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THE EFFECT OF DROUGHT ON ECONOMICALLY OPTIMAL NITROGEN FERTILIZATION RATES OF DRYLAND WHEAT IN THE SUMMER RAINFALL AREA

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ABSTRACT

A quadratic nitrogen response model for dryland wheat with moisture stress dependent coefficients is described and validated. The model was used to estimate the effects of moisture stress on the nitrogen levels corresponding to a maximum yield and an economically optimal yield, respectively.

For the range of stress values representative of dryland cropping conditions in South Africa the nitrogen level needed for a maximum yield was largely independent of the stress level. In contrast, the nitrogen level needed for an economically optimal yield increased sharply with increasing moisture stress. The implications of these results with respect to the problem of nitrogen fertilization in semi-arid regions are discussed.

INTRODUCTION

In a recent article Van Zyl, Van der Vyver & Groenewald (1987) showed with the help of multiple regression that drought, general economic conditions and the effect of structural inflation influence the debt burden of the farming sector. In another study the effects of structural input price inflation, interest rate and initial solvency position (as influenced by debt burden) on the financial results of a farming enterprise were analysed (Van Zyl, Van der Vyver & Mostert, 1987). This article investigates the effects of the other major factor that influences the debt burden of farming enterprises specialising in dryland crop production significantly, namely drought. More specifically the effects of moisture stress on nitrogen fertilizer response of dryland wheat in the summer rainfall area are analysed.

The large expense involved in conducting long-term field studies needed to establish N fertilization norms for dryland wheat has stimulated a search for appropriate yield N response models. Several mechanistic and statistical-type models have been proposed. In mechanistic models the various processes governing N uptake by the plant are described mathematically, and parameters involved are estimated by curve-fitting, or obtained from laboratory studies. In statistical models the yields are related to the relevant soil and climatic parameters by means of multiple regression equations. Neither one of the presently existing models appears to be entirely satisfactory. The mechanistic models, the most elaborate of which is the CERES model developed by Kissel, Ritchie & Richardson (1975), include many parameters which are difficult to estimate from simple experiments. On the other hand, multiple regression models (Read, Warder & Cameron, 1982) are usually site-specific and restricted to the range of climatic conditions under which they had been developed.

One of the main objectives of a nitrogen fertilizer response model should be the ability to predict the effect of climatic conditions, in particular moisture stress, on yield response. The available information on the effect of N application on wheat yields in semi-arid areas of the world is sometimes conflicting. For example, in studies conducted in the USA and Canada application of N generally increased yields and the crop water use efficiency (Read, *et al.,* 1982; Ramig & Rhoades, 1963; and Wader, Lehane, Hinman & Staple, 1963). In Australia, however, yield depressions due to the application of high levels of N have frequently been reported (Storrier, 1975; Fisher & Kohn, 1966; Dann, 1969). This so called "haying off" effect occurred primarily in relatively dry seasons (Taylor, 1965) and was attributed to increase in soil moisture stress due to a pre-stress vegetative growth stimulation by N (Storrier, 1975). Studies have shown that in semi-arid regions, variability in precipitation and the associated variability in the degree of moisture stress, may account for up to 85 per cent of the variability in the yield of wheat (French & Schultz, 1984). In order to explain the contradictory findings on N response in dryland wheat, quantitative information on the magnitude of moisture stress and its effect on plant development is needed. Very little information on this subject is available in the literature, since in most fertilizer N trials the magnitude of the moisture stress has not been monitored.

In this work we describe a simple model relating the N yield response to the levels of applied N and the degree of moisture stress, S, based on soil moisture and meteorological data. This model allows for estimating the optimum N fertilizer requirements and yield levels, based on the expected amount of moisture stress during the season.

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THE MODEL

Description

In order to account for the effects of moisture stress (S) and nitrogen (N) application levels on dryland wheat grain yields in the summer rainfall area, the following model is proposed:

$$Y = (a_0 + a_1 S) + (a_2 + a_{12} S) N + bSN^2 \quad \text{.... (Eq. 1)}$$

The model is a quadratic N response model in which the coefficients are linear functions of the seasonal stress index S. The value of S is normalised so that it varies from S = 0 (maximum stress) to S = 1 (no stress). The values of the parameters of the model are specific for a given wheat variety, and may also depend on the soil available N level.

