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ABSTRACT

The production of pearl millet [*Pennisetumn glaucum* (L.) R. Br.] in the low fertility sandy soils of the Sahel region of northern sub-Saharan Africa requires careful management. An experiment was established in 1993 at the Niamey Center of the International Crops Research Institute for the Semi-Arid Tropics, Niger. The objectives were to (i) determine the effect of long-term applications of fertilizer, crop residue, cattle manure, and combinations of these on changes in grain yield (GY) and total dry matter (TDM) of pearl millet; (ii) determine the effect of management on nitrogen application efficiency (NAE) and nitrogen use efficiency (NUE), using data from 1998 and also from 2005 and 2006. Fertilizer use showed significant positive effects on GY and TDM from 1998 to 2006. The positive effects of organic matter appeared rather later, that is, around 8 yr after the start of the experiment. The GY and TDM were strongly affected by N and P but not K. From 1998 to 2000, N-fertilizer strongly affected GY and TDM, but TDM increased gradually with the total amount N application, including N from organic matter. Nitrogen uptake by pearl millet was similar among treatments except for control in 2005, but in 2006 was higher in the treatments that combined fertilizer and organic matter. The NAE in combined applications of fertilizer and crop residue, and NUE in the treatments with residue showed higher trends than other treatments. This suggested that residue had more potential than cattle manure to enhance the effect of fertilizer.

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The Sahel region in Niger has low productivity due to degraded soils and low and erratic rainfall (Abdoulaye and Sanders, 2006). The depletion of N and P has a negative impact on crop growth (van Keulen and Breman, 1990). For 15 yr, for example, from 1993 to 2008, GY of pearl millet was about 706 kg ha^{-1} in Mali, 754 kg ha^{-1} in Burkina Faso, 626 kg ha^{-1} in Senegal, and 415 kg ha^{-1} in Niger, and had barely increased over this period (FAO, 2013). The use of fertilizer is one of the ways to address nutrient deficiencies but this is not a viable option for resource-poor smallholder farmers in the region, due to the high prices (Sanchez et al., 1997; IFPRI., 2002). In relative terms, fertilizer use in the countries of the Sahel is only 1 to 10% of the amount used in developed countries (FAO, 2013). Even if the farmers can obtain small amounts, they cannot spare sufficient for pearl millet cultivation because they are accustomed to using fertilizer for cash crops (Abdoulaye and Sanders, 2005).

A fallow system of 2 to 3 yr without cultivation to restore soil fertility (Wezel and Haigis, 2002; Hiernaux and Ayantunde, 2004), a practice common among Sahelian farmers in the past, is no longer practicable due to the annual population growth and increased food demand (Wezel and Haigis, 2002; Achard and Banoin, 2003). The farmers generally use locally available household waste, livestock manure, and crop residue instead of fertilizer and the fallow system. Corralling livestock, enclosing domestic animals so that they drop their feces directly on the fields, is a traditional soil management strategy (Hoffmann et al., 2001; Schlecht and Buerkert, 2004; Suzuki et al., 2014). This manure is managed with household waste and manure accumulating near homes and transported to the fields by cart or by hand to increase soil nutrients and promote the accumulation of soil organic matter (Suzuki et al., 2014); it can help to improve the cation exchange capacity (CEC) and enhance the buffering capacity of soil pH in the region (de Ridder and van Keulen, 1990; Manu et al., 1991; Bationo and Buerkert, 2001; Bationo

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Abbreviations: CEC, cation exchange capacity; GY, grain yield; NAE, nitrogen application efficiency; NUE, nitrogen use efficiency; SSP, single super phosphate; TC, total carbon; TDM, total dry matter; TK, total potassium; TN, total nitrogen; TP, total phosphorus; WAP, weeks after planting.

et al., 2007; Suzuki et al., 2014). This is especially important for these sandy soils with extremely low content of clay and organic matter (Pieri, 1979; Pichot et al., 1981; de Ridder and van Keulen, 1990). Thus, deleterious effects on crop growth are expected following sole application of fertilizer as urea and single super phosphate (SSP) due to increase of Al ion in the soil (Pieri, 1979; Kretzschmar et al., 1991). This negative effect often appears when fertilizer has been applied exclusively for a long time (Pieri, 1979, 1992; Pichot et al., 1981; Hafner et al., 1993; Bationo et al., 1993, 1998), and long-term experiments provide a good opportunity for such analyses. Using experiments conducted since the 1960s at Bambey in Senegal, Pieri (1979, 1992) showed that combined management with rice straw and fertilizer, compared with sole fertilizer, could increase GY of groundnut (*Arachis hypogaea* L.), improve soil pH, and decrease the concentration of the toxic Al^{3+} ion (Pieri, 1979, 1992). This and other previous studies (Hafner et al., 1993; Bationo et al., 1993, 1998) showed the importance of combined applications of fertilizer with organic matter to maintain efficacy.

In the previous studies, crop residues {sorghum [*Sorghum bicolor* (L.) Moench] [Pichot et al., 1981]; rice straw [Pieri, 1979]; pearl millet [Hafner et al., 1993; Bationo et al., 1993, 1995, 1998, Yamoah et al., 2002; Abdou et al., 2012]} or manure (Pichot et al., 1981) were used to elucidate the efficacy of applications combined with fertilizer. The long-term experiment in Saria, Burkina Faso, showed that manure has a higher potential to enhance sorghum GY than sorghum residue (Pichot et al., 1981). However, they did not apply the same amounts of crop residue and manure; hence differences in efficacy between residue and manure as amendments to be combined with fertilizer have not yet been elucidated.

With this background, we focused on the long-term experiment in which application of fertilizer, crop residue, and cattle manure had continued since 1993 in the test field of ICRISAT-Niamey (13°15′ N, 2°18′ E, altitude 221 m) (Akponikpe et al., 2008), and this experimental field was the fallow since the establishment of ICRISAT-Niamey in 1983. The objectives were to (i) determine the effect on pearl millet of the long-term applications of fertilizer, crop residue, cattle manure, and combinations of these amendments on the change in GY and TDM; (ii) determine the effect of management on NAE and NUE using data accumulated from 1998 and our data collected from 2005 to 2006, and (iii) identify the differences in the efficacy of residue and manure through the results of (i) and (ii).

