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CROPS AND SOILS RESEARCH PAPER

Impact of depth of placement of mineral fertilizer micro-dosing on growth, yield and partial nutrient balance in pearl millet cropping system in the Sahel

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SUMMARY

A study was carried out in the rainy seasons of 2008 and 2009 in Niger to investigate the effects of fertilizer micro-dosing on root development, yield and soil nutrient exploitation of pearl millet. Different rates of diammonium phosphate (DAP) were applied to the soil at different depths and it was found that although micro-dosing with DAP increased grain yield over the unfertilized control to a similar level as broadcast DAP, doubling the micro-dosage did not increase it further. Increasing the depth of fertilizer application from 5 to 10 cm resulted in significant increases in root length density, and deep application of fertilizer resulted in higher yields, although the increases were generally not significant. It was postulated that the positive effect of micro-dosing resulted from better exploitation of soil nutrients because of the higher root volume. Levels of nutrients exported from the soil were at least as high in plants receiving micro-dosing as the unfertilized control, and plants receiving micro-dosing exported 5–10 times more phosphorus from the soil than the amount added through fertilization.

INTRODUCTION

The Sudano Sahel can be defined as the region bordered by the 300 and 800 mm/year rain isohyets. Pearl millet (*Pennisetum glaucum* L.) and grain sorghum (*Sorghum bicolor* L., Moench) are the major cereal crops of this region: sorghum is produced mostly on the finer textured soils whereas pearl millet is planted mostly on the coarse-textured soils.

The sandy soils of the Sudano Sahel are inherently very poor in plant nutrients, particularly in phosphorus (P) and nitrogen (N) (Bationo *et al*. 1998). Farmers do not apply fertilizers, mainly because of their high cost and lack of availability, but also because in the semi-arid regions frequent droughts make fertilizer application a risky option (Buerkert *et al*. 2001). This lack of fertilizer use results in negative nutrient balances (Stoorvgel & Smaling 1990).

The soil of the Sudano Sahel is being eroded by wind and water, resulting in massive nutrient loss (Buerkert & Hiernaux 1998). In addition most African soils, particularly the sandy soils of the Sahel, are very poor in organic matter. Marenya & Barrett (2009) demonstrated that degraded soils with low soil organic matter content limit the marginal productivity of mineral fertilizer such that it becomes unprofitable at prevailing prices.

Spot application of fertilizers, so-called 'micro-dosing', was developed at the International Crops Research Institute for the Semi Arid Tropics (ICRISAT) in Niger (Tabo *et al*. 2007). The promoters of this technique expect that poor farmers will be ready to purchase small amounts of fertilizers (0·20–0·30 of the recommended rate) if they will receive the same yield as with the higher amount. Muehlig-Versen *et al*. (2003) demonstrated that micro-dosing of P fertilizers on pearl millet in an acid, sandy soil at a rate of 3–5 kg/ha gave almost the same grain yield and total dry matter as broadcasting P fertilizer at a rate of 15–20 kg/ha, which is the recommended rate in the Sahel (Bationo & Mokwunye 1991). Fertilizer micro-dosing has been adopted by the

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Alliance for a Green Revolution in Africa (AGRA) as a major innovation to benefit 360 000 farmers in the Sahelian region of Africa (Bationo & Waswa 2011).

However, very few, if any, attempts have been made to explain why a small amount of fertilizer given as a micro-dose results in dry matter and grain yield similar to that obtained by the recommended rate of fertilizer applied through broadcasting. The hypothesis that more of those fertilizers spread over the whole field are lost through leaching without reaching the roots than those applied near the plant is only partially true. Millet roots are well spread (horizontally and vertically) over the field (Hafner *et al*. 1993) and should therefore be able to capture broadcast fertilizers. In pearl millet fertilizers, particularly phosphorus, result in marked increases in root biomass production (Bagayoko *et al*. 2000a). Spot application of manure combined with nitrogen–phosphorus–potassium (NPK) fertilizer also significantly increased root development of watermelon under rain-fed conditions in the Sahel (Fatondji *et al*. 2008).

It is therefore reasonable to suggest that a major effect of fertilizer micro-dosing is induction of root proliferation. This, in turn, should result in better exploration of the soil for nutrients, thus explaining the remarkable benefits of micro-dosing. If the benefit of fertilizer micro-dosing is manifested through root proliferation then deep placement of fertilizer should result in higher root development in deeper soil layers and hence in better nutrient exploitation.

