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Destructive and non-destructive measurements of residual crop residue and phosphorus effects on growth and composition of herbaceous fallow species in the Sahel

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Abstract

Little is known about the residual effects of crop residue (CR) and phosphorus (P) application on the fallow vegetation following repeated cultivation of pearl millet [*Pennisetum glaucum* (L.) R. Br.] in the Sahel. The objective of this study, therefore, was (i) to measure residual effects of CR, mulched at annual rates of 0, 500, 1000 and 2000 kg CR ha^{-1}, broadcast P at 0 and 13 kg P ha^{-1} and P placement at 0, 1, 3, 5 and 7 kg P ha^{-1} on the herbaceous dry matter (HDM) 2 years after the end of the experiment and (ii) to test a remote sensing method for the quantitative estimation of HDM. Compared with unmulched plots, a doubling of HDM was measured in plots that had received at least 500 kg CR ha^{-1}. Previous broadcast P application led to HDM increases of 14% compared with unfertilised control plots, whereas no residual effects of P placement were detected. Crop residue and P treatments caused significant shifts in flora composition. Digital analysis of colour photographs taken of the fallow vegetation and the bare soil revealed that the number of normalised green band pixels averaged per plot was highly correlated with HDM (r = 0.86) and that red band pixels were related to differences in soil surface crusting. Given the traditional use of fallow vegetation as fodder, the results strongly suggest that for the integrated farming systems of the West African Sahel, residual effects of soil amendments on the fallow vegetation should be included in any comprehensive analysis of treatment effects on the agro-pastoral system.

Introduction

On sandy Sahelian soils, low levels of plant available phosphorus (P), organic carbon (Corg) and wind erosion have been identified as major constraints to the growth of pearl millet [*Pennisetum glaucum* (L.) R. Br.] (Geiger and Manu, 1993; Michels et al., 1993). Numerous studies have quantified the effects of management options to reduce soil degradation caused by wind erosion. Among these were the use of windbreaks (Brenner et al., 1995; Leihner et al., 1993; Michels et al., 1998), the application of crop residues (CR) broadcast on the soil (Bationo et al., 1993; Buerkert and Stern, 1995; Hafner et al., 1993; Rebafka et al., 1994) or concentrated on low productivity areas of farmers fields (Lamers et al., 1998) and tillage practices (Klaij and Hoogmoed, 1993). Similarly, on-station and on-farm experiments showed increases in millet straw and grain yield of over 100% with the application of mineral P fertilisers (Bationo et al., 1992; Buerkert and Stern, 1995).

While the direct and residual effects of P and CR application on crop growth have been well documented, surprisingly little is known about the residual effects of mineral fertilisers and CR on the growth and species composition of herbaceous fallow vegetation that follows a period of consecutive cropping cycles. In the integrated crop-livestock systems of the Sahel,

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fallow vegetation is an important source of cattle feed and building material and in drought years, seeds from fallow grasses and legumes may even serve as sources of human food. Moreover, fallow vegetation has an important role in the regeneration of soil fertility on acid sandy soils of the region. As such, it has been reported to enrich the topsoil with nitrogen (N) by between 5 and 10 kg N ha^{-1} yr^{-1} through diazotrophic N_2-fixation from the herbaceous layer or shrubs and by the decay of leaves, twigs and woody plant components (Hiernaux, 1983; Krul et al., 1982). Fallow effects were also explained by the capture of bird droppings estimated at up to 40 kg DM ha^{-1} yr^{-1} with 2.2 kg N, 0.4 kg P and 0.7 kg K (Soumaré, 1995) and by the collection of substantial amounts of potassium (K)-rich ‘Harmattan’ dust from the Sahara desert. The latter are reported to contribute up to 3 kg N, 1 kg P and 15 kg K ha^{-1} yr^{-1} (Herrmann et al., 1994).

