PN-ABC-532
77779

# STAFF PAPER

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PN-ABL-531

**Making Economically Viable**

**Fertilizer Recommendations for Niger**

by

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89-9 October 1988

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Presented at the Farming Systems Research/Extension Symposium, Fayetteville, Arkansas, October 9-12, 1988.

**Abstract**

Biological and economic constraints to agricultural production are numerous in the West African Semi-Arid Tropics (WASAT). Among the natural resources requiring attention in this region is soil fertility. Adequate management of soil fertility seems to play a large part in the ability of farmers to attain a higher and sustainable yield level. In Niger, economic rates of fertilization have not been determined. Furthermore, existing recommendations do not in general take into account the specificity of local conditions.

A multiple input linear spline function for millet response to phosphorus (P) and nitrogen (N) was estimated based on different moisture conditions. Results from this model underscore the importance of P fertilizer in improving yields on sandy soils, and the riskiness associated with the use of N in an environment with irregular rainfall.

Recommendations for economical rates of P fertilization were derived from the multi-input model and compared with recommendations arrived at by using a more conventional form used in such analyses in an effort to evaluate the former's usefulness in providing a simple way to generate fertilizer recommendations. A simpler method based on this model could be used by extension personnel to determine economical fertilization rates based on trials which reflect local soil and environmental conditions.

# Making economically viable fertilizer recommendations for Niger

## 1. Introduction.

Soil fertility is widely believed to be a primary constraint to millet production, the main food crop in Niger (Brown; Enger et al; Roesch and Pichot; Josserand; Wendt). In many years, moisture seems sufficient to support adequate plant growth, but nutrients, especially macro-nutrients phosphorus (P) and nitrogen (N), are usually in short supply (Penning de Vries et al).

In Niger, fertilizer recommendations for millet are uniform throughout the country, and based on trials conducted mostly in the Maradi region where the main agricultural experiment station at Tarna is located. Such recommendations do not take into account wide differences in environmental conditions, especially rainfall, encountered in various regions of Niger.

Involving regional extension centers in experimentation may provide environmentally sensitive recommendations. However, a relatively simple method for determining adequate fertilization levels must be devised so the analysis can be performed easily. The main objective of this paper is to compare methods that could be used for this purpose to others that are more popular in economic analyses.

Specifically, the proposition that yield response to crucial nutrients can adequately be represented by linear splines is tested for its value in making recommendations against more conventional polynomial forms used in response analysis. In the second section, recent

developments in the use of linear response and plateau (LRP) or spline functions are reviewed, and a dynamic model of fertilization based on different response functions is summarized. In a third section, data collected in Western Niger are presented. These are used in section four to evaluate the models' performance. Conclusions are drawn in section five.

## 2. Polynomial and LRP functions and optimal fertilization.

Polynomial models are often used to approximate the response patterns of crops to fertilizer. These models are easy to fit and deriving optimal fertilization rates from them is not complicated (Anderson and Nelson).

The linear response and plateau (LRP) specification arises from von Liebig's 'Law of the Minimum', according to which plant growth is proportional to the supply of the most limiting factor called the 'minimum factor', until a plateau maximum defined by some absolute limiting factor is reached (Redman and Allen). While proportionality in response may not always strictly hold, the linearity assumption may constitute an adequate and useful approximation (Wagonner and Norvell).

The LRP specification is similar to a procedure described by Cate and Nelson that divides response data into classes determined by the yield limitations induced by each input. In the case of a single nutrient, Cate and Nelson have shown that this type of analysis using a single split (high vs low nutrient supply) was applicable to many different plants and environmental conditions. The input level at which two classes are divided is called the critical point, and is related to

the input level at which two splines of the LRP intersect (knot). This level is the minimum nutrient level necessary to attain the maximum (plateau) yield obtainable under given soil and rainfall conditions. In general, this function can be written:

$$(1) \qquad Y = \min [\, a_{0i} + a_{1i} W_i,\ m \,] \qquad i = n, p.$$

where Y is yield, $W_i$ are inputs used by plants (which are a function of the soil nutrient content and added nutrients), and subscripts n and p are nitrogen and phosphorus respectively. Response parameters, $a_{0i}$ and $a_{1i}$, and yield plateau m are to be estimated by non-linear estimation techniques.

Wagonner and Norvell found the law of the minimum to appropriately describe corn yield response to N and P applications. Some economists have recently used LRP functions (Lanzer, Paris and Williams; Lanzer and Paris; Ackello-Ogutu et al; Grimm et al; Jomini and Lowenberg-DeBoer) recognizing, as Perrin indicated, the informational value and theoretical soundness of the LRP specification for some crops.

Anderson and Nelson recognized the tendency of polynomial functions to overstate fertilizer needs. This is especially important at relatively low input prices. Polynomial functions do not adequately reflect the plateau maxima displayed by response data at high input levels (see for example Tisdale and Nelson).

