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Effects of long-term application of mineral and organic fertilizers on dynamics of nitrogen pools in the sandy soil of the Sahel region, Niger



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ABSTRACT

Our study on soil N dynamics was conducted in the rainy season of 2005 and 2006. It focused on the effects of soil managements with sole and combined applications of mineral and organic fertilizers in the long-term experiment conducted since 1993 in the Niamey Center of the International Crop Research Institute for the Semi-Arid Tropics, Niger. Treatments were established with each three input levels of chemical fertilizer as urea and SSP, pearl millet residue, and cattle manure. The lowest and highest levels were focused in our study. Treatments with 2700 kg ha⁻¹ of applied crop residue showed high total N in the soil surface (< 30 cm), but did not show any change in the deeper layer (> 30 cm) or seasonal changes. Phosphate-buffer extractable organic nitrogen (PEON) as an indicator to estimate available N in the soil was not affected by the different treatments; however, similar seasonal changes were identified in all treatments. PEON in soil surface was high right before the rainy season began, then gradually decreased with increasing rainfall and remained at approx. 10 mg kg⁻¹ until the end of the season. In deeper layer, leaching was identified after heavy rainfall but at least 5 mg kg⁻¹ of PEON remained during the season. Inorganic N (NO₃-N plus NH₄-N) increased in the soil surface right after fertilizer application but its effect disappeared in a few weeks. The 'Birch effect' affected the fluctuations of PEON and inorganic N at the start of rains in the Sahel region of Niger.

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1. Introduction

Pearl millet [*Pennisetum glaucum* (L.) R. Br.] is the staple crop in the Sahel region of West Africa with the potential to survive under harsh conditions (Hoshikawa, 1980) but extremely low productivity. The means of pearl millet yields from 1961 to 2013 in five countries, Senegal, Mali, Burkina Faso, Niger, and Nigeria, was highest in Nigeria, but only 1030 kg ha⁻¹. For the others, the means of yields for 52 years were 584 kg ha⁻¹ in Senegal, 738 kg ha⁻¹ in Mali, 589 kg ha⁻¹ in Burkina Faso, and 424 kg ha⁻¹ in Niger (FAO, 2015). Thus, for 52 years they did not have a yield of more than 1 t ha⁻¹. According to the other study conducted at two villages in the Sahel region of Niger from 2008 to 2010, the storage of millet in the agricultural production unit (UPA, this presents the groups

composed by two or three families who have the blood relationship.) was approx. 700–1300 kg as mean (Suzuki et al., 2015). Calculating the consumption per UPA (as 15 persons) using the daily consumption that is about 500–1000 g per person, the annual consumption should be about 2738–5475 kg (Suzuki et al., 2015). This explained that the current yield of pearl millet cannot cover for an UPA.

This low productivity is due to the small and erratic amount of rainfall and the low soil fertility (Abdoulaye and Sanders, 2006; Bagayoko et al., 2011; Suzuki et al., 2015). Breman and de Wit (1983) reported that plant growth is frequently limited more by low availability of N and P than by low rainfall. Suzuki (2008) attempted to elucidate the correlation between rainfall amounts and total dry matter (TDM) of pearl millet from 1998 to 2006. TDM did not show any correlation with the annual amount of rainfall but increased with the application of fertilizer and organic matters (Suzuki, 2008). This explained that the main factor for low productivity is low soil fertility in the Sahel region.

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The Sahelian soil is extremely sandy; more than 90% is sand and less than 10% is silt and clay; the dominant clay mineral is kaolinite (West et al., 1984; Buerkert et al., 2000). Therefore, cation exchange capacity (CEC) is very low, about $1.0 \text{ cmol}_c \text{ kg}^{-1}$ (West et al., 1984; Buerkert et al., 2000; Bationo et al., 2007). Owing especially to low CEC, soil nutrients are easily lost by leaching (Buerkert et al., 2000). Brouwer and Powell (1995, 1998) reported that the amounts of nutrients (ha^{-1}) lost with leaching were 1070 kg C, 91 kg N, and 19 kg P after 9–10 t ha^{-1} of manure had been applied in the Sahel region of Niger.

The depletion of N and P nutrients is a very serious constraint for crop production in the region (van Keulen and Breman, 1990; Baidu-Forsan and Bationo, 1992). According to our latest results in the long-term experiment at the Niamey Center of International Crop Research Institute for the Semi-Arid Tropics (ICRISAT), N and P nutrients significantly affect the grain yield and total dry matter (TDM) of pearl millet. In particular, the total amount of applied N has a significant effect on TDM (Suzuki et al., 2016). Given the dominant role of the N nutrient for crop growth, soil management to avoid N loss and restore N nutrient content is very important (Giller et al., 1997; Zougmoré et al., 2004).

To restore soil fertility in the Sahel region, farmers used to employ a long fallow, more than 15 years (Wezel and Haigis, 2002). However, due to the high population pressure (World Bank, 2015)

farmers have been employing short fallows (Hiernaux and Ayantunde, 2004) or using arable fields continuously with the affordable amendments: small amounts of fertilizer, livestock manure, household waste, and crop residue (Schlecht and Buerkert, 2004; Suzuki et al., 2014).

The accumulated results of previous studies in the long-term experimental fields of some countries in West Africa have explained that soil management which integrates fertilizer and organic matters, manure and crop residue, is optimum for improving crop production in the Sudano-Sahelian regions (Pieri, 1992). In the Niamey Center, another long-term experiment has been conducted since 1983 to elucidate the effects of the integrated application of fertilizer and crop residue. According to the data of previous studies, this integrated application can contribute to enhance grain yield and TDM of pearl millet (Hafner et al., 1993; Bationo et al., 1993, 1995, 1998; Yamoah et al., 2002; Abdou et al., 2012) also N uptake, N nutrient content in the soil surface, N balance (Hafner et al., 1993), organic matter content in the soil surface (Bationo et al., 1993, 1998; Abdou et al., 2012), and fertilizer use efficiency (Bationo et al., 1995; Yamoah et al., 2002). According to our latest results (Suzuki et al., 2016) in the Niamey Center, the integrated application of fertilizer and crop residue has the high potential to enhance TN and TC in soil surface and the N use efficiency (NUE) of pearl millet. However, in the data