In efforts to quantitatively monitor the spatially highly variable crop growth in the Sahel, non-destructive techniques based on radiometry or high resolution aerial photography have recently been shown to allow a reliable biomass determination of low density millet (Gérard and Buerkert, 1999; Lawrence et al., 2000). However, these techniques have not been used for the study of relatively dense species mixtures. The objectives of the present study, therefore, were (i) to determine the residual effects of CR and P application to a previous millet crop on the primary production of the subsequent fallow vegetation 2 years after the last millet harvest and (ii) to test the efficiency of non-destructive compared with destructive methods in quantifying those effects at the field scale.

Materials and methods

Field experiment

On a site used from 1991 to 1996 for a soil fertility experiment with pearl millet (Buerkert and Stern, 1995; Muehlig-Versen et al., 1998) at ICRISAT Sadoré station (13° 14′ N latitude, 2° 17′ E longitude, 235 m altitude) in south-western Niger, large treatment related differences in the primary production and species composition of the fallow vegetation were observed in 1998. The soil at this site is classified as a Psammentic Paleustalf, sandy, siliceous, isohyperthermic (West et al., 1984). It has in the upper 0 – 0.2 m a native P-Bray concentration of 2.8 mg kg^{-1}, Corg of 2.3 g kg^{-1}, mineral N of 5 mg kg^{-1} and a cation exchange capacity of 1.1 cmol$_c$ kg^{-1}. The climate is characterised by a unimodal rainy season from June to September and a dry season throughout the rest of the year. Average annual rainfall is 560 mm with a high inter-annual variability in total precipitation and in the onset of the rainy season. Total precipitation was 544 mm in 1996, the last year of millet cropping, 384 mm in 1997, the first year of fallow vegetation growth and 721 mm in 1998, the year when the reported measurements were performed. In 1991, 48 treatments were applied in two replicates to 96 plots of 10 × 10 m separated by eight alleys of 1 m width. The completely randomised experiment comprised the following factors: (i) four millet genotypes; (ii) millet crop residues broadcast at a rate of 500 kg and 2000 kg stalks ha^{-1} or as ash from burning of 2000 kg CR ha^{-1}; (iii) broadcast single superphosphate (SSP) at a rate of 0 and 13 kg P ha^{-1} and (iv) a factor that was molybdenum (Mo) application at 0 and 200 g Mo ha^{-1} in 1991 and hill-placed SSP application at sowing at 0 and 500 g P ha^{-1} in 1992 and 1993. In 1995 and 1996, the treatment set-up was modified with only one millet genotype remaining. There were six levels of CR including the unmulched control. Three CR rates were broadcast at 500, 1000 and 2000 kg ha^{-1} and two consisted of CR aligned in planting rows at 500 and 1000 kg CR ha^{-1}. There were also two levels of broadcast SSP at 0 and 13 kg P ha^{-1} and four levels of placed SSP at 0, 1, 3, 5 and 7 kg P ha^{-1}.

Biomass and ground cover measurements

On 25 August 1998, total dry matter of the herbaceous dry matter (HDM) and the ground cover of dominant plant species was determined for each plot. To this end species composition and ground cover of dominant species was recorded in eight subsamples of 1 m^2 per plot that were arranged in a uniform pattern (Figure 1A). For subsequent dry matter determination, all plant material was cut and oven-dried at 65 °C to constant weight. Herbaceous species were separated in five groups based on the size, shape and inclination of the leaves and on the biological type of the plant: Narrowly linear leaf shape in grasses and sedges; medium, linear leaves in erected dicots; composed or minutely dissected leaves in prostrate dicots; medium or large size and ovate leaves in erected dicots; and medium or large size and ovate leaves in prostrate dicots. The contribution of each type was calculated

