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Organic amendment decomposition, nutrient release and nutrient uptake by millet (Pennisetum glaucum (L.) R.Br.) in a traditional land rehabilitation technique (zai) in the Sahel

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List of Acronyms and abbreviations:

θ_v	Volumetric soil water content
AE	Agronomic Efficiency
ARF	Apparent Recovery Fraction
DOS	Date of Sowing
DAS	Days After Sowing
ECEC	Effective Cation Exchange Capacity
FAO	Food and Agricultural Organization
F.prob	F probability
ICRISAT	International Crop Research Institute for the Semi-Arid Tropics
INRAN	Institut National de Recherche Agronomique du Niger
ITCZ	Intertropical Convergence Zone
NUE	Nutrient Utilization Efficiency
OA	Organic Amendment
^oC	degree Celsius
PAW	Plant available water
PET	Potential Evapotranspiration
SIR	Substrate Induced Respiration
S_w	Stock of water
TDM	Total Dry Matter
T_{max}	Maximum temperature
T_{min}	Minimal temperature
vs	Versus

1 INTRODUCTION

Sustainable land use implies harmony between man's use of land and the ability of the land to maintain or renew its quality. Once this balance is upset, land degradation occurs (Katyal et al. 2000). From the agricultural point of view, land degradation refers to a temporary or permanent decline in its productive capacity. According to Blaikie and Brookfield (1987), land degradation is a weakening in the capacity of land when put to a particular use with a specific set of management options. This definition implies that land can be degraded for some purposes and not for others.

The problem of land degradation is important worldwide. The FAO reported that 16% of the total arable land area has been degraded by human activity since the 1950s. According to the Global Land Assessment of Degradation (GLASOD) (Oldeman et al. 1990) and the study of Dregne and Chou (1992), 38% of the world total cropland have been degraded since mi-century. The same source reported that 65% of the cropland in Africa is degraded. In the Sahelian zone of West Africa, land degradation through wind and water erosion, nutrient mining and excessive exploitation of the vegetation cover, lack of organic matter and minerals induced by repeated burning constitute a major concern (Roose et al. 1993). It is one of the main constraints to sustainable agricultural production. In Niger the problem is particularly severe and needs increased attention. Due to the increasing population pressure and the resulting increase in cropped land area, fertility restoration through the fallow system is becoming increasingly inefficient (Ssali et al. 1985). The limited availability of fertile land is pushing the farmer to rely on degraded lands for agricultural production, as is now the case in the Passore region in Burkina Faso and the Tahoua region in Niger. The conventional techniques used to rehabilitate those lands are limited and costly for small-scale farmers who are the major food producers in the Sahelian zone of West Africa (Roose et al. 1992).

1.1 Some practices to sustain agriculture in the Sahel

1.1.1 Organic amendments application

In the Sahelian zone of West Africa, where farmers use very little or no inorganic fertilizers because of their high cost (McInter et al. 1986), organic amendments constitute the principal source of nutrients for sustainable agriculture. Among those organic amendments are crop residues (millet straw, groundnut haulm), green manure (fallow vegetation), animal manure (from cattle, sheep or goat) and other organic residues, some of which are discussed here. They can be applied to the soil surface as mulch or incorporated into the soil. In the present study, the organic materials were incorporated into the soil.

- **Crop residues**

In recent years, the effect of crop residues application on soil degradation processes, and the associated changes in the soil's physical conditions have received considerable attention. Lamers and Feil (1995) reported that the application of crop residues constitutes an effective means for rehabilitation of degraded land but is practiced by farmers only on a limited scale. Crop residues can be used as mulch and as organic amendment. As mulch they can control wind erosion. From a study conducted at the International Crop Research Institute for the Semi-Arid Tropics (ICRISAT) in Niger, Michel et al. (1995) reported a nearly 50% reduction of wind-transported soil from plots mulched with crop residues compared to bare plots. Crop residues also control soil surface temperature. Buerkert et al. (1996) observed that the presence of 2 t ha^{-1} of millet stover reduced the maximum soil temperature during the day by 8^oC at 1 cm depth and by 4^oC at 5 cm depth. This is important for the emergence of millet since, at the onset of the rains, the temperature of the first centimeters of the soil, can reach 50^oC (Buerkert et al. 1996). The presence of crop residues attracts termites, which play an important role in soil regeneration processes (Chase and Boudouresque, 1987, Mando et al 1999). The mulch also stimulates microbial activity, which determines the chemical and physical properties of the soil and controls the release of plant nutrients and thus crop productivity. The activity of termites and microorganisms are essential for the mineralization of the nutrients contained in the organic matter.

The long-term application of crop residues leads to a decrease in soil Al saturation (low Al concentration) (Bationo et al. 1989). This increases phosphorus (P) concentration, which enhances P uptake by plant (Kretzschmar et al. 1991). The same author also observed proliferation of root hairs in a solution with high Al concentration when millet stover was added. All this suggests that surface application of crop residues as mulch or their incorporation can help sustain millet production. However, the incorporation of organic material with high C:N ratio like crop residues can lead to temporary nutrient immobilization and consequent delay of their mineralization (Tian et al. 1992; Thomas et al. 1993).

- **Cattle manure**

The role of cattle manure in maintaining the soil's chemical structure and sustaining soil productivity has received major attention. Pichot et al. (1981) and Pieri (1986) reported that it increases crop and forage yield and, when sufficient quantities are applied on a continuous basis, it might permit stable intensified crop production. In a study conducted under water- limiting conditions (rainfall less than 300 mm) on sandy soils in the center-northern part of Senegal, Ganry et al. (1994) found that after 8 years of farmyard manure (FYM) application at the rate of 2 t ha^{-1} every two years, yields were significantly higher than in non-treated plots, even in years when plants experienced drought stress. Cisse et al. (1988) reported a shallow wetting front in plots treated with FYM compared to non-amended plots, and hypothesized that FYM application may enhance root development and favors a better utilization of the limited amount of water. Cisse (1988) reported that the application of FYM improves the soil fertility by reducing the soil pH, the rate of exchangeable Al, and increasing the amount of exchangeable bases. Broadcast application was used in most of these studies; however, hill placement of manure may further improve its use efficiency.

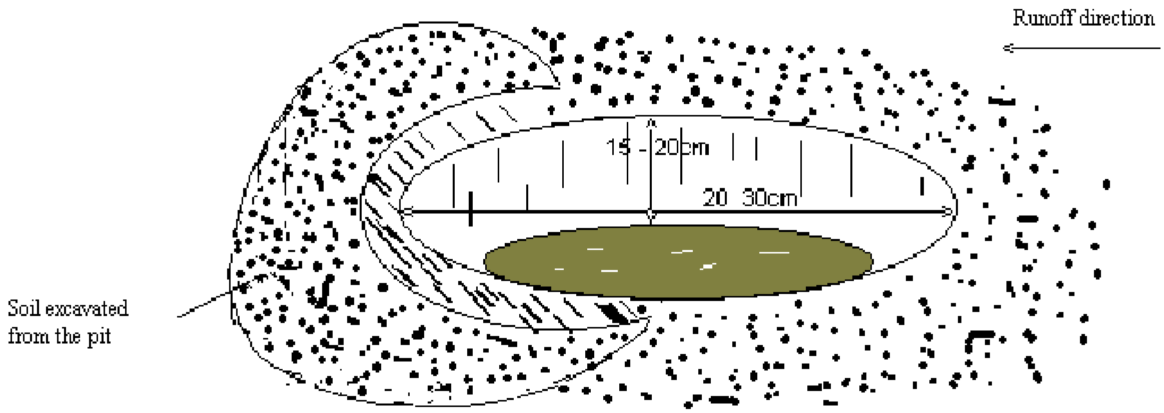
Nutrients from the organic amendments are made available to the plants roots through the decomposition of the amendments. Some of the factors that governed this process are the chemical status of the amendment, soil humidity, soil temperature, the presence of soil macro, meso and micro fauna and microorganisms (Cadish and Giller 1997). Investigations done on the chemical characteristics showed that the C:N ratio determines the rate of decomposition and nutrient release from organic amendments. Parnas (1975) reported a critical C:N ratio of 30, above which N immobilization occurs. Palm et al. (1991) reported that the polyphenol to N ratio determines N release from leaves of tropical legumes. Thomas et al. (1993); Lehmann et al. (1995); Tian et al (1992) observed that lignin and polyphenolic content were of major importance in the process of organic amendment decomposition. In spite of the lack of consensus on which characteristics are more important, the general idea is that N must be sufficiently available to the decomposers to assimilate for the synthesis of their cell material (Wood, 1995). Otherwise N immobilization might occur in the process of amendment decomposition. All these parameters must be considered when using organic amendments as a source of nutrients to the plant. Agbim (1987) and Cortez (1998) reported the importance of the soil humidity and temperature in the decomposition of leaf litter from different plant species. Both soil moisture content and temperature regulate the activities of decomposer microorganisms (Runge 1983). Finally, soil fauna plays a critical role in the decomposition and nutrient release of organic amendments. Soil animals fragment the litter and make it accessible to microorganisms and grazing micro-flora (Anderson et al. 1983). According to Tian et al. (1992), who studied the decomposition of plant residues with contrasting chemical compositions, soil fauna plays an important role in the decomposition and nutrient release from litter. Hofer et al. (2001), in a study of litter decomposition in Amazonia, observed that the macro fauna was the driving force, and their exclusion with smaller mesh size litterbags caused a significant reduction of the rate of litter decomposition.

