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AN EMPIRICAL ANALYSIS OF THE SIMULTANEOUS EFFECTS OF NITROGEN, PHOSPHORUS AND POTASSIUM IN MILLET PRODUCTION ON SPATIALLY VARIABLE FIELDS IN SW NIGER

by

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Abstract

Low soil fertility is a major constraint for increasing millet production on the acid sandy soils of the West African Sahel. On these soils, all three macronutrients: Nitrogen (N), Phosphate (P) and Potassium (K), may be expected to limit crop yields. The important question is therefore: which of them is the most critical and would, if applied in small amounts, increase yields significantly? This paper addresses this question with an empirical approach, thus avoiding the commonly observed difficulty in the interpretation of agronomic research, caused by the extreme local soil variability which characterizes Sahelian coversands. We actually exploit soil variability by using novel non-parametric techniques for data exploration in combination with spatial methods of parametric model estimation. Apart from N, P and K, the effects of surface crusting, local topography, manure levels, farmer behaviour and spatial dependence are taken into account, since these may confound the true effects of N, P and K. A quadratic formulation conforms best to the data and explains 81 percent of the yield variation. The equation highlights the importance of interactions among variables and thus confirms the possible impact of native soil conditions on the outcome of fertilizer treatments in experimental research. The results of much earlier, multi-year, research are confirmed remarkably well by this single year study. In addition, a spatially explicit assessment on the crop response to increasing nutrient levels highlights that blanket fertilizer applications are inefficient, because yield *in*creases in some places will be accompanied by yield *de*creases at other sites. Cash-constrained farmers therefore have to resort to precision farming techniques to maximize returns from minimal external input packages. However, a large part of the good explanation of millet yield variability over space derives from spatial autocorrelation, and not directly from topsoil N, P and K. This calls for further research on the factors that affect millet yield and on the characterization and classification of sites, followed by experimental work to design site-specific fertilizer technologies.

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Section 1
Introduction

In the West African Sahel, large population concentrations are found on poor sandy soils, where the climatically-defined Length of the Growing Period (LGP) is generally short and of variable length. Under these conditions, a relatively stable food supply may be obtained only by planting millet crop varieties whose growth cycle is comfortably contained within the prevailing LGP. Provided this is done, and in the absence of periods of mid-season drought, soil fertility is likely to become the main constraint for crop production (e.g. Van Keulen, 1975; Penning de Vries and Djitèye, 1982; Breman and de Wit, 1983; Rockström and de Rouw, 1997; Buerkert and Hiernaux, 1998). The low nutrient status of these sandy soils may indeed imply that large yield increases can be obtained from manure or fertilizer applications. However, low inherent fertility levels coincide with a poor capacity of the soil to retain added nutrients (West et al., 1984; Deckers, 1993). The application of large amounts of manure or fertilizer may therefore be inefficient and, in addition, could cause local pollution of groundwater. Thus, the environmental setting (poor nutrient retention and climatic risks) calls for a fertilizer technology that consists of modest doses of fertilizer types that are well-tailored to the environmental conditions. Moreover, due to the socio-economic circumstances (farmers' cash constraint) it is likely that, rather than wanting to achieve very high yields based on large amounts of external inputs, farmers are more interested in knowing which nutrients, if applied in small quantities, can bring appreciable yield improvement. The options for such external-input- minimizing strategies can be reliably explored through analysis of the empirical relation between crop yield and plant nutrients available in the soil. We consider that this approach, which we pursue in this paper, may provide a good starting point for well-targeted agronomic research.

Given the nature of the prevailing sandy and acid soils, one may expect that there is a deficiency of all macronutrients, as well as some micronutrients, which together limit crop yields (Deckers, 1993, Buerkert and Hiernaux, 1998; Krogh, 1999). However, in practice, agronomic research has frequently identified Phosphorus (P) as the single most important macronutrient deficiency in these soils (e.g. Piéri, 1985; Bationo et al., 1990; Klaij et al., 1994). Even so, only modest fertilizer P levels are required to achieve 90 percent of the maximum yield (Bationo and Mokwunye, 1991a). Indeed, their graphs clearly show that initial response to increasing P is high, but also that, at higher doses, returns to additional P diminish very sharply (near to zero), suggesting that other nutrients become limiting.

It is also generally accepted that high yields cannot be obtained on these soils without Nitrogen (N) applications. Consequently, many studies have concentrated on both P and N. Indeed, a good response of millet to applied N fertilizer has also been observed on these soils (e.g. Bationo et al., 1990; Christianson et al., 1990; Bationo et al., 1991; Christianson and Vlek, 1991). All the same, response to N is often lacking when the P requirement is not met (Traoré, 1974; Bationo et al., 1986; Wendt, 1986). In addition, plant uptake of applied fertilizer N is usually low and volatilization losses are high on the sandy soils concerned (Christianson et al., 1990). Moreover, response to N depends on moisture availability and planting density: better moisture availability improves the efficiency of applied N and response to N is often greater at higher plant densities (Bationo et al., 1990; Christianson et al., 1990; Christianson and Vlek, 1991; Bationo et al., 1992). Their graphs, as in the case of

P, again clearly imply decreasing returns to N, even to the extent that, at very high N rates, yields actually decline.

Low Potassium (K) levels are also known to have an adverse effect on crop yield, but in general the responses to K are often weak in Sub-Saharan Africa (Piéri, 1986). In addition to that, the Sahel is subject to an annual influx of dust, which has a relative high K content (Hermann et al., 1995). Maybe these are the reasons why the possible yield-improving effect of K fertilizer seems under-researched, if compared with P and N. However, with respect to the Sahelian sandy soils, it is also frequently mentioned that intensive cropping would cause rapid depletion of K, because available native levels are very low (Piéri, 1982; Piéri, 1985; De Ridder and Van Keulen, 1990). In this context, it is important to note that farmers in this area often apply crop residues to selected micro-sites with low productivity (Lamers and Feil, 1995, Lamers et al., 1998) and that experimental research has identified the combination of P fertilizer with crop residues as being quite effective in raising yields substantially (e.g. Geiger et al., 1992; Bationo et al., 1993; Hafner et al., 1993; Rebafka et al., 1994; Buerkert, 1995). Crop residues, in terms of macronutrients, are notably high in K (e.g. Bationo and Mokwunye, 1991b; Hebel, 1995) and the yield-raising effect of this practice may thus be indicative of a K deficiency as well in these sandy soils. Indeed, Scott-Wendt et al. (1988a, 1988b) established empirically that, on a transect from poorly-growing to well-growing crops, millet shoot weight was best correlated with plant K concentration and the latter was highly correlated with the location on the transect. Similarly, Hafner et al. (1993) observed K deficiency symptoms in millet, and Wendt (1986) established response to K, but, as with N, only when P requirements were met. More recently, Rebafka et al. (1994) and Hebel (1995) observed large responses to K fertilizer when crop residue treatments were omitted, thus confirming a possible K deficiency in these soils.

In short, low levels of all three macronutrients, P, N and K, may be suspected to limit millet yield in this environment and fertilizer efficiency seems to depend both on the dose applied and on interactions between nutrients. However, many of the above authors have emphasized that the interpretation of results of agronomic experiments is often difficult due to soil variability over very short distances, the causes of which are still poorly understood. Such local soil variability is reflected in very large differences in millet growth and leads to large variations among replications of experimental treatments (e.g. Moorman and Kang, 1978; Scott-Wendt et al., 1988b; Brouwer et al., 1993; Wendt et al., 1993; Hermann et al., 1994; Manu et al., 1996; Brouwer and Bouma, 1997). This local variability of millet growth has been attributed to differences in soil chemistry (e.g. Scott-Wendt et al., 1988a, 1988b; Kretschmar et al., 1991; Wendt et al., 1993; Stein et al., 1997), but also correlates with differences in soil surface crusting levels and local topography (e.g. Scott-Wendt et al., 1988b; Geiger and Manu, 1993; Hermann et al., 1994; Manu et al., 1996; Gaze et al., 1997; Rockström and De Rouw, 1997; Brouwer and Powell, 1998; Rockström et al., 1999). Crop growth differences may thus be caused by nutrient and/or moisture availability, as well as by their interactions, and correlation with a single factor is often difficult to establish (Rockström et al., 1999). Clearly, this very local variability creates problems for agronomic research where discrete replicated treatments are used. However, at the same time, it provides an opportunity for empirical research if the continuous soil variability is taken into account and quantified, and when most of the possible yield determinants are considered simultaneously.

In this paper, the role of N, P and K is emphasized because these nutrients are the ones most needed by plants and they are the most frequently available in various fertilizer types. Moreover, fertilizers are relatively simple to manage and their use often constitutes a first step towards improved farming. We thus exploit natural soil variability and explicitly take into account the continuous variation of topsoil N, P and K levels. The objective is to identify empirically which of the macronutrients, if applied in small amounts, could increase crop yields substantially. To this end, econometric methods are applied in combination with non-parametric kernel density regression and spatial statistics. The non-parametric technique is specifically designed for data exploration. The spatial methods take into account that some of the spatial patterns of yield may be caused by variables other than N, P and K. In this way, the true effects of the macronutrients can be quantified. For the same reason, the earlier-mentioned local relief and surface-crusting levels, and also levels of small ruminant and cattle manure as well as farmer behaviour, are considered, because such factors may confound the real effect of N, P and K.

The data used refer to a millet crop grown by a local farmer without fertilizer, during 1992, on a soil derived from sandy aeolian deposits (coversands), which occupy vast expanses of the Sahel. The within-field yield variation is very large indeed. At the same time, topsoil N, P and K levels are low and small differences in the absolute sense thus become large in relative terms. This, in combination with the large yield variation, is likely to reliably reveal potential yield impacts of small doses of fertilizer.

In Section 2, we first briefly describe site conditions and the data used. Methods of data exploration and analysis are explained in Section 3. Section 4 presents the best performing regression equations, which are evaluated with respect to fertilizer technologies in Section 5. The implications of the findings for future research are discussed in Section 6 and Section 7 concludes.

Section 2
Site conditions and data

The data used in this study refer to a 1 ha field farmed in the village of Bellaré, one km east of the ICRISAT Sahelian Centre and 40 km southeast of Niamey, Niger. The environment is characterized as follows: an altitude of about 240 m amsl; an average annual temperature of 29°C; and an average rainfall of 545 mm, falling in a well-defined season from May to September. The soils of the field are classified as Ferralo-Luvic Arenosols, i.e. poor sandy soils, with some clay content that shows signs of downward displacement. Overall, the topography is almost flat (slopes of about 1 percent), but small micro-topography differences may have important ecological consequences in this type of terrain (e.g. Scott-Wendt et al., 1988b; Geiger et al., 1992; Wendt et al., 1993; Manu et al., 1996; Hermann et al., 1994; Brouwer and Powell, 1998). Some of these small differences in elevation seem to result from ongoing local wind erosion and deposition (Geiger et al., 1992; Sterk, 1997), but these processes have also been operative on much larger scales during various episodes in the more distant past (Sombroek and Zonneveld, 1971; Zonneveld et al., 1971).

