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MULTI-SITE TIME-TREND ANALYSIS OF SOIL FERTILITY MANAGEMENT EFFECTS ON CROP PRODUCTION IN SUB-SAHARAN WEST AFRICA

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SUMMARY

Soil fertility constraints to crop production have been recognized widely as a major obstacle to food security and agro-ecosystem sustainability in sub-Saharan West Africa. As such, they have led to a multitude of research projects and policy debates on how best they should be overcome. Conclusions, based on long-term multi-site experiments, are lacking with respect to a regional assessment of phosphorus and nitrogen fertilizer effects, surface mulched crop residues, and legume rotations on total dry matter of cereals in this region. A mixed model time-trend analysis was used to investigate the effects of four nitrogen and phosphorus rates, annually applied crop residue dry matter at 500 and 2000 kg ha^{-1}, and cereal-legume rotation *versus* continuous cereal cropping on the total dry matter of cereals and legumes. The multi-factorial experiment was conducted over four years at eight locations, with annual rainfall ranging from 510 to 1300 mm, in Niger, Burkina Faso, and Togo. With the exception of phosphorus, treatment effects on legume growth were marginal. At most locations, except for typical Sudanian sites with very low base saturation and high rainfall, phosphorus effects on cereal total dry matter were much lower with rock phosphate than with soluble phosphorus, unless the rock phosphate was combined with an annual seed-placement of 4 kg ha^{-1} phosphorus. Across all other treatments, nitrogen effects were negligible at 500 mm annual rainfall but at 900 mm, the highest nitrogen rate led to total dry matter increases of up to 77% and, at 1300 mm, to 183%. Mulch-induced increases in cereal total dry matter were larger with lower base saturation, reaching 45% on typical acid sandy Sahelian soils. Legume rotation effects tended to increase over time but were strongly species-dependent.

INTRODUCTION

The yield-enhancing effects of surface-applied crop residue (CR) mulch, mineral phosphorus (P) and nitrogen (N) fertilizers, and of legume rotations have been reported frequently with respect to the nutrient-depleted, acid sandy soils of West Africa (Bationo *et al.*, 1992; 1993; 1998; Buerkert and Hiernaux, 1998; Bationo and Ntare, 2000). However, most of the available results and the derived conclusions referred to pearl millet (*Pennisetum glaucum*), sorghum (*Sorghum bicolor*), and maize (*Zea mays*). Much less is known about the effects of CR, P, and N on legume growth and on cereal legumes (Hafner *et al.*, 1992; Rebafka *et al.*, 1993b).

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In view of the need to intensify production with population growth exceeding 3% in sub-Saharan West Africa, these results are difficult to extrapolate to a wider area given the large range of rainfall regimes and soil types in this region. More general conclusions will certainly require the combination of (i) large data sets to verify the derived conclusions in identical experiments conducted across several sites and years, and (ii) an understanding of the bio-chemical and physical processes in the soil-plant continuum governing crop responses to the application of CR, legume rotations, and different sources and amounts of mineral P and N fertilizers.

Basic research into the mechanisms of CR effects on cereal growth has made some progress in recent years. Under the harsh environmental conditions of the West African Sahel characterized by (i) nutrient-poor sandy soils; (ii) annual potential evapo-transpiration around 2290 mm (Sivakumar *et al.*, 1993); (iii) frequent drought spells, and (iv) the occurrence of convective storms of high intensity, the removal of physical constraints to crop growth through a broadcast surface coverage with CR seems crucial for sustainable cereal production. Mulch-induced increases in surface roughness provide early season protection against wind and water erosion that otherwise would lead to the removal or sand-coverage of seedlings. Such protection has been found to translate into growth-enhancing effects throughout the four months vegetative period (Michels *et al.*, 1995; 1998). Given the low water-holding capacity of the predominantly sandy soils, a significant reduction of peak surface soil temperature with mulch, and a better water availability during the physiologically critical stages of flowering and grain filling through increased infiltration are similarly important (Buerkert and Lamers, 1999). The second mechanism proposed to explain CR effects on crop growth relates to the improvement of the crops' mineral nutrition through the capture of Harmattan dust and a subsequent enhanced P availability with dust-related increases in pH (Kretzschmar *et al.*, 1991; Herrmann *et al.*, 1993; Sinaj *et al.*, 2001). Enhanced P uptake, as a consequence of increased root growth in a less compacted surface soil following higher termite activity, improved potassium (K) availability from decomposing CR and, for groundnut (*Arachis hypogaea*), improved molybdenum (Mo) availability have also been reported (Hafner *et al.*, 1993a;b; Buerkert and Stern, 1995; Mando and Stroosnijder, 1999). Nevertheless, the significance of these causes for the relative expression of CR effects under a range of edaphic and climatic conditions in West Africa, as well as the time-dependent increase of CR effects across locations, merit further investigation.

Site-specific increases in cereal total dry matter (TDM) were also detected with the application of mineral N and P fertilizers. Experimental evidence indicates that the relative importance of N compared with P increases with rainfall from north to south and that at most sites of the Sudano-Sahelian zone P is more limiting for crop growth than is N (Poulain *et al.*, 1974). This, however, has never been investigated systematically. For P application, in the last few years there has been a renewed debate about the efficiency of locally available rock phosphate (RP) (McClellan and Notholt, 1986) as an alternative to imported soluble P fertilizers. At some strongly acid sites with high rainfall, RP application has been reported to be nearly (76%) as effective as single superphosphate (SSP) in doubling millet yields, whereas at nearby locations the respective yield increases were only marginal (Bationo *et al.*, 1990; 1992; Buerkert and Hiernaux, 1998).

For legume rotation-induced increases in the TDM of cereals, the following mechanisms have been reported recently by Alvey *et al.* (2000) and Bagayoko *et al.* (2000a;b): (i) a decrease in nematode infestation; (ii) an increase in early season mineral N (Nmin); (iii) enhanced infection with arbuscular mycorrhizae (AM), and (iv) rhizosphere effects such as pH increases by up to two units, by 74% enhanced acid phosphatase activity and, caused thereby, duplication of P-Bray in the root zone at 37 days after sowing (DAS). Despite these results from individual sites, it remains unclear whether yield differences between continuous and rotation cereals are due to an absolute yield decline in continuous cereals over time or to an increase in the yield of rotation cereals. Under both field and controlled conditions most of the observed effects were strongly dependent upon the legume species involved, with larger effects at groundnut than at cowpea (*Vigna unguiculata*) sites.