MATERIALS AND METHODS

Long-Term Experiment

In 1993, a long-term experiment was established in the experiment field of the Niamey center of ICRISAT, Niger. However, the data of crop yield from 1993 to 1997 were not available, thus we focused on data from 1998 to 2006. The experiment consisted of a split plot with the whole plots arranged in a randomized complete block design with three replications. The main plots (10 by 20 m) consisted of three different nutrient sources. Each at three levels as application factors, that is, (i) fertilizer as urea and SSP, (ii) dried pearl millet residue, and (iii) cattle manure. Levels of fertilizer (F) application in kg ha^{-1} were 0N + 0P (F0), 15N + 4.4P (F1), and 45N + 13.1P (F2). Levels of residue (R) application in kg ha^{-1} were 300 (R0), 900 (R1), and 2700 (R2). Levels of cattle manure (M) application in kg ha^{-1} were 300 (M0), 900 (M1), and 2700 (M2). There were four subplots (5 by 10 m) in each treatment with different cultivation systems, that is, sole pearl millet, intercropping pearl millet, and rotating pearl millet and cowpea [*Vigna unguiculata* (L.) Walp.] (Fig. 1). Pearl millet residue was applied on the soil surface before the crop

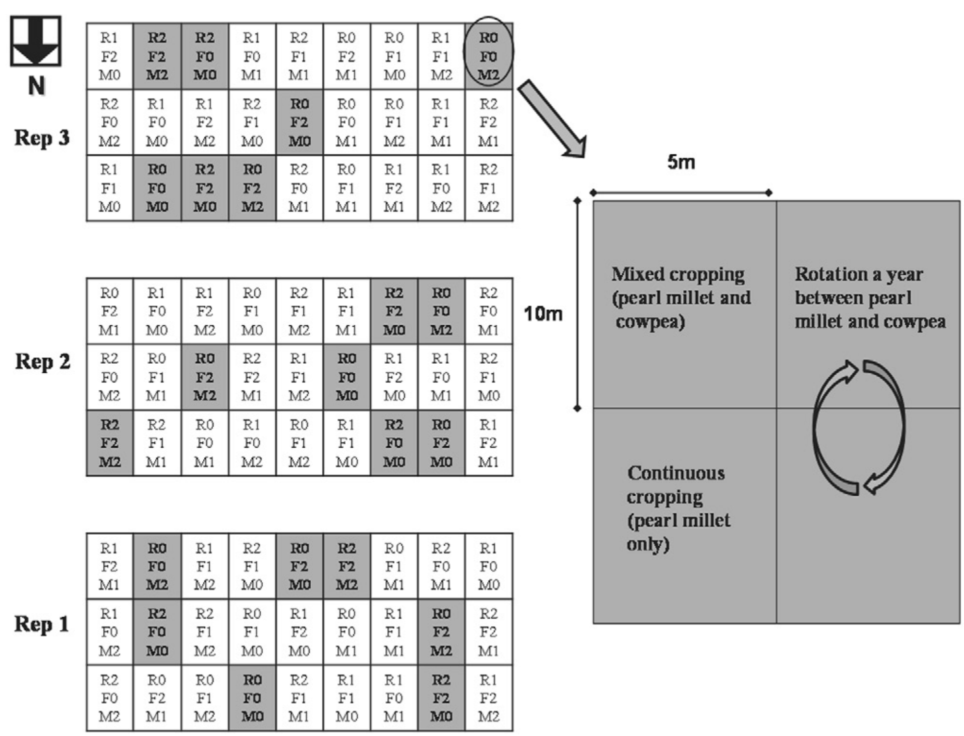

Fig. 1. Plot design of the long-term experiment in the Niamey center of ICRISAT, Niger. Attention was focused on the gray plots to collect plant and soil samples.

was planted and SSP was broadcast straightaway after planting. Manure was applied on the surface at the first weeding and incorporated at a depth of 5 cm by the traditional manual hoe (*Hilaire* in French and *Koumbou* in the local language, Zarma). Urea was broadcasted on the soil surface during weeding operations at about 2 and 7 to 8 wk after planting (WAP).

The soils are Pasammentic Paletustalf and the A horizon has more than 90% sand, 3% silt, and 2.9 to 5.3% clay. Sand content is about 85% in the B horizon, thus silt and clay contents were higher than in the A horizon (West et al., 1984). Soil organic carbon, pH, exchangeable K and CEC in A horizon were 1.2 to 1.7 g kg^{-1}, 5.4 to 5.6 (soil/water = 1:1), 0.1 $cmol_c$ kg^{-1} and 1.0 $cmol_c$ kg^{-1} (West et al., 1984). According to the analysis data conducted in 2000, the available P in A horizon under R0F0M0 was 2.9 to 4.9 g kg^{-1} (extracted with Bray 1; A. Bationo, personnel communication, 2004).

Mean annual rainfall was about 528 mm from 1998 to 2006, but extremely low in 2000 (Fig. 2). The rainfall pattern in each year was very different (Fig. 2). The rainfall patterns in 2002 and 2005 were better for pearl millet cultivation; the rainfall started at the end of April and increased gradually from June, decreased gradually, and stopped in November. The risky patterns were in 1998 and 2006 because rainfall increased suddenly in July and stopped in October. From 1998 to 2006 daily temperatures were 35 to 41°C (max.) and 21 to 25°C (min.).

We focused on a total of seven treatments, each with a factor application level of 0 and 2; R0F0M0, R0F2M0, R0F0M2, R0F2M2, R2F0M0, R2F2M0, and R2F2M2. The treatments were identified as C (R0F0M0 as control), F, M, FM, R, RF, and RFM, focusing on two levels of application. We selected sole pearl millet as the only subtreatment. Therefore, the experimental design that we are dealing with in this paper is completely randomized block design with seven treatments and three replications. From the results of analyzing the past yield data, we considered that it was important to establish the effect on crop growth of the combination of fertilizer and organic matter, so the treatment of R2F0M2 was excluded from analysis in the field.

Field Management

Seeds were planted at the beginning of the rainy season immediately after about 20 mm of rainfall. Following the farmers' practice, holes 10- to 15-cm deep were made with a long