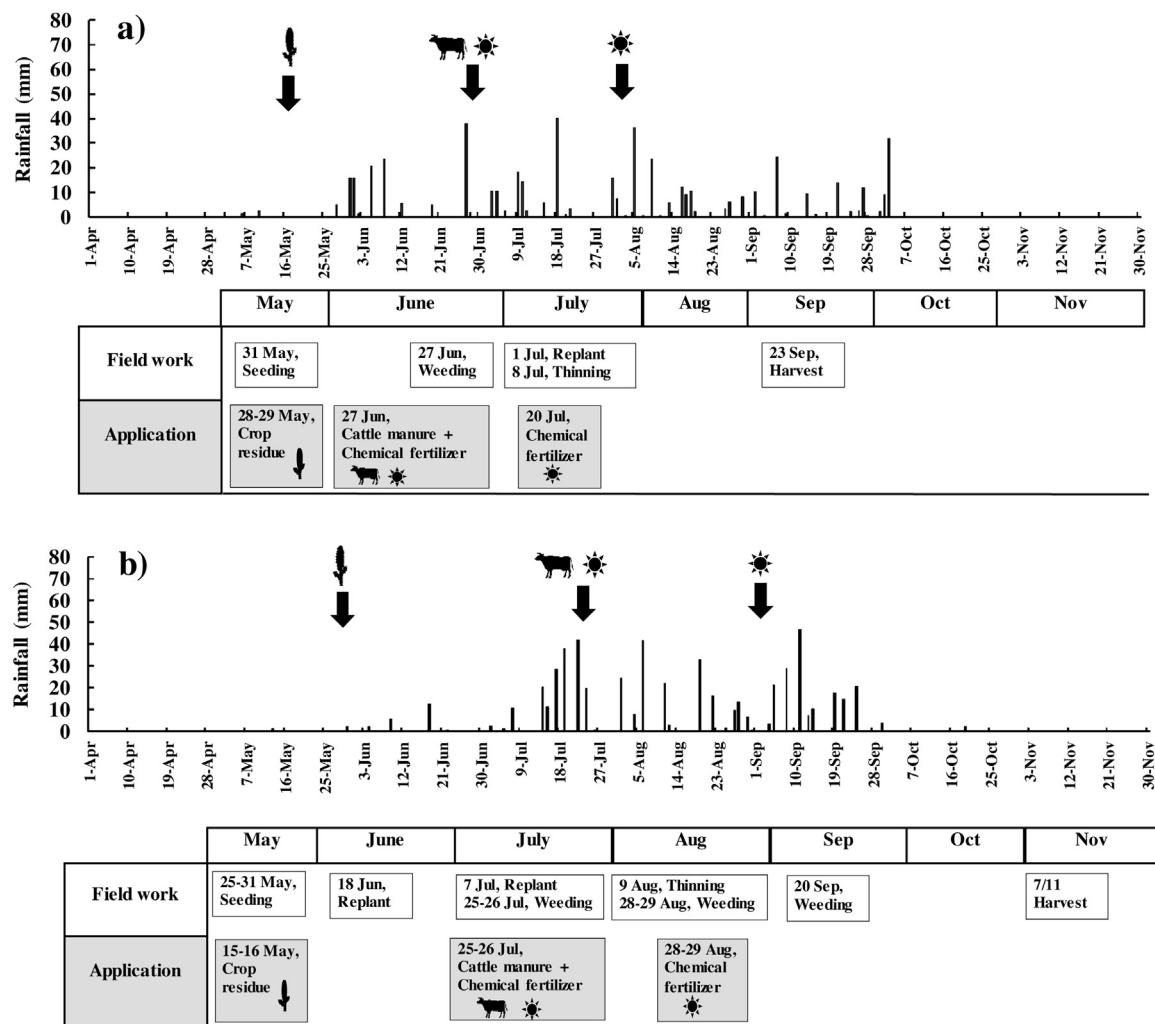


Fig. 1. Rainfall patterns and schedules for field work and applications conducted in (a) 2005 and (b) 2006. The crop, cow, and sun represent the application of crop residue, cattle manure, and fertilizer, respectively.

accumulated through many previous studies related to long-term experiments in West Africa, there are no data to explain the effects of the integrated application of fertilizer and organic matters on the seasonal dynamics of each N pool: TN, available N, and inorganic N in the Sahelian soil.

Hence we focused on this long-term experiment with the integrated application of fertilizer and organic matters which commenced in 1993 and attempted to elucidate the effects of this integrated application on each N pool in the sandy Sahelian soil, concentrating on the different effects of crop residue and manure as the amendments to be integrated with fertilizer.

2. Materials and methods

2.1. Long-term experiment

In 1993, the long-term experiment was established in the test field of the Niamey Center (13°15'N, 2°18'E), 45 km southeast of Niamey, the capital of Niger.

The experimental design consisted of a fully factorial randomized block experiment with three replications. There were three application factors on three levels. Each treatment size was 10 m × 20 m and four sub-treatments were established in each treatment with different cultivation systems. These sub-treatments were established in 1998, and the size was 5 m × 10 m (Suzuki et al., 2016). Our study was conducted in 2005 and 2006.

The crops cultivated in this long-term experiment were rainfed (Fig. 1). The rainfall in 2005 showed the trend that the heavy rainfalls were scattered during the rainy season (Fig. 1a). Other side, the rainfall in 2006 showed the trend that the heavy rainfalls were concentrated from the beginning July to the beginning of September (Fig. 1b).

2.2. Treatments

The three application factors were (i) fertilizer as urea and single super phosphate (SSP), (ii) pearl millet residue, and (iii) cattle manure. Levels of fertilizer application (kg ha^{-1}) were F0 (ON + OP), F1 (15N + 4.4P), and F2 (45N + 13.1P). Levels of residue application (kg ha^{-1}) were R0 (300), R1 (900), and R2 (2700). Levels of cattle manure application (kg ha^{-1}) were M0 (300), M1 (900), and M2 (2700). The broadcast application of urea on the soil surface was conducted twice at weeding (first at about 2 weeks after planting (WAP) and then at about 7 or 8 WAP). SSP was broadcast on the soil surface straightaway after planting. On the soil surface pearl millet residue was applied before planting and cattle manure was applied at the first weeding and mixed into the soil at a depth of 0–5 cm with the use of the traditional manual hoe (called *Hilaire* in French and *Koumbou* in the local language, Zarma).

The sub-treatments were growing sole pearl millet, intercropping, and two sub-plots for rotating pearl millet and cowpea [*Vigna unguiculata* (L.) Walp]. The rotation between pearl millet and cowpea has been conducted between two sub-plots (Suzuki et al., 2016).

2.3. Focused treatments

In this study, we focused on seven treatments: R0F0M0 identified as control (C), R0F2M0 (F), R0F0M2 (M), R0F2M2 (FM), R2F0M0 (R), R2F2M0 (RF), and R2F2M2 (RFM). We selected only the sub-treatment of growing sole pearl millet.

2.4. Field managements

Seeds were planted immediately after about 20 mm rainfall at the beginning of the rainy season. Planting was conducted according to the farmer's practice; holes of 10–15 cm depth were dug with a long hoe and approximately 30–40 seeds of pearl millet (cv. CIVT) were put in each hole. The plants started to emerge after about 2–3 days and 4 or 5 plants per hole were left at 4 WAP. In 2005 and 2006, pearl millet was replanted in some holes as there was insufficient rainfall after planting. Harvest was conducted at 4 months after planting. The panicles were cut but the stems were left in the fields during the dry season. The remained stems were cut before starting the rainy season. Other aspects of field management were explained by Suzuki et al. (2016).

2.5. SPAD measurement

In the rainy season of 2006, the chlorophyll content of the most fully expanded second leaves was estimated by the Minolta SPAD 501 every 2 weeks. The blade of fully grown leaves becomes about 50–60 cm long, thus we measured at three points; 10 cm from the leaf base, at the leaf tip, and midpoint. These points were about 2–3 cm from the leaf margin except at the leaf center line, and the SPAD value was identified from the mean of the three values.

Some earlier studies had measured the SPAD value of pearl millet in the Sahel but these studies measured leaves of different ages (Génard and Buerkert, 2001; Pandey et al., 2001). In our study, we had verified that it was the best to measure the most fully expanded second leaf through researching the SPAD value of all leaves of a plant selected from RFM (the best level of growth) and from C (the worst level of growth) from early growth to flowering (data not shown).

In 2006 we used the data accumulated since 1998 (A. Bationo, pers. com. 2004) to understand the correlation between SPAD value and TDM or grain yield of pearl millet.

2.6. Soil characteristics and soil sampling

The soil under the long-term experiment in ICRISAT-Niamey is classified in Pasammentic Paletustalf (West et al., 1984). The A layer has 90% of sand, 3% of silt, and 2.9–5.3% of clay. However, sand is about 85% in the B layer, thus silt and clay increase there, compared with the A layer (West et al., 1984). Soil organic carbon, pH, exchangeable K and CEC in A layer were 1.2–1.7 g kg^{-1} (Walkley-Black method), 5.4–5.6 (soil:water = 1:1), 0.1 $\text{cmol}_c \text{kg}^{-1}$ and 1.0 $\text{cmol}_c \text{kg}^{-1}$ (determined with atomic absorption spectrometer, West et al., 1984). From the analysis data conducted in 2000, the available P in A layer under R0F0M0 was 2.9–4.9 g kg^{-1} (extracted with Bray 1; A. Bationo, personnel communication, 2004).

