Effect of Zai Soil and Water Conservation Technique on Water Balance and the Fate of Nitrate from Organic Amendments Applied: A Case of Degraded Crusted Soils in Niger

D. Fatondji, C. Martius, P.L.G. Vlek, C.L. Bielders, and A. Bationo

Abstract Experiments were conducted on degraded crusted soils to study water status and nitrogen release in the soil during the dry seasons of 1999 at ICRISAT research station and on-farm during the rainy seasons of 1999 and 2000 in Niger. Zai is a technology applied on degraded crusted soil, which creates conditions for runoff water harvesting in small pits. The harvested water accumulates in the soil and constitutes a reservoir for plants. The organic amendment applied in the Zai pits releases nutrients for the plants. Soil water status was monitored through weekly measurement with neutron probe; access tubes were installed for the purpose. Nutrient leaching was measured as soil samples were collected three times throughout the cropping season. A rapid progress of the wetting front during the cropping period was observed. It was below 125 cm in the Zai-treated plots 26 days after the rain started versus 60 cm in the non-treated plots. Applying cattle manure leads to shallower water profile due to increased biomass production. Total nitrate content increased throughout the profile compared to the initial status, suggesting possible loss below the plant rooting system due to drainage, which was less pronounced when cattle manure was applied. This study shows that the system improves soil water status allowing plants to escape from dry spells. However, at the same time it can lead to loss of nutrients, particularly nitrogen.

Keywords Drainage · Dry spells · Organic amendment · Water harvesting · Wetting front · Zai

Introduction

Land and soil degradation is one of the major problems facing agricultural production nowadays. Sundquist (2004) reported that desertification along the Sahara desert proceeds at an estimated area of 1,000 km^2/year, which is in line with the findings of the Global Land Assessment of Degradation (GLASOD) (Oldeman et al., 1990), which reported that in Africa, 65% of the cropland is degraded to some extent. In the Sahelian zone, soil fertility restoration through the vegetative fallow system is becoming ineffective due to population pressure, which leads to shorter fallow periods or simply to land abandonment (Amissah-Arthur et al., 2000). Experience revealed that due to the mounting population pressure and the limited availability of fertile land, farmers in the desert margin are forced to rely on marginal or degraded lands for agricultural production.

Zai is one of the several techniques available for the rehabilitation of marginal lands. The Zai is prepared during the dry season as farmers dig small pits in the soil to collect water, wind-driven soil particles and plant debris around the plant. About two handfuls (equivalent to 300 g) of organic amendments such as millet straw, cattle manure or their composted form are added to the pits right after digging (Roose et al., 1993; Ouédraogo and Kaboré, 1996). Nutrient released from amendment added is used by crops sown in the pit. The soil excavated from the pit is put down the slope of the pit to act as water catchment area. Likewise, runoff water is collected in the pit to help the plant escape dry spells that are frequent in the Sahel.

In Burkina Faso, it was found that on the zipele (lateritic soil) it is mostly the hardpan that hinders

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water infiltration and also limits crop production. In the Sahel of Niger, in addition to the crust, soil fertility is also a limiting factor (Hassan, 1996; Rockstom et al., 1999; Fatondji et al., 2006). Under both conditions, breaking the crust would increase water infiltration and deep percolation favoured by termite holes. The Zai technique thus combines water harvesting with nutrient management practices (Roose et al., 1992). The main investment required by the technology is manpower for digging the Zai holes, but the work is done during the dry period of the year when the farmers can invest more time to Zai making. According to Fatondji et al. (2006), Zai alleviates the effect of dry spells during plant growth and improves rain use efficiency by a factor of 2 compared to traditional flat planting, effects that are not only due to the water harvesting but also due to the amendments, and can be increased when using high-quality amendments. The use of Zai enables runoff water to be collected in small water pockets. The water accumulates and infiltrates in the soil profile and constitutes a reservoir for the crop. The crop planted in the Zai uses the nutrients released from the organic manure applied, but the nutrients can also be leached into deeper soil layers. However, no attempts have been made to study the pattern of water movement in the profile in Zai-treated plots and also to estimate the potential nutrient losses that can occur under these conditions. Therefore, experiments were carried out in the Sahelian zone of Niger, on-station under controlled water supply in 1999 and on-farm at Damari during the rainy seasons of 1999 and 2000 to address this problem. The objective of the on-station experiment was to determine the optimum application rate of organic amendments for pearl millet (*Pennisetum glaucum*) production as a function of the type of amendment. In the on-farm experiment, we studied resource use efficiency of millet under rainfed conditions in the Zai as compared to planting on flat soil. In the present chapter, the emphasis will be on water status of the soil throughout the cropping period and the effect on possible nutrient losses through the study of nitrate content in the soil profile at different sampling dates.