The data used were collected on a one ha area (100X100 m) of an unfertilized farmer's field, cultivated in the year 1992. The crop of pearl millet (*Pennisetum glaucum* (L) R. Br.) was planted on two dates. After the first sizeable rains (16 May), about 80 percent of the field was planted and the remainder on 26 May. At harvest (15 and 16 September), millet yield was measured separately for plots of 5X5 metres. Intercropped Cowpea (*Vigna unguiculata* (L.) Walp.) was sown late and formed only a very minor component in this field. Hence we concentrate on millet production only. The yield data, as all other data, were converted to a 10X10 metre grid, since the soil chemistry data were only available at that level (see below). Mean millet yield for the 10 metre grid was 649 kg/ha with a minimum and maximum of 12.3 and 1632 kg/ha, respectively, and a coefficient of variation of 0.49. Spatial autocorrelation of millet yield was tested and proved to be high (for the queen's case: Moran's I is 0.54 with a random z-score of 10.32). Such autocorrelation levels suggest spatial patterns of clusters with higher and lower yielding sites.

Rainfall is not likely to vary much within one hectare, but its analysis provides important background information. The rainy season of 1992 was generally considered as good and no intra-season drought periods were observed. To verify this, various options of the FAO/SOW-VU Agro-Ecological Zones (AEZ) crop growth modelling software (Voortman and Buurke, 1995) have been applied. For this purpose, daily rainfall data collected from a rain gauge at the field boundary were used in combination with other climatic factors, such as wind speed and radiation, from the nearby synoptic station at Niamey. The analysis confirms the absence of intra-season droughts that could have affected moisture availability to the crop. Any evidence of moisture availability playing a role must therefore derive from local differences in infiltration and/or overland flow.

To account for the potential effect of overland flow we quantified local landform (the relative altitude and degree of convexity/concavity of the terrain) with a simple terrain model using a topographic survey conducted on a 5X5 metre grid. The value for each observation point is the sum of the differences in altitude between adjacent observations and itself, which is then scaled such that all observations are positive (variable '*hydroc*', see Fig. 1). Thus, low values refer to convex potentially water-shedding sites and high values to concave potentially water-receiving sites. Surface crusting also may influence moisture availability through its

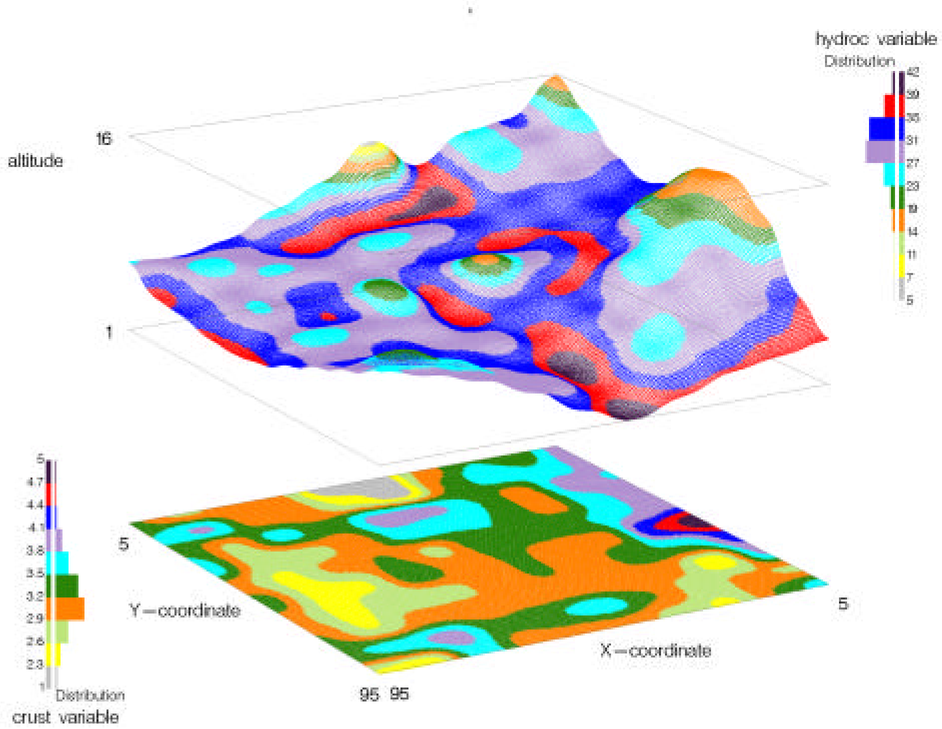

Figure 1: Relative altitude (height of the upper blanket, in decimetres) in relation to coordinates, with 'hydroc' shown in colour on the blanket (low value = convex and water-shedding) and crusting level shown in colour on the lower plane (high value = low crusting). Bar-charts show frequency distribution of classes.

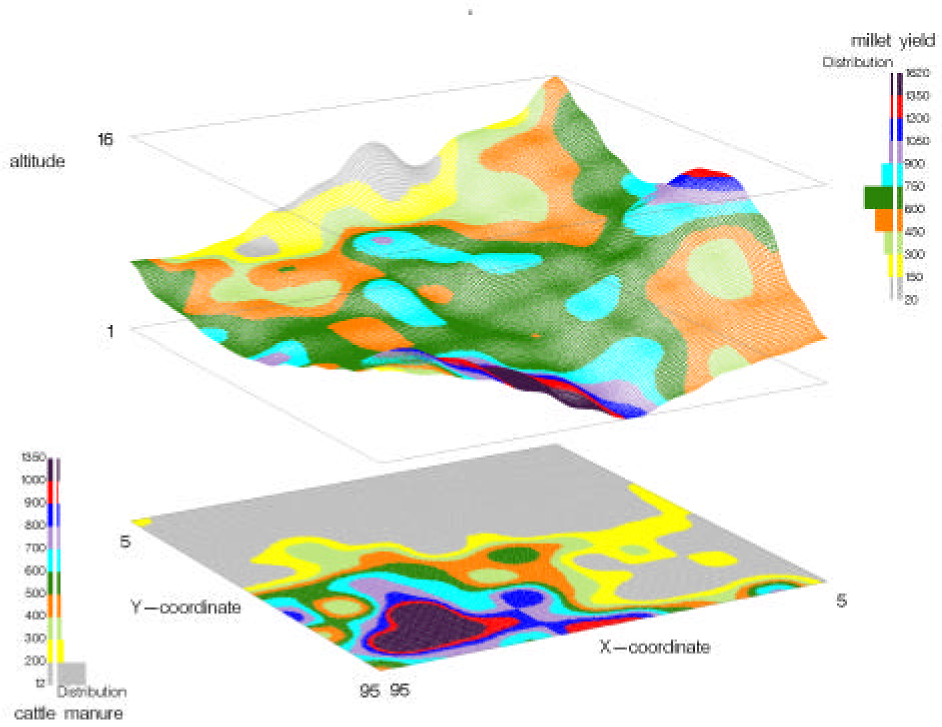

Figure 2: Relative altitude (in decimetres) in relation to coordinates with millet yield (kg/ha) shown in colour on the upper blanket and cattle manure levels (kg/ha) shown in colour on the plane

effect on infiltration. Crusting levels were recorded in the field in a semi-quantitative manner, on a scale of 1 to 5, where 1 stands for high levels of crusting and 5 to its absence (variable '*crust*', Fig. 1)[1]. In addition, manure levels (kg/ha) of cattle and small ruminants, as present at the surface at the beginning of the season, were estimated ('*mancat*' and '*manshe*'), the planting date registered ('*plantd*'), and the number of seed pockets counted ('*pocksco*'). The presence and spatial distribution of animal manure derives from the presence of a deep well just outside the field that is used for watering livestock. The amount and spatial distribution of manure in previous years therefore was likely to be similar, but certainly not identical. The residual effect of manure levels in previous years may therefore not be fully captured by the manure levels of 1992. Clearly, the levels of manure are likely to be good indication of levels of urine deposited, but ex-post these obviously could not be estimated. The spatial variation of millet yield and cattle manure is presented in Figure 2. The clustered spatial pattern of high and low yielding sites is perfectly evident from this figure.

Soil samples were taken for each 5X5 metre plot at 3 depths: 0-0.2 m, 0.2-0.4 m and 0.7-0.9 m. Unfortunately, before chemical analysis, the samples had to be bulked to 10X10 metre plots for financial reasons, which was also why it was not possible to undertake soil texture analysis. In total, there are 98 observations, since two of the bulked samples were lost. Table 1 presents the mean values of some soil fertility-related chemical characteristics of the topsoil (0-0.2 m). These figures clearly confirm the low fertility status of the soil concerned. For N and P, various figures were available, as derived from different laboratory methods. In the case of N, N-total (Kjeldahl) was selected because it is most commonly analysed and thus allows comparison with other studies. In the case of P, the P-Bray value was chosen because earlier studies established that the values obtained with this method explain local millet yield best (Bationo et al., 1991). The value of K was established as exchangeable K (cmol/kg), but in the remainder of the paper we use parts per million to facilitate comparison with N and K. In accordance with common practice in agronomic research, the N, P and K values from the topsoil are used. However, it was first verified whether topsoil values are indeed more closely correlated to yield than subsoil data. This proved to be generally the case, although for K the correlation with the second horizon (0.2-0.4 m) is almost as strong as for the topsoil.

Table 1: Soil chemistry statistics (0-0.2 m depth) for experimental area (n=98)

Variable	*Mean*	*CV*	*Minimum*	*Maximum*	*Dimension*
pH value	5.15	0.04	4.66	5.85	
Nitrogen-total (Kjeldahl)	112.66	0.16	64.00	163.00	ppm
Phosphorus-Bray	2.63	0.50	0.11	11.06	ppm
Potassium (Exchangeable)	0.12	0.32	0.06	0.31	cmol/kg[a]
Total Exchangeable Bases	0.58	0.29	0.30	1.10	cmol/kg

[a] In the remainder of the paper K expressed as ppm will be used.