1.1.2 Water harvesting

Optimizing soil water use is concerned with the whole ‘water path’ from the moment rain or irrigation water reaches the soil surface until the crop productively transpires it. At all stages it is essential to minimize the diversion of water into unproductive side-paths and to ensure that its utilization by the crop is as efficient as possible. Among the techniques used in collecting rainfall water and improving its infiltration are the half moon, the stone bunds (made only from stones) with a large base up to 1 m, the ”diguettes” or ”digues filtrantes” (made of sand alone or stones with a base not as wide as that of stone bunds. These techniques have proved to give substantial yield increases in low-rainfall seasons. However, on clay soils in wet years, yield either was not affected or it was sometimes depressed due to water logging. A technique that combines water harvesting and nutrients concentration in the crop’s rooting zone is the zai technique (Kabore, 1995; Roose et al. 1992; Roose et al. 1993; Ouedraogo et al. 1996).

1.1.3 Zai, an indigenous technique for land rehabilitation

The zai is a traditional technique, which uses locally available materials and can deal with the limited availability of organic amendments in the Sahel (Williams et al. 1995; Baidu Forson, 1995); which makes it accessible to farmers. They use this technique to combat land degradation and to restore soil fertility. In ”Moore”, a language of Burkina Faso, zai is drawn from ”zaiegre” which means to get up early and prepare one’s land (Roose et al. 1993). In the zai technique called “Tassa” by the Haoussa in Niger, the soil’s physical and chemical fertility are restored by mixing small quantities of organic material, e.g. compost or manure, in small holes (20 – 40 cm diameter and 10 – 15 cm depth) (Figure 1.1) dug into the degraded, crusted soil. When digging the pit, some of the dug-out soil is deliberately placed in a small bund downslope of the pit to produce a mini-water catchment. The decomposition of the organic material releases nutrients required for the growth of the crop. Biological activity and especially the action of termites favor the development of soil macro porosity that improves water infiltration. Furthermore, the pit is not entirely refilled with soil such that it can collect water efficiently. Hence, besides the supply of nutrients required for crop growth, the zai pits promote a better infiltration of water. Since this water infiltrates deeper than would normally occur, the technique ensures that at least a sizable fraction of the water percolates to depth where losses by evaporation become negligible. The zai technique is labour intensive. About 60 working days (based on an average of 5 hours per day) are needed to dig 1 ha of zai (Ouedraogo et al. 1996). But since the zai pits can be dug during the dry season, labor limitation is generally of minor concern.



I Figure 1.1: General view of a planting pit (zai)

The zai pits are of varying dimensions and sizes. Traditionally, they have 20 cm diameter and about 10 cm depth (Wedum et al. 1996), whereas the improved zai usually have 20 – 40 cm diameter and 10 – 15 cm depth (Roose et al. 1993). The farmers dig the pits in alternate rows (Roose et al. 1993; Kabore 1995) (Figure 1.2). The non-cultivated area is five times the cultivated area (Wright, 1982; Roose and Rodriguez, 1990). During the dry season, the zai pits trap litter, some organic materials and fine sand deposited by wind. The following year, new pits are dug in the areas left free the preceding year. Studies on the zai have been conducted in Burkina Faso, in Mali, where the Mossi people on the Dogon plateaux have adopted the technique, and on the Keita plateaux in Niger. Hassan (1996) reported millet yields of 400 kg ha^{-1} with the zai in low rainfall years compared to zero yield without zai treatment.

The same author has compared millet yields obtained using different water harvesting techniques and found that in drought years, millet performed better in the half moon than in the zai. However, during a good rainfall year the tendency was reversed. The probable explanation was that the bigger size of the half moon allowed more water to be collected and the plants in the half moons suffered less from drought. This suggests that there is a need to find the optimum size of the zai in drought-prone areas.

In most studies so far, the technique has not been investigated from the point of view of resource use efficiency.

The present study was, therefore, conducted to address the issue of resource use efficiency in the zai technique. The research was conducted on-station at ICRISAT Niamey in Niger during the dry seasons of 1999 and 2000 and on-farm at Damari and Kakassi (Niger) during the rainy seasons of the same years. It aimed at understanding the interactions between water and nutrient management with the zai technique. Attention was focused on (1) the decomposition and nutrient release from different sources of locally available organic amendments, (2) on water harvesting and use, and (3) on nutrient uptake by millet.

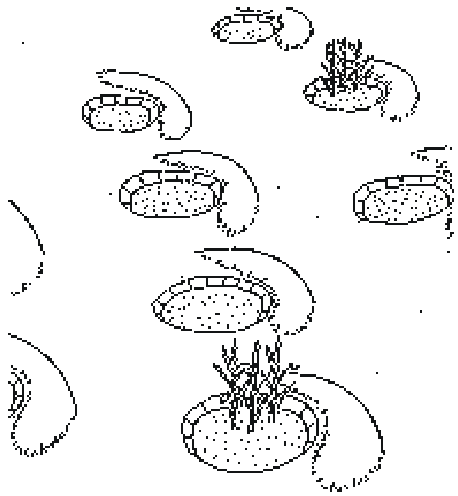


Figure 1.2: Spatial placement of the zai holes in the field (Kassogué et al. 1996)

The following hypotheses were formulated:

1. The benefits of the zai technique depend on both water catchment area and organic amendment input. Optimizing the ratio of water catchment to quantity for various sources (type) of organic amendment will provide the highest return on investments.
2. The zai technique will be beneficial only under restricted rainfall regimes.

To address these questions, the following objectives were set for the study:

- To determine the efficiency of the zai planting technique compared to flat planting in relation to nutrient release, nutrient and water use.
- To determine the optimum combination of organic amendment type and rate in the zai technique.
- To study the nutrient release from different sources of locally available organic amendments in the zai technique and nutrient uptake by millet.
- To determine on-farm nutrient use efficiency in the zai technique under two contrasting rainfall conditions on abandoned, degraded cropland, and simulated dry spells.

2 MATERIALS AND METHODS

2.1 General description of Niger

2.1.1 Climate of Niger

The climate of Niger is predominately Sahelian and controlled by the seasonal fluctuations of the Intertropical Convergence Zone (ITCZ). The rainfall pattern is monomodal. Rain falls between May/June and September/October with a maximum in August, with high spatial and temporal variability. The annual rainfall varies from 800-900 mm in the southwest to less than 100mm in the north (Sivakumar et al. 1993) (Figure 2.1).

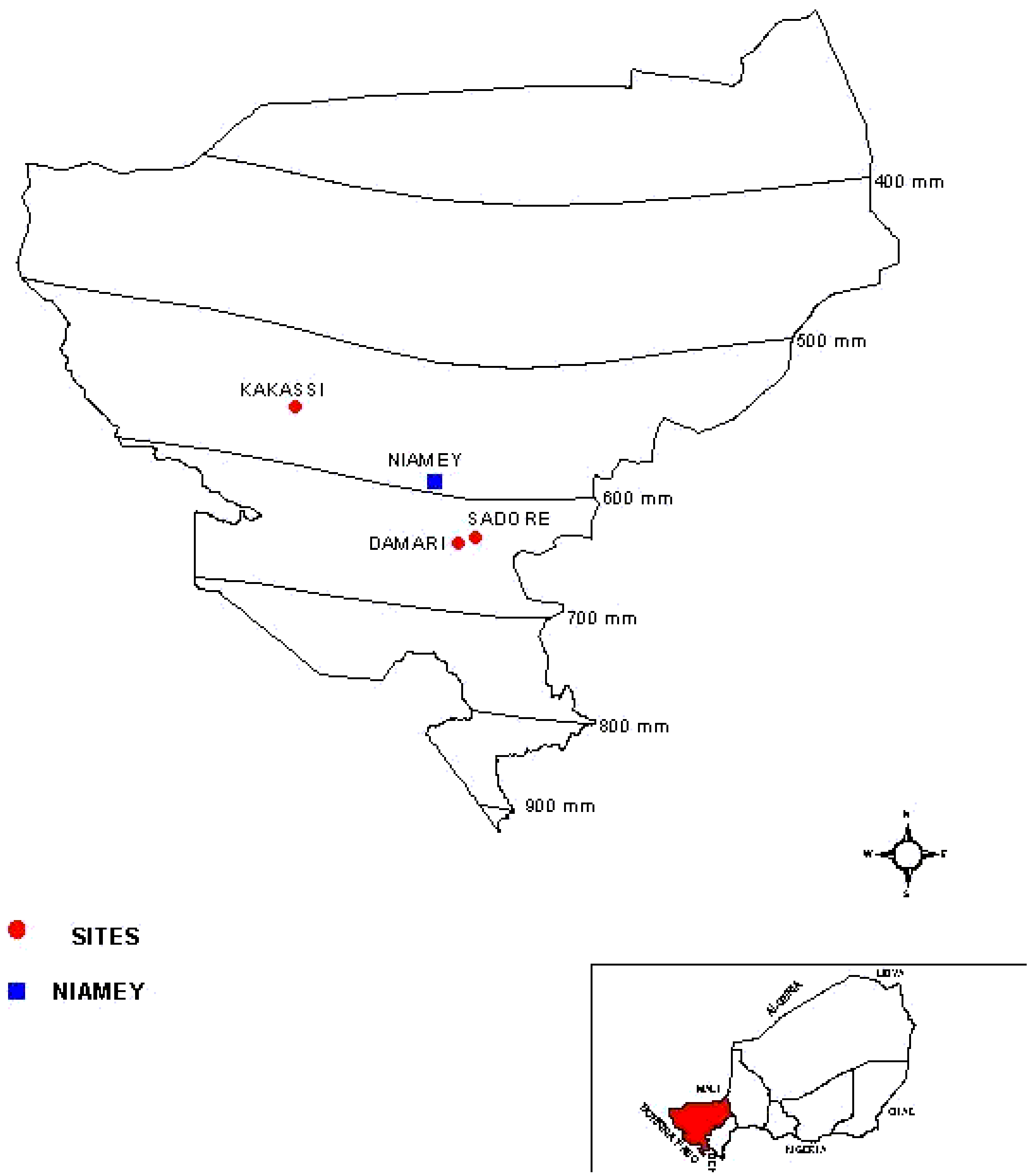


Figure 2.1: Map of the department of Tillaberi (Niger) with experimental sites and the isohyets