Materials and Methods

Site Description

The on-station experiment was conducted under controlled water supply at the ICRISAT research station at Sadoré (13° 15′ N, 2° 17′ E) in Niger from March to May 1999. Long-term average annual rainfall at this site is 550 mm, which falls between June and September. Monthly temperature varies between 25 and 41°C. The soils are classified as Psammentic Paleustalf (West et al., 1984). It is acidic with relatively high Al saturation and very high sand content (Table 1). The experiment was conducted on a field that had been subjected to severe wind and water erosion for a period of 4 years and that had developed extensive erosion crusts (Casenave and Valentin, 1989).

The on-farm trial was conducted during the rainy seasons of 1999 and 2000 at Damari (13°12′N and 2°14′E). Long-term average annual rainfall and monthly temperature amplitudes at Damari are similar to those at the ICRISAT research station. The soil at Damari is classified as Kanhaplic Haplustult (Soil Survey Staff, 1998). It is acidic, with 84% sand content

Table 1 Selected initial soil properties of the experimental fields at Sadoré, Damari and Kakassi (0–20 cm soil depth)

Soil characteristics	Sadoré	Damari	Kakassi
pH (H_2O)	4.5	4.2	6.4
pH (KCl)	3.9	3.9	5.4
Exchangeable base (cmol/kg)	0.4	1.7	7.9
Exchangeable acidity (cmol/kg)	0.7	1.1	0.04
ECEC[a] (cmol/kg)	1.0	2.8	7.9
Al saturation (%)	47	29	0
Base saturation (%)	37	61	99
P-Bray 1 (mg/kg)	2.3	2	0.8
C org (%)	0.1	0.2	0.2
Total N (mg/kg)	120	116	169
Bulk density (kg/m)	1.5	1.6	1.8
Sand (%)	92	84	69
Silt (%)	3	3	6
Clay (%)	5	13	25

Adapted from Fatondji et al. (2006)

[a] Effective cation exchange capacity

and relatively low effective cation exchange capacity (ECEC). The vegetation was an open bush with scattered trees. The selected field had been left fallow for 3 years prior to the experiment. In addition to small patches of loose sand deposits, which were cropped by the farmer, the field contained large patches of bare crusted soil, which were selected for installing the experimental plots.

Experimental Layout

On-station (at Sadoré)

Effects of amendment type (millet straw and cattle manure) and rate of application (1, 3, and 5 t/ha) on dry matter production of millet (*P. glaucum* L. R. Br) were evaluated in Zai pits under controlled irrigation. The field was sprinkler irrigated uniformly throughout the growing period at a weekly rate of 20 mm, with a total of 220 mm of water applied to harvest. The experimental design was a randomized complete block design (RCBD) with four replications. The control treatment was a non-amended pit. A local millet variety "Sadoré local" (120 days growing cycle) was sown on 17 March and the stover harvested on 25 May before grain production not only to avoid interference of rain with the treatments but also due to the photosensitivity of the crop. Zai holes were dug in all the plots.

On-farm

Effect of planting technique (planting on flat versus planting in Zai pits) and amendment type (millet straw and cattle manure) on millet yield was studied for over 2 years. In both years, the experimental design was an RCBD with four replications. The control plots received no organic amendment. The millet variety "Sadoré local" was sown on 29 June in 1999 and 26 June in 2000 and harvested at maturity. On-station as well as on-farm planting density was 10,000 pockets/ha and the crop thinned to three plants per pocket approximately 3 weeks after planting.

In both years, rain started towards the end of June (Fig. 1a and b). Cumulative rainfall was 499 mm in 1999 and 425 mm in 2000, which was below the long-term average of 550 mm. The same field was used in both years; therefore the pits dug in 1999 were used for 2000 but renewed.

Data Collection

Soil moisture profiles were measured weekly at 15-cm intervals down to 240 cm depth using a Didcot neutron probe (Didcot Instrument Company Limited, Wallingford, UK) starting from the day of planting. The first measurement was done before the first irrigation or rainfall. For that purpose, two 48-mm inner diameter aluminium access tubes were installed in each plot, one tube between the pockets and the other on the pocket close to the plant.

The depth of the shallowest tube was restricted to 45 cm due to the presence of a lateritic layer, while the deepest reached 300 cm. The probe had been calibrated in situ for the soils of the experimental sites applying the gravimetric method. Data of the tubes installed between the pockets are reported in this chapter.

From the neutron probe data, the volumetric soil water content was calculated. It is expressed here as