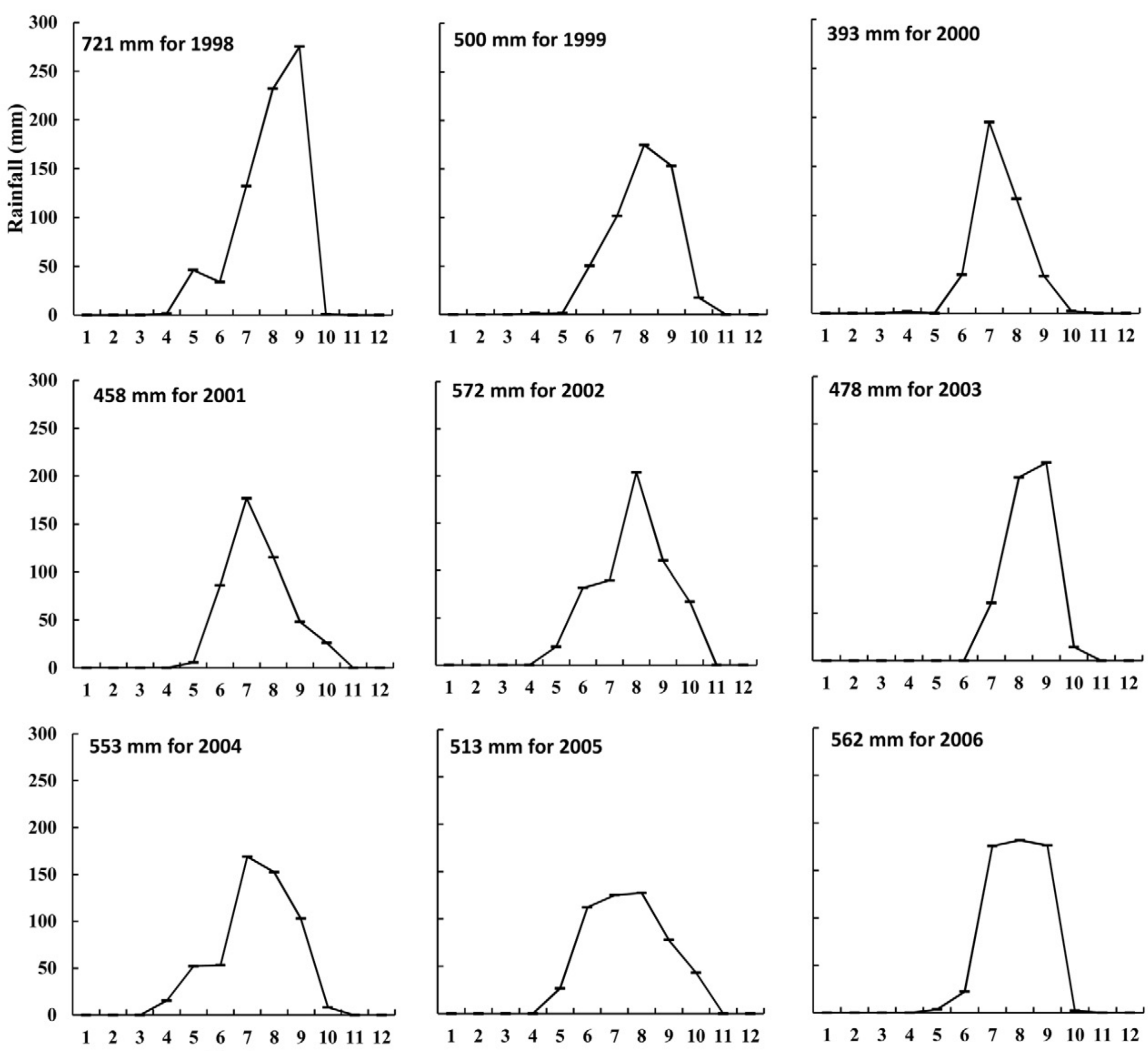

Fig. 2. Rainfall patterns during 9 yr since 1998. The mean of rainfall during 9 yr is 528 mm.

hoe and approximately 30 to 40 seeds of pearl millet (cultivar CIVT) were placed in each hole. The plants started to emerge after about 2 to 3 d and four or five plants per hill were left at 4 WAP. In 2004 and 2006, we replanted seeds in some hills as there was insufficient rainfall after planting.

Weeding with the traditional long-handled hoe (Ooyama, 2006) was usually done twice in the rainy season (but three times in 2006) at 2 to 3 and 7 to 8 WAP. The crop was harvested at around 4 mo after planting. First, the panicles were harvested but the stems were left in the fields to dry naturally. All plants were harvested except those on the borders in every subtreatment plot. Pearl millet was sufficiently dry at harvest, thus the panicles from 24 hills in each subtreatment were weighed immediately after being cut. Weighing the panicles, wind threshing, and manual cleaning were conducted and GY was measured. The following May, before the beginning of the rainy season, the dry stems were cut at the base and weighed as dry matter. We calculated TDM as the sum of the weights of panicles and stems.

Pesticide was rarely used except where there was insect infestation. This happened once during the study to deal with locust swarms from the Sahara desert in 2004. In this year, numerous locust swarms were on move across the Sahelian countries of West Africa (FAO, 2004).

Nitrogen, Phosphorus, and Potassium Contents in the Applied Organic Matter

Before planting in 2005, we collected samples of crop residue and cattle manure to be used in the experiment. The samples were air-dried in an oven at 65°C for 2 d and milled with a grinder (Rotor Speed Mill Pulverisette 14; FRITSH, Idar-Oberstein, Germany). The ground samples were passed through a 0.5-mm sieve for the analysis of N, P, and K contents.

Total nitrogen (TN) was determined by automated dry combustion method (Sumigraph NC22F; Sumika, Tokyo, Japan). Total phosphorus (TP) was measured with the molybdenum-blue method and total potassium (TK) with the atomic absorption spectrophotometer (AA6700F; Shimazu, Kyoto, Japan), after digestion with sulfuric acid following the method of Matsunaga and Shiozaki (1989).

Analysis of Nitrogen Uptake by Pearl Millet

During the 2005 and 2006 cropping seasons, two plants were sampled from each treatment at harvest to analyze N uptake. After sampling, panicles and stems were separated and dried in the oven at 65°C for 2 d. They were then ground with the grinder and passed through a 0.5-mm sieve. Grain samples were also ground similarly. The content of N was determined by the automated dry combustion method (Sumigraph NC22F; Sumika, Tokyo, Japan), and N uptake was calculated from the dry weight of plants.

Nitrogen Application Efficiency and Nitrogen Uptake Efficiency

The nitrogen application efficiency (NAE) was calculated as follows:

$$NAE = (TDM_t - TDM_c)/(NA_t - NA_c)$$

where TDM_t is total dry matter (kg ha^{-1}) in each treatment; TDM_c is total dry matter (kg ha^{-1}) in the control; NA_t is amount of nitrogen application (kg ha^{-1}) in each treatment; and NA_c is amount of nitrogen application (kg ha^{-1}) in the control.

Additionally, the NUE was calculated using the modified method of Craswell and Godwin (1984) as the indicator of the relationship between N uptake and N application,

$$NUE = (PN_t - PN_c)/(NA_t - NA_c)$$

PN_t; nitrogen content of aboveground dry matter of plants in each treatment, PN_c; nitrogen content of aboveground dry matter of plants in the control, NA_t; nitrogen application in each treatment, NA_c; nitrogen application in the control.

Total Nitrogen and Total Carbon Analysis of Soil Samples

Soil samples were collected from the seven treatments with the monoculture of pearl millet from 2004 to 2006 mainly at seeding, vegetative growth, heading, and after harvesting. The undisturbed soil samples (diam. 5 cm) were taken from five spots and combined for one composite sample per plot. The sampling depths were 0 to 10 and 10 to 20 cm in 2004 and 0 to 15 cm in 2005 and 2006. The collected soil samples were air-dried, passed through a 2-mm sieve, and analyzed. The contents of TN and TC were determined by automated dry combustion method (Sumigraph NC22F; Sumika, Tokyo, Japan).