In the case of immobile nutrients such as P, carryover effects may be economically important. This requires a dynamic framework to conduct an adequate analysis. In this case, especially when the soil nutrient content may be variable, it is more appropriate to relate yields to estimates of available nutrients rather than applied. Lanzer and Paris

show the importance of carryover in their study of Brazilian soil fertility and extension recommendations. The amount of a nutrient in the soil at the beginning of a cropping season is a function of the previous nutrient stock, and flows during the previous period:

$$(2) \qquad b_{it+1} = F_i[b_{it}, X_{it}, M_{it}, E_{it}] \quad i = n, p.$$

where $b_{it}$ is the soil test value of input i at time t, $X_{it}$ is the application level of input i, $M_{it}$ is the amount of input i exported from a plot by plant uptake, and $E_{it}$ is the net export of nutrient i due to wind and hydraulic erosion.

The theoretical framework for economic choices in terms of soil fertility is well developped (see Dillon). In general, if a positive rate of discount exists, the long run, steady-state solution to the fertilization problem reduces to the single-period's, if care is taken to account for the carryover effects (Jamini et al). In the short run, Kennedy shows that the optimal strategy consists in reaching the optimal long run solution as quickly as possible.

Assuming the farmer's objective is to maximize expected net income over his economically relevant time horizon, and no constraints to the use of fertilization (e.g. capital, labour) the optimal levels of P and N to be supplied to plants are such that the additional income generated by an extra unit is larger than this additional unit's cost. This is expressed in the familiar marginal equation:

$$(3) \qquad \frac{\delta\pi}{\delta b_i} = \frac{(1+r)}{r}\left[\frac{1}{(1+\sigma)}\, p\, \frac{\delta Y}{\delta b_i} - w_i\right] \leq 0$$

where $\pi$ is net income, $b_i$ is the soil content of input i, r is the long run (annual) discount rate, $\sigma$ is the discount rate within the season (see Kennedy; or Jamini et al for an exposition of the single nutrient

problem and solution method, and the role of discounting in dynamic optimization), p is millet price, and $w_i$ is the cost of increasing the soil's content of input i by 1 unit. Geometrically, this amounts to comparing the slope of the input response function and that of the corresponding input output price ratio ($PR_i$). In the case of the IRP function, the above condition means that if $PR_i$ is steeper than the response slope, then input i should not be applied and a low level equilibrium is obtained. Conversely, if $PR_i$ is smaller than the response slope, then a higher yield and income level equilibrium is achieved in the long run. In the quadratic case, an optimal interior solution is found when both slopes are equal.

## 3. Data from Western Niger.

The data used in this study were collected by the International Fertilizer Development Center (IFDC) on the International Crop Research Institute for the Semi-Arid Tropics (ICRISAT) Sahelian Center experiment station in Sadore near Niamey, Niger between 1982 and 1986. Soils are sandy, low in P and organic matter content, and have low P fixation capacity (Bationo et al). This means that little P is needed to obtain significant yield response. These soil characteristics are representative of a majority of soils in Niger.

Rainfall parameters for each year are presented in Table 1. The length of the rainy season was defined according to Sivakumar. Rainfall for 1984 was extremely bad both in quantity and distribution. During this year, the rainy season started very late, making for a very short season. The most critical period at which moisture can affect plants is

that of flowering, which occurs some 50-70 days after planting. Again, in 1984, rainfall in this period was extremely low, and little moisture reserves were available.

Data from two experiments were used for this study. The first data set stems from the 'benchmark experiment'. In this experiment, millet was grown in 1982, 1984, 1985 and 1986, and cowpeas were grown in 1983 on the same site. Only the millet data are used. In this multi-year experiment, plots were treated in the same manner each year, making it possible to follow the evolution of fertility. All plots received 30 kg/ha of N in the form of urea applied 21 days after planting; this level is generally considered non-limiting. Treatments include five different levels of P between 0 and 40 kg $P_2O_5$/ha, applied in the form of simple superphosphate (SSP, 18% $P_2O_5$), the form of P most available in Niger, which was broadcast and incorporated into the soil before planting.

In order to supplement these data for 1983 and with data reflecting different levels of N, results from another experiment were also used. Here, P varied between 0, 15, 30, and 45 kg $P_2O_5$/ha, and urea was applied at 0, 30, 60, 90 and 120 kg N/ha in split applications 21 and 42 days after planting. Two levels of potassium (0 and 30 kg $K_2O$/ha) were tested, but not found to affect results, confirming previous findings (e.g. Brown) that this element is not in short supply at the current level of soil phosphorus in Niger. In both experiments, soil samples were taken in April-May before each cropping season and soil P concentration was measured by the Bray P1 method.