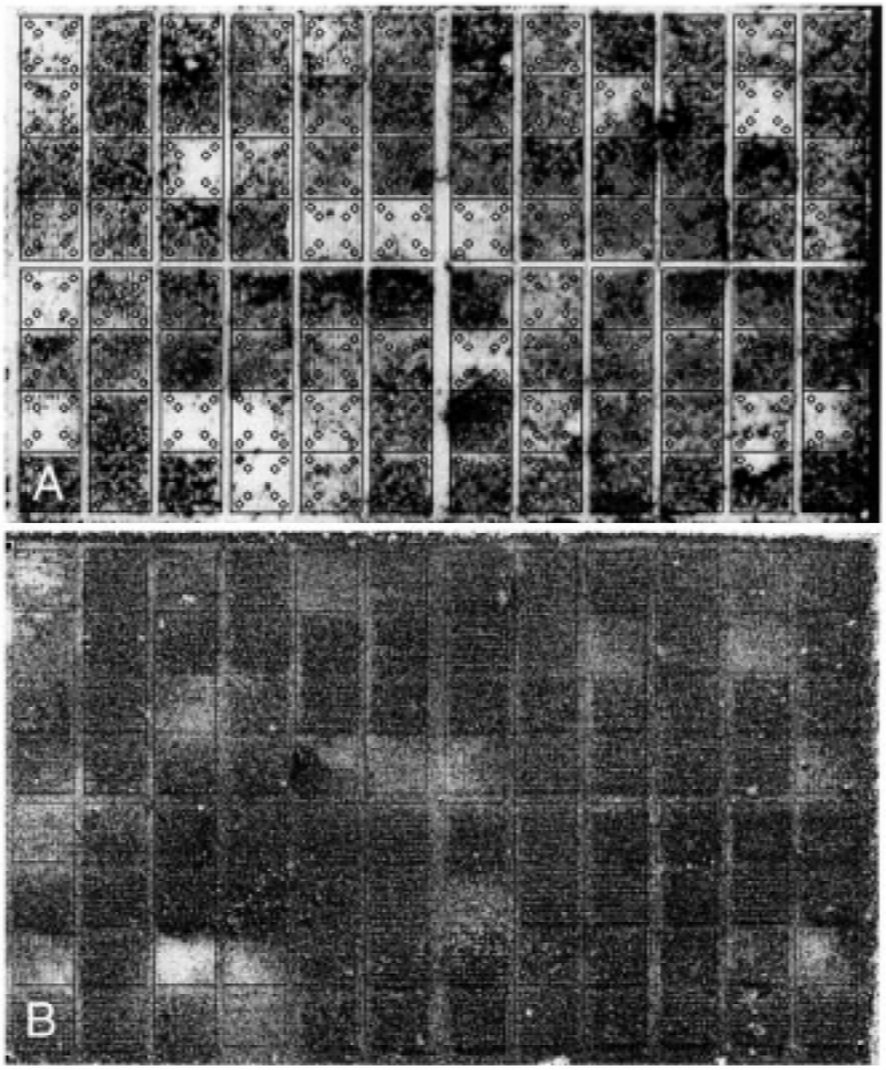

Figure 1. Normalised green band image with destructive sampling areas (the darker the pixels the denser the vegetation) derived from the aerial photograph taken at peak fallow vegetation on 18 August 1998 (A) and normalised red band from the aerial photograph taken on 18 June 1997 showing soil reflectance differences (crusted areas appear lighter) between mulched and unmulched plots (B). The experiment measured 140 $\times$ 83 m, size of individual plots was 10 $\times$ 10 m.

from its estimated cover per plot. The species cover estimates were used to assess the residual effects of CR and P on the species composition of the fallow with an analysis of variance. The data of the subsamples were aggregated at the plot level to be compared with the plot average normalised difference vegetation index (NDVI) values obtained from radiometer measurements or the total of normalised green band and normalised red band pixels of the aerial photographs.

Aerial photographs

True colour aerial images of the field experiment were taken from a kite or a balloon with the equipment described by Gérard and Buerkert (1999) at an altitude of 300 m. In 1997, these photographs were taken at the onset of the rainy season on 18 June 1997 with an almost bare soil as the remaining dry vegetation from the previous year had been grazed by cattle. In 1998, photographs were taken on 18 August, the time of maximum field coverage by fallow vegetation. Aerial photographs were scanned, rectified and registered in a Geographic Information System (GIS) using ArcView®. For the photographs of the bare soil, the red band was normalised by dividing the pixel reflectance in the red band by the total pixel reflectance (sum of the red, green and blue band; Figure 1A). Similarly, for the vegetation photographs, the green band was normalised by dividing the green band pixel reflectance by the total pixel reflectance (Figure 1B). The spatial analyst module in ArcView® was then used to combine and average the information from the normalised images at the plot level. Plot average values were linearly rescaled from 0 to 100 and exported for analysis of variance.