The equation is similar to the equation used by Kissel, *et al.* (1975) describing yield response to N in barley, except for the absence of a single effect quadratic N^2 term in Eq. 1. Here we have assumed that at high stress levels, i.e. when $S \rightarrow 0$, the response to N tends to be linear rather than quadratic. Furthermore, under those conditions the response to N may be negative (the "haying off" effect) indicating that coefficient a_2 is likely to be negative.

Stress factor

In most dryland wheat fertilizer N trials conducted in South Africa soil moisture data have not been collected. Because of the lack of soil moisture data, it was decided to use the amounts of rainfall received during each phenological growth period as an estimate for actual evapotranspiration during that period. This approximation should be valid for sandy soils, in which the changes in soil moisture content during the season are small compared to the amount of rainfall received during the season (Korentajer, Berliner & Dijkhuys, 1986).

To calculate the value of the seasonal stress factor (S), the following equation proposed by Korentajer, *et al.* (1986), was used:

$$S = \pi\, (ET/ETp)_i^{\,0{,}25} \quad \text{.................. (Eq. 2)}$$

where the index i refers to the various growth stages namely, (1) emergence to boot, (2) boot to head, (3) heading to soft dough and (4) soft dough to maturity; and ET and ETp stand for actual and potential evapotranspiration for the i-th growth stage, respectively. The value of S varies from 0-1, so that S = 0 corresponds to the situation of maximum stress (no transpiration), and S = 1 describes the situation of no stress when water loss is dictated by climatological factors. ET can be easily calculated from seasonal soil moisture and precipitation data. The parameters needed to calculate the ETp are usually available or can be reasonably approximated from basic climatological data (Doorenbois and Pruitt, 1977).

Estimating Nmax (N level at maximum yield)

By differentiating the right hand side of Eq. 1 with respect to N, and equating it to 0, the following expression for the optimum N level required for maximum yield, Nmax, is obtained:

$$Nmax = (0{,}5/b)\, a_{12} + (0{,}5/b)\, a_2/S \quad \text{.......... (Eq. 3)}$$

The usual assumption that $b < 0$ (the necessary analytical condition for the existence of Ymax) holds. From Eq. 3, assuming that $a_2 < 0$, it is obvious that with increasing stress (decreasing value of S), the amount of N needed to obtain maximum yield is decreased. This is in agreement with results of field studies indicating that the amount of N needed to obtain maximum yield are generally smaller during dry years than during years of relatively good precipitation.

However, since Eq. 1 is hyperbolic in S, this effect will decrease with decreasing stress levels (increasing S). The threshold S value beyond which a change in stress has a relatively minor effect on the value of Nmax will depend on the value of the coefficients a_2, a_{12}, and b.

Estimating Nopt (N level needed for maximizing economic returns)

The value of Nmax, as calculated from Eq. 2, is the N level needed to obtain a maximum yield. This amount will be higher than Nopt, i.e. the N level needed for maximizing profits. In order to calculate the value of Nopt, the price of grain, price of the fertilizer, and the expected yield levels should be considered. A brief economic analysis of these factors follows.

In order to calculate Nopt consider the slope of a yield versus N level curve. This slope, which will depend on S and N levels, indicates the amount added to the yield by a unit amount of N. In economic terms, the slope is the marginal product of the variable input (N level). Profit is maximized if the value of the marginal product, for a given variable factor, is equal to the price of the factor (Heady and Dillon, 1961). Thus, for optimum N level, the marginal product is equal to the ratio of the unit prices of N and Y (Eq. 4):

$$\frac{dY}{dN} = a_2 + a_{12}S + 2bSNopt = Pn.\ Py^{-1} \quad \text{...... (Eq. 4)}$$