Soil sampling was conducted from 2005 to 2006 at the three replications of the plots of pearl millet monoculture in the seven treatments mentioned in Section 2.3. Principal soil sampling was conducted in the stages of seeding, at vegetative growth and heading, and after harvesting. Another soil collection to research the change in soil N dynamics with time was conducted every 2 weeks until harvest. The soil samples (diameter 5 cm) were taken from five spots and combined for one composite sample per plot. In 2005, soil samples were taken from every 15 cm until the 105 cm depth. Soil samples in 2006 were also collected by the method employed in 2005, but samples from the 75–105 cm depth were taken at every 30 cm. The collected soil samples were air-dried, passed through a 2 mm sieve, and analyzed.

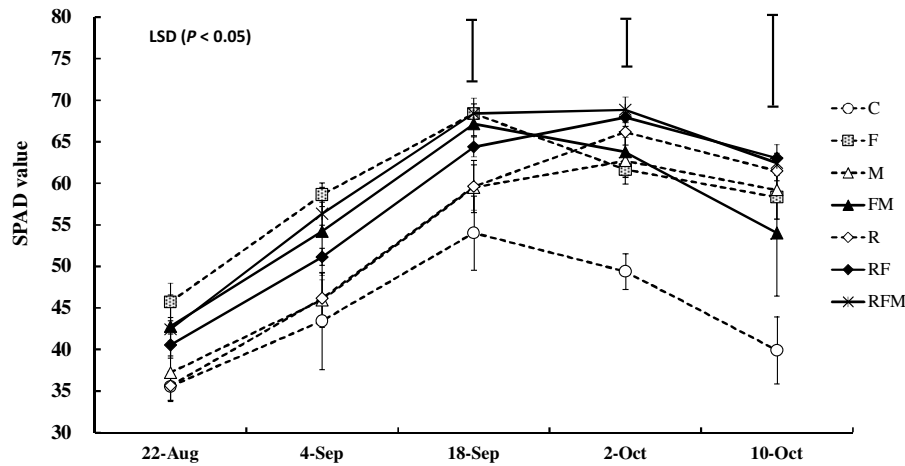


Fig. 2. Changes of pearl millet SPAD values during cultivation in 2006.

C, Control; F, Fertilizer; M, Manure; R, Residue; FM, Fertilizer plus Manure; RF, Residue plus Fertilizer; RFM, Input of all factors. Thin vertical bar represents standard error. Thick vertical bar represents LSD value ($P < 0.05$). The arrows represent the trends of the increase or decrease for SPAD values from 18 September.

2.7. Soil analyses

Total N and total C were determined using an automatic NC analyzer (Sumigraph NC22F; Sumika, Tokyo, Japan). For inorganic nitrogen, nitrate nitrogen ($\text{NO}_3\text{-N}$) and ammonium nitrogen ($\text{NH}_4\text{-N}$) were extracted with 50 ml of 2 M KCl solution using 5 g of air-dried soil (Keeny and Nelson, 1982) and their concentrations were determined with an automatic analyzer (TRAACS, BRAN + LUEBBE).

As the indicator of available N, 0.067 M phosphate-buffer extractable organic nitrogen (PEON) was used: its adaptability to the Sahelian sandy soils had been elucidated in the previous study (Suzuki et al., 2008). The determination of PEON was conducted according to the method of Ogawa et al., 1989: 5 g of air-dried soil was extracted with 25 ml of 0.067 M phosphate-buffer and the content of $\text{NO}_3\text{-N}$ and $\text{NH}_4\text{-N}$ was determined after shaking the extract for 1 h using an automatic analyzer (TRAACS, BRAN + LUEBBE). Additionally, total N content in the extract was also determined with a micro total N auto-analyzer (TN-100; Mitsubishi Chemical Corporation, Tokyo). PEON concentration was defined by subtracting mineral N from total N in the extract.

2.8. Statistical analysis

Pearson product moment correlation coefficient was used to identify the correlation between grain yield and SPAD value or between TDM and SPAD value. To identify the significant differences of the SPAD value and the amount of total N in every 15 cm under the different soil managements, the LSD is only used when the *F* test is significant ($P < 0.05$).

3. Results

3.1. Effects of different treatments on SPAD value

SPAD value increased in every treatment by 17 September (Fig. 2) and then started to decrease in C, F, and FM treatments. In M, R, RF, and RFM treatments, high levels of SPAD value continued to the beginning of ear emergence (around 20 September; Fig. 2).

SPAD value showed a significant and positive correlation with grain yield from the middle of vegetative growth (4 September 2006) to the end of heading time (Table 1). TDM also had a significant correlation with SPAD value in the later stages of vegetative growth. Both grain yield and TDM showed the highest correlation with SPAD value in the later stages of vegetative growth and at heading time (Table 1).

3.2. Effects of each treatment on the seasonal changes of total N in the soil surface and vertical changes until 105 cm depth

Focusing on the starting time of the rainy season in 2005 (seeding time), the effects of each treatment on the vertical changes in total N were identified (Fig. 3). The contents of total N in the treatments of R, RF, and RFM, in which crop residue was applied, were higher than in M and FM (Fig. 3). In contrast, the contents of total N were low in F and C without the application of sufficient organic matters. These differences were recognized in the soil surface but not in the deeper layer (Fig. 3). To understand the effects of each treatment on total N in the soil surface, the relationship between the mean of total N in the 0–15 cm depth during the rainy season from 2004 to 2006 and total amount of N

Table 1
Correlations between SPAD value and grain yield or total dry matter (TDM) of pearl millet in 2006.

Date	Growth stage	Grain yield vs SPAD value	TDM vs SPAD value
22-Aug	Later young growth	0.704	0.697
04-Sep	Middle of vegetative growth	0.811*	0.720
12-Sep	Later vegetative growth	0.912**	0.805*
02-Oct	Heading time	0.857*	0.774*
10-Oct	Later heading time	0.759*	0.739

** $P < 0.01$.

* $P < 0.05$.

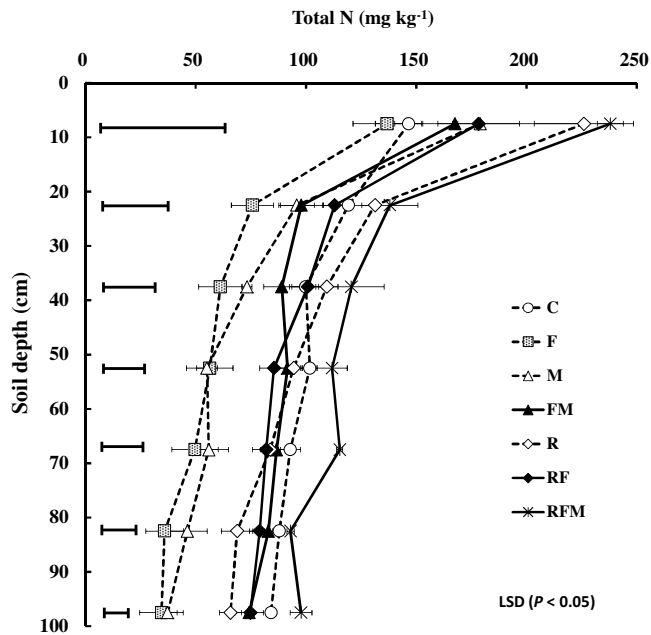


Fig. 3. Total nitrogen contents under each treatment in June 2005.