Other characteristics include (a) high air temperature (T_{min} =11-27 ^{o}C; T_{max}: 27-41 ^{o}C); (b) the low average daily relative humidity (13% - 66%); (c) the alternating wind systems: the ‘Harmattan’, hot and dry north-eastern continental wind that blows from November to February and carries soil particles; and the monsoon, humid south-western maritime wind; and (d) the high annual potential evapotranspiration (PET)(2000 - 2800 mm) (Amadou et al. 1999). The PET exceeds rainfall in all months except August (Sivakumar et al. 1993) (Figure 2.2).

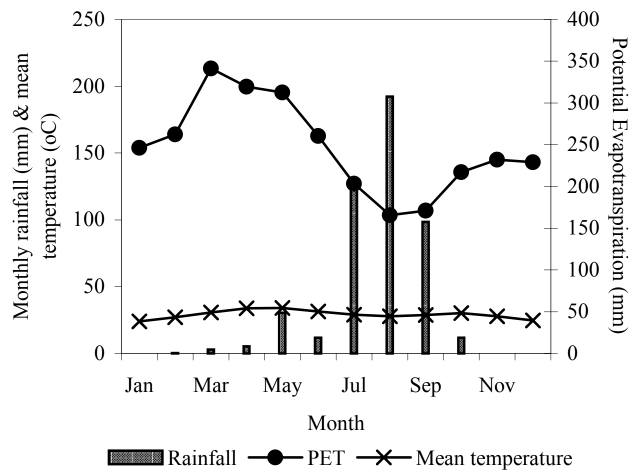


Figure 2.2: Monthly variation of rainfall, potential evapotranspiration (PET) and temperature at Sadore ICRISAT research station (Niger – ICRISAT’s climatic data base 1983 – 1999)

2.1.2 Soils and vegetation

According to the classification proposed by INRAN and FAO (1997), the soils in Niger can be classified into 6 groups: the mineral soils, the weakly developed soils (Ustoxic Quartzipsamment according to the US classification), subarid soils, ferruginous tropical soils (Psammentic Paleustaef according to the US classification), hydromorphic soil, and Vertisols. Out of these, the ferruginous and the hydromorphic soils are the major types used for agriculture. The ferruginous tropical soils have a sandy texture (on average 87% sand - ICRISAT annual report, 1999) and are easy to till. They have a low water holding capacity and low soil fertility but a high permeability. They are suitable for less demanding crops like pearl millet (Pennisetum glaucum L. R. Br.). However, they are susceptible to surface crusting and wind and water erosion (Penning de Vries et al. 1982).

In general, the vegetation is open bush savanna with scattered small trees, the density of bushes and trees being closely related to the annual rainfall. Beside this, a large variation in vegetation cover due to overgrazing, land use and soil differences are also observed.

2.2 Experimental site description

2.2.1 Geographical situation

Experiments were conducted during a two-year period at three locations: Sadoré, Damari and Kakassi. At Sadore (13° 15' N, 2° 17' E), approx. 40 km southwest of the capital city Niamey, dry season experiments were carried out at the ICRISAT-Niger research station in 1999 and 2000 from March to May. The long-term average annual rainfall at this site is 550 mm.

Rainy season experiments were conducted at 2 sites:

(1) Damari (13°12' N and 2°14' E) is located at approximately 45 km southwest of the capital city of Niamey (Figure 2.1). It is approximately 10 km west of the ICRISAT experimental station at Sadoré. The long-term average daily rainfall and temperature are similar to those of Sadore (Figure 2.2). (2) Kakassi (13°50' N and 1°29' E) is located approximately 80 km northwest of the capital city of Niamey (Figure 2.1) with a long-term average annual rainfall of approximately 450 mm. The monthly rainfall and temperature variation of the region are shown in Figure 2.3. The 2 sites have contrasting drought hazards. Lower rainfall and low soil permeability at Kakassi resulted in a higher drought risk than at Damari. The experimental fields were chosen based on 2 main criteria:

1) They had been used in the past for millet production but had not been cropped for several years as a result of loss of productivity;

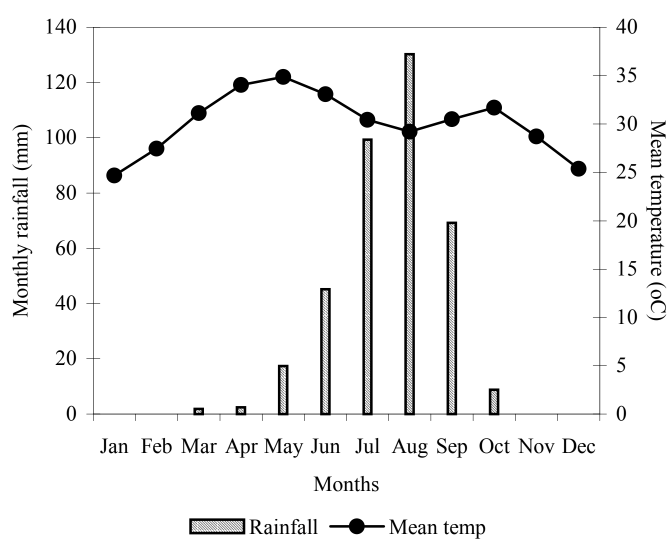


Figure 2.3: Monthly variations of rainfall and temperature in the department of Tillabery, 1970-1999 (Direction National de la météorologie du Niger)

2) They presented clear signs of degradation, such as extensive crust formation, wind/water erosion signs, hardpan formation, etc.

At both the Damari and Kakassi sites, one trial was conducted during the rainy seasons of 1999 and 2000. In addition, a small trial was installed at both locations in 2000 to test for the impact of termite activity.

2.2.2 Soil and vegetation

The soils at Sadore are classified as Psammentic Paleustalf (West et al. 1984). Since the zai technique is intended as a land rehabilitation technique, all experiments here were carried out on an experimental field that had been subject to severe degradation by wind and water erosion for a period of 4 years prior to the present experiments. The field had not been cropped for a long time prior to the experiment nor received any fertilizer. Within a 2 ha experimental field, 3 parallel blocks 18 m by 200 m in size oriented north-south were kept free of vegetation through repeated manual weeding from 1995 to 1998. As a result of the combined action of wind and water, the field developed extensive hardpans, locally known as "Gangani" (Figure 2.4), that is characteristic of severely degraded land. The soil at Sadore is acidic with relatively high Al saturation and high percentage of sand (Table 2.1).

Figure 2.4: Hardpan developed under the effect of water and wind erosion; ICRISAT-Niger experimental station

At Damari, the experimental field was located on an upper glacis, eolian sand over laterite, severely eroded by wind and water. Soil depth to the laterite ranges from 0.45 to 2 m. The vegetation was an open bush with scattered trees. The selected field had been left fallow for 3 years prior to the experiment. Except for small patches of loose sand deposits, which were cropped by the farmer, the field presented large patches of bare soil, which were selected for installing the experimental plots (Figure 2.5). The soil is acidic with relatively high Al saturation and very high sand content (Table 2.1).

Table 2.1: Chemical and physical properties of the experimental soils (initial sampling 0 – 20 cm soil depth)

	Experimental sites		
Soil characteristics	Sadoré	Damari	Kakassi
pH (H_20)	4.5	4.2	6.4
pH (KCl)	3.9	3.9	5.4
Exch base (cmol kg^{-1})	0.4	1.7	7.9
Exch. Acidity (cmol kg^{-1})	0.7	1.1	0.04
ECEC* (cmol kg^{-1})	1.0	2.8	7.9
Al saturation (%)	47	29	0
Base saturation (%)	37	61	99
P-Bray (mg kg^{-1})	2.3	2	0.8
C org (%)	0.1	0.2	0.2
Total N (mg kg^{-1})	120	116	169
Bulk density (Mg m^{-3})	1.5	1.6	1.8
Sand (%)	93	84	69
Silt (%)	2.7	3	6
Clay (%)	5.4	13	25

* Effective Cation Exchange Capacity

Figure 2.5: General view of the experimental field at Damari before trial installation

The experimental field at Kakassi was located on an extended plateau severely eroded by wind and water. The vegetation was an open bush with scattered trees. It was located on a bare soil in a fallow, with scattered patches of cropped land (Figure 2.6). The field had been left as uncultivated fallow for more than 10 years prior to the installation of the experiment. The soil has almost neutral reaction with 0% aluminum and relatively high clay content (Table 2.1).
The available P and the percentage of organic carbon were very low at the three sites. Available P was lower at Kakassi, which may be an indication of the advance stage of degradation.

