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Coversand land ecology and site-specific millet yield functions in SW Niger

by

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Contents

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Abstract

In this study, we apply novel tools for data exploration to a detailed environmental and crop yield database from a spatially very variable farmer's field in SW Niger. Rather than the entire field, as we did in earlier studies, we now consider two individual field parts that derive from different parent materials (coversands). The objective is to verify if site-specific yield function analysis leads to a better understanding of soil chemistry-yield relationships and if these then allow fine-tuning of possible external input technologies. Our findings show that the type of variables that explain millet yield well across soil types are also important at the level of individual field parts. However, the functional forms for the two parts are quite different: they conform better to theoretical knowledge than the overall equation; they are easier to interprete; they indeed identify site-specific operating mechanisms; and, consequently, they lead to different promising input technologies. These findings confirm earlier observations that farmers in this environment need to apply low-tech precision farming in order to achieve greater efficiency of external input use. Regarding analytical methods, this study highlights the importance of the selection of variables and the functional form, which should not be imposed from the outset, but derived from the data themselves. We further conclude that process-based crop growth models, as yet, cannot accommodate the full complexity of soil chemistry and its effect on crop yield. Empirical on-farm research, as presented in this paper, could be the answer and identify the most significant soil fertility complexities that need to be addressed in real-world situations aiming at the design of external input technologies that combine low cost with substantial yield improvement.

Key words: Sahel, Coversands, Soil chemistry, Millet production, Site-specific yield functions, Empirical analysis

1. Introduction

The modelling of plant or crop growth, for instance for the assessment of land resource potentials or the impact of global change, is often restricted to matching crop physiological properties with climatic variables. Crop growth models, when considering soil fertility at all, often only evaluate the effect of Nitrogen (N) on plant growth; sometimes Phosphorus (P) is also taken into account, and only very rarely Potassium (K) (Hunt et al., 1998). Moreover, mostly only the topsoil levels of these nutrients are considered. Nevertheless, it goes unquestioned that, besides climatic conditions, plant nutrient availability in the soil is a main, and sometimes overruling, determinant of plant growth and crop yield. The poor representation of soil chemistry in crop growth models stems from the unfortunate situation that the effect of soil chemistry on plant growth is still insufficiently understood. One may add that even if all three macronutrients, N, P and K, were considered, this would still be a poor representation of soil fertility, since, as general handbooks confirm, a number of soil chemistry complexities and interactions among the various elements determine actual nutrient uptake by the plant (e.g. Ministère de la Coopération, 1980; ILACO, 1981; Landon, 1984). Real-world applications therefore need to consider at least the most significant soil fertility complexities, to ensure that reasonable confidence can be placed in model outputs (Hunt et al., 1998).

One such real-world situation, where it matters to understand the role of soil chemistry in agricultural production, is in the Sudano-Sahelian zone in West Africa. Here, large concentrations of people live on chemically poor and acid sands of aeolian origin (coversands). The climatically defined Length of the Growing Period (LGP) is on average short in the Sahel, but it is also variable of length. Farmers therefore use low-yielding, short-duration varieties of millet that can comfortably complete their cycle within the LGP in most years. Although intra-season droughts affect millet yield as well, the farmers in this way at least ensure that the total season length does not constrain production levels. Under such conditions, it is only natural to suspect that the low soil fertility is a major constraint to high crop yields and that large yield increases can be obtained from fertilizer applications. The design of appropriate fertilizer technologies thus seems to be the key to increase land productivity, to ensure food security and to foster rural development in general.

A vast body of literature documents the experimental research aiming at fertilizer-based yield improvement on Sudano-Sahelian coversands (for an overview see e.g. Pieri, 1992; Buerkert and Hiernaux, 1998). This agronomic research also has paid most attention to the macronutrients N, P and K. In short, it proves that all three macronutrients may be deficient in these poor sandy soils (Deckers, 1993; Buerkert and Hiernaux, 1998). Given the cash constraint of farmers, the question therefore is: which of the macronutrients is the most critical, and would, if applied in small amounts, substantially increase land productivity? As yet there is no straightforward answer to this question. One of the reasons is the extreme local soil variability that characterizes the area (Brouwer and Bouma, 1997), the causes of which are still poorly understood (Buerkert, 1995). Such local variability dramatically affects millet growth over distances as short as a few metres (Brouwer et al. 1993). Many authors regard this as problematic for the interpretation of agronomic research findings, because it leads to large variations among replications of agronomic treatments (e.g. Moormann and Kang, 1978; Scott-Wendt et al., 1988a, 1988b; Wendt et al., 1993; Hermann et al., 1994; Manu et al., 1996).

Although it has long been known that not all coversands are the same in SW Niger (West et al. 1984), the few attempts to specifically identify the causes of short-distance yield variation all focused on soil chemistry, to the exclusion of soil genesis. Scott-Wendt et al. (1988a, 1988b) investigated a transect from very poorly-growing to well-growing millet and observed that low yields were correlated with high Aluminum (Al) saturation levels and lower cation levels {Calcium (Ca), Magnesium (Mg) and K}. Manu et al. (1996) pair-wise compared good and poor spots and they also identified Al saturation to be higher in poorly-growing spots, while at the same time the pH value was lower. These studies, however, were restricted to topsoil properties only. Further empirical research that seeks to identify the sources of millet yield variation consist of regression analysis (Stein et al., 1997; Gandah et al., 1998, 2000; Rockström et al., 1999) Unfortunately, in all these cases linear relationships were assumed from the outset, and explanatory power proved to be relatively modest. Nevertheless, Gandah et al. (1998, 2000), who do not restrict themselves in variable selection, never find N to be significant and P only occasionally so. Most often it are again Al saturation, pH and the cations that explain millet yield best. The fact that Al saturation seems to play a role in this arid area is remarkable, as is the consistent negative correlation of yield with pH found. Further we observe that the sign of response to Mg, K and P, at least in a linear specification, apparently can be both positive and negative (Gandah et al., 1998, 2000). In any case, these empirical studies invariably establish that there is more to millet yield than only N, P and K, and that soil acidity and the properties of the cation exchange complex appear to exert a significant effect on millet growth and yield.

In an earlier empirical study on data from a farmers' field, we also tried to explain millet yield variation on the basis of *topsoil* N, P and K levels (Voortman and Brouwer, 2002). Rather than imposing a functional form from the outset, we first applied non-parametric techniques to identify the functional forms implied by the data (using Keyzer and Sonneveld, 1997), and only then parametrically estimated the equations so derived. With the commonly used Ordinary Least Square (OLS) technique, 68 percent of the millet yield variation could be explained on the basis of topsoil N, P and K, manure levels, crusting, local relief and planting density. However, the good explanatory power obtained with OLS proved to be misleading, as rigorous tests of the equations with spatial econometric tools (using Anselin, 1992) indicated very strong spatial autocorrelation in the residuals. This leads to the conclusion that topsoil N, P and K levels are *not* the true sources of millet yield variation and indeed that other factors are involved in the spatial yield variability.

In a follow-up study we considered all soil chemistry variables from the whole soil profile (upper 1 m) and identified the true sources of soil variability (Voortman et al., 2002). Within a single farmers' field of 1 ha three different soil types could be identified and mapped. The evidence provided suggests a parent material connection to soil variability, due to shallow layers of different coversands. These coversands indeed differ in the properties of the cation exchange complex and, related to that, the Al saturation profile. Such parent material-related properties also explain millet yield differences very well. Poor yields occur when the proportion of Mg and Na at the exchange complex (cation ratios) in the topsoil is high, which is associated with low subsoil Al saturation levels. Yields are high when topsoil Mg and Na are relatively low, but then Al saturation levels of the subsoil are higher. The likely operating mechanism is the destabilizing effect of Mg and Na on the clay fraction of the topsoil, which causes surface sealing and, consequently, limits water infiltration and hampers seedling establishment. Lower water infiltration levels, when Mg and Na are high, are confirmed by the lower Al saturation levels in the subsoil. Somewhat perversely, higher yields are then obtained when subsoil Al saturation is higher, because its negative effect is more than compensated for by its causes, namely higher moisture availability. Regressions across the three soil types, that include such variables, explained 82 percent of the yield variation and spatial autocorrelation of the residuals was eliminated.

