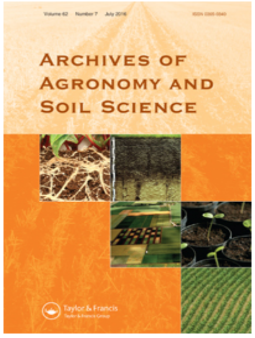

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Archives of Agronomy and Soil Science

ISSN: 0365-0340 (Print) 1476-3567 (Online) Journal homepage: https://www.tandfonline.com/loi/gags20

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ARCHIVES OF AGRONOMY AND SOIL SCIENCE, 2016
VOL. 62, NO. 7, 947–962
http://dx.doi.org/10.1080/03650340.2015.1104414

Improvement in physical quality of a Sahelian Arenosol and implications on millet yield

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ABSTRACT

Poor soil fertility remains a threat to crop production and livelihoods in the Sahel. Understanding the impacts of proposed soil fertility management technologies on soil fertility status and millet yield is essential. We conducted a 2-year experiment to assess changes in selected physical properties of an Arenosol and their impacts on millet yields at Karabedji, Niger. Treatments consisted of four fertilizer rates applied on top and bottom farm types selected from a long-term experiment. Mixed-model analyses indicated considerable effects (P = 0.055) of fertilizer rates and farm types on soil structural stability being higher in the top farm than in the bottom farm type. Dexter's soil physical quality index (*S*) varied significantly with soil depth. A significant correlation (R^2 = 0.24) was found between the aggregate stability index and *S*. Plant available water recorded in fertilizer-treated soil was higher than the control and higher on the top farm than in the bottom farm. Fertilizer rates and farm types influenced millet yields. Moreover, we obtained positive relationships between millet yield and soil aggregate stability, and plant available water, thereby elucidating the significant role played by soil physical properties in influencing crop yields. *S* can be a simple way for assessing the physical quality of Sahelian sandy soil.

ARTICLE HISTORY
Received 26 May 2015
Accepted 2 October 2015

KEYWORDS
Soil physical quality; Psammentic Paleustalfs; semi-arid Africa; soil structural stability index; mixed model analysis

Introduction

Pearl millet is generally produced on highly weathered sandy soils in Niger which are inherently low in fertility – deficient in available phosphorus and in nitrogen contents. The poor fertility status of these soils combined with high variability in rainfall and high temperatures, characteristic of the Sahel region, exacerbate the situation by leading to more serious and frequent droughts responsible for crop failure.

Fertilizer micro-dosing technology was developed in an attempt to increase the affordability of mineral fertilizers while promoting early provision of adequate nutrients for optimal plant growth. The micro-dosing technology consists of applying relatively small quantities of fertilizer (2–6 g hill^{-1}) at sowing time, thus decreasing substantially the recommended amount of fertilizer that subsistence farmers needed to apply per hectare [i.e., from 170 to 20 kg P_2O_5 ha^{-1} in the case of di-ammonium phosphate (DAP)]. The implementation of this technology has resulted in enhanced nutrient use efficiency (Buerkert et al. 2001; Bationo & Kumar 2002; Tabo et al. 2005). Strategically

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targeted fertilizer-use together with organic nutrient resources to increase fertilizer use efficiency and crop productivity at the farm scale are basic principles of Intégrated Soil Fertility Management (ISFM; Vanlauwe & Giller 2006).

The results obtained from long-term experiments have so far helped to understand the long-term impacts of different soil management practices on crop yields and soil chemical properties – especially organic carbon (OC) which decreases with years of cultivation across all management practices in the Sahel (Subbarao et al. 2000; Bationo et al. 2011).

According to Bationo et al. (2011), the results of long-term experiments on soil fertility management in sub-Saharan Africa generally showed decline in organic carbon cutting across the soil fertility management practices with years of cultivation. Also, crop yields and soil fertility decline have been reported in prolonged application of inorganic inputs alone.

An increase in organic matter can significantly improve soil physical quality, thereby increasing nutrient availability and water holding capacities (Bationo et al. 2007). The practices that deplete the organic matter content of the soil (such as continuous cropping without addition of Organic Matter) and tillage are examples of management practices that negatively influence the soil structure (Kay & Munkholm 2004).

The impacts of long-term management practices on soil physical properties on the Sahelian sandy soils have received little attention. Long-term changes in soil physical quality and their associated impacts on phosphorus and water availability, as affected by management, are not known currently.

Dunjana et al. (2012) reported that 7 years addition of cattle manure and inorganic N-fertilizer did not significantly increase the bulk density, macro aggregate stability, and aggregate protected carbon on sandy soils of the Meruwa smallholder farming area of Zimbabwe. However, these parameters were conversely improved on clayey soils. Lal (1997) reported no effect of long-term tillage treatments on bulk density on a tropical Alfisol of Western Nigeria.

Addition of organic manure and crop residue mulch has been reported to improve soil structural stability through their influence on soil organic matter (Blanco-Canqui & Lal 2009). Crop residue mulch protects soil surface against insolation and erosive impacts of raindrops and blowing winds (Blanco-Canqui & Lal 2009).

According to Dexter (2004), the slope of the soil water retention curve (S) at its inflexion point is indicative of the extent to which the soil porosity is concentrated into the narrow range of pore size. In most soils, larger values of S are consistent with the presence of a well-defined micro-structure. However, some limitations related to the appropriateness of the critical S values have been reported (Garba et al. 2011; Moncada et al. 2015) for some soils.

Understanding the inter-related physico-chemical and hydrological processes affecting pearl millet growth in the Sahel could help in explaining the frequently observed fluctuation and in better prediction of crop yields. This could contribute to the knowledge of soil fertility implications of each management practice over long term and will help in identifying the most sustainable management practices suitable to local conditions.