In an effort to provide policy makers with comparable information about where to apply what type of input, the present study is aimed at drawing more general conclusions about the effects of CR, mineral N and P application, and legume rotations on crop yields across a typical range of environments in sub-Saharan West Africa. To this end a time-trend analysis, using a mixed model regression approach, was conducted in the combined analysis of a multi-factorial crop rotation and soil fertility experiment conducted over four years in sub-Saharan West Africa.

MATERIALS AND METHODS

Sites, treatments, experiment layout and data collection

Sites. The experiment consisted of a series of multi-factorial trials conducted from 1995 to 1998 under rainfed conditions at six sites in Niger and Burkina Faso, and from 1996 to 1999 at two additional sites in Togo (Figure 1). The chosen sites covered a wide range of edaphic and climatic conditions in the region with a single growing season of four to six months (Tables 1 and 2). The climatic data and the chemical properties of the upper 0 to 0.2-m soil layer at the sites were used as covariates to model environment-specific time trends. All trials were laid out as split-plot designs with completely randomized mainplots of 10×10 m, except for the Fada site in Burkina Faso where the replicates were arranged in blocks.

Mainplots. CR at two levels, P at four levels and N at four levels were factorially combined and replicated twice in each trial. Crop residues of cereal species were broadcast at 500 (traditional farmers' level) or 2000 kg ha^{-1} (dry matter) in January of each year, the middle of the dry season. The four P levels consisted of (i) a control without P (P_0); (ii) an annual broadcast at 13 kg ha^{-1} of single super phosphate (SSP_{13}); (iii) a broadcast once every three years of 'soft' Tahoua rock

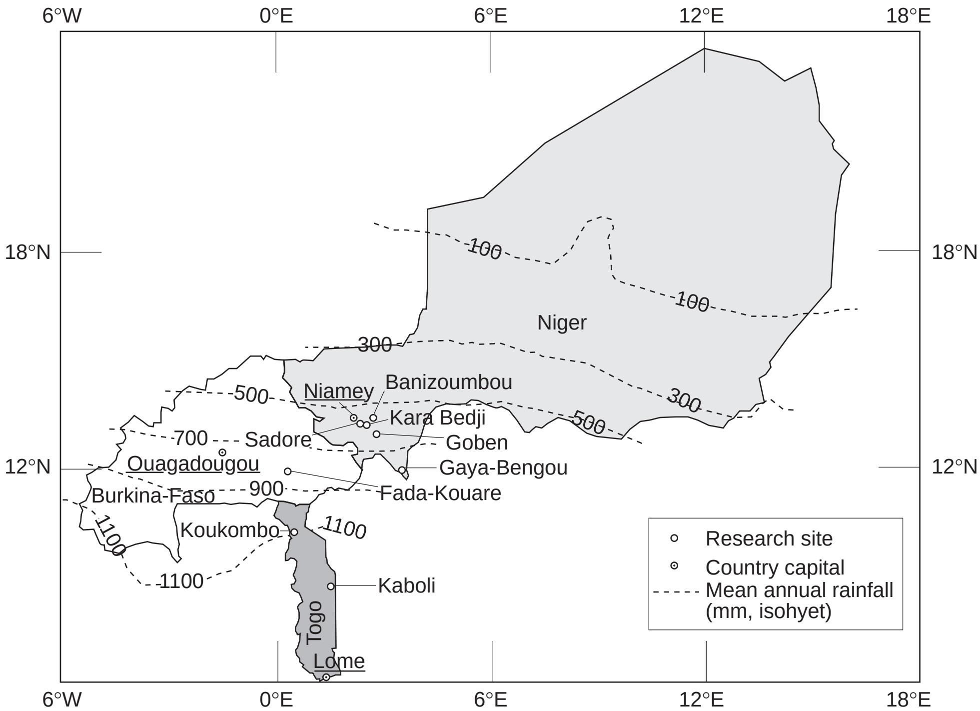

Fig. 1. Map of the eight research sites in sub-Saharan West Africa showing lines of the same average annual rainfall (isohyets) which define growing periods (White, 1986) of 60 to 100 days for the 'Southern Sahelian zone' (300 to 600 mm annual precipitation), of 100 to 150 days for the 'Northern Sudanian zone' (600 to 900 mm), of 150 to 210 days for the 'Southern Sudanian zone' (900 to 1200 mm), and of 210 to 270 days for the 'Northern Guinean zone' (1200 to 1400 mm).

Table 1. Initial soil chemical parameters at 0 to 0.2 m depth for eight sites in West Africa in May 1995 (data from Buerkert *et al.*, 2000).

Site	pH†	Clay g kg^{-1}	C_{org} g kg^{-1}	P-Bray I mg kg^{-1}	P-water‡ µg kg^{-1}	Ca^{2+} cmol kg^{-1}	CEC§ cmol kg^{-1}	BS¶ %	N_{min} mg kg^{-1}
Banizoumbou	4.4	50	1.50	1.5	300	0.4	0.8	74	5
Sadoré	4.5	30	2.26	2.8	440	0.4	1.1	86	n.a.
Kara Bedji	4.2	40	1.57	1.9	130	0.2	0.8	56	4
Goberi	4.1	30	1.55	1.7	280	0.2	0.8	50	2
Gaya-Bengou	4.2	130	3.30	2.5	140	0.4	1.3	66	9
Fada-Kouaré	5.4	150	5.20	1.3	320	1.8	2.8	99	3
Koukombo	5.6	50	3.67	2.0	1100	1.3	1.9	97	12
Kaboli	4.7	160	6.46	3.8	1250	1.3	3.3	71	18

† pH in 0.01 *M* KCl (1:2.5).
‡ P-water determined after Sissingh (1971) but with incubation time reduced to 5 min at a soil:water ratio of 1:10.
§ Effective cation exchange capacity.
¶ Base saturation.
n.a.= not available.

Table 2. Average and annual precipitation at the eight sites in West Africa.

Site	Precipitation (mm)					
	Average†	1995	1996	1997	1998	1999
Banizoumbou	510	494	484	442	687	–
Sadoré	560	494	544	384	721	–
Kara Bedji	590	336	557	391	621	–
Goberi	600	500	499	360	597	–
Gaya	800	513	714	768	809	–
Fada-Kouaré	850	n.a.	797	817	1076	–
Koukombo	1100	–	n.a.	n.a.	n.a.	n.a.
Kaboli	1300	–	n.a.	n.a.	n.a.	n.a.