Radiometer measurements

On 24 August 1998, radiometric measurements of the fallow vegetation growing on the former experimental site were taken with a bicycle-wheel mounted radiometer described by Lawrence et al. (2000). The equipment consisted of a light, single wheeled hand cart with an odometer and a sensor composed of a red and an infrared photo-sensitive diode oriented downward and positioned at 1.0 m distance from the soil surface. Electronic circuits read the sensor data and converted them to normalised difference vegetation index (NDVI) values which were sent to a differential GPS-data logger and stored as georeferenced measurements with sub-meter accuracy (Figure 2). The equipment was set to take measurements every 0.9 m on north-south transects, each transect being separated by 2 m. The NDVI measurements were corrected for soil background reflectance (Lawrence et al., 2000) and imported in ArcView® to obtain average NDVI values at the plot level (Table 1).

Soil mechanical resistance

Measurements of the soil mechanical resistance were performed prior to the onset of the last two cropping seasons on 4 May 1995 and 3 May 1996 for 0 – 0.02 m and 0 – 0.05 m soil depths with a hand held penetrometer (Eijkelkamp, The Netherlands) equipped with tips of 35 mm for the upper and 15 mm for the lower depth. In each plot, 20 measurements were made at each depth, averaged at the plot level and analysed with depth as a split-plot factor.

Statistical analysis

The 1995/1996 treatment set-up was taken to analyse CR and P effects on topsoil reflectance. Regression analysis and analysis of variance within GENSTAT release 3.2 (Lawes Agricultural Trust, 1993) was used to study the relationship between the destructively measured HDM and non-destructive NDVI measurements from aerial photographs and the radiometer. The post stratification classification of the field into areas of low and high productivity performed in 1991 (Buerkert et al., 1995) was included in the analyses to examine the duration of differences in initial soil productivity and to test if CR and P treatments had levelled these differences over time.

Results

Residual treatment effects on herbaceous species growth

Residual effects of CR application led to large increase in HDM compared with the unmulched control. Regardless of the type of application, broadcast or aligned, a mulch of 500 kg CR ha^{-1} increased HDM by over 100% (Table 1). The residual mulch effects on HDM only partly reflected those on millet dry matter in the last experimental year of 1996 (Table 1). Beyond 500 kg ha^{-1}, neither the rate nor the type of application appeared to have a large residual effect on HDM, whereas application rates of 1000 or 2000 kg CR ha^{-1} had led to further increases in millet dry matter. Compared with the unfertilised control, residual effects of broadcast SSP application led to a significant but only 14% increase in HDM. This compares to a 48% increase in millet dry matter with broadcast P application. In contrast to the large immediate P placement effects on millet, there were no residual effects of former P placement on HDM (Table 1).

Plant cover estimates

As a residual effect of CR mulch, the cover and specific contribution of species such as *Phyllantus pentandrus* grew with increasing application rate, whereas other species such as *Eragrostis tremula* decreased in cover and others were indifferent (Table 2). Residual effects of P fertiliser treatments were seldom significant.