Here Pn and Py refer to the unit prices of N and the grain, respectively. From Eq. 4 we obtain the following expression for Nopt. (Eq. 5):

$$Nopt = (Pn.Py^{-1} + a_2 + a_{12}S)\,(2bS)^{-1} \quad \text{......... (Eq. 5)}$$

The difference between Nmax and Nopt is equal to $Pn.Py^{-1}/(2bS)$. Clearly, this difference will increase with decreasing S value (increasing stress), due to the lower economic returns resulting from low grain yields during the high stress years. Conversely, the difference between Nmax and Nopt will decrease with increasing S values, but will never be equal to 0, except in the limit $Py \rightarrow \infty$ (infinite grain price) or where $Pn = 0$.

CALIBRATION AND VALIDATION OF THE MODEL

Calibration

The regression model described in Eq. 1 was calibrated using a two year moisture stress and N response study. The experiment was conducted on a farmer's field plot near Viljoenskroon during the 1983 and 1984 growing seasons (July-December). The design was a completely randomised block with two replicates and two factors (pre-plant irrigation and N level); and four replicates and one factor (N level) in 1983 and 1984 seasons, respectively. Yield data was obtained from each plot by combining three rows of plants.

Actual evapotranspiration losses were computed from changes in the soil moisture content and rainfall data using the method proposed by Rasmusen and Hanks (1978). Potential evapotranspiration was estimated by means of Penman's formula (Doorenbois and Pruitt, 1977), using meteorological data obtained from a station located two km from the site.

Utilising the model described in Eq. 1, the resulting regression equation is as follows:

$$Y = 0{,}59 - 0{,}00067N + 7S + 0{,}0711SN - 0{,}000322SN^2$$

$$R^2 = 0{,}94 \quad \text{(Eq. 6)}$$

(Y – Mg ha^{-1}, N – kg ha^{-1})

Here the variable S stands for the seasonal stress index, which is a "weighted" product of the ratios ET/ETp (actual to potential evapotranspiration) obtained during four phenological development periods: emergence to boot, boot to head, head to soft dough, and soft dough to maturity.

Validation

The model was validated using yield and meteorological data obtained from several NxP and NxPxK factorial fertilizer wheat trials on wheat (*Triticum aestivum* va. Betta) conducted during the period of 1979-1984. The experiments selected represent the variability of climatic conditions and range of yield values obtained during that period. Experiments 1-6, and 7-8 (Table 1) were conducted by the Fertilizer Society of South Africa and the Small Grain Centre (Dept. of Agriculture, Bethlehem), respectively.

The levels of N varied from 0 to 60 kg N ha^{-1} (LAN, broadcasted pre-plant). The design was a randomised complete block with two, four and six replicates, for Experiments 3-6, 7 and 8, respectively. Other experimental details are available from the annual reports of the respective organizations.

Mean yields, N application levels, and moisture stress values for the validation study (Experiments 3-8) are presented in Table 1. The yields ranged from 1,0 to 2,59 Mg ha^{-1}, and the ET/ETp ratio values ranged from 0,01 to 0,64. The minimum and maximum ET/ETp values for the different experiments occurred during different phenological stages, reflecting the variability in the distribution of rainfall events. The values of S varied from 0,084 to 0,215.

The plot of the predicted (viz. Eq. 6) versus the observed yield values for the entire data set (calibration and validation studies, 50 data points in total) is presented in Fig. 1. The correlation between the predicted and the observed yields was relatively high ($R^2 = 0{,}87$, standard error of the estimate 0,246 Mg ha^{-1}). Using only the validation study data, the correlation between the predicted and the observed yields was lower ($R^2 = 0{,}63$), but the standard error of the estimate remained essentially unchanged (0,266 Mg/ha^{-1}). These results indicate that for sandy soils (such as those used for validation study) the model's assumptions and approximations, in particular the method of estimating the value of S from meteorological data, are basically correct.