Another aspect that is not discussed by the promoters of fertilizer micro-dosing is the fact that the relatively large amount of dry matter that is produced through fertilizer micro-dosing may remove more nutrients from the soil than the amount supplied through fertilizer micro-dosing. In other words, fertilizer micro-dosing could result in nutrient depletion of the soil and eventually in soil impoverishment.

The present study was therefore conducted to: (i) evaluate the effect of mineral fertilizer micro-dosing on root growth; (ii) evaluate the effect of deep placement of fertilizer micro-dose on millet yield and (iii) assess the partial nutrient balance under fertilizer micro-dose technology.

MATERIALS AND METHODS

Experimental site

The experiment was conducted at the Sadoré research station of the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) in Niger (13°15′N and 2°18′E, 240 m a.s.l.). The climate is characterized by a rainy season that occurs between June and September, and a dry season that prevails during the rest of the year. The mean annual rainfall at Sadoré is 560 mm (Sivakumar & Salaam 1999) and average temperature is 29 °C (West *et al*. 1984). The soil is classified as a sandy siliceous isohyperthemic Psammentic Paleustalf in the USDA Soil Taxonomy (Soil Survey Staff 1999). It belongs to the Labucheri type, characterized by a high sand content, low native fertility with low organic matter and low cation exchange capacity that limits nutrient storage and water holding capacity. These soils are generally very strongly to strongly acidic (pH 4·5–5·0), with aluminium comprising a high proportion (0·47) of the exchangeable cations (West *et al*. 1984). Soil water content at field capacity is 0·09–0·10 m^3/m^3 (Klaij & Vachaud 1992).

Experimental design

The trial was conducted in the 2008 and 2009 rainy seasons. The experimental fields had been left fallow for 7 years; soil chemical characteristics of the two fields are presented in Table 1. The micro-dosing treatments used in 2008 were 20 and 40 kg/ha of diammonium phosphate (DAP), corresponding to 2 and 4 g DAP, applied at a depth of 5 and 10 cm in each planting hole, termed a pocket (each pocket occupied 1 m^2), and a control treatment without fertilizer. In 2009, an additional treatment was added: 200 kg DAP/ha broadcast over the plots. The application of 20 kg DAP/ha contains 4 kg P/ha and 3·6 kg N/ha as ammonium. The experiments were arranged in a randomized complete block design with five replications. Individual 7 × 7 m plots were separated by a 1·5 m alley.

Pearl millet seeds (local variety Sadoré) were sown on 19 June 2008 and 13 June 2009 in pockets dug with a hand hoe spaced at 1 × 1 m, giving a density of 10 000 pockets/ha. Millet seedlings were thinned to two plants per pocket 3 weeks after planting and plots were weeded twice in each experimental year with a long-handled hoe known as a *hilaire*.

Data collection and analysis

Rainfall data were recorded by means of a rain gauge located at the experimental site. Soil samples were taken from each plot in 2008 and 2009 at the onset of the experiment at depths of 0–10, 10–20 and 20–

Table 1. *Chemical properties of the soil before planting*

	2008				2009			
	pH-H_2O (1 : 2·5)	OC (g/kg)	Total-N (mg/kg)	P available (mg/kg)	pH-H_2O (1 : 2·5)	OC (%)	Total-N (mg/kg)	P available (mg/kg)
Depth (cm)								
10	5·0	1·8	182	17	5·0	2·3	207	26
	(0·04)	(0·02)	(21·6)	(3·2)	(0·12)	(0·03)	(23·2)	(2·2)
20	5·3	1·2	119	11	5·1	1·4	130	14
	(0·01)	(0·02)	(16·2)	(1·4)	(0·04)	(0·01)	(9·4)	(3·9)
40	5·2	0·8	96	3·3	5·1	1·0	92	4
	(0·03)	(0·01)	(8·2)	(0·36)	(0·07)	(0·00)	(7·3)	(1·8)
60	5·1	0·8	102	3·5	5·0	0·7	84	2·1
	(0·05)	(0·01)	(8·8)	(0·27)	(0·07)	(0·01)	(7·4)	(0·18)

H_2O, water; OC, organic carbon; N, nitrogen; P, phosphorus.
Numbers in brackets indicate standard error.

40 m. Each sample was analysed for pH (measured using distilled water) (ammonium acetate (NH_4AcO) at pH 7; soil/water ratio of 1 : 2·5), organic carbon (Walkley & Black 1934) and total N using the Kjeldhal method (Houba *et al*. 1995). Available phosphorus was determined with the Bray1 method using extraction with a combination of 0·025N hydrochloric acid (HCl) and 0·03N ammonium fluoride (NH_4F), and the colorimetric method of the phosphomolybdate complex, reduced with ascorbic acid (Houba *et al*. 1995).

