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DETERMINANTS OF FERTILIZER MICRODOSING-INDUCED YIELD INCREMENT OF PEARL MILLET ON AN ACID SANDY SOIL

By ALI IBRAHIM†‡§, ROBERT CLEMENT ABAIDOO†¶, DOUGBEDJI FATONDJI‡ *and* ANDREWS OPOKU†

†*Department of Crop and Soil Sciences, Kwame Nkrumah Univeristy of Science and Technology, Kumasi, Ghana*, ‡*International Crops Research Institute for the Semi-Arid Tropics, BP: 12404 Niamey, Niger and* ¶*International Institute of Tropical Agriculture (IITA), PMB 5320, Ibadan, Nigeria*

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SUMMARY

Recent studies have reported the benefits of fertilizer microdosing in increasing crop yields in low input cropping systems. Little information is however available on the mechanisms underlying this effect. The objective of this study was therefore to explore the root-based mechanisms governing the growth enhancing phenomena of the fertilizer microdosing technology. A two-year experiment was conducted at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Research Station in Niger. Four treatments comprising (i) 2 g hill^{-1} of diammonuim phosphate (DAP), (ii) 6 g hill^{-1} of compound fertilizer NPK, (iii) broadcasting of 200 kg ha^{-1} of compound fertilizer NPK (recommended rate) and (iv) unfertilized control was arranged in a randomized complete block design with four replications. On average, fertilizer microdosing treatments (2-g DAP hill^{-1} and 6-g NPK hill^{-1}) achieved 86% and 79% of the grain yields recorded from broadcasting of 200-kg NPK ha^{-1}, respectively, in 2013 and 2014. The leaf area index and leaf chlorophyll content significantly increased with fertilizer microdosing at the early stage of millet growth. At the same stage, fertilizer microdosing enhanced the lateral root length density in the topsoil (0–20 cm) by 72% and 40% at respective lateral distances of 25 cm and 50 cm from the centre of the hill compared with broadcast of 200-kg NPK ha^{-1}. Fertilizer microdosing did not significantly change soil pH in the root zone. It is concluded that the positive effect of fertilizer microdosing in increasing millet yield results from the better exploitation of soil nutrients due to early lateral roots proliferation within the topsoil.

INTRODUCTION

Fertilizer microdosing or hill application of mineral fertilizer, a technology originally developed by the International Crops Research Institute for the Semi Arid Tropics, Sahelian Center (ICRISAT-SC) with partners in Germany, reduces the quantity of fertilizer application drastically (Rebafka *et al.*, 1993). This technology comprises the application of a small quantity of mineral fertilizer together with seeds of the target crop in the planting hole at sowing or few weeks after planting (Hayashi *et al.*, 2008;

§Corresponding author. Email: ibramali@myway.com
The research was carried out at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), P.O. Box 12404, Niamey, Niger

ICRISAT, 2009). Fertlizer microdosing relies on smaller quantities of placed mineral fertilizers targeting in priority the most limiting element, i.e. phosphorus (P) (Buerkert *et al.*, 2001).

Recent studies in Niger have shown that fertilizer microdosing results in a positive economic return to the use of fertilizer and improves fertilizer use efficiency (Tabo *et al.*, 2007). An earlier study by Muehlig-Versen *et al.* (2003) on phosphorus placement on an acid sandy soil in Niger has demonstrated that hill application of 3, 5 and 7-kg P ha^{-1} led to 72%, 81% and 88% of grain yield, respectively, produced by broadcasting 13-kg P ha^{-1}, which is the recommended rate in Niger (Bationo and Mokwunye, 1991; Buerkert *et al.*, 2001). In Mali, results based on a three-year study using small amount of diammonuim phosphate (DAP) (3 to 10 kg ha^{-1}) showed that grain yields increased by 42% and 55% for sorghum and millet, respectively (Aune and Bationo, 2008). Based on the positive effects of this technology in improving crop yields and contributing food security of smallholder farmers in West Africa, fertilizer microdosing has been considered as a pathway to Africa's Green Revolution (Twomlow *et al.*, 2010). This technology has therefore been described by Alliance for a Green Revolution in Africa (AGRA) as a major innovation to benefit number of smallholder farmers in the Sahelian region of Africa (Bationo and Waswa, 2011).

Although field studies have consistently confirmed the benefits of fertilizer microdosing in increasing crop yields in low input farming systems, there is little information that elucidates the mechanisms underlying this effect. Elsewhere, a study on a calcareous soil (pH = 8.1) of China demonstrated that localized application of phosphorus and ammonium improves growth of maize seedling by stimulating root proliferation and rhizosphere acidification (Jing *et al.*, 2010). However, the earlier work on phosphorus placement reported by Buerkert *et al.* (2001) and Rebafka *et al.* (1993), which led to the fertilizer microdosing recommendation, was conducted on an acid sandy soils (pH – KCl = 4.1–4.5), and no studies have so far been published to better understand the possible response of crop root growth dynamics to the localized application of small amount of mineral fertilizer. The objective of the current study was therefore to explore the root-based mechanisms governing the growth enhancing phenomena of the fertilizer microdosing technology.

MATERIALS AND METHODS

Experimental site description

The experiment was conducted at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) Research Station, Sadoré, Niger (13°15′ N and 2°18′ E). The local climate was characterized by a uni-modal rainy season that occurred between June and September. The long-term (1983–2014) annual rainfall at Sadoré was 551 ± 110 mm (±standard deviation (SD)). The average temperature of the locality was 29 °C (ICRISAT climate data 2014, unpublished data). The soil was classified as a Psammentic Paleustalf and isohyperthermic in the USDA Soil Taxonomy and as a Luvic Arenosol by the FAO system (West *et al.*, 1984). The experimental soil was sandy with low soil organic carbon ranging from 0.26% at 10-cm to 0.19% at

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Table 1. Initial soil physical and chemical properties ($n = 16$).

