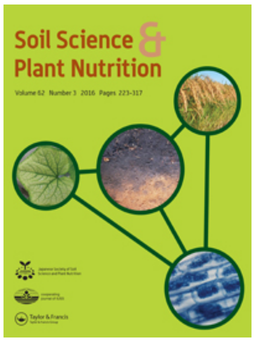

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ORIGINAL ARTICLE

Fertilizer micro-dosing increases crop yield in the Sahelian low-input cropping system: A success with a shadow

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ABSTRACT
Over the years, a scarcity of information on nutrient gains or losses has led to overemphasis being placed on crop yields and economic income as the direct benefits from fertilizer micro-dosing technology. There is increasing concern about the sustainability of this technology in smallholder Sahelian cropping systems. This study was designed in the 2013 and 2014 cropping seasons to establish nutrient balances under fertilizer micro-dosing technology and their implications on soil nutrient stocks. Two fertilizer micro-dosing treatments [2 g hill^{-1} of diammonium phosphate (DAP) and 6 g hill^{-1} of compound fertilizer Nitrogen-Phosphorus-Potassium (NPK) (15-15-15)] and three rates of manure (100 g hill^{-1}, 200 g hill^{-1} and 300 g hill^{-1}) and the relevant control treatments were arranged in a factorial experiment organized in a randomized complete block design with three replications. On average, millet (Pennisetum glaucum (L.) R.Br.) grain yield increased by 39 and 72% for the plots that received the fertilizer micro-dosing of 6 g NPK hill^{-1} and 2 g DAP hill^{-1}, respectively, in comparison with the unfertilized control plots. The average partial nutrients balances for the two cropping seasons were −37 kg N ha^{-1}yr^{-1}, −1 kg P ha^{-1}yr^{-1} and −34 kg K ha^{-1}yr^{-1} in plots that received the application of 2 g DAP hill^{-1}, and −31 kg N ha^{-1}yr^{-1}, −1 kg P ha^{-1}yr^{-1} and −27 kg K ha^{-1}yr^{-1} for 6 g NPK hill^{-1}. The transfer of straw yields accounted for 66% N, 55% P and 89% K for removal. The average full nutrient balances for the two cropping seasons in fertilizer micro-dosing treatments were −47.8 kg N ha^{-1} yr^{-1}, −6.8 kg P ha^{-1} yr^{-1} and −21.3 kg K ha^{-1} yr^{-1} which represent 7.8, 24.1 and 9.4% of N, P and K stocks, respectively. The nutrient stock to balance ratio (NSB) for N decreased from 13 to 11 and from 15 to 12 for the plots that received the application of 2 g DAP hill^{-1} and 6 g NPK hill^{-1}, respectively. The average NSB for P did not exceed 5 for the same plots. It was concluded that fertilizer micro-dosing increases the risk of soil nutrient depletion in the Sahelian low-input cropping system. These results have important implications for developing an agro-ecological approach to addressing sustainable food production in the Sahelian smallholder cropping system.

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fertilizer micro-dosing; sustainability; nutrient balances; nutrient stocks; pearl millet

1. Introduction

Soil nutrient depletion is a major constraint to crop production in sub-Saharan Africa (Drechsel *et al*. 2001; Cobo *et al*. 2010). Earlier reports on soil nutrient balances from several African countries indicate that soil nutrients are depleted at alarming rates (Smaling *et al*. 1993; Henao *et al*. 2001). In the Sahelian countries where low-input small-scale farming systems are predominant, such depletion of soil fertility is not unusual.

In Niger, most of the soils allocated for crop production are degraded and characterized by low availability of soil nutrients including nitrogen (N) and phosphorus (P; Manu *et al*. 1991; Gandah *et al*. 2003). Increasing crop production under such conditions should necessarily come from improved soil nutrient availability. Application of inorganic fertilizers plays a crucial role in increasing yields and reducing soil nutrient 'mining' (Bindraban *et al*. 2014). However, the use of mineral fertilizer remains very low in Niger and represents only less than 5 kg ha^{-1} yr^{-1} according to the Fertilizer Summit held in Abuja, Nigeria, in 2006. The high cost of inorganic fertilizer relative to the income of small-scale farmers and the risk associated with its application in dry spell-prone areas are the major constraining factors for fertilizer use in Niger (Abdoulaye and Sanders 2005).

Several soil fertility management options to enhance pearl millet (*Pennisetum glaucum* (L.) R.Br.) productivity on Sahelian sandy soils in Niger have been developed (Bationo *et al*. 1998b). Fertilizer micro-dosing technology, which consists of the application of a small quantity of mineral fertilizer together with seeds of the target crop in the planting hole at sowing (ICRISAT 2009), is becoming the most common technology employed by small-scale farmers across sub-Saharan West Africa (Bationo and Waswa 2011; Buerkert and Schlecht 2013). This technology has been promoted to improve crop yield, fertilizer use efficiency and income in small-scale cereal-based systems (Tabo *et al*. 2007).

Over the years, scarcity of information on complete evaluation of nutrient gains or losses has led to overemphasis on crop yields and economic income generated through fertilizer micro-dosing technology (Aune and Ousman 2011; Bagayoko *et al.* 2011; Tabo *et al.* 2011; Bielders and Gérard 2014). However, evaluation of its sustainability has received less attention and the research community continues to believe that the small dose of mineral fertilizer applied results in higher crop yields

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and thus high nutrient uptake (Hayashi *et al.* 2008; Ibrahim *et al.* 2014). The debate concerning the increase of soil nutrient depletion risk under fertilizer micro-dosing technology is intensifying (Breman 2012; Buerkert and Schlecht 2013; Aune and Coulibaly 2015). Recently, Camara *et al.* (2013: 1) reported that 'micro-dosing complied with all except agronomic sustainability, because in the long term it may cause nutrient depletion of the soil and consequently, decreased soil fertility and crop productivity'. Camara and co-workers supported their statement with nutrient uptake data recorded under fertilizer micro-dosing which corresponded to 34–75 kg N ha^{-1} and 8–20 kg P ha^{-1} compared with 6.1 kg N ha^{-1} and 15.6 kg P ha^{-1} applied. It is clear that the increase in yield results in greater extraction of soil nutrients which could lead to the depletion of soil nutrient stocks and eventually to the decline in crop yields (Vanlauwe and Giller 2006). However, it seems simplistic to assess the long-term sustainability of a technology or a system on the basis of partial nutrient balance exclusively, as was argued by Camara *et al.* (2013). Nutrient balances (whether partial or full) cannot be used as a sustainability indicator without consideration of nutrient stocks in the soil (Vanlauwe and Giller 2006). According to Hilhorst *et al.* (2000), agricultural practice with a stock decline for total nitrogen of more than 1% was considered not sustainable. The objective of the current study was, therefore, to establish the nutrient balances under fertilizer micro-dosing technology and their implications on soil nutrient stock.