† Average of five to ten years.
n.a. = data not available.
Dashes = no data available because the experiment was not conducted at these sites in these years.

phosphate at 39 kg ha^{-1} (TRP_{39}), and (iv) TRP_{39} with an additional annual placement (with seed at sowing) of 4 kg ha^{-1} ($P_{4placed}$) as SSP in 1995 and 1996 and as NPK (15%N, 15% P_2O_5 and 15%K_2O) in 1997, 1998 and 1999. To study the residual effects of broadcast P application, P was reapplied only as $P_{4placed}$ in treatment (iv) in the fourth year. Despite generally higher TDM production in the wetter zones and differences in the cereal species sown, CR mulch, and P levels were kept constant to facilitate the comparison of treatment effects on crop growth and soil properties across environments. In contrast, the four rates of mineral N applied as calcium ammonium nitrate (CAN) were modified according to environments. At the sites with low sowing densities in the Sahelian zone of Niger, namely, Banizoumbou (13°31′N, 2°39′E), Sadoré (13°14′N, 2°17′E), Kara Bedji (13°15′N, 2°32′E) and Goberi (12°58′N, 2°50′E) and in the Sudanian zone, namely, Gaya-Bengou (11°59′N, 3°32′E) in Niger and Fada (11°59′N, 0°19′E) in Burkina Faso, N applications were 0 (control), 30, 60, and 120 kg ha^{-1}. At the two Guinean-zone sites in Togo with high plant densities and larger potential TDM production, namely, Koukombo (10°17′N, 0°23′E) and Kaboli (8°45′N, 1°35′E), N rates were 0, 60, 90, and 150 kg ha^{-1}. In order to examine the Mo effects on crop growth during the first two years of the experiment (1995 and 1996), N had been applied at only two rates, 0 and 30 kg ha^{-1} (0 and 60 kg ha^{-1} in Togo) each with and without foliar Mo at 500 g ha^{-1}. As there were no Mo effects at any site, N treatments were modified as described. The total N rate was split into three equal amounts, with one each applied after emergence, at thinning, and at booting. In the Sahelian and the Sudanian zone of Niger, the cereal sown was millet at 10 000 hills ha^{-1}. In the Sudanian zone of Burkina Faso, sorghum was sown at 40 000 hills ha^{-1} and, in the Guinean zone of Togo, maize was sown at 53 330 hills ha^{-1}.

Subplots. The following four crop rotation treatments were randomly assigned one each to subplots (5 × 5 m) in each of the 32 mainplots: continuous cereal, both phases of the cereal-legume rotation, and cereal-legume intercropping. Of these treatments, only the first three were considered in the analyses reported here. This was because cereal-legume intercropping followed local practices and therefore was not suitable for a multi-site analysis. In the legume plots, the entire above-ground biomass was removed from the field; for groundnut this also comprised the coarse roots attached to the pods. In Niger, the legume sown at all sites was cowpea at 40 000 hills ha^{-1}; at Fada, Koukombo, and Kaboli, groundnut was sown at 55 550 hills ha^{-1}. The legume species chosen at each site depended on farmers' preferences in the predominant local cropping system; the location-specific choice of legume and cereal species was considered as an integral part of the systems under study. While it is understood that this perspective necessitated a confounding of locations with species, it was preferred over a design involving all location × species combinations, which would have resulted in a large number of locally un-adapted treatments.

To avoid germination problems due to early-season droughts, the legumes were sown after the rainy season was well established, usually 20 to 30 days after the cereal. At harvest, the plants in each plot, with the exception of border rows, were cut and the dry weight of grain, heads, and remaining straw determined at 65 °C to compute TDM. Further details of the crop husbandry were reported by Bagayoko *et al.* (2000b).

Statistical analysis. The main objective of the study was to provide conclusions for a range of environments in sub-Saharan West Africa exploiting physical and chemical covariate information on trial locations (Table 1). This called for a mixed model analysis taking the location factor as random, thus allowing broad inferences (Littel *et al.*, 1996). The modelling approach acknowledges the purposeful selection of locations along a rainfall gradient by incorporating gradient variables through a fixed-effects regression approach for treatment × location interaction, while taking unexplained residual interactions as random. Due to the regression approach, the model allows an interpolation among sites, thereby allowing the prediction of yield trends across a range of possible values for the covariates, including settings that depart from those observed in the actual trials. An advantage of this approach is a broadening of the inference space, that is, inferences can be made relative to a population of locations of which the ones tested form just a sample. At Fada, the only site where replicates were grouped into blocks, the analyses did not reveal any block effects. Overall, variation appeared to be large but was distributed randomly reflecting the typical patchiness of plant growth over short distances (Buerkert *et al.*, 1995). Despite the low number of true replicates, this 'micro-variability' was addressed by the factorial structure of the experiments leading to substantial hidden replication.

Yields in the fourth year were analysed to study treatment effects, since these were expected to increase over time. Time trends were assessed by simple linear regression on year, and the regression slope was subsequently used as a derived response variable for further mixed model analysis (Diggle *et al.*, 1994). The authors also used the same approach to test the quadratic term for a time trend; however this analysis did not show significance for any of the treatment factors. The derived-variable approach (regression slope) was preferred over an explicit modelling of temporal dependencies among year-specific observations using time series variance-covariance models. This was because the short time series did not allow a reliable model identification and the validity of statistical inferences via Wald tests in time series models is questionable (Kenward and Roger, 1997). The analysis of the derived slope variable was straightforward and robust in the sense that it did not require explicit modelling of temporal autocorrelation. It greatly simplified the analysis, since the original three-way classification of year × location × treatment for TDM was condensed to a two-way classification of location × treatment for the derived trait and allowed the use of standard analysis-of-variance procedures. The authors' attention focused on the linear trend component, since they were interested mainly in whether this trend was up or down. This does not imply, however, that time trends did not show any non-linearities (though the linear component was found to dominate the trend). The authors believe that with a short time series of only four points, an assessment of the linear component is at the limit of what can be extracted from the data. Any attempt to identify an appropriate non-linear model among a multitude of candidates would have involved a high risk of over-fitting, thus obscuring rather than extracting the main features of the data.

As for the legume rotation there were two phases. In each year one of the rotations produced a cereal crop. The time series (four years) was studied on a subplot basis by simple linear regression. In the case of the rotation, data from the two cereal subplots (different phases) within a mainplot were merged for the same crop. Thus, within a mainplot there was one time series for continuous cereal, one time series for rotation cereal and one time series for rotation legume, with each series consisting of four points in time (corresponding to four years). For a given subplot treatment, this series was labelled Y1, Y2, Y3, and Y4. The regression slope for a time series (SLOPE in kg ha^{-1} a^{-1}) was used as a response variable in a subsequent analysis of variance for the series of eight trials. This approach is known as two-stage or derived-variable analysis and is one way of tackling the problem of autocorrelation in longitudinal data (Diggle *et al.*, 1994). Occasionally, an observation in one of the series was missing. In that case, derived variables were computed from the incomplete data without any adjustment for the missing data. Since only very few data were missing, this approach was deemed satisfactory. The regression was also used to obtain two derived variables, that is, the predicted yield in the first and the fourth years (P1 and P4) which were needed to graphically display regression trend lines. The analyses for the cereal comprised two levels of the subplot factor (continuous cropping and rotation), while the analysis for legumes was restricted to the rotation.