Correlation among the independent variables was also checked (Pearson correlation coefficients; see Table 2). Topsoil N levels are entirely unrelated to the level of P, but correlation with K is positive and significant. Apparently, native K levels have a greater impact on N accumulation than do P levels. The level of K and N are also higher when

[1] Later in this paper, for analytical reasons, a variable 'crust**c**' is created, where the grading is reversed. Thus, for crust**c,** 1 refers to low levels (low resistance/good infiltration) and 5 to high levels (high resistance/poor infiltration).

surface crusting is less (i.e. when the variable 'crust' has a higher value). Crusting thus not only impacts upon moisture availability, but is also reflected in available nutrients. The negative correlation of crusting with local landform indicates that in locally low concavities the chances of higher crusting levels are greater. Late planting is correlated with low K-levels, higher surface crusting and a smaller number of seed pockets in the early growth stages. Due to these multiple correlations and the dummy nature of planting date itself, we abstain from further use of this variable. Throughout the field, the number of seed pockets is significantly higher when crusting levels are lower. We thus observe that farmer behaviour, in terms of planting date and number of pockets seeded, correlates with physical and chemical features, notably crusting levels and soil K levels. Apparently, the farmer recognizes these conditions and adjusts his actions accordingly. Manure is not included in Table 2, but the only significant correlation found was between cattle manure and topsoil K (probably caused by the high K levels in urine). We conclude that the correlation between the independent variables is generally modest but significant in a number of cases.

Table 2: Correlation between independent variables used in this study[a]

	N-total	*P-Bray*	*K*	*Crust*	*Hydroc*	*Pocksco*	*Plantd*
N-total	1.00						
	0						
P-Bray	0.06	1.00					
	0.5869	0					
K	0.35	0.08	1.00				
	0.0004	0.4088	0				
Crust[b]	0.22	0.12	0.24	1.00			
	0.0308	0.2246	0.0174	0			
Hydroc[b]	0.00	-0.11	-0.01	-0.25	1.00		
	0.9981	0.2878	0.9484	0.0129	0		
Pocksco[b]	0.02	-0.03	0.02	0.42	0.03	1.00	
	0.8385	0.7376	0.8553	0.0001	0.7922	0	
Plantd[b]	-0.17	-0.17	-0.28	-0.23	-0.01	-0.42	1.00
	0.101	0.1019	0.0049	0.0202	0.9353	0.0001	0

[a] For each variable: the first row is the correlation coefficient and the second row is the probability that the correlation is zero.
[b] See text for definition of variables.

Section 3
Methods of data exploration and analysis

A suite of statistical research tools and methods were applied, in an iterative manner, to achieve the objectives of this study. These include correlation, step-wise regression, non-parametric data exploration, model estimation using ordinary least squares (OLS) and maximum likelihood estimation (ML) of models that take spatial dependence into account. Here we will describe these methods in a sequential manner.

First simple correlation (Pearson correlation coefficient) was established and then followed by step-wise regression analysis using SAS (SAS, 1989). However, stepwise regression is not directly suitable for our purpose since it imposes linear structure from the outset. In part, we have circumvented this property of the technique by creating new variables consisting of quadratic terms for each variable and the cross products of all pairs of variables. This allows the identification of quadratic relationships that include interactions between nutrients. Although step-wise regression establishes parametric relationships directly, due to its limitations it was mainly used to identify promising variables and formulations that were further explored with non-parametric methods.

Clearly, in this kind of exercise, it is preferable not to impose parametric structure from the outset, but to let the functional forms be determined by the relationships within the data, in other words, to let the data speak for themselves. For this purpose we use multivariate non-parametric kernel density regression. The programme used, allows the visualization of highly flexible non-linear functional relationships in 3-D images (e.g. Figures 1 and 2), without compromising on statistical rigour (Mollifier programme, see Keyzer and Sonneveld, 1997). These images consist of the smoothed values y(x) that are calculated by a Nadaraya-Watson estimate:

$$y_\theta(x) = \sum_{s=1}^{S} y^s P_\theta^s(x),$$

where observations are indexed s, s= 1,…S, y^s is the observed dependent, x is a multidimensional vector of exogenous variables and $P_\theta^s(x) = \psi((x^s - x)/\theta)/\Psi_\theta^S(x)$ is a probability function of y^s being the correct value of y(x). ψ and Ψ are the normal and the cumulative normal density function, respectively. Control parameter θ (window width) determines the influence of observations in the neighbourhood of x.

First, the relation between millet yield and topsoil N, P and K was investigated. Thereafter additional factors were considered. Based on such explorations, functional forms were selected and parametrically estimated. Two methods for estimation have been implemented, namely the ordinary least squares (OLS) method using SAS (1993) and the maximum likelihood (ML) method using Anselin (1992). The latter method is required when spatial autocorrelation is taken into account, while OLS in such cases does not achieve consistency. Below we briefly outline the spatial estimation techniques.

In general matrix form, we can write the relationship between dependent and independent variables as follows:

$$Y = X\beta + \varepsilon.$$

Spatial dependence can be expressed either through the dependent variable or through the error term: spatial lag (MLLAG) and spatial error (MLERR), respectively. In the case of spatial lag, the above equation can be decomposed in the following mixed regressive, spatial autoregressive model:

$$Y = \rho W y + X\beta + \varepsilon,$$

where W is a spatial weights matrix that structures the dependence between observations and ñ is the spatial autoregressive coefficient. In case of spatial error, that is when å is not well behaved (non-iid), the autoregressive process is expressed as follows:

$$\varepsilon = \lambda W \varepsilon + \xi,$$

where ë is the autoregressive coefficient, W is the spatial weights matrix and î is a well-behaved error term (iid). In both cases a spatial weights matrix is required to identify which neighbouring observations to take into account and which weights to apply between observations.

In the case of ML, the maximized log likelihood is the main criterion for goodness of fit, but it cannot be compared with conventional OLS results. Consequently, we also calculate the maximized log likelihood for the OLS models. For comparison of the performance of equations, we further calculate a Pseudo-R^2 for the ML models. The Pseudo-R^2 consists of the ratio of the variance of the predicted values of the dependent variable over the variance of the observed values.

The performance of regression equations is further judged with a number of tests to assess whether or not basic statistical assumptions are violated. These tests include the probabilities of heteroscedasticity (Breusch and Pagan, 1979; Koenker and Bassett, 1982) and Moran’s I for spatial error (Moran, 1948; Cliff and Ord, 1972; 1981). An essential requirement for these tests is the normality of errors, which is tested according to Jarque and Bera (1980) and Kiefer and Salmon (1983). The appropriateness of spatial lag and spatial error models is assessed with lagrange multiplier tests. Current software versions of spatial statistics allow analysis of linear problems only. Therefore, here too, new variables were created, consisting of the squared terms of each variable and the cross products of all variables. These software limitations are the reason that some complex non-linear models, estimated for the sake of data exploration, have only been implemented in OLS and not in ML models.

Section 4
Explaining millet yield: results and discussion

In this section, we first briefly discuss correlation and next, we report on data exploration with the Mollifier. This is followed by the presentation of non-linear regressions with a high explanatory power. Initially, only N, P and K are considered and the results obtained are discussed in relation to a group of non-linear specifications that have attracted considerable attention from the theoretical viewpoint (e.g. Mitscherlich). This section concludes with the presentation of non-linear regressions that simultaneously account for topsoil N, P and K and for other soil, terrain and management variables.

4.1 Correlation

All but one of the variables are significantly correlated with millet yield, the exception being the 'hydroc' variable, referring to relative relief and slope form (Table 3). We thus have an ideal situation for regression analysis where the correlation between independent variables is weak to modest, and correlation between millet yield and the independent variables is good. For the macronutrients, correlation is best with K, closely followed by N and at some distance by P.

Table 3: Correlation of millet yield (Ymillet) with the independent variables used[a]

	N-total	*P-Bray*	*K*	*Crust*	*Hydroc*	*Mancat*	*Manshe*	*Pocksco*	*Plantd*
Ymillet	0.41	0.21	0.54	0.49	-0.11	0.48	0.33	0.31	-0.49
	0.0001	0.0428	0.0001	0.0001	0.2903	0.0001	0.0009	0.002	0.0001

[a] For each variable: the first row is the correlation coefficient and the second row is the probability that the correlation is zero.

4.2 Data exploration results

Examples of data exploration results are given in Figures 3 and 4. They show yield as a function of two macronutrients on the x- and y-axes. Yield is expressed as the height of the upper 'blanket'. In both the blanket and the lower plane, the derivatives of the macronutrients are represented in colour. These non-parametrically obtained derivatives were first calculated on the actual data points and they represent the amount of yield increase per unit of increase of the independent variables on the x- and y-axes.

Plotting yield against N and P (Fig. 3) shows that the response to increasing N levels is generally positive and almost independent of P levels. At low N, the derivative of N is highest and it gradually decreases with increasing N. In other words, at low N, the addition of an extra unit of N produces the greatest yield increase (decreasing returns to scale). At the highest N levels, referring to a limited number of observations, yields even decrease: the derivative becomes negative and most strongly so when N and P are both high. From the plots of N against K (not shown here), it is observed that yield increases due to N strongly depend on the K level. At low K levels, there is first a strong response when N increases, but from medium N levels onwards no further response is observed. By contrast, when K is high

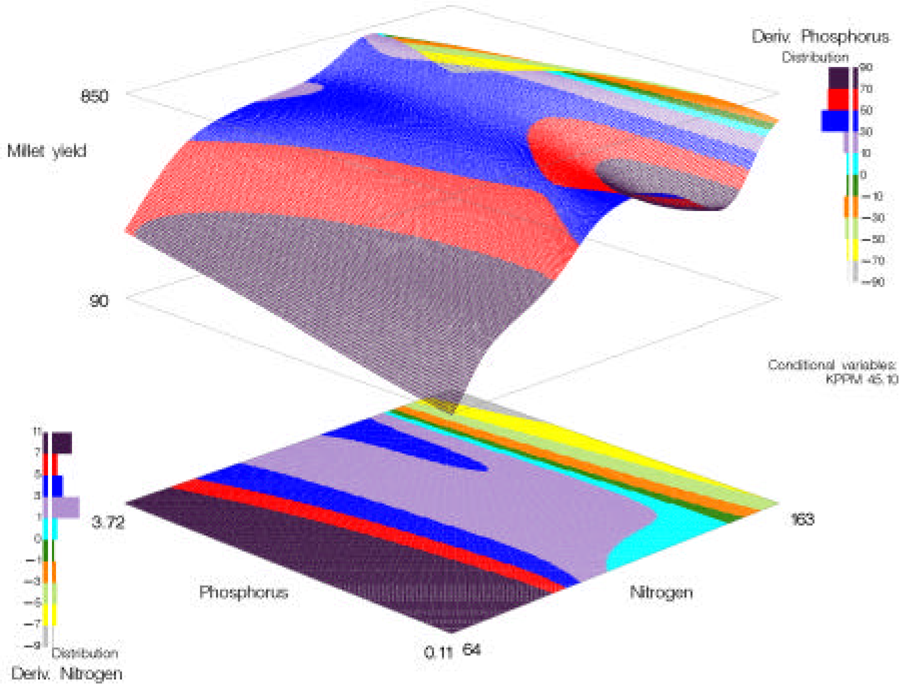

Figure 3: Millet yield (height of upper blanket, in kg/ha) as a function of N and P (both in ppm.), with the derivative to P (Ä yield per ppm. increase of P) shown in colour on the blanket and the derivative to N shown in colour on the lower plane (two observations with very high phosphorus are not included).