Root samples were collected on each plant sampling date (26, 65 and 87 days after sowing (DAS) in 2008 and 38, 65 and 87 days after planting in 2009) with a metal frame measuring 20 × 20 × 10 cm from 0 to 20 cm. Below this depth, root samples were collected at 20 cm increments with an aluminium tube of 7·5 cm internal diameter. The sampling depth was measured from the soil surface. The roots were washed and root length was determined by the grid counting method (Newman 1966). A grid size of 2 × 2 cm was used for coarse roots and 1 × 1 cm for fine roots. The coarse roots were counted on a sub-sample of 2 g taken from the main sample. In the case of the fine roots, if the fresh weight of the total sample was >1 g, a sub-sample of 1 g was taken for the count. The samples were cut into small pieces of 1 cm and spread in a dish with a small amount of water. Roots were weighed after oven-drying at 65 °C for 48 h. Root length (R) was calculated using the following formula (Tennant 1975):

$$R = (N \times \text{total root fresh weight})/\text{Root sub} - \text{sample}$$

where N is number of intersections counted. Root length density (RLD) was determined using $RLD = R/V$, where R is root length and V is soil volume of corresponding depth.

Harvest dates were 20 October 2008 and 14 October 2009 and the harvested area was 5 × 5 m. The number of tillers/m^2 and number of heads/m^2 were counted for the plants in 12 planting holes (pockets) randomly selected in each treatment and averaged to obtain the number of tillers or heads/m^2. Thousand grain weight was measured using an electronic balance with an accuracy of 0·001 g. To determine grain yield and dry matter yield, samples of straw and manually threshed millet panicles collected from the harvested area (25 m^2) were oven-dried at 65 °C for 48 h, weighed and expressed in kg/ha. In order to determine nutrient uptake by the millet, whole plants were sampled from five pockets in each treatment. The samples were separated into leaves, stems, glumes and grains and oven-dried at 65 °C for 48 h. Sub-samples of the dried plant material were milled for total N, P and K analysis. Samples were digested with sulphuric acid (H_2SO_4)+salicylic acid+hydrogen peroxide (H_2O_2)+selenium. The quantitative determination for total N was carried out using an auto-Analyser (Pulse Instrumentation Ltd, Saskatoon, Saskatchewan, Canada) using the colorimetric method based on the Bertholet reaction (Houba *et al*. 1995). Total P was determined with the colorimetric method based on the phosphomolybdate complex, reduced with ascorbic acid (Houba *et al*. 1995) and total K was determined with flame emission spectrophotometry. A partial nutrient balance was calculated