The somewhat unexpected positive yield effects of subsoil Al saturation is at variance with theory and clearly should not lead to the conclusion that increasing Al saturation will raise yields. The findings can derive from the fact that regression analysis was conducted across parent materials as in such cases equations usually perform much poorer than those that are limited to a single parent material (Jenny, 1980). It might be that Al saturation stands in for soil physical and chemical complexities that are associated with the differences in parent materials. In this paper, we therefore further pursue the econometric line of research and assess the parent material-specific relationship between millet yield and soil chemistry. Our objective is to identify for individual sites the most significant real-world soil chemistry complexities, and their operating mechanisms, as they affect millet yield. We further want to verify if such an approach leads to: i) less complex equations and higher explanatory powers, ii) equations that do not contradict theory, and iii) functional specifications that allow fine-tuning of recommendations for site-specific low external input technologies and well-targeted experimental research.

In Section 2, we first describe the environment and the data used. We further define some guiding principles that have been used to characterize soil fertility. Section 3 presents the methods of data exploration and analysis. The results of data exploration and regression analysis are presented in Section 4. In Section 5 the results are discussed and promising input strategies derived. Section 6 concludes.

2. Environmental setting, data and variable selection

The physical environment

This study uses data of the year 1992 and they derive from a 1 ha field cultivated by a local farmer just outside the village of Bellaré, near the ICRISAT Sahelian Centre, 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 average rainfall of 545 mm in a well-defined rainy season, lasting from May to September. The soils are developed in sandy aeolian deposits and are classified as Ferralo-Luvic Arenosols, i.e. poor sandy soils with some clay content that shows signs of downward displacement. The general topography is almost flat (slopes of about one percent), but microtopographic height differences can be in the order of 1 m over a distance of 10-50 m.

Data

The database used is described in detail in Voortman and Brouwer (2002). The data were collected on the basis of a 5 x 5 m regular grid over a square 1 ha farmers' field. Due to lack of financial resources for soil analysis, the soil samples were bulked so as to represent a 10 x 10 m regular grid. The values of all other variables were also aggregated to this level (by means of averaging). Each observation has a value for millet yield and standard soil chemistry analyses were done for 3 depths: 0-20 cm, 20-40 cm and 70-90 cm. For convenience, these sample depths will henceforth be referred to as having been taken at 10, 30 and 80 cm, respectively. Unfortunately textural analysis could not be done for financial reasons as well. Manure levels of cattle and small ruminants (kg ha^{-1}) as present on the surface at the beginning of the growing period, are equally taken into account (variables '*mancat*' and '*mansrum*'), since manure may confound the effect of native soil chemistry. Manure levels are likely to represent urine levels as well, since it originates from animals resting in or passing through the field during the dry season. Surface crusting levels were directly recorded in the field in a semi-quantitative manner, scored on a scale of 1 to 5 (variable '*crust*'[1]). Topographic position and slope form have been quantified by applying a simple terrain model to the results of a topographic survey (variable '*hydroc*'). Low values refer to convex sites and high values to concave sites. For details see Voortman and Brouwer (2002).

Variable selection

In accordance with the earlier paper (Voortman et al., 2002), we deliberately choose *not* to use compound soil characteristics such as Cation Exchange Capacity (CEC) and Base Saturation (BS). Instead, we prefer to characterize the exchange complex through Total Exchangeable Bases (TEB), Al saturation (defined as Al x 100/(Al+TEB) and Exchangeable Sodium Percentage (ESP, defined as Na x 100/TEB), which each have a distinct and different effect on plant growth. Soil organic matter content has not been considered either, because of its compound nature and since it may be viewed as an endogenous variable. We also consider

[1] Crusting levels were scored on a scale of 1 to 5, where 1 refers to heavy crusting, high resistance, poor infiltration and 5 to absence of crusting, low resistance, good infiltration.

ratios between cations in addition to their absolute levels, since relative levels proved to have a significant impact on millet yield (Voortman et al., 2002). And we continue to use cross-products of variables, because these can account for interactions between variables.

3. Data exploration and analysis methods

A series of research tools and methods were applied, in an iterative manner, to achieve the objectives of this study. The econometric analysis on the individual field parts started with the exploration of the relationship between millet yield and the independent variables using step-wise regression (SAS, 1989). In fact, this method is not directly suitable for our purpose, since it imposes linear structure. In part, we have circumvented this property of the technique by creating new variables consisting of quadratic terms for each variable, the cross products of all pairs of variables, and the cross product of each variable with each quadratic term. Such cross products do not enhance the ease of interpretation, but have the theoretical advantage that interactions between variables may be identified (e.g. Russell, 1973). A practical advantage is that, since many soil chemical characteristics are related, cross products may partly correct for the inevitable small laboratory errors. This is particularly relevant in the present case because the values for most soil chemistry variables are very low, and a small error in the absolute sense therefore becomes large in the relative sense. Step-wise regression was conducted at different significance levels, using both step-wise and forward options, with and without some variables that cannot be directly related to crop yield (such as ΔpH). The outcomes were compared and only the most common and significant terms were selected for further use.

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. Multi-variate non-parametric kernel density regression (using the Mollifier programme; see Keyzer and Sonneveld, 1997) played a central role and was used for exploration of functional forms. The programme used allows the visualization of highly flexible non-linear functional and spatial relationships in 3-D images, without compromising on statistical rigour. Technically, 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. Examples of the use of this tool will be presented in the section on results. The non-parametric data explorations lead to the selection of promising functional forms, which then were parametrically estimated in SAS (1993).

4. Results: data exploration and parametric regressions

This section reports on non-parametric data exploration and parametric regressions with a high explanatory power that allow meaningful interpretation. Of the three coversand types earlier identified only two have sufficient observations to do meaningful analysis: part/type A and B in the following (see Figure 1 for their distribution over the field and Table 1 for their mean properties). Since fertilizer inputs consist of chemicals mostly applied to the topsoil, we first take only topsoil chemistry into account, then subsoil chemistry is included in the analysis and thereafter the earlier mentioned additional factors are also considered. One may observe that in this section small ruminant manure is not present in the regressions. Its levels are generally low and it did not exert a significant effect on millet yield when total soil chemistry, local relief, surface crusting and cattle manure had been taken into account.