THE EFFECT OF S ON N RECOMMENDATIONS

Nmax and Nopt levels

Substituting the model parameters (viz. Eq. 6) into Eq. 3 and Eq. 5 we now estimate the effect of stress on the maximum and optimum N levels, *viz.* Eq. 3 and Eq. 5, respectively. The respective curves

TABLE 1 - Mean yields *, ET/ETp-ratios and seasonal moisture stress values obtained in the N response study

Location and season	Yield (Mg ha^{-1})	ET/ETp Growth stage 1	2	3	4	S**
			Model calibration study			
(1) Viljoenskroon 1983	3,18	0,14	0,36	0,56	0,23	0,28
(2) Viljoenskroon 1984	1,70	0,11	0,18	0,20	0,06	0,13
			Model validation study			
(3) Viljoenskroon 1979	2,61	0,15	0,30	0,24	0,19	0,22
(4) Frankfort 1980	1,52	0,10	0,12	0,27	0,39	0,19
(5) Frankfort 1981	1,29	0,19	0,01	0,08	0,45	0,09
(6) Wesselsbron 1982	2,16	0,14	0,57	0,64	0,03	0,19
(7) Wesselsbron 1983	2,56	0,21	0,12	0,19	0,42	0,21
(8) Bethlehem 1984	2,64	0,30	0,20	0,23	0,34	0,26

The numbers in parentheses refer to the experiment number
* Meaned over the N levels and replicates
**Calculated from Eq. 2

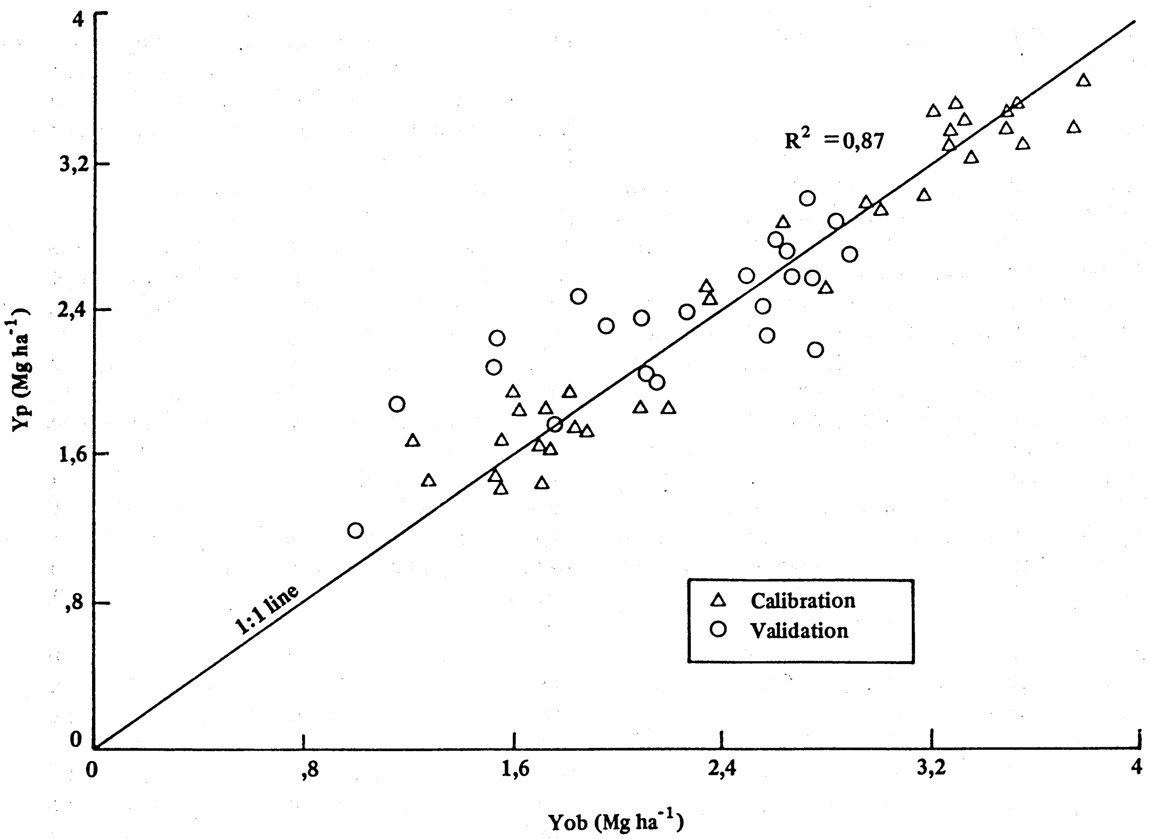

FIG. 1 - Predicted (Yp) versus observed (Yob) yield values for the calibration and validation studies

