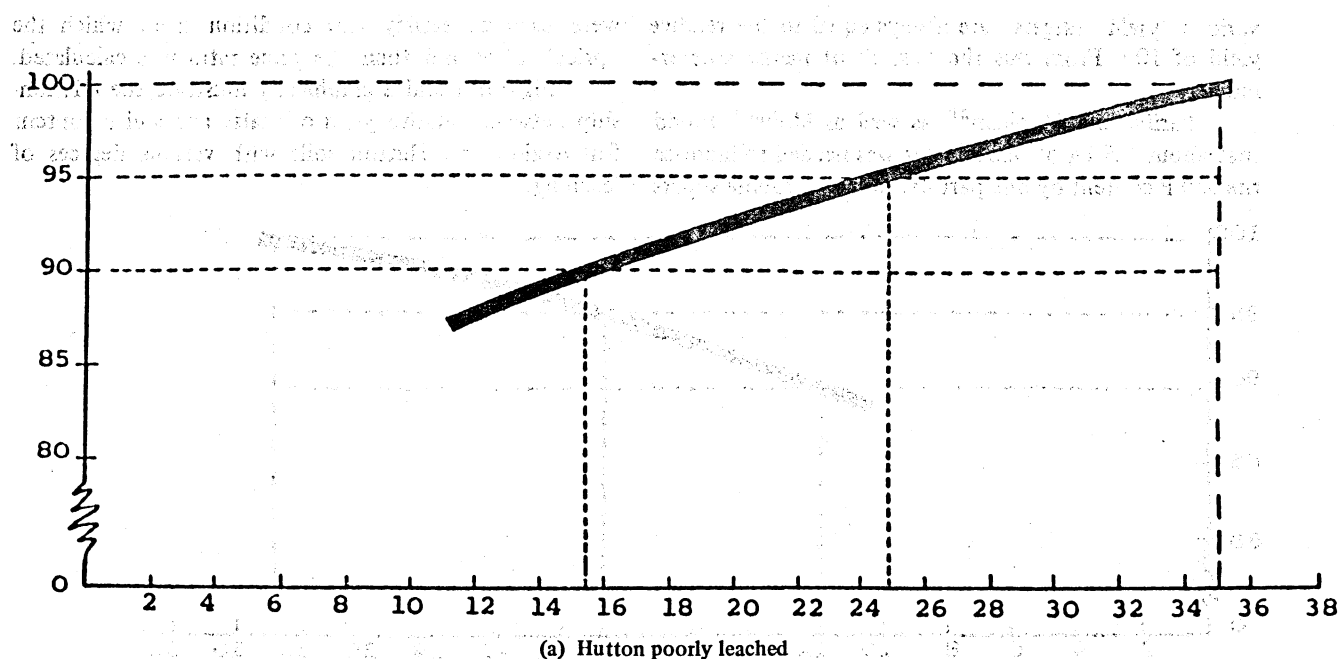


FIG. 2 - Relationship between soil phosphorous and relative yield, Hutton soils

TABLE 2 - Calculated biological optimum and economic optimum soil P contents for a number of soil types

Soil type	Calculated biological optimum soil P contents in ppm	Economic optimum soil P contents for a number of yield targets (expressed in mt) in ppm (Bray 2)*								
		2t	3t	4t	5t	6t	7t	8t	9t	10t
Poorly leached Avalon	29	3	5	7	9	11	13	16	18	20
Medium leached Avalon	30	4	6	8	11	14	17	20	23	26
Well leached Avalon	35	5	9	13	18	23	28	35	41	47
Poorly leached Hutton	35	3	5	7	9	11	13	15	17	20
Medium and well leached Hutton	38	5	9	13	17	21	25	30	35	41

* Calculated as for prices of maize and phosphate fertiliser on 30 June 1977.

4. COMPARISON OF TWO FERTILISING STRATEGIES

4.1 Method of calculation

This comparison was done with the aid of a theoretical budgeting model. The production potential of a specific soil type in a rainfall district, actual rainfall a year for the period 1966-1975, prices of fertiliser (N, P and K) and maize prices were used to determine margins after fertilising costs for the two fertilising strategies.

Results of analyses in two areas will be given — one area is considered to be a high potential maize area with a low risk level in maize production and the other area is usually considered to be a relatively low potential area with high risks involved in maize cultivation.

The choice of areas was based largely on the analysis of De Villiers²² in which he showed how yields, gross income and profits and losses on maize vary from year to year in different districts. He found, *inter alia*, that the Districts of Bethal, Delmas and Heidelberg usually realise high yields and good profits, with a relatively low level of physical and financial risk. An area incorporating large parts of these districts is grouped together as a rainfall district by the Weather Bureau²³. This area, which will be referred to as Area I in the rest of this report, is as follows:

Area I (Rainfall District 74) (According to station names)

Villiers, Heidelberg, Delmas, Vereeniging, Leeuwpoot, Leslie, Oranjeville, Randfontein, Pretoria, Vlaktefontein, Zuurbekom, Rietbult, Johannesburg, Greylingstad and Brakpan.