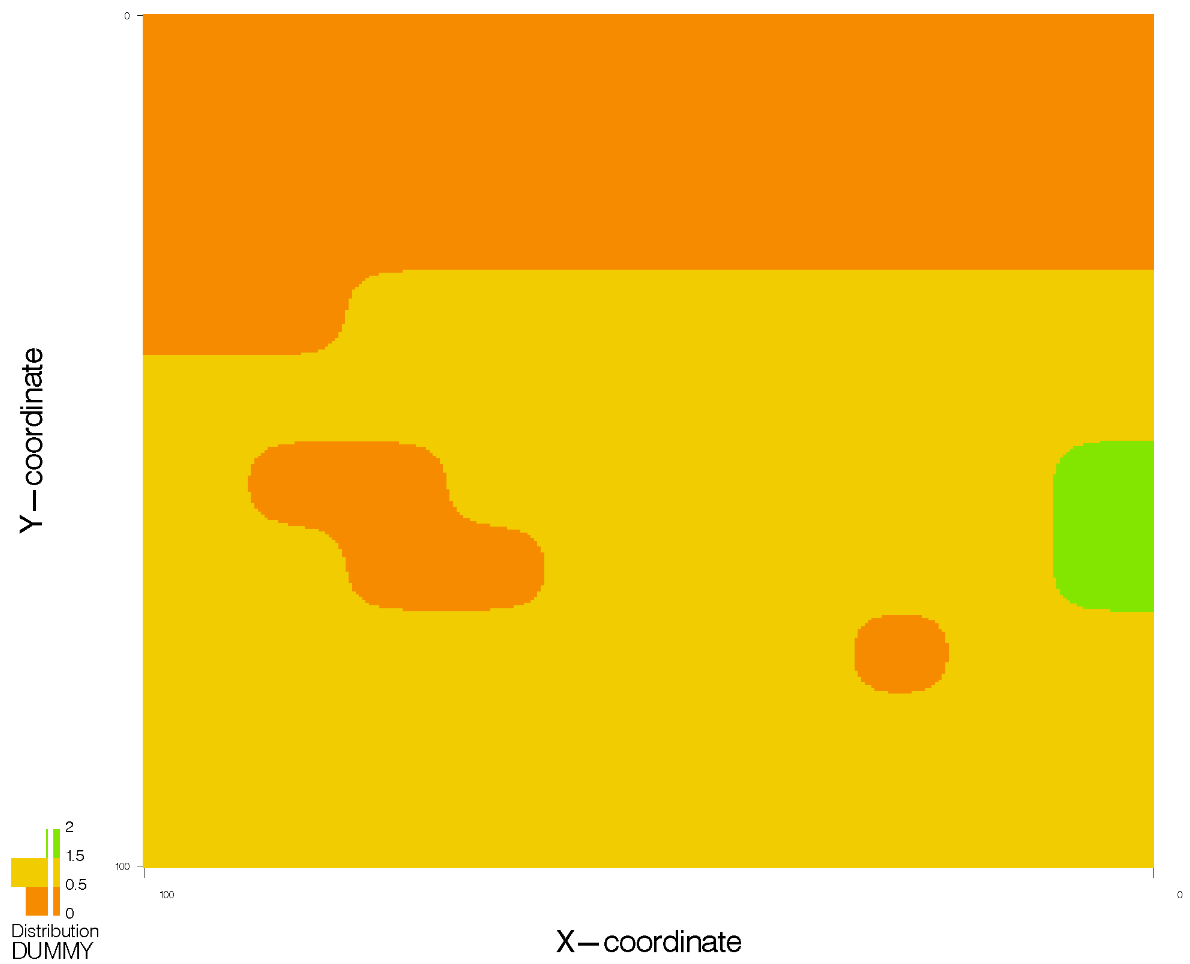

Figure 1 Map showing 3 individual field parts referring to different parent materials (coversands): part A is orange, part B is yellow and part C is green.

Table 1: Chemical properties at 10, 30 and 80 cm depth and millet yield for field parts A, B and C.

Variable	*Dim.*	*Part A*			*Part B*			*Part C*		
Depth	cm	10	30	80	10	30	80	10	30	80
N-total	ppm.	109.05	92.76	57.51	115.00	94.51	60.10	109.50	102.00	74.00
P-Bray	ppm.	2.32	1.41	0.78	2.65	1.57	0.85	7.61	3.04	1.26
K	cmol/kg	0.10	0.09	0.08	0.12	0.10	0.08	0.12	0.11	0.08
(Ca+Mg)/K	-	5.69	5.56	8.77	3.17	2.86	4.75	4.31	3.91	3.06
Ca/Mg	-	2.32	2.18	2.15	1.89	1.83	1.74	2.69	1.96	1.22
Mg/K	-	1.71	1.75	2.82	1.11	1.02	1.74	1.17	1.32	1.36
Na/TEB	%	4.2	4.9	3.9	3.5	3.8	3.1	1.6	1.8	4.4
Al/(Al+TEB)	%	33.00	40.00	29.00	33.00	52.00	37.00	10.00	22.00	52.00
Yield	kg/ha	451			749			1339		
n	-	37			59			2		

4.1 Field part A

Part A covers slightly more than 1/3 of the entire field (37 observations), and, on average, has the lowest observed yields. Soil chemistry, compared to part B, is characterized by a high (Ca+Mg)/K ratio, a high proportion of Mg at the exchange complex, relative high Na levels and a modest Al saturation in de subsoil (see Table 1). Before dealing with the parametric regressions, we first use this part of the field to explain the application of non-parametric kernel density regression and how it may be used to identify promising equations. Thereafter, parametric equations are presented and their implications discussed.

Data exploration example: interactions between Al saturation and P-Bray

Stepwise regression for this field part invariably indicates that yields increase when the level of P-Bray in the topsoil increases and they decrease when Al saturation increases. Figure 2 shows a 3-D plot of millet yield against topsoil Al saturation and P-Bray. The independent variables are plotted on the x- and y-axis, and the z-axis (the height of the upper 'blanket') represents millet yield. The colouring of the blanket indicates the location and density of observations (likelihood ratio), and the colours of the bottom plane represent a measure of reliability at each point (see also Keyzer and Sonneveld, 1997). The general trend of the effect of P-Bray and Al saturation on yield is as follows. Yields are highest when Al saturation is low and P-Bray is high and, as expected, the lowest yields are obtained when P-Bray is low and Al saturation is high. When P-Bray is low, an increase in Al saturation, already from levels as low as 10 percent onwards, immediately causes a negative yield effect; at high P-Bray this effect is almost absent. In terms of parametric functional forms, this means that the following equation could capture the observed relationship:

$$Y = \alpha_0 + \alpha_1 P_{10} \cdot Al_{10} + \alpha_2 Al_{10}^{\;2},$$

where, Y is millet yield, P_{10} and Al_{10} are P-Bray and Al saturation at 10 cm, respectively, and α_0, α_1 and α_2 are the coefficients to be estimated. This equation indeed explains, with very significant coefficients, 46 percent of the variation in millet yield. However, the blanket of Figure 2 is still rather bumpy, and reliability is modest (colouring of the plane), indicating that more variables need to be added to improve the fit of the model. With similar data

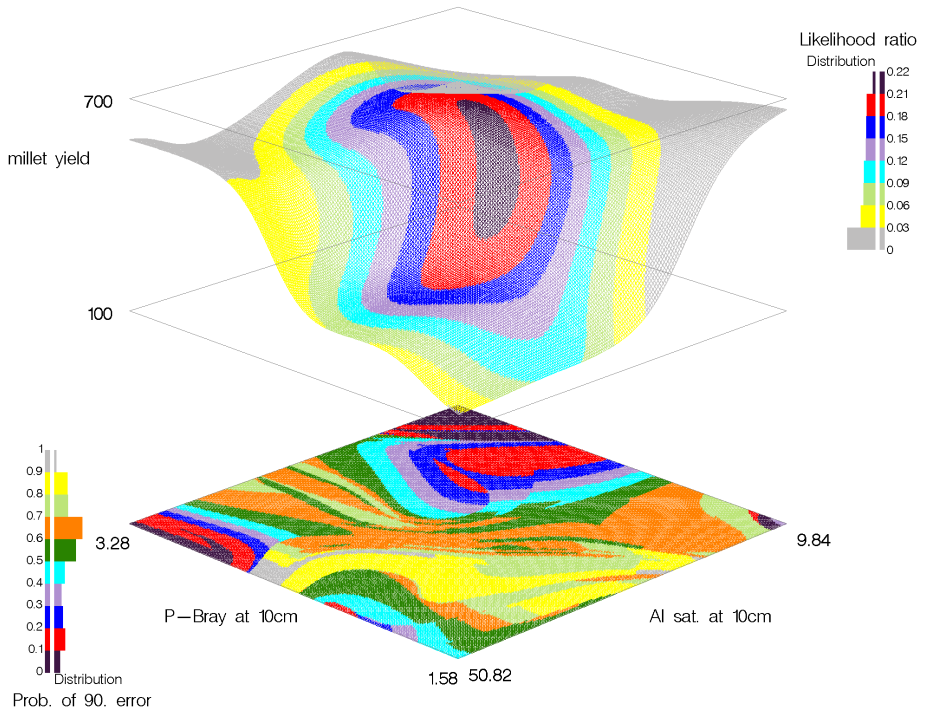

Figure 2 Millet yield (height of upper 'blanket') in field part A as a function of topsoil Phosphorus (P-Bray) and Aluminum saturation (the colours on the blanket indicate location of observations and the colours on the plane represent reliability)