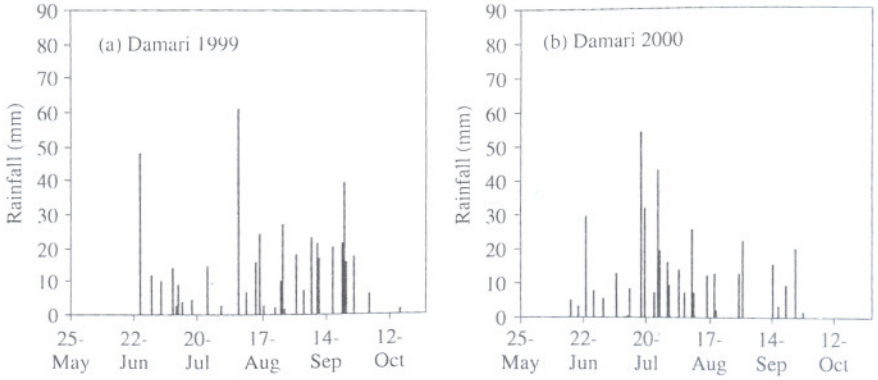

Fig. 1 Rainfall pattern at the experimental site in two seasons of 1999 and 2000

dimensionless ratio (cm^3/cm^3). In the same experiment, amendment decomposition was studied with litterbags and related samples collected three times during the cropping period. Along with these samples, soil samples were collected to estimate nitrate content. For each sampling, the maximum depth was determined in accordance with the progress of the wetting front. The level of the profile wetting front was determined as a function of soil water content in a given layer at a given time of measurement compared to its level before the rain or irrigation started. The samples were collected in three replications out of four. Prior to installation of the experiment in 1999, on-station soil samples were collected to evaluate the initial status of the soil with regard to nitrate content. Sample collection was done with an aluminium tube of 7.5 cm diameter. They were collected in/on the hole or the pocket after the plants had been removed. From 0 to 20 cm, samples were taken at 10-cm interval. Below 20 cm, samples were taken at 20 cm increment. The samples were kept in sealed bags and stored in a freezer until use.

Nitrate content was determined semi-quantitatively using nitrate test strips (Reflectoquant) and an RQflex reflectometer as described by Merck KgaA (64271 Darmstadt, Germany). KCl solution (50 ml) was added to 70 g of soil sample and the mixture shaken for 10 min. A sub-sample of the mixture was put in a test tube and left to elutriate, and then the nitrate content was read. The test strips have two reaction zones, which turn red-violet on contact with solutions containing nitrate, and the colour intensity depends on the nitrate concentration. To convert the reading into nitrate N, the values obtained must be multiplied by 0.226. At harvest, crop yield data were collected. Total dry matter for both on-farm and on-station experiments as well as seed dry weight and harvest index (on-farm only) was estimated.

Results and Discussion

Rainfall Pattern in Both Rainy Seasons at the Experimental Site

As mentioned earlier, in both years, rainfalls started on-farm in June. In 1999, the first important rainfall event occurred on 28th June (Fig. 1). The cumulative rainfall to planting was 60 mm. Thirty-four events were recorded out of which nine were above 20 mm, giving 57% of the total rainfall. In 2000, the rain started earlier with smaller rainfall events. The first important rain with which crops were planted occurred on 25 June. The cumulative rainfall to planting was 38 mm. A total of 30 events were recorded out of which seven were above 20 mm, giving 48% of the total rainfall. This year was also characterized by two dry spells of which the first of 9 days occurred during grain filling at the end of August and the second of 14 days at the beginning of September. This shows better rainfall distribution in 1999 than in 2000, but also higher cumulative rainfall in 1999.

On-station Under Controlled Water Supply

Effect of Amendment Type and Rate on Soil Profile Wetting Front

Figure 2 presents the wetting front on the respective dates of soil sampling, which was done purposely to study the relation between the progress of the wetting front and potential nutrient losses.

In all treatments, the wetting front was below or close to 200 cm 36 DAS (days after sowing). Figure 2 indicates a rapid progress favoured by the breakage of the soil crust but also the sandy loose structure of the soil on the station. According to Fatondji et al. (2006), the sand content of the experimental soil was 92% with 5% clay. Under such conditions, Fatondji (2002) observed 70% drainage of 220 mm irrigation applied during 72 days. Under similar conditions, Rockstom et al. (1999) also observed infiltration rates ranging from 15 to 182% of individual rainfalls depending upon the measurement position on a toposequence of 1–3% slope. The wetting front was still close to 200 cm at harvest in all treatments except for manure-treated plots, particularly the largest rate of application (5 t/ha) where the front was around 60 cm deep at harvest. This could be due to increased water consumption under this treatment because of higher biomass production. According to yield data collected in this experiment, 5 t/ha of manure produced the highest yield of 4,500 kg/ha total dry matter (Fatondji et al., 2006).