2. Materials and methods

2.1. 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, 2°18′E; 240 m above sea level). The climatic conditions are typical of the southern edge of the Sahelian zone, with rainfall and high temperature throughout the year (Sivakumar *et al.* 1993). The mean annual rainfall (1983–2014) at the Research Station of Sadoré is 551 ± 110 mm (± standard error) and the average temperature is 29°C. The soil was classified as a Psammentic Paleustalf and isohyperthermic in the United States Department of Agriculture (USDA) Soil Taxonomy, and as a Luvic Arenosol by the Food and Agriculture Organization of United Nations (FAO) system (West *et al.* 1984). The soil chemical and textural properties of the experimental field indicate that the soil is sandy and very strongly acid (pH H_2O = 4.7–5.1) with a low level of organic carbon (0.31%) in the topsoil depth (0–10 cm). The total N content ranged from 311 mg kg^{-1} at 0–10 cm down to 135 mg kg^{-1} within 20 to 40 cm soil depth. The available P content was 8.9 mg kg^{-1} in the topsoil (0–10 cm) and 3.7 mg kg^{-1} within the 20 to 40 cm soil depth. The exchangeable calcium (Ca) and magnesium (Mg) were very low at 1.0 cmol$_c$ kg^{-1} and 0.4 cmol$_c$ kg^{-1}, respectively, within the top 10 cm soil depth. The properties of this soil are representative of the soils in Niger characterized by sandy texture and low levels of nutrients and organic matter (Manu *et al.* 1991).

2.2. Experimental set-up

The experiment was initiated in 2010. The data presented in the current paper were collected during the 2013 and 2014 rainy seasons. Two fertilizer micro-dosing options (2 g diammonium phosphate (DAP) hill^{-1} and 6 g Nitrogen-Phosphorus-Potassium (NPK) hill^{-1}) and three application rates of cattle manure (1000 kg ha^{-1}, 2000 kg ha^{-1} and 3000 kg ha^{-1}) and relevant control treatment were arranged in randomized complete block design (RCBD) with three replications. The fertilizer micro-dosing rates were applied at planting at 2 g DAP hill^{-1} and 6 g NPK hill^{-1} corresponding to 20 kg ha^{-1} of DAP (diammonium phosphate) and 60 kg ha^{-1} of compound fertilizer NPK (15–15–15), respectively. Cattle manure was applied before sowing in the planting hole at rates of 100 g hill^{-1}, 200 g hill^{-1} and 300 g hill^{-1} corresponding to 1000 kg ha^{-1}, 2000 kg ha^{-1} and 3000 kg ha^{-1}, respectively. The cattle manure was collected from a barn in Sadoré village. The quantity of nutrient content in each treatment is given in Table 1.

Around 15 seeds of improved pearl millet variety ICMV-IS 89305 (110 maturity days) were sown according to the onset of the rainy season on 10 July 2013 and 1 June 2014 in the planting hill at a spacing of 1 × 1 m (10,000 hills ha^{-1}). Each individual treatment plot (5 m × 6 m) was separated from the others by a 1 m alley. Three weeks after planting, the millet plants were thinned to three plants per hill. There were three weeding events during the growing period. The harvest periods occurred on 10 October in 2013 and 15 September in 2014. To determine straw and grain yields, the straw samples and millet panicles threshed by hand were collected from the harvested area of 4 m × 5 m (20 m^2), sun-dried and weighed (expressed in kg ha^{-1}).

2.3. Soil and plant sampling and analysis

At the onset of the experiment in 2013, soil samples were collected from the experimental field at 0–10 cm, 10–20 cm and 20–40 cm in each treatment plot for initial chemical and physical characterization. The samples were taken to the laboratory for determination of pH (1: 2.5 soil/water ratio), exchangeable acidity (H^+ and Al^{3+}) was extracted by 1 M Potassium chloride (KCl) solution and titrated with 0.025 M Sodium hydroxide (NaOH) (van Reeuwijk 1993). The exchangeable bases were determined by extraction with 0.01 M silver thiourea complex cation (AgTU) and the cation concentrations were measured with an atomic absorption spectrophotometer (van Reeuwijk 1993). Organic carbon was determined using Walkley and Black's method as described by van Reeuwijk (1993). The total N was determined by the Kjeldahl method (Houba *et al.* 1995), and available phosphorus by the Bray 1 method (van Reeuwijk 1993). Bulk density (*BD*) was determined by the core method (Blake and Hartge 1986). The particle size distribution was determined using Robinson method as described by ICRISAT Soil and Plant Laboratory (Houba *et al.* 1995). At harvest, entire plants were sampled in each treatment plot. The samples were separated into leaves, stems, glumes and grains, which were sun-dried thereafter. The dried samples were milled and sub-samples were subjected to total N, P and potassium (K) analysis. Total nitrogen was analyzed by Kjeldahl methods using a mixture of salicylic acid, sulphuric acid (H_2SO_4) and selenium for the digestion. The quantitative determination of total N was done with an auto-analyzer using the colorimetric method based on the Bertholet

Table 1. Nutrient flows used in the current study (kg ha^{-1}).