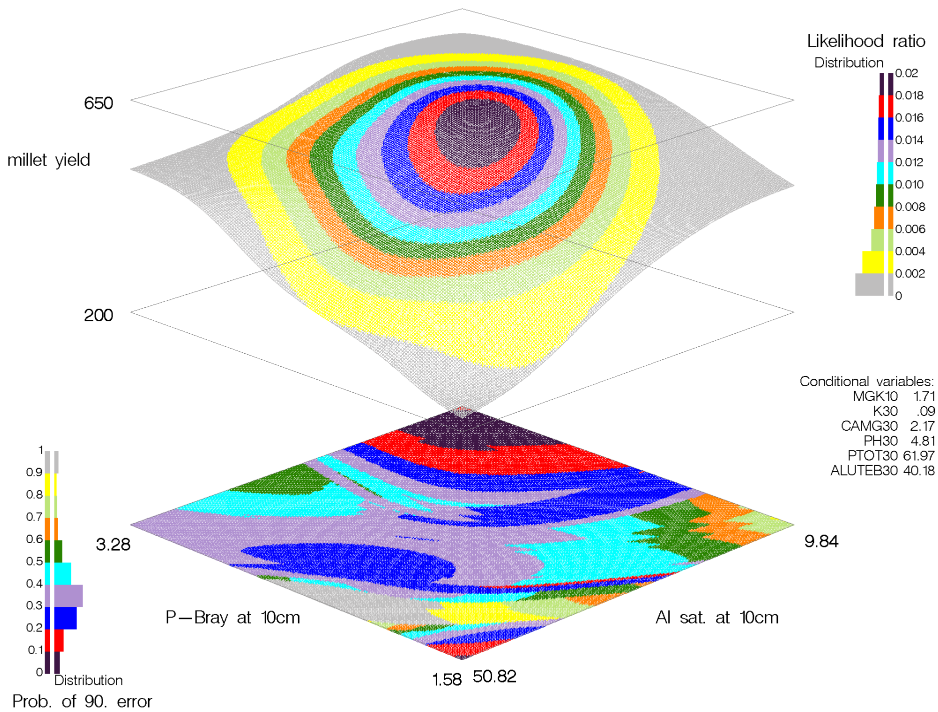

Figure 3. Millet yield in part A as a function of topsoil Phosphorus (Bray) and Aluminum saturation and some conditional variables

explorations, other promising variables were identified. We now use these as well, as conditional variables, by fixing them at their mean values, and plot again the same relationship (Fig. 3; for details of the procedures see Keyzer and Sonneveld, 1997). The result is a near-perfectly smooth surface that conforms remarkably well to the above parametric specification and reliability is also drastically improved. Medium yield levels are obtained when either Al saturation is low and, simultaneously, P is low, or when high Al occurs in combination with high P levels. Thus, low Al saturation may substitute for high P. The use of this technique forms the basis for the regression equations established below.

Topsoil chemistry

The just described interaction between topsoil P-Bray and Al saturation is one of the principal soil chemistry complexities that affect millet yield in field part A (Table 2, regression A1). Such interactions are well known from literature and they have a nutritional implication and also an impact on root elongation (e.g. Lambers et al., 2000). Substituting P-total for P-Bray gives much lower significance levels and explanatory power. For interpretation purposes this is somewhat problematic, because it is difficult to assess to what extent applied P behaves as P-Bray, since the Bray analysis measures the more easily available forms of P, and part of the applied P may be subject to fixation.

Table 2: OLS estimation results for the field part A based on topsoil chemistry, total soil chemistry and all variables (regressions A1, A2 and A3 respectively). T-values are given in parentheses. Significance is indicated with ***, ** and * for the 1, 5 and 10 percent level, respectively. Al refers to Aluminum saturation.

Regression		*A1*	*A2*	*A3*
Data source		Topsoil Chemistry	Total Soil Chemistry	All Variables
Intercept		-143.03	-2030.11***	-1845.13***
	Depth	*(-0.56)*	*(-3.96)*	*(-4.10)*
P-Bray x Al	10	7.85***	5.76***	5.12***
		(4.81)	*(6.05)*	*(6.14)*
$(Al)^2$	10	-0.157**	-0.170***	-0.166***
		(-2.25)	*(-4.13)*	*(-4.92)*
Al x Mg/K	10	-6.67***	-2.81***	-2.14***
		(-5.10)	*(-3.29)*	*(-2.91)*
$(TEB)^2$	10	519.47***	191.73*	
		(3.19)	*(1.93)*	
pH x P-total	10	1.04		
		(1.61)		
Al x Mg/K	30		-3.34***	-3.52***
			(-3.72)	*(-4.53)*
pH x P-total	30		0.692*	0.786**
			(1.78)	*(2.33)*
N-total x Ca/Mg	30		0.996**	0.903**
			(2.34)	*(2.45)*
K x Ca/Mg	30		3.15***	2.98***
			(3.06)	(3.50)
pH	80		366.89***	327.12***
			(3.91)	(3.96)
$(Crust)^2$				12.53***
				(3.69)
R^2		0.77	0.95	0.96
Adjusted R^2		0.74	0.93	0.95

Further analysis of the role of topsoil chemistry in field part A indicates that the cross product of Al saturation and the Mg/K ratio has a highly significant negative effect on yield. Apparently there is an additional negative effect of Al saturation beyond its effect on P nutrition. However, since high Al inhibits Mg uptake (Lambers et al., 2000), it is remarkable that high Mg is exacerbating rather than counteracting the effect of Al saturation (as the substitution mechanism observed for P and Al). The negative effect of high relative Mg may thus be indicative for its negative effect on K nutrition, an effect which is apparently enhanced when Al saturation is high, or conversely Al saturation may be less restrictive when K is relatively high. However, relative high K and relative low Mg are correlated with a lower tendency for crust formation and greater water percolation levels (Voortman et al., 2002). The negative effect of the Mg/K ratio itself may therefore assess the effect on surface sealing and the cross product with Al saturation then indicates that Al saturation is less restrictive when moisture availability is better, and vice versa. In any case, the Mg/K ratio, in relation to Al saturation, seems to account for complex interactions of soil chemistry and physics that affect seedling emergence and moisture availability to crops as well as plant nutrition.

Furthermore, topsoil TEB has a positive correlation with yield, as could be expected. The cross product of pH and P-total, which is at the limit of significance, provides further evidence on P being a main limiting factor in this field part. At the present pH range (4.7-5.5), this term clearly stands for P availability. Substituting P-Bray for P-total in this term gives a much lower significance level; consequently, P-total, next to P-Bray, provides an additional measure of P availability. The adjusted R^2 of 0.74 for this equation indicates that topsoil properties explain a large part of the yield variation in this field part.

Total soil chemistry

We now consider soil chemistry from all three sampled depths. Employing the methods earlier described rather straightforwardly leads to regression A2 (Table 2), which shows that native soil chemistry explains 93 percent of the yield variation in field part A. The addition of subsoil chemistry greatly enhances the significance of the topsoil terms describing the P-Al interaction, thus confirming its importance. The effect of the interaction of Al saturation and the Mg/K ratio is further highlighted by an additional significant term from the subsoil. Since the term derives from the subsoil, it cannot evaluate the effect of the Mg/K ratio on surface sealing and moisture infiltration and, therefore, indicates that plant nutrition effects are operative as well: high Mg relative to K is detrimental to yield and high relative K may alleviate the negative effect of Al saturation. The cross product of pH and P-total in the topsoil equation is taken over by the values at 30 cm, now being significant.

Topsoil N and K (other than through the Mg/K ratio) did not significantly impact on yield, but the subsoil levels do contribute to the explanation of millet yield. In both cases the response is conditional on the Ca/Mg ratio. This provides further evidence on the negative effects of high relative Mg levels at the exchange complex and the effect the Ca/Mg ratio may have on macronutrient nutrition, as earlier established for P by Sanik et al. (1952). Millet yield is further positively correlated with the pH at 80 cm, indicating that, at least in a year of good rainfall, the properties of the deeper subsoil have an effect on millet growth as well.

Soil chemistry and additional variables

With the high explanatory powers already achieved, it cannot be expected that the additional variables contribute much to the explanatory power, but they could render soil chemistry variables insignificant. However, cattle and small ruminant manure levels are very low in part A and do not contribute significantly to the explanation of millet yield. Local relief also does not play a role in this field part. Crusting level is significant and its squared term replaces topsoil TEB^2 (Table 2, regression A3), slightly increasing the adjusted R^2 from 0.93 to 0.95. The high explanatory power of the total soil chemistry equation and the small additional contribution of crusting level suggest that soil chemistry and crusting are well related. Figure 4 shows the very good relation between yields estimated on the basis of equation A3 and the actually observed yields in field part A.