It was, therefore, hypothesized that on the highly weathered Sahelian Arenosol, soil fertility degradation processes are driven by changes in soil physical quality, such as structural stability, water retention characteristics, and organic carbon content, all of which affect water and nutrient availability, and ultimately crop yields. It was also speculated that the magnitude of implication on millet yield depends on the initial soil fertility level of the farm (farm type), and that soil physical quality indicators obtained from long-term experiments can be used to predict millet yields.

The main objective of this study was to identify and recommend appropriate management practices for sustained yield of pearl millet on smallholder farms in the Sahelian zone of Niger. Specifically, (i) assess the effect of long-term inorganic fertilizer application on selected soil physical properties; (ii) determine the effects of soil fertility management practices on soil physical and hydrological properties; (iii) identify and evaluate key indicators of soil physical quality and their effect on crop yields.

Materials and methods

Description of the study area

This study was carried out at Karabédji (13°16′17′N, 2°30′33′E) which is situated at about 60 km from Niamey in the southwestern part of Kouré District, Niger (Figure 1). The climate is of the Sahelo-Soudanian zone characterized by 3–4 months growing season (from July to September) and 8–9 months of dry season (October–June). Rainfall in the area is highly variable in time and in space (Van Vyve 2006). The average rainfall is about 600 mm per annum (Figure 2). The average minimum and maximum temperature range is between 16 and 42 °C, characteristic of the semi-arid regions (Greaf & Haigis 2001).

The dominant soil at the study site is sand classified as Arenosol (International Union of Soil Sciences Working Group 2014) or Psammentic Paleustalfs (Soil Survey Staff 2014). This soil is characterized by coarse texture, high infiltration rate, low organic carbon content, and low nutrients and water holding capacities. The dominant agricultural system is a subsistence crop-livestock system typical in the Southern Sahel. Pearl millet (*Pennisetum glaucum* L.) is grown by farmers in sole, in mixed cropping with sorghum *(Sorghum bicolor*), groundnut (*Arachis hypogaea* L.), and cowpea and in rotation with legumes viz. cowpea (*Vigna unguiculata* L. Walp), bambara nut (*Vigna subterranea* [L.] Verdcourt), and groundnut.

Experimental setup and treatments

This study was conducted over 2 growing seasons (2012 and 2013) on 8 farmers' fields selected from 23 farmers who were involved in an on-going long-term evaluation of soil fertility restoration technologies. This evaluation of soil fertility restoration technologies was established in 1999 and consisted of millet grown under four treatments (inorganic fertilizer rates) laid out in a Randomized Complete Block Design (RCBD) with two blocks each on 23 farmers' fields. Over the 13-year long term

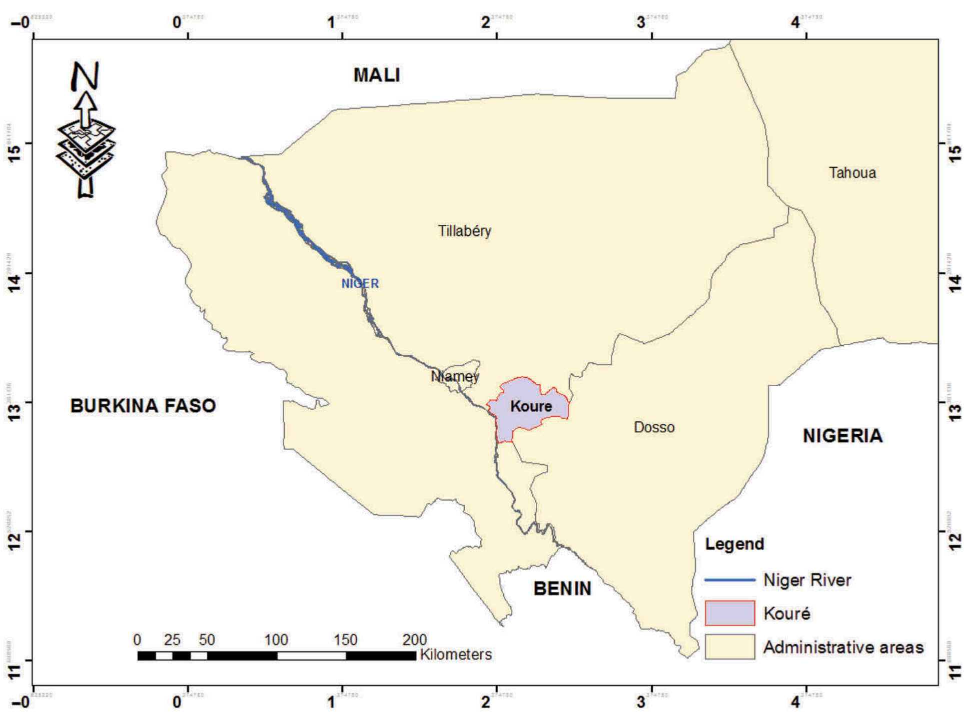

Figure 1. Location of experimental site in Kouré District, Tillabéri, Niger.