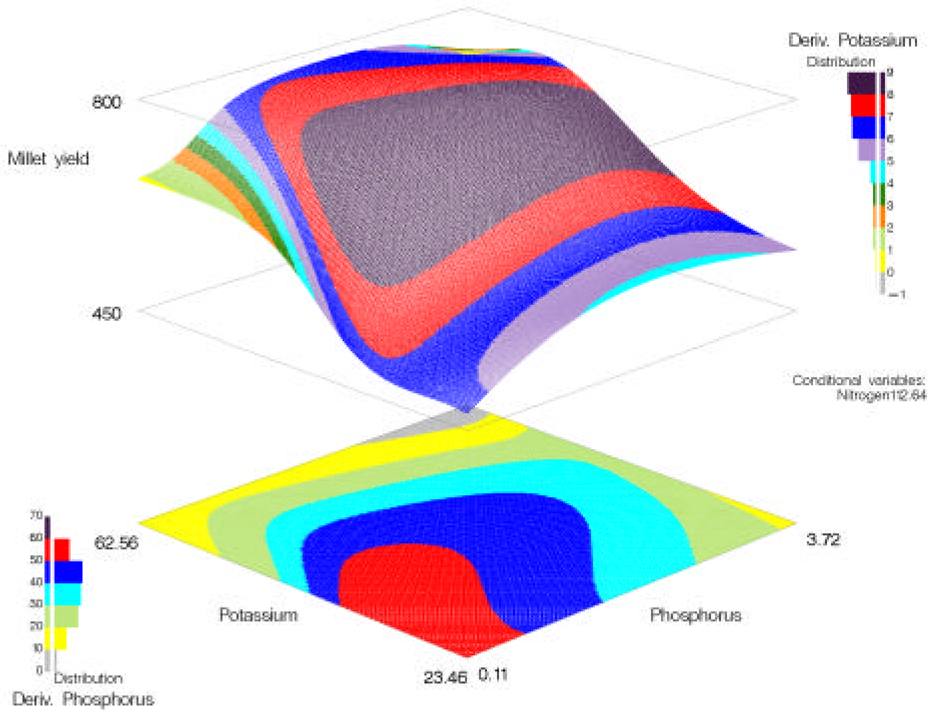

Figure 4: Millet yield (height of upper blanket, in kg/ha) as a function of P and K (both in ppm.), with the derivative to K shown in colour on the blanket and the derivative to P shown in colour on the lower plane (five percent of the observations with either high P or high K are not included).

and N is low, there is no response to N, but at higher N levels a substantial positive response occurs.

Yield increases with increasing P levels seem to be very modest (Fig. 3), but here we should keep in mind that the range of P levels occurring in the data set is narrow. The legends of the derivatives indicate that response the addition of one ppm for P is about 10 times higher than N (this also applies to negative responses). At the same N level, the derivative of P is generally lower when P is high. Response to P is thus greatest when both N and P are low. At the highest N levels, the response to increasing P is negative, independently of the P level, and most negative when both P and N are high. At low K, yield response to increasing P is positive and quadratic (Fig. 4), but, at high K, increases of P have very little effect. The strongest response to P is observed when K and P levels are simultaneously low (the plane of Fig. 4).

With respect to K, we see a broad positive response to increasing K levels throughout the whole N range. Response to K is somewhat lower when N is very high and when very high K occurs in combination with very low N (not shown here). We observe some substitution effects, i.e. yields at high K and low N are similar to those under conditions of low K and high N. The plot of K against P (Fig. 4) confirms the broad positive response to K, but also shows that yield increases due to increases of K, at low P levels, are lowest when K is already high.

The picture that emerges from this excursion into data exploration is, first of all, that response to P is generally higher than to N and K. However, some observations also indicate a very strong negative response to P. Negative responses are also observed for N and K, but these are much less severe. For each of the macronutrients, the response is usually strongest when their current levels are low and for all three it was observed that, at the highest levels, responses decrease and may even become negative. However, the response to one nutrient also depends on the available levels of the others and we observed mechanisms such as synergy, antagonism and substitution. In combination, these findings, that is decreasing returns to scale and nutrient interactions, suggest that a quadratic formulation, including product terms, may well capture the effects of topsoil macronutrients on crop yield.

Obviously, we have also implemented linear specifications, but these, on various grounds, are not well behaved (non-iid), thus indicating that they do not conform well to the data. Had we, for instance, judged linear OLS specifications only on R^2 and significance of the coefficients, then the conclusion would be that they perform well and explain a considerable portion of the yield variation. These equations show that millet yield is most significantly related to K followed by N and P, in that order. However, when subjected to more rigorous tests, they appear to have undesirable statistical properties and their good performance clearly reflects averaging over non-linearity. As such, the obtained equations cannot be used for interpretation of the possible effects that nutrient applications might have.

At this point, we may also conclude that N, P and K, in combination, explain only a modest portion of the yield variation. This is evident from the limited yield range that Figures 3 and 4 cover, if compared with the actual range (12-1632 kg/ha). Indeed, a non-parametric regression on the actual data points learns that N, P and K, in combination, at the maximum explain 59 percent of the yield variation. In parametric estimates, this percentage is likely to be considerably less.

4.3 Non-linear regressions on the basis of N, P and K only

In this section, we first investigate the explanatory power of the quadratic formulation, which, as the previous section showed, conforms well to the data. Then we briefly compare our findings with the performance of some other well-known non-linear specifications. From the outset, it is important to mention here that non-linear equations imply that response to an element varies with its present level. Meaningful interpretation in terms of possible fertilizer needs and efficiency thus critically depends on knowledge of how the levels of N, P and K vary over space.

The spatial models have been estimated with the spatial lag specification, since the diagnostic tests indicate that MLLAG is the most appropriate model in the present case. A spatial weights matrix (W) of a simple binary form (0,1) with all neighbouring observations proved to fit best to the spatial scale of autocorrelation. The full quadratic formulation, with spatial lag, reads as follows:

$$\begin{aligned} Y = \; & \rho Wy + \alpha_0 + \alpha_1 N + \alpha_2 N^2 + \alpha_3 P + \alpha_4 P^2 + \alpha_5 K + \alpha_6 K^2 + \alpha_7 NP + \\ & \alpha_8 NK + \alpha_9 PK + \varepsilon. \end{aligned}$$

The OLS version of this equation suffers from non-normality of errors, spatial autocorrelation of the residuals and spatial error (Table 4: regression 1). These undesirable properties are absent in the spatial lag formulation (MLLAG). The very high and highly significant coefficient for the spatial lag term indicates that the OLS results are seriously biased, which is confirmed by the shift in the coefficients. The MLLAG equation explains 67 percent of the yield variation, but the coefficients α_2, α_6 and α_9 prove to be insignificant (Table 4: regression 1). Sensitivity analysis on the insignificant terms shows that K^2 and PxK may be deleted (Table 4: regression 2). N^2 then becomes significant and, with two terms less, the maximized log likelihood and R^2 are hardly affected (in the OLS case the adjusted R^2 even improves one point). The other statistical properties, however, do not improve.

As opposed to the linear case, a quadratic formulation, including spatial lag, identifies P as being the most significant of N, P and K, with a very high response when native P levels are low. This response pattern was already established in the previous section and clearly highlights the importance of finding the most appropriate functional form, before commencing parametric model estimation. The equation furthermore emphasizes the importance of nutrient interactions (N with both P and K). Therefore, native nutrient levels, and thus micro-variability, may indeed have large impacts on agronomic experiments. We will not further evaluate this equation here, since it is more appropriate to do so when additional variables are considered as well.

We now compare our findings with the performance of the well-known non-linear Mitscherlich and Mitscherlich-Baule formulations. These equations are theoretically attractive, because, like the quadratic one, they allow for factor substitution as well as plateau growth. For N, P and K these read as follows:

Mitscherlich:

$$Y = \alpha_0 \; (1-\exp(-\alpha_1 N)) \; (1-\exp(-\alpha_2 P)) \; (1-\exp(-\alpha_3 K)) \; ;$$

Mitscherlich-Baule:

$$Y = \alpha_0 \; (1-\exp(-\alpha_1-\alpha_2 N)) \; (1-\exp(-\alpha_3-\alpha_4 P)) \; (1-\exp(-\alpha_5-\alpha_6 K)).$$

We will evaluate these equations on the basis of OLS only, since they are difficult to linearize, which is required for spatial estimation techniques. Mitscherlich produces an adjusted-R^2 of 0.36 and Mitscherlich-Baule 0.38, both well below the quadratic OLS

Table 4: Estimation results for OLS and spatial lag (MLLAG) versions of equations 1-3 (t-values for OLS and z-values for MLLAG in parentheses). Significance is indicated with ***, ** and * for the 1, 5 and 10 percent level, respectively.