In the treatment × location analyses of derived variables (SLOPE; P1, P4) and of yields in the fourth year (Y4), locations were regarded as a random factor. Environmental covariates (average precipitation, soil pH, base saturation and organic C concentration) were considered to model treatment × location interactions. Average precipitation rather than actual rainfall for trial years was used as a covariate because the intention of this study was to derive results characteristic for typical environments and not for individual years. While interaction terms involving a covariate were treated as fixed effects, residual (unexplained) interaction effects with location were considered as random.

The analysis of the series of trials for the derived variable SLOPE and for Y4 proceeded in three steps. First, the full model, excluding covariates, was fitted using the GLM procedure of the SAS System (SAS Institute, 1990). In this analysis, sequential sums of squares (SAS type I sums of squares) were computed formally treating all effects except error (subplot error in this case) as fixed. Expected values of mean squares were then computed taking random effects into account. Pseudo-F-tests were constructed based on expected mean squares. The Satterthwaite method was used to compute approximate degrees of freedom for pseudo-F tests, that is, tests where either the numerator or denominator of the F statistic involve a linear combination of more than one mean square (Milliken and Johnson, 1984). Fixed model terms significant at $P = 0.05$ were retained. In addition, all random interactions of significant fixed terms with location and the mainplot error were retained. In the second step, a stepwise approach was used to examine whether location main effects and interactions of treatment × location could be modelled by a regression on the covariates. For example, if the preliminary model contained the two-way interaction P × location, the model was augmented by a term P × covariate, provided the latter effect was significant in an analysis of variance. Finally, the selected model was subjected to mixed model analysis (restricted maximum likelihood, REML) using the MIXED procedure of the SAS System (SAS Institute, 1997). PROC MIXED was used instead of PROC GLM, because only the former procedure allows a computation of appropriate standard errors and denominator degrees of freedom (via the Satterthwaite method) for estimable functions in the linear mixed model. Least squares means were computed for the significant qualitative model terms. When a term corresponding to an environmental covariate was significant, least square means involving this term were evaluated at a range of relevant values for the covariate. Note that the examples are not designed to match settings observed at any particular trial location since the aim was to draw general conclusions rather than to perform site-specific analyses. The least squares means were compared by t-tests, using Satterthwaite degrees of freedom where appropriate.

The model selected for the derived variable SLOPE was used subsequently to analyse the derived traits P1 and P4. The main purpose of these analyses was to generate graphical displays showing the time trend for different factor levels and different values of the quantitative covariates for a number of significant terms. A scatter was displayed around the trend lines given by least squares means for the original data (Y1, Y2, Y3, and Y4) based on separate analyses for the four years using the same linear mixed model as that selected for SLOPE. The graph contains a least significant difference (LSD = 0.05) for the vertical distance between regression lines in the first and fourth year. This LSD is based on the relevant standard error of a difference from the REML analysis of the derived variables P1 and P4. Multiple mean comparisons were conducted and displayed as described by Piepho (2000a;b).

The full and reduced models were formulated with the following explanatory variables:

Classification variables (factors):
CR = crop residues (0 = 500, 1 = 2000 kg ha^{-1})
P = mineral P rate (0 = P_0, 1 = SSP_{13}, 2 = TRP_{39}, 3 = TRP_{39}+$P_{4placed}$)
N = mineral N rate (0 = control, 1 = 30 or 60 kg ha^{-1}, 2 = 60 or 90 kg ha^{-1}, 3 = 90 or 150 kg ha^{-1})
SYSTEM = cropping system (1 = continuous cereal, 2 = rotation cereal)
LOCATION
PLT = a running number for mainplots at any given location

Quantitative explanatory variables:
PRECIPITATION = average annual rainfall (mm)
BS = base saturation (%)
CEC = cation exchange capacity (cmol kg^{-1})
P-H_2O (μg kg^{-1} soil)

RESULTS

Legumes

Phosphorus was the only treatment factor that significantly affected legume TDM across sites after four years (Table 3). Three consecutive applications of SSP_{13} led to an 18% TDM increase compared with the control without P, whereas the combined application of TRP_{39} once and subsequent annual P placement ($P_{4placed}$) increased legume TDM by 35%.

The results of the time trend analysis across all eight locations confirmed the overall surprisingly small treatment effects on legume TDM. Yields tended to

Table 3. Legume total dry matter yield as affected by phosphorus (P) application. Results of a mixed model ANOVA across eight sites in West Africa in the fourth year of treatment application.

	Legume total dry matter (kg ha^{-1})
Phosphorus (kg ha^{-1})	
0	1740
13 SSP[†]	2050
39 TRP[‡]	2280
39 TRP + 4 NPK[§]	2340
$LSD_{0.05}$	250

[†] Single superphosphate.
[‡] Tahoua rockphosphate applied once every three years.
[§] NPK (15-15-15) mineral fertilizer applied annually with the seed.

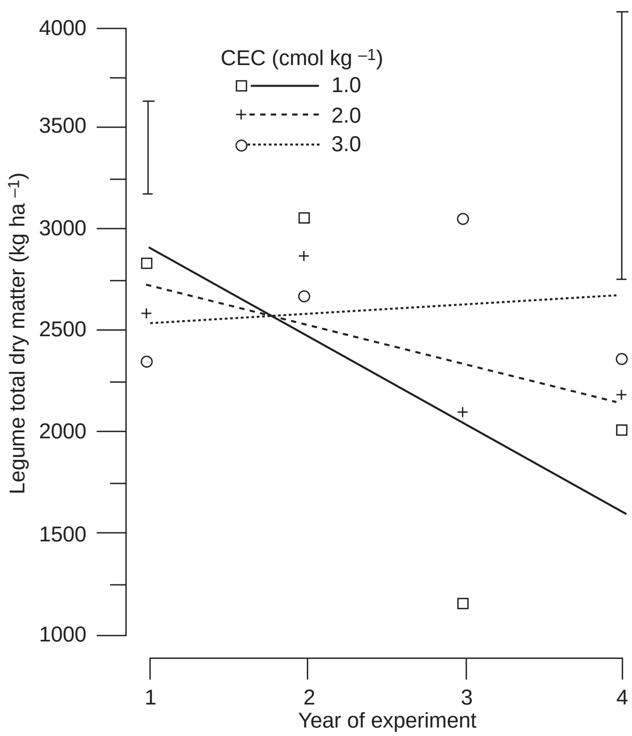

Fig. 2. Legume total dry matter as affected by cation exchange capacity (CEC) of the topsoil in sub-Saharan West Africa. The scatter data are least squares means based on analyses by year using the same linear mixed model for the description of multi-factorial treatment effects as for the time trend (SLOPE) variable. Trend lines were obtained by connecting predictions in year 1 (P1) and year 4 (P4). The three CEC levels were not significantly different. Vertical bars show least significant differences ($LSD_{0.05}$) comparing predicted means differing in CEC by one unit in year 1 (P1) and in year 4 (P4). The LSD for means differing by two units is twice that given in the figure.