Thin horizontal bar represents standard error. Thick horizon bar represents LSD value ($P < 0.05$). See Fig. 2 for legend detail.

application were investigated. This result explained that R, RF, and RFM, the treatments with applied crop residue, can enhance total N in the soil surface more than the others (Fig. 3).

3.3. Seasonal changes in PEON in 0–15 cm depth during the rainy season

When research was focused on PEON every week in 2006, the effects of each treatment on the dynamics of PEON were not identified. Each treatment showed the same trend: PEON was high before the rainy season started and became low immediately after the rainy season began (Fig. 4). This decrease stopped after it had reached about 10 mg kg^{-1} and then PEON under all treatments (except RF and RFM) was continuously kept at about 10 mg kg^{-1} during the rainy season (Fig. 4). These two treatments tended to have higher amounts of PEON than the others, but these were 15 mg kg^{-1} even if at the highest level.

3.4. Seasonal changes in the vertical distribution of PEON under each treatment

The treatment in F was lower than in other treatments including C (Fig. 5(1)). Elsewhere, under the treatments with applied organic matters, the different trends were high; R and RF showed a high amount of PEON at 0–15 cm depth and M and FM showed a high amount at 15–30 cm depth (Fig. 5(1)). Furthermore, RFM tended to be high at both depths 0–15 and 30–45 cm (Fig. 5(1)).

On 25 July, one and a half months after the rainy season had begun, every treatment showed increases of PEON in all soil depths (Fig. 5(2)). Subsequently, PEON decreased until 3 October, harvesting time (Fig. 5(3)). This explained that treatments with enough organic matters (M, R, FM, RF, and RFM) can be altered to decrease PEON compared with F and C which lack enough organic matters (Fig. 5(3)). On 7 November, a month after harvesting time (3 October), every treatment showed PEON restored in the 0–30 cm depth and the amount reached 10 mg kg^{-1} approximately (Fig. 5(4)).

To understand in more detail the dynamics of PEON, in 2006, research in the vertical changes for PEON over time was conducted every 2 weeks in the RFM treatment only. During the rainy season in 2006, remarkable seasonal changes were not identified in the surface soils. However, on 19 July and 27 September when heavy rainfall continued, the content of PEON decreased in the 0–15 cm depth and increased in the 15–30 cm depth (Fig. 6(3) and (8)). Otherwise, PEON in the lower layer did not change but remained at about 5 mg kg^{-1} continuously (Fig. 6).

3.5. Seasonal changes of inorganic N in the 0–15 cm depth

According to the results for inorganic N in the soil surface conducted every week during 2006, the amount of $\text{NH}_4\text{-N}$ was high before the start of the rainy season in each treatment and kept at the same levels for approximately one month. After that, $\text{NH}_4\text{-N}$ became low (Fig. 7). $\text{NO}_3\text{-N}$ started to increase after an increase of $\text{NH}_4\text{-N}$ and continued to keep a high level. Similarly with $\text{NH}_4\text{-N}$, $\text{NO}_3\text{-N}$ also decreased after a month. During the rainy season, the levels of $\text{NH}_4\text{-N}$ and $\text{NO}_3\text{-N}$ remained low except at the time of fertilizer application in treatments F, FM, RF, and RFM (Fig. 7). However, the effects of fertilizer application on an increase of $\text{NH}_4\text{-N}$ appeared to be temporary and disappeared after 2 or 3 weeks.

3.6. Seasonal changes of the vertical distribution in inorganic N under each treatment

The results in 2005 for seasonal changes of the vertical distribution (0–105 cm depth) of inorganic N showed an increase in the soil surface right after the rainy season had begun (Fig. 8(1)) as well as the results mentioned in Section 3.6. In 2006, high amounts in both $\text{NO}_3\text{-N}$ and $\text{NH}_4\text{-N}$ were identified, but in 2005, only $\text{NO}_3\text{-N}$ was remarkably high early in the rainy season (Fig. 8(1)). On 25 July 2005, $\text{NO}_3\text{-N}$ started to decrease in the soil surface, but in the deep layer under treatments C, M, and R, an increase of $\text{NO}_3\text{-N}$ occurred at the same time (Fig. 8(2)). At harvest time and afterwards, the amounts of inorganic N were very low (Fig. 8(3), (4)).

Further detailed researches were conducted every 2 weeks in 2006 to understand the inorganic N dynamics in the soil at 0–105 cm depth, focusing on the RFM treatment. According to the results, as well as the trends in 2005, high amounts of $\text{NO}_3\text{-N}$ and $\text{NH}_4\text{-N}$ were identified in the soil surface right after the rainy season had started (Fig. 9(1), (2)). On 19 July 2006, however, 3 weeks after the beginning of the rainy season, the amounts of inorganic N decreased in the soil surface (Fig. 9(3)) but in the deeper layer (40–60 cm especially), increases of $\text{NO}_3\text{-N}$ were identified. The increase of $\text{NO}_3\text{-N}$ was continuously detected in the soil at 90–105 cm depth on 2 August (Fig. 9(4)). After that, the application of urea and manure affected the increases of $\text{NH}_4\text{-N}$ in the soil surface on 30 August 2006 (Fig. 9(6)). The effects were continuously maintained until 12 September, but disappeared on 27 September (Fig. 9(7), (8)). At heading and harvesting times, the amount of $\text{NH}_4\text{-N}$ showed a rather high level, but as the general trend, the amounts of inorganic N did not show the remarkable increase as well as the trends of 2005, especially of $\text{NO}_3\text{-N}$ (Fig. 9(9), (10)).

4. Discussion

4.1. Change of N nutrient status of pearl millet and its effect on crop growth and yield

From the results of research in SPAD value in pearl millet leaves in the early stage of vegetative growth (Fig. 2), all treatments with