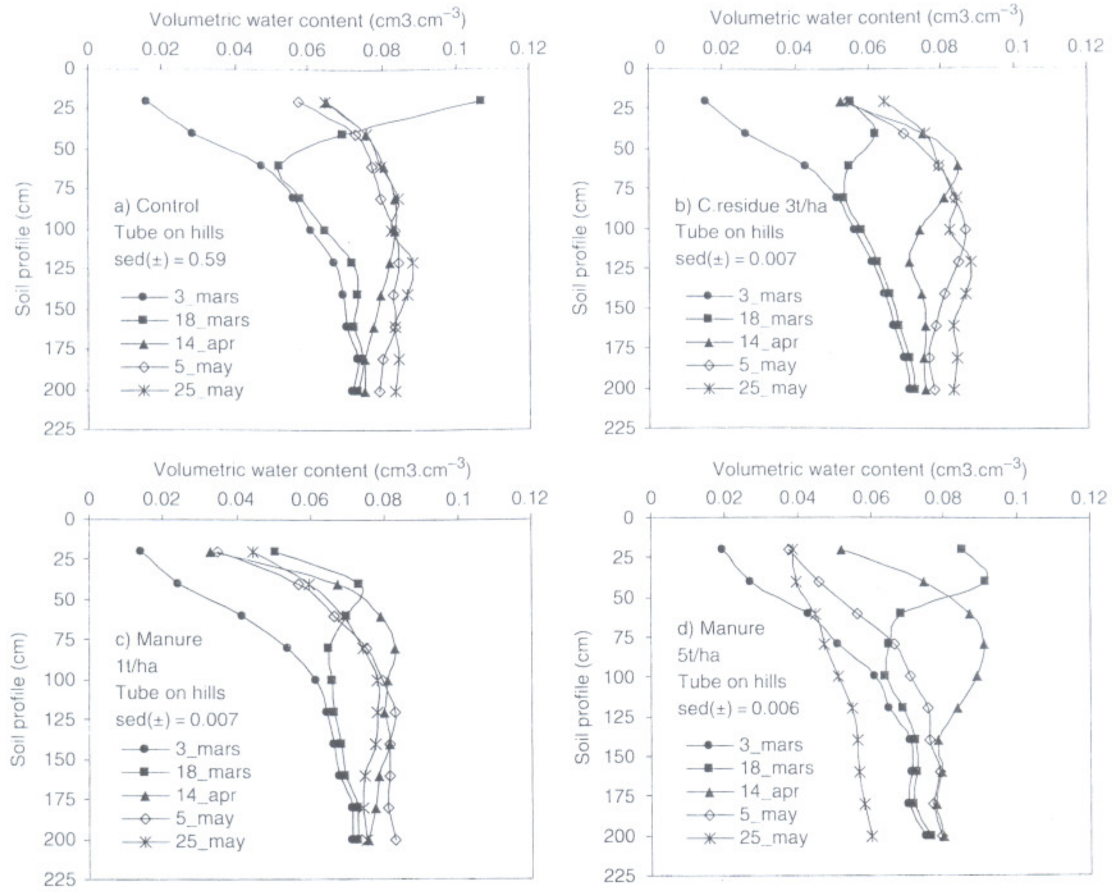

Fig. 2 Effect of amendment type and rate of application on soil wetting front; Sadoré off-season 1999, sed, standard error of difference between means; c.residue, crop residue

On-farm Experiment

Effect of Planting Technique on Soil Profile Wetting Front

In all cases in 1999, the wetting front was already below 200 cm on the day of planting in the Zai-treated plot (Fig. 3a, c and e), which confirms the trend observed on-station under the same conditions, while the wetting front was shallower on the same date in the non-Zai-treated plots (Fig. 3b, d and f).

The results indicate that despite the sandy structure of the experimental soil, breaking the surface crust and digging the pits was highly favourable for water infiltration compared to the flat treatment. Volumetric soil water content (VWC) was still very high at the deeper layer in the Zai than in the flat even towards the end of the season. In 1999, in the Zai control, for instance, at 200 cm depth, VWC was 0.084 cm^3/cm^3 compared to the initial level of 0.060 cm^3/cm^3, while in the flat control, it was 0.059 cm^3/cm^3 compared to the initial level of 0.055 cm^3/cm^3. The same trend was observed in 2000 but it was less pronounced (Fig. 4).

Effect of Amendment Type on Soil Profile Wetting Front

In both years, soil water profile was shallower in the manure-treated plots than the other treatments. Towards the end of the cropping season, in the Zai as well as on flat with cattle manure, soil water content decreased significantly compared to plots treated with millet straw, indicating high water consumption of the