	IN1*			IN2			IN3			IN4	OUT1*			OUT2			OUT3		OUT4	OUT5		
Treatments	N	P	K	N	P	K	N	P	K	N	N	P	K	N	P	K	N	K	N	N	P	K
2013																						
Control (no mineral fertilizer, no manure)	0	0	0	0	0	0	6.09	1.3	17	2.7	2.5	0.3	0.4	13.1	0.8	13.6	18.7	0.1	0.5	11	7.1	5.4
0 g mineral fertilizer + 100 g manure hill^{-1}	0	0	0	9.8	3.7	16	6.09	1.3	17	2.7	4.1	0.6	0.8	18.2	1.4	31.3	19.3	8.9	1.7	11	7.1	5.4
0 g mineral fertilizer + 200 g manure hill^{-1}	0	0	0	19.6	7.4	32	6.09	1.3	17	2.7	6.8	1.1	1.1	18.1	1.4	21.5	20.5	17.6	3	11	7.1	5.4
0 g mineral fertilizer + 300 g manure hill^{-1}	0	0	0	29.4	11.1	48	6.09	1.3	17	2.7	11.5	1.7	2.4	18.7	1.5	25.4	21.4	26.4	4.3	11	7.1	5.4
2 g DAP hill^{-1} + 0 g manure hill^{-1}	3.6	4	0	0	0	0	6.09	1.3	17	2.7	7.9	1	1.2	21.9	1.4	33.6	16.9	0.1	0.9	11	7.1	5.4
2 g DAP hill^{-1} + 100 g manure hill^{-1}	3.6	4	0	9.8	3.7	16	6.09	1.3	17	2.7	11.6	1.8	2.1	33.1	2.9	60.6	16	8.9	2.2	11	7.1	5.4
2 g DAP hill^{-1} + 200 g manure hill^{-1}	3.6	4	0	19.6	7.4	32	6.09	1.3	17	2.7	16.9	2.2	2.3	34.4	2.9	43.7	16.6	17.6	3.5	11	7.1	5.4
2 g DAP hill^{-1} + 300 g manure hill^{-1}	3.6	4	0	29.4	11.1	48	6.09	1.3	17	2.7	19	2.8	3.4	40.6	3	67.5	16.9	26.4	4.8	11	7.1	5.4
6 g NPK hill^{-1} + 0 g manure hill^{-1}	9	3.9	7.5	0	0	0	6.09	1.3	17	2.7	5.7	0.7	0.7	22.3	1.4	23.1	18.1	4.2	1.6	11	7.1	5.4
6 g NPK hill^{-1} + 100 g manure hill^{-1}	9	3.9	7.5	9.8	3.7	16	6.09	1.3	17	2.7	10.2	1.4	1.6	27	1.8	40	18.3	13	2.9	11	7.1	5.4
6 g NPK hill^{-1} + 200 g manure hill^{-1}	9	3.9	7.5	19.6	7.4	32	6.09	1.3	17	2.7	9.4	1.6	1.6	22.7	1.9	38.8	20.9	21.7	4.2	11	7.1	5.4
6 g NPK hill^{-1} + 300 g manure hill^{-1}	9	3.9	7.5	29.4	11.1	48	6.09	1.3	17	2.7	19.4	2.5	2.9	50.6	3.6	78.3	16.1	30.5	5.5	11	7.1	5.4
2014																						
Control (no mineral fertilizer, no manure)	0	0	0	0	0	0	7.5	1.5	17.4	3.1	13.3	2.3	5.3	18.2	2.5	22.4	10.4	0.1	0.6	11	7.1	5.4
0 g mineral fertilizer + 100 g manure hill^{-1}	0	0	0	15	2.8	7.2	7.5	1.5	17.4	3.1	21.3	4.8	8	39.3	6.8	50.1	6.5	4.5	2.6	11	7.1	5.4
0 g mineral fertilizer + 200 g manure hill^{-1}	0	0	0	30	5.6	14.4	7.5	1.5	17.4	3.1	22.3	5.9	9.6	33.9	5.8	44.3	9	8.9	4.5	11	7.1	5.4
0 g mineral fertilizer + 300 g manure hill^{-1}	0	0	0	45	8.4	21.6	7.5	1.5	17.4	3.1	28.3	6.8	11.4	48.1	9.1	61.1	10.4	13.3	6.5	11	7.1	5.4
2 g DAP hill^{-1} + 0 g manure hill^{-1}	3.6	4	0	0	0	0	7.5	1.5	17.4	3.1	19.1	3.3	6.6	32.6	4.5	27.4	4.3	0.1	1.1	11	7.1	5.4
2 g DAP hill^{-1} + 100 g manure hill^{-1}	3.6	4	0	15	2.8	7.2	7.5	1.5	17.4	3.1	34.3	8.9	14.3	41.7	6.3	89.2	1.9	4.5	3.1	11	7.1	5.4
2 g DAP hill^{-1} + 200 g manure hill^{-1}	3.6	4	0	30	5.6	14.4	7.5	1.5	17.4	3.1	32.9	9	13.5	34.7	6.8	38.8	9.1	8.9	5	11	7.1	5.4
2 g DAP hill^{-1} + 300 g manure hill^{-1}	3.6	4	0	45	8.4	21.6	7.5	1.5	17.4	3.1	40.3	9.2	14.5	49.3	10.2	69.7	5.8	13.3	7	11	7.1	5.4
6 g NPK hill^{-1} + 0 g manure hill^{-1}	9	3.9	7.5	0	0	0	7.5	1.5	17.4	3.1	18.3	3.4	6.4	33.4	4.5	39.2	4.9	4.7	1.8	11	7.1	5.4
6 g NPK hill^{-1} + 100 g manure hill^{-1}	9	3.9	7.5	15	2.8	7.2	7.5	1.5	17.4	3.1	30.3	7.3	12.3	26.7	4.6	29.9	10.7	9.1	3.8	11	7.1	5.4
6 g NPK hill^{-1} + 200 g manure hill^{-1}	9	3.9	7.5	30	5.6	14.4	7.5	1.5	17.4	3.1	31.8	7.7	11.9	37.4	6.3	45.9	10.1	13.5	5.7	11	7.1	5.4
6 g NPK hill^{-1} + 300 g manure hill^{-1}	9	3.9	7.5	45	8.4	21.6	7.5	1.5	17.4	3.1	29.4	7.7	13	54.4	6.4	77.7	17.5	17.8	7.7	11	7.1	5.4

reaction (Houba *et al.* 1995). The same digest was used to determine total P and K. Total P was quantified with the colorimetric method based on the phosphomolybdate complex, reduced with ascorbic acid. The total K was determined with flame emission spectrophotometry (Houba *et al.* 1995).

3. Calculations

3.1. Nutrient stocks

The stocks of N, P and K in each treatment plot were calculated from the soil samples collected at the onset of the experiment in 2013. The stock of nutrient was calculated from the formula used by Bond (2010) as follows:

$$Stock\ (kg\ ha^{-1}) = Nutrient\ concentration\,(mg\ kg^{-1}) \times bulk\ density\,(kg\,m^{-3}) \times soil\ depth\,(m) \times 10^{-2} \quad (1)$$

3.2. Nutrient balances

The partial nutrient balances at plot level were calculated by subtracting the quantity of nutrients removed in the harvested products, grain (OUT1) and crop residue (OUT2) from the corresponding total quantities of nutrients applied through mineral fertilizer (IN1) and manure (IN2) in each treatment plot. The OUT1 and OUT2 were calculated as follows:

$$OUT1 = Grain\ yield\,(kg\ ha^{-1}) \times nutrient\ content\ of\ grains\,(kg\ kg^{-1}) \quad (2)$$

$$OUT2 = Crop\ residuere\ moved\,(kg\ ha^{-1}) \times nutrient\ content\ of\ crop\ residue\,(kg\ kg^{-1}) \quad (3)$$

The full nutrient balance at plot level was calculated by estimating the difference in the different nutrient flows. Following the approach of Stoorvogel and Smaling (1990), four major inputs (IN1–4) and five major outputs (OUT1–5) of nutrients were identified in the current study (Table 3). The difficult-to-quantify flows (not measured) were calculated from the transfer functions and the secondary data from the literature as described below. It is worthy to note that input IN5 (sedimentation), which referred to the nutrient inputs in irrigation water and input in sediment as a result of water erosion, was not taken into account in this study due to the fact that the experiment was conducted without an irrigation system and also the naturally flooded water was neglected as a result of the sandy texture of the experimental field.

3.3. Estimation of inputs not directly measured in this study

3.3.1. Atmospheric depositions (IN3)

The input of nutrients by atmospheric depositions consists of two components: wet deposition associated with rainfall, and dry deposition related to Harmattan dust. The N and P depositions from the rainfall were calculated using the formulae developed by de Ridder *et al.* (1982) as follows:

$$Ndep = 0.0065 \times Annual\ precipitation\ (mm) \quad (4)$$

$$Pdep = 0.0007 \times Annual\ precipitation\ (mm) \quad (5)$$

where Ndep is nitrogen from rainfall depositions and Pdep is phosphorus from rainfall depositions.

The correlations between atmospheric deposition and rainfall found by de Ridder *et al.* (1982; i.e., Equations 4 and 5) were suitable for the Sahelian zone with an average annual rainfall generally of less than 700 mm. These equations were found appropriate for the study area where the total rainfall recorded was 475 mm and 689 mm in 2013 and 2014, respectively. Therefore, Ndep values of 3.09 and 4.49 were assumed to apply for 2013 and 2014, respectively. These values are close to the value of 3.5 kg N ha^{-1} yr^{-1} reported in the southwest of Niger (570 mm rainfall) by Buerkert and Hiernaux (1998). Phosphorus values from rainfall depositions (Pdep) derived from Equation (5) were set to be 0.33 kg ha^{-1} yr^{-1} in 2013 and 0.48 kg ha^{-1} yr^{-1} in 2014.