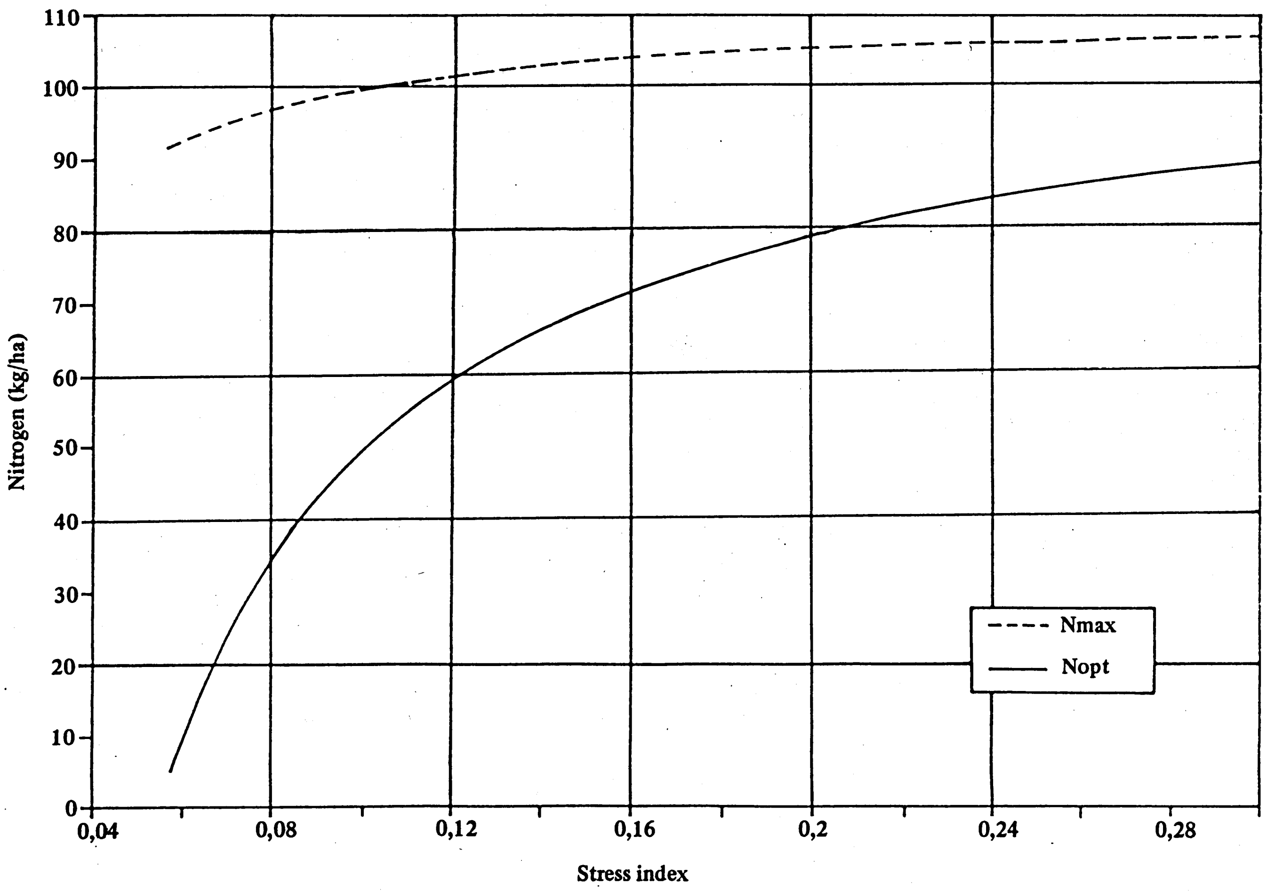

FIG. 2 - The effect of stress on maximum (N max) and optimum (N opt) nitrogen levels, 1986