Parameters	Depth (cm)	
	10	20
Soil texture (%)		
Sand	94.6 ± 0.2	94.7 ± 0.2
Silt	2.4 ± 0.1	2.0 ± 0.04
Clay	3.0 ± 0.2	3.3 ± 0.2
Soil chemical properties		
pH – H_2O (1:2.5)	5.4 ± 0.04	5.3 ± 0.01
pH – KCl (1:2.5)	4.6 ± 0.02	4.2 ± 0.04
Total N (mg kg^{-1})	231.2 ± 8.1	159.4 ± 5.2
P – Bray 1 method (mg kg^{-1})	3.33 ± 0.2	2.41 ± 0.1
Organic carbon (%)	0.26 ± 0.01	0.19 ± 0.04
Exchangeable bases ($cmol_c$ kg^{-1})	2.1 ± 0.1	1.72 ± 0.1
H^+ ($cmol_c$ kg^{-1})	0.04 ± 0.02	0.06 ± 0.01
Al^{3+} ($cmol_c$ kg^{-1})	0.01	0.22 ± 0.01

±Standard error of mean values.

20-cm soil depth (Table 1). The nitrogen and available phosphorus contents were very low and decreased with depth. The available phosphorus content was lower than the critical level (8 mg kg^{-1}) required to achieve 90% of maximum millet yield in the sandy soils of Niger (Manu *et al.*, 1991). Soil pH-H_2O was about 5, indicating a risk of aluminium (Al) toxicity. The exchangeable aluminium content at 10-cm soil depth was 0.4 $cmol_c$ kg^{-1} (Table 1).

Experimental design and crop management

The trial was conducted during the 2013 and 2014 rainy seasons in a randomized complete block design with four replications. Four treatments were used in the current study as follows: (i) application of DAP fertilizer (18-46-0; 2 g of fertilizer per hill), (ii) application of NPK fertilizer (15-15-15; 6 g of fertilizer per hill). These are the current fertilizer microdosing rates recommended in the study area (Tabo *et al.*, 2007). The rates of DAP and NPK were calculated to supply an equivalent quantity of phosphorus per hill (0.4-g P $hill^{-1}$), which is the most limiting element in the study area. (iii) Broadcasting of 200 kg ha^{-1} of compound fertilizer NPK (15-15-15), which is the blanket recommended rate of fertilizer in the study area (Hayashi *et al.*, 2008) and (iv) control (no fertilizer application). It is worthy to note that the same plots were used for the treatments during each year. Individual 5 × 6-m plots were separated by a 1-m alley, and seeds of improved pearl millet variety ICMV 89305 (95 to 100 maturity days) were sown at 1 × 1-m spacing (10,000 hills ha^{-1}). Millet stands were thinned to three plants per hill at three weeks after planting with subsequent three weeding events during the cropping period. Millet panicles were harvested on 10 October in 2013 and 15 September in 2014, which coincided with the harvest maturity stage. To determine grain yield and dry matter yield, samples of straw and manually threshed millet panicles were harvested from the central 3 × 4 m of each plot and sun-dried, therewithal weighed and expressed in kg ha^{-1}.

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Soil sampling and analysis of chemical properties

The initial soil samples were taken at the onset of the experiment before the treatments application from each plot at depths of 0–10, 10–20 and 20–40 m. Each sample was analysed for pH-H_2O (soil/water ratio of 1:2.5). Organic carbon was determined according to the Walkley and Black method as described by van Reeuwijk (1993), total nitrogen (N) by the Kjeldhal method (Houba *et al.*, 1995) and available phosphorus by the Bray-1 method (Van Reeuwijk, 1993). Exchangeable bases (Na^+, K^+, Ca^{2+} and Mg^{2+}) were determined by the ammonium acetate (NH_4OAc) solution at pH 7 using the extraction method described by van Reeuwijk (1993). Ions H^+ and Al^{3+} released on exchange by an unbuffered KCl solution was determined using the method described by van Reeuwijk (1993). The particle size distribution was determined using the Robinson method as described by ICRISAT soil and plant laboratory.

Measurements of leaf area and chlorophyll content

Leaf area (LA) was determined using leaf length and width at tillering, stem elongation and flowering stages. At each measurement stage, two pearl millet hills selected randomly were harvested from each plot. The green leaves were taken to the laboratory for leaf length and leaf width measurements, and leaf area was calculated using the formula given by Ma *et al.* (2013) as follows:

$$\text{Leaf area } (LA) = \text{leaf length} \times \text{maximum width} \times k, \quad (1)$$

where k is the shape factor with the value of 0.5 for partially unfolded leaves and 0.75 for completely unfolded leaves.

The leaf area index (LAI) was calculated as the ratio of LA to the plot area sampled. Chlorophyll content of leaves was measured using a Soil-Plant Analyses Development (SPAD)-502 chlorophyll meter (Minolta Corp., Ramsey, NJ, USA) at the same growth stages when LA measurements were made.

Soil moisture monitoring and evapotranpiration (ET) calculation

Daily rainfall data were recorded with a rain gauge located in the experimental field. Soil moisture was monitored weekly with a neutron probe (Didcot Instrument Company Limited, Station Road, Abingdon, Oxon, OX143 LD) through 2-m long access tubes installed in the middle of each plot. The access tubes had 7.5-inch inner diameter. Before the measurements, the neutron probe was calibrated *in situ* using the gravimetric method as described by the manufacturer. Measurements were taken at every 15 cm from 0 to 200-cm depth in all the plots. Evapotranspiration was calculated using the equation giving by Payne (1997) as follows:

$$ET = R - (dS + D), \quad (2)$$

where ET is the evapotanspiration, R is the rainfall, dS is the change in soil water storage in the root zone and D is the root zone drainage. Drainage was determined using the method developed by Klaij and Vachaud (1992). The run-off was neglected in the

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water balance equation used because the slope of the experimental fields was less than 2%, and also due to the sandy structure of the soil. Water use efficiency (WUE) was calculated as the ratio of grain yield or total dry matter (TDM) to evapotranspiration (Hatfield, 2011).