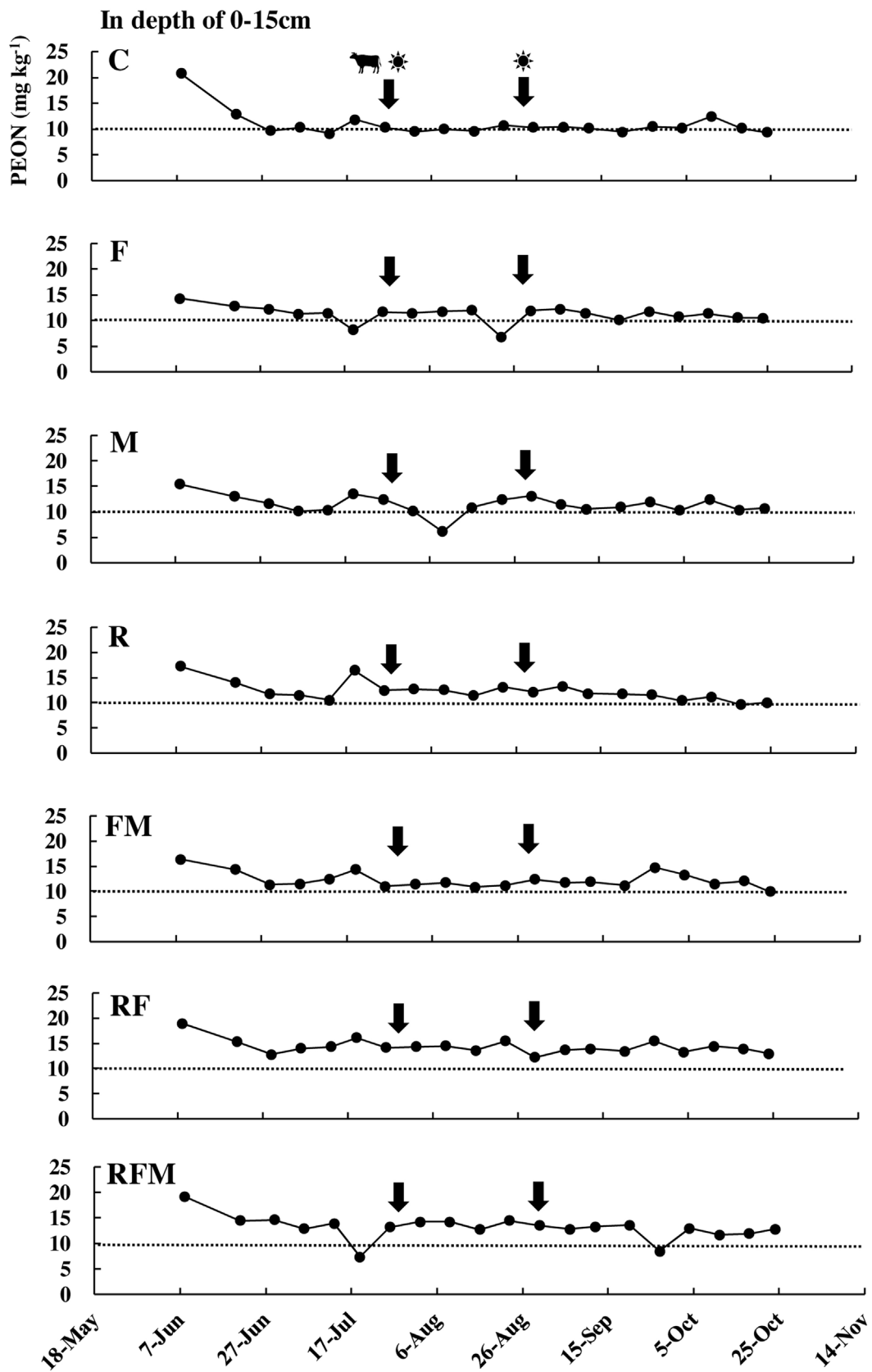


Fig. 4. Rainfall pattern in 2006 and dynamics of phosphate-buffer extractable organic nitrogen (PEON) in the 0–15 cm depth every week during the rainy season in 2006. The dotted line represents the amount of 10 mg kg⁻¹. The cow represents manure application and the sun represents fertilizer application. The arrows show the timing of their applications in 2006. Crop residue was applied on 15–16 May.

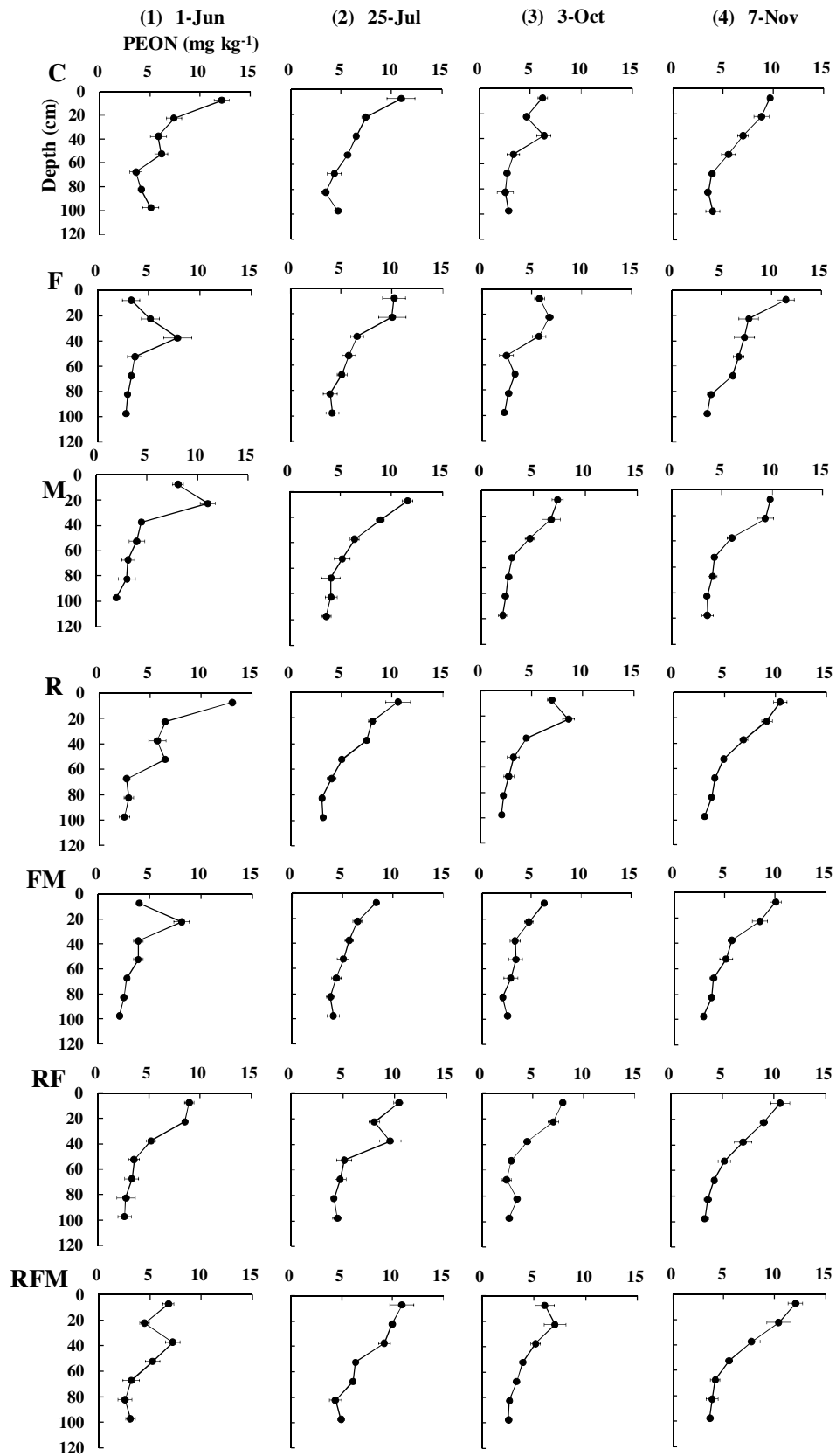


Fig. 5. Dynamics of phosphate-buffer extractable organic nitrogen (PEON) in the 0–105 cm depth at (1) seeding, (2) young growth stage, (3) harvest, and (4) after harvest during the rainy season in 2005. Horizontal bar represents standard error. See Fig. 2 for legend detail.