Mulch and P treatments applied to previous millet influenced the plant cover of some of the weed spe-

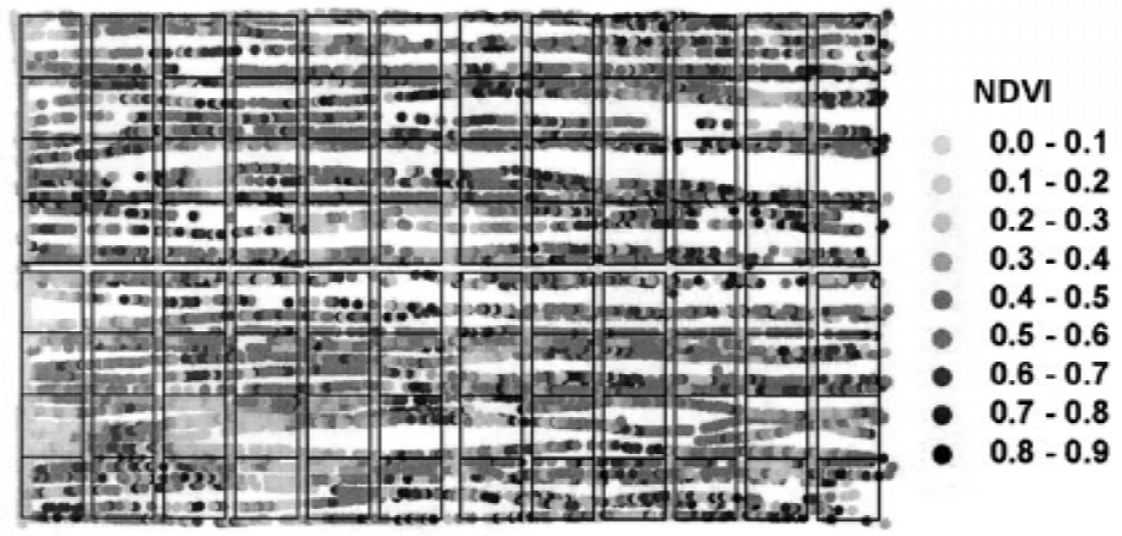

Figure 2. Punctual normalised difference vegetation index (NDVI) map obtained from radiometer measurements of the fallow vegetation on 24 August 1998.

Table 1. Crop residue and phosphorus (P) effects on millet total dry matter (1996) and subsequent residual treatment effects on normalised red band pixel number of the bare soil (18 June 1997), herbaceous dry matter (25 August 1998), visually estimated herb cover, normalised green band pixel number of an aerial photograph (11 August 1998) and on radiometric NDVI measurements (24 August 1998)

	1996	1997	1998			
Treatment ($kg\ ha^{-1}$	Millet total dry matter ($kg\ ha^{-1}$)	Normalised red band of bare soil	Estimated herb cover (%)	Normalised green band of vegetation	NDVI	Herbaceous vegetation dry matter ($kg\ ha^{-1}$)
Crop residues						
0	1907	57.8	7.0	13.9	0.36	728
500 broadcast	3484	25.6	14.0	36.5	0.48	1456
500 aligned	3883	31.5	15.3	41.8	0.48	1454
1000 broadcast	5627	18.6	18.0	56.4	0.54	1598
1000 aligned	5213	19.5	19.6	55.7	0.52	1723
2000 broadcast	4956	20.6	18.9	57.4	0.51	1710
LSD [a]	*603*	*9.0*	*3.8*	*9.9*	*0.06*	*223*
Broadcast P						
0	3365	31.3	14.3	38.6	0.47	1348
13	4992	26.6	16.7	48.6	0.49	1542
LSD	*348*	*5.2*	*2.2*	*5.6*	*0.04*	*129*
Placed P						
0	3499	28.2	13.7	36.5	0.47	1316
3	4265	30.7	16.0	45.5	0.47	1451
5	4485	26.6	17.2	47.8	0.50	1534
7	4465	37.0	14.9	44.7	0.49	1478
LSD	*492*	*9.4*	*3.2*	*8.0*	*0.04*	*183*

[a] Least Significant Difference of means.