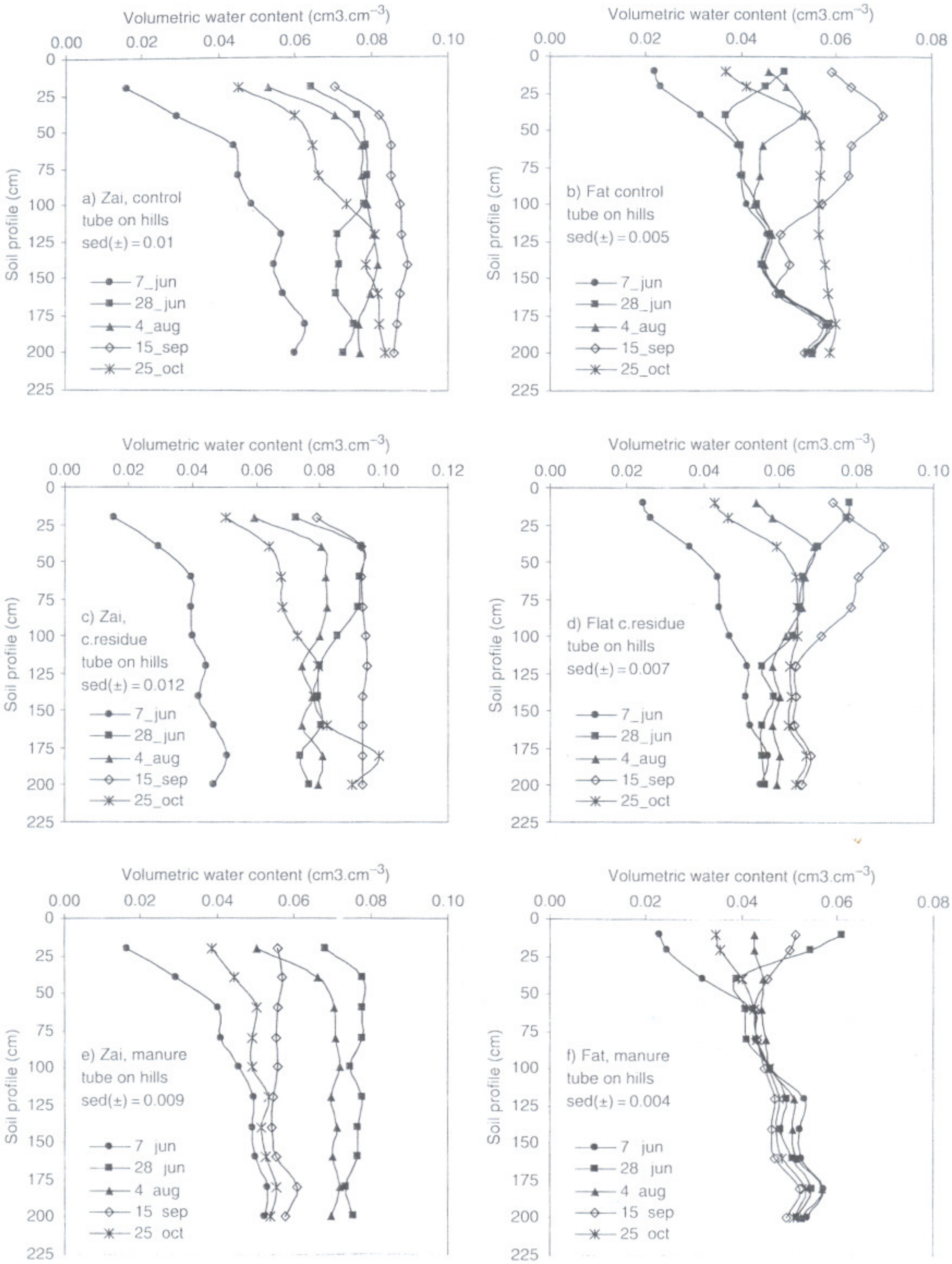

Fig. 3 Effect of planting technique and amendment type on soil water profile; Damari 1999. sed, standard error of difference between means; c.residue, crop residue