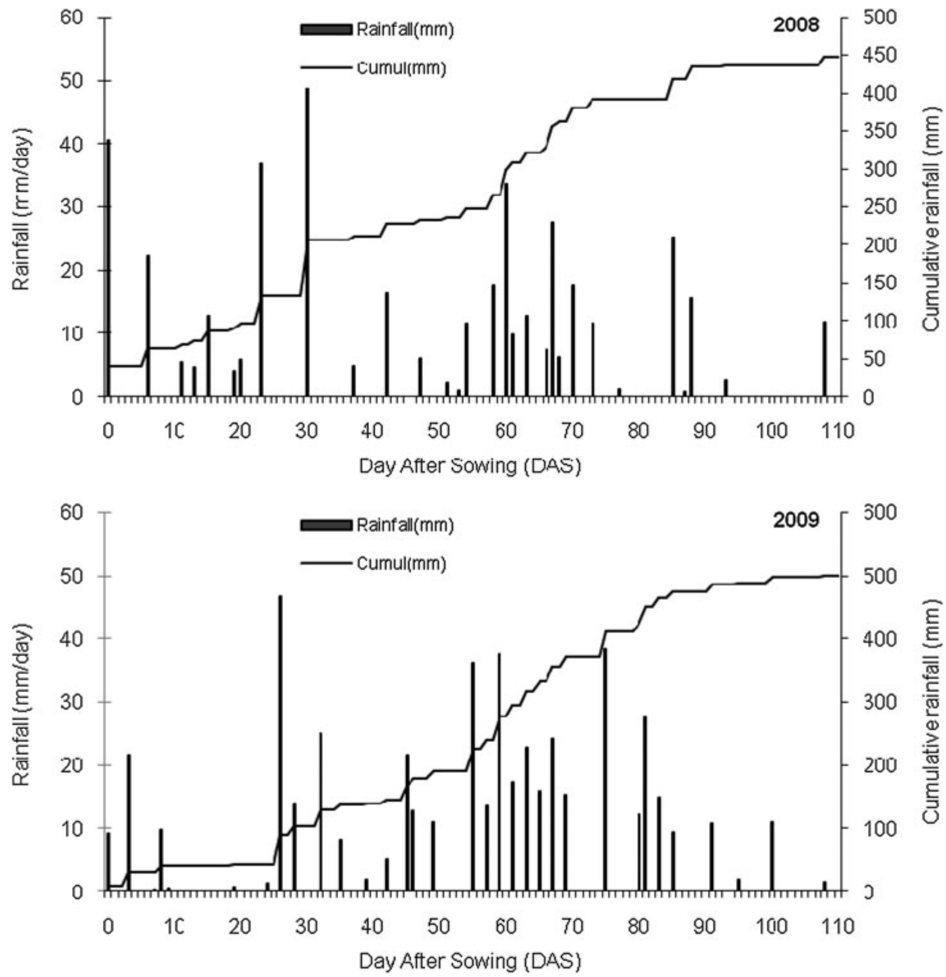

Fig. 1. Accumulation and distribution of rainfall during the experimental period in 2008 and 2009.

by subtracting the amount of N, P or K taken up by the (grain, glumes and straws) from the total amount of N, P or K added through fertilizer.

Statistical analysis

Data collected were subjected to analysis of variance within each year using GENSTAT v. 9 (Lawes Agricultural Trust 2007). Means were compared between treatments by least significant difference (LSD) at $P < 0{\cdot}05$.

RESULTS

Rainfall distribution

Rainfall and cumulative rainfall during the two experimental years are given in Fig. 1. Total rainfall was 450 mm in 2008 and 500 mm in 2009. Rainfall distribution during the growing season was fairly even in 2008 except for a long dry spell towards the end of the season. Rainfall distribution in 2009 was also satisfactory except for a dry spell at the beginning of the growing season.

Characteristics of experimental field

Soil fertility parameters prior to sowing in the two experimental years are presented in Table 1. Soil organic carbon in the two experimental fields was very low, ranging from 2 g/kg at the 10 cm soil layer down to about 0·8 g/kg at the 40 and 60 cm layers. Soil pH was about 5 at all depths in both experimental fields. The 2009 field had a higher initial concentration of P and N as compared with the 2008 field.

Effect of treatments on millet grain yield and yield components

The effect of experimental treatments on grain yield and total dry matter of pearl millet in 2008 and 2009

Table 2. *Effect of treatments on pearl millet grain yield and total dry matter in two consecutive years*

	2008		2009	
Treatments	Grain yield (kg/ha)	Total dry matter (kg/ha)	Grain yield (kg/ha)	Total dry matter (kg/ha)
Control	508 ± 78	2126 ± 263	562 ± 38	2094 ± 87
DAP (20 kg/ha) at10 cm	1097 ± 101	3501 ± 225	1336 ± 127	3876 ± 254
DAP (20 kg/ha) at 5 cm	918 ± 76	3231 ± 192	1091 ± 170	3488 ± 211
DAP (40 kg/ha) at 10 cm	1053 ± 155	3475 ± 296	1225 ± 131	3667 ± 199
DAP (40 kg/ha) at 5 cm	909 ± 85	3298 ± 264	1008 ± 68	3281 ± 213
DAP (200 kg/ha)	–		1127 ± 212	3669 ± 132
P	<0·001	<0·01	<0·001	<0·001
LSD (0·05)	225	776	318	736
CV (%)	19·5	18·4	23·2	16·7

Table 3. *Effect of micro-dosing placement and of fertilizer amount on yield parameters in pearl millet*