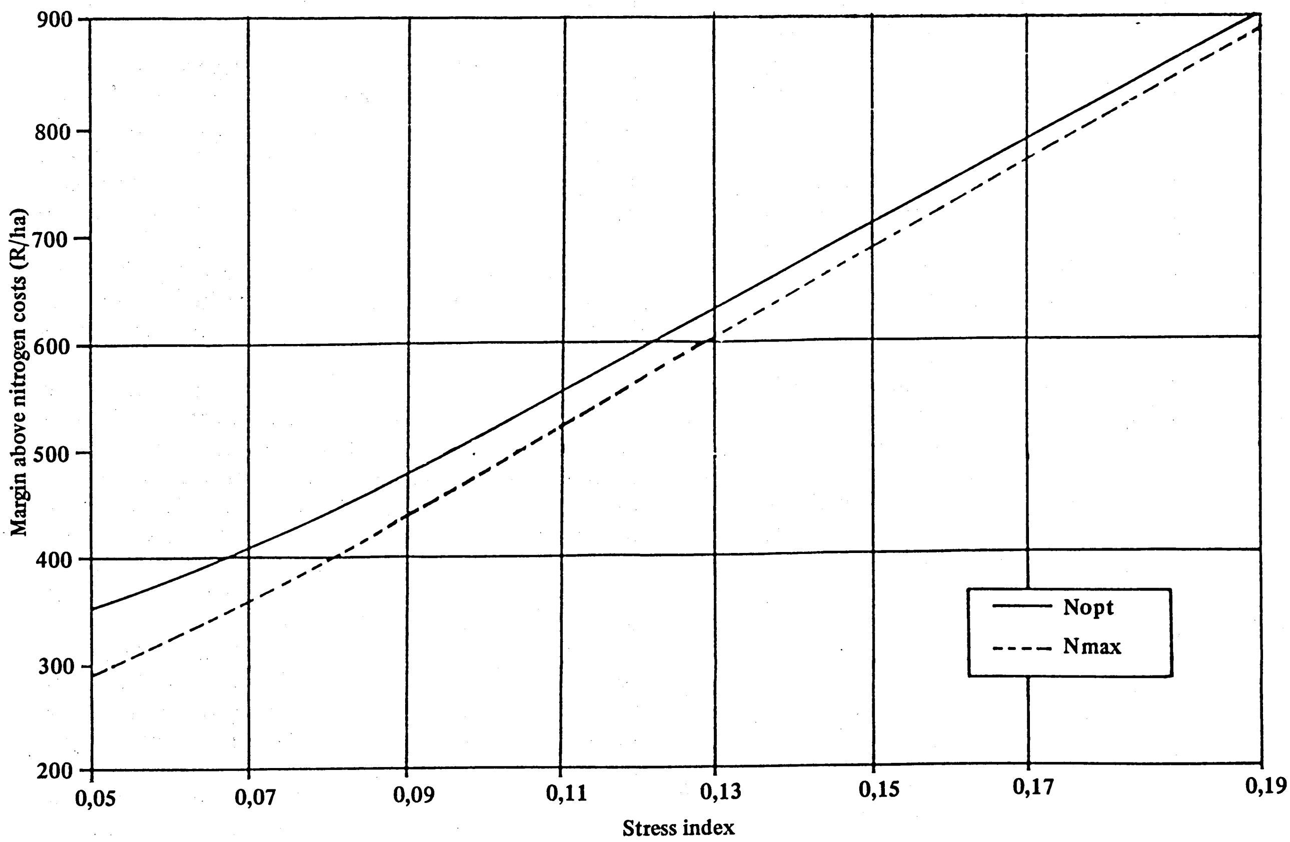

FIG. 3 - Marge above nitrogen costs for Nopt and Nmax at different stress levels, 1986