Rhizosphere pH measurements

The rhizosphere soil was collected from the roots sampled at 0–20 cm during tillering, stem elongation and flowering stages for rhizosphere soil pH determination. After carefully removing roots from the soil, most of the soil adhering to root surface was shaken off and the rhizosphere soil was carefully taken from the soil tightly adhering the root surface. pH measurements were done immediately after sampling using a pH meter (Hanna Instruments Ltd, Carrollton, TX, USA).

Root sampling and determination of root length

In 2013, two millet hills were tagged from each plot and roots were collected on each plant sampling date (tillering, stem elongation and flowering stages) with a metal frame measuring 15 × 10 × 10 cm from 0 to 20 cm directly under the hill. Roots were subsequently collected at 20-cm depth increment with an access tube of 7.5-cm inner diameter following the first sampling depth of 0–20 cm. All root samples were washed, and debris and died roots were removed. The root length was calculated by determining root intersections (N) using the line intersection method (Tennant, 1975). A grid size of 2 × 2 cm was used for coarse roots and a grid size of 1 × 1 cm for fine roots. Coarse roots were counted on a sub-sample of 2 g taken from the main root sample. For fine roots, if the fresh weight of the total sample was more than 1 g, a sub-sample weight of 1 g was taken for the count. Samples were cut into small pieces of 1 cm and spread in the dish with a small amount of water. Root length was calculated using the following formula:

$$R = \frac{N \times \text{total root fresh weight}}{\text{Root weight of sub-sample}}, \tag{3}$$

where N is the number of intersections counted. Root length density (RLD) was determined by the following formula $\text{RLD} = R/V$, where R is root length and V is soil volume of the corresponding depth.

In 2014, roots were sampled at three positions: directly under the hill and at two lateral distances (25 and 50 cm) relative to the hill in four directions. After washing and removing the dead roots and debris, all root samples collected were scanned with 200-dpi resolution. Root images were analysed using WinRhizo Pro software (Regent Instruments Canada Inc.) to calculate root length, and then RLD was calculated from the root length and the soil core volume.

Statistical analysis

Prior to analysis, the data were checked for normality using residual plots in GENSTAT v.9 (Trust, 2007). RLD data were square root transformed before analysis

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Table 2. Millet grain yields and total dry matter.

	Grain yields (kg ha^{-1})		Total dry matter (kg ha^{-1})	
	2013	2014	2013	2014
Broadcast 200-kg NPK ha^{-1}	812 ± 57	1243 ± 79	3290 ± 166	4204 ± 343
2-g DAP hill^{-1}	780 ± 24	1039 ± 74	3216 ± 157	3750 ± 301
6-g NPK hill^{-1}	611 ± 46	921 ± 139	3030 ± 176	3306 ± 293
Control	402 ± 18	618 ± 115	1605 ± 171	2667 ± 301
	F.pr			
Year	<0.001		<0.001	
Treatments	<0.001		<0.001	
Year × treatments	0.157		0.053	
	Least significant difference (LSD) (0.05)			
Year	70		209	
Treatments	99		296	
Year × treatments	140		418	

±Standard error of mean values.
F.pr = F probabilities.

of variance to ensure normal distribution of residuals. However, the untransformed data were presented in the manuscript. All the data collected were subjected to analysis of variance in GENSTAT v.9 using a general treatment structure (in randomized blocks). Model of ANOVA included treatments, year and their interactions. Mean values were compared between treatments using the least significant difference (LSD) method at a 5% probability level.

RESULTS

Rainfall distribution during the cropping periods

The rainfall distribution during the cropping period in 2013 and 2014 is illustrated in Figure 1. The total rainfall recorded during 2013 cropping period was 481 mm, which was less than the long-term (1983–2014) rainfall average of 551 mm yr^{-1} at the experimental site (ICRISAT, climate database). Most of the rain events occurred in August (from 40 to 65 days after sowing), which accounted for 75% of the the total rainfall recorded during the 2013 cropping period. There was a dry spell of 27 days in September–October 2013, which coincided with the flowering and grain filling stages. In 2014, rainfall was evenly distributed with 689 mm recorded through the cropping period in comparison to 2013.

Grain and total dry matter yields

Grain yields were significantly affected by the treatments and the cropping year (Table 2). However, no significant year by treatments interaction was found. Grain yields were significantly higher in 2014 in comparison with the 2013 cropping season. The highest grain yields (812 ± 57 kg ha^{-1} and 1243 ± 79 kg ha^{-1}, respectively, in 2013 and 2014) were recorded for broadcasting of 200-kg NPK ha^{-1} (Table 2). However, these grain yields were not significantly different from the 2-g DAP hill^{-1} treatment