decline over time and appeared to do so more on sites with low than with high CEC (Figure 2).

Cereals

Phosphorus. The regression analysis of treatment effects in the fourth year revealed P as the most important factor affecting cereal TDM across sites (Table 4). There was some evidence of site-specific differences in P effects ($P = 0.04$) but there were no other interactions with P. For a typical Sudanian site with 900 mm annual rainfall, a base saturation of 75%, and 700 μg P kg^{-1} soil, the residual effects of annual SSP_{13} application increased cereal TDM by 24%, whereas the residual effects of TRP_{39} led to a TDM increase of 39%. Additional P placement increased TRP_{39} effects to 51% (Table 4).

The time trend analysis showed P effects on cereal growth to be independent of rainfall and remarkably constant over the duration of the experiment. The application of TRP was the least effective across environments. At similar total P

Table 4. Cereal total dry matter yields (kg ha^{-1}) for different annual rainfall regimes (mm), base saturation (BS, %), and P-water (μg kg^{-1} soil) in the topsoil as affected by annually applied mineral phosphorus (P) and nitrogen (N) fertilizers, crop residue application and cropping system (SYST). Results of a mixed model ANOVA across eight sites in West Africa in the fourth year of treatment application. Numbers in brackets indicate $LSD_{0.05}$ for vertically arranged groups of means. For the comparison of more than two means, LSD values are averages across comparisons and are given for descriptive purposes only. For each comparison, a slightly different LSD applies. Line displays, however, are based on the exact pairwise LSD values.

Treatment level (kg ha^{-1})	P > F	Exemplary site characteristics								
		Rain	BS	P-water	Rain	BS	P-water	Rain	BS	P-water
Phosphorus	0.0001				900	75	700			
0						3500 (410)				
13 SSP[†]						4340				
39 TRP[‡]						4850				
39 TRP + 4 NPK[§]						5270				
Nitrogen[¶] × *Rain*	0.0001	500	75	700	900	75	700	1300	75	700
0			3830 (1260)			3180 (450)			2520 (1240)	
30 / 60			5100			4230			3360	
60 / 90			6090			5010			3930	
90 / 150			6230			5540			4860	
Nitrogen × *P-water*	0.0014				900	75	200	900	95	1200
0						2820 (950)			3400 (1150)	
30 / 60						2900			5640	
60 / 90						2950			7110	
90 / 150						3190			7890	
Crop residues × BS	0.0234	900	55	700	900	75	700	900	95	700
500			4010 (880)			4020 (970)			4040 (890)	
2000			5770			4950			4140	
SYST × *Rainfall*	0.0435	500	75	700	900	75	700	1300	75	700
Continuous cereal			5180 (880)				3880 (650)		2590 (1290)	
Rotation cereal			5450				5070		4740	

[†] Single superphosphate [‡] Tahoua rock phosphate applied once every three years
[§] NPK (15–15–15) mineral fertilizer applied with the seed
[¶] Nitrogen rates were higher in the Sudano-Guinean zone with higher annual rainfall than in the Sahelian zone

rates, broadcast SSP application and the combination of a three-yearly broadcast application of TRP plus an annual $P_{4placed}$ application led to a 53% increase in cereal TDM (Figure 3).

Nitrogen

Across all sites and treatments the fourth year's data showed highly significant ($P = 0.002$) N effects on cereal yield but the magnitude of these effects strongly depended on location ($P = 0.0001$) and precipitation ($P = 0.005$). At the highest P level, N-induced cereal TDM increases varied between 63% at 500 mm rainfall and 93% at 1300 mm. With TDM increases of 13% at water-soluble P levels of

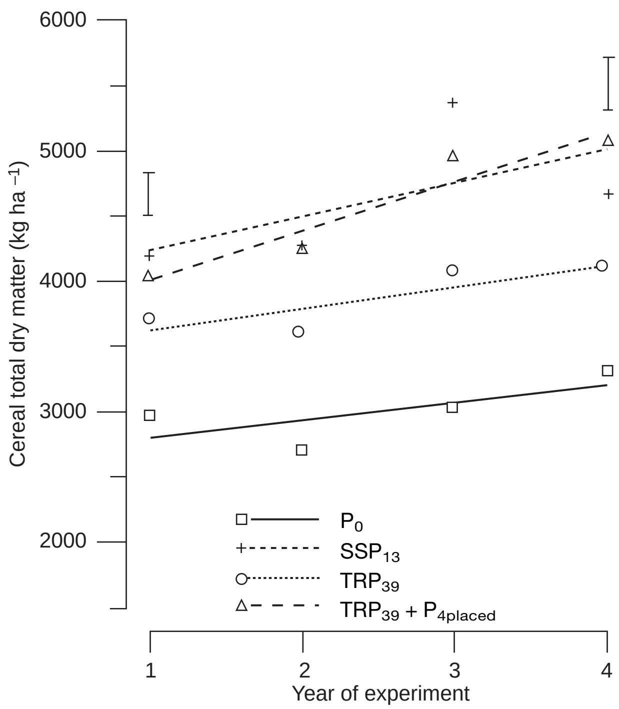

Fig. 3. Cereal total dry matter as affected by phosphorus (P) applied annually at 13 kg ha^{-1} as single superphosphate (SSP_{13}), at 39 kg ha^{-1} every third year as Tahoua rock phosphate (TRP_{39}), and as TRP_{39} combined with an annual placement with seed of NPK at 4 kg ha^{-1} ($P_{4placed}$) compared with a control without P (P_0) for a site with 900 mm annual rainfall and a base saturation of 75% in sub-Saharan West Africa. Neither SSP nor TRP were applied in the fourth year of the experiment. Vertical bars show least significant differences ($LSD_{0.05}$) comparing predicted means in year 1 (P1) and in year 4 (P4). For further explanations see Figure 2.