Figure 2.6: General view of the experimental field at Kakassi

2.3 Characterization of the organic amendments used in the study and litterbag description

2.3.1 Crop residues

Millet stems and leaves were collected each year at ICRISAT's research station at Sadore. In 1999, this straw was cut manually into small pieces of about 10 cm, while in 2000 it was done mechanically. The pieces were sun-dried before weighing.

2.3.2 Compost

The compost preparation was done according to the method suggested by Attikou (1998). In 1999, we used only crop residues and soil mixed with urine from the barn at ICRISAT as a source of microorganisms. Due to the low quality of the compost of 1999, we decided to use cattle manure as a source of microorganisms in 2000, but in the same proportion as the barn soil used in 1999. Two holes 0.8 m deep, 2.5 m long and 1.5 m wide were used to prepare the compost. In 1999, the holes were filled on 27 January with successive layers of crop residues and soil from the barn at ICRISAT. The proportion of straw to soil was 4/5 to 1/5. Fifteen kg of barn soil were spread on 60 kg straw. In this way, 6 layers were put in each hole. Each layer was well irrigated before the next layer was added. A total of 300 kg straw and 90 kg of barn sand were put in each hole. The holes were covered with plastic. They were irrigated twice a week with 200 liters of water for three months. The compost was mixed for the first time 2 weeks after installation and one month later. A third mixing was done 2 weeks before the end of the composting period. In 2000, the same holes were filled on 2 February. The same proportion of crop residues and cattle manure as in 1999 was used. The same care was taken as in 1999.

2.3.3 Cattle manure

Cattle feces were collected from the barn at the ICRISAT research station at Sadore in 1999 as well as in 2000. The feces were sun-dried before weighing.

The C/N ratio of the crop residues was high compare to that of the compost and the manure (Table 2.2). Though the C:N ratios of the compost and the manure were similar in 1999, the N content of manure was twice the N content of both the crop residues and the compost. The nutrient content of the amendment used in 2000 was higher than that of 1999.

Table 2.2: Characteristics of organic amendment used in 1999 and 2000

Organic amendment	N (%)	P (%)	K (%)	C/N
	1999			
Crop residues	0.83	0.10	0.98	50
Compost	0.82	0.08	0.15	23
Manure	1.74	0.82	0.86	20
	2000			
Crop residues	1.18	0.10	1.57	50
Compost	1.04	0.10	0.23	32
Manure	2.53	0.94	1.72	21

2.3.4 Litterbag

In order to study amendment decomposition and nutrient release, litterbags made of iron netting of 2 mm mesh size were used. The dimensions of the bags were 20 x 20 x 5 cm. In all experiments, the bags were filled with 100 g of amendment except for experiment S2, where 50 g were weighed in the bags of plots receiving crop residues and those receiving 100 g of cattle manure per hill. In the dry season trials, 6 hills were selected at random, whereas in the rainy season experiments 8 hills were selected. One bag was installed in the field on each hill.

2.4 Experimental layout

2.4.1 Dry season experiments

Experiments were conducted during the dry season (March to May) in 1999 and 2000. The plots were irrigated using ground water supplied through line sprinkler irrigation. The experiments were laid out in a randomized complete block design RCBD with 4 replications except for the control of experiment S1 (see below), which was repeated twice. The zai pits were 25 cm large and 20 cm deep. The plot size was 5 m x 5 m. A local millet (Pennisetum glaucum L. R. Br.) variety (Sadore local) was sown. The hill density was 10000 ha^{-1}. The crop was harvested before grain production because of its partial photosensitivity, which increases the growing period and can result in non-typical grain yields during the increasing day-length phase of the dry season. Furthermore, the crop may not reach grain maturity before the start of the rainy season. At harvest, one border row was left out on each side of the plots.

Experiment – 1 Effect of water regime and planting technique on millet performance and amendment decomposition (S1)

The objective of the experiment was to determine the effect of the zai planting technique on millet growth, nutrient release and crop water use compared to surface application of manure. Two water regimes (20 mm weekly and 30 mm weekly) and 2 planting techniques (planting in zai pits and traditional flat planting) were studied. The layout details are reported in Table 2.3. Due to logistical constraints, plots with the same irrigation regime were grouped, resulting in 2 blocks (corresponding to the 2 irrigation regimes). The blocks were analyzed separately. All plots received cattle manure applied at the rate of 300 g (dry weight) per hill. In the plots where flat planting was applied, shallow incorporation of the manure was done to prevent losses by erosion. Millet was harvested after 65 days of cropping.

Experiment – 2 Effect of amendment type and rate on the performance of millet in zai technique (S2)

The objective of the experiment was to determine the optimum application rate as a function of organic amendment type in the zai technique. Two amendment types (crop residues and cattle manure) and 4 rates of application (0 t ha^{-1}, 1 t ha^{-1}, 3 t ha^{-1}, 5 t ha^{-1} – dry weight) were studied. The plots were all treated with zai except for a control non-amended flat, added for comparison. Details of the layout are reported in Table 2.3. The plant was harvested after 67 days of cropping. The plots received 20 mm weekly irrigation until harvest.

Experiment – 3 Recovery from drought and growth of millet in zai technique (S3)

The objective was to evaluate the ability of a millet crop grown with the zai technique to recover from dry spells. Three water regimes (continuous irrigation, 3 and 4 weeks dry spells) and 2 planting techniques (planting in zai pit and traditional flat planting) were tested. Details of the experimental layout are given in Table 2.3. Uniform irrigation of 30 mm was applied weekly to all treatments from 1 - 22 March. After this, the plots were either irrigated with 30 mm weekly until harvest (water regime 1), or the irrigation was stopped for 3 weeks until millet panicle initiation (42 days after sowing), followed by 30 mm irrigation weekly until harvest (water regime 2), or the water supply was stopped for 4 weeks and restored one week after water regime

2 until harvest (water regime 3). Cattle manure was applied at the rate of 300 g (dry weight basis) per hill. The crop was harvested 78 DAS.

2.4.2 Rainy season experiments

The experiments were conducted on-farm during the rainy seasons 1999 and 2000 at Damari (D) and Kakassi (K) in Niger. A randomized complete block design with 4 replications was used in the study. The plot size was 6 m x 6 m. A local millet variety (Sadore local at Damari and Darinkoba at Kakassi) was sown. The hill density was 10000 ha^{-1}. Amendments were applied at the rate of 300 g per hill (dry weight). At harvest, one border row was left out on each side of the plots. The harvest area was 25 m^2.

Experiment - Effect of catchment area and amendment type on the development and yield of millet (D1&K1)

The objective of the experiment was to study the effect of different pit sizes and nutrient management techniques on the performance of the millet crop. The combination of 3 planting techniques (traditional flat planting, zai pits of 25 cm and pits of 50 cm diameter), 3 types of amendments (crop residues, compost, and cattle manure), and a control non-amended was studied. Details of the experimental layout are reported in Table 2.3. In both years, the plant growth was retarded due to heavy rains in 1999 at Damari (sand covered the young seedlings in the zai), and to dry spells at the beginning of the rainy season in 2000 at both sites. Weeding was not necessary at Damari. At Kakassi, in 1999 the field was weeded once 60 DAS, whereas in 2000 it was weeded 55 DAS.

Table 2.3: Details of experiment layout for Sadore, Damari and Kakassi; dry season and rainy season 1999 and 2000

Experiment identification	Year	Site		Treatments	Plot size	Pits digging	Amendment application	First irrigatio	Pesticide treatmen	Date of sowing	Gap filling	Plant thinning	Date of harvest
S1	1999	Sadore	On-station	2 planting techniques (planting in pit or without Two water regimes (20 mm or 30 mm weekly) + 1 control flat no-amended	5m x 5m	16-Feb	13-Mar	11-Mar	-	17-Mar	-	21 DAS	21-May
S2	1999	Sadore	On-station	3 rates of manure + 3 rates of crop residues (1, 3, 5 t ha^{-1}) + 1 control zai pit + 1 control flat	5m x 5m	22-Feb	13-Mar	12-Mar	-	18-Mar	7 DAS	27 DAS	25-May
S3	2000	Sadore	On-station	2 planting techniques (planting in pit or without X 3 water regimes (continuous irrigation, 3 and 4 weeks dry spells)	5m x 5m	18-Jan	11-Feb	22-Feb	-	1-Mar	-	23 DAS	17-May
D1	1999	Damari	On-farm	3 planting techniques (flat, 25 cm and 50 cm diameter zai) x (3 amendment types (millet residue, compost, cattle manure)	6m x 6m	12-May	24-May	-	-	29-Jun	14 DAS	22 DAS	26-Oct
	2000	"	"	"	"	12-May	7-Jun	-	-	26-Jun	10 DAS	22 DAS	23-Oct
D2	2000	Damari	On-farm	2 planting techniques (planting in pit or without X 2 pesticide treatments (with or without pesticide)	6m x 6m	16-May	2-Jun	-	31-May 8-Jun 7-Aug	23-Jun	-	23 DAS	11-Oct
K1	1999	Kakassi	On-farm	3 planting techniques (flat, 25 cm and 50 cm diameter zai) X (3 amendment types +control) (millet residue, compost, cattle manure)	6m x 6m	29-May	4-Jun	-	-	1-Jul	15 DAS	22 DAS	21-Oct
	2000	"	"	"	"	29-May	12-Jun	-	-	1-Jul	13 DAS	20 DAS	31-Oct
K2	2000	Kakassi	On-farm	2 planting techniques (planting in pit or without X 2 pesticide treatments (with or without pesticide)	6m x 6m	30-May	6-Jun	-	1-Jun 10-Aug	20-Jun		23 DAS	19-Oct