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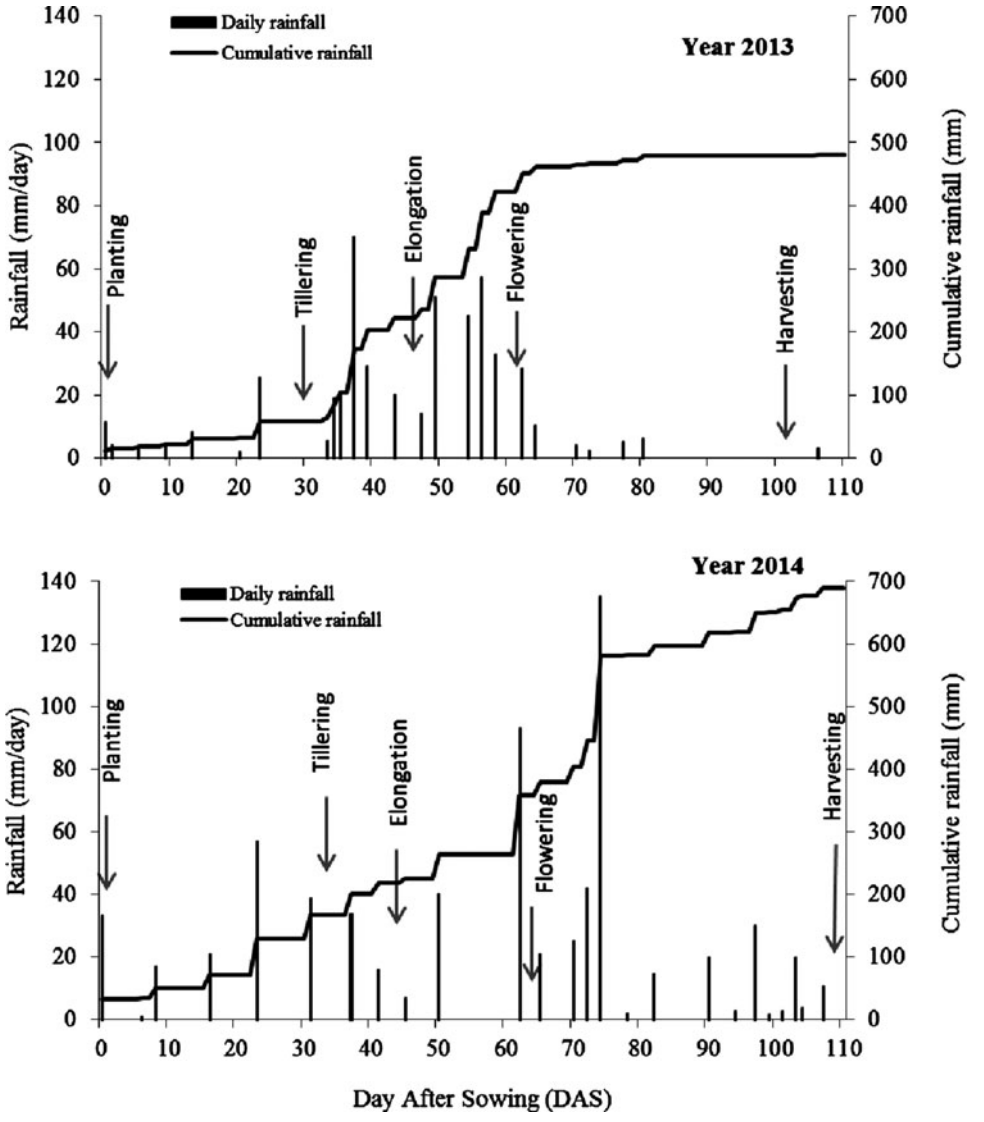

Figure 1. Rainfall distribution in 2013 (upper panel), and 2014 (lower panel).

(780 ± 24 and 1039 ± 74 kg ha^{-1} in 2013 and 2014, respectively). On average, both fertilizer microdosing treatments (2-g DAP hill^{-1} and 6-g NPK hill^{-1}) achieved 86% and 79% of grain yields recorded from broadcasting of 200-kg NPK ha^{-1} in 2013 and 2014, respectively. The lowest grain yields (402 ± 18 kg ha^{-1} and 618 ± 115 kg ha^{-1} in 2013 and 2014, respectively) were obtained from the unfertilized control plots. Similarly, the TDM production was significantly affected by the treatments and cropping year (Table 2). However, no year by treatments interaction in TDM were detected. The TDM yields recorded in both fertilizer microdosing plots accounted for 95% and 84% of those recorded with broadcasting of 200-kg NPK ha^{-1} in 2013

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Table 3. Evapotranspiration (ET) and grain water use efficiency (WUE).

	Evapotranspiration (mm)		Grain WUE (mm kg^{-1})	
	2013	2014	2013	2014
Broadcast 200-kg NPK ha^{-1}	291 ± 27	304 ± 9	2.8 ± 0.2	4.1 ± 0.2
2-g DAP hill^{-1}	267 ± 17	292 ± 8	2.9 ± 0.1	3.6 ± 0.3
6-g NPK hill^{-1}	263 ± 15	292 ± 6	2.3 ± 0.1	3.2 ± 0.4
Control	276 ± 24	293 ± 9	1.5 ± 0.1	2.1 ± 0.5
	F.pr			
Year	0.046		<0.001	
Treatments	0.460		<0.001	
Year × treatments	0.917		0.525	
	LSD (0.05)			
Year	20		0.6	
Treatments	29		0.8	
Year × treatments	40		1.2	

±Standard error of mean values.
F.pr = F probabilities.

and 2014, respectively. The unfertilized control treatment produced the lowest TDM yield.

Evapotranspiration and grain yield water use efficiency

Evapotranspiration and water use efficiency in grain are presented in Table 3. Evapotranspiration was significantly higher during 2014 cropping season compared with 2013 cropping season. There was however no significant differences in evapotranspiration among the treatments. Water use efficiency in grain was significantly affected by the treaments. Broadcasting of 200-kg NPK ha^{-1} and microdosing of 2-g DAP hill^{-1} were more efficient in using water than other treatments. In fact, the plots receiving fertilizer microdosing treatments recorded 93% and 83% of water use efficiency in grain yields achieved by broadcasting of 200-kg NPK ha^{-1} plots in 2013 and 2014, respectively. There were no significant year-by-treatment interactions in grain water use efficiency (Table 3).