Table 2. Residual effects of crop residue mulch and phosphorus applied for 6 years to previous millet on weed species observed in the second year of fallow. Weeds whose relative contribution to total weed cover grew with the intensity of the treatment were named 'increasers', those whose relative contribution declined 'decreasers' and those whose relative contribution remained unaffected 'indifferent' species. Rarely observed species are not listed

Treatment applied at increasing rate	Decreasers	Increasers	Indifferent
Crop residues	*Andropogon gayanus*	*Alysicarpus ovalifolius*	*Cleome viscosa*
	Ctenium elegans		*Hibiscus asper*
	Eragrostis tremula	*Cassia mimosoides*	*Sesamum alatum*
	Fimbristylis hispidula	*Ceratotheca sesamoides*	
	Indigofera strobilifera		
	Merremia tridentata	*Hibiscus sabdariffa*	
	Tephrosia gracilipes	*Indigofera pilosa*	
	Waltteria indica	*Phyllantus pentandrus*	
Phosphorus	*Aristida sieberiana*	*Ceratotheca sesamoides*	*Commelina forskalei*
	Borreria stachydea		*Hibiscus sabdariffa*
	Ctenium elegans	*Cleome viscosa*	
	Merremia tridentata	*Fimbristylis hispidula*	
	Mitracarpus scaber	*Indigofera pilosa*	
	Phyllantus pentandrus	*Merremia pinnata*	
	Walteria indica	*Tephrosia gracilipes*	

Table 3. Residual effects of crop residue mulch (kg ha^{-1}) and phosphorus broadcast at 0 or 13 kg P ha^{-1} and placed at 0 or 3 to 7 kg P ha^{-1} applied to previous millet on the weed species contribution to the total herbaceous cover of the fallow (%). The mean canopy cover (cm^2 m^{-2}) per treatment is also given for each species

Species response	Decreaser		Increaser		Indifferent	
	Walteria indica		*Cassia mimosoides*		*Sesamum alatum*	
Crop residues (kg ha^{-1})	Contribution (%)	Cover (cm^2 m^{-2})	Contribution (%)	Cover (cm^2 m^{-2})	Contribution (%)	Cover (cm^2 m^{-2})
0	13.35	77	6.95	40	0.95	4
500	4.20	55	9.46	144	0.44	6
1000	1.85	33	8.00	140	0.69	13
2000	1.99	37	10.42	183	0.75	13
LSD [a]	*2.21*	*20*	*3.54*	*48*	*0.82*	*10*
Phosphorus (kg ha^{-1})	*Mitracarpus scaber*		*Merremia pinnata*		*Hibiscus sabdariffa*	
0	0.49	6	9.58	130	6.06	83
3–7 placed	0.36	4	7.51	112	5.35	94
13 broadcast	0.24	4	16.42	202	5.91	131
13 + 3–7	0.17	2	10.96	192	6.42	134
LSD	*0.40*	*4*	*4.14*	*60*	*4.28*	*99*

[a] Least Significant Difference of means.

Table 4. Residual effects of crop residue application on the herbaceous cover (%) of five groups of plants classified by size, shape and inclination of their foliage

Leaf size and shape	Linear	Linear	Ovate	Dissected	Ovate
Biological type	Grasses & sedges	Erected dicots	Erected dicots	Erected dicots	Prostrate dicots
Crop residues (kg ha^{-1})					
0	2.1	6.1	50.6	22.4	18.8
500	0.8	3.2	43.7	40.2	12.1
1000	0.6	3.0	40.8	44.2	11.4
2000	0.5	2.1	48.1	39.3	10.1
LSD [a]	*0.8*	*4.4*	*8.0*	*7.4*	*5.0*

[a] Least Significant Difference of means.

cies and their relative contribution to total plant cover (Table 3). Compared with the control treatment, the relative contribution of *Cassia mimosoides* increased with CR application, whereas that of *Merremia pinnata* increased with P application. Reversibly, the contribution of *Walteria indica* and *Mitracarpus scaber* decreased with the rate of CR and P application (Table 2). Erected dicotyledons with medium to large size, ovate or compound and flat leaves such as *Alysicarpus ovalifolius* and *Hibiscus sabdarifa* largely dominated in all plots (Table 4). They were followed in importance by the erected dicotyledons with compound or dissected leaves (*Cassia mimosoides*, *Crotalaria microcarpa*) and by the prostrate dicotyledons (*Phyllantus entandrus*, *Merremia pinnata*, *Jacquemontia tamnifolia*). Linear narrow leaf grasses and dicotyledons contributed less than 10% to the total herbage cover. The relative importance of these three groups of plants decreased with the intensity of the past mulching treatment (Table 4), whereas the group of erected dicots with compound leaves tended to increase its contribution up to a CR rate of 1000 kg ha^{-1}.