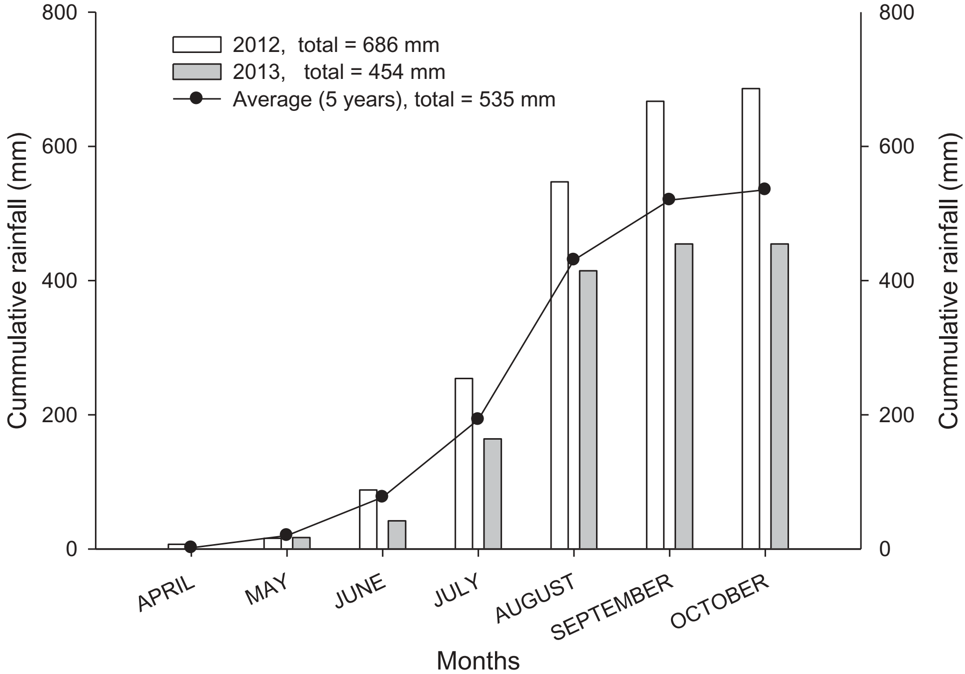

Figure 2. Rainfall distribution at Karabédji, Niger.

experiment farmers use these four rates of inorganic fertilizer under their various organic resources management conditions. The aim of this long-term on-farm trial was to identify sustainability indicators and optimize the use of both organic and inorganic resources available to farmers. The treatments were designed to test two sources of P used for fertilizer micro-dosing and the full rate of P from 'Tahoua' Rock Phosphate (TRP) commonly found in Niger that could mitigate the potential risk of soil mining of available P after continuous applications of micro-dose rate. TRP, a locally available agro-mineral material, has been proposed as an alternative P source (Buerkert et al. 2001; Abdou et al. 2011) for its economic advantage over the soluble P sources poorly accessed by local farmers (Bationo et al. 1998). The experiment consisted of four inorganic fertilizer rates laid out in RCBD with four replications in each of the two farmer types (top and bottom farmers). No manure addition was done on the experimental plots during the 2-year experiment. However, top and bottom farmers are distinguished through soil fertility management practices, particularly the amounts of household manure they used to apply and crop residues left after harvest. Top farmers commonly apply higher quantities of manure and retained crop residues after harvest on their farm than the bottom farmers.

The treatments consisted of: T_0 = control (farmer practice with no inorganic fertilizer applied); $T_1 = 4$ kg P ha^{-1} as DAP; $T_2 = 4$ kg P ha^{-1} as nitrogen (N) phosphorus (P) potassium (K) 15–15–15 ha^{-1}; and $T_3 = 4$ kg P ha^{-1} as NPK 15–15–15 + 13 kg P as TRP. TRP contains 25% of P_2O_5, DAP contains 18% N and 46% P_2O_5, and NPK contains 15% N, 15% P_2O_5 and 15% K_2O. Each plot measured 15 × 15 m with a 1 m alley allowed between treatments. These treatments were based on the two fertilizer micro-dosing rates being disseminated to farmers i.e. 2 g of DAP and 6 g of NPK 15–15–15 per millet hill, and TRP broadcasted at 13 kg.ha^{-1} in addition to the NPK 15–15–15 rate.

Experimental field selection

In selecting the experimental fields, farmers were ranked based on an average of 13 years (long-term) millet grain yields. This criterion was complemented with the diagnosis of soil fertility status of each farm. One block was selected on each of the four top farmers' fields (those with highest yield records), and on each of the four bottom farmers' fields (those with lowest yield records). A socio-economic survey was conducted to study the effects of farmer's socio-economic conditions on soil fertility management practices. Crop residues and manures application are common management practices among farmers. Organic manures used by farmers in the study area consisted of farmyard manure, household manure, cattle and sheep and goat manure, and generally contained 33–36% total carbon, 0.56–2.26% total N, 0.057–0.20% available P and 0.27–0.87% for exchangeable K (AFNET 2002; Suzuki et al. 2014). Locally used manure has been reported to be of poor quality due to its C:N ratio varying from 15–30 resulting from its high crop residues C and low N contents (Suzuki et al. 2014).

Planting and crop management

Pearl millet (*Pennisetum glaucum* L.) variety 'Haini kirey', commonly used by farmers in the region, was planted at a density of 10,000 hills per hectare (1×1 m) in June 2012 and in July 2013, respectively. Fertilizer was applied just after rainfall at approximately 2 weeks after planting. All other agronomic practices such as thinning, weeding, fertilizer application and harvesting were carried out by farmers themselves under close supervision by a technician. Rainfall amounts were measured using rain gauges which were read immediately after each rain event.

Soil sampling

For the determination of soil chemical properties, five soil samples were taken at random from each plot by means of auger, at the beginning and at the end of the growing season. The five samples were then bulked and composite samples representative of each plot taken. The soil samples were taken at depths of 0–10 and 10–20 cm. Composite samples were put in plastic bags, labelled and taken to the laboratory where they were air-dried at room temperature and sieved using a 2 mm mesh for laboratory analyses.

For water-stable aggregate and structural stability determinations, natural clods were randomly collected, by means of shovel, from 0 to 20 cm depth at three spots from each plot. These clods were then composited and put in labelled plastic bags and carefully taken to the laboratory. To avoid clods breaking, rigid containers were used during transportation.

For soil water retention characteristic curve (SWRC) and water content at field capacity determination, undisturbed moist soil core samples were randomly taken from two (2) spots in each plot at 0–10 and 10–20 cm depths using labelled Kopecky core rings (with a ring depth of 0.05 m and a radius of 0.025 m). Care was taken to remove the upper 2.5 cm before inserting the core rings (in order to avoid collecting grasses, leaves, pebbles, and other debris). After taking the sample, each ring was immediately covered with plastic sheet, then labelled and put in a sampling box.