Effect of fertilizer application methods on millet growth parameters

Leaf chlorophyll concentration was significantly different among the treatments at different millet growing stages (Table 4). Chlorophyll concentration was highest with the microdosing treatment (2-g DAP hill^{-1}) at tillering and stem elongation stages with 32 and 36 SPAD units and 33 and 44 SPAD units in 2013 and 2014, respectively. However, there was no significant difference in leaf chlorophyll concentration at tillering between treatment receiving the broadcast of 200-kg NPK ha^{-1} and the fertilizer microdosing treatments. At the stem elongation and flowering stages, application of 6-g NPK hill^{-1} had significantly lower leaf chlorophyll content than those of the broadcasting of 200-kg NPK ha^{-1} and 2-g DAP hill^{-1} treatments.

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Table 4. Chlorophyll concentration (SPAD reading with a chlorophyll meter) at different developmental stages of millet.

	2013			2014		
	Tillering	Elongation	Flowering	Tillering	Elongation	Flowering
Broadcast 200-kg NPK ha^{-1}	$26^{a,b} \pm 1$	$34^{a} \pm 7$	$41^{a} \pm 9$	$28^{b} \pm 1.1$	$40^{a} \pm 0.5$	$52^{a} \pm 4.5$
2-g DAP hill^{-1}	$32^{a} \pm 4$	$36^{a} \pm 6$	$39^{a} \pm 7$	$33^{a} \pm 1.4$	$44^{a} \pm 1.4$	$57^{a} \pm 2.9$
6-g NPK hill^{-1}	$27^{a,b} \pm 2$	$33^{b} \pm 9$	$36^{a} \pm 5$	$30^{a} \pm 1.2$	$36^{b} \pm 1.7$	$46^{b} \pm 1.4$
Control	$22^{b} \pm 1$	$24^{c} \pm 6$	$24^{b} \pm 4$	$25^{b} \pm 2.2$	$33^{b} \pm 2.7$	$42^{b} \pm 0.6$
F.pr	0.043	<0.001	0.004	0.039	0.043	0.035
LSD (0.05)	6.4	2	6.5	4.2	6.9	9
CV (%)	12	13.2	9.2	6.4	9	9

±Standard error of mean values.
Mean values within a column followed with the same letters are not significantly different at $p < 0.05$.
F.pr = F probabilities.

Table 5. Rhizosphere pH at different developmental stages of millet.

	Developmental stages		
Treatments	Tillering	Elongation	Flowering
200-kg NPK ha^{-1} broadcast	5.4 ± 0.1	5.1 ± 0.1	5.0 ± 0.1
2-g DAP hill^{-1}	5.6 ± 0.1	5.2 ± 0.1	5.1 ± 0.04
6-g NPK hill^{-1}	5.5 ± 0.1	5.2 ± 0.03	5.2 ± 0.01
Control	5.4 ± 0.1	5.4 ± 0.01	5.3 ± 0.1
F.pr	0.509	0.186	0.065
LSD (0.05)	0.4	0.3	0.2
CV (%)	13.9	12.6	12.3

±Standard error of mean values.
F.pr = F probabilities.

During flowering stage, the highest chlorophyll concentration (41 SPAD units) was obtained from the broadcast of 200-kg NPK ha^{-1} in 2013. Variation in LAI (Figure 2) followed the same trend as that of the chlorophyll concentration. The LAI was significantly different among the treatments and peaked at flowering stage with the highest value of 1.4 and 1.8 recorded from broadcast of 200-kg NPK ha^{-1} treatment in 2013 and 2014, respectively. However, these values were not significantly different from those of 2-g DAP hill^{-1}.

Effect of fertilizer application methods on rhizosphere pH

There was a rapid change in rhizosphere pH at tillering stage with fertilizer microdosing treatments compared with the broadcast of 200-kg NPK ha^{-1} (Table 5). However, at flowering growth stage, a decrease in rhizosphere pH by 0.4 units was recorded for broadcast of 200-kg NPK ha^{-1} in comparison with the rhizosphere pH level at tillering stage. This decrease in rhizosphere pH was less marked with the fertilizer microdosing (6-g NPK hill^{-1}) and control treatments.

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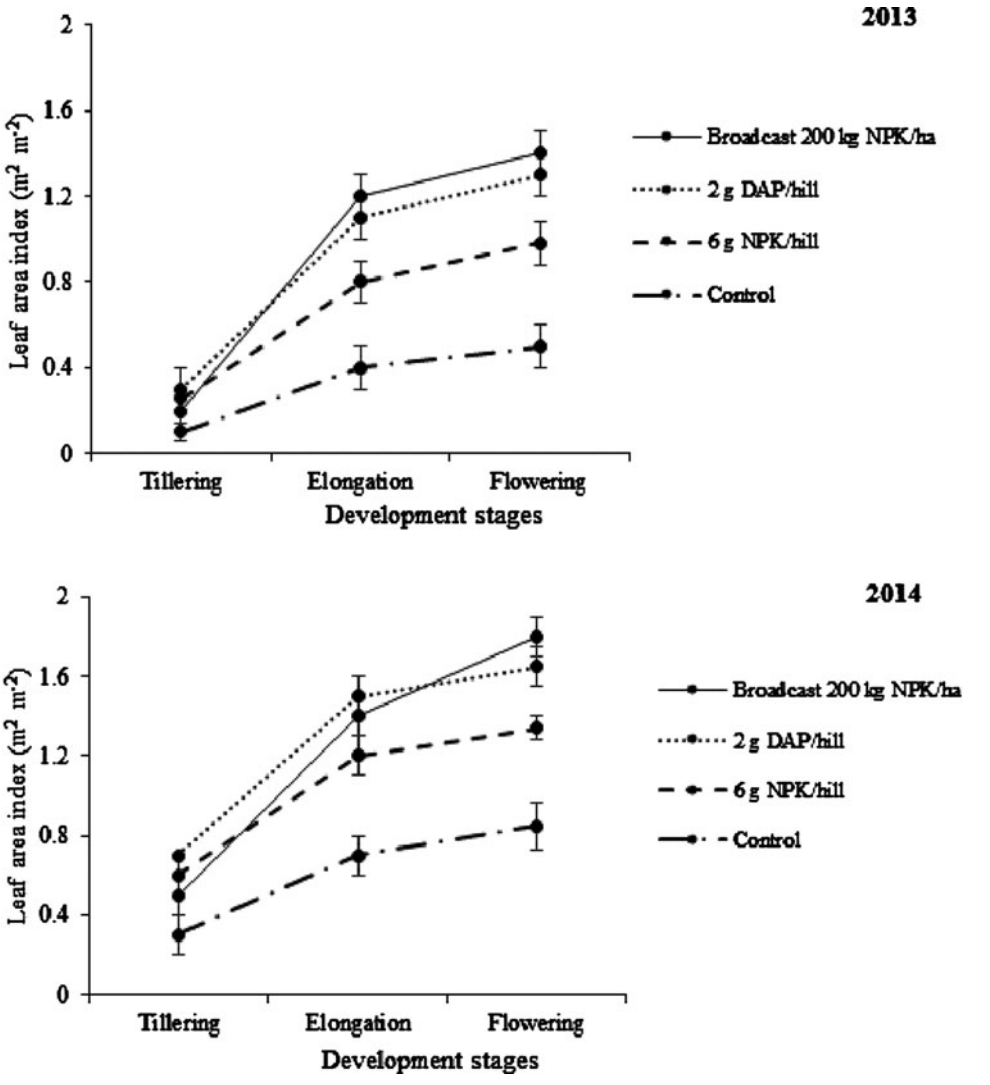