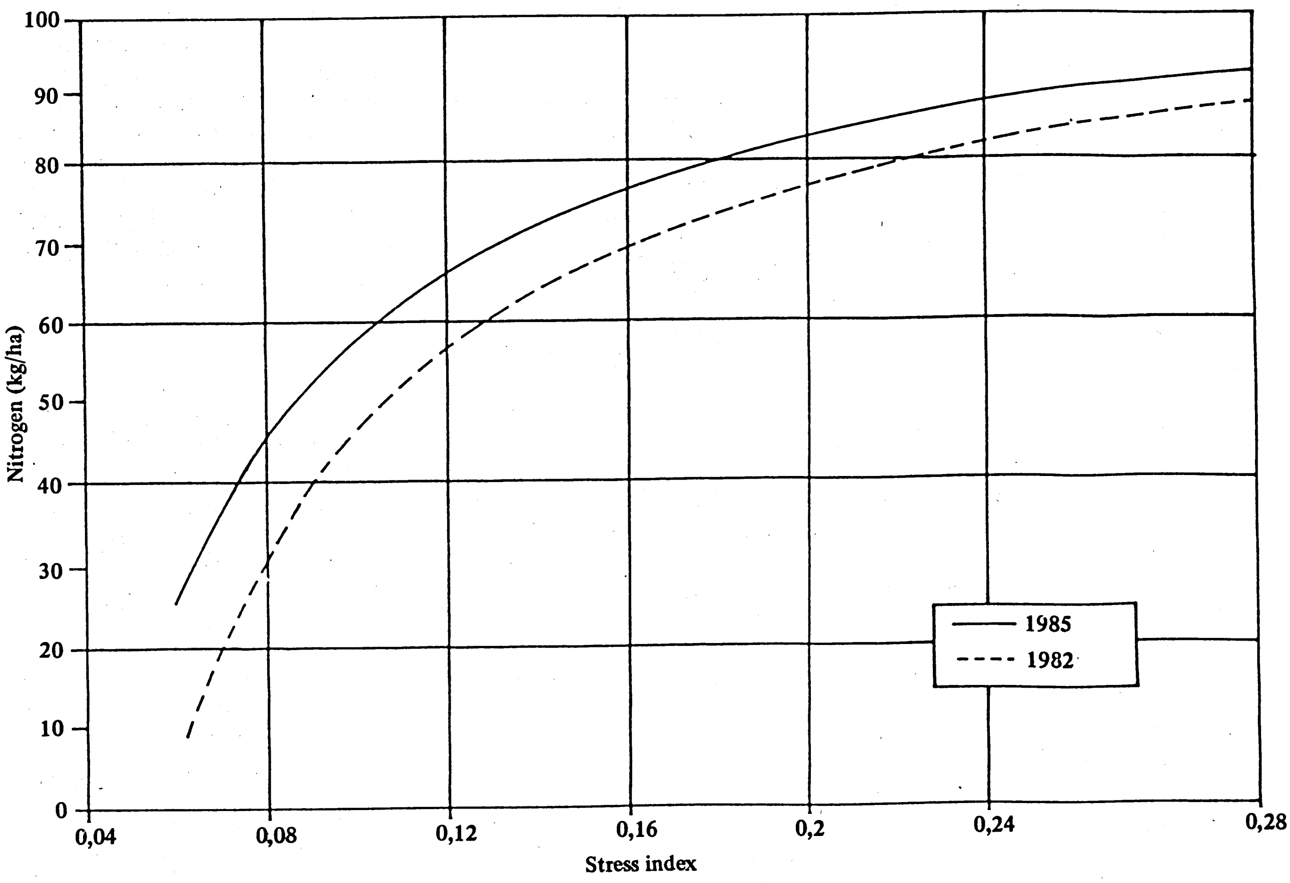

FIG. 4 - The effect of S on Nopt for respectively the highest (1982) and the lowest (1985) price ratios (Pn Py^{-1}) since 1960

of Nmax and Nopt for 1986 year are presented in Fig. 2. An Pn/Py price ratio of 0,0032 was used to calculate the results for Nopt (*Abstract,* 1987). Fig. 3 shows the margin above nitrogen costs for Nmax and Nopt for 1986 year.