The potassium from rainfall deposition was calculated with the transfer function developed by Roy and Misra (2003) as follows:

$$K2Odep = 0.11 \times \sqrt{Annual\ precipitation\ (mm)} \quad (6)$$

where K2O dep is potassium deposition from rainfall.

The values of Potassium oxide (K_2O) obtained from the Equation (6) were multiplied by 0.83 to convert K_2O to K. Estimated values for potassium deposition from rainfall were 2.0 kg ha^{-1} yr^{-1} and 2.4 kg ha^{-1} yr^{-1}, respectively, in 2013 and 2014.

In addition to the quantities of N, P and K calculated from rainfall deposition, 3 kg N ha^{-1} yr^{-1}, 1 kg P ha^{-1} yr^{-1} and 15 kg K ha^{-1} yr^{-1} were added as the amount of nutrients deposited annually with the dust load in Niger (Buerkert and Hiernaux 1998). The total nutrients from atmospheric depositions estimated as nutrients inputs via rainfall and harmattan dust in the current study were therefore set to be 6.09 kg N ha^{-1} yr^{-1}, 1.33 kg P ha^{-1} $yr^{-1}$and 17 kg K ha^{-1} yr^{-1} in 2013; 7.49 kg N ha^{-1} yr^{-1}, 1.48 kg N ha^{-1} yr^{-1} and 17.4 kg N ha^{-1} yr^{-1} in 2014.

3.3.2. Biological nitrogen fixation (IN4)

Nitrogen fixed from the atmosphere is generally an important source of nitrogen input in several agricultural cropping systems. Input by biological nitrogen fixation (BNF) consists of diverse parts, i.e., symbiotic N fixation by leguminous crops and non-symbiotic N fixation. It is worthy to note that the symbiotic nitrogen fixation was not considered in the current study because the study dealt with a cereal in mono-cropping system. The non-symbiotic N fixation (expressed in kg N ha^{-1}) was estimated using the equation developed by Roy and Misra (2003) as follows:

$$N\ fixed = 0.5 + 0.1 \times \sqrt{precipitation(mm)} \quad (7)$$

The values of non-symbiotic N fixation were therefore 2.7 kg N ha^{-1} and 3.1 kg N ha^{-1}, respectively, in 2013 and 2014. These non-symbiotic N values fall in the range of nitrogen fixation values (1 to 5 kg N ha^{-1} yr^{-1}) reported the in Sahelian rangelands by Kurl *et al.* (1982).

3.4. Estimation of outflows not directly measured in this study

3.4.1. Leaching (OUT3)

Leaching losses were considered for N and K. Phosphorus is often strongly bound by soil particles. The extent of the losses depends on soil physical properties (texture and structure), quantities of N and K applied, soil nutrient retention capacity, crop species, and amount and distribution of rainwater.

The quantities of N lost annually through leaching were estimated from the transfer function established by De Willigen (2000) as follows:

$$OUT3\ N = 21.37 + (\frac{P}{C} \times L) \times (0.0037 \times Nf + 0.0000601 \times OC - 0.00362 \times Nu) \quad (8)$$

where P is annual precipitation (mm yr^{-1}), C is the clay content (%) of the topsoil, L is rooting depth (m), Nf is N applied through mineral fertilizer and/or organic fertilizer (kg ha^{-1}), OC is organic carbon content (%) of the topsoil and Nu is N uptake by the crop (kg ha^{-1} yr^{-1}).

The amount of K lost through leaching was calculated using the formula described by Smaling *et al.* (1993) as follows:

$$OUT3\ K = (Ke + Kf) \times (0.00029 \times precipitation + 0.41) \quad (9)$$

where Ke is the exchangeable K ($cmol_c$ kg^{-1}) in the top soil and Kf is the amount of K derived from applied amendment.

3.4.2. Gaseous losses (OUT 4)

Gaseous N losses from the soil were estimated from a regression model developed by Roy and Misra (2003). The equation consisted of two parts: a regression model for the nitrous oxide (N_2O) losses through denitrification and a direct loss factor for volatilization of ammonia (NH_3) as follows:

$$OUT4 = (0.025 + 0.000855 \times P + 0.01725 \times F + 0.117 \times OC) + 0.113 \times F \quad (10)$$

where P is the rainfall (mm), F is the amount of nitrogen in mineral and organic fertilizers (kg N ha^{-1}) and OC is the organic carbon content (%).

3.4.3. Erosion (OUT5)

According to Buerkert and Hiernaux (1998), wind erosion is often described as the major threat to soil productivity and crop yield on the unprotected sandy soils of Niger characterized by 95% sand content. The data (11 kg N ha^{-1} yr^{-1}, 7.1 kg P ha^{-1} yr^{-1} and 5.4 kg K ha^{-1} yr^{-1}) published by Buerkert *et al.* (1996) on soil nutrients losses due to wind erosion at the plot level in millet field were considered as OUT5 in the current study.

The full nutrient balances were therefore quantified as follows:

$$Nutrient\ balance = (IN1 + IN2 + IN3 + IN4) - (OUT1 + OUT2 + OUT3 + OUT4 + OUT5) \quad (11)$$

3.5. Stock to nutrient balance ratio

The nutrient stock to nutrient balance ratio, which gives an indication of the length of time a cropping system could sustain production at the same level with the available nutrients, was calculated using the formula given by Defoer *et al.* (2000) as follows:

$$NSB = \frac{Nutrient\ stock}{Full\ nutrient\ balance} \quad (12)$$

3.6. Data analysis

Prior to the analysis, all the data collected were carefully checked for normal distribution in GENSTAT v. 9 using 'Distributions' options. Thereafter, the data were subjected to analysis of variance in GENSTAT v. 9 (Trust 2007) using a general treatment structure (in randomized blocks). The model of analysis of variance (ANOVA) included the fertilizer micro-dosing option, manure rate, year and their interactions. It is worthy to note that for the treatments where full balances were positive, the balance to stock ratio for those treatments was omitted in the analysis and therefore an unbalanced design structure was used for analysis of variance of nutrient balance to stock ratio, particularly in 2013. Differences among treatments were considered at error probabilities ≤ 0.05.

4. Results and discussion

4.1. Rainfall distribution during the cropping periods

The rainfall distribution during the cropping period in 2013 and 2014 is illustrated in Fig. 1. The total rainfall recorded during the 2013 cropping period was 475 mm, which was less than the long-term (1983–2014) rainfall average of 551 mm yr^{-1} at the experimental site. Most of the rain events occurred during August (from 40 to 65 days after sowing), which accounted for 75% of 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.

4.2. Soil nutrient stocks

Total stocks of N, P and K in the upper 20 cm of the soil depth ranged from 562 to 695 kg N ha^{-1}, with 12–48 kg ha^{-1} as available P and 166–289 kg ha^{-1} as exchangeable K (Table 2). There were no significant differences in soil total N and exchangeable K stocks among the fertilizer micro-dosing option and manure rates. The level of N stock is low but higher than the range of N stock (178–278 kg ha^{-1}) reported by Opoku (2011) in the traditional farms of southwest Niger. The available P and exchangeable K stocks were generally within 18–75 kg ha^{-1} and 120–300 kg ha^{-1}, respectively, estimated to be the average levels agronomically adequate for crop growth (Defoer *et al.* 2000).