Treatment effects on fallow vegetation as detected by aerial photography and radiometry

The normalised green band values from the aerial photograph averaged at the plot level were highly correlated (r = 0.86) with the destructively measured HDM (Figure 3) and the statistical analysis of both types of measurements gave similar results (Table 1). The correlation between NDVI values taken with the radiometer (Figure 2) averaged at the plot level and HDM was low (r = 0.64). The relationship between plot average NDVI and HDM appeared non linear with

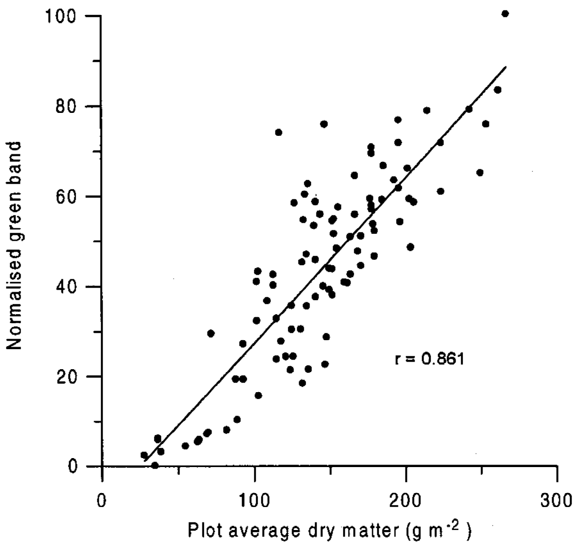

Figure 3. Relationship between normalised green band of the 18 August 1998 aerial photograph and destructively determined herbaceous dry matter (HDM) measured on 26 August 1998. Data points show averages of eight replications at the plot level.

Table 5. Effects of broadcast millet crop residues on soil penetrometer resistance (kN m^{-2}) at 0 – 0.02 and 0 – 0.05 m depth at the end of the dry season in May 1995 and 1996

Residue rate (kg ha^{-1})	Penetrometer resistance (kN m^{-2})				LSD[a]	$P > F$[b]
	0	500	1000	2000		
1995						
0 – 0.02 m	224	118	58	90	*35*	<0.001
0 – 0.05 m	3556	2199	1911	2347	*475*	<0.001
1996						
0 – 0.02 m	246	120	75	78	*46*	<0.001
0 – 0.05 m	3161	1809	1210	1391	*457*	<0.001

[a] Least Significant Difference of means.
[b] Probability of a treatment effect (significance level).

NDVI reaching a plateau at higher HDM values. The analysis of variance of the radiometric measurements showed similar CR and P effects than the analysis of variance of HDM (Table 1).

Treatment effects on soil mechanical resistance

The effects of mulch treatment on the soil penetrometer resistance (Table 5) after 6 yearly applications of CR were highly significant ($p < 0.001$) with a net decrease of the resistance for the plots where CR were applied. For the measurements of 0 – 0.02 m depth, large significant differences in penetrometer resistance were observed between the application of 500 kg and higher rates of CR, but for the 0 – 0.05 m depth, differences were not as pronounced.

Treatment effects on soil surface colour

The analysis of the red band reflectance revealed highly significant CR effects but no SSP effects on soil surface colour. During the dry season (without vegetation cover), the surface soil of unmulched plots and of plots with aligned CR application at 500 kg ha^{-1} was clearly more reddish than that of mulched plots. At higher CR levels, however, the mode of CR application (broadcast *versus* aligned) failed to affect soil surface colour. A weak but highly significant correlation (r = 0.34; $p < 0.001$) of the normalised red band 1997 values and the 1998 HDM was found. The linear regression of the normalised red band (1997) and topsoil penetrometer resistance in 1996 at depth 0 – 0.05 m was similarly weak but significant (r = 0.47; $p < 0.001$).