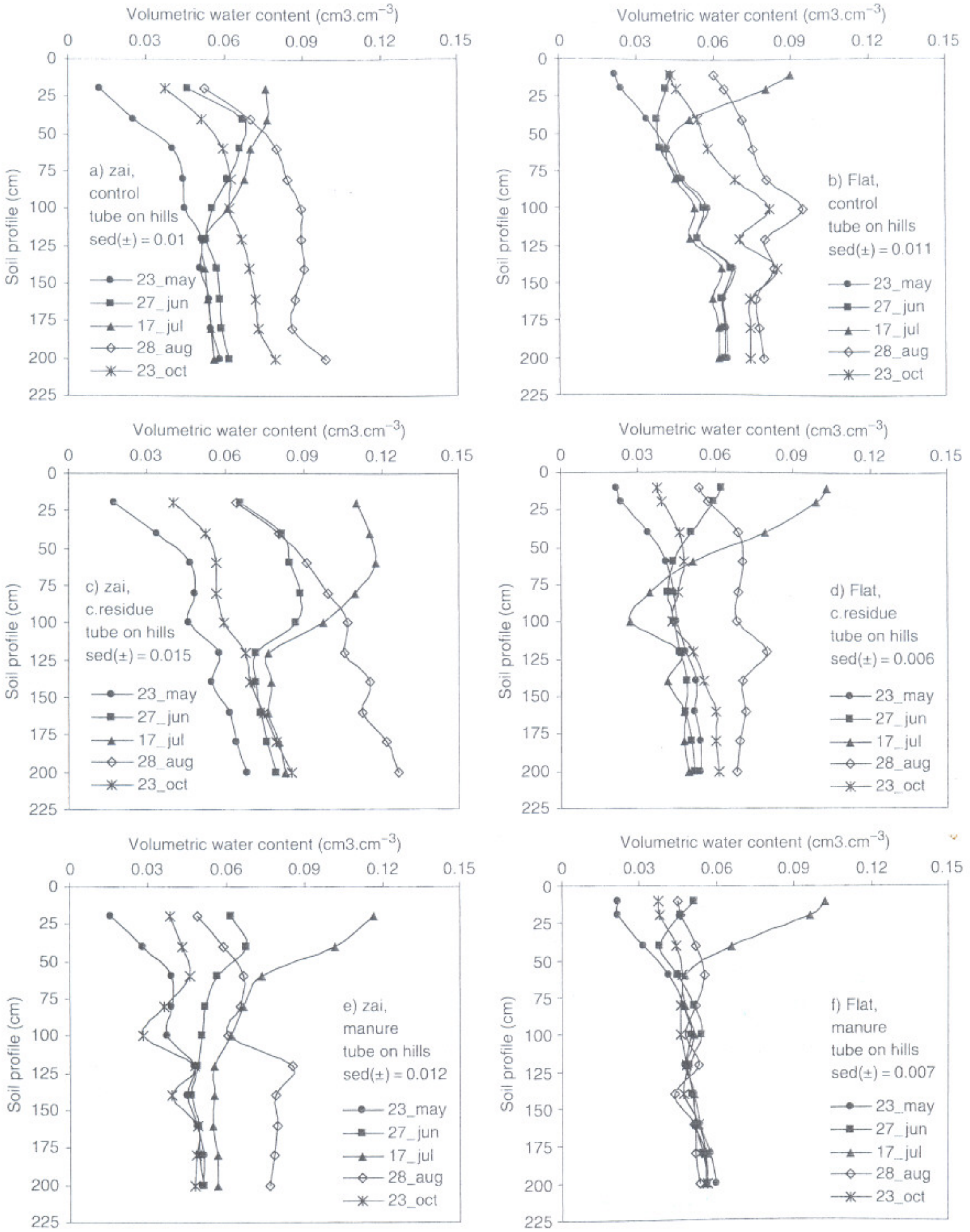

Fig. 4 Effect of planting technique and amendment type on soil water profile; Damari 2000. sed, standard error of difference between means; c.residue, crop residue

crop due to increased biomass production. Fatondji et al. (2006) reported rain water use efficiency of 8 kg/mm in manure-treated plot versus 2 kg/mm for millet straw on average calculated on total dry matter basis under similar conditions, which was accompanied by high yield. Particularly in non-Zai-treated plots amended with cattle manure, the wetting front remained at 60 cm during the whole growing period, which is due to not only the presence of crust that hampers infiltration but also increased crop uptake as reported by Payne et al. (1996) and Zaongo et al. (1997), who found that manure application increases soil water retention and favours root development and water uptake. All these resulted in increased crop yield.

Effect of Amendment Type and Rate of Application on Nitrate Content in the Profile

Compared to the initial nitrate content in the profile, nitrate level increased in all treatments during the growing period but more in plots with crop residue (Fig. 5). In these plots, the level increased at deeper layer, which presumes possible loss beyond the rooting depth. Nevertheless, in all treatments, nitrate content was close to or less than the initial level, particularly in the manure-treated plots, where it is observed that below 60 cm in the profile, nitrate content was lower than the initial level after 67 days of plant growth, indicating not only increased crop uptake following increased biomass production but also possible percolation in deeper layer that was compensated for by nitrate movement for upper layers. The observed trend