**4. Results and discussion.**

In Niger, sandy soils and high temperatures result in high rates of denitrification. It was therefore assumed that the amounts of nitrogen carrying over are negligible, and the following carryover equation corrected for heteroskedasticity was estimated from data from the benchmark experiment:

$$(4) \qquad b_{pt+1} = \underset{(0.25)}{1.95} + \underset{(0.07)}{0.48}\, b_{pt} + \underset{(0.04)}{0.33}\, X_{pt} - \underset{(0.03)}{0.14}\, Y_t$$

where t is 1982, 1984, and 1985, b is the soil test level of P expressed in ppm, X is the amount of P supplied, in ppm, assuming a useful soil depth of 15 cm and a soil bulk density of 1.6 g/cm$^3$, and Y is millet grain yield expressed in quintals (100 kg)/ha. A separate variable for other nutrient losses was not included for lack of data. However, the $R^2 = 0.85$ indicates good explanatory power.

Standard errors are supplied in parentheses. All coefficients are statistically significant at the 1% level, and their signs and magnitudes are reasonable. The intercept term indicates the amount of P released into the stock of plant-available P by soil particle weathering. The coefficient on b indicates that almost 50% of currently plant-available P contributes to the following period's soil P content, while the coefficient on X shows that one third of applied P is only available then. Plant export of P amounts to 0.6-1.3 ppm (1.4-3.1 kg/ha) depending on the yield achieved. These estimates are close to amounts obtained by Mahaman in plant analyses.

The immediate conversion of applied P into plant available form is given by the ratio $\mu = 0.33/0.48 = 0.70$. Its standard error is 0.16. In testing whether this coefficient is equal to 0.95, this hypothesis is

rejected at the 5% significance level. This shows an appreciable amount of soluble P (30%) is rapidly adsorbed to soil particles a aluminium compounds (see Wendt) when applied.

Due to data limitations, a separate variable for rainfall was not included in response estimations. However, in a separate attempt to link yield to rainfall, this input was found in 1984 to be constraining, possibly significantly affecting input output relations. Significant constraining factors included the total amount of rainfall in the season and moisture availability in the critical flowering period (Table 1). Hence, response estimates were produced for both cases of sufficient (using data from 1982, 83, 85 and 86) and constraining (using data from 1984) rainfall conditions.

Non-linear estimation techniques are necessary to obtain the LRP parameters. The search for a least square combination of splines was conducted using SAS procedure PROC NLIN. The procedure consisted of a grid search on the parameters, followed by the use of the DUD (Doesn't Use Derivatives) method described by Ralston and Jennrich.

Results for the LRP and quadratic functions when rainfall is sufficient and constraining are shown in tables 2 and 3. Results for the LRP are plausible. The high value of $b_0$ dramatically illustrates the importance of supplying additional P before any response to N can be expected. Signs on some nitrogen coefficients in the quadratic case are unexpected, but are not statistically significant. The quadratic specification cannot capture the urgency of initially responding to soil P deficiencies.

The significant negative response to N application with insufficient rainfall reflects the phenomenon locally referred to as 'fertilizer burn', and may be due to excessive acidity accumulated when concentrated N reacts with the soil in a dry environment (Tisdale and Nelson). This should be taken into consideration when making fertilizer recommendations.

Using prices prevailing in 1985, optimal fertility levels and rates of fertilization were calculated, and are shown in Table 4. The prices used are 80 FCFA/kg millet, 50 FCFA/kg SSP, and 60 FCFA/kg urea. Following CIMMYT, a seasonal discount rate of 40 % is assumed to account for the farmer's time preference for money and for some of the risks involved with these cash outlays. In this partial budeting approach, costs are just the monetary cost of fertilizer, and added net income is the difference between the monetary value of the unfertilized crop (assuming a 4 ppm long term natural fertility equilibrium) and that of the fertilized crop.

Based on the IRP function, optimal levels of both fertilizers are recommendable when rainfall is adquate. In bad years, only P should be applied, and at only about half the rate required in good rainfall conditions. However, P should be applied early in the season, when information about its development is not available to farmers. They then run the risk of spending too much on fertilizer if they blindly follow the higher input level. This may in part explain the tendency of farmers to wait for the season to be well under way before applying P. Little is known currently about the effects of retarding the application of P. The financial aspect of this risk may be a constraint to the efficient use of

P, since cash in rural Niger is a relatively scarce commodity and no credit system (either formal or informal) is currently available for the purchase of inputs (Graham et al; Krause et al). In spite of this, the use of chemical fertilizers, although a risky financial proposition can result in a substantial income increase for farmers in the area described earlier in which per capita income is of the order of 200-300 US$ per year.