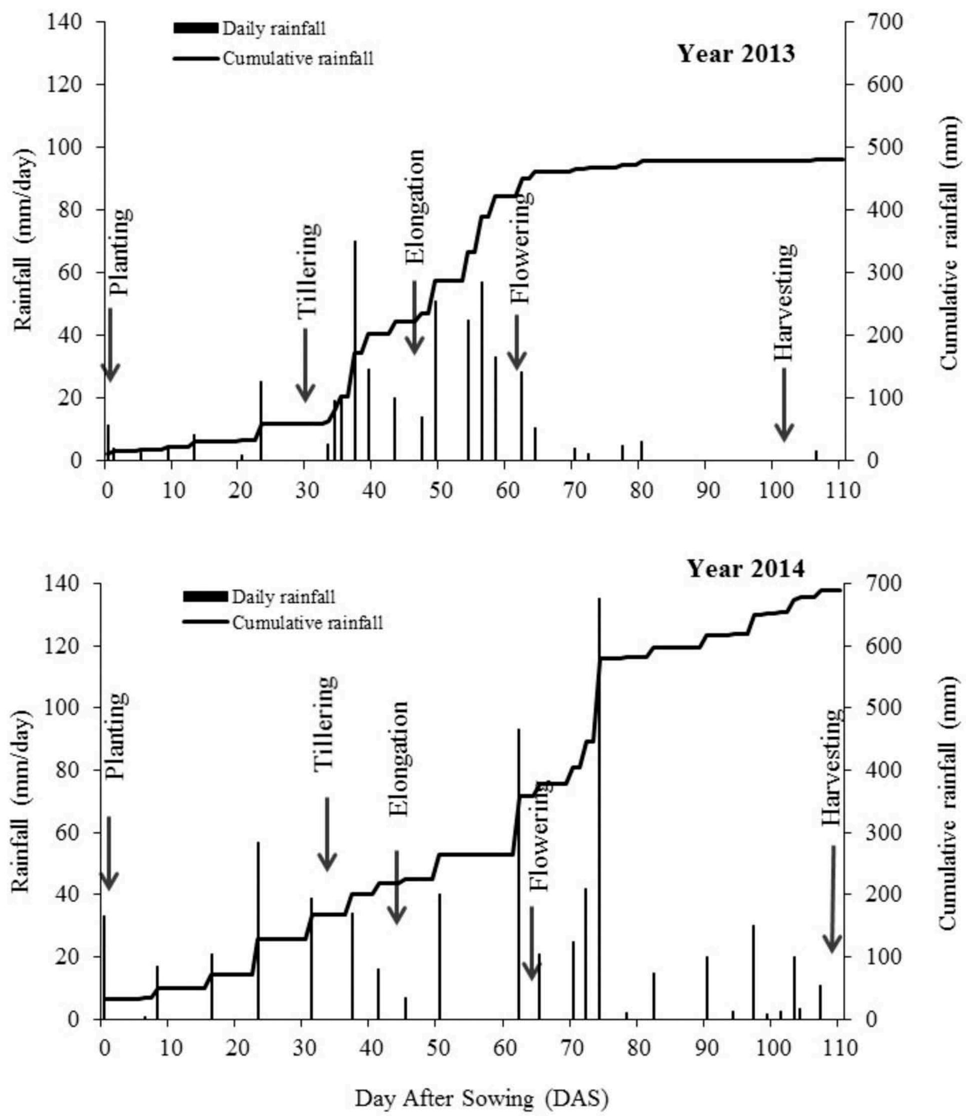

Figure 1. Rainfall distribution in 2013 (upper panel) and 2014 (lower panel).

Table 2. Soil nutrients stocks in the rooting zone* of the soil.

Fertilizer micro-dosing option	Manure rate (g hill^{-1})	Nutrient stock (kg ha^{-1}) Total N	Available P	Exchangeable K
0	0	562.3 ± 65.6	12.3 ± 2.4	165.5 ± 32.7
	100	629.4 ± 66.9	21.9 ± 4.5	257.5 ± 54.6
	200	655.4 ± 65.5	20.5 ± 4.8	243.4 ± 61.1
	300	682.7 ± 63.6	22.5 ± 5.6	265 ± 58.4
2 g DAP hill^{-1}	0	614.4 ± 72.4	25.8 ± 7.9	196.2 ± 35.5
	100	633.4 ± 73.8	36.1 ± 7.7	242.2 ± 39.8
	200	626.5 ± 61.6	27.0 ± 6.2	281 ± 65.9
	300	648.1 ± 61.5	41.1 ± 10.7	289.1 ± 69.6
6 g NPK hill^{-1}	0	617.2 ± 45.6	30.5 ± 3.2	257.3 ± 70.0
	100	594.7 ± 73.6	30.6 ± 6.6	219.2 ± 43.0
	200	675.6 ± 83.7	22.5 ± 8.4	289.4 ± 70.3
	300	695.2 ± 82.3	47.7 ± 9.9	278.4 ± 54.9
Probability for:				
Fertilizer micro-dosing (F)		0.945	0.009	0.773
Manure (M)		0.524	0.047	0.395
F × M		0.985	0.762	0.956
LSD (5%) for:				
Fertilizer micro-dosing (F)		96.6	9.8	79.5
Manure (M)		111.5	11.32	91.8
F × M		193.1	19.61	159

* Rooting zone refers to the soil layer where most of the roots are concentrated; ± standard error.

4.3. Millet grain and straw yields

The grain and straw yields recorded in 2013 and 2014 are presented in Table 3. The grain yields ranged from 106 to 852 kg ha^{-1} in 2013. These grain yields were significantly lower than those produced in 2014, which ranged from 607 to 1875 kg ha^{-1}. There was a significant year effect ($P < 0.001$) on the millet grain yields recorded in the current study. The difference in grain yields between the two cropping seasons could be attributed to the inter-annual variability and intra-annual rainfall distribution observed between the rainy seasons in the study area (Fig. 1), where dry spells during the cropping seasons are common occurrences (Sivakumar and Salaam 1999). This inter-annual yield difference could also be explained by the difference in quality of manure applied; more N input was supplied through manure in 2014 compared with that supplied in 2013 (Table 1).

The grain yields were significantly higher ($P < 0.001$) in the fertilizer micro-dosing treatment plots compared with those in unfertilized control plots. Millet grain yield increased by 39% and 72% for the plots that received the fertilizer micro-dosing of 6 g NPK hill^{-1} and 2 g DAP hill^{-1}, respectively, in comparison with the unfertilized control plots. The increase in millet yields observed in this study is in line with the results of other recent studies on fertilizer micro-dosing in West Africa (Tabo *et al*. 2007; Hayashi *et al*. 2008; Ibrahim *et al*. 2015). 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.