Regression equation	*1*	*1*	*2*	*2*	*3*	*3*
Estimation method	OLS	MLLAG	OLS	MLLAG	OLS	MLLAG
Constant	-2100.62***	-1392.38***	-2255.6***	-1573.47***	-1526.30***	-1107.89***
	(-2.75)	*(-2.60)*	*(-3.06)*	*(-2.98)*	*(-2.63)*	*(-2.62)*
N	30.56**	16.81**	30.50***	19.14**	22.13**	16.93**
	(2.53)	*(1.97)*	*(2.67)*	*(2.33)*	*(2.40)*	*(2.54)*
P	753.93***	626.83***	896.70***	720.69***	580.28***	472.48***
	(2.65)	*(3.17)*	*(4.03)*	*(4.57)*	*(3.25)*	*(3.71)*
K	-23.99*	-24.71**	-25.07*	-27.12***	-23.44**	-28.65***
	(-1.68)	*(-2.48)*	*(-1.80)*	*(-2.75)*	*(-2.13)*	*(-3.58)*
N^2	-.10*	-.06	-0.11*	-0.07*	-0.09*	-0.08**
	(-1.76)	*(-1.59)*	*(-1.89)*	*(-1.71)*	*(-1.94)*	*(-2.49)*
P^2	-18.59***	-14.14***	-20.48***	-14.83***	-13.38***	-11.42***
	(-2.66)	*(-2.91)*	*(-3.23)*	*(-3.30)*	*(-2.65)*	*(-3.18)*
K^2	-0.06	-0.08				
	(-.80)	*(-1.45)*				
N x P	-5.96***	-4.91***	-5.74***	-4.91***	-3.64**	-3.01***
	(-3.31)	*(-3.92)*	*(-3.30)*	*(-3.99)*	*(-2.61)*	*(-3.04)*
N x K	0.27*	0.29***	0.29**	0.27***	0.26***	0.28***
	(1.96)	*(3.05)*	*(2.44)*	*(3.26)*	*(2.75)*	*(4.10)*
P x K	1273.36	753.94				
	(0.79)	*(0.67)*				
Mancat x Crust					0.20***	0.11***
					(3.84)	*(2.73)*
$Mancat^2$					-0.0003*	-0.0002
					(-1.84)	*(-1.62)*
Hydroc x Crust-c					-2.22***	-2.64***
					(-3.14)	*(-5.25)*
Pocksco					24.02***	21.66***
					(2.68)	*(3.38)*
W-y		0.71***		0.67***		0.638***
		(9.37)		*(9.08)*		*(9.50)*
Adj.-R^2 /Pseudo-R^2	0.46	0.67	0.47	0.66	0.68	0.81
Max. Log Likelihood	-682.30	-656.28	-682.73	-657.34	-654.82	-631.24
Non-Normality of errors	8.11**		8.74**		0.83	
Heteroscedasticity	9.19	10.07	3.91	5.26	21.98**	10.86
Moran's I	6.94***		6.92***		5.70***	
Spatial error	38.74***	0.30	38.39***	0.68	21.33***	1.34

formulation. Moreover, many of the coefficients are insignificant: Mitscherlich: one out of the three; and Mitscherlich-Baule: four out of six. Thus, however attractive these formulations may seem, their performance is substantially lower than the quadratic equation. Moreover, from a practical point of view, the Mitscherlich equations are disappointing as well, while, if two or more variables are considered, the parameters are very difficult to estimate.

In summary, a quadratic formulation describes best the relationship between millet yield and N, P and K in the present data set, and the explanatory power achieved is satisfactory. However, a large portion of the explanation derives from the spatial lag term, rather than from the exogenous variables. Possibly, other factors, beyond N, P and K, vary in spatial patterns and have an important impact on millet yield. These factors we will now consider.

4.4 Non-linear regressions on the basis of all variables

In addition to topsoil N, P and K levels, we now also take into account: crusting levels, cattle manure, small ruminant manure, local relief and number of planting pockets. First we calculated the residuals of regression 2 (Table 4) and then, with non-parametric techniques, searched for the variables and functional forms that explain these differences between estimated and observed millet yields.

Plotting the residuals against the independent additional variables shows a very weak relation with small ruminant manure. The relation with cattle manure ('mancat') is much stronger. Based on N, P and K alone, millet yield is overestimated at low levels of cattle manure, and strongly underestimated when cattle manure levels are high (data not shown). The yield difference can thus possibly be explained by a linear, and maybe an additional quadratic, term for cattle manure levels. The effect of cattle manure also depends on the level of crusting. Plotting the residuals against local landform and crusting level indicates overestimation when crusting is high (low value) and when the value for local landform is also high, i.e. when crusted areas occur on concave sites at a relatively low elevation (data not shown). Reciprocally, millet yield is underestimated at convex sites on high terrain with low crusting levels. We consequently create the variable 'crust**c**' (see footnote 1) and use the cross-product 'crust**c**'x'hydroc'. Yield is further is further underestimated when the number of seed pockets is high. Although various formulations were explored, these observations quite straightforwardly lead to regression specification 3 in Table 4. The OLS case shows that errors are now normally distributed, but heteroscedasticity, spatial autocorrelation and spatial error are still significant. These undesirable properties are remedied by the spatial lag specification. This equation thus has all the desirable statistical properties and its explanatory power is high.

The addition of four terms maintains significance levels of the terms of regression 2, and, with the notable exception of P and NxP, the coefficients are rather stable as well. The squared term for cattle manure is just significant in the OLS case and in the MLLAG equation it virtually lays on the limit of significance. In combination with the cross product of manure with crusting, it indicates a strong response to manure when current levels are low, but response per unit applied decreases, when more manure is applied. The cross product itself implies that the effectiveness of manure depends on site conditions and thus confirms the findings of Brouwer and Powell (1998). The negative yield impact of the cross-product of 'hydroc' and the reversed crusting value confirms earlier observations that lower yields are often associated with micro-low positions, particularly when these are strongly crusted (e.g. Scott Wendt et al., 1988; Wendt et al., 1993; Hermann et al., 1994; Manu et al., 1996). The positive effect of the number of seed pockets suggests that in this particular year (1992), with good rainfall, a higher yield could have been obtained, if planting density had been higher.

This section demonstrates that, next to searching for the most appropriate functional form, the identification of the right independent variables can also improve statistical properties as well as explanatory power. The spatial lag version of regression 3, at 81 percent, near perfectly describes the spatial pattern of variation of millet yield, but a large portion of the explanation still derives from the spatial lag term (ñWy), or in other words from the yield levels of neighbouring observations (Figure 5). Therefore, one may suspect that still other

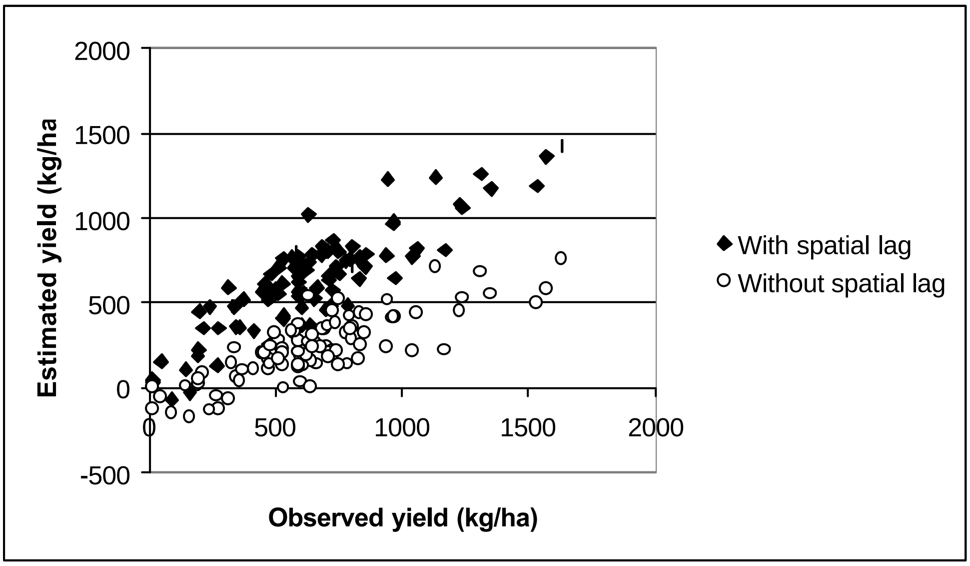

Figure 5: Observed versus estimated yield with and without spatial lag effects (regression 3).

factors vary over space in a systematic manner and have a considerable yield impact. However, without specifying these, the spatial lag formulation accounts for them and therefore we may be confident about the coefficients and proceed with the evaluation of the regression equation.

Section 5
Yield function evaluation

In this section, we describe the implications of regression 3 (Table 4) with respect to the likely yield response to external inputs of N, P, K or manure. From the outset, we wish to emphasize that empirical regressions do not necessarily establish causal relationships and some caution is therefore in place. Moreover, although common practice, the effects of native soil chemistry levels can, strictly speaking, not be directly used to derive the effects of added fertilizer. Possible yield effects clearly need empirical verification through agronomic research. Nevertheless, one may expect that responses to added fertilizer, to a considerable extent, follow the impact of native nutrient levels. Yield function evaluation is therefore useful for the design of well-targeted experimental work. In this context, we recall work of Christianson and Vlek (1991), who studied the response to added fertilizer N on millet, sorghum and maize under a broad range of climatic conditions. They also use a quadratic specification and their coefficients for N and N^2 are remarkably similar to the ones obtained in the present study.

The spatial lag version of equation 3 gives a very good description of the spatial variation of millet yield and the coefficients of the independent variables are correct. However, its explanatory power, to a considerable extent, is due to the autoregressive term. Although perfectly suited to equation diagnostics and parameter estimation, one may have some doubts about the use of the spatial model for the estimation of fertilizer impacts, because of the processes, which the autoregressive term represents. The equation namely implies that inputs applied at a certain location would have effects on neighbouring observations as well. In fact, such effects permeate, although very rapidly decreasing in magnitude with distance, through the whole field. To some extent, such processes may be real, because we use soil chemistry observations obtained from the centroid of a grid, which may not be representative for the grid as a whole, in combination with yield figures from the entire grid. Nevertheless, it is unlikely that such effects are as strong as the autoregressive term suggests. We therefore mainly evaluate the MMLAG equation without its spatial lag term (MLLAG- as opposed to MLLAG+): we do not account for the yield effect of the yields of neighbouring observations but only for the independent variables. We will show shortly that doing so does not affect the essence of the conclusions.

Conventional yield function analysis often depicts the yield or the yield contribution of a single variable, while keeping the other variables constant, mostly at their mean value. Such graphical representations have the advantage of being easily understood. The response curves for P, N and K, derived from the MLLAG- version of equation 3 (Table 4), are depicted in Figures 6, 7 and 8. The yield response to N and P confirms the earlier observed decreasing returns to scale for these nutrients (Bationo et al., 1990; Christianson et al., 1990, Bationo and Mokwunye, 1991a; Christianson and Vlek, 1991). In both cases, the response derives from a linear and squared term of the element itself and, in case of P, from interaction with N levels, while response to N is dependent on both P and K. The shape of the curve of P indicates that response to P, when its current levels are low, is very steep, but response also rapidly decreases with P level and at high levels it becomes negative. The same applies to N, but initial yield increases are less than for P, while at the same time decreasing returns are

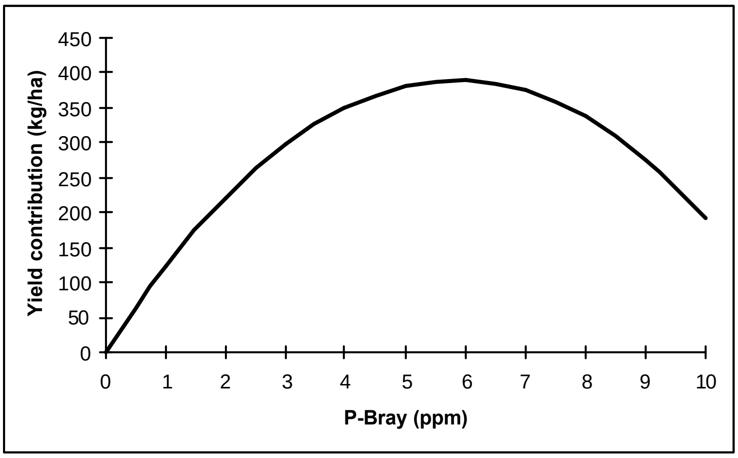

Figure 6: Stylized yield response to P-Bray (yield contribution of P, P^2 and PxN combined, at mean N levels for current range of P-Bray (regression 3, MLLAG-).