	2008			2009		
Treatments	No. tillers/m^2	No. heads/m^2	1000 grain weight (g)	No. tillers/m^2	No. heads/m^2	1000 grain weight (g)
Control	4·0 ± 0·41	2·3 ± 0·15	8·5 ± 0·25	6·4 ± 0·28	3·3 ± 0·12	8·7 ± 0·35
DAP (20 kg/ha) at10 cm	6·4 ± 0·38	3·4 ± 0·17	10·8 ± 0·33	9·0 ± 0·35	5·1 ± 0·39	11·7 ± 0·15
DAP (20 kg/ha) at 5 cm	6·1 ± 0·49	3·2 ± 0·14	9·5 ± 0·13	8·6 ± 0·36	4·1 ± 0·59	10·6 ± 0·40
DAP (40 kg/ha) at 10 cm	5·6 ± 0·30	3·3 ± 0·28	9·7 ± 0·21	8·7 ± 0·30	4·3 ± 0·32	10·4 ± 0·38
DAP (40 kg/ha) at 5 cm	5·7 ± 0·49	3·0 ± 0·26	9·3 ± 0·27	7·5 ± 0·58	3·8 ± 0·15	9·7 ± 0·35
DAP (200 kg/ha)	–	–	–	8·4 ± 0·54	3·9 ± 0·13	9·2 ± 0·34
P	<0·05	<0·001	<0·01	<0·01	<0·05	<0·001
LSD (0·05)	1·3	0·4	1·0	1·4	1·1	1·1
CV (%)	17·8	12·2	14·8	12·6	19·7	8·5

is presented in Table 2. The grain yields were higher in 2009 compared with 2008 but there was no significant difference in grain yield between the two fertilizer application depths (5 and 10 cm) in the 2 years. However, grain yield of pearl millet with deeper fertilizer placing tended to be higher than in the shallower placing in all instances, with one case in 2009 being significantly higher (1336 *v.* 1008 kg/ha). In both years fertilizer micro-dosing doubled the grain yield of pearl millet as compared with the non-fertilized control. In 2009, broadcasting of 200 kg DAP/ha did not increase grain yield when compared with micro-dosing. Doubling fertilizer rate had no effect on grain yield. Fertilizer application increased total dry matter production of pearl millet as compared with the unfertilized control but there were no differences in dry matter yield as a result of depth of fertilizer application or of amount of fertilizer. The effects of micro-dosing placement and fertilizer amount on three determinants of grain yield are presented in Table 3. In 2009, fertilizer micro-dosing increased the number of tillers, the number of heads/m^2 and the grain weight of millet as compared with the non-fertilized control. In the same year, fertilizer micro-dosing with 20 kg DAP/ha at 10 cm resulted in higher numbers of tillers (6·4 *v.* 5·7) and of heads/m^2 (5·1 *v.* 3·8) than fertilizer micro-dosing of 40 kg DAP/ha at 5 cm.

Effect of treatment on root length density

There were no significant differences in RLD between the 20 and 40 kg/ha fertilizer treatments. Although some pearl millet roots could be found at a depth of 200 cm, most of the roots were concentrated in the upper 40 cm of the soil profile at all times (Figs 2 and 3). The RLD increased significantly ($P < 0.05$) with millet development in all treatments. At all