Statistical Analysis

Analysis of variance was used to identify the effects of the three amendments on GY and TDM. Pearson product-moment correlation coefficient was used to identify the correlation between the essential nutrients (N, P, and K) and GY and TDM. To identify the significant differences of N uptake under the different soil managements, the LSD is only used when the F test is significant ($P < 0.05$).

RESULTS

Effects on Grain Yield and Total Dry Matter

Fertilizer application significantly affected GY from 1998 but the effects of crop residue and manure appeared from 2001 (Table 1). The interactions of two among the three elements appeared in 1998 only. The effect of fertilizer application on TDM also appeared from 1998 but the effects of residue and manure started to appear from 1999 or 2000. The interaction of these application factors showed different trends. Although a significant interaction on TDM between residue and fertilizer had been recognized four times since 2001, other interactions had seldom been recognized.

Correlation between Grain Yield or Total Dry Matter and Nitrogen, Phosphorus, and Potassium Application

In this long-term experiment, the application of N, P, and K was mixed and the application rates differed proportionally in each treatment. Thus, the effects of N, P, and K nutrients on GY and TDM were evaluated separately using the results of analyses for N, P, and K contents in the organic matter applied in 2005.

Table 1. Significance of the effects of different applications on grain yield and total dry matter of pearl millet from 1998 to 2006.

Treatment	Year								
	1998	1999	2000	2001	2002	2003	2004	2005	2006
					With grain yield				
Residue (R)	ns†	ns	ns	*	**	*	ns	**	ns
Fertilizer (F)	**	**	**	**	**	**	**	**	ns
Manure (M)	ns	ns	ns	**	**	**	**	ns	*
R×F	*	ns	ns	ns	ns	ns	ns	ns	ns
F×M	*	ns	ns	ns	ns	ns	ns	ns	ns
R×M	*	ns	ns	ns	ns	ns	ns	ns	ns
R×F×M	ns	ns	ns	ns	ns	ns	ns	ns	ns
					With total dry matter				
Residue (R)	ns	**	**	**	**	*	ns	ns	**
Fertilizer (F)	**	**	**	**	**	**	**	**	**
Manure (M)	*	ns	*	**	**	**	**	**	ns
R×F	ns	ns	ns	*	ns	*	*	*	ns
F×M	ns	ns	ns	ns	ns	ns	ns	ns	*
R×M	ns	ns	ns	ns	ns	ns	ns	ns	ns
R×F×M	*	ns	ns	ns	ns	*	ns	ns	ns

* $P < 0.05$.
** $P < 0.01$.
† ns, nonsignificant.

The TDM was significantly and highly correlated with N and P application from 1998 and GY from 1999 (Table 2). Throughout the experiment GY and TDM were not significantly correlated with K application.

Relationship between Total Dry Matter and Total Amount of Nitrogen Application

We further focused on the relationship between TDM of pearl millet and total amount of N application from 1998 to 2006 (Fig. 3). In 1998, at the fifth year after application had started, the TDM tended to increase with the levels of fertilizer application (either F0, F1, or F2). This trend seems to have continued up to 2000. From 2001, however, TDM showed a different trend: it increased with the total amount of N application (either in fertilizer or organic matter or both). The correlation coefficient for the relationship between TDM and the total amount of N applied increased gradually: $r = 0.747$ ($P < 0.001$) in 1998, 0.920 ($P < 0.001$) in 2001, and 0.945 ($P < 0.001$) in 2004. The correlation coefficients in 2002 and 2006 were low ($r = 0.693$ and 0.776, $P < 0.001$) for unknown reasons.

Changes of Grain Yield and Total Dry Matter in Different Fertilizer/Organic Matter Applications

Figure 4 showed the changes of GY (Fig. 4a) and TDM (Fig. 4b) from 1998 to 2006 in the focused seven treatments. The TDM in F treatment (application of 45N and 13.1P kg ha^{-1} as urea and SSP) was higher than that in C (no-application of fertilizer). However TDM in F did not show increases at the beginning of the experiment (from 1998 to 1999). As a whole, GY and TDM in the combined applications of fertilizer and organic matter (FM, RF, and RFM) tended to be higher than in the sole applications (F, M, and R).

Changes in Nitrogen Application Efficiency, Nitrogen Uptake, and Nitrogen Use Efficiency

From 1998 to 2006, NAE tended to be high in RF and F (Fig. 5) but low in RFM and FM where the application of fertilizer and organic matter was integrated. In the treatments applying organic matter sole, NAE in M tended to be lower compared with F, except in 2001 and 2004; NAE in R did not show a consistent trend and was very erratic.

Table 2. Correlation matrix between main nutrients (N, P, and K) and grain yield and total dry matter of pearl millet from 1998 to 2006.

Applied nutrients	Year								
	1998	1999	2000	2001	2002	2003	2004	2005	2006
					With grain yield				
N	0.69	0.78*	0.88**	0.94**	0.99**	0.99**	0.96**	0.87*	0.86**
P	0.88**	0.91**	0.97**	0.92**	0.90**	0.89**	0.87**	0.88**	0.91**
K	0.06	0.23	0.25	0.48	0.58	0.57	0.49	0.49	0.43
					With total dry matter				
N	0.83*	0.80*	0.93**	0.95**	0.94**	0.96**	0.97**	0.94**	0.73*
P	0.97**	0.87**	0.95**	0.86**	0.93**	0.94**	0.86**	0.94**	0.87**
K	0.18	0.31	0.46	0.59	0.50	0.49	0.54	0.45	0.26

* $P < 0.05$.
** $P < 0.01$.