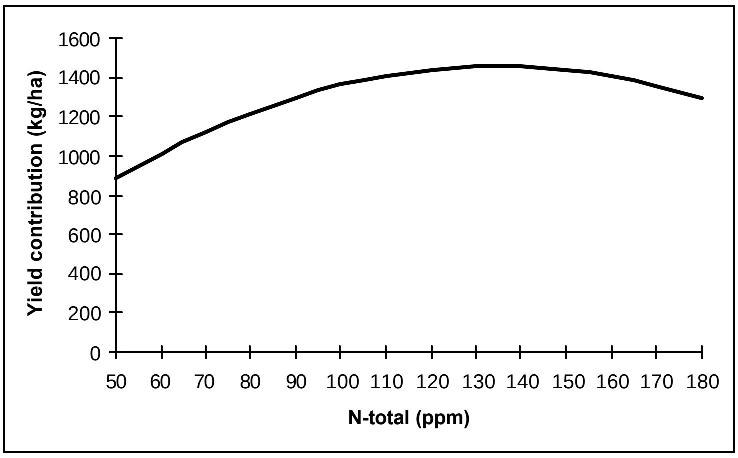

Figure 7: Stylized yield response to N-total (yield contribution of N, N^2 , NxP and NxK combined), at mean P and K levels for current range of N-total (regression 3, MLLAG-).

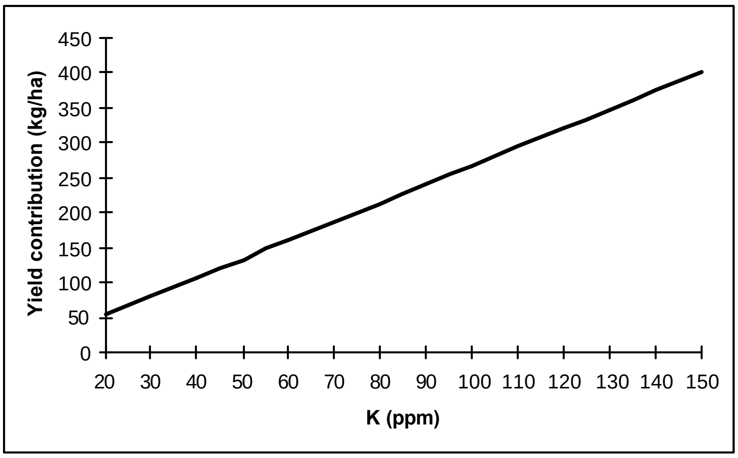

Figure 8: Stylized yield response to K (yield contribution of K and KxN combined), at mean N level for current range of K (regression 3, MLLAG-)

less strongly defined. The high significance of the two product terms (NxP and NxK) in equation 3 emphasizes the importance of nutrient interactions: an antagonism between high N and high P; synergy between high N and high K; and substitution in both cases. The negative interaction between N and P could indicate that unbalanced P/N ratios are operative (e.g. Dabin, 1980). However, this could not be confirmed[2]. A further evaluation of the equation shows, that, at mean N levels, the maximum yield increase due to P is reached at 5.8 ppm of P-Bray, and above that, yields may actually decline. This figure is slightly lower than the one observed by Bationo and Mokwunye (1991a), who found that 7.9 ppm P-Bray in the soil is sufficient to achieve 90 percent of the maximum yield (established at the ICRISAT Sahelian Centre, 1 km away on similar soils). At mean N levels, the response to K is linear, positive and independent of current K levels (Figure 8). Based on theory, one would expect decreasing returns at higher K levels, since other nutrients would then become limiting. Apparently, the high K requirements of millet (Norman et al., 1984), in combination with the very low K levels in the soil (cf. Boyer, 1972), prevent that such effects are identified in the current data set.

The stylized graphs of N, P and K can be easily understood, but they cannot be used for fertilizer technology recommendations, even if current levels of N, P and K are known. They namely hide the impact of nutrient interactions and the effect that variation in the native levels of other elements has. To demonstrate this, we present the N-dependent response to P and the crusting-dependent response to cattle manure (Figures 9 and 10). At high N[3], additional P gives little response, while at low N the yield response to P is rather steep. With decreasing N levels, the satiation point for P also moves upward and at low N levels its value is at 8.8 ppm, somewhat higher than the value obtained by Bationo and Mokwunye (1991a). The crusting level-dependent response to cattle manure gives a very similar picture (Figure 10). Cattle manure is more effective when crusting levels are low, but manure levels may become too high as well. For mean crusting levels, yields start to decrease at 916 kg/ha of manure and at low crusting this value is 1527 kg/ ha. This figure confirms the findings of Brouwer and Powell (1998) that, on good sites, annual applications of 1.5 ton/ha are sufficient to obtain high yields. Farmers can therefore redistribute available manure from crusted to non-crusted sites or adopt night-coralling strategies that maximize returns to available local resources. Both graphs are obviously more informative than the earlier stylized ones, but also clearly demonstrate that the design of fertilizer technologies cannot be based on the value of a single variable.

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[2] The negative sign of the multiplicative term N·P could possibly point towards unbalanced P/N ratios as a cause for reducing yields. Consequently, we tried the following quadratic formulations with P/N ratios where the response to P and N depends on the their ratio:

$$Y = \acute{a}_0 + (\acute{a}_1 \cdot P/N + \acute{a}_2 \cdot (P/N)^2) \cdot P + (\acute{a}_3 + \acute{a}_4 \cdot P/N) \cdot N + \acute{a}_5 \cdot (N)^2 + (\acute{a}_6 + \acute{a}_7 \cdot N) \cdot K + \mathring{a}$$

and

$$Y = \acute{a}_0 + (\acute{a}_1 \cdot P/N + \acute{a}_2 \cdot (P/N)^2) \cdot P + (\acute{a}_3 + \acute{a}_4 \cdot P/N) \cdot N + \acute{a}_5 \cdot (N)^2 + \acute{a}_6 \cdot K + \mathring{a}$$

Some terms from a full formulation should obviously be deleted because of double occurrences. These two expressions explain the yield differences nearly as well as the quadratic formulation (OLS: adjusted R^2 of 0.45 and 0.42, respectively). This does, however, not come as a surprise, because if we multiply out the various terms, the result is quite similar to the quadratic formulation with basic variables. It is therefore difficult to conclude whether or not the P/N ratio plays a role in determining crop yields.

[3] ‘Low’levels are defined as the upper limit of the lower decile and ‘high’ levels as the lower limit of the upper decile.

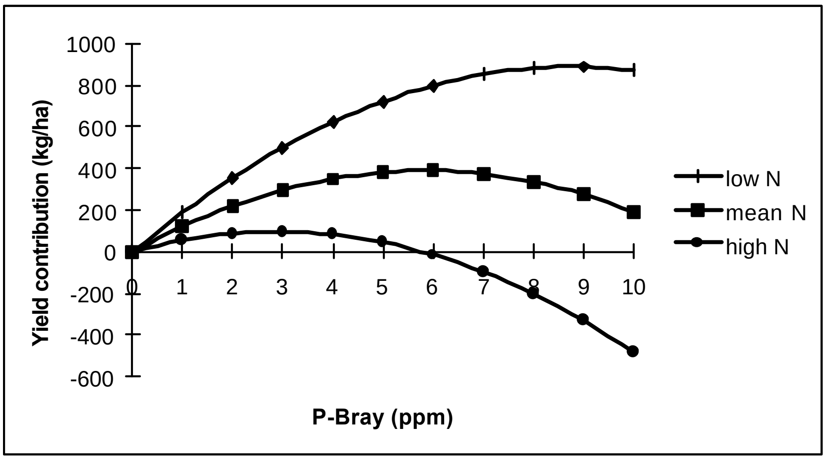

Figure 9: N-dependent yield response to P-Bray (yield contribution of P,P^2 and PxN combined from regression 3, MLLAG-).

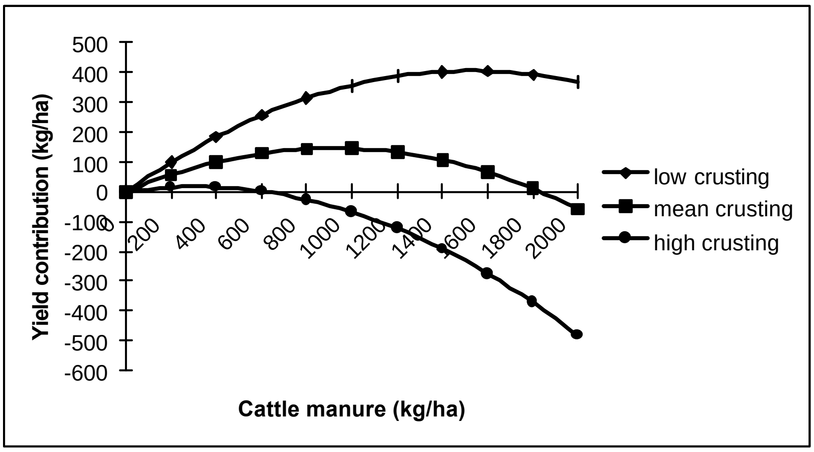

Figure 10: Crusting-dependent yield response to cattle manure (yield contribution of 'mancat'x'crust' and $(\text{'mancat'})^2$ combined from regression 3, MLLAG-).