Figure 2. Leaf area index (LAI) at different developmental stages of millet; vertical bars denote standard error of mean values.

Root length density dynamics in response to fertilizer placement

Nutrient addition improved root growth at all the stages of millet development (Figure 3). At tillering stage, topsoil (0–20 cm) RLD of millet was higher in the fertilizer microdosing treatments, while in deeper soil layers, RLD was highest for broadcasting of 200-kg NPK ha^{-1} plots. However, at node formation this gap was narrowed for broadcasting of 200-kg NPK ha^{-1}. Nevertheless, at flowering stage, microdosing with 2-g DAP $hill^{-1}$ and broadcasting of 200-kg NPK ha^{-1} resulted in similarly higher RLD in the topsoil (0–20 cm), while at deeper soil layers, RLD was still higher for the broadcasting of 200-kg NPK ha^{-1}. Lateral RLD in the topsoil (0–20 cm) was

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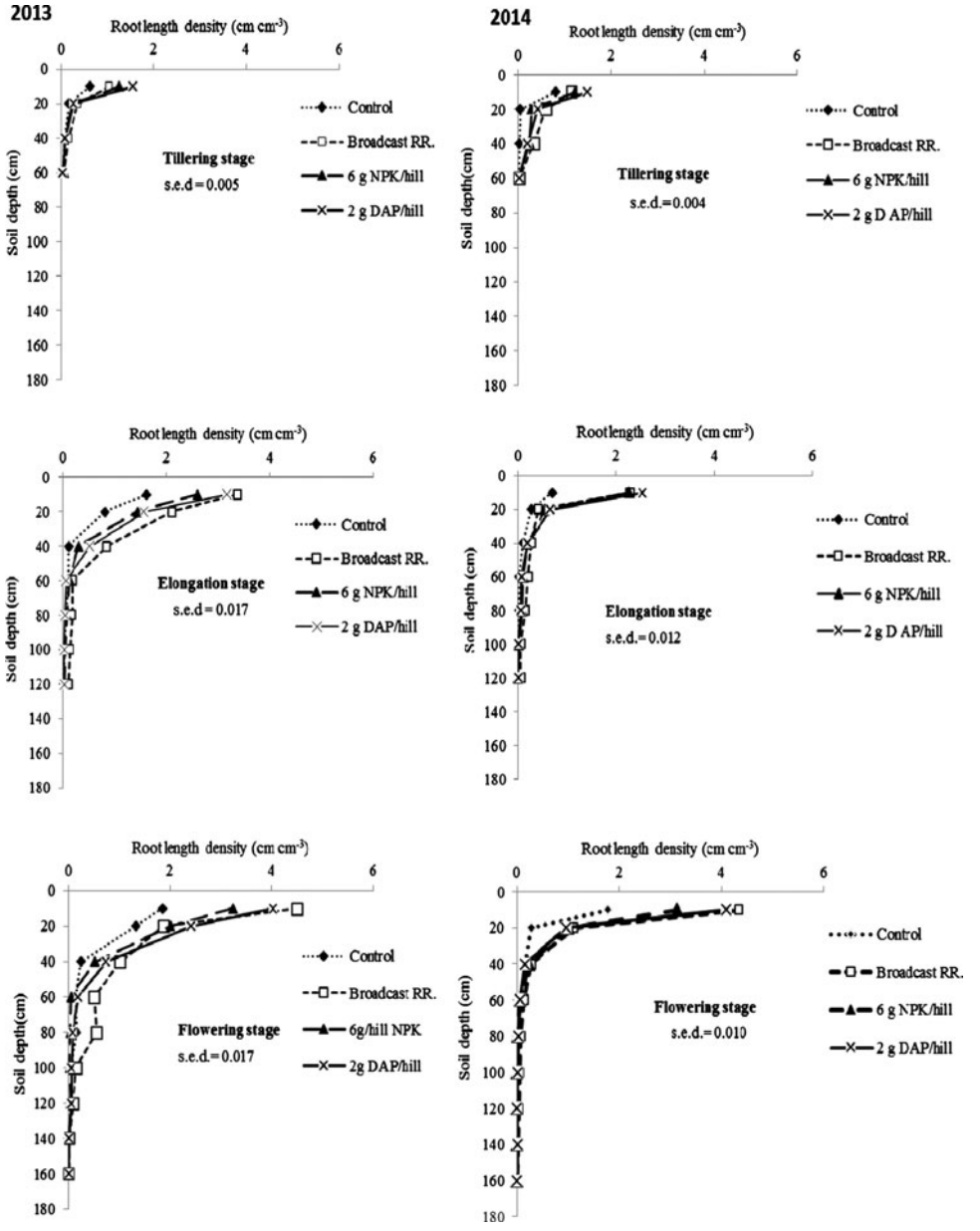