200 μg kg^{-1} and 132% at 1200 μg kg^{-1}, the dependence of N effects on cereal growth upon P availability in the topsoil was particularly heavy (Table 4).

The time trend analysis indicated a positive relationship between TDM production and rainfall, which was consistent with the higher stand density of sorghum and maize, compared with millet (Table 5 and Figure 4). Across the large range of environments examined the effects of increasing N rates on the time trend SLOPE strongly depended on rainfall. Across all other treatments, N effects were negligible at 500 mm rainfall. In the first year of application, however, with 900 mm rainfall TDM effects of N at 60 and 90 kg ha^{-1} were already 40% higher than for control plots without N. In the fourth year, TDM in plots with 90 kg ha^{-1} N was 77% above control plots without N. The highest N responses were predicted for locations with 1300 mm annual rainfall. At these locations the predicted increase of cereal TDM at the highest N rate was 99% compared with the control in the first year and 183% in the fourth year. With the highest rainfall, cereal TDM yields without N were also much lower than at low rainfall locations (Figure 4).

Table 5. Reduced mixed model ANOVA (SAS type I sums of squares) for the regression of the legume rotation / soil fertility experiment conducted over four years at eight sites in West Africa.

Source of variation†	df	F-value	P > F
LOC	7	9.95	0.0001
CR	1	15.20	0.0080
N	3	13.41	0.0001
P	3	4.69	0.0117
SYST	1	9.40	0.0182
PRECIPIT*N	3	5.94	0.0053
BS*CR	1	11.87	0.0137
LOC*N	18	4.13	0.0001
LOC*P	21	2.34	0.0008
LOC*CR	6	3.61	0.0017
LOC*SYST	7	16.43	0.0001
LOC*PLT	448	1.74	0.0001

† CR = crop residues (0 = 500, 1 = 2000 kg CR ha^{-1})
P = mineral P rate (0 = P_0, 1 = SSP_{13}, 2 = TRP_{39}, 3 = TRP_{39} + $P_{4placed}$)
N = mineral N rate (0 = control, 1 = 30 or 60 kg N ha^{-1}, 2 = 60 or 90 kg N ha^{-1}, 3 = 90 or 150 kg N kg ha^{-1})
SYST = rotation system (1 = continuous cereal, 2 = rotation cereal)
LOC = location
PLT = a running number for mainplots at any given location
PRECIPIT = average annual rainfall (mm)
BS = base saturation (%)

Crop residues

After four years of application, site-specific increases in cereal growth due to CR application amounted to 44% on sites with low base saturation, typical of the Sahel. No CR effects on cereal TDM were noted for the Sudano-Guinean zone with its much higher base saturation (Table 4).

The results of the time trend analysis revealed broadcast CR mulching as the most important factor determining the SLOPE variable. It was followed in order of magnitude by cumulative effects of N, cropping systems, and P (Table 5). Nevertheless, the analyses confirmed that CR effects on cereal TDM depended strongly on location. On acid sandy Sahelian soil types with low base saturation, the increase in CR effects on cereal TDM over the four-year duration of the experiment was highly significant. After four years TDM in plots with an annual CR application of 2000 kg ha^{-1} was 45% higher than in plots with 500 kg ha^{-1}. This difference declined, however, to 23% for soil types with a base saturation of 75%. On the heaviest soils with high base saturation, CR effects were negligible throughout the entire duration of the experiment (Figure 5).

Rotation

Rotation effects appeared to be negligible at low rainfall sites, typically planted to cowpea. With groundnut at sites with 1300 mm annual rainfall, however, yields of rotation cereals were up to 83% higher than those of continuous cereals (Table 4).

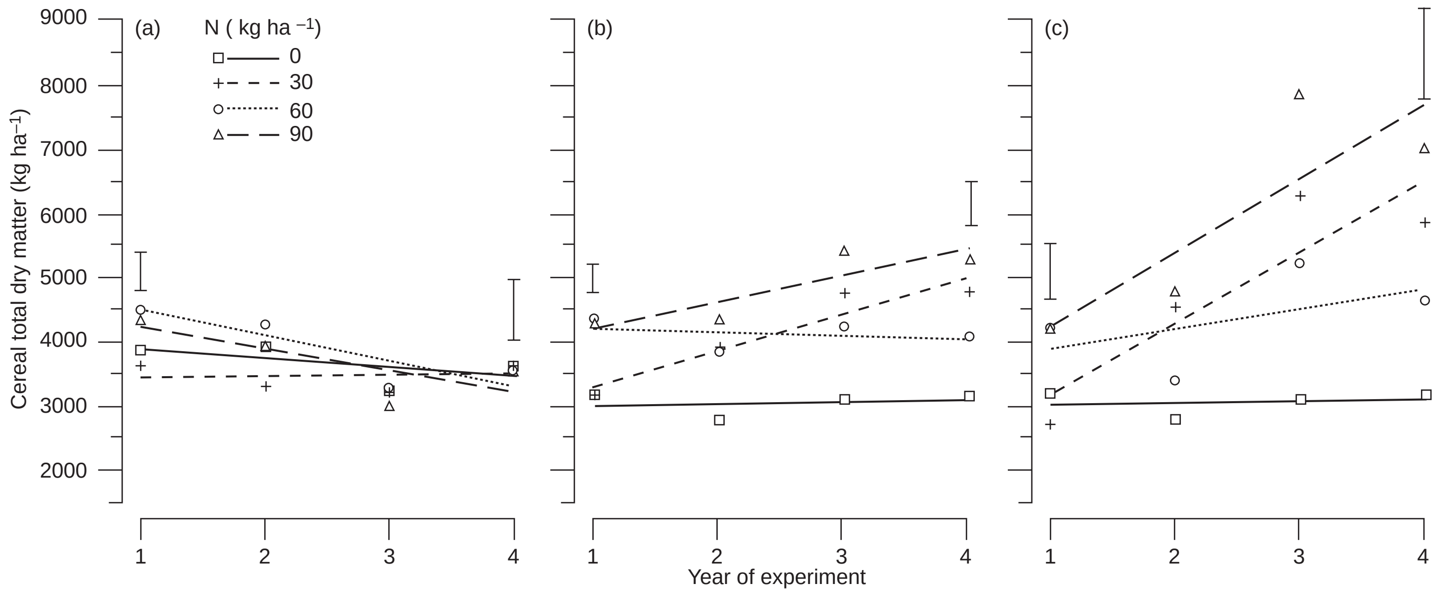

Fig. 4. Cereal total dry matter as affected by mineral nitrogen (N) applied annually as calcium ammonium nitrate (CAN) at four rates on a soil with a base saturation of 75% and (a) 500, (b) 900 and (c) 1300 mm annual rainfall in sub-Saharan West Africa. For further explanations see Figure 2.