Laboratory analyses

Plant available water capacity (PAWC)

PAWC indicates the soil's ability to store and provide water that is available to plant roots:

$$\mathrm{PAWC}(m^3 m^{-3}) = \theta_{\mathrm{FC}} - \theta_{\mathrm{PWP}}, \tag{1}$$

where θ_{FC}($m^3\ m^{-3}$) is the water retained at field capacity and θ_{PWP}($m^3\ m^{-3}$) is the water content at permanent wilting point; $0 \leq \mathrm{PAWC} \leq \theta_{\mathrm{FC}}$.

Field capacity and permanent wilting point were determined in the laboratory from soil water retention characteristics using undisturbed core ring procedures as described by Cornelis et al. (2005).

Soil structural stability

The most common procedure for assessing water stability of soil aggregates is the wet sieving method (Yoder 1936). However, the attempt made to use the wet sieving method resulted in the disintegration of all aggregates due to the sandy nature of the soil. Soil structural stability was therefore assessed using the water drop method (Diallo et al. 2004) and the Dexter structural stability index:

The water drop method: a clod of about 4 g, placed on a small holder, was subjected to a flux of 0.1 mL volume drops of water falling from a burette placed 1 m above. The material from the disintegration of the clod was passed through a funnel and was collected below in a 250 mL beaker. A 2 mm sieve was placed on the beaker to collect macro aggregates which were later dried and weighed. The volume of water (in mL) necessary to completely disintegrate the clod was directly read on the burette (adapted from Diallo et al. 2004).

Dexter index of soil physical quality (S): The S value represents the magnitude of the slope of the water release curve at the inflexion point when the curve is expressed as gravimetric water content, θ_g(kg kg^{-1}), versus the natural logarithm of pore water tension head (Dexter 2004). The resulting parameters of the Van Genuchten (1980) equation for soil water retention were used to obtain S (Cornelis et al. 2005) which was reported by Dexter (2004) to be related to the sharpness of pore size distribution and indicative of the presence of micro-structure. S can also be used to predict soil friability and breakup during tillage. It is expressed as:

$$S = -n(w_s - w_r)\left[1 + \frac{1}{m}\right]^{-(1+m)}, \qquad (2)$$

where S is the soil physical quality index, w_s and w_r are the saturated and residual gravimetric water contents, respectively, m and n are dimensionless parameters related to pore size distribution, $m = (1 - \frac{1}{n})$ is a van Genuchten parameter for soil water retention. Note that Dexter (2004) set $w_r = 0$. This was also done in this study when determining the van Genuchten parameters by curve fitting using the gravimetric water content.

Soil organic matter

Organic matter content of soil for each treatment was determined by the method described by Walkley and Black (1934).

Statistical analysis

The data was processed and analysed using the Restricted Maximum Likelihood (REML) method of mixed model analysis in Genstat (9th Edition, 2007, Lawes Agricultural Trust) statistical package. The data comprised treatment and farm type as independent variables and farm as block. The model used is as follows:

$$\begin{array}{l} \text{Fixed component} = \text{Fertilizer} + \text{Type} + \text{Fertilizer x Type} \\ \text{Random component} = \text{Block} + \text{Main plot} + \text{residual} \\ \text{Y} = \text{Fertilizer} + \text{Type} + \text{Fertilizer} * \text{Type} + \text{Block} + \text{TP} + \text{E} \end{array},$$

where Block, TP, and E are random terms with variances σ_b, σ_{tp} and ε, respectively. Farms by the farm type were samples from wider population of farms, and were therefore defined as random components. Regression analyses were used to determine the degree of relationships existing between measured parameters.

Table 1. Effect of fertilizer application, farm type, and interaction on the stability index of soil aggregates (water drop method).

Fertilizer type	Soil aggregate stability (mL of water per aggregate)		
	Top farms		Bottom farms
Control	3.66		2.89
DAP	4.18		3.01
NPK 15 15 15	4.98		2.66
NPK 15 15 15+TRP	4.13		3.40
χ^2 pr. farm type × fertilizer		0.055	
s.e.d. farm type × fertilizer		0.77	

Note: *Treatment means are average of four replicates; DAP = di-ammonium phosphate fertilizer.

Results

Soil structural stability index

The results of the analysis of the water drop soil stability index are shown in Table 1. The interaction between fertilizer treatments and farm type was almost statistically significant (P = 0.055; Appendix 1) in soil structural stability index. Higher values of the index were, however, observed in top farm type compared to bottom farm type (Table 1). For example, aggregates under DAP were 39% more stable in the top farm type than in the bottom farm type. Similarly, stability index under NPK 15–15–15 + TRP treatment was 21% higher in the top farm type than in the top bottom type. The control treatment consistently recorded the lowest values in both farm types.

Dexter's soil physical quality index

The effects of fertilizer application, farm type and soil depth on the Dexter soil physical quality (S) are shown in Table 2. Statistically significant difference (P = 0.001; Appendix 2) in S was observed only between soil depths. As expected, higher values were observed in the top soil (0–10 cm) than in the subsoil (10–20 cm). The values were 4–6 times higher in the former than in the latter. Generally, control treatments had the lowest values in both farm types while NPK 15–15–15 + TRP had consistently produced the highest values. All observed values were far above the 0.035 which was set as critical value by Dexter. Moreover significant and positive relationship (R^2 = 0.24, P < 0.05) between stability of aggregate and soil physical quality index (Figure 3) was obtained.

PAWC

The interaction between farm type, fertilizer treatment and soil depth to affect PAWC was almost statistically significantly (P = 0.057; Appendix 3; Table 3). The observed values ranged from 10.6 to

Table 2. Effects of fertilizer application, farm type, and interaction on Dexter soil physical quality index (S).

Farm type	Fertilizer type	Soil physical quality index		
		0–10 cm		10–20 cm
Top	Control	0.087		0.014
	DAP	0.102		0.015
	NPK 15 15 15	0.097		0.016
	NPK 15 15 15+TRP	0.105		0.016
Bottom	Control	0.087		0.015
	DAP	0.081		0.019
	NPK 15 15 15	0.096		0.015
	NPK 15 15 15+TRP	0.109		0.013
χ^2 pr. depth			0.001	
s.e.d. depth			0.004	

Note: Treatment means are average of four replicates; DAP = di-ammonium phosphate fertilizer.