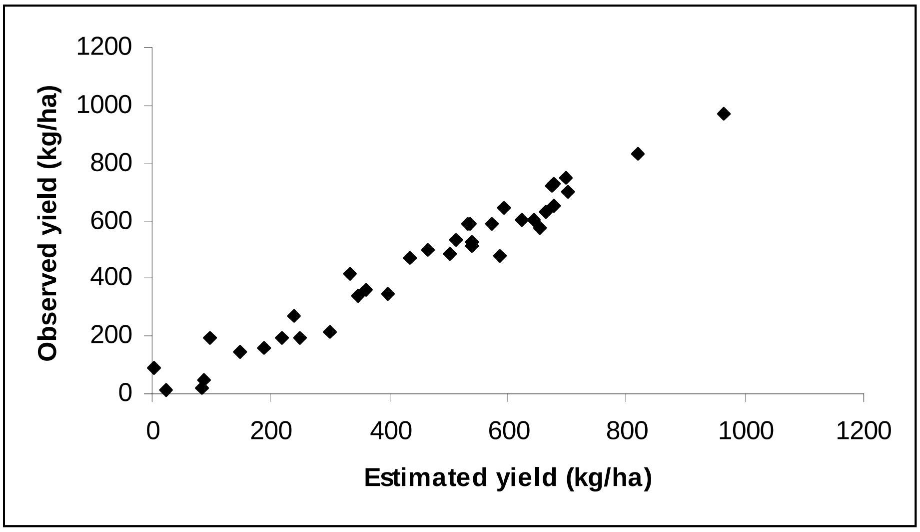

Figure 4. Estimated versus observed yield in part A based on regression A3 (adjusted $R^2 = 0.95$)

4.2 Field part B

Part B, with 59 observations, covers some 60 percent of the field. Yields are substantially higher than in part A. The main distinguishing features with respect to part A are the higher proportion of K at the exchange complex and higher subsoil Al saturation levels (see Table 1).

Topsoil chemistry

The topsoil equation for part B, at 55 percent, explains substantially less of the yield variation than its counterpart of part A (Table 3, regression B1). As in part A, the topsoil Mg/K ratio is an important determinant of millet yield, but the direct interaction with Al saturation is absent. While the response to increasing Mg/K is linear and negative in part A, here initially the response is positive when the ratio is low, but from a value of about 1.2 further increases have a negative yield effect as well. This value is close to the minimum value occurring in part A (0.9). Thus, across soil types, at higher Mg/K levels the response is consistently

Table 3: OLS estimation results for the field part B based on topsoil chemistry, total soil chemistry and all variables (regressions B1, B2 and B3 respectively). T-values are given in parentheses. Significance is indicated with ***, ** and * for the 1, 5 and 10 percent level, respectively. Al refers to Aluminum saturation

Regression number		*B1*	*B2*	*B3*
Data Source		Topsoil Chemistry	Total Soil Chemistry	All variables
Intercept		-516.17	-123.61*	458.02
	Depth	*(-1.46)*	*(-0.26)*	*(1.35)*
Mg/K	10	1470.29***	1929.12***	1102.33***
		(3.08)	*(5.37)*	*(4.26)*
$(Mg/K)^2$	10	-613.25***	-737.82***	-514.12***
		(-3.49)	*(-5.36)*	*(-5.22)*
P-total x K	10	0.184***	0.214***	0.150***
		(7.17)	*(5.12)*	*(4.35)*
Al x $(K/(Ca+Mg))^2$	10	-10.56**		
		(-2.12)		
Al x $(K/(Ca+Mg))^2$	30		-20.92***	-13.63**
			(-2.83)	*(-2.60)*
pH x TEB	30		-386.59***	-373.06***
			(-2.71)	(-3.76)
P-total x Al	30		-0.125**	-0.120***
			(-2.08)	*(-2.79)*
K^2	30		0.086**	0.079***
			(2.41)	(3.15)
Al x (Ca+Mg)/K	80		1.65**	
			(2.41)	
$(TEB)^2$	10			712.84**
				(2.39)
K/(Ca+Mg) x $(hydroc)^2$	10			-0.469***
				(-3.30)
Al x $(crust)^2$	10			0.745***
				(4.49)
Mancat x ((Ca+Mg)/K)	10			0.025***
				(5.20)
R^2		0.58	0.69	0.86
Adjusted R^2		0.55	0.64	0.83

negative, but for each soil type separately, the functional form is different, simply because of their data ranges.

As in part A, millet yield is also well-correlated with topsoil P, but, rather than P-Bray, P-total performs best. Substituting P-Bray for P-total, gives a lower significance level and explanatory power of the equation reduces to 0.44. The cross product of P-total with K indicates synergy and substitution between topsoil P and K. The next term (Al x $(K/(Ca+Mg))^2$) indicates that topsoil Al saturation has a negative yield effect, which, quite contrary to part A, is further aggravated when relative K is high, but now in relation to the sum of Ca and Mg. The operating mechanism of this term can be explained from the workings of Al saturation, since it inhibits the uptake of both Ca and Mg (Lambers et al., 2000). The effect therefore, quite logically, is most negative if Al saturation is high and Ca and Mg are low. The two Mg/K terms thus imply that increasing relative K levels would produce a positive effect, but such effects could be subdued supposedly on sites that are relatively low in Ca. Indeed, if we replace the ratio with simply K/Ca the explanatory power is only slightly lower. Yields thus suffer when the balance of K and Ca is unfavourable and the cross product indicates a more direct interaction of Al saturation and Ca, whereby the negative effects of Al saturation are less when Ca relatively high.

We now observe that all terms of this topsoil equation contain K. Absolute K levels have a positive effect; the sign of response to increasing K levels in the case of the Mg/K ratio depends on the level of Mg; and the K/(Ca+Mg) ratio indicates a negative response, when relative K increases. This calls for further data exploration on the role of absolute and relative K levels. We visualize these multidimensional relationships in 3-D space again with the 'Mollifier' tool (Keyzer and Sonneveld, 1997).

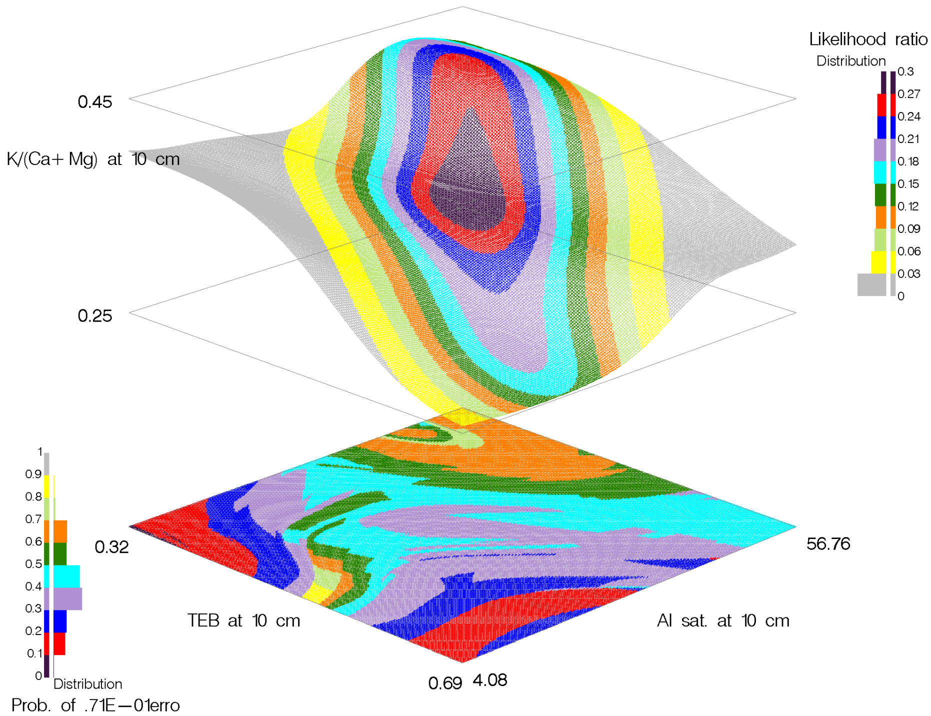

Figure 5. The topsoil K/(Ca+Mg) ratio as a function of topsoil Total Exchangeable Bases (TEB) and Aluminum saturation for part B.