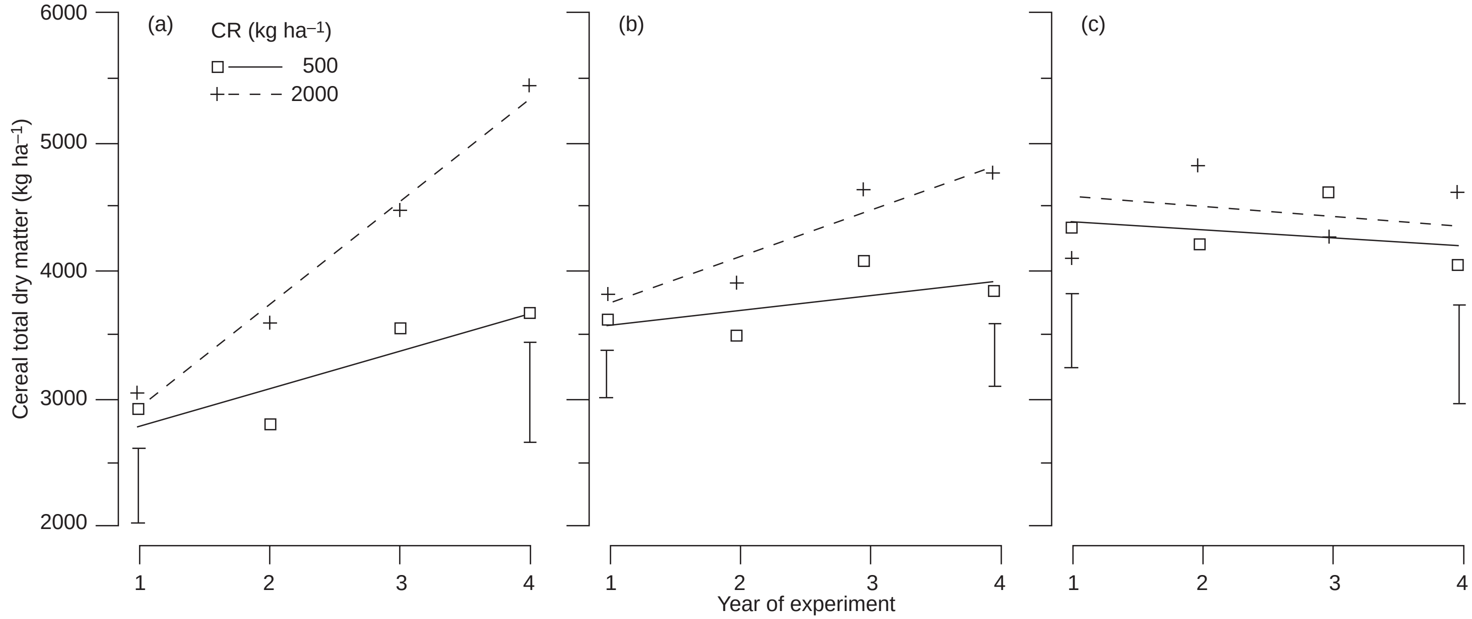

Fig. 5. Cereal total dry matter as affected by crop residues (CR) applied annually to the soil surface as broadcast cereal stalks at two rates, and at a site with 900 mm annual rainfall and a soil base saturation of (a) 55%, (b) 75% and (c) 95% in sub-Saharan West Africa. For further explanations see Figure 2.

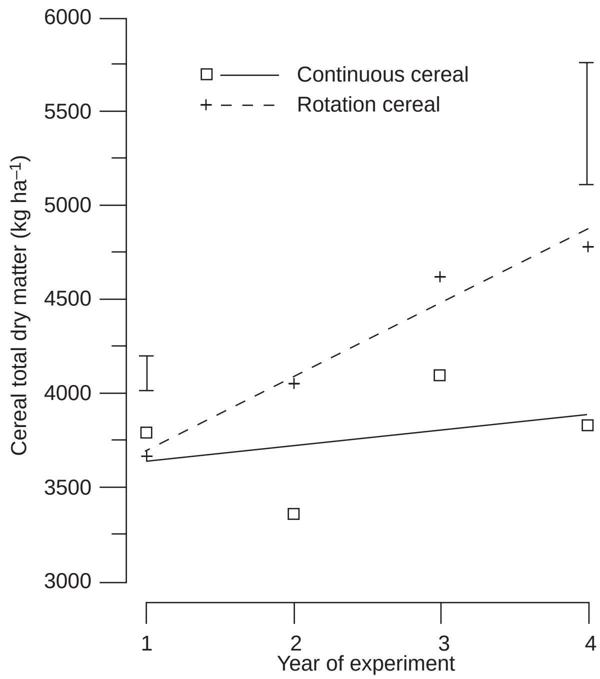

Fig. 6. Cereal total dry matter as affected by continuous cereal and a cereal after legume (rotation cereal) cropping system at a site with 900 mm annual rainfall and a soil base saturation of 75% in sub-Saharan West Africa. For further explanations see Figure 2.

Similarly, the time trend (SLOPE) of rotation-induced increases in cereal TDM strongly depended on location (which in this design was confounded with crops) but was independent of CR, N, and P applications (Table 5). The graphical display of CR effects at 900 mm rainfall also revealed that rotation effects tended to increase over the four seasons. This increase appeared to be due to progressively higher yields of rotation cereals rather than a yield decline in continuous cereals (Figure 6).

DISCUSSION

Legumes

The comparatively marginal effects of broadcast CR and N applications on legume growth are likely the result of the delayed sowing of legumes and that, by nature, legumes are less dependent on soil N than are cereals. One of the causes for CR mulch-induced increases in cereal growth is their anti-erosive effect at the onset of the rainy season. Effects of CR, therefore, will be less prevalent at later plantings when the major abrasive sandstorms have passed. Due to the systems perspective, the experimental design did not allow differentiation between the individual effects of legume species, planting density, and location. Phosphorus nutrition has been shown repeatedly to affect legume growth through its positive effects on N_2 fixation, governed by nodulation, nodule dry weight, and specific nitrogenase activity (Cassman *et al.*, 1980; Israel, 1987). The relatively high effectiveness of TRP_{39} compared with SSP_{13} in increasing legume TDM may be partly explained by SO_4^{2-}-induced Mo deficiency from SSP application. The same was reported by Rebafka *et al.* (1993a) for groundnut on a Sahelian soil. The more negative time trends for legume TDM with lower CEC on the Sahelian soils with their low clay contents point to the traditional role of fallow periods on these easily eroded sandy soils (Figure 2).