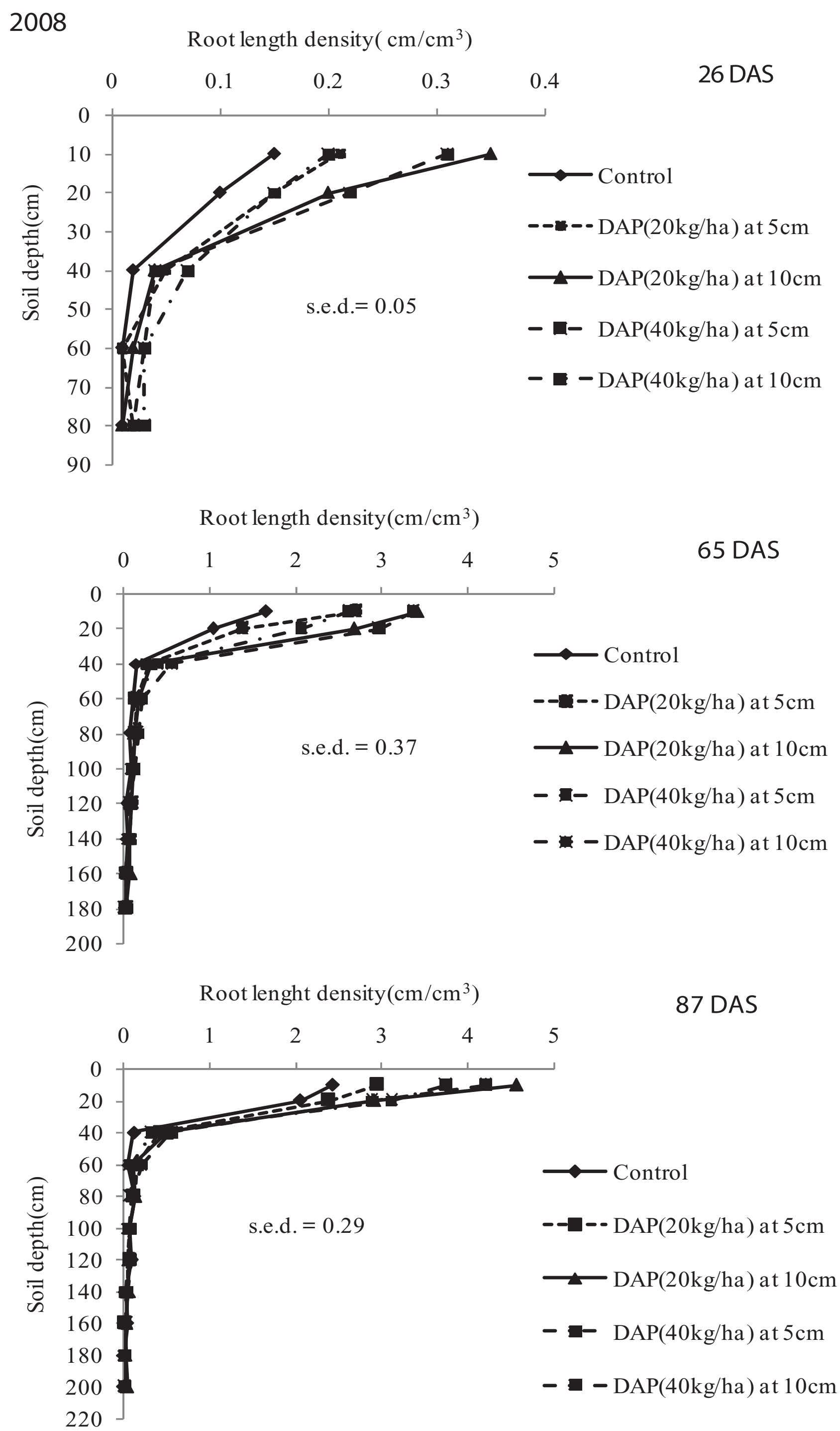

Fig. 2. RLD of pearl millet at 26, 67 and 87 DAS in 2008 rainy season. DAP, diammonium phosphate.

sample dates, RLD of the fertilizer micro-dosing treatments and of the broadcast fertilizer were significantly ($P < 0{\cdot}05$) higher than that of the non-fertilized control. During the early stages of millet growth (26 and 38 days after planting), RLD in the 10 cm-deep treatment was *c*. 50% greater than the RLD in the 5 cm-deep treatment. The differences between these two treatments diminished with time. In 2009, RLD of plants receiving 200 kg/ha DAP broadcasted was similar to that of the plants receiving fertilizer micro-dosing.