Relative amounts of topsoil K, defined as K/(Ca+Mg), are quite reliably related to Al saturation and TEB (Fig. 5). The ratio value or relative K level is highest when Al saturation is high and TEB is low, that is, when the soil is most leached. Conversely, at low leaching levels its value is low and the inverse ratio, (Ca+Mg)/K, is then obviously high. The same principles were found to apply to the two subsoil horizons. Such relationships confirm the observations of Pieri (1985) for this environment, namely that leaching intensity of cations varies in the sequence Ca > Mg > K (based on Pieri, 1982, Gigou, 1982 and Chabalier, 1984). We now plot millet yield against absolute and relative K levels, the latter expressed as K/(Ca+Mg), using some relevant conditional variables (Fig. 6). Excluding outliers, we zoom

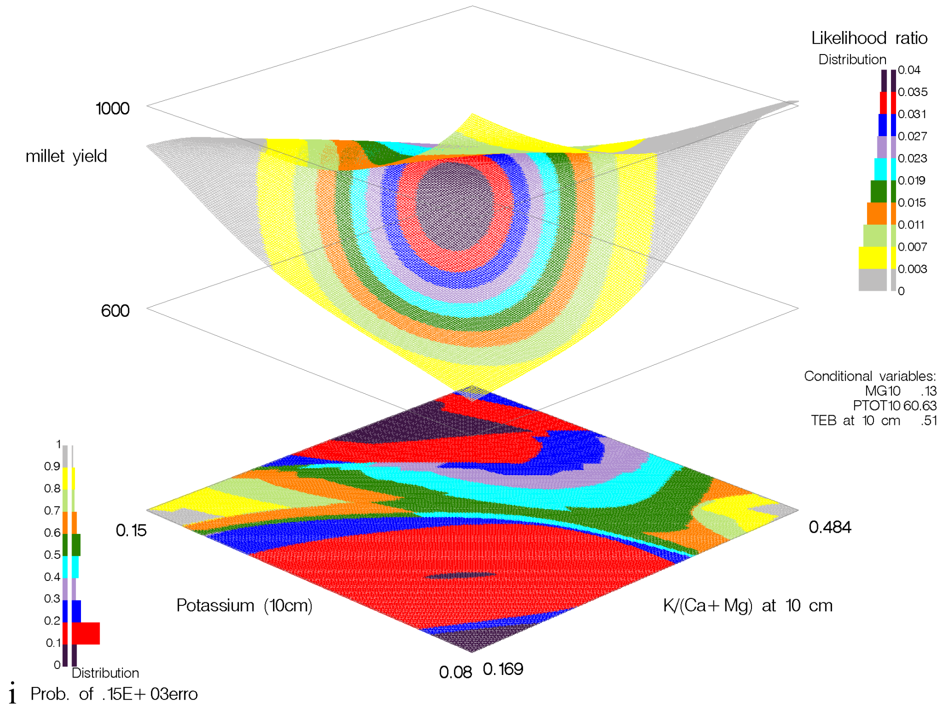

Figure 6. Millet yield in part B as a function of absolute and relative topsoil Potassium levels and some conditional variables.

in on 90 percent of the observations, which results in a perfectly smooth blanket with a highly reliable fit (see the colours of the lower plane). Yields prove to be lowest when both absolute and relative K levels are low. We further observe a positive and increasing response to absolute K levels when the relative level is low and a similar response to relative levels when the absolute level is low. Negative responses to increasing K occur in some observations, when both absolute and relative levels become high. Under such conditions K is apparently in excess, or, conversely, Ca or Mg, or both, are deficient. At the lower side of absolute and relative K levels, where most observations are located, we observe near perfect substitution between absolute and relative K levels. This may have a nutritional interpretation, namely that when absolute K levels are low the plant's K requirements can still be satisfied if the relative level is high, and vice versa. However, while K/(Ca+Mg) is high when TEB is low and Al saturation is high, that is when the soil is most leached, we may also interprete its value as representing water percolation levels, and, consequently, moisture availability. Doing so implies that K levels may substitute for moisture availability and vice versa. This finding is in accordance with the evidence provided by Pieri (1985, 1992), namely that in this environment high K levels or K applications reduce moisture stress and consequently stabilize yields over the years. Such mechanisms have also been observed in other environments (Wyrwa et al., 1998).

Total soil chemistry

A modest improvement of explanatory power (to 64%) is achieved when subsoil chemistry is taken into account, and doing so has again the effect that the remaining topsoil terms greatly gain in significance (Table 3, regression B2). The cross product of Al saturation with $(K/(Ca+Mg))^2$ for the topsoil is now replaced by its subsoil value (at 30 cm). Subsoil Al saturation and leaching, the levels of which are higher than in the topsoil, thus have a greater and more significant negative impact on yield than topsoil levels. The multiplication with $(K/(Ca+Mg))^2$ performs much better than a squared term for Al saturation, thus confirming that under leached conditions, next to Al saturation, the resulting unbalance of K relative to Ca also matters (the ratio K/Ca has again similar explanatory power). However, the next term (pH x TEB) suggests that high pH and high TEB, which both are usually higher when leaching levels are low, have a negative impact as well, thus indicating the existence of some optimum balance between nutrient and moisture supply.

Equation B2 further identifies, somewhat unexpectedly, a negative effect of subsoil P-total, which is further aggravated when Al saturation is high, while at the same time topsoil P-total has a positive sign. This clearly indicates that millet in this field part may be much less responsive to P application, if compared to part A, even though current P levels are quite similar (Table 1). To further investigate this point we plot the derivative to P-total for both the topsoil and subsoil term combined in relation to subsoil Al saturation levels (Figure 7). It shows that additional P has no effect when Al saturation in the subsoil is about 60 percent and that the effectiveness of P substantially increases when subsoil Al saturation decreases. If, for instance, the Al saturation levels were reduced to the average level of part A (40 %), then the response to P would be considerable and positive (as also was found for part A). As in the case of Mg/K, this suggests universality of the sign of response across parent materials, but in this case does not find expression in the functional form, not because the levels of P itself are different, but because other variables associated with the parent material (Al saturation) have consistently different values. The efficiency of P in part B can thus be raised when Al saturation is reduced, which further emphasizes the need for Ca application in this part of the field. Similarly, subsoil Al saturation itself, at similar levels, is more restrictive in part B, if compared with part A (Figure 8).

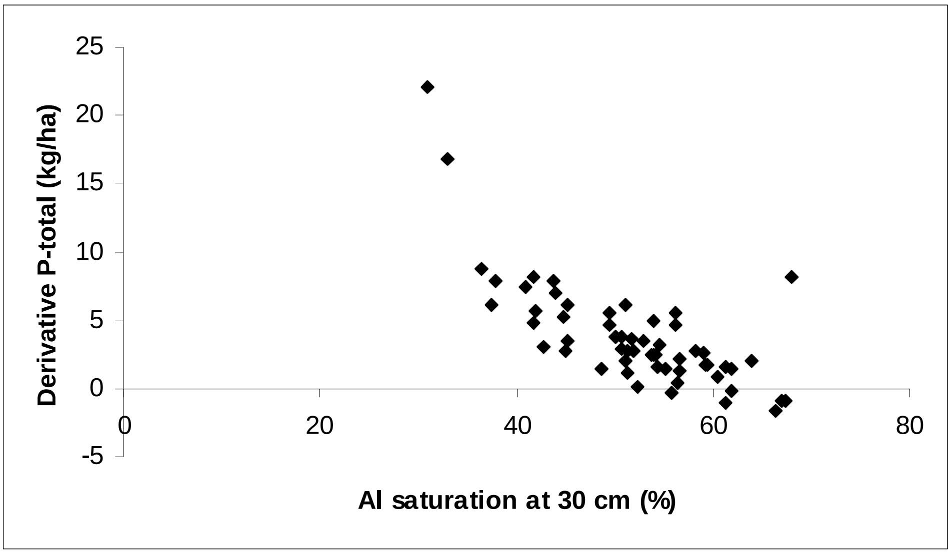

Figure 7. The derivative to topsoil and subsoil P-total (dy/dx: change of yield in kg/ha when both topsoil and subsoil levels of P-total change 1ppm) as dependent on subsoil Al saturation levels in field part B.