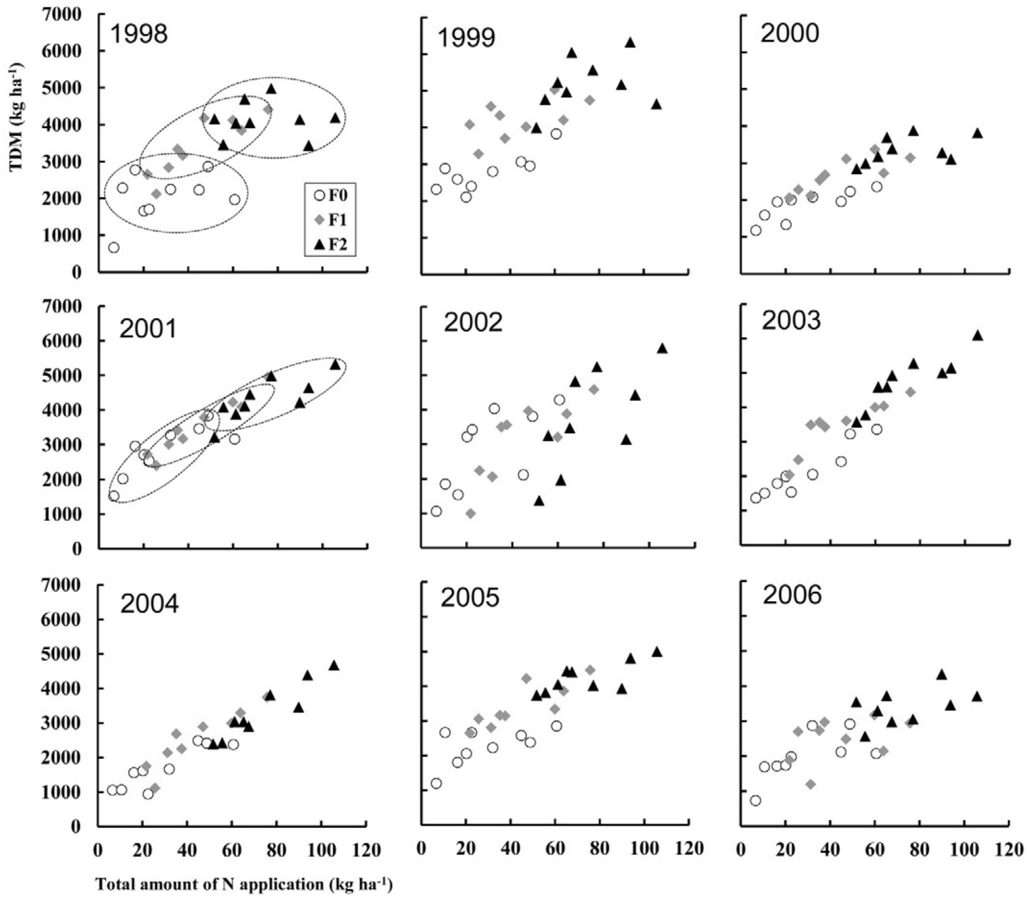

Fig. 3. Trends of relationships between total dry matter (TDM) of pearl millet and N applied from 1998 to 2006. The application levels of chemical fertilizer are F0; 0N + 0P, F1; 15N + 4.4P, F2; 45N + 13.1P (kg ha^{-1}). Total amount of N application on the *x* axes is consisted of N contents from the applied chemical fertilizer, crop residue, and cattle manure.

In 2005, N uptake by pearl millet was significantly higher in RFM where all amendments were applied at the highest level (Fig. 6a). Other treatments did not show a significant difference in their N uptake except for C where it was significantly lower than that in other treatments. In 2006, N uptake in RF and RFM was significantly higher than in C, M, and R, but not significantly different from that in F and FM (Fig. 6b). Though F, M, R, and FM showed a significant difference in N uptake in 2005, they did not show this in 2006, compared with C. The NUE in R was the highest among all treatments (Fig. 7a; 1.21 in 2005; Fig. 7b; 0.80 in 2006). The NUE in RF also tended to be higher than in FM and RFM in the combined treatment of fertilizer and organic matter.

Total Nitrogen and Total Carbon Contents in the Surface Soil

To estimate TN and TC contents in the soil, we focused on the average TN and TC contents in the surface soil layers across the sampling times from 2004 to 2006. The reason to focus on surface soil was that the dynamics of TN and TC to a depth of 105 cm were measured but the remarkable changes in the deeper soil layers were not detected (data not shown).

As a whole, TN content in the surface soil layer for 3 yr tended to be higher in R, RF, and RFM compared with others (Fig. 8). The R and RF especially showed higher trends compared with M and FM, although their application rate in N was lower. The amount of TC in surface soil from 2004 to 2006 was higher in RF and RFM (Fig. 9) and in FM tended to be lowest in the combined treatments of fertilizer and organic matter. Among sole applications of F, M, and R, the highest result was from R except in 2004. The correlation between TN and TC in the surface soil was significantly high ($r = 0.768$, $P < 0.001$).

DISCUSSION

Decreases in Crop Yield under Sole Fertilizer Application in the Sahel Region

The GY and TDM in sole fertilizer application showed increases from 1998 to 2006 only in 2005 (Fig. 4a, 4b) in contrast to FM, RF, and RFM where fertilizer and organic matter had been applied together.

Several long-term experiments have been conducted in the Sahel or the Sudano-Sahelian region so far; three in the Niamey center of ICRISAT (Hafner et al., 1993; Bationo et al., 1993, 1998; Subbarao et al., 2000; Bielders et al., 2002, Abdou et al., 2012), one in Saria, Burkina Faso, 12°15′ N, 2°10′ W; (Pichot et al., 1981; Mando et al., 2005a, 2005b), one in Bambey 14°41′ N, 16°28′ W; (Pieri, 1979, 1992), and one in Thilmakha (15°2′ N, 16°15′ W; Wey et al., 1987), Senegal. Results demonstrated that the application of fertilizer alone had made crop yields lower, year by year (Pieri, 1979, 1992; Pichot et al., 1981; Wey et al., 1987; Hafner et al., 1993; Bationo et al., 1998). The application efficiency of fertilizer {FAE; [GY in sole F (kg ha^{-1})] – [GY in the control (kg ha^{-1})/[amount of fertilizer application ($N + P_2O_5 + K_2O$; kg ha^{-1})]} was also gradually reduced after 10 or 20 yr with continuous