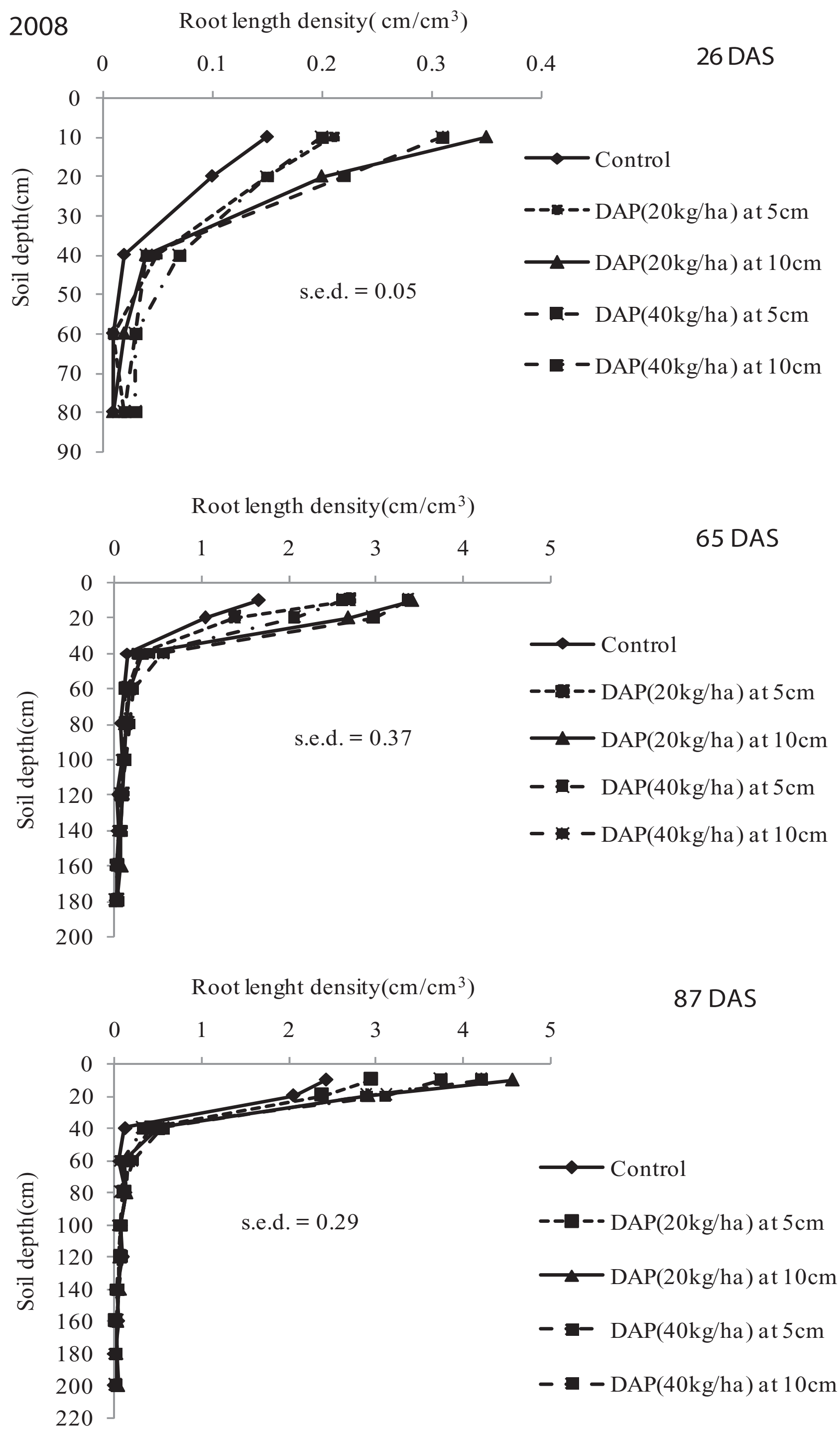

Fig. 3. RLD of pearl millet at 38, 67 and 87 DAS in 2009 rainy season. DAP, diammonium phosphate.

Effect of treatments on nutrient uptake

Table 4 gives the partial balance of N, P and K when micro-dosing and fertilizer broadcasting were applied. These values were achieved by subtracting the amount of nutrients in the pearl millet (grain, glumes and straws) from the amount of nutrients (N and P) given to the field in the form of DAP. In 2009, less K and more P and N were extracted from the soil as compared with 2008. In 2009 the amount of P extracted by the control plants that did not receive fertilizer was 19 kg/ha. The average amount of P extracted from the soil in the four micro-dosing

Table 4. *Effect of fertilizer micro-dosing on N, P and K partial nutrients balance* (±*standard error*)

Treatments	2008 N	2008 P	2008 K	2009 N	2009 P	2009 K
Control	−8 ± 1·0	−2 ± 0·3	−12 ± 3·4	−35 ± 2·3	−11 ± 0·8	−75 ± 2·2
DAP (20 kg/ha) at10 cm	−15 ± 1·8	−1 ± 0·1	−25 ± 6·3	−65 ± 7·4	−17 ± 1·4	−115 ± 9·3
DAP (20 kg/ha) at 5 cm	−13 ± 3·4	−2 ± 0·8	−21 ± 2·3	−56 ± 9·3	−14 ± 2·3	−105 ± 8·7
DAP (40 kg/ha) at 10 cm	−13 ± 2·3	3 ± 0·4	−24 ± 4·1	−64 ± 8·4	−11 ± 4·2	−115 ± 11·3
DAP (40 kg/ha) at 5 cm	−11 ± 3·3	3 ± 0·9	−22 ± 3·2	−42 ± 2·4	−9 ± 1·9	−95 ± 9·4
DAP (200 kg/ha)	–	–	–	−16 ± 4·2	24 ± 2·4	−114 ± 8·4
P	NS	<0·001	<0·05	<0·001	<0·001	<0·05
LSD (0·05)	7·0	2·3	7·3	19·8	6·2	24·6
CV (%)	19	27·6	26·4	32·4	34·2	18·1

NS, not significant.

treatments was 27·5 kg/ha, i.e. 45% more than in the control. Similarly, the micro-dosed plants extracted 65% more N from the soil compared with the non-fertilized control. In 2008 the situation was similar but less striking than in 2009. In the plots receiving 200 kg DAP/ha via broadcasting, more phosphorus was left in the soil than was taken by the plants.