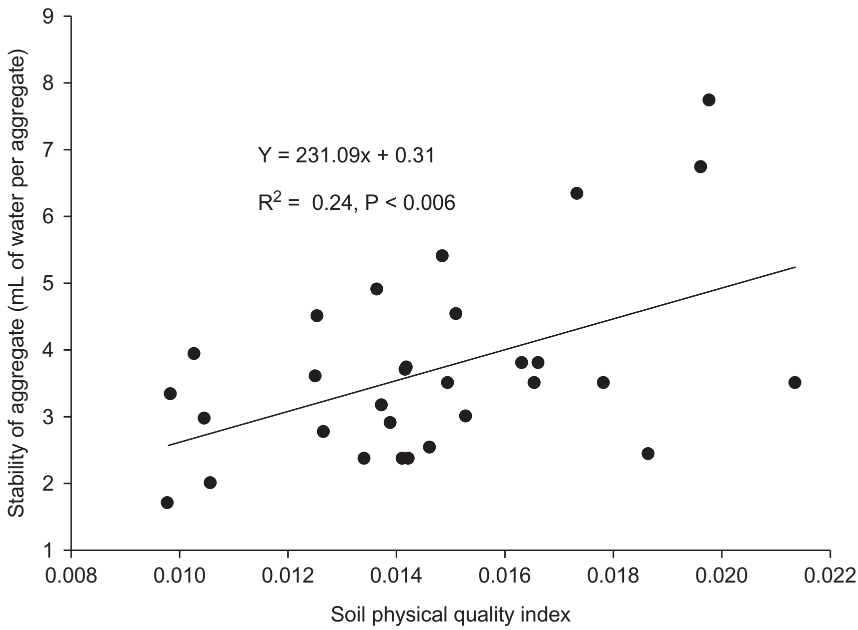

Figure 3. Relationship between stability of aggregate and soil physical quality index.

Table 3. Effects of fertilizer application, farm type, and interaction on plant available water capacity.

		Plant available water (mm)	
Farm type	Fertilizer type	0–10 cm	10–20 cm
Top	Control	13.1	10.3
	DAP	14.3	12.1
	NPK 15 15 15	13.0	10.7
	NPK 15 15 15+TRP	12.8	13.4
Bottom	Control	10.6	12.5
	DAP	11.6	11.2
	NPK 15 15 15	11.7	10.6
	NPK 15 15 15+TRP	11.4	09.8
χ^2pr. farm type × fertilizer × depth		0.057	
s.e.d. farm type × fertilizer × fepth		1.5	

Note: Treatment means are average of four replicates; DAP = di-ammonium phosphate fertilizer.

11.7 mm and from 12.8 to 14.3 mm for bottom and top farm types respectively, in the 0–10 cm layer. Treatment means were lowest in the control of the top farm 10–20 cm layer and in the bottom farm 0–10 cm layer. Generally, lower values were obtained in the bottom farm type than the top farm type. Also lower values were obtained in the 10–20 cm than the 0–10 cm soil layer for the two farm types.

Soil organic carbon content

Soil organic carbon C varied from 0.100% to 0.115% in top farm type and from 0.100% to 0.103% in bottom farm type in 2012 and from 0.116% to 0.132% in top farm and from 0.110% to 0.126% in bottom farm type in 2013. There was no significant ($P > 0.05$) effect of fertilizer application and farm type on OC during both 2012 and 2013 seasons. However, relatively lower OC content values were observed in the control treatment compared to treated plots and in bottom farm compared to top type. The OC content of both farm types were generally low in both years of this study.

Millet yield

Inorganic fertilizer application and farm type interaction significantly affected ($P < 0.05$) millet grain yield (Table 4) in 2012 growing season. Treatment NPK 15-15-15 + TRP recorded the highest grain yield followed by NPK 15-15-15 and DAP in both farm types. However, the increase in grain yield in treated plots over the control was much more pronounced in top farmers compared to bottom farmers (Table 4). Millet grain yield recorded on top farms were more than two fold those recorded on bottom farms.

The results obtained in 2013 (Table 4) showed statistically significant difference in farm types ($P < 0.05$) and highly statistically significant ($P < 0.01$) effect with fertilizer application. Highest average grain yields in both farm types were recorded under DAP treatment whereas the lowest values were recorded by the control. Higher gain yield was recorded in 2013 than in 2012. For example; under DAP fertilizer, millet grain yield increments of 259 and 331 kg, respectively, were recorded on top and bottom farms. Similarly, millet grain yield increments of 192 kg and 287 kg were recorded on plots treated with NPK 15-15-15 on top and bottom farm types, respectively. The observed yield increment in 2013 over that of 2012 was more drastic in the bottom farms than in the top farms. The results of combined analysis showed the highly significant influence of year by fertilizer treatment interaction ($P < 0.001$) on millet grain yield (Figure 4). Fertilizer application and year interacted to influence ($P < 0.05$) millet stubble yield (Table 4, appendix 4). The trend in variation of stubble yield among fertilizer treatment and farm types was similar to that observed with millet grain yield. On top farm type, highest yields were obtained in NPK 15-15-15 + TRP and DAP treatments while the control recorded the lowest yield in 2012 and 2013. Similar trend was also observed in the bottom farm type.

Relationships between soil properties and millet yield

Statistically significant and positive relationships were obtained between millet grain yield and the index of aggregate stability for top farm types (R^2 = 0.24, P = 0.02) and for bottom farm types (R^2 = 0.36, $P < 0.05$) (Figure 5). Furthermore, significant and positive relationship (Figure 6) was obtained between grain yield and plant available water for the top farm type (R^2 = 0.32, P = 0.021).

Table 4. Effects of fertilizer application, farm type, and interaction millet grain yield.