De Villiers's calculations show that the Districts of Bloemhof and Hoopstad have a considerably lower maize yield at a higher risk than Bethal, Delmas and Heidelberg in the long term. A rainfall district incorporating parts of these magisterial districts was chosen as Area 2.

Area 2 (Rainfall District 91) (According to station names)

Bloemhof, Rooipoort, Brakpan, Vaalbank, Driekoppies, Noodshulp, Hoopstad, Leeudoringstad, Ottosdal, Zevenfontein, Doornplaat, Klipfontein, Hollowaysrust and Rietpan.

Table 3 gives rainfall figures for the two areas for the period 1921 to 1975

TABLE 3 - Rainfall data for Areas 1 and 2, 1921 to 1975

Items	Area 1	Area 2
Average rainfall	700	516
Highest rainfall	950	822
Lowest rainfall	433	340
Standard deviations	120	130

For determining potential the following formula was used²⁴:

$$\text{Yield potential} = \frac{\text{Average rainfall in mm} \times \text{soil depth (cm)}}{12,8}$$

This formula was also applied to the realised annual rainfall to determine a theoretical yield.

The yield potential, in turn, was used to determine the application of potassium over a period of 10 years as a certain fixed annual quantity.

In the model, nitrogen was applied annually according to the rainfall. This procedure was considered to be realistic because nitrogen can be applied long after planting time with good results. In this way nitrogen applications can be harmonised with weather conditions. In contrast, phosphorus and potassium must be applied before or during planting.

In order to test the various situations, the following procedures were followed as regards prices and price ratios:

- (i) Calculations were first done in which the actual prices pertaining to the period 1966 to 1975 were used
- (ii) In order to eliminate the effect of price changes, the calculations were repeated with an assumption

that, the 1966 maize and fertiliser prices would apply throughout.

- (iii) Because it is also of importance to determine how the two fertilising strategies would compare over a period in which product prices would rise consistently relative to fertiliser prices, it was assumed in a further analysis that fertiliser prices were constant and maize prices rose at an annual rate of 4 per cent.
- (iv) Finally, an analysis was done in which the prices of maize were kept constant over the whole period, and fertiliser prices were assumed to increase annually by 4 per cent. From this the effect of relatively rising fertiliser prices on fertilising practices was ascertained.

It was assumed throughout that fertiliser prices for the early season applied throughout the entire season. For example, fertiliser prices in 1966 were used for the 1966/67 season. The maize price, however, was that received for the crop. The 1966/67 maize price therefore applied to that year. It was assumed that the soil was Hutton sandy loam, with a soil depth of 120 cm and an initial soil P status of 10 ppm, a K/Mg ratio of 1:2 and a soil potassium content of between 100 and 200 ppm; all calculations were based on one hectare.

Trace elements were applied in standard quantities; pH and other conditions were assumed to be optimum. In addition it was assumed that there were no serious insect pests or plant diseases, and that 6,5 kg of P was needed to increase soil P by 1 ppm²⁵. For the sake of convenience it was assumed that where phosphorus was accumulated, the accumulation took place within the first year. The needed nitrogen for each year was applied as laid down by the maize calculator²⁶ according to the yield potential as explained earlier, and the rainfall of that specific year. Based on Möhr²⁷, it was assumed that one ton of maize grain removed 3,5 kg of phosphorus from the soil. The following two examples show how the calculations for each year were done, when actual prices were used.

Area 1: The average rainfall was 714 mm a year for the 10 years under consideration and 700,03 mm for the period 1921-1975. By approximation 700 mm was taken as the long-term average.

$$\begin{aligned}\text{Yield potential} &= 700 \times 120 \\ &= 12,8 \\ &= 6,56 \text{ tons/hectare}\end{aligned}$$

(a) Accumulation of P to a biological optimum (38 ppm)

Fertilising costs 1966: (Rainfall for year = 433 mm)

Cost of P (928 kg double supers)	R55,63
Cost of N (208 kg LAN (26))	R10,47
Cost of K (39 kg KCl)	R 1,72
Total	R67,82

Calculated maize yield 4,06 tons @ R36,47 per ton
= R148,47

Margin after fertilising costs = R 80,25

Fertilising costs 1967: (Rainfall for year = 950 mm)

The crop just harvested (4,06 tons) withdraws P at a rate of 3,5 kg, a total quantity of 14,21 kg of P.

Therefore:

Cost of P (72,45 kg double supers)	R 4,67
Cost of N (637 kg LAN (26))	R31,05
Cost of K (39 kg KCl)	R 1,68
Total	R37,40

Calculated maize yield 8,9 tons @ R33,79 per ton
= R300,73

Margin after fertilising costs = R263,33

(b) Applications of P at average economic optimum fertilising level 1966

With prices of phosphate and maize as in 1966 the economic optimum soil P content is approximately 14 ppm with which 79 % of the potential maximum yield for that year can be achieved.