DISCUSSION

The present study was undertaken to evaluate the effect of placement of fertilizer micro-dosing on root development and on yield of pearl millet and to assess the partial nutrient balance under fertilizer micro-dosing technology. The results showed that micro-dosing with DAP results in significant growth and proliferation of pearl millet roots, especially when fertilizer was placed at a depth of 10 cm compared with the common placement depth of 5 cm. Proliferation of pearl millet roots under fertilizer micro-dosing can be explained by the low level of P in the soil. Bagayoko *et al*. (2000*b*) demonstrated that application of P to severely P-deficient soils in West Africa resulted in large increases in early root growth, a pre-requisite for early mycorrhizal infection and later for the significant contribution of vesicular arbuscular mycorrhizae to enhanced plant growth and nutrient uptake. This is probably what has happened in the present study. The increase in root growth observed in the present study with deep placement of mineral fertilizer was in line with the findings reported by Fatondji *et al*. (2008), who showed that the deep placement of soil amendments markedly increased watermelon root development in deeper soil layers.

Fertilizer micro-dosing with DAP (2 g/m^2) at 10 cm resulted in higher numbers of tillers and of heads/m^2 than fertilizer micro-dosing applied at 5 cm. This could explain the higher grain yield obtained for the 10 cm-deep treatment. Grain yields recorded in 2009 were higher than those obtained in 2008, which could be attributed to the relatively higher levels of available P and total N in the soil, as well as to higher rainfall and better rainfall distribution in 2009. These findings confirm the results of earlier works that show the importance of soil fertility and water availability for enhancing crop production in Sahelian zones (Bationo & Mokwunye 1991; Bationo *et al*. 1993). In 2009 broadcasting of 200 kg DAP/ha did not increase grain yield compared with micro-dosing. This reinforces the case for fertilizer micro-dosing as a means to save fertilizer for grain millet production (Bagayoko *et al*. 2000*b*, 2011; Buerkert *et al*. 2001; Tabo *et al*. 2007; Aune & Bationo 2008; Twomlow *et al*. 2011). The application of 20 kg DAP/ha in the form of micro-dosing can double the grain yield compared with zero application of fertilizer; however, doubling this rate (from 20 to 40 kg/ha) had no effect on grain yield. Perhaps there were limiting factors (Von Liebig 1940) that prevented expression of the additional fertilizer in terms of yield increase: for example, in the present study, the low level of soil organic carbon could be a major limiting factor restricting millet response to doubling the level of mineral fertilizer. Zingore *et al*. (2008) showed that application of N fertilizer in a soil rich in organic matter increased grain yields of maize significantly; however, application of N fertilizer in a soil poor in organic matter did not have any effect on grain yield. Marenya & Barrett (2009) also demonstrated that soil organic carbon can become a 'limiting factor' for mineral fertilizer application. Bationo *et al.* (1998) showed that fertilizer application to a field receiving manure for 30 years resulted in a 2500 kg/ha millet grain yield. If the same amount of fertilizer was applied to a field that did not receive manure, grain yield was only 900 kg/ha. The results obtained in the present study showed that increasing application of DAP above 20 kg/ha will not apparently be effective without an increase in the organic matter content in the soil.

The high quantity of nutrients taken up by grain, glumes and straw in the various fertilizer micro-dosing treatments shows that the amount of nutrients applied through micro-dosing fertilizer was not sufficient to meet crop needs for biomass production.

Stoorvogel & Smaling (1990) demonstrated that farmers in the Sahel are severely depleting the nutrients stored in the soil because they are not adding fertilizers (the so-called 'soil mining' activity). This leads to land degradation. Table 4 shows that nutrient depletion by plants receiving micro-dosing can be significantly greater than depletion by plants that do not receive fertilizer. In other words, micro-dosing might not be a sustainable technology because it might lead to even more soil degradation than zero fertilizer application. The current results showed that millet response to fertilizer micro-dosing can be improved through deep placement of fertilizer, leading to an increase in root development which results in increased millet yield. In addition, the current work demonstrated that there is a need to identify the limiting factors for fertilizer application in Sahelian soils and to study the long term effects of fertilizer micro-dosing on soil fertility.

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