	Millet yield (kg ha^{-1})							
	Top farm				Bottom farm			
	2012		2013		2012		2013	
Fertilizer type	Grain	Stubble	Grain	Stubble	Grain	Stubble	Grain	Stubble
Control	451	3123	586	3087	161	2500	365	2600
DAP	642	3967	901	4587	245	2960	576	3375
NPK 15 15 15	703	3967	895	3450	256	3210	544	3000
NPK 15 15 15+TRP	845	4653	797	3612	345	3773	487	2938
Grain								
χ^2 pr. year × fertilizer				< 0.001				
s.e.d. year × fertilizer				119				
Stubble								
χ^2 pr. fertilizer × year				0.005				
s.e.d. fertilizer × year				298				

Note: Treatment means are average of four replicates; DAP = di-ammonium phosphate fertilizer.

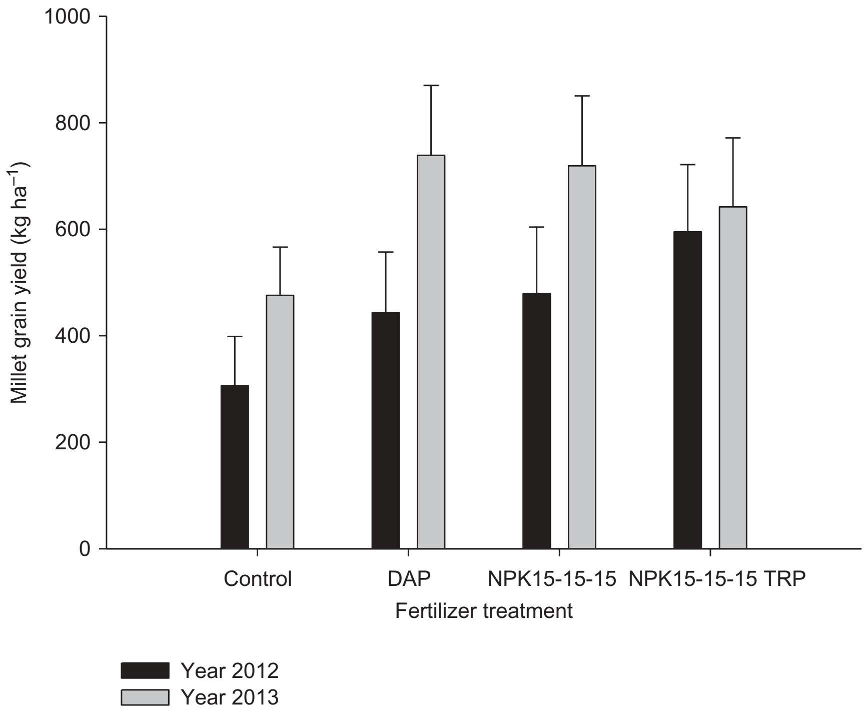

Figure 4. Effect of fertilizer treatment × year interaction on millet grain yield at Karabédji (error bar represent standard error of mean).

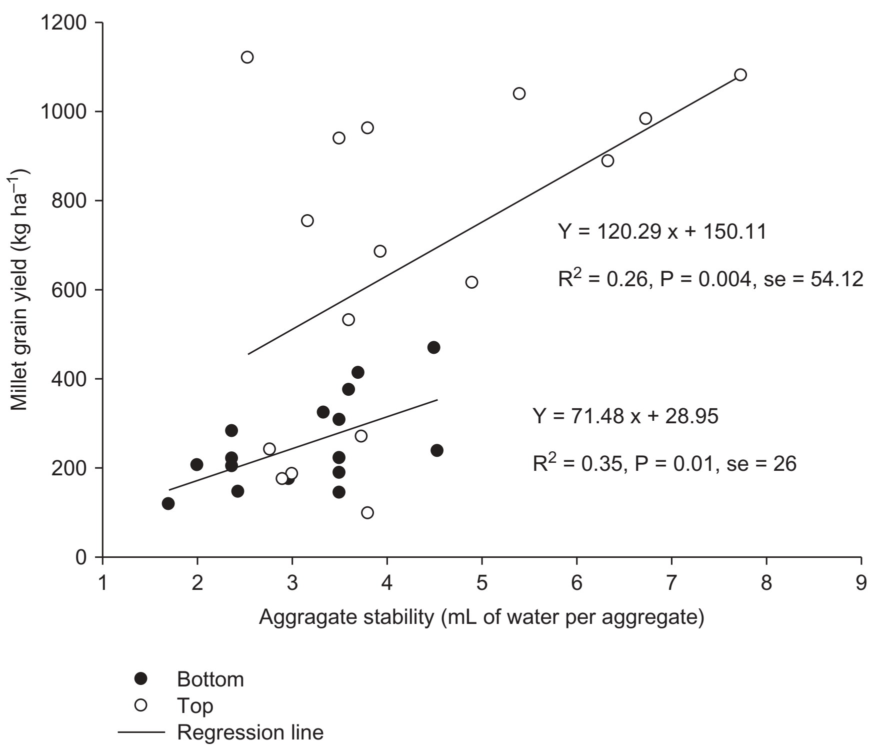

Figure 5. Relationship between millet grain yield and stability aggregate by farm type.