DAS is Days after sowing

Experiment - Effect of termite exclusion and zai technique on cattle manure decomposition and millet yield (D2 and K2)

During the first experimental year, we observed that termites had a strong influence on amendment decomposition at Damari. To better understand the impact of the termites' activity, an experiment was conducted in 2000 at Damari and Kakassi. In this satellite trial, 2 planting techniques (planting in zai pit and traditional flat planting) and 2 pesticide treatments (pesticide and no pesticide treatments) were studied. Details on the experimental layout are presented in Table 2.3. The pesticide used was Fipronil (Rhone-Poulenc). It was applied at the rate of 2 l (liquid) per ha. The pits were 20 cm deep and 25 cm in diameter. Cattle manure was applied at the rate of 300 g per hill.

2.4.3 Observations

- **Plant growth and yield**

In all dry season experiments and at Damari in 1999, the number of leaves, tillers, nodes and plant height were recorded weekly. In 1999 in the dry season experiments, 8 plants were marked on 8 hills at random on which the measurements were taken, whereas in 2000, 12 plants were marked instead and the measurements were done on 6 plants every week to minimize the effect of continuous manipulation on the plants. At Damari in 1999, 16 hills were selected and labeled in each plot. Eight of the marked plants were observed every week. In 2000, only plant number at emergence, days to flag leaves and other observations were taken at Damari. Due to the remoteness of the site of Kakassi, observations on plant growth were taken only at harvest. Details of the observations are reported in Table 2.4.

- **Plant sampling**

In order to study nutrient uptake during plant growth, whole plants were sampled from 2 hills in the border rows 3 times during the cropping period. The samples were collected from 3 replications out of 4, except for the control of experiment S1, where we had only 2 replications. The first samples were collected approximately 3 weeks after sowing. Afterward, plant samples were taken every 3 weeks to harvest in the dry season experiments. In the rainy season experiments, the following samples were taken approximately 9 weeks after sowing and at harvest. The details of the dates of plant sampling for all the experiments are reported in Table 2.4.

Table 2.4: Details of observations on the experiments conducted in 1999 and 2000 at Sadore, Damari and Kakassi

Experiment identificatio	Year	Phenological observation	Soil sampling (DAS)	Soil sampling Depth(cm)	Plant Sampling (DAS)	Litterbag installati	Litterba samplin (DOE)	Root Sampling (DAS)	Root Sampling Depth (cm)	Soil sample for Nitrate N leaching (DAS)	Soil sample for Nitrate N leaching Depth(cm)	Soil sample for biomass DAS	Soil sample for biomass Depth(cm)	Observations at harvest
S1	1999	Weekly leaf,	Initial	20	23	5-Mar	23	23	0 - 60	23	0 - 60	-	-	Number of hill,
		tillers and nodes	44	20	44		44	44	0 - 80	44	0 - 80			Total dry
		count, plant height			65		65	65	0 - 100	65	0 - 100			
		measurement												
		from 31 DAS												
S2	1999	Weekly leaf,	Initial	20	27	5-Mar	27	27	0 - 60	27	0 - 60	-	-	Number of hills,
		tillers and nodes	47	20	47		47	47	0 - 80	47	0 - 80			Total dry
		count, plant height			67		67	67	0 - 100	67	0 - 100			
		measurement												
		from 29 DAS												
S3	2000	Weekly leaf	Initial	20	20	11-Feb	20	78	0 - 160	20	0 - 100	-	-	Number of hills,
		& tillers count			44		44			44	0 - 160			& tillers, straw
		from 24 DAS			78		78			78	0 - 200			weight,
D1	1999	Days to emergence	Initial	20	36	24-May	72	119	0 - 150	36		-	-	Number of hills,
		Plant number at	76	20	76		91			76				Tillers; straw,
		emergence. Leaves,			119		112			119				head and grain
		tillers, and nodes					133							Weight; plant
		Plant height												height. 1000
	2000				25	7-Jun	41	25	0 - 80	25	0 - 80	25	0 - 20	mass.
					67		62	67	0 - 100	67	0 - 100	67	0 - 20	Same as 1999
					122		83	122	0 - 200	122	0 - 200			
							104							
D2	2000	Plant number at	Initial	20	24	2-Jun	45	-	-	-	-	-	-	Number of hills,
		emergence, days to			67		67							plant height,
		flag leave, to			110		87							plant/hill,
		emergence and					108							straw head and
K1	1999	At Kakassi	Initial	20	22	4-Jun	49	113	0 - 110	-	-	-	-	Same
		No phenological	65		65		75							as at Damari
		observations were			113		96							
		done because of the					117							
	2000	remoteness of the			20	12-Jun	39	20	0 - 60	-	-	20	0 - 20	Same
		site			62		61	62	0 - 100			62	0 - 20	as at Damari
					123		82	123	0 - 140					
							103							
K2	2000	-	Initial	20	23	6-Jun	37	-	-	-	-	-	-	Same
					65		58							as at Damari
					121		79							
							100							

DAS is Days after sowing
DOE is Days of exposure

- **Plant sample preparation and analysis**

The plant samples were cleaned and dried at 65°C for 48 hours, then weighed and ground to pass a sieve of 1 mm mesh size. A sub-sample of 5 g was analyzed for total N, P and K. Prior to the quantitative determination of these nutrients, the samples were digested using the Kjeldahl method (Houba et al. 1995). The digestion was done with H_2SO_4 + salicylic acid + H_2O_2 + selenium. The quantitative determination of total N was done with an auto-analyzer using the colorimetric method based on the Bertholet reaction (Houba et al. 1995). The total P was determined with the colorimetric method based on the phosphomolybdate complex, reduced with ascorbic acid (Houba et al.1995). The total K was determined with flame emission spectrophotometry (Houba et al.1995).

- **Litterbag sampling**

Two litterbags were collected on each sampling date. The litterbag collection was in line with the date of plant sampling so that the amount of nutrient released and the total nutrient absorbed could be compared. Details of the date of litterbag installation and collection are reported in Table 2.4. The amendment remaining in the litterbags was sun dried, cleaned of sand, weighed and ground. Five grams of the litter of each bag of a plot were mixed to make a sub-sample. The sub-samples were analyzed for total N, P and K using the same analytical methods used to determine the total N, P and K in the plant samples.

To determine the correction factor of the amendments with regards to sand content we used the method proposed by Martius and Beck (2001).

- **Soil samples**

Prior to the trial layout, one-core soil samples were collected from 0 – 20 cm to determine the characteristics of the soil at the experimental sites. These samples were analyzed for pH-H_2O (1:2.5), pH-KCl (1:2.5), and exchangeable acidity (H^+ and Al^{3+}) using extraction in 1M KCl solution and titration with 0.025 M NaOH (Van Reeuwijk, 1993). Exchangeable bases (Na^+, K^+ Ca^{2+}, Mg^{2+}) were also determined using extraction in 0.01M AgTU (silver thiourea complex cation) and atomic absorption spectrophotometry (Van Reeuwijk, 1993); except for K^+, which was determined by flame emission spectrophotometry (Houba et al.1995). Extractable P was determined with the Bray-1 method using extraction with a combination of 0.025N HCl and 0.03N NH_4F, and the colorimetric method of the phosphomolybdate complex, reduced with ascorbic acid (Van Reeuwijk, 1993). Organic carbon was determined with the method of Walkley and Black. The soil was digested with a mixture of H_2SO_4 and $K_2Cr_2O_7$ (potassium dichromate), and then the remaining $K_2Cr_2O_7$ was titrated with ferrous sulphate ($FeSO_4.2H_2O$) (Van Reeuwijk, 1993). For soil texture determination, the samples were oxidized with H_2O_2, and then dispersed with a solution of $(NaPO_3)_6$ (sodium hexametaphosphate). The particles greater that 50 μm were separated by sieving and then weighed. Those less than 50 μm were determined with the pipette method (Van Reeuwijk, 1993). The Effective Cation Exchange Capacity (ECEC) was calculated as the sum of exchangeable base and exchangeable acidity.