When based on the quadratic function, N cannot be recommended since the response surface is not concave along this direction. Assuming no N is applied, the optimal level of P application is slightly higher than in the case of the LRP under sufficient rainfall. In the event rainfall is lacking however, results from using the quadratic are markedly different from those obtained with the LRP. This obtains because of the high value of the constant term, and low presumed response to P under these conditions.

## 5. Conclusions

1. Under the fertility and moisture stress conditions characterizing agriculture in Niger, the LRP is better able to capture the effects of the law of the minimum that seem to be at work. Statistical tests described by Davidson and McKinnon and used by Jomini et al may permit a better assessment of this. However, such tests are beyond the scope of this paper.

2. Drastic P deficiencies, and uncertainty linked to the use of urea make the appropriate determination of optimal rates of P depending on rainfall and soil conditions very important. If N is not tested, the

problem reduces to that of a single nutrient, and the simple technique advocated by Cate and Nelson is applicable.

3. In order to better ascertain the optimal level of P fertilization using this method or the LRP formulation, Anderson and Nelson advocate the use of multiple levels of fertilization in experiments, and concentrating successive trials around the presumed optimal levels. While this analysis was conducted in terms of fertility, it can also be conducted at a simpler level of fertilizing units if soils are relatively homogeneous.

Table 1. Annual and seasonal rainfall patterns; Sadore, Niger 1982-1986.

| Year | 82 | 83 | 84 | 85 | 86 |
|---|---|---|---|---|---|
| rainfall (mm): | | | | | |
| total | 372 | 580 | 216 | 560 | 546 |
| season [a] | 372 | 423 | 83 | 558 | 459 |
| rainy season characteristics: | | | | | |
| begin [b] | 152 | 188 | 221 | 167 | 168 |
| end [b] | 286 | 279 | 273 | 262 | 254 |
| length (days) | 134 | 91 | 52 | 95 | 86 |

notes: [a] defined according to Sivakumar (1988).
[b] in Julian days (151 = June 1).

Table 2. Linear response and plateau functions; available phosphorus and nitrogen.

| Rainfall: | sufficient | constraining |
|---|---|---|
| Parameters [a] | | |
| $a_{0p}$ | 0.23<br>(0.29) | 0.31<br>(1.01) |
| $a_{1p}$ | 0.56*<br>(0.03) | 0.63<br>(0.21) |
| $b_{0n}$ | 7.56*<br>(0.27) | 6.33*<br>(0.45) |
| $b_{1n}$ | 0.05*<br>(0.01) | -0.03*<br>(0.007) |
| m | 9.19*<br>(0.74) | 5.62*<br>(0.29) |
| observations | 274 | 160 |
| MSE | 5.49 | 3.29 |

notes: [a] function is as described in equation 1.
* significant at 1% level

Table 3. Quadratic response functions; available phosphorus and nitrogen.

| Rainfall: | sufficient | constraining |
|---|---|---|
| Parameters [a] | | |
| $a_0$ | 0.373<br>(0.512) | 2.187*<br>(0.620) |
| $b_1$ | 0.590*<br>(0.053) | 0.400*<br>(0.089) |
| $b_2$ | -0.011*<br>(0.001) | -0.098*<br>(0.003) |
| $c_1$ | 0.003*<br>(0.0001) | -0.022*<br>(0.0001) |
| $c_2$ | 0.00002<br>(0.0001) | 0.00005<br>(0.0001) |
| $d_2$ | 0.0015**<br>(0.0008) | -0.0003<br>(0.0009) |
| observations | 274 | 160 |
| MSE | 5.43 | 3.48 |

notes: [a] function is: $y = a_0 + b_1W_p + b_2W_p^2 + c_1W_n + c_2W_n^2 + d_2W_nW_p$

where $W_i = b_i + \mu_i X_i$

** significant at 5% level

* significant at 1% level

Table 4. Economically optimal long run fertility and fertilization levels.

| Functional form: | | LRP | | Quadratic | |
|---|---|---|---|---|---|
| Rainfall Conditions: | | suff. | constr. | suff. | constr. |
| | units | Optimal soil phosphorus | | | |
| fertility (W) | ppm | 16.0 | 9.6 | 16.6 | 0.9 |
| carryover (b) | ppm | 8.4 | 5.7 | 8.9 | 2.0 |
| | | Fertilizer applications | | | |
| P205 (xp) | kg/ha | 26 | 13 | 27 | 1.7 |
| N (xn) | kg/ha | 33 | 0 | 0(*) | 0(*) |
| expected yield (Y) | 100 kg/ha | 9.2 | 6.3 | 7.2 | 2.5 |
| cost | US$ | 38 | 12 | 25 | 1.6 |
| added net income | US$ | 141 | 82 | 123 | 5.0 |

notes: (*) optimum at 0 due to the convexity of the response function.

- exchange rate: 300 FCFA = 1 US$.

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