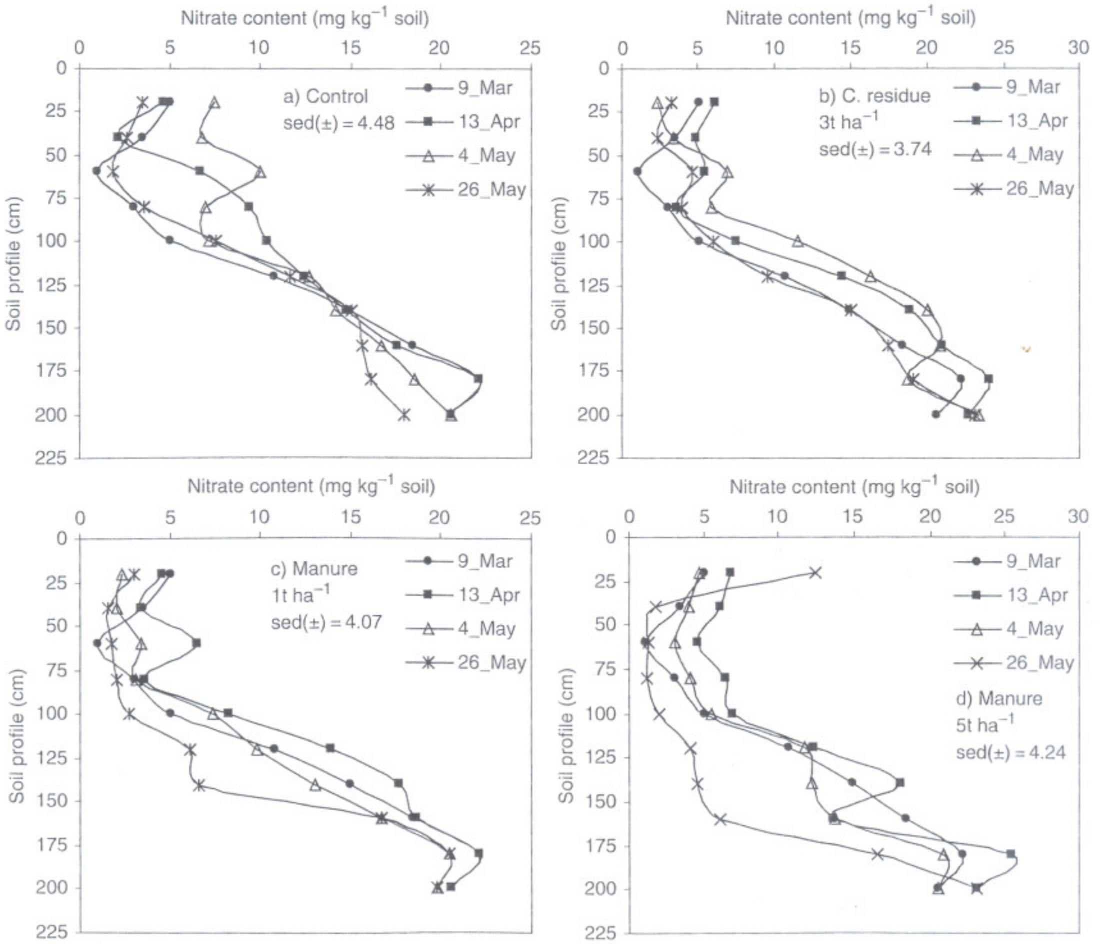

Fig. 5 Nitrate content in the profile as affected by amendment type and rate of application; Sadoré off-season 1999. sed, standard error of difference between means; c.residue, crop residue