Together with the plant samples, soil samples on the same hill, were also collected in the dry season experiments and at Damari in 2000 to study nitrate leaching. The sampling depth was in line with the progress of the wetting front, which was assessed on the basis of the soil moisture profile, measured with a Didcot neutron probe (see water balance). The samples were collected with an aluminum tube of 7.5 cm diameter. They were collected in/on the hole or hill after the plants had been removed. From 0 to 20 cm, the samples were taken at 10 cm interval. Below 20 cm, samples were taken at 20 cm increament. The samples were kept separate in self-sealed bags, and stored in a freezer until use. Other details of the sampling procedures are reported in Table 2.4

Nitrate content was determined semi-quantitatively using nitrate test strips (reflectoquant) and an RQflex reflectometer as described by Merck KgaA (64271 Darmstadt, Germany). Fifty ml of KCl solution 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 2 reaction zones, which turn red-violet in contact with solutions containing nitrate, the intensity of the color depending on the nitrate concentration. To convert the reading into nitrate N, it must be multiplied by 0.226. Due to the localized application of the amendment, nitrate leaching from the applied amendment will occur mainly at the place of application. To avoid an overestimation of the nitrate leached, the calculation was done taking into account the diameter of the zai pit.

In 1999, one-core soil samples were taken in all experiments from 0 to 20 cm to study the effect of the treatments on the soil chemical properties. Except for the soil texture, the analyses were the same as those done on the samples taken prior to the start of the experiments. Details of sampling dates are reported in Table 2.4

To gain an overview of the microbial activity in the different treatments in the process of amendment decomposition, in 2000 soil samples were collected from 2 hills in 2 replications on the first and second soil sampling dates. Details on sampling dates are reported in Table 2.4. One-core samples were taken with a soil auger of 2 cm diameter from 0 – 20 cm. They were put in self-sealed bags and kept in a freezer until use. The statistical analysis of the amendment decomposition data revealed no difference between the 2 pit sizes. Therefore the samples of these treatments were bulked before the sample analysis. Due to logistic problems and quantity of samples needed for the analysis, the replications were bulked. Finally, samples from 8 treatments were used to determine soil respiration using the Substrate Induced Respiration (SIR) method described by Anderson and Domsh (1978). The procedure involved mixing the soil samples with glucose in the proportion of 4 mg glucose for 1 g soils on a dry weight basis. The soil samples were adapted to 22° C (calibration temperature of the method) prior to measurements. Glucose and the soil were thoroughly mixed just before introduction of the sample into a glass cuvette of an Infra Red CO_2 Gas Analyzer (IRGA) of the ECT (Ecotoxicology GmbH, Florsheim) soil respiration device (Figure 2.7).

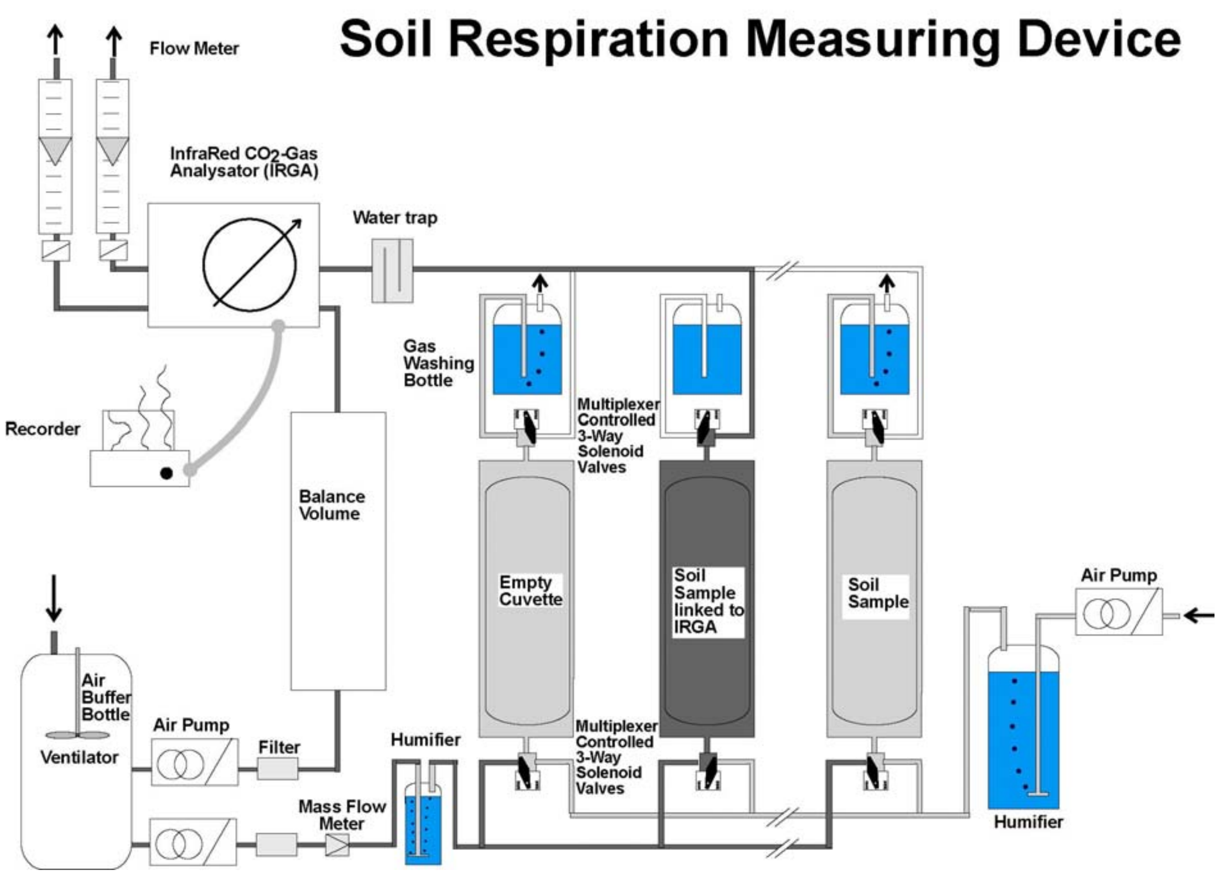


Figure 2.7: Flow chart of soil respiration device

The ECT´s soil respiration measuring device consists of 17 measuring cuvettes connected to an infra-red gas analyser (IRGA) via 3-way solenoid valves. Soil samples are filled into the measuring cuvettes and are flushed continuously with moist ambient air. The solenoid valves are controlled by an electronical multiplexer. One cuvette after the other is measured at time intervals controlled by the multiplexer. After measuring the last cuvette, the system starts automatically with the first cuvette. The difference of the CO_2 content between the air stream going through the measured cuvette and the air stream that is passing only a balanced volume is detected by the IRGA. The flow rate of the air stream is measured by a mass flow meter. From the measured values, the CO_2 content in mL/g soil can be calculated. The data are corrected for the CO_2 values measured from cuvettes without soil (blanks). To enhance sensitivity of the IRGA, a water trap reduces the water content of the gas. The reading time of the cuvettes was set at 6 min. The respiration measurements were done under continuous flow-through conditions.

- **Root samples**

On each plant sampling date, at Sadore soil for root samples was collected with an aluminum tube of 7.5 cm diameter. At Damari and Kakassi, the root samples were collected with a metal frame measuring 20 x 20 x 10 cm from 0 – 20 cm. Below this depth, root samples were collected at 20 cm increment with an aluminum tube of 7.5 cm diameter at Damari and with a soil auger of the same dimension at Kakassi. Details of the dates of sampling and the sampling depth are reported in Table 2.4. The sampling depth was measured from the soil surface. The roots were washed, and root length as well as root radius was determined by the grid counting method (Newman 1966). The grid size of 2 x 2 cm was used for the coarse roots and 1 x 1 cm for the fine roots. The coarse roots were counted on a sub-sample of 2 g taken from the main sample. In the case of the fine roots, if the fresh weight of the total sample was more than 1 g, a sub-sample of 1 g was taken for the count. The samples were cut into small pieces of 1 cm and spread in the dish with a small amount of water. Roots were weighed after oven-drying at 65^oC for 48 hours.

- **Water balance**

To study the water balance, measurements were done weekly using the Didcot neutron probe (Didcot Instrument Company Limited; Station Road Abingdon, Oxon OX14 3 LD). Two 48 mm diameter aluminum access tubes were installed in each plot. One tube was installed between the hills while one was installed in/on the hole or hill close to the plant. The maximum depth of measurement was 240 cm at Sadore. At Damari, the shallowest tube was at 45 cm, while the deepest reached 200 cm. At Kakassi, it was 100 cm for the shallowest tube and 165 cm for the deepest. As proposed by the manufacturer, the probe had been calibrated in-situ for the soils of the experimental sites applying the gravimetric method using a 297 cm^3 soil sampling cylinder. The regression equations derived from the neutron probe calibration on the different sites are:

Sadore:	0 to 15cm	$y = 73.13x + 0.31$;	$R^2 = 0.97$
	> 15cm	$y = 67.8x - 1.85$;	$R^2 = 0.99$
Damari:	0 to 15cm	$y = 62.124x - 0.0387$;	$R^2 = 0.99$
	15 to 30cm	$y = 59.809x - 1.3418$;	$R^2 = 0.99$
	30 to 45cm	$y = 61.266x - 1.7563$;	$R^2 = 0.99$
	> 45cm	$y = 63.349x - 2.0595$;	$R^2 = 0.99$
Kakassi:	0 to 15cm	$y = 73.238x - 4.448$;	$R^2 = 0.98$
	15 to 30cm	$y = 64.058x - 4.336$;	$R^2 = 0.99$
	…..> 30cm	$y = 64.338x - 4.4913$;	$R^2 = 0.96$

Where y is the volumetric soil water content

x is the relative count ratio; it is the ratio of the neutron probe reading to the standard count, which is the reading of a tube installed in pure water

The data collected were used to calculate the volumetric soil water content, the stock of water at different soil depths, and the plant available water. Drainage was calculated only at Sadore.