To further emphasize the issue raised, we now consider observation-specific yield responses, which take the values of other variables into account (for MLLAG-). Rather than yield contributions, we calculate what, in fact, we are more interested in, namely the derivative. The derivative (dy/dx) quantifies the yield increase when the independent variable is raised one unit (1 ppm in the case of N, P and K, and 1 kg for cattle manure). The results for N, P, K and cattle manure are presented in Figures 11-14. They confirm the, on average, high response to P and modest responses to N and K. We should, however, be cautious about the level of response to P, because it critically depends on the selection of P-Bray as being representative for P-availability. The increase of one unit, in this case, on average represents an increase of about 50 percent of current levels. Moreover, the values for P-Bray do not vary much, except for two observations with high values (see Figure 12). The functional form and coefficients are therefore to a large extent determined by these two high values. Excluding these or replacing them with Mollified values renders all three terms with P insignificant. If only single P is maintained it is significant, but then the coefficient is only 59. However, in

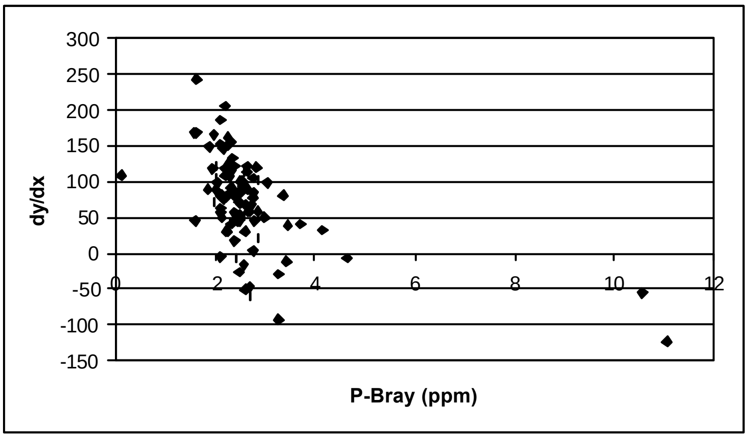

Figure 11: Response to P (dy/dx), accounting for nutrient interactions ((regression 3, MLLAG-).

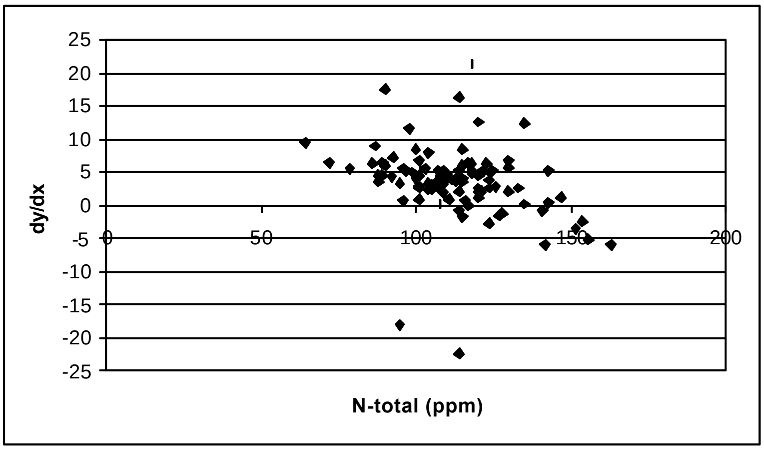

Figure 12: Response to N (dy/dx), accounting for nutrient interactions ((regression 3, MLLAG-).

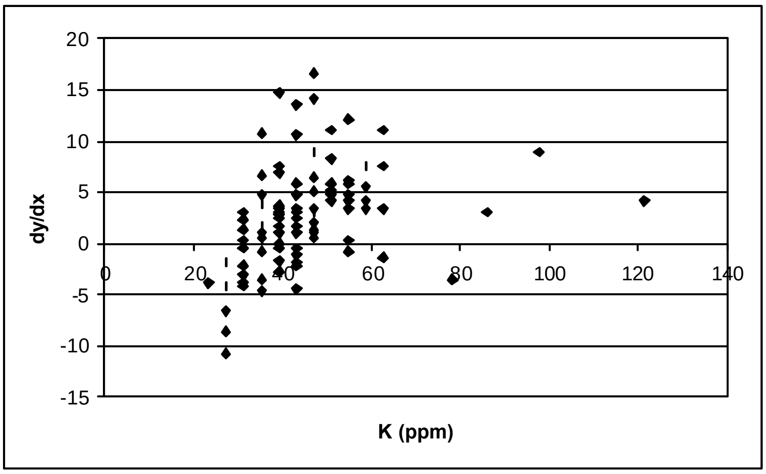

Figure 13: Response to K (dy/dx), accounting for nutrient interactions (regression , 3 MLLAG-).

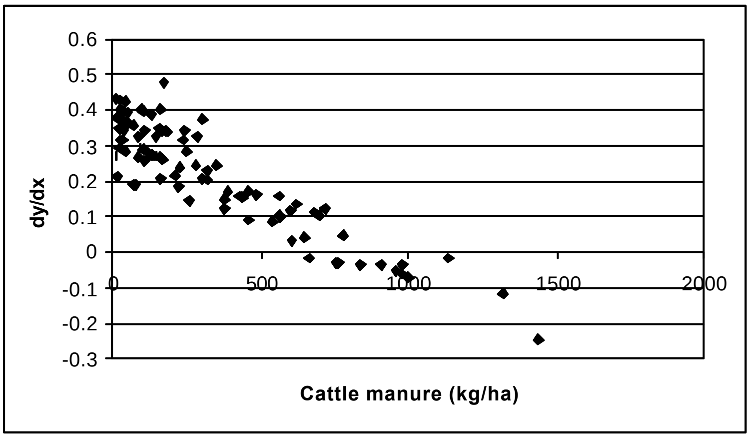

Figure 14: Response to cattle manure (dy/dx), accounting for interactions with crusting levels (regression 3, MLLAG-).

both cases the equation suffers from spatial error, although only just significantly so. For N, P and cattle manure the scatterplots indeed show a decreasing response when their current level increases, and at very high levels the derivative can become negative. However, the spread in response at a given value of the independent variable is very high. For instance, in the case of P, when native P levels are just above two ppm, the yield response can be anything between 50 kg negative to 200 kg positive. In case of K, the response at a considerable portion of the observations, rather than positive, proves to be negative. Also for K, the variation of response, at a given level of K, was large.

The large variation of response to native nutrient levels is problematic for deriving fertilizer recommendations, unless, of course, if such variation has a spatial dimension. In fact, this is what we are actually most interested in. Therefore, we plot the derivatives in geographic space. Figure 15 shows the spatially explicit response to P for OLS and MLLAG without and with the autoregressive term. The spatial distribution of response indeed proves to be far from random, and rather than that, is clustered. The three maps indicate generally a positive and high response to P, but locally negative responses occur and at other places the response is well above average. The spatial patterns are very similar in all three maps. Most of the sites that give a negative response in MLLAG- are also present in the OLS case. The main difference between the two is that high responses in MLLAG- are matched with even higher responses in OLS, a perfect example of the undesirable statistical properties of the OLS equation. The spatial patterns of MLLAG+ are again quite similar to MLLAG-, the main difference being the scale, which is three times higher for MLLAG+. This brief comparison shows that the yield response pattern is robust to the exclusion of the autoregressive term. We may thus be confident about the spatial pattern, about whether response is positive or negative and about the relative magnitude of response.

The variation of response to P, even to the extent of a change of sign, implies that blanket fertilizer applications would be inefficient. High yield increases would then be achieved at some places, but elsewhere yield reductions would occur. Such inefficiencies may compromise the adoption of fertilizer technologies by cash-constrained farmers. However, rather than considering within-field variability as a nuisance, it may be exploited

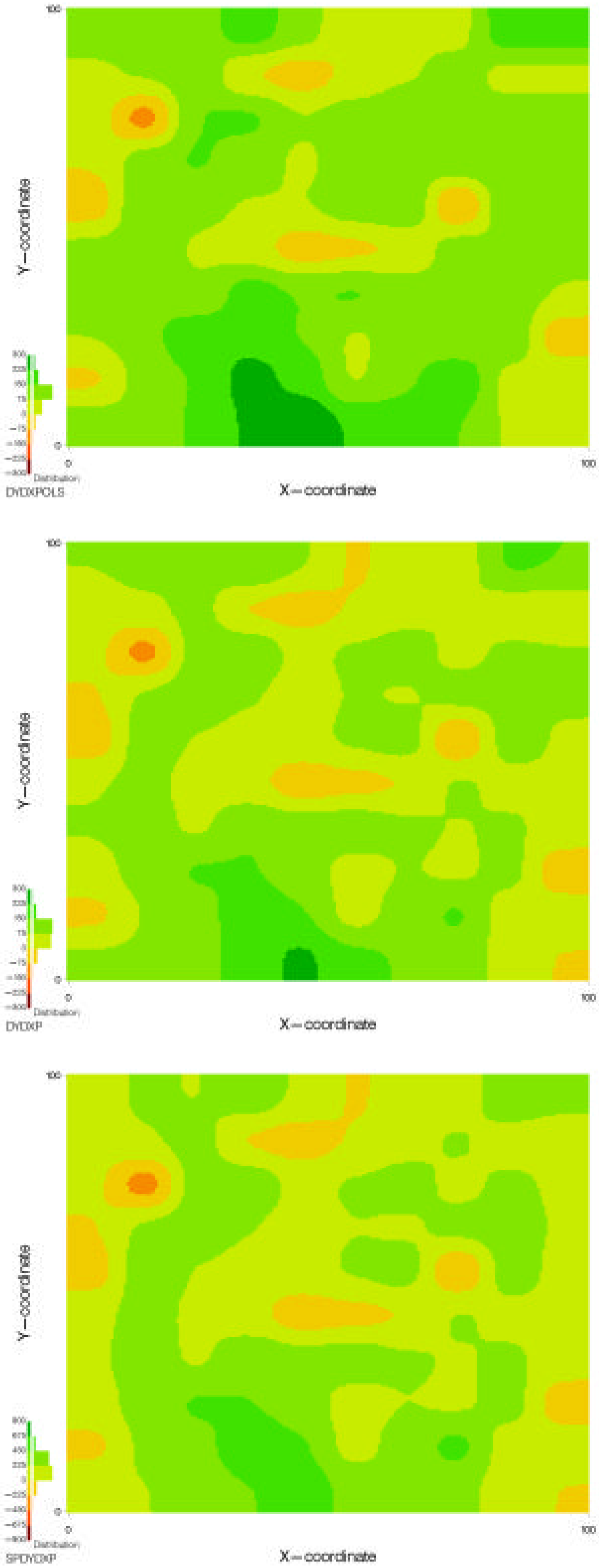

Figure 15: Spatially explicit derivatives to P-Bray for OLS (top; scale –300 to 300), MLLAG minus autoregressive effects (middle; scale –300 to 300) and MLLAG plus autoregressive effects (bottom; scale –900 to 900). Positive derivatives start from yellowish green onwards, becoming stronger towards dark green. Negative derivatives start from orange onwards, becoming more negative towards darker red.