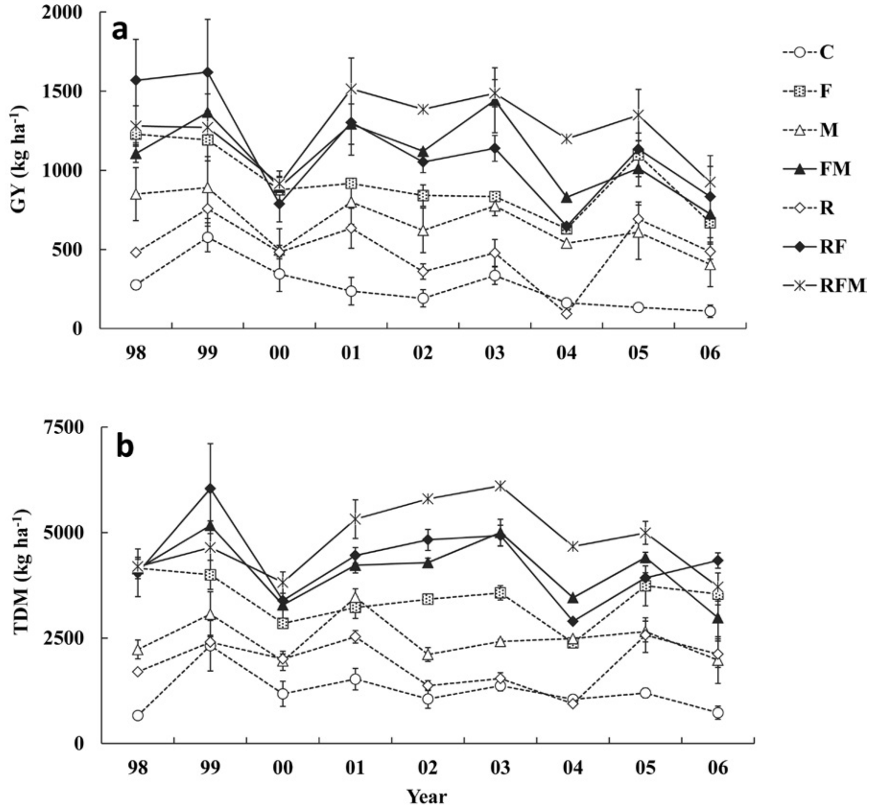

Fig. 4. Changes in (a) grain yield (GY) and (b) total dry matter (TDM) of pearl millet from 1998 to 2006. C, Control; F, Fertilizer; M, Manure; R, Residue; FM, Fertilizer + Manure; RF, Residue + Fertilizer; RFM, Residue + Fertilizer + Manure. Vertical bar represents the standard error.

application (Pieri, 1986, 1992). In the long-term experiment at Saria in Burkina Faso, FAE decreased from 9.4 (the average from 1963–1970) to 3.3 (the average from 1971–1978) in the treatment with a small amount of fertilizer and from 8.3 to 1.7 in the treatment applying large amounts. This experiment clearly showed that the decrease in the rate of FAE was strongly affected by the amount of fertilizer applied (Pichot et al., 1981; Pieri, 1992). One of the principal reasons for the decreasing yield with sole fertilizer was the decline in soil pH which increased free Al ions and decreased P mobilization in the soils (Pichot et al., 1981; de Ridder and van Keulen, 1990; Pieri, 1992).Therefore, with the application of calcium carbonate in 1978, FAE increased by 7.2 (average from 1978–1983) in treatments with lower rates of fertilizer application and by 7.3 in those with higher rates.

Application of urea or ammonium sulfate as ammoniated N fertilizer can enhance H^+ in soil along with nitrification and decrease soil pH with continuous use. In our study, soil pH at 0- to 20-cm depth did not change but it decreased from 4.9 in 1995 to 4.6 in 2005 at 20- to 40-cm depth (the mean of 1995, soil: H_2O = 1: 2.5; A. Bationo, personal communication, 2004) and was showing a significant difference ($P < 0.01$). Consequently, we understood that the decline of soil pH is a factor contributing to the gradual decrease of GY and TDM in the treatment with a high level of fertilizer applied sole.

The soils in the Sahel or the Sudano–Sahelian region are low in clay and organic matter content (Pichot et al., 1981; West et al., 1984; Bationo et al., 2007), thus the buffering capacity of pH and CEC is very low and soil pH strongly affects CEC in soils. The long-time application of organic matter can contribute to promoting the accumulation of soil organic C, improve the buffering capacity of pH, and increase CEC (Pichot et al., 1974; de Ridder and van Keulen, 1990; Bationo et al., 2007). With the application of organic matter, soil pH is also improved with an increase of cations such as Ca, Mg, and K (Pichot et al., 1974; de Ridder and van Keulen, 1990; Bationo et al., 1993; Buerkert et al., 2000; Bationo and Buerkert, 2001; Bationo et al., 2007). Thus, these results from long-term experiments explain that it is extremely important to apply fertilizer with organic matter to improve GY and TDM in these agro-ecosystems.

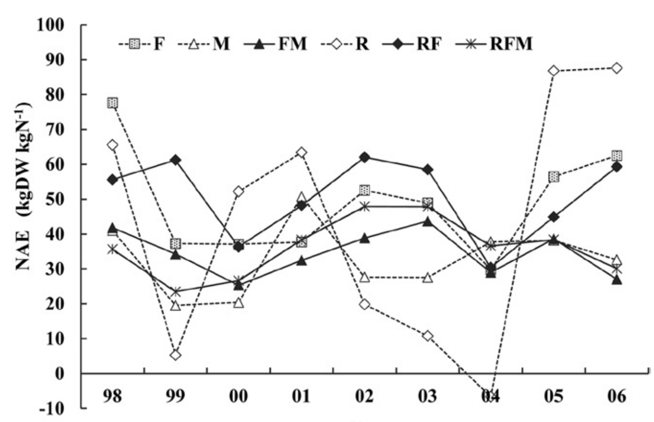

Fig. 5. Changes in nitrogen application efficiency (NAE) from 1998 to 2006. F, Fertilizer; M, Manure; R, Residue; FM, Fertilizer plus Manure; RF, Residue plus Fertilizer; RFM, Input of all factors with the highest application level.

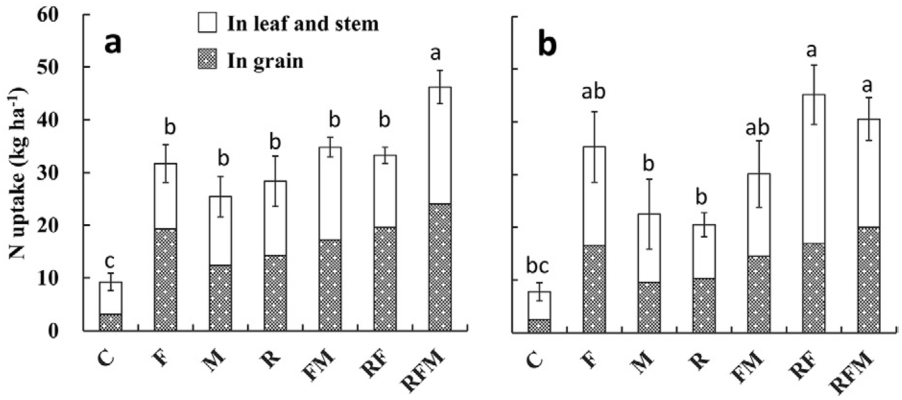

Fig. 6. Nitrogen uptake by pearl millet in the growing season of (a) 2005 and (b) 2006. Different letters show the significant differences with LSD, $P < 0.05$. See Fig. 4 for legend detail. Vertical bar represents standard error.