There was an additive effect of fertilizer micro-dosing and manure on millet grain yields. The grain yield increased markedly when manure was added to fertilizer micro-dosing treatments (2 g DAP hill^{-1}and 6 g NPK hill^{-1}) regardless of the rate of manure applied. Basically, a similar trend was observed for the data on the straw yields. The highest straw yields were produced in the plots that received combined application of fertilizer micro-dosing treatments with manure, regardless of manure rates applied. Generally, application of mineral fertilizer along with organic amendment increased nutrient availability, which resulted in high grain yield and dry matter production (Abd El-Lattief 2011). The positive effect of combined application of manure and mineral fertilizer micro-dosing in increasing millet yields could be attributed not only to an increase in soil macronutrient availability (N, P and K) but also to the supply of additional nutrients such as Ca and Mg (Bayu *et al*. 2005; Zingore *et al*. 2008) from manure which are particularly lacking in sufficient quantity in most Sahelian sandy soil. The increased yields due to manure addition could also be explained by the low level of organic matter content in this extremely sandy experimental soil which limits soil water and nutrient retention. The combined use of mineral fertilizer and manure therefore generates favorable soil conditions by enhancing the soil water holding capacity and increasing crop nutrient availability.

4.4. Nutrients flows

Table 1 summarizes the nutrient flows (inputs and outputs) applied in the current study. Manure (IN2) was the main input of N, P and K

Table 3. Grain and straw yields recorded in 2013 and 2014.

Fertilizer micro-dosing option	Manure rate (kg hill^{-1})	Grain yield (kg ha^{-1}) 2013	Grain yield (kg ha^{-1}) 2014	Straw yield (kg ha^{-1}) 2013	Straw yield (kg ha^{-1}) 2014
0	0	106 ± 20	607 ± 112	563 ± 36	2000 ± 314
	100	185 ± 38	999 ± 79	792 ± 42	3458 ± 463
	200	325 ± 34	1019 ± 65	1000 ± 115	4167 ± 300
	300	548 ± 47	1337 ± 86	1000 ± 144	4833 ± 210
2 g DAP hill^{-1}	0	354 ± 90	876 ± 36	1000 ± 72	2792 ± 216
	100	517 ± 73	1431 ± 162	1438 ± 108	3944 ± 242
	200	790 ± 62	1503 ± 105	1667 ± 150	4014 ± 251
	300	802 ± 87	1875 ± 262	1958 ± 102	5278 ± 174
6 g NPK hill^{-1}	0	237 ± 37	753 ± 91	750 ± 43	2750 ± 181
	100	459 ± 62	1399 ± 191	1233 ± 41	3014 ± 174
	200	499 ± 16	1449 ± 152	1333 ± 166	3528 ± 201
	300	852 ± 63	1441 ± 188	2125 ± 188	3194 ± 324
Probability for:					
Year (Y)		<.001		<.001	
Fertilizer micro-dosing (F)		<.001		0.002	
Manure (M)		<.001		<.001	
Y × F		0.673		0.006	
Y × M		0.045		0.046	
F × M		0.814		0.535	
Y × F × M		0.529		0.023	
LSD (5%) for:					
Year (Y)		98		259	
Fertilizer micro-dosing (F)		119		317	
Manure (M)		138		366	
Y × F		169		449	
Y × M		195		518	
F × M		239		635	
Y × F × M		339		896	
CV (%)		24.2		22.6	

± standard error; CV is coefficient of variation.

among all the inflows. Although the same rates of manure (1000 kg ha^{-1}, 2000 kg ha^{-1}, and 3000 kg ha^{-1}) were applied in 2013 and 2014 rainy seasons, the N inputs supplied by manure in 2014 were higher than those of 2013. However, the highest P and K inputs were supplied by manure in 2013. The rainfall and dry depositions (IN3) brought a high quantity of potassium in comparison to that applied through mineral fertilizer (IN1). The contribution of non-symbiotic N fixation was estimated to be 2.7 kg N ha^{-1} and 3.1 kg N ha^{-1} in 2013 and 2014, respectively. Nutrient exports from crop residue (OUT2) were on average 28 kg N ha^{-1}, 2.0 kg P ha^{-1}, and 40 kg K ha^{-1} in 2013. Greater N and P exports from crop residue were recorded in 2014 (54.4 kg N ha^{-1}and 10.2 kg P ha^{-1}) while the highest export for K (78.3 kg ha^{-1}) was documented in 2013. The nutrients transferred through crop residue were greater than those from grain yields (OUT1). Nutrients losses through leaching (OUT3) and erosion (OUT5) were the main sources of nutrient exports (N and P) among the outputs indirectly measured. The amount of N leaching obtained in 2013 ranged from 16.0 to 21.4 kg N ha^{-1} which is not far away from the range of 19 to 21 kg N ha^{-1} reported by Opoku (2011) in Niger. Generally, crop residue (OUT2), leaching losses (OUT3) and wind erosion (OUT5) were the major sources of nutrient removal in the current study.

4.5. Partial nutrient balances

The partial nutrient balances (IN1 + IN2 – OUT1 – OUT2) in 2013 and 2014 are presented in Table 4. The partial nutrient balances in 2013 were −26.2 kg N ha^{-1} yr^{-1}, +1.6 kg P ha^{-1} yr^{-1} and −34.8 kg K ha^{-1} yr^{-1} in plots that received the application of 2 g DAP hill^{-1}, and −19.0 kg N ha^{-1} yr^{-1}, + 1.8 kg P ha^{-1} yr^{-1} and −16.4 kg K ha^{-1} yr^{-1} for application of 6 g NPK hill^{-1}. There was a significant year effect ($P < 0.001$) on the partial nutrient balances among fertilizer micro-dosing options. The partial N, P and K balances recorded in 2013 from fertilizer micro-dosing plots (2 g DAP hill^{-1} and 6 g NPK hill^{-1}) were significantly lower than those obtained in 2014. These inter-annual partial nutrient balances recorded could be attributed to the highest grain and straw yields obtained in 2014.

In both cropping seasons, the N and K partial balances recorded in fertilizer micro-dosing plots were significantly greater than those obtained in the control plots. In 2013, the partial N balances were negative in all plots that received the application of fertilizer micro-dosing treatments. Combined application of manure and fertilizer micro-dosing generally increased the negative nutrient balance due to the increment in soil nutrient uptake as a result of enhancing nutrient availability with manure addition. The P partial balances were positive in all of the amended plots, while K partial balance showed negative trend for the applied nutrients excluding the plots that received a sole application of 200 g manure hill^{-1} or 300 g manure hill^{-1}. In 2014, the partial balances for N, P and K were more negative compared with 2013 in all treatments except in the plots that received the combined application of 6 g NPK hill^{-1} with 200 g manure hill^{-1} or 300 g manure hill^{-1}, where the partial P balances were + 0.6 kg P ha^{-1} yr^{-1} and + 3.3 kg P ha^{-1} yr^{-1}, respectively. The positive partial balance for P documented in these treatments could be attributed to the relatively low P uptake by the plants in these treatments as compared to P applied.