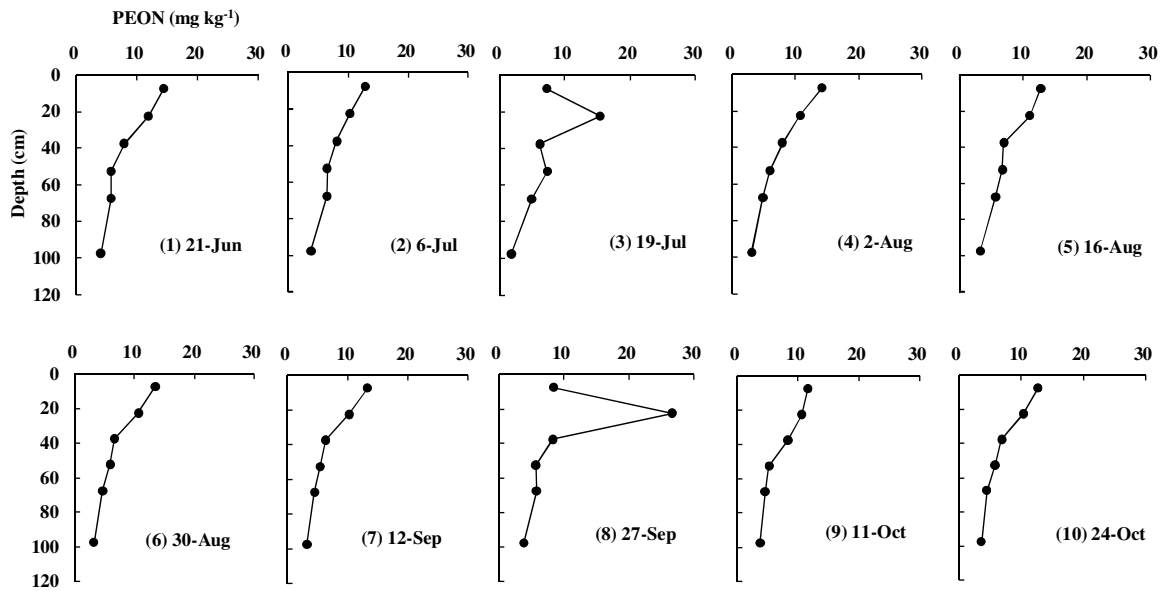


Fig. 6. Dynamics of phosphate-buffer extractable organic nitrogen (PEON) in the 0–105 cm depth under the treatment that applied all factors at every 2 weeks during the rainy season in 2006.

fertilizer application showed high effects on the N nutrient status of the leaves but in the treatments where sole organic matters were applied, the effects on N nutrient status were low. Afterwards, however, the application of organic matters continued to affect the N nutrient status of the crop until heading time (Fig. 2).

Pandey et al. (2001) explained that the N nutrient status of pearl millet around heading time is an important factor to identify grain yield and TDM.

For our results also, SPAD value had a significant and positive correlation with grain yield from the middle of vegetative growth (4 September 2006) to the end of heading time (Table 1). TDM had a significant correlation with SPAD value and both grain yield and TDM showed the highest correlation with SPAD value in the later stages of vegetative growth and at heading time (Table 1).

In the same region of Niger, Génard and Buerkert (2001) reported that the correlation between the chlorophyll content of leaves during the growth period and grain yield was not recognized under the treatments with different amounts of N application with fertilizer (Génard and Buerkert, 2001). Other previous studies reported that SPAD value before heading time correlated significantly with grain yield ($r \geq 0.8$, $P < 0.05$; Pandey et al., 2001) in four different research fields in Niger. These previous studies and our study's results showed that the N nutrient status of pearl millet around heading time is a very important factor in obtaining good grain yield and TDM.

4.2. Seasonal changes of available and inorganic N

The effects of each treatment on the total N pool were identified as above; the treatments with applied crop residue can increase the pool of total N in the soil surface but the effects appeared in the soil surface only (Fig. 2). Total N is the macro N pool, so it did not show so high a dynamic. Following this result, we considered that we should focus on the micro N pools; the available N and the inorganic N from the pool of soil N, to understand the N dynamics in Sahelian soil.

As the available N indicator, PEON has started to be employed in Japan instead of the incubation method (Ogawa, 1997). In this study, the remarkably different effects of the different treatments on the amount and seasonal changes of PEON were not identified

(Fig. 4). On the other hand, for inorganic N, the application of fertilizer mainly enhanced the amounts of inorganic N but its effects disappeared within only 2 or 3 weeks (Fig. 7). In the treatments without the application of fertilizer, this phenomenon was not recognized. Consequently, the amounts of PEON and inorganic N were not affected by the different treatments except for the increase of $\text{NH}_4\text{-N}$ with the application of fertilizer, and all treatments showed similar seasonal changes.

4.3. Importance of the increase of initial amounts of inorganic N (Birch effects) in the soil surface of the Sahel region

According to the seasonal changes of PEON, the trend was high right before the rainy season started and decreased after the rainy season had begun (Fig. 4). Inorganic N was linked to the dynamics of PEON; $\text{NO}_3\text{-N}$ and $\text{NH}_4\text{-N}$ showed a continuous increase for one month after PEON started to decrease gradually (Fig. 7). PEON was reported to consist of protein N from the bacteria in the soil (Marumoto et al., 1974; Higuchi, 1981, 1982; Matsumoto et al., 2000), that is, the detected high concentration of PEON would be composed of the accumulation of dead bacteria due to the severe drought during the dry season. Additionally, the organic matters applied in the last season would be accumulated as small organic particles via decomposition by termites (Ooyama, 2005) and solar radiation (Austine and Vianco, 2006). These decomposable organic matters would be smoothly starting to re-decompose and mineralize under the wet conditions from rainfall as the results showed the increase of inorganic N after the rainy season had started.

This phenomenon has been reported as the 'Birch effect' since the middle 1950s (Birch and Friend, 1956; Birch, 1958). Most of farmers in the Sahel region know very well the importance of the appropriate time for seeding and they usually start seeding after about 20 or 30 mm rainfall. Young plants can have only small rhizospheres as their roots are short, thus the inorganic N accumulated in the soil surface by the Birch effect will be extremely helpful for young plant growth. However, the Sahelian farmers usually have vast fields dotted around the village. Hence, they sometimes cannot catch the Birch effect because of a delay in seeding caused by insufficient labor and the replanting due to insufficient rainfall after the first seeding, and so on. According to