- **Calculations**

The following parameters were calculated

Total dry matter or grain yield (kg ha^{-1})

Y = (A/B)*10000

Y is total dry matter or grain yield (kg ha^{-1})

A is straw or grain dry weight per plot (kg)

B is the harvest area from each plot (m^2)

N, P and K uptake

(C x S)/100

C is nutrient content in millet straw or grain (%)

S is the dry matter or grain yield at sampling (kg ha^{-1})

Agronomic Efficiency (AE)

AE = (Δ yield / Quantity of nutrient applied)

Δ yield is the difference between the yield obtained with amendment and that obtained with the control

Apparent Recovery Fraction (ARF) (Christianson et al. 1991)

$ARF = (N_{ab} / N_{ap})$

N_{ab} is the difference between total nutrient absorbed by plants in amended and non-amended plots

N_{ap} is quantity of nutrient applied through the amendments

Nutrient Utilization Efficiency (NUE) (Christianson et al. 1991)

NUE = (Yield / Total nutrient absorbed)

Yield is millet straw or grain yield per plot

Total nutrient absorbed is total nutrient uptake of millet straw or grain

Though this technique is not as precise as if a labeled amendment was used, it does provide a measure of how effectively the crop can use the amendment.

Volumetric soil water content (θ_v(%)) :

$\theta_v = a + b \times (C/Cs)$

θ_v is volumetric water content expressed here in %

a is the intercept of the calibration curve

b is the slope

C is the neutron count read with the probe in the field

Cs is a standard count, which is the reading of the probe in access tube installed in pure water

Stock of water – S_w (mm):

Soil layer 0 to 15cm:

$S_w = (\theta_v /100) \times (\Delta z \times 10)$

Where S_w is the stock of water in the soil layer from 0 to 15cm (mm)

θ_v is the volumetric soil water content (%)

Δz is the thickness of the soil layer; NB: Δz is multiplied by 10 to convert it in mm,

The Σ of the S_w gives the total stock of water in the profile at a time **t.**

Soil layer > 15cm:

$S_w = ((\theta_v(a) + \theta_v(b))/200 \times (\Delta z \times 10)$

$\theta_v(a)$ is volumetric water content at depth a

$\theta_v(b)$ is volumetric water content at depth b

Δz is the thickness of the soil layer

Plant available water – PAW (mm)

PAW = S_w (at Zr) – S_w (at Zr) at wilting point

Zr is the maximum rooting depth (cm)

The volumetric water content at wilting point was measured with a pressure plate at 15 bar.

Drainage – Q (mm)

The formula to calculate the drainage is

$Q = K(\theta) \times PG$

Q is the drainage in mm

K is the hydraulic conductivity at the depth Zr. It is a function of the soil water content.

PG is the Potential Gradient, which depends on the forces, controlling water movement around depth Zr.

The variation in volumetric soil water content was small, so we assumed that the PG was equal to '1'. Therefore the drainage was considered to be equal to the hydraulic conductivity.

- **Data processing and statistical analysis**

The data processing was done with Excel and the statistical analysis was done using ANOVA of the statistical software GENSTAT 5 release 4.1 developed at the Rothamsted Experimental Station in UK. In the statistical analysis of experiment S1, the 2 irrigation regimes were initially considered as 2 environments, but the coefficient of variation was higher than 20% in almost all of the parameters under study. So the 2 environments were not pooled together in a combined analysis (Gomez and Gomez, 1984), but were analyzed individually. The phenological data taken weekly were analysed with the AREPMEASURES procedure of Genstat used to analyse data of repeated measurements.

In experiments S2 and D1, due to the large differences between the amended plot and the controls in terms of total dry matter and grain yield, the statistical analysis was done on a set of data composed only of amended plots. Another set of data composed of data from the control plots was analyzed separately. Total nutrient uptake and nutrient utilization efficiency were analyzed the same way. Almost no significant interactions were observed between the treatments in the individual experiments, but wherever any were observed, all of the treatment combinations were presented in the tables.

3 RESULTS AND DISCUSSIONS

3.1 Effect of water regime and planting techniques on millet performance and amendment decomposition (S1)

Two planting techniques (zai vs flat) were tested under 2 water regimes (20 vs 30 mm irrigation weekly), which allowed studying their effect on millet growth.

3.1.1 Total biomass production

The differences between the amended and the non-amended plots were strongly expressed. Millet total dry matter (TDM) on non-amended plots was very low at 3 kg ha^{-1} for the 20 mm weekly water regime and 7 kg ha^{-1} for the 30 mm weekly water regime (Figure 3.1). This reflects the very severe degradation status of the experimental field, making it unsuitable for agricultural production without rehabilitation techniques.

Zai pits increased millet TDM yield considerably in the 20 mm weekly water regime (P=0.02) compared to flat planting. Under this water regime, a 3-fold increase in TDM was obtained with zai treatment (Figure 3.1), (3086 vs 991 kg ha^{-1}). There was no significant difference between zai and flat planting under the 30 mm water regime – P>005, (Figure 3.1) (2558 vs 1929 kg ha^{-1}).

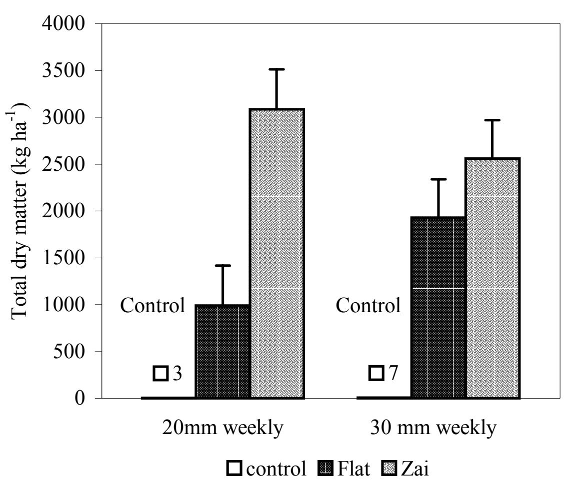


Figure 3.1: Millet total dry matter production under 2 water regimes as affected by planting techniques (zai vs flat); Sadore, dry season 1999
Control = flat planting without manure. Zai and flat received 3 t ha^{-1} manure hill placed - error bars are standard errors of differences between means

The zai technique increased TDM yield per hill compared to flat planting by 68% under the 20 mm irrigation regime and 36 % under the 30 mm regime.

No planting technique effect was observed on the hill survival regardless of the water regime (P>0.05). Nevertheless, under the 30 mm water regime 94% of the hills in the non-zai treated plots were harvested, while only 74% were harvested from the zai-treated plots.

3.1.2 Growth parameters

Under the 20 mm weekly irrigation, the zai treatment improved the plant growth in terms of plant height as compared to the flat planting (P<0.001) (Figure 3.2 a). The final height was 1.02 m in the zai, compared to 0.65 m in flat planting. For the 30 mm weekly irrigation regime, this effect was apparent only at the end of the cropping period (Figure 3.2 b). The heights were 1.17 m and 0.78 m for zai and flat planting, respectively. The plant height in the control non-amended plots was 0.16 m at harvest and was not affected by the water regime.

During the early stages of growth, more tillers were formed in the flat plantings amended with manure than in zai pit, regardless of the water regime (Figure 3.2 e and f). Later (45 DAS), no differences were observed between the planting techniques. The plants in the control plots did not produce any tillers.