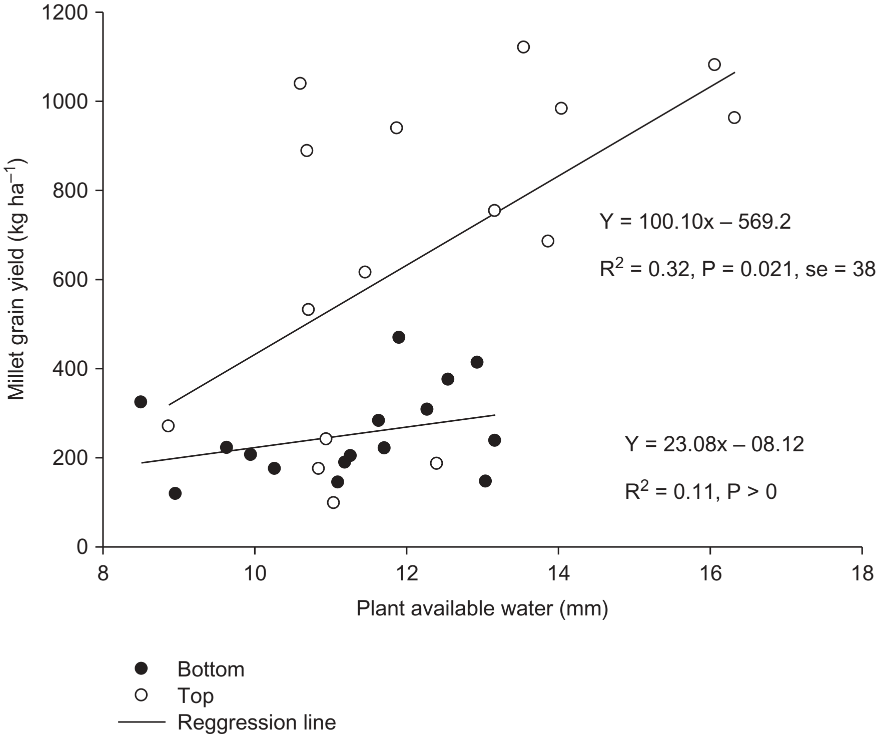

Figure 6. Relationship between millet grain yield and plant available water in top and bottom farm types.

Discussion

The study showed that mineral fertilizer application and farm type influenced soil structural stability index and plant available water capacity on the Sahelian Arenosol. The Dexter soil physical quality index varied with depth and was positively and significantly correlated with *S*.

Effect of fertilizer application, farm types, and interaction on soil structural stability of sandy soil

Soil structural stability was influenced by the treatments and farm type under the water drop method. The observed effect of fertilizer application by farm type interaction suggests that the effect of the fertilizer application on the stability of aggregate depends on the type of management practices of the farm. As expected, the control treatment recorded low values thereby showing the ease at which aggregates could be disintegrated under the control treatment by rain drop impacts. This low structural condition could facilitate not only leaching of nutrients and clay-sized particles and or their export through runoff water, but adversely affect soil water holding capacity and ultimately crop growth. Similar report (Diallo et al. 2004) showed changes in aggregate stability of an Alfisol, Vertisol and Entisol under conventional and minimum tillage practices. The authors emphasized positive effect of farming practices that promote the stability of the top soil structure on the susceptibility of soil to erosion. The higher mean values in top fertilized plots than in the control and in the top farm, observed in this study, than in the bottom type farm type could be an indication of increased cohesion between soil particles. The highest structural stability was obtained in the amended treatments of the top farm type.

Effect of fertilizer application, farm types, and interaction on Dexter's soil physical quality index (S)

S is a measure of soil microstructure that controls many key soil physical properties (Dexter 2004). The observed values were within the range of typical S values for sandy soils (Dexter 2004). The Dexter's critical values are: $S \geq 0.05$ (very good physical quality), $0.035 \leq S < 0.050$ (good physical quality), and $S < 0.035$ (poor physical quality). Therefore all observed values in the 10 to 20 cm depth from both top and bottom farm types are within the poor physical quality range. The decrease of S with depth could be an indication of decrease in soil physical quality though soil organic carbon content did not show any significant decrease with the assessed depths. This parameters has been reported to have great effect on S (Dexter 2004).

Effect of fertilizer application, farm types, and interaction on plant available water capacity

Plant available water content was considerably sensitive to the combined action of farm type, fertilizer treatment and soil depth ($P = 0.057$; Table 3). The fact that no clear effect of fertilizer was noticed, as no rate consistently recorded higher plant available water over the control treatment, suggests that the relatively higher organic carbon content (Table 4) in the top farm than in the bottom farm type had played a role. The relatively higher organic matter content observed in top farm and in fertilized plots might have had positive impact on soil structural stability which, in turn, resulted in higher plant available water. Similar report (Manyame 2006) showed no significant influence of fertilizer micro-dosing on water balance on a Sahelian sandy soil at Banizoumbou and Bagoua, Niger. Crop residues, organic manure and mineral fertilizer application and corralling are common management practices used to improve soil organic matter status among farmers. However, farmers differ substantially in their ability to increase and maintain the fertility status of their farms. Soil water content has been reported to be among the most sensitive parameters to crop residue removal (Blanco-Canqui & Lal 2009).

Effect of fertilizer application, farm types, and interaction on soil organic carbon content

The observed soil organic carbon in all the treatments was generally very low (< 0.2%). Values reported earlier (IFDC 2002; Fofana et al. 2008) were 0.15% and 0.16% on outfields and infields of Karabédji, respectively. Low organic carbon status of most sub-Saharan African soils is as a result of low carbon sequestration due to low carbon inputs, and to the microbes and termite-induced rapid turnover (Bationo & Buerkert 2001). Farmers' capacity to manage the fertility of their soil varies with differences in livelihood strategies. Consequently, this reflects on their farms as farmers live in intimacy with their lands. Commonly used practices to improve soil organic matter content by farmers are the application household manures and retention of crop residues after harvest.

It has been established in the literature (Gandah et al. 2003; Manyame 2006; Suzuki et al. 2014) that practices that enable regular addition of manure and in small amount: viz. corralling and addition of organic manure (Smithson & Giller 2002) are more effective in improving soil organic matter content. And there is a strong and positive relationship between soil organic matter level and grain yield (Bationo et al. 2007).

Variability in soil organic carbon resulting from field-specific management is common among farming systems in Sub-Saharan Africa (Tittonell et al. 2005a, 2005b; Bationo et al. 2007; Dunjana et al. 2012). Differences in organic matter content between rich and poor farmers' fields were previously reported among maize growers in Zimbabwe (Mtembanengwe & Mapfumo 2008).The decrease in organic matter with depth has been established (Bationo et al. 2007). However, in this study the effect of soil depth was not obvious. This is possibly due to frequent mixing of soil surface during weeding operations (tillage).