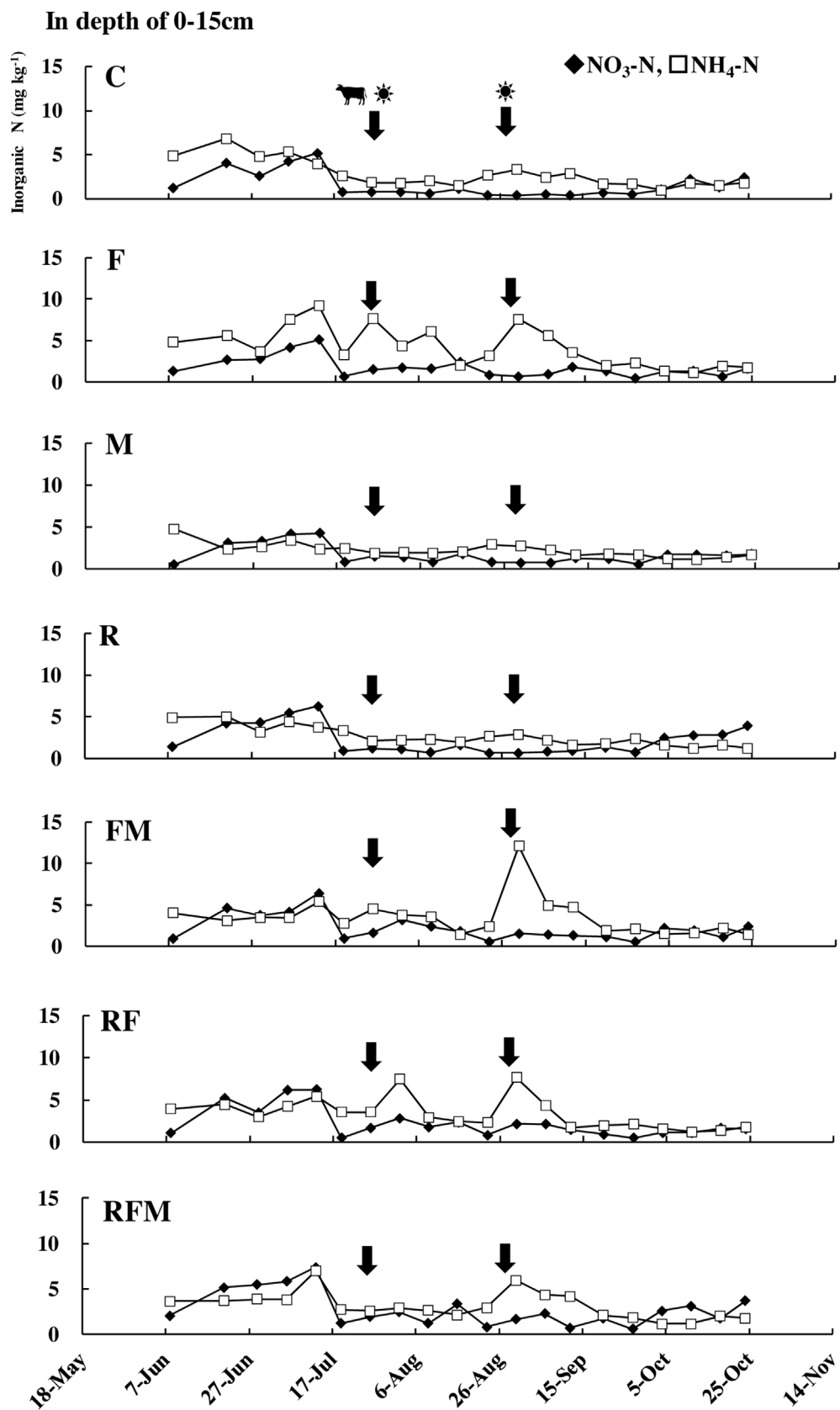


Fig. 7. Dynamics of nitrate ($\text{NO}_3\text{-N}$) and ammonium ($\text{NH}_4\text{-N}$) in the 0–15 cm depth every week during the rainy season in 2006. The cow represents manure application and sun represents fertilizer application. The arrows show the timing of their applications in 2006. Crop residue was applied on 15–16 May. See Fig. 2 for legend detail.

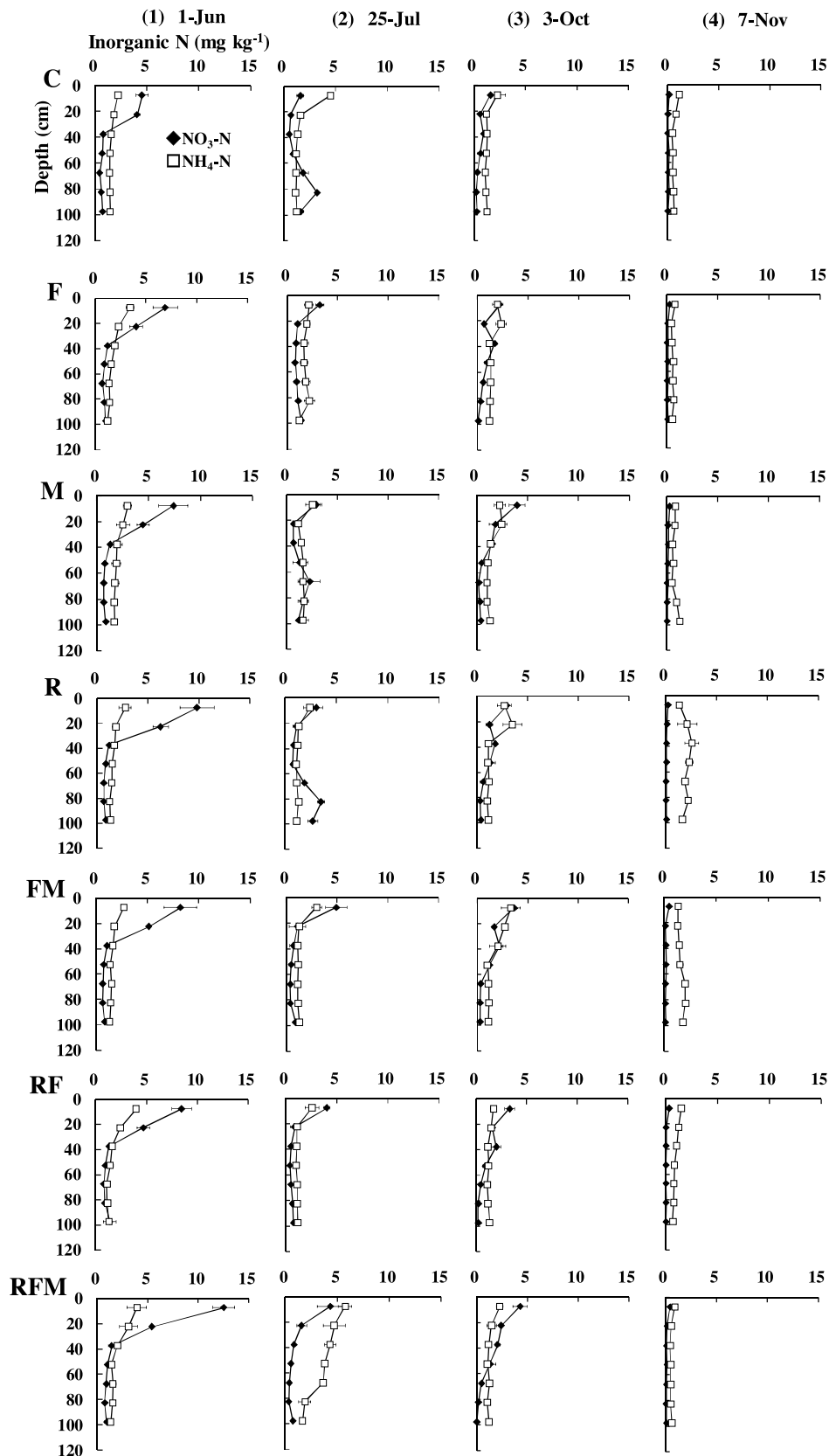


Fig. 8. Dynamics of nitrate ($\text{NO}_3\text{-N}$) and ammonium ($\text{NH}_4\text{-N}$) in the depth 0–105 cm at (1) seeding, (2) young growth stage, (3) harvest, and (4) after harvest during the rainy season in 2005. Horizontal bar represents standard error. See Fig. 2 for legend detail.

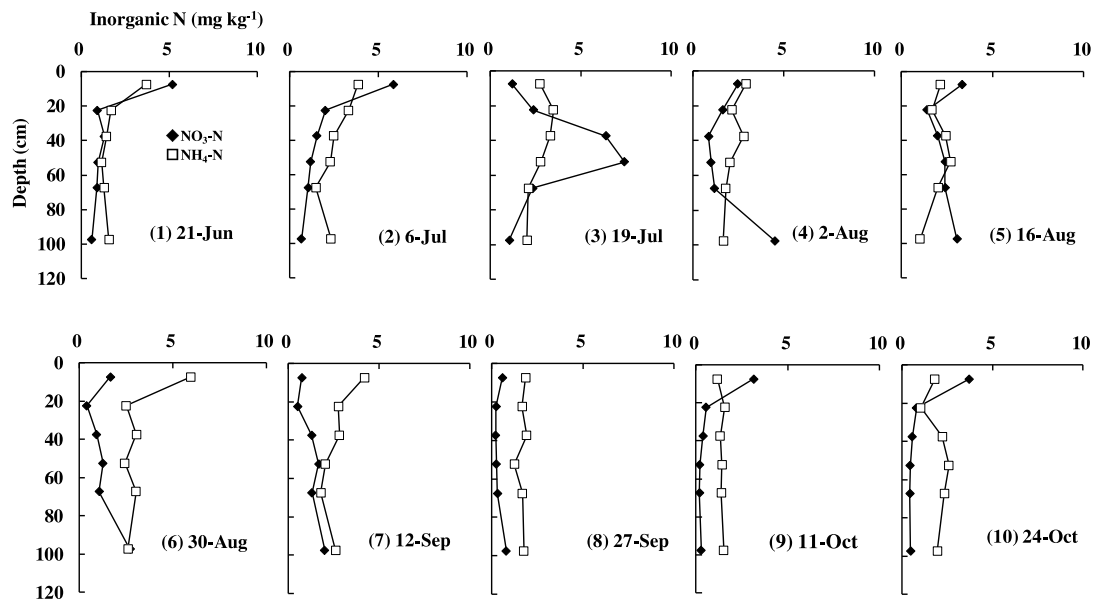


Fig. 9. Rainfall pattern in 2006 and dynamics of nitrate ($\text{NO}_3\text{—N}$) and ammonium ($\text{NH}_4\text{—N}$) in the 0–105 cm depth under the treatment with all factors applied every 2 weeks during the rainy season in 2006.

our observations in the fields, when the Birch effect was lost, crop growth conditions were not good for the whole of the rainy season. Presumably the elongation of young roots became slow because the opportunity had been lost to take up the accumulated inorganic N. This information is very interesting and useful for the farmers, thus further researches will be necessary to elucidate the relationship between the Birch effect and the growth of young plants, especially the young roots.