Dynamics in Effects of Nitrogen Nutrient from Fertilizer and Organic Matter on Grain Yield and Total Dry Matter

In our study, the continuous and positive effect of applied fertilizer appeared from 1998, but the effects of crop residue and cattle manure appeared from 2001 (Table 1). In a previous study in the same long-term experiment from 1994 to 1995, the effects of fertilizer on yield were identified in 1994 and of cattle manure in 1995, and the effects on yields of all applications including crop residues were significantly recognized in 1995 (Akponikpe et al., 2008). According to their results, the effect of organic matter on crop yield appeared straightaway after the establishment of the field. However, the decomposition of organic matter is easily affected by environment conditions; thus, the effects on crop yield will not be stable immediately after application begins. Consequently, it will be difficult to explain the effect of organic matter on yield via short-term research, especially for organic matter such as crop residue that is very slow to decompose.

The amount of applied N and P nutrients correlated highly with TDM and GY in all years from 1998 (Table 2). Their effectiveness was attributed to the depletion of N and P which is a serious problem for crop cultivation in the Sahel region (de Ridder and van Keulen, 1990; Bationo and Mokwunye, 1991). However, TDM and GY did not correspond completely with K in all years (Table 2). Presumably K is often supplied by sand storms in the Sahel (Harris, 1999) and the K content in the soil is sufficient for crop growth. Certainly, N and P nutrients are essential for pearl millet growth, and we focused on N to suggest the importance of NUE to plants for soil management, for the following reasons: (i) a lot of N is needed for good growth since plants contain more N than P (Foth, 1980). Cereals especially need more N than legumes that can fix N_2 from the air. (ii) Sahelian farmers cannot apply sufficient N owing to the limited affordability of fertilizers and the shortage of organic

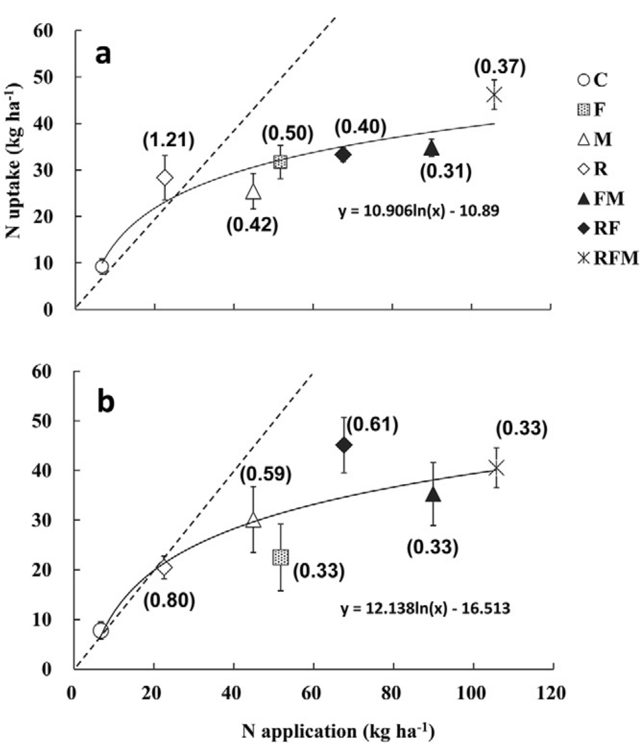

Fig. 7. Relationship between N application and N uptake by pearl millet in (a) 2005 and (b) 2006. The values in parentheses show the nitrogen use efficiency (NUE) in each treatment. See Fig. 4 for legend detail. Line shows logarithmic curve and dotted line shows the relationship of 1: 1 between N uptake and N application. Vertical bar represents the standard error.

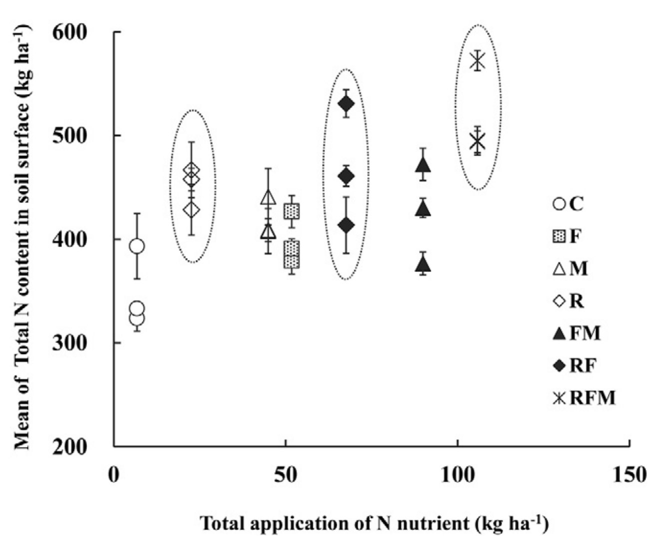

Fig. 8. Relation between total application of N and mean amount of total N in the soil surface (0–15-cm depth) from 2004 to 2006. The dotted cycles enclose the treatments applied crop residue. See Fig. 4 for legend detail. Vertical bar represents the standard error.

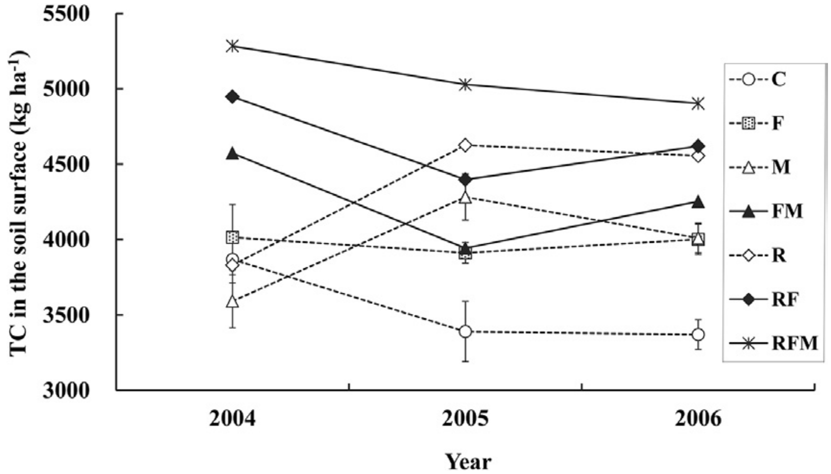

Fig. 9. Total carbon (TC) contents in the soil surface (0–15-cm depth) from 2004 to 2006. See Fig. 4 for legend detail. Vertical bar represents the standard error.

matter in this region. (iii) Few studies have reported in detail about the effects on N of the application of different kinds of organic matter on crop growth in the Sahel.