Figure 3. Root length density of hill-planted pearl millet at different soil depths and growth stages; s.e.d: standard error of difference of mean values.

significantly increased by 72% and 40% with fertilizer microdosing treatments at the lateral distances of 25 and 50 cm, respectively, from the centre of the hill compared with broadcast of 200-kg NPK ha^{-1} (Figure 4). In all treatments, overall RLD decreased with increasing soil depth. However, this decrease in RLD was less drastic in broadcast

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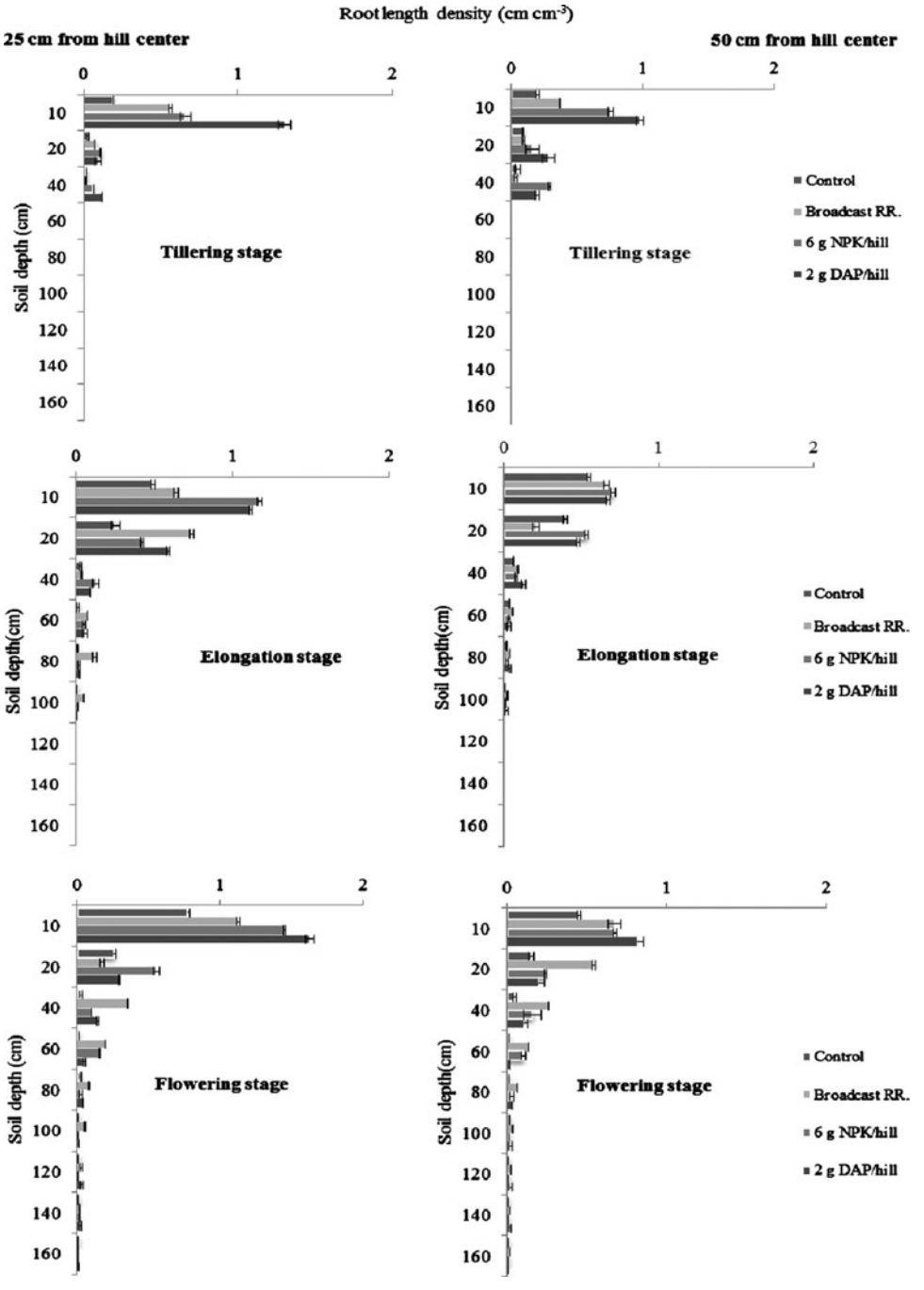

Figure 4. Root length density of pearl millet in 2014 at 25- and 50-cm lateral distances from the hill. Error bars denote standard error of mean values.

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of 200-kg NPK ha^{-1} than in fertilizer microdosing treatments where the roots were mostly concentrated in nutrient-rich patches.

DISCUSSION

The increase in millet yields observed in this study was in line with the results of other recent studies on fertilizer microdosing in West Africa (Hayashi *et al.*, 2008; Ibrahim *et al.*, 2014; Tabo *et al.*, 2011). The response of pearl millet to low application rates of mineral fertilizer in Sahelian sandy soils can be explained by the low inherent fertility, which leads to positive responses following any improved soil fertility management practice.