4.4. Factors for the seasonal changes of PEON and inorganic N

PEON decreased gradually after the start of the rainy season, but the amount of 10 mg kg^{-1} continuously remained in the surface soil under all treatments (Fig. 4). This phenomenon is very remarkable. Normally, organic N as PEON exists as an insoluble form in the soil because it is fixed by iron or aluminum ions. That is, it cannot be extracted by water but can be extracted with phosphoric acid. Therefore, we considered that only PEON fixed by iron or aluminum ions would continuously remain in the soil surface. It suggests that the maximum level for the capture capacity of PEON in the Sahelian sandy soil will be approximately 10 mg kg^{-1} in the soil surface and it explained that the possibility of leaching in PEON to the deeper layer in the sandy soil is due to the low capture capacity. Fig. 6 showed that the peak of the PEON amount appeared in the 15–30 cm depth when heavy rains continued. In Japan, it was reported that much organic N leached in the tea fields after excessive N application (Miura and Ae, 2005). The Sahelian soil has the trait of being extremely sandy with low contents of clay, thus the capture capacity of organic N as PEON must be very low. Fig. 6 showed evidence about the leaching of PEON. However, we could not catch continuous leaching to the layer deeper than 15–30 cm (Fig. 6). Probably, PEON was mineralized immediately after moving to the deep layer.

After the Birch effect, inorganic N did not show remarkable changes in the treatments with organic matters (Fig. 9). On the other hand, in the treatments with applied fertilizer, $\text{NH}_4\text{—N}$ increased, but soon decreased (Fig. 9). This decrease would be due to absorption by plants or from leaching. In the previous studies, Hafner et al. (1993) and Brouwer and Powell (1995, 1998) also reported the leaching of inorganic N ($\text{NO}_3\text{—N}$ and $\text{NH}_4\text{—N}$) in

Sahelian sandy soils. We also detected that $\text{NO}_3\text{—N}$ was leached by the continuous heavy rains through the research for the dynamics of $\text{NO}_3\text{—N}$ and $\text{NH}_4\text{—N}$ until the 105 cm soil depth (Figs. 6 and 9).

4.5. Importance of enhancing total N pool to enhance the available N amount

The important N pools for plants are decomposable organic N as PEON and inorganic N in the soil N pool. Suzuki et al. (2008) reported that PEON can be a good indicator to estimate the available N pool in Sahelian soils because of the high positive correlation between PEON and N estimated by the incubation method. However, because of the characteristics of these soils, PEON is a very unstable N pool under some conditions, i.e., continuous heavy rain.

The percentage of PEON and inorganic N (the available N pool for plants) in the soil N pool generally differ with soil types and soil fertility managements. For the Sahelian soil with a low level of available N, the relationship between the available N pool and total N pool have not yet been well elucidated. Hence, the relationship between the available N pool and total N pool will be affected by these characteristics.

In the soil surface of farmers' fields in the Sahel, total N had a significant positive correlation with PEON + inorganic N ($r = 0.769$, $P < 0.001$; Suzuki et al., 2008). Total N showed a significant positive correlation with mineralized N estimated by the incubation method + inorganic N ($r = 0.927$, $P < 0.001$; Suzuki et al., 2008). The angles of these regression lines were 0.045 and 0.058 respectively. These suggested that the percentage of the available N pools for plants in the total N pool is 4–6% approximately. Additionally, the previous study in Senegal conducted the incubation of the Sahelian soils (Psammentic ustropept; USDA) for 20 days with 32°C and reported that the percentage of mineralized N in the total N amount was about 6.1% (Bernhard-Reversat, 1982). This result did not include the amount of inorganic N which existed before incubation started, but it was very similar to our result. This suggested that we can consider that the N pool in Sahelian soil is low, so the pool of available N is also low. Consequently, the enhancement of total N pool is the key concept

to improve the available N pool in this soil to supply more N nutrient to crops.

4.6. How to enhance the total N pool in Sahelian sandy soil

The positive effects of crop residue application on the amount of total N in the soil surface were recognized (Fig. 3). Suzuki et al. (2016) also reported that the treatments with applied crop residue can increase the total N pool in the soil surface compared with other treatments (Suzuki et al., 2016).

The decomposition rate of organic matters is affected by its qualities and the C/N ratio used to be employed as its indicator; organic matters with a C/N ratio more than 20 have the trait of being decomposed slowly (Foth, 1980; Qian and Schoenau, 2001). Pearl millet residue applied in this experiment had a C/N ratio of 69 which was very much higher than the C/N ratio of manure (21). So decomposition is very slow. The previous study also reported that crop residue of pearl millet decomposed more slowly than cowpea residue (Franzluebbers et al., 1994). These results suggested that pearl millet residue will remain as large particles of organic matter and can contribute to increase the amount of total N in the soil surface. Other previous studies also supported this phenomenon from reports that the application of pearl millet residue increased the contents of carbon (Bationo et al., 1993, 2007; Buerkert et al., 2000) and of total N (Bationo and Mokwunye, 1991; Bationo and Buerkert, 2001) in the surface soil. In Sahelian sandy soils, additionally, this is the first elucidation that pearl millet residue makes a more useful contribution to enhancing the total N content than cattle manure. One of the traditional soil managements was 'transporting manure' to apply more crop residue than only 'corralling' livestock to supply manure and this was able to enhance the total N content in the surface soil of farmers' fields in Niger (Suzuki et al., 2014). Additionally, according to results from a couple of years (2005–2006) for NUE by cultivated pearl millet in the same long-term experiment, NUE in the treatment where sole pearl millet residue was applied at the highest level (R) was the highest among all treatments. The treatment that combined the application of fertilizer and pearl millet residue (RF) also showed higher trends than the treatment combining fertilizer and manure (FM), and the treatment that applied all amendments (RFM) (Suzuki et al., 2016). Consequently, these results explain that pearl millet residue has the potential to enhance the total N pool and the capacity to supply N to plants in Sahelian sandy soils.

5. Conclusion

The Birch effect exists in the Sahelian soil and it could be an important source of available N nutrient for young pearl millet plants. However, the characteristics of these soils mean that inorganic N, especially $\text{NO}_3\text{-N}$, made by the Birch effect or the application of fertilizer, will be frequently lost by leaching with heavy rainfall during the rainy season. The decomposable organic N as PEON is normally fixed with iron or aluminum ions, so it will not be lost by leaching. However, the current results showed the possibility that PEON was leached to the deeper layer. That is, PEON is an unstable N pool in the sandy soil in the Sahel region.

The usable N nutrients for plants, the decomposable N nutrient such as PEON and inorganic N, occupied approx. 4–6% in total N pool. Therefore, the most important issue in the region to enhance the N supply capacity for plants is to increase the total N pool size. Pearl millet residue has a higher potential to enhance the N supply capacity of Sahelian sandy soils than cattle manure.

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