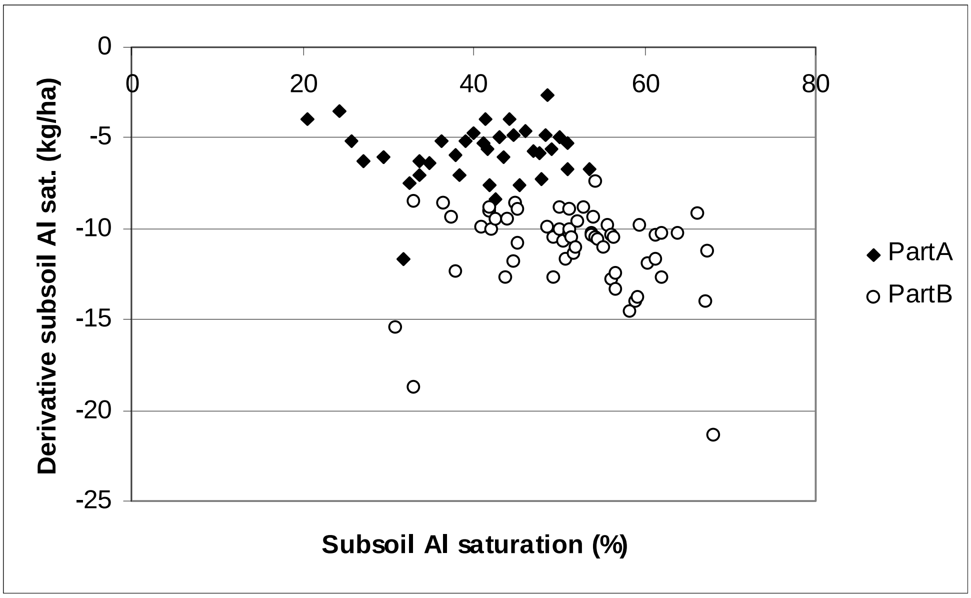

Figure 8. The derivative to subsoil Al saturation (dy/dx: change of yield in kg/ha when topsoil Al saturation changes 1 percent) for the two field parts.

Furthermore, a quadratic response to subsoil K was identified, which in combination with the topsoil terms, suggests that K applications may be very effective in this field part, in particular when Ca levels are raised as well. The last term (Al x (Ca+Mg)/K, which derives from the deeper subsoil, has an unexpected positive sign. However, the positive effect of (Ca+Mg)/K is likely to reflect cattle manure accumulations at a site where the soil materials that characterize the parent material of part B are very shallow and overly part A type materials in the subsoil, which have a generally unfavourable high (Ca+Mg)/K ratio. As we will see later, this term indeed becomes insignificant if cattle manure levels are accounted for. The positive effect of Al saturation in the deeper subsoil confirms earlier observations that evidence of deep water percolation is positively correlated with millet yield (Voortman et al., 2002).

Soil chemistry and additional variables

When additional variables, including cattle manure, are taken into account, then topsoil TEB appears to have a significant positive yield effect (Table 3, regression B3). As with P-total, topsoil values thus compensate for the negative effect of subsoil levels. Further, while such effects were not evident in part A, in part B millet yield is related to landform (variable 'hydroc'). The term indicates that yields are lower in depressions and particularly so if the topsoil there is strongly leached as expressed by a high K/(Ca+Mg) ratio. Conversely, this term implies that higher yields were obtained on micro-high positions with low leaching levels. The implication is that Ca application may be particularly effective on micro-low positions. In addition, low crusting levels (when variable crust has a high value) obviously have a positive yield effect and particularly so when greater water infiltration is actually confirmed by higher Al saturation levels in the topsoil. The last term indicates that cattle manure quite naturally has a positive effect, and is most effective where relative K levels are

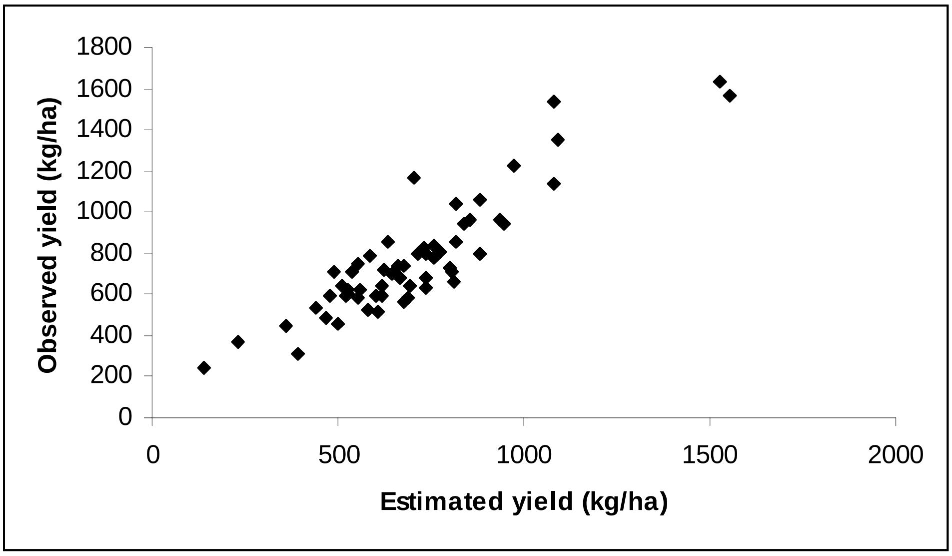

Figure 9. Estimated versus observed yield in part B based on regression B3 (adjusted $R^2 = 0.83$).

low. Figure 9 presents the relation between observed yields and estimated yields on the basis of regression B3.

5. Discussion

The field part-specific millet yield functions identified in the previous section are only slightly less complex than those observed across parent materials (Voortman et al., 2002). In one case explanatory power was substantially improved (part A), but in part B explanatory powers did not improve much supposedly due to the greater variability deriving from a very uneven manure distribution and variability in the depth to the underlying coversand that in part A occurs at the surface. The type of variables that explain yields well across parent materials also do so at the level of the individual field parts. Cation ratio's, Al saturation levels, K levels and their interactions, constituting the cause and effect of soil surface sealing and water percolation, which affects seedling emergence and moisture availability, explain millet yields well also at the field part level. Together with pH and TEB, these variables provide the basic structure to the equations and other variables often interact with them: their effect depends on the basic total soil chemistry constellation as determined by cation ratio's, Al saturation, pH and TEB.

Quite contrary to those derived for the entire-field, the field part-specific equations do not contradict theory: across parent materials, subsoil Al saturation showed a positive yield effect, but Al saturation was more restrictive when the (Ca+Mg)/K ratio was high (Voortman et al., 2002). However, the field part-specific yield functions show a consistently negative effect of higher Al saturation levels and Al saturation proves to be more restrictive when the ratio is low, as could be expected. As the (Ca+Mg)/K ratio and the Al saturation profile constitute the essential difference between the two parent materials (Voortman et al., 2002), the equation at the entire-field level apparently captured the effect of the total soil chemistry and physical constellation that defines the two different coversands. It particularly evaluated the differences in moisture availability, where high subsoil Al saturation stands in for greater moisture availability and a higher (Ca+Mg/K) ratio represents lower water infiltration levels due to a greater soil surface sealing tendency when the relative level of Mg is high. Equations across parent materials may therefore not reflect the effect the functional form suggests, but rather the difference in the total constellation of different parent materials. Extreme caution is therefore required when interpreting agronomic or ecological research when the data derive from different parent materials. In the Sudano-Sahelian zone this is more often than not the case, since short-distance soil and millet growth variability often derives from shallow layers of different coversands (Sombroek and Zonneveld, 1971; Zonneveld et al., 1971; Voortman et al., 2002).