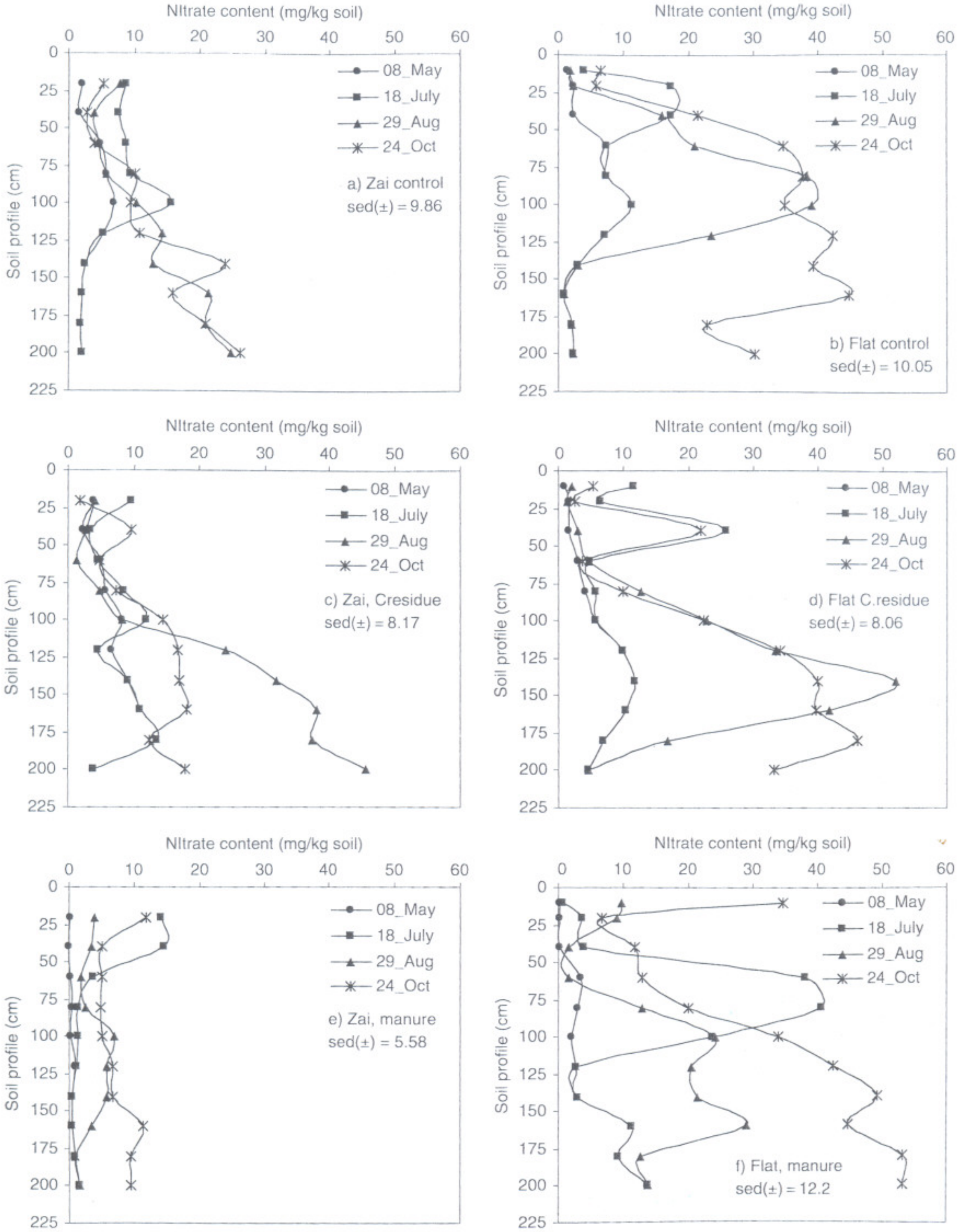

Fig. 6 Profile nitrate content as affected by planting technique and amendment type; Damari rainy season 2000. sed, standard error of difference between means; c.residue, crop residue

confirms the findings of Addiscot et al. (1991), who reported 5 kg/ha nitrogen uptake in a fast-growing crop.

Effect of Planting Technique on Nitrate Content in the Profile

Nitrate content in the soil of the Zai-treated plots was lower than the level observed in flat planted plots. Possible reason for this could be deeper percolation due to water harvested in the pits as opposed to the flat planting conditions. As reported earlier, water infiltration and percolation beyond the rooting zone was very fast in the Zai, whereas we observed that on flat, the wetting front was shallower throughout the growing period. Under these conditions, nitrate losses through drainage have also occurred (Fig. 6b, d and f) but in a limited proportion, which could explain the high concentration of nitrate observed in the measured profile, particularly in deeper layers.

The overall low level of nitrate content in the Zai pit could also be due to better plant development and the resulting increased plant nutrient uptake, particularly in the plots amended with cattle manure. Fatondji et al. (2006) reported 3–4 times grain yield increase and N and P uptake improvement in the range of 43–64 and 50–87%, respectively, due to Zai application in similar conditions.

Effect of Amendment Type on Nitrate Content in the Profile

In Zai-treated plots, nitrate content in the upper layer was slightly higher or similar to the initial level in the control as well as in plots with crop residue. Nitrate content was higher in manure-amended plots in the same layer. In deeper layer, nitrate content increased slightly, particularly under crop residue, compared to the initial level. This was more pronounced 3 months after amendment application, while in the plots with cattle manure it was relatively low throughout the cropping season. This could be due to increased crop uptake.

In non-Zai-treated plots (flat), nitrate content remained high in lower layers at the end of the cropping period compared to the initial level under all amendment management practices.

The trend observed with regard to soil water profile and nitrate content indicates that following crust breaking with the Zai pits, water infiltration increases. Therefore, water percolates to deeper layer in the Zai-treated plots. This water could recharge the water table. To improve soil fertility and plant growth and yield, organic amendment was applied in the Zai, but part of the nutrients released by this amendment may be drained to deeper layer and possibly not available to the crop. Nevertheless, not all but small proportion of this nutrient may be lost as reported by Addiscott (1996), who observed that 6–8% of nitrogen applied at a rate of 190 kg/ha was lost by leaching in winter wheat experiment. Even though this experiment was not conducted under similar condition with the actual study, it does give an indication of the potential loss. In plots amended with cattle manure, the crops developed higher biomass; therefore, water and nitrate losses were limited but not prevented. According to Fatondji et al. (2006), 4,500 kg/ha of dry matter was produced on-station and 5,000 kg/ha was produced on-farm with cattle manure in the Zai in 1999 and 3,000 kg/ha in 2000, which has resulted in higher nutrient uptake, limiting possible loss of nutrient by drainage.

Conclusion

From the above results and discussion, the following conclusions are made. Zai technology offers numerous advantages with regard to rehabilitation of degraded land and also facilitates sustainable cropping on marginal lands. Studies have shown that the most important benefits lie in the water-harvesting feature and also the concentration of nutrients in the rooting zone of crops (application of manure in Zai pit), which may favour crop root development and hence yield increase. Results further indicated that surface crust breakage improves water harvesting in the planting pits which later percolates to deeper layer together with part of the nutrient applied, particularly the mobile forms of nitrogen like nitrate, which when in excess can become a pollutant to the underground water. It is also concluded that plant uptake due to increased vegetative mass can limit this percolation. The results of the study enable to make a recommendation that amendments applied should be of good quality to draw the best from the technology and reduce nutrient losses due to improved plant water uptake resulting from increased vegetative growth. Under experimental conditions, water harvesting through the use of Zai technology is necessary to provide and store water in the soil for crop use, as it was shown that in plots amended with manure and not treated with Zai, the wetting front was limited to 60 cm. This would avoid shortage of water for the plants due to dry spells that are common during the growing season in the Sahel.

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