Discussion

The large residual effects of CR on HDM appear to be in contrast to the results of Rebafka et al. (1994) who reported a rapid decline of CR effects in continuous millet in the first year following the withdrawal of mulch. Even more surprising, however, are the only minor effects of SSP application on HDM given the P deficiency of local soils and the large increases in millet and weed growth with P reported earlier from this experiment (Table 1; Buerkert and Stern, 1995; Buerkert et al., 1997; Muehlig-Versen et al., 1998). These P effects on plant growth reflected increases in P-Bray concentrations from 3.8 (unfertilised control) to 6.3 mg kg^{-1} (after 3 years of broadcast SSP at 13 kg P ha^{-1}) at 0 – 0.2 m depth. It is likely that the residual effects of CR on HDM reflect mulch-induced changes in soil physical properties of the topsoil. These lead to reduced penetrometer resistance at 0 – 0.02 and 0 – 0.05 m depth (Table 5), to an increase in pH by 0.4 units and to improved P availability (Buerkert et al., 2000; Muehlig-Versen et al., 1998). The changes in soil physical conditions with CR application, reflected in the different soil surface colours between formerly mulched and unmulched plots, apparently had a lasting impact on the propagation of weeds and the colonisation by pioneer fallow species. The maintenance of favourable seed reserves for weeds during the cropping years and a subsequent rapid establishment of the herbaceous vegetation at the beginning of the fallow period may have been important causes for the higher HDM in formerly mulched plots. In contrast, unmulched plots were heavily eroded, the soil surface being covered by a crust that was unfavourable for the establishment of herbaceous species.

Mulch treatments also influenced the species composition of the fallow. Mulching favoured prolific erected dicotyledons such as *Phyllantus pentandrus* and *Hibiscus sabdariffa* and erected legumes such as *Alysicarpus ovalifolius* and *Cassia mimosoides*. In contrast, CR application hampered the growth of grasses, small size sedges and of some long cycle annual dicotyledons such as *Walteria indica* and *Tephrosia gracilipes*. Results for P were less clear than for CR but most of the ‘decreasers’ (Dyksterhuis, 1958) with CR were also ‘decreasers’ with P except for *Phyllantus pentandrus*. Similarly, most of the ‘increasers’ with CR were ‘increasers’ with P except for the small sedges *Fimbristylis hispidula* and *Tephrosia gracilipes*. It is likely that this treatment effect on species composition developed during the propagation of weed species and colonisation by pioneer weeds at an early stage through differences in physical topsoil properties. The production of a very large number of small seeds by some of these weeds such as *Phyllantus pentandrus*, *Mitracarpus scaber*, *Fimbristylis hispidula* and the limited radius of most seed dispersion could explain that these initial differences in species composition tended to increase in the second year of fallow.

Only minor differences in plant composition were observed between treatments after species were grouped for size, shape and inclination of their leaves. These traits affect the ratio of leaf area to dry matter (Hanan et al., 1997), and could thus explain some of the unexplained variation in the regressions between normalised green band values or radiometer NDVI and the measured herbage mass.

The stratification of the experiment based on productivity areas of 1991 did not indicate any differences in HDM between former low and high productivity plots. The pattern in spatial variability of plant growth detected prior to the establishment of the trial in 1991 thus appeared to have been effectively masked by the effects of CR and P applied during the 6 experimental years.

The observed residual effects of CR mulch on fallow vegetation following intensive cropping should be confirmed by further studies and the durability of the effects on herbaceous vegetation need to be evaluated under various grazing pressures. The consideration of residual effects of CR and P application on HDM will permit a better assessment of the effects these soil amendments may have on Sahelian production systems as a whole. The non-destructive methods used in this study were efficient to detect treatment effects on herbaceous vegetation and on soil reflectance. Such methods should be used more extensively in the monitoring of Sahelian fallow vegetation as they permit to estimate HDM at the field scale where spatial variability would otherwise require intensive destructive sampling.

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