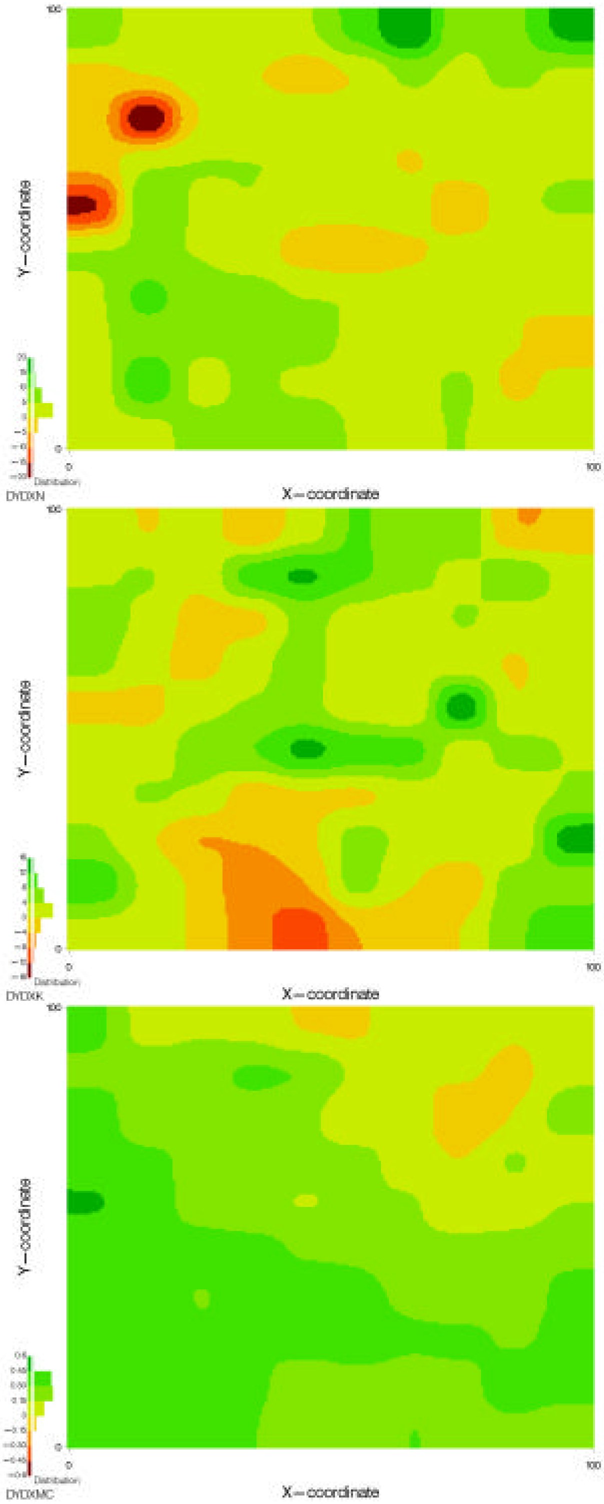

Figure 16: Spatially explicit derivatives (MMLAG minus autoregressive effects) to Nitrogen (top), Potassium (middle) and cattle manure (bottom). Scales for N: -20 to 20; K: -16 to 16; and cattle manure:-0.60 to 0.60. Positive derivatives start from yellowish green onwards, becoming stronger towards dark green. Negative derivatives start from orange onwards, becoming more negative towards darker red.

through low technology precision farming, provided that farmers can recognize these sub-units in their field and appropriate fertilizer technologies for such sub-units are available.

Figure 16 presents the results of the MLLAG- specification for N, K and cattle manure. Compared to P, the response to N and K is generally modest. Negative responses to N tend to coincide with negative responses to P. The effect of additional K shows almost a mirror image of the response to P: where the derivative of K is negative, the response to P is high, and, when the derivative of K is high, additional P has a negative yield effect. The response to cattle manure is greatest on the area where it currently is absent. Further application of manure at sites where current levels are high shows a negative effect. As discussed earlier, crusting levels modify this general pattern. The spatially explicit response patterns of N and K, in relation to those observed for P, further emphasize the opportunities for low technology precision farming.

Section 6
Discussion

This study shows that spatial variability of millet yield, as dependent on topsoil N, P and K levels, can be well explained, if some additional variables are considered as well and only if spatial dependence is taken into account. However, operational implications are limited to the present field and clearly similar soil surveys and laboratory analyses are not affordable for most farmers. Moreover, a large part of the explanation of millet yield variation derives from spatial autocorrelation, rather than from the exogenous variables. The good explanation of spatial variability of millet yield obtained in this study, therefore, rather than solving a problem, defines a research agenda with respect to further empirical research, site characterization, assessment of representativeness and well-targeted experimental research to identify site-specific fertilizer technologies.

First of all, the relation between millet yield and soil chemistry can be further investigated. Possibly, other variables explain millet yield without having to seek recourse to functional forms that account for spatial autocorrelation. Previously, it has already been observed for instance that Aluminium saturation (Scott-Wendt et al., 1988a, 1988b, Manu et al., 1998, Gandah et al., 1998), the soil pH value (Buerkert, 1995; Manu et al., 1998: Gandah et al., 1998; van Groeningen et al., 2000) and cation (Ca and Mg in addition to K) levels (Scott-Wendt et al., 1988a, 1988b; Gandah et al, 1998) are correlated with, or have significant effects on, crop yield. These variables may have a direct yield effect by themselves, but interactions with N, P and K may also be expected. A better understanding of the most important soil chemistry complexities and their operating mechanisms seems essential to reliably match site conditions with fertilizer technologies. Moreover, one may suspect, in the sandy soils concerned, that, in parts of the growing season, the topsoil dries out and that the crop relies on moisture and nutrients from the subsoil. Consequently, subsoil chemistry can have a yield impact as well.

Another issue refers to characterization of sites. Clearly, site-specific fertilizer technologies are only meaningful, when farmers can identify such sites in the field. A cursory analysis of the yield response in relation to site conditions in the present case, for instance, shows that some of the locations, where response is negative to P and positive to K, are characterized as minor local high conditions with intermediate crusting levels as well as yields (compare Figures 1, 15 and 16). Such observations need to be systematized in a classification framework. This kind of effort is likely to benefit from some soil survey work, preferably a mapping exercize, conducted with the perspective that local soil variability may be related to the occurrence of shallow layers of different coversands, which derive from various episodes of erosion and deposition. In this context, we recall our earlier observation that farmers apparently recognize variation in field conditions, and adapt their management accordingly. Therefore, farmer participation in such research is called for. In addition, one may suspect, given the large magnitude of millet yield variability over short distances, that this variability is also reflected in the species composition of arable weed communities. Elsewhere, the weeds present in arable fields, even when fertilized, have proven to be a good indicator of soil fertility and moisture availability (Bannink et al., 1974). Arable weeds could possibly be used to establish a site classification, which, in turn, would serve agronomic research as well as the dissemination of its findings.

Once a site classification is established, then further well-targeted experimental research is required to empirically verify crop response to added fertilizer, while accounting for native soil conditions. We suggest that the obtained results be analyzed with the methods used in this paper.

Section 7
Summary and conclusions

In this empirical study, we analyzed the relationship between millet yield and topsoil N, P, and K, as well as other soil, terrain and management variables. The data derive from a farmers' field that is characterized by extreme local variation of millet growth. Such variation is a common phenomenon on Sahelian coversands, but its causes are still poorly understood. Spatial variability is generally considered as a nuisance for agronomic research. However, rather than seeing it as problematic, we exploited within-field soil and crop growth variability to achieve the purpose of this paper, namely to identify low-external-input technologies that are likely to produce substantial yield improvements. To this effect, we applied econometric tools to a comprehensive and spatially explicit data set and assessed the simultaneous yield effects of the independent variables.

This study shows that with the kind of data set and the methods used, it is perfectly possible to come to grips with spatial variability of millet growth, provided that three issues are taken care of. The first point is the selection of variables. Although our main interest was in N, P and K, other variables had to be taken into account to arrive at high explanatory powers and to establish the true effect of N, P and K. Secondly, the identification of the appropriate functional form proved to be of paramount importance. Had we, for instance, used a simple linear regression and not rigourously tested its statistical properties, then our conclusion would have been an entirely different one, and erroneous. Non-parametric kernel density regression used for data exploration proved to be instrumental for the identification of the functional form implied by the data. Thirdly, the use of spatial econometric tools to spatial data was fundamental to arrive at equations that combine desirable statistical properties with high explanatory powers. Moreover, apart from establishing the right coefficients, it provided the proper perspective in the sense of how much of the yield variation is determined by the independent variables and how much is due to spatial autocorrelation.

The best performing equation explains 81 percent of the yield variation. Its functional form confirms earlier research findings of decreasing returns to N and P. Response to K was found to be linear. On average, response to P is strongest and the effect of N and K is modest. This result critically depends on the use of P-Bray as an indicator of P availability, since its current levels are very low. The study further confirms approximate satiation levels for P, response levels to N, and that the efficiency of cattle manure depends on site conditions, notably crusting levels. This study further identifies an antagonism between N and P, and synergy between N and K. An observation-specific analysis shows that, at a given level of N, P, K or cattle manure, the effect to increased levels is very variable, sometimes even from highly positive to negative. A spatially-explicit representation of these variable responses reveals spatial clusters of negative as well as highly positive yield effects. A negative yield impact of P, in most cases, is matched with negative responses to N as well. In such cases, the effect of additional K is often strongly positive. On the other hand, where response to K is negative, additional P usually gives a very high response. Blanket fertilizer technologies applied to the entire field are, therefore, inefficient. These findings highlight the opportunities for a within-field diversification of fertilizer strategies that seek to minimize the use of external inputs and that could vary with, for instance, fertilizer availability, their cost, the weather and the farmers' cash constraint in a particular year. Moreover, the analysis shows that farmers can redistribute available manure or adopt night-corralling strategies that maximize returns to available local resources. This study, with all its limitations of only one year of data, thus brings good news for the cash-constrained farmers. They can exploit within-field variability with precision farming practices in a low technology context in order to maximize returns and to minimize costs.

This paper confirms the importance of within-field soil variability and its impact on millet yield. Furthermore, yields are determined by interactions among nutrients, manure and crusting (moisture availability), which affect the response to inputs applied. Therefore, native soil conditions and nutrient levels can have a large impact on the outcome of agronomic experiments and their interpretation. Moreover, the macro-nutrients N, P and K explain only a modest part of the yield variation. Consequently, we suggest further research on the characterization of site conditions, on crop response patterns and the identification of the underlying causes. Publications are planned to pursue these issues and to further explore the data here presented on the causes and agronomic implications of soil spatial variability on Sahelian coversands in Southwest Niger.

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