The N partial balances of sole application of fertilizer micro-dosing ranged from −26 to – 48 kg ha^{-1} yr^{-1} for 2 g DAP hill^{-1} and −19 to −43 kg ha^{-1}yr^{-1} for 6 g NPK hill^{-1}. These N values were higher than the average net N mining, estimated to be 15 kg ha^{-1} yr^{-1}, for the traditional fields planted with pearl millet in the southern Sahel (Buerkert and Hiernaux 1998). The results of the current study indicated that the grain and straw yields of 350 kg ha^{-1} and 1000 kg ha^{-1}, respectively, led to N depletion of 26 kg ha^{-1} yr^{-1} under fertilizer micro-dosing. This value is within the 13 to 56 kg N ha^{-1} yr^{-1} range of losses reported by Ibrahim *et al.* (2014) with the application of 2 g DAP hill^{-1} for millet production under fertilizer micro-dosing. The K partial balance showed a negative balance in all of the plots that received sole application of fertilizer micro-dosing. The depletion of K was more intense in the plots with DAP application where no K input was applied. The implication is that the native K could serve as the main source of K uptake when diammonium phosphate was used as a nutrient source. Although the K stock was within the average level (120–300 kg ha^{-1}) set by Defoer *et al.* (2000), it is clear that continuous cropping without soil K replenishment will lead to the depletion of this stock.

In both cropping seasons, the partial nutrient balances were exacerbated by the millet straw produced (OUT2) which accounted for, on average, 66% N, 55% P and 89% K losses. Although crop residues were an important source of nutrient removal, most of the studies that dealt with nutrient depletion under fertilizer micro-dosing (Buerkert and Schlecht 2013; Aune and Coulibaly 2015) did not consider the quantity of nutrients removed through crop residue. It was observed in the current study that nutrient accumulated in grain yield which exceeds 570 kg ha^{-1} led to nutrient imbalance under fertilizer micro-dosing treatments (Table 4). The grain yields of pearl millet reported in fertilizer micro-dosing technology, on sandy soils across a broad range of climatic and soil conditions in West Africa, ranged from 547 to 577 kg ha^{-1} (Bagayoko *et al.* 2011). It therefore appears that the addition of nutrients removed from crop residue to the reported levels of grain yields will negatively affect the partial nutrient balance. This result agrees with the work of Elias *et al.* (1998) in southern Ethiopia who identified the total removal of crops from the field as a major cause for negative nutrient balances.

4.6. Full nutrient balance

Table 4 provides the full nutrient balances. There were significant differences among fertilizer micro-dosing options in N, P and K full balances. The N full balances were negative for all of the plots that received a sole fertilizer micro-dosing treatment, and ranged from −40.9 kg ha^{-1} to – 46.2 kg ha^{-1} in 2013 and from – 49.8 kg ha^{-1} to – 53.9 kg ha^{-1} in 2014. The full balances for P in 2014 were also negative in all the treatments. However, positive full P balances were obtained in 2013 in the plots that received the application of micro-dosing treatments combined with 200 g manure hill^{-1} or 300 g manure hill^{-1}. The full K balances followed the same trend as the full P balances where negative balances were obtained for all treatments, except for sole applications of 200 g manure hill^{-1} and 300 g manure hill^{-1}.

Table 4. Effect of treatments on partial and full nutrient balances.

		Partial nutrient balances (kg ha^{-1})						Full nutrient balances (kg ha^{-1})					
		N		P		K		N		P		K	
Fertilizer micro-dosing option	Manure rates (g hill^{-1})	2013	2014	2013	2014	2013	2014	2013	2014	2013	2014	2013	2014
0	0	−15.6	−31.5	−1.0	−4.8	−13.9	−27.7	−37.0	−42.9	−6.8	−10.4	−22.7	−27.6
	100	−12.5	−45.6	+1.7	−8.8	−16.1	−50.9	−35.7	−55.1	−4.1	−14.4	−13.4	−43.4
	200	−5.3	−26.2	+4.9	−6.1	+9.4	−39.5	−31.0	−40.1	−0.9	−11.7	+3.4	−36.4
	300	−0.8	−31.4	+7.9	−7.5	+20.2	−50.9	−28.6	−48.7	+2.1	−13.1	+5.4	−52.2
2 g DAP hill^{-1}	0	−26.2	−48.1	+1.6	−3.9	−34.8	−34.0	−46.2	−53.9	−4.2	−9.5	−23.3	−22.1
	100	−31.3	−57.4	+3.1	−8.5	−46.7	−96.3	−51.8	−62.8	−2.7	−14.1	−44.0	−88.8
	200	−28.1	−34.0	+6.3	−6.3	−14.0	−37.9	−50.4	−48.5	+0.5	−11.9	−20.0	−34.8
	300	−26.6	−41.0	+9.2	−7.1	−22.9	−62.6	−50.5	−54.2	+3.4	−12.7	−37.7	−63.9
6 g NPK hill^{-1}	0	−19.0	−42.7	+1.8	−4.0	−16.4	−38.0	−40.9	−49.8	−4.0	−9.6	−9.0	−30.7
	100	−18.4	−33.0	+4.5	−0.1	−18.1	−27.6	−41.8	−47.9	−1.3	−5.7	−19.5	−24.7
	200	−3.5	−30.2	+7.9	+0.6	−0.9	−35.9	−30.8	−46.4	+2.1	−5.0	−11.0	−37.4
	300	−31.6	−16.8	+8.9	+3.3	−25.7	−25.7	−55.3	−36.2	+3.1	−2.3	−44.6	−31.5
Probability for:													
Year (Y)		< 0.001		< 0.001		< 0.001		< 0.001		< 0.001		< 0.001	
Micro-dosing option (F)		< 0.001		< 0.001		< 0.001		< 0.001		< 0.001		< 0.001	
Manure rate (M)		< 0.001		< 0.001		< 0.001		< 0.001		< 0.001		< 0.001	
Y × F		< 0.001		< 0.001		< 0.001		< 0.001		< 0.001		< 0.001	
Y × M		< 0.001		< 0.001		< 0.001		0.010		< 0.001		< 0.001	
F × M		0.022		0.002		< 0.001		0.261		0.002		< 0.001	
Y × F × M		< 0.001		< 0.001		< 0.001		< 0.001		< 0.001		< 0.001	
LSD (0.05) for:													
Year (Y)		2.2		0.7		2.8		2.3		0.6		9.5	
Micro-dosing option (F)		2.7		0.9		3.3		2.8		0.8		4.2	
Manure rate (M)		3.1		1.0		3.8		3.3		1.2		4.9	
Y × F		3.9		1.3		4.7		4.0		1.5		6.0	
Y × M		4.4		1.4		5.5		4.6		1.3		6.9	
F × M		5.4		1.8		6.7		5.7		1.6		8.5	
Y × F × M		7.7		2.5		9.4		8.0		2.7		12.0	
Coefficient of variation (%)		27.1		28.9		19.5		25.0		27.4		24.0	

In all treatments, the full N, P and K balances were significantly greater in 2014 as compared to the 2013 cropping season. All of the treatments exhibited negative full balances for N, P and K in 2014, and the full N balance during this cropping season ranged from −36.2 kg ha^{-1} yr^{-1} to −62.8 kg ha^{-1} yr^{-1}, while the full balances of P varied from −2.3 kg ha^{-1} yr^{-1} to −14.4 kg ha^{-1} yr^{-1} and full K balances ranged from −22.1 kg ha^{-1} yr^{-1} to −88.8 kg ha^{-1} yr^{-1}. The average annual nutrient losses for the two cropping seasons ranged from −35.6 kg ha^{-1} to −57.3 kg ha^{-1} for N and −9.3 kg ha^{-1} to +0.4 kg ha^{-1} for P, while K losses varied from −16.5 kg ha to −66.4 kg ha^{-1} with the highest N (−57.3 kg ha^{-1} yr^{-1}) and K (−66.4 kg ha^{-1} yr^{-1}) losses being recorded with 2 g DAP hill^{-1} combined with 100 g manure hill^{-1}. The average annual losses of nutrients for the two cropping seasons in the plots that received the application of fertilizer micro-dosing treatments (2 g DAP hill^{-1} and 6 g NPK hill^{-1}) were −47.8 kg N ha^{-1} yr^{-1}, −6.8 kg P ha^{-1} yr^{-1} and −21.8 kg K ha^{-1} yr^{-1}, which represented 7.8, 24.1 and 9.4% of N, P and K stocks, respectively. The nutrient depletion recorded from the fertilizer micro-dosing plots show that the quantity of nutrients applied through this technology was not adequate to meet crop requirements for crop biomass production.