Effect of fertilizer application, farm types, and interaction on millet yield

The extent of the increase in millet grain and stubble yields observed in amended plots, over the two growing seasons, relative to control treatment depended on farm type. Top farm produced higher grain yield than the bottom farm type. This performance of the top farm type could be attributed to difference in livelihood strategies between two groups of farmers which probably influenced soil fertility management practices and ultimately resulted in significantly higher water and nutrient availabilities in top than in bottom farm types. Differences in soil fertility management practices induced by variations in livelihood strategies among farmers could have resulted in a gradient in water and nutrient availability between top and bottom farmers. The results were as previously reported (Abdou et al. 2011) where higher millet grain yield in amended plots compared to the control cutting across farmers' field at Karabédji were obtained. Similarly, differences of millet yield were also reported earlier based on farm distance to homestead (Bationo et al. 2007; Fofana et al. 2008). The authors attributed higher grain yield from infields than outfields to an ISFM-induced drought tolerance of soils of the former farms as result of higher organic matter content. The relationships between millet yield and soil stability index and plant available water illustrate the key role played by soil physical properties in yield variation.

Conclusions and recommendations

The results revealed that variations were observed in aggregate stability under water drop method between fertilizer rates by farm type interaction. More stable aggregates were found in fertilizer-treated plots than in non-fertilizer-treated plots and on top farm type than on bottom farm type. Plant available water decreased with depth and relatively higher values were recorded in top compared to bottom farm type. No significant effect of fertilizer rates and farm type was recorded on soil organic carbon content.

The study has also showed significant changes in soil physical quality index (S) with depth under different fertilizer rates and farm type and indicated that S matched with the critical values set by Dexter. S can adequately be used to detect changes in soil physical quality of the Sahelian sandy soil although no direct relationship was found between *S* and pearl millet yield. Moreover, significant positive correlation was obtained between stability of aggregate and S.

Aggregate stability and S are key indicators of soil physical quality because of their sensitivity to soil fertility management practices. However, further studies would be required to find critical values for the Dexter physical quality index for the Sahelian Arenosols.

The study has also demonstrated that responses of millet grain and stubble yields to fertilizer rates depended much on farm type and the NPK 15-15-15 + TRP on top farm type consistently recorded the highest values. Furthermore, significant relationship of pearl millet grain yield with the stability of aggregate and plant available water were found thereby showing the importance of soil physical properties in explaining variations in millet yield.

Effect of fertilizer application was more pronounced with higher management practice of the top farm than the bottom farm type. Soil physical parameters were more favourable for millet production on top farm type. Therefore, the disseminated three fertilizer micro-dosing rates namely DAP, NPK 15-15-15 at 4 kg P ha^{-1} and NPK 15-15-15 + TRP at 13 kg P ha^{-1} should be used by farmers in combination with practices such as manure application and reduced crop residue removal after harvest for sustainable crop production in the Sahel.

Acknowledgement

We would like to thank the Alliance for Green Revolution in Africa (AGRA) for sponsoring the project through its Soil Health Program (SHP). We are grateful to Prof Kaku Sagary Nokoe for his advice during the statistical analysis. We notably thank Adamou Abdou, Harouna and Hassane Ide for the assistance during the field work.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was supported by the Alliance for Green Revolution in Africa (AGRA).

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Appendix 1. Mixed model analysis for fertilizer application, farm type, and interaction effects on the stability index of soil aggregates (water drop method)

Random term	Component	s.e.	Variance (%)
Farm by farm type	1.346	0.911	54
Residual	1.126	0.189	46
Total	2.472		
Fixed term	Wald statistic	d.f.	χ^2 pr.
Type	1.86	1	0.172
Fertilizer treatment	4.37	3	0.224
Type × fertilizer treatment	7.61	3	0.055

Appendix 2. Mixed model analysis for fertilizer application, farm type, and interaction effects on Dexter's soil physical quality index (*S*)

Random term	Component	s.e.	Variance (%)
Farm by farm type	0.000161	0.000115	37
Residual	0.000273	0.0000618	63
Total	0.000434		
Fixed term	Wald statistic	d.f.	χ^2 pr.
Type	0.04	1	0.833
Fertilizer treatment	3.67	3	0.299
Depth	357.26	1	< 0.001
Type × fertilizer treatment	0.95	3	0.813
Type × depth	0.28	1	0.597
Fertilizer treatment × depth	3.51	3	0.319
Type × fertilizer treatment × depth	1.81	3	0.612

Appendix 3. Mixed model analysis for inorganic fertilizer application, farm type, and interaction effects on plant available water

Random term	Component	s.e.	Variance (%)
Farm by farm type	0.000212	0.000147	43
Residual	0.000285	0.000068	57
Total	0.000497		
Fixed term	Wald statistic	d.f.	χ^2 pr.
Type	0.94	1	0.332
Fertilizer treatment	1.63	3	0.654
Depth	4.10	1	0.043
Type × fertilizer treatment	4.41	3	0.221
Type × depth	2.60	1	0.107
Fertilizer treatment × depth	1.32	3	0.724
Type × fertilizer treatment × depth	7.50	3	0.057

Appendix 4. Mixed model analysis for fertilizer application, farm type, and interaction effects on millet stubble yield

Random term	Component	s.e.	Variance (%)
Farm by type by year	406659	252869	92
Residual	33692	7352	8
Total	440351		
Fixed term	Wald statistic	d.f.	χ^2 pr.
Type	126.30	1	< 0.001
Fertilizer treatment	24.54	3	< 0.001
Year	1.58	1	0.208
Type × fertilizer treatment	2.12	3	0.549
Type × year	0.14	1	0.711
Year × fertilizer treatment	12.78	3	0.005
Type × fertilizer treatment × year	0.42	3	0.937