The need for prudence when interpreting research findings across parent materials is further emphasized by the different functional forms for individual sites and their implications. In the case of the topsoil Mg/K ratio, the functional form differs between field parts A and B, but this merely reflects the different data ranges associated with each coversand. The findings imply universality at least in the sign of response across parent materials, as depending on current levels. However, for instance, in the case of P and Al saturation, the site-specific yield functions indicate a different response depending on the parent material even when their level is the same. Their effect apparently depends on the total soil chemistry and physical constellation of the soil. This, as well, might be a source of mis-interpretation in agronomic and ecological research when conducted across parent materials.

The need for better geo-referencing in agronomic research has already been emphasized (White et al., 2002), but possibly even more important is the characterization of sites and the verification if different parent materials are involved or not. Failing to do so causes that research results cannot be compared and, consequently, leads to inefficiency. Even more seriously, it hampers the dissemination of research findings. This study also shows that characterization of sites according to some soil taxonomic class is clearly insufficient as the soils concerned exhibit only minor differences in terms of criteria used in such taxonomies and yet these minor differences have far-reaching ecological and agricultural consequences. The current study further emphasizes that site characterization should not be limited to topsoil properties. Subsoil properties not only prove to have an important impact on yield themselves, but their consideration can also greatly enhance the significance of topsoil chemistry complexities. Moreover, how values of a single variables change with depth can be very informative as was the case of the Al saturation profile. For instance, based on topsoil properties, some earlier research did indicate that, at 'bad spots', Al toxicity was likely to be the principle factor causing low yields and lower levels of cations were observed as well (Scott-Wendt et al., 1988a, 1988b). However, in the present case the bad spot (part A) has topsoil Al levels very similar to those of the better part B, while the topsoil cation levels are even higher at the bad spot. The latter in combination with lower, rather than higher, subsoil Al saturation in fact characterizes the bad spot. As there is a clear need for up-scaling of local research findings these need to comparable in order to fit into a common analytical framework. This requires a detailed site typology paying due attention to parent material as a potential source of soil variability.

The parent material-specific yield functions do not contradict theory and they can be much more directly interpreted without much inference. Greater confidence can therefore be put in the interpretation with respect to the likely effect of external input applications. In addition they reveal soil chemistry complexities that across parent materials are not identified and, consequently, a more comprehensive view of possible deficiencies is obtained. They therefore also allow fine-tuning of possible external input technologies that combine substantial yield improvement with low external input requirements that need further verification in experimental research.

The equations for part A now explicitly establish our earlier inferences that to reduce the proportion of Mg at the exchange complex, K application can be sufficient. An additional insight obtained is that raising relative K levels can alleviate the effect of Al saturation (supposedly because of lower crusting tendencies and greater moisture availability). P did not contribute much to explaining millet yield across parent materials. However, in part A the interaction of P and Al saturation is one of the main soil chemistry complexities affecting millet yield. It has sometimes been questioned whether this well known interaction between P and Al, in the present area, is a matter of Al toxicity, or P deficiency, possibly induced by high Al saturation levels (Kretschmar et al., 1991; Wendt et al., 1993). We cannot establish unequivocal causality in this empirical study, but show that P and Al saturation levels do interact: they are two sides of the same coin (see Fig. 2). Both raising P levels and lowering Al saturation levels would have a positive effect on yield. Ca application can therefore be beneficial as well and at the same time would further reduce the proportion of Mg at the exchange complex. It would further enhance N and K nutrition from the subsoil, since these are conditional on the Ca/Mg ratio. Site-specific yield function analysis for the coversand occurring in part A thus reveals that P and K, and possibly Ca can be expected to raise yields.

Similarly for part B, from the equation at the entire field level (Voortman et al., 2002) it was clear that generally K application could be beneficial and Ca only locally. It was further hypothesized that Ca application could have a positive effect, because of the high Al saturation levels, but this was not directly evident from the equations. However, at the field part-specific level a clear negative effect of Al saturation was established and the functional form indicates that indeed Ca application directly alleviates the effect of Al saturation. The field part-specific equation further shows that little response to P may be expected, unless Al saturation levels are reduced. The most immediate external input needs on this parent material are therefore Ca and K. These findings thus confirm earlier observations of Pieri (1992), namely that liming at intervals is indispensable on these soils, when leaching levels are high.

The fertilizer strategy that suggests itself across parent materials is the ‘structural’ application of Ca and K to reduce sealing tendencies and to improve moisture availability, seedling establishment and plant nutrition. Improved moisture availability and better plant establishment reduces the farmers’ risk associated with cash expenditures, which for risk-averse farmers is essential for technology adoption. Moreover, improved moisture availability is likely to improve response to other nutrients particularly of N and P (Bationo et al., 1990; Bationo et al., 1992; Christianson et al., 1990; Christianson and Vlek, 1991). The technology of K and Ca application and the effect it has on on- and off-site moisture availability, especially during years with intra-season droughts, clearly requires further experimental research in this environment.

6. Conclusions

To date, process-based crop growth models cannot accommodate the full complexity of soil chemistry and its effect on crop yield. The present paper shows that pursuing this as an objective may be even futile as the crop response to soil chemistry is not only complex, but cannot be captured in a universally applicable manner, since it depends on the total chemical and physical constellation of the soil deriving from parent material characteristics. Such crop growth models can therefore not substitute for experimental research. However, local soil variability will also continue to be an obstacle for the interpretation of agronomic research in the conventional experimental set-up of blocks with repetitions of treatments, unless such variability is subject of study as well and properly identified and characterized.

Furthermore, research becomes inefficient if research sites and their variability are not adequately characterized, because the dissemination of results to farmers then becomes quite impossible. The empirical approach pursued in this paper that accounts explicitly for spatial variability can be a viable alternative, certainly as a precursor for further well-targeted experimental research. However, also in this case, spatial variability due to parent material differences needs to be identified. Parent material and other factors of soil formation, such as climate and time, and their effect on leaching, determine cation ratio's, Al saturation, pH and TEB, which provide the basic structure of parent material-specific yield functions. These variables have a direct effect on plant growth themselves and the response to other plant nutrients often depends on them. Process-based crop growth models, therefore, need to account for these variables, or suitable proxies, and cannot solely consider macronutrient levels in the soil, or macronutrient levels applied, if confidence is to be placed in model findings.

Although considered a viable real-world alternative, regression analysis also has some problems of its own, namely the selection of explanatory variables, which soil depths to take into account and the selection of an appropriate functional form. We show that consideration of all variables from all soil depths and accounting for all possible interactions leads to equations that not only explain millet yield very well, but they also allow meaningful explanation in terms of current scientific knowledge. Further, some unconventional variables prove to be very significant (cation ratios). Due to the many interactions within the soil chemistry complex, a-priori selection of variables, or the selection of single variables, or the specification of a linear relationship from the outset, instead of accounting for interactions and non-linear relationships, are likely to produce low explanatory powers or misleading results. Our approach requires comprehensive data sets that may be costly to establish, but this obviously has to be weighed against the cost of experimental research and the applicability of its findings.

We hope to have convincingly shown that spatially-explicit empirical research can fill a knowledge gap and identify the most significant soil fertility complexities that need to be addressed in real-world situations aiming at the design of external input technologies that combine low cost with substantial yield improvement.

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The Centre for World Food Studies (Dutch acronym SOW-VU) is a research institute related to the Department of Economics and Econometrics of the Vrije Universiteit Amsterdam. It was established in 1977 and engages in quantitative analyses to support national and international policy formulation in the areas of food, agriculture and development cooperation.

SOW-VU's research is directed towards the theoretical and empirical assessment of the mechanisms which determine food production, food consumption and nutritional status. Its main activities concern the design and application of regional and national models which put special emphasis on the food and agricultural sector. An analysis of the behaviour and options of socio-economic groups, including their response to price and investment policies and to externally induced changes, can contribute to the evaluation of alternative development strategies.

SOW-VU emphasizes the need to collaborate with local researchers and policy makers and to increase their planning capacity.

SOW-VU's research record consists of a series of staff working papers (for mainly internal use), research memoranda (refereed) and research reports (refereed, prepared through team work).

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