Several studies have indicated that a negative nutrient balance does not necessarily imply the threat of soil nutrient depletion through nutrient mining (Bindraban *et al.* 2000; Vanlauwe and Giller 2006). However, this holds particularly when soil nutrient stock is large and able to cushion negative nutrient balances. In a situation such as that of the study area where the soil nutrients stock levels are not large (Table 2), crop production could not be sustained for long. According to Hilhorst *et al.* (2000), agricultural practice with an annual stock decline for total nitrogen of more than 1% was considered not sustainable which was found under a fertilizer micro-dosing practice where the annual N losses accounted for 7.8% of N stock. It thus appears that fertilizer micro-dosing may not be ecologically friendly since the huge quantities of nutrients used by millet come mainly from the soil native nutrients, as indicated by the negative contribution of fertilizer micro-dosing to the nutrient stocks.

4.7. Nutrient stock to balance ratio

The nutrient stock to balance ratio (NSB) in 2013 ranged from 12 to 24 for nitrogen, 2 to 23 for P and 6 to 67 for K (Table 5). These NSB ratios decreased significantly in 2014, ranging from 10 to 16 for N, 1 to 21 for P and 3 to 10 for K. The application of fertilizer micro-dosing plots alone recorded the lowest NSB ratio for N compared to control plots. The NSB ratios for P were 6 and 8 in 2013 for the plots that received the applications of lone 2 g DAP hill^{-1} and 6 g NPK hill^{-1}, respectively. These NSB ratios for P dropped to 3 for the same treatments in 2014. The NSB ratios for K of the sole application of 2 g DAP hill^{-1} were 8 and 9 in 2013 and 2014, respectively. For the plots that received a sole application of 6 g NPK hill^{-1}, the NSB ratios for K were 29 and 8 in 2013 and 2014, respectively.

The combined application of fertilizer micro-dosing with manure (200 g hill^{-1}or 300 g hill^{-1}) in 2013 offered a positive full P balance which means that the system can continue forever, and therefore the NSB of P for such a system would have no physical meaning. The greater value of NSB for P was estimated to be 23 and was similarly obtained in the plots that received the application of 6 g NPK hill^{-1}

Table 5. Effect of treatments on nutrient stock to balance ratio.

Fertilizer micro-dosing option	Manure rate (g hill^{-1})	N 2013	N 2014	P 2013	P 2014	K 2013	K 2014
0	0	15	13	2	1	67	10
	100	18	11	5	2	19	6
	200	21	16	23	2	-	7
	300	24	14	-	2	-	5
2 g DAP hill^{-1}	0	13	11	6	3	8	9
	100	12	10	13	3	6	3
	200	12	13	-	2	14	8
	300	13	12	-	3	8	5
6 g NPK hill^{-1}	0	15	12	8	3	29	8
	100	14	12	23	5	11	9
	200	22	15	-	4	26	8
	300	13	16	-	21	6	4
Probability for:							
Year (Y)		< 0.001		< 0.001		< 0.001	
Fertilizer micro-dosing (F)		< 0.001		< 0.001		0.021	
Manure (M)		< 0.001		< 0.001		0.032	
Y × F		0.002		0.011		0.065	
Y × M		0.757		< 0.001		0.234	
F × M		0.112		0.007		0.724	
Y × F × M		< 0.001		0.009		0.293	

along with 100 g manure hill^{-1} and the sole application of 200 g manure hill^{-1} in 2013, while the highest value of NSB ratio for P of 21 was recorded in the plots that received the combined application of 6 g NPK hill^{-1} with 300 g manure hill^{-1} in 2014 (Table 5). There was a marked decrease in the NSB ratio for K when fertilizer micro-dosing was applied together with manure. However, the decrease in NSB ratio for K appeared to be higher in the plots that received application of manure exclusively in 2014. The NSB ratio for K was 29 with the application of 6 g NPK hill^{-1} and decreased to 8 for the plots that received the lone application of 2 g DAP hill^{-1}. Generally, the NSB ratios for K were lower in the plots where DAP fertilizer was applied compared with the plots that received the application of NPK fertilizer (Table 5).

The NSB, which provides an indication of how long farming can continue in the same way, given the available nutrients (Defoer *et al.* 2000), decreased significantly ($P < 0.001$) from 2013 to 2014 (Table 5). The NSB ratio for N dropped from 13 to 11 years for the plots that received a lone application of 2 g DAP hill^{-1} and from 15 to 12 years in the plots that received the sole application 6 g NPK hill^{-1}. This implies that under the current fertilizer micro-dosing practice, crop yields could be sustained for only 11 to 12 years before reducing the current soil N stock. The situation is even worse in NSB ratios for P and K. The NSB for P did not exceed 3, for the plots that received a sole application of a fertilizer micro-dosing treatment (2 g DAP hill^{-1} and 6 g NPK hill^{-1}), indicating that the P stock sustains crop production for just 3 years with the current level of yields (Table 3). These results indicate that if the stocks of available nutrients are not large, such as in the case of Sahelian sandy soils where soils have mostly low to moderate inherent soil fertility (Bationo *et al.* 1998a), the fertilizer micro-dosing could not support sustainable yields. The results obtained in the current study suggest that for the small-holder farmers, fertilizer micro-dosing technology should be considered as just a stop-gap option.

5. Conclusion and recommendation

The partial and full balances of nutrients obtained in this study were negative and presented 7.8, 24.1 and 9.4% of N, P and K stocks, respectively. These results indicate that fertilizer micro-dosing increases the risk of soil nutrient losses in a low-input millet-based cropping system. Combined application of fertilizer micro-dosing and manure was not able to balance the nutrients exported by the obtained yields. The export of nutrients from crop residue was found to exacerbate the nutrient depletion. Retaining crop residues to the fields could therefore influence reversing the potential soil mining effect of fertilizer micro-dosing technology. It is therefore suggested that for sustained crop production under fertilizer micro-dosing technology, recycling of crop residues must be considered in low-input millet-based cropping systems. The retention of crop residues in the fields has important implications not only for increasing soil nutrient availability (Geiger *et al.* 1992) but also for protecting soil against wind erosion which is one of the major sources of soil nutrient losses in the Sahel (Bielders *et al.* 2001). The exploration of other alternative sources for crop residue is also vital for sustaining crop production in low-input cropping systems. Long-term study is, however, recommended to establish the long-term impact of fertilizer micro-dosing on nutrient mining.

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