Table 1 showed that the effect of fertilizer on TDM and GY was significant from 1998, but the stable effects of organic matter on TDM and GY appeared gradually from 2001. Fertilizer affects yield immediately through its fast release but organic matter needs time to release nutrients. Furthermore, in the relationship between the total amount of N application and TDM (Fig. 3), in 1998 and 1999, TDM increased with the amount of fertilizer applied (F0, 1, and 2) and tended to clump at each level of application. From 2000, however, TDM started to increase along with the total amount of N application, not only with levels of fertilizer application. Subsequently, a more obvious trend appeared (Fig. 3). These results explained that TDM was affected by the amount of total N application and about 8 yr would be needed for a stable form of N effectiveness on crop growth to be achieved via the decomposition of applied organic matter. This study is the first to identify the years necessary for N from organic matter to affect TDM and GY of pearl millet under this long-term experiment in the Sahel region, Niger.

Differences in Nitrogen Application Efficiency, Nitrogen Uptake, and Nitrogen Use Efficiency in the Treatments with Applied Crop Residue and Cattle Manure

From 1998 to 2006, NAE (total dry matter production per unit of N application) was estimated with TDM data collected from 1998 to 2006 (Fig. 5). The NAE in RF tended to be higher than in other treatments for 9 yr. The previous study from the same long-term experiment also reported that the combination of crop residue and fertilizer positively affected yield in 1995 (Akponikpe et al., 2008). They had established that the grain and stem weight was able to increase with the application of a large amount of crop residue and fertilizer.

Incidentally, NAE in R treatment was very erratic (Fig. 5). The NAE in R was low in 1999, 2002, 2003, and 2004 and TDM in R was also low in the same years and was very similar to C. The rainfall patterns in these 4 yr showed better conditions for pearl millet cultivation (Fig. 2). The rainfall amounts were also better; 500 mm in 1999, 572 mm in 2002, 478 mm in 2003, and 553 mm in 2004. Crop residue had low N content (0.66% in 2005) and the C/N ratio was 69. Therefore, even under better rainfall conditions, it will be very slow to release N. If N nutrient is not released at the time appropriate for crop growth, N depletion affected yield negatively. In crop residue, the speed of decomposition and nutrient release can be easily affected by the environmental conditions. The amount of N uptake and GY or TDM had a significant high correlation, ($r \geq 0.9$, $P < 0.001$, data not shown).

The NUE in R was the highest among all treatments in both 2005 and 2006 (Fig. 7a, 7b). This explained that crop can use the applied N nutrient more efficiently in R without loss than in F and M. However, GY and TDM in R (Fig. 4) tended to be lower than in F and M. As mentioned above, this also explained that the speed of decomposition and nutrient release is very important for crop growth, even when the applied N nutrient is the optimum amount for uptake by crop. For the combined treatments of fertilizer and organic matter, NUE in RF tended to be higher than that in FM. Additionally, NUE in RF was higher than that in RFM which had received all amendments at the highest level of N (Fig. 7a, 7b).

The results of NAE and NUE explained that the application of sole crop residue can mitigate N nutrient loss but the speed of nutrient release is very slow due to the low rate of decomposition. Therefore, the combination of slow-releasing residue and quick-releasing fertilizer can be a better method to supply the N nutrient regularly for crop growth without much loss, considering the time lag in mineralization. The combined application of residue and fertilizer was already proposed by the previous study in this long-term experiment as a management option with the potential to improve N and P use efficiency (Akponikpe et al., 2008). When insufficient residue was applied, the effect of fertilizer in enhancing N did not appear. Meanwhile, the combined application of fertilizer and cattle manure also significantly increased N and P use efficiency (Akponikpe et al., 2008). However, the combined effect of cattle manure and fertilizer was not observed; fertilizer has the stronger effect on crop growth compared with cattle manure in this combination. The results of both studies indicated that the residue plays an important role in enhancing the effect of N nutrient from fertilizer.

Importance of Pearl Millet Residue Application

Application of crop residue has the potential of improving available P (Kretzschmar et al., 1991; Buerkert et al., 2000; Bationo and Buerkert, 2001), increasing K (Rebafka et al., 1994), improving root elongation (Hafner et al., 1993; Buerkert et al., 2000), decreasing soil firmness (Buerkert and Stern, 1995), improving soil water content and reducing soil temperature (Buerkert and Lamers, 1999) and preserving the soil surface (Geiger et al., 1992; Buerkert et al., 2000; Bielders et al., 2002). Additionally, the most important role of residue application is to enhance soil organic matter. According to the results of TN and TC contents in the surface soil (0–15 cm), residue application had a high potential to enhance the contents of TN and TC, under the conditions with or without combined applications with manure and or fertilizer. A previous study using the model of Roth C; Nakamura et al. (2011) also reported that the application of crop residue has a very important role particularly in retaining organic C contents in the Sahelian sandy soils.

A highly significant correlation was identified between TN and TC in the surface soil; in this study ($r = 0.768$, $P < 0.001$). The previous studies also showed the same results in Sahelian soils (Bationo and Mokwunye, 1991; Manu et al., 1991; Bationo et al., 2007; Suzuki et al., 2014). Basically, the enhancement of soil organic matter content with crop residue would increase the N pool in the Sahelian sandy soils. In this study also, we understood that TC in the surface soil in R was higher than in M during cropping seasons for 3 yr (Fig. 9) and TC in RF was also higher than in FM. Probably, the differences in their rate of decomposition and method of application would have a strong effect the C/N ratio of crop residue (69; TC, 45.25% and TN, 0.66%) was much higher than that of cattle manure (21; TC, 33.71% and TN, 1.59%). Additionally, in this long-term experiment, crop residue was applied on the soil surface in the traditional method of soil management (Suzuki et al., 2014). Manure was incorporated into the soil surface by the traditional manual hoe at weeding. Thus, manure would be more easily decomposed by soil microorganisms than crop residue.

According to our observation for 3 yr from 2004 to 2006, manure disappeared during the cropping season in every year; crop residue on the soil surface gradually decomposed from inside the stems and then only the hulls remained for about a year. In this way, crop residue becomes a gradual C source for the soils and plays an important role in capturing nutrients due to the carboxyl groups (Bot and Benites, 2005). For the Sahelian sandy soils, the content of clay which has a function in capturing nutrients is extremely low; <10% (West et al., 1984). Therefore, crop residue as a gradual C source instead of clay would play a very important role in the capture of nutrients.

CONCLUSIONS

Through analyzing past data and from our research, we understood that it is necessary to apply a combination of fertilizer and organic matter (crop residue and cattle manure) to enhance the effect of fertilizer on crop yields in the Sahel regions but a stable N nutrient supply from manure and residue would commence at about 8 yr after continuous applications had started. Pearl millet residue had more potential to enhance the effect of fertilizer on crop growth and yield than cattle manure. Consequently, the application of fertilizer with pearl millet residue was the more useful soil management practice that with manure or with both organic resources to improve N nutrition for crop growth and yield in the Sahel region.

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