The S values which are relevant for the wheat cropping season in summer rainfall areas are in the range $0,05 < S < 0,3$ *(viz.* Table 1). Fig. 2 shows that, for this range, Nmax is almost constant and approximates its theoretical maximum of 109 kg N ha^{-1} (calculated from Eq. 2 by substituting $S = 1$). However, the value of Nopt is greatly affected by S (Fig. 2). As mentioned earlier, the difference between Nmax and Nopt increases with decreasing S values. For example, at $S = 0{,}054$ $Nopt = 0$ (*viz.* Eq. 4), indicating that at that stress level the application of N would result in decreased profits. In contrast, for the same S value we obtain Nmax = 91,1 kg N ha^{-1}. It is clear that economic profitability and not Nmax, should be the main consideration for fertilizer N use.

Economic considerations

Prices of grain and N fertilizer change frequently. The effects of changes in these prices on Nopt is described by Eq. 5. In general, changes in agricultural production brought about by price changes result from the fact that the ratio of the price of the input (Pn) to the price of the product (Py) is altered (Rae, 1977). If Pn and Py change in the same proportion, the ratio of the two and thus the most profitable N level remain unchanged (*viz.* Eq. 5).

Fig. 4 shows the effect of S on the most profitable nitrogen level (Nopt) for two different price ratios ($Pn.Py^{-1}$): 0,0026 and 0,0034 (*viz.* Eq. 5). These values correspond to the lowest and the highest price ratios that have been encountered since 1960 - in 1982 and 1985, respectively, (Abstract, 1987). Fig. 4 shows that the effect of the price ratio changes on Nopt is relatively small, as compared to the effect of S. This result re-emphasizes the importance of stress in determining the most profitable N input levels.

Other criteria

Equation 4 is valid when the capital available to the farmer is unlimited and the profits from selling the grain can be maximized. However, some farmers do not have access to unlimited capital. They must employ criteria other than the marginal value product, in specifying the optimum quantity of N (Bishop and Toussaint, 1978). For these farmers, the quantity of N which maximizes the rate of return on capital investment is perhaps as relevant as the amount of N which maximizes the profits. In such case inputs other than the level of applied N, (e.g. the levels of other fertilizers, the cost of applying herbicides and pesticides, etc) should be considered. The farmer with limited capital maximizes profits if he invests in each input category in such way that the marginal return per rand invested is equal among all input categories.

CONCLUSIONS

Pooled data from several N response trials were analyzed using NxS regression model. There was a relatively good correlation ($R^2 = 0{,}63$) between the predicted and the observed yield values, with a standard error of the estimate being 0,266 Mg ha^{-1}. The calculated values of Nopt (N level required to maximize economic returns) decreased with increasing moisture stress. In contrast, for the same range of moisture stress index, the value of Nmax (N level needed to maximize yields) remained essentially unchanged.

The study shows the need for moisture stress parameters to be included in statistical models of N yield response in dryland wheat. Utilizing the available meteorological data one may use the model to estimate the expected wheat yields and the norms for optimal N recommendations. In this way the model may prove useful for land use planners in determining areas best suitable for wheat cultivation under dryland cropping conditions.

Moisture stress has important effects on economically optimal N applications (Nopt) and the resulting margins above nitrogen costs. The sensitivity of Nopt and the resulting margin above nitrogen costs at different stress levels, especially in the range encountered in South African dryland production, is an indication of the importance of moisture stress on optimal nitrogen fertilization. It also seems that the effect of the value of the stress index on Nopt is much more important than that of the variations of Pn/Py encountered since 1960.

The major problem in die recommendation of optimal N fertilization applications for wheat thus seems to be the determination of S, because one does not know beforehand what conditions will prevail during any production season. There are however indications that the expected value of S can be estimated for different locations from climatological data. Given the expected value of S and the price ratio ($Pn.Py^{-1}$), Nopt can then be calculated.

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