Millet grain yields and TDM production were significantly affected by the cropping seasons. The yields were significantly higher in the 2014 cropping season than the 2013 cropping season (Table 2). Earlier research reported the residual effect of fertilizer, particularly phosphorus fertilizer, in increasing the productivity of subsequent crop in Niger (Bationo *et al.*, 1992). It is, however, unlikely that large differences in yields obtained in the current study could be due to the residual effect of fertilizer because, for instance, with the small quantity of phosphorus applied (4 kg ha^{-1}), a minimal residual effect could be expected. Moreover, no residual effects of phosphorus placement at 5 to 7 kg ha^{-1} were detected in TDM yields, two years after the last addition of SSP to millet plots on Luvic Arenosol in the Sahelian zone of Niger (Gérard *et al.*, 2001). Rather, higher yields obtained in 2014 could be attributed to the larger amount and better distribution of rainfall observed throughout the growing period in 2014 (Figure 1), which translated into higher millet growth and biomass production. The inter-annual yield differences as a result of rainfall variability have been extensively reported in the Sahelian zone (Akponikpé *et al.*, 2008; Ibrahim *et al.*, 2015; Sivakumar and Salaam, 1999).

Millet response to fertilizer microdosing depends on the type of fertilizer applied. In general, increases in yields were higher with DAP than with NPK compound fertilizer (Table 2). The same conclusion was also reached by Bielders and Gérard (2014). It seems possible that the higher grain yield obtained with DAP was due to its ability to increase soil pH in the immediate vicinity of roots, i.e. the rhizosphere upon dissolution (Black *et al.*, 1985; Fan and Mackenzie, 1993). Change in rhizosphere pH at the early stage of crop growth increases soil nutrients' availability such as extractable P, Ca and Mg close to roots zone (Bagayoko *et al.*, 2000). However, this increase in pH with DAP may not persist for longer period (Khasawneh *et al.*, 1980) as the pH drops with the transformation of ammonium to nitrate. The early season (millet tillering stage) increase in rhizophere pH recorded in this study followed by a decrease of pH at flowering stage (0.4 units) cannot be attributed merely to the effect of the type of fertilizer applied since the same situation has been observed in other treatments (Table 5). Decrease in rhizophere pH can be attributed to the poor pH buffering capacity of soil due to low soil organic matter content (Hinsinger *et al.*, 2003), which is the case of this experimental sandy soil characterized by very low soil organic matter (Table 1). There is, however, another plausible explanation related to the leaching of

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ions, such as nitrate, leading to a loss of ionic balance in soil solution (Rengel *et al.*, 2000; Russo *et al.*, 2014; Weligama *et al.*, 2008).

The effect of fertilizer microdosing in improving crop yields has been largely attributed to early crop development (Hafner *et al.*, 1993; Tabo *et al.*, 2007). This is consistent with the finding of the current study that provides an empirical evidence of increase in leaf chlorophyll concentration at tillering stage, leading to an increased production of photosynthates for enhanced leaf area development and biomass production (Table 4 and Figure 2).

There was a significant difference in the water use efficiency of treatments (Table 3). Broadcast of 200-kg NPK ha^{-1} and microdosing of 2-g DAP $hill^{-1}$ were more efficient in using water as a result of the highest yields obtained in these treatments. These results are in close agreement with the earlier studies which reported an increment of millet water use efficiency in response to soil fertility management options in the Sahelian zone due to increase in biomass production (Payne, 1997; Yamoah *et al.*, 2002). Moreover, Viets (1962) explained that since the evapotranspiration is little affected by the management, as was the case in the current study (Table 3), any factor that increases yield will increase water use efficiency. Small differences observed in evapotranspiration among the treatments could be explained by the fact that under dry climatic conditions and sandy soils in Niger, practically all the plant available water (PAW) is used by the crop, and since evapotranspiration losses are largely controlled by meteorological conditions, seasonal evapotranspiration is almost the same whether yields are high or low (Sivakumar and Salaam, 1999).

Rapid root growth and desired architecture development play an important role in nutrients and water acquisition by the plants in low soil fertility and dry environments (Brück *et al.*, 2003; Vadez *et al.*, 2007). RLD in this study was mostly concentrated in the topsoil (0–20 cm) and declined drastically within the lower soil depths. This decrease in RLD can likely be attributed to the progressively lower pH of soil in the experimental field (Table 1), which probably limited root development (Marschner, 1991). In the current study, the millet roots under fertilizer microdosing treatments did not expend energy to penetrate in deeper soil layers to scavenge for nutrients and water as compared with the broadcast of mineral fertilizer (Figure 3). The concentration of millet roots in the topsoil with fertilizer microdosing was in line with the crop response to the localised application of nutrients leading to proliferation of roots in patches with high nutrient concentration (Hodge, 2004). It has been postulated that the reason of fertilizer microdosing inducing higher crop yields was due to the positive effect of this technology in stimulating root growth in deeper soil layers and therefore enhancing crop nutrient and water uptake (Aune and Bationo, 2008). In the sandy soil, such as in this case, with shallow soil depth where most of the nutrients are concentrated in the topsoil, the lateral proliferation of roots within the upper soil layer can be of immense benefit to crops. Increase in lateral RLD at early millet growth with fertilizer microdosing (Figure 4) could subsequently stimulate the uptake of native phosphorus because of the particularly high uptake capacity of young roots for this nutrient (Ma *et al.*, 2013; Smit *et al.*, 2013). This sequence is a plausible explanation for the positive effect of fertilizer microdosing in increasing millet yields on acid sandy soil. However,

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in drought prone areas, the extraction of water accumulated in deeper soil layers is of utmost importance for a crop to cope with the recurrent dry spells throughout the cropping period. The development of a deep rooting system is therefore important for improving further nutrients and water use by the crop. This was not however the case with fertilizer microdosing because the results of water use obtained in this study showed that fertilizer microdosing could not improve plant water use (Table 3). It therefore becomes necessary to supplement fertilizer microdosing with organic amendments to promote rapid and deep root growth. Therefore, further experimental work deserves to be undertaken to establish the potential effects of combined use of fertilizer microdosing and organic amendment on root growth and water use.

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