Cereals

Compared with the other P levels, the apparent time trend effect of broadcast TRP combined with annual $P_{4placed}$ may be explained by the use of the more efficient NPK rather than SSP as a placed fertilizer in the last two years of the experiment (Figure 3). The variation in the effects of SSP_{13} on cereal yields in the fourth year (Table 4) and on the time trend of cereal TDM across sites (Figure 3) seem to reflect durable differences in P solubility between the P sources. The initial assumption that the availability of TRP_{39}-P would increase over time could not be verified in the combined analysis. Data analyses for individual sites confirmed that P availability was time-independent but strongly site-specific. Mahamane *et al.* (1997) drew similar conclusions after comparing the agronomic efficiency of different P sources at different sites in Niger over five years. The small amount of seed-placed soluble NPK, however, led to large increases in P-use efficiency from the first year onward. Most likely, this was due to the combined effects of N (as NH_4^+) at 5 kg ha^{-1} and the easily available P in the placed-P treatment which stimulated seedling growth and subsequent P uptake from a larger rooting system (Strasser and Werner, 1995). Given its considerably lower investment costs, placement of small quantities of P appears to be a much more feasible strategy to increase soil productivity for resource-poor farmers than are broadcast applications of either RP or SSP, unless these are subsidized as soil amendments by government programmes to increase long-term P reserves in the soil. In addition to its limited effectiveness on most Sahelian soils, RP application is to overturn farmers' scepticism about a product that, due to its powdery nature, is easily translocated to neighbouring fields by wind.

Field trials have shown repeatedly that the importance of N as a primary growth-limiting nutrient for crops in sub-Saharan Africa increases with rainfall (Halm and Dartey, 1991; Jallah *et al.*, 1991; Maduakor, 1991). This may be explained by the increased NO_3^- losses with leaching and an overall higher TDM production. As expected, these earlier findings were confirmed by the present experiment, showing clearly the dependence of N effects on the P-status of a soil (Table 4). However, larger N effects with increasing rainfall may also be partially due to the confounding of locations with higher absolute N rates in the Guinean-zone sites of Togo. The observed increase in N effects over time may be partly explained by an increasing impoverishment of soil N. From the farmers' points of view N application may only be profitable with high rainfall where its effects on crop growth are large and the cereals grown, sorghum and maize, are of higher value than millet. This needs to be verified in future economic analyses, however.

The present understanding of the mechanisms leading to CR-induced increases in cereal growth can at least partly explain the large differences in cumulative CR effects with increasing base saturation derived from the time trend analyses reported here. The cumulative nature of CR effects on millet yields in the Sahelian zone has been shown previously (Rebafka *et al.*, 1994; Buerkert *et al.*, 1995) and was largely attributed to the progressive redistribution of wind- and water-eroded soil between mulched and un-mulched soil surfaces (Geiger *et al.*, 1992). For cross-location comparisons of CR effects, base saturation, being a parameter integrating the physical and chemical surface soil characteristics that govern cereal growth responses to CR mulch, appears to be a better indicator of site properties than is average rainfall. The anti-erosive effects of CR surface-mulching are more important in the Sahelian zone than in the Sudanian and Guinean zones. This is likely due to the increased clay content, better aggregate formation and less intensive but more frequent rainfall in the latter two regions. Likewise, locations with heavier soils and higher base saturation, such as in the Sudano-Guinean zone, are much less prone to CR effects on topsoil pH and subsequent increases in P availability to cereal seedlings than are the lighter soils predominating in the Sahel (Buerkert *et al.*, 2000; Sinaj *et al.*, 2001). With respect to the high rate of CR mulch applied, it must be noted that cereal straw is a highly valuable resource in sub-Saharan West Africa. It has multiple competitive uses and is traditionally only applied to the least fertile parts of farmers' fields (Lamers and Feil, 1993). Under on-farm conditions its widespread broadcast application as a surface mulch at 2000 kg ha^{-1} may be highly desirable from a soil conservation point of view and to sustain crop yields, however, its use is unlikely unless CR availability increases through the application of mineral fertilizers such as placed P.

The site-specific differences in the absolute magnitude of legume rotation effects on cereal growth across all sites support the results reported by Bagayoko *et al.* (2000b) for four of the locations analysed individually. These authors showed that rotation-induced TDM increases of millet after cowpea varied between 8 and 37% at Sadoré, Goberi and Gaya, and of sorghum after groundnut by between 12 and 37% at Fada. They concluded that improved early season N nutrition in combination with lower nematode infestation led to increased seedling growth and a subsequent higher uptake of P, the most growth-limiting nutrient at those sites. They also attributed legume-specific differences in residual Nmin to differences in the atmospheric N_2 fixation between groundnut and cowpea. Such differences were shown previously by Peoples and Craswell (1992) who reported an annual N_2 fixation for groundnut of between 37 and 206 kg ha^{-1} but only between 9 and 39 kg ha^{-1} for cowpea. Recent results reported by Bationo and Ntare (2000), in contrast, showed similarly large effects of cowpea and groundnut rotations on millet TDM. In the time trend analysis across sites performed in this study, legume species were confounded with location. Therefore, the large site-specific differences in rotation effects on cereal yields (Table 5) may be largely due to differences in actual N_2 fixation between the locally preferred legume species.

CONCLUSIONS

The results demonstrate the power of time-trend analysis to draw general conclusions about the effects of mineral N and P application, CR mulch, and legume rotation on cereal and legume growth across multiple environments in sub-Saharan West Africa. Across sites, the data reconfirm the role of edaphic and climatic factors on the magnitude of CR and rock phosphate effects on cereals. In designing better fertilizer application strategies for cash-poor farmers, rock-phosphate as a soil amendment should be combined with small rates of soluble P to increase its short-term efficiency. This holds true even for rock phosphate sources of high solubility such as TRP and in those cases where they are available cheaply through government programmes. Legume rotation-induced increases in cereal yields can be attributed to absolute increases in rotation cereals rather than to a progressive decline in continuous cereals. This underlines the yield-enhancing role of legume rotations for small farmers' cereal production in the region. The clear dependence of crop responses to N, on soil P availability and rainfall, calls for a systematic definition of recommendation domains for both these mineral nutrients across sub-Saharan West Africa.

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