The phosphorus needed to increase the soil P content to 14 ppm is 26 kg of P.

Therefore:

Cost of P (133 kg double supers)	R 7,95
Cost of N (123 kg LAN)	R 6,19
Cost of K (30 kg KCl)	R 1,33
Total	R15,46

Calculated maize yield 3,2 tons @ R36,47 per ton
= R116,70

Margin after fertilising costs = R100,24

Fertilising costs 1967:

The price ratio (PX/PY) changes to such an extent that the economic optimum soil P content is now 12 ppm with which 76 % of the potential maximum yield can be achieved.

11,2 kg of P is removed by the previous grain crop, and the soil P content therefore drops to 12 parts per million. Thus, no phosphate supplementation is needed.

Therefore: Cost of N (438 kg LAN 26))	R20,20
Cost of K (30 kg KCl)	R 1,68
Total	R21,88

Calculated maize yield 6,76 tons @ R33,79 per ton
= R228,42

Margin after fertilising costs = R206,54

The calculated fertilising costs and margins for each year were discounted back to the basic year, 1966,

at a rate of 5 % per annum with the aid of the following formula²⁷:

$$PV = \frac{S_n}{(1 + i)^n}$$

where PV = present value
 S_n = future value
 i = discount rate
 n = number of years

4.2 RESULTS

Calculations were done for each area with the various price assumptions for both strategies for each year over the 10 year period 1966 to 1975. The results were reported elsewhere²⁸.

For purposes of this article only the average values for the period are given. These results appear in Tables 4 and 5.

TABLE 4 - Results of simulation of fertilising strategies, Area 1, 1966 to 1975

Price assumption	Accumulation of phosphorus to biological optimum			Annual application according to optimum on average production function		
	Yield* value	Fertilising* costs	Margin*	Yield* value	Fertilising* costs	Margin*
Average, rand per hectare per year						
Actual prices	210,6	33,5	177,1	164,0	20,2	143,8
Prices constant, 1966 level	186,0	28,8	157,2	145,2	19,0	126,2
Fertiliser prices, 1966 level - maize price rises at 4 % per annum	201,1	28,8	172,3	184,4	20,0	162,4
Maize price at 1966 level - fertiliser prices rise at 4 % per annum	186,0	31,9	154,1	140,9	20,1	120,8

* Discounted back to 1966

TABLE 5 - Results of simulation of fertilising strategies, Area 2, 1966 to 1975

Price assumption	Accumulation of phosphorus to biological optimum			Annual application according to optimum on average production function		
	Yield* value	Fertilising* costs	Margin*	Yield* value	Fertilising* costs	Margin*
Average, rand per hectare per year						
Actual prices	165,3	23,0	142,3	118,6	11,2	107,4
Prices constant, 1966 level	144,5	20,9	123,6	103,7	9,6	94,1
Fertiliser prices, 1966 level - maize price rises at 4 % per annum	168,8	20,9	147,9	132,6	11,9	120,7
Maize price at 1966 level - fertiliser prices rise at 4 % per annum	144,5	32,7	120,8	100,4	10,8	89,6

* Discounted back to 1966

5. CONCLUSION

The results show that in all the cases where the two strategies were compared, accumulation of soil phosphorus gave a higher average discounted margin over 10 years. Percentually the margins differ as shown in Table 6.

TABLE 6 - Percentual differences in margins after fertilising costs for two fertilising strategies, 1966 to 1975

Price assumptions	Area 1	Area 2
	%	
Actual prices	23,2	32,5
Prices constant, 1966 level	24,6	31,3
Fertiliser prices, 1966 level; maize price rises at 4 % per annum	6,1	22,5
Maize price constant, 1966 level; fertiliser prices rise at 4 % per annum	27,6	34,8

In Area 2, the less stable area, the advantage of accumulation of phosphorus is relatively greater than in the more stable Area 1. It also appears that the relative

advantage of phosphorus accumulation is greater if the price of fertilisers rises relative to maize prices. As is to be expected, margins after fertilising costs are larger in the area with the higher yield potential (Area 1).

It should be accepted that, *inter alia*, liquidity problems could make it very difficult or even impossible for many farmers to accumulate the soil phosphorus content within a single year to the biological optimum or to a level approaching it. It need not, however, be done in one year, but can take place over a number of years. A period of approximately five years may be considered realistic in most cases. During this time the farmer will have to ensure that he always applies more phosphorus than was withdrawn by the previous crop. Present tax legislation may make this potentially very profitable, because purchases of fertiliser for this purpose are deductible as a cost. After an exceptionally good crop, a farmer can save tax by building up his soil phosphorus.

This strategy could even make it worthwhile to

build up the phosphorus content to above the biological optimum directly after a very good crop. If a poor crop with resultant liquidity problems should follow shortly thereafter, the farmer can save during the next season by spending less or even nothing on phosphorus fertilizer; he will be able, without fear of lowering his yield, to draw on accumulated reserves for a limited time, such as one season.

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