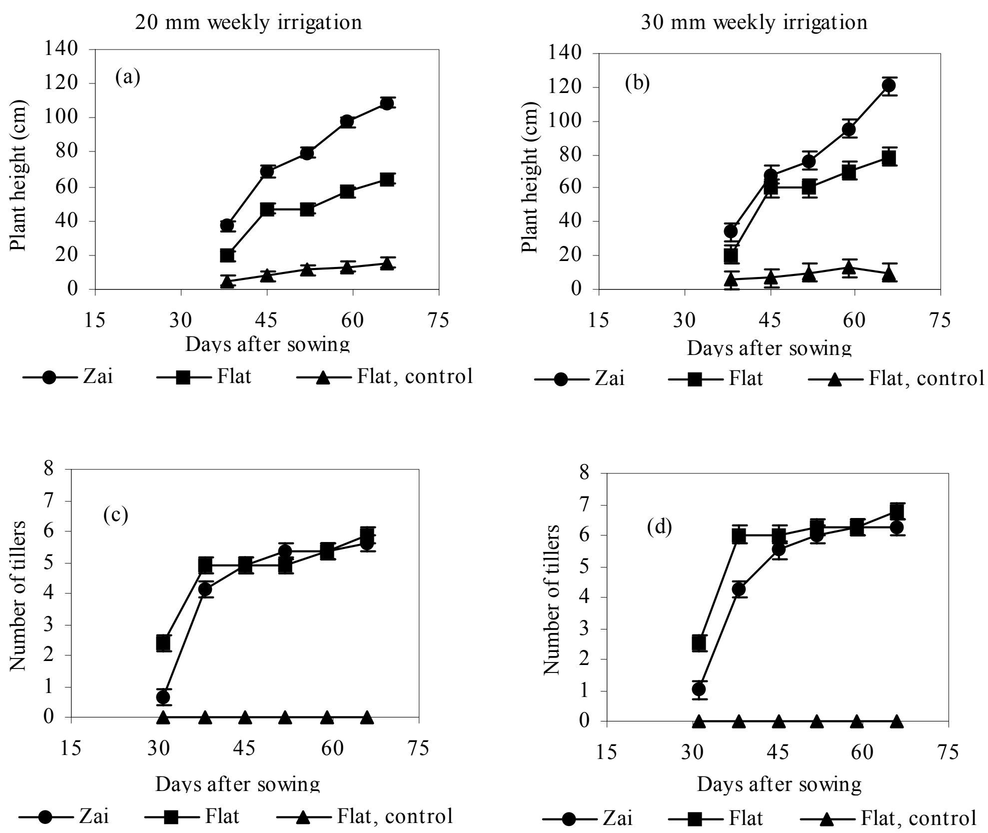


Figure 3.2: Millet growth and development as affected by water regime and planting techniques (zai vs flat); Sadore, dry season 1999 (a, c - Plant height and number of tillers under 20 mm weekly irrigations); (b, d - same parameters for 30 mm weekly irrigations) – error bars are standard error of differences between means

These results suggest that regular irrigation with 20 mm of water could assure normal growth and TDM production only in plots treated with zai. The technique promotes water collection and therefore increases the soil water content in the root zone (Hassan et al. 1996, Roose et al. 1993, Kabore 1995, Ouedraogo et al. 1996). The similarity in TDM yields between zai and flat planting (65 DAS) under the 30 mm irrigation regime reflects the relatively high hill survival in non-zai treated plots, which compensated for the low TDM yield per hill.

3.1.3 Organic amendment decomposition and nutrient release

The trend in manure decomposition was similar for both water regimes throughout the period of litterbag exposure. Under both water regimes, the decomposition tended to be faster in the flat planting as compared to zai (Figure 3.3 a and b). Under the 20 mm water regime, 8% of the exposed cattle manure remained after 31 days of litter exposure in flat planting, whereas 19% remained in the zai. Under the 30 mm water regime, 9% and 23% remained in the flat planting and zai, respectively, after 31 days of litter exposure.

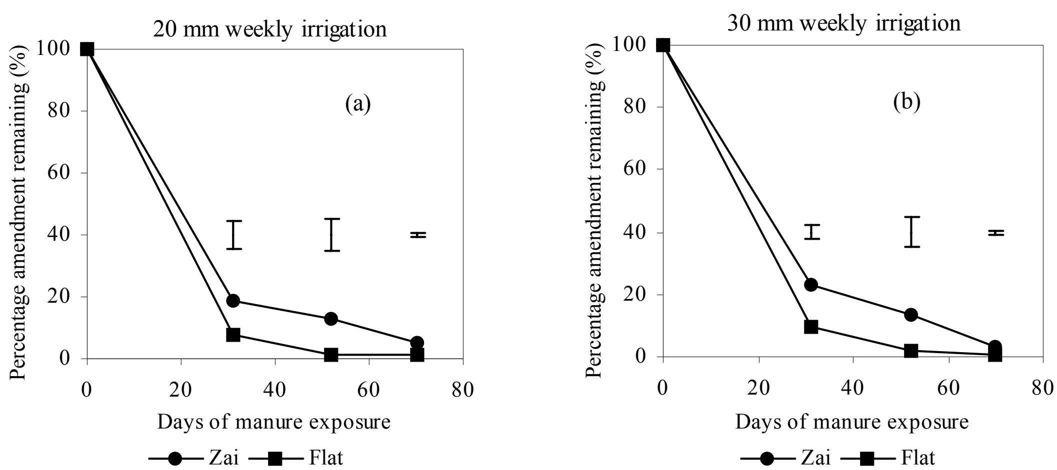


Figure 3.3: Effect of planting techniques (zai vs flat) and water regime on cattle manure decomposition; Sadore, dry season 1999 - error bars are standard error of differences between means

At the end of the period of litter exposure, almost all of the manure was decomposed under both conditions of litter exposure. It is important to mention that a high rate of termite activity was observed in the field, and this would have influenced the rate of the amendment decomposition. The differences between the planting techniques were small but statistically significant.

Less N and P was released in the zai compared to flat planting under both water regimes throughout the period of litter exposure (Table 3.1). Significant differences were observed between the planting techniques in terms of K release only under the 30 mm weekly irrigation regime at the end of the cropping period ($P<0.05$, Table 3.1).

Table 3.1: Effect of planting techniques (zai vs flat) on millet N, P and K release from cattle manure; Sadore, dry season 1999

	31 Days of exposure				52 Days of exposure				73 Days of exposure			
	Zai	Flat	$LSD_{0.05}$	F.prob.	Zai	Flat	$LSD_{0.05}$	F.prob.	Zai	Flat	$LSD_{0.05}$	F.prob.
20 mm irrigation weekly												
N	29.2	37.9	1.5	0.002	30.8	40.2	2.3	0.003	38.5	40.4	0.9	0.010
P	15.0	18.2	2.7	0.036	15.7	19.1	1.8	0.014	18.8	19.2	0.3	0.032
K	17.6	19.4	3.5	>0.05	18.6	20.0	2.8	>0.05	19.9	20.0	0.2	>0.05
30 mm irrigation weekly												
N	31.0	37.1	1.9	0.005	34.2	39.8	10.9	>0.05	39.2	40.8	0.9	0.02
P	15.1	17.8	1.2	0.01	17.1	19.0	4.3	>0.05	19.0	19.3	0.2	0.02
K	16.0	19.2	5.0	>0.05	19.5	20.0	1.0	>0.05	20.0	20.1	0.1	0.03

NB: F.prob = F probability; $LSD_{0.05}$ = least significant difference at 0.05 probability level

In general, the trend of decomposition observed was similar to the findings of Somda et al. (1993), who studied the decomposition of various organic amendments including cattle manure, and found that after 14 days of exposure 60% of the manure was decomposed. Esse et al. (2001) also reported similar results. It is important to underline the active influence of termites in the process of decomposition. Tian et al. (1992) used different mesh sizes in a study of the decomposition of various litters. They found that decomposition was faster in the bags with a bigger mesh size since the soil macro and meso-fauna could more easily cause the comminution of the litter and its rapid colonization by soil microorganisms. This helps to explain my results. Nevertheless, rapid comminution due to termite activities might not necessarily mean that the nutrients would be rapidly available to the crop. In the soil surface litter exposure, the disintegrated manure could also be washed away by run-off water. This might not happen in the zai pits.

Nutrient release followed the trend of manure decomposition. This finding is supported by the studies of Somda et al. (1993), and Esse et al. (2001). The amount of N and P released from the manure was higher in the soil surface exposure than in the zai pit.

3.1.4 Millet N, P, and K uptake

Under both water regimes, N, P and K uptake was higher in the zai compared to flat planting throughout the cropping period except for the 30 mm water regime 23 DAS, although the differences were not significant (Table 3.2). Yet, for instance, at final harvest under the 20 mm irrigation regime, N, P and K uptake was 3 – 4 times higher in zai compared to flat planting. At harvest, plant N, P and K uptake in flat planting was 2 times higher under the 30 mm than under the 20 mm water regime. These findings largely reflect the differences in TDM production.

The amount of N, P and K applied with the manure in this experiment was 41, 19, 20 kg ha^{-1}, respectively. At harvest, N uptake in the zai was almost 2-fold the amount applied. The K uptake was 4 times higher than the amount applied. This suggests that additional N, P and K were taken from the soil nutrient pool to meet the nutritional needs of the plant. The application of readily mineralizable amendment improved the utilization of the native nutrient. Azam (1993) reported a similar increase of soil N availability due to manure application.

Table 3.2: Millet N, P and K uptake as affected by planting techniques (zai vs flat); Sadore, dry season 1999

	23 Days after planting				44 Days after planting				65 Days after planting			
	Zai	Flat	$LSD_{0.05}$	F.prob	Zai	Flat	$LSD_{0.05}$	F.prob	Zai	Flat	$LSD_{0.05}$	F.prob
20 mm irrigation weekly												
N	0.28	0.21	0.5	>0.05	15.5	8.7	11.7	>0.05	79.3	24.9	58.4	>0.05
P	0.05	0.04	0.1	>0.05	1.6	0.8	0.9	>0.05	3.8	0.9	3.2	>0.05
K	0.57	0.38	1.0	>0.05	27.6	13.4	19.0	>0.05	95.1	22.9	46.6	0.022
30 mm irrigation weekly												
N	0.19	0.27	0.17	>0.05	15.1	10.2	14.3	>0.05	67.0	45.9	61.4	>0.05
P	0.03	0.06	0.03	>0.05	1.5	0.9	0.8	>0.05	4.0	1.8	3.9	>0.05
K	0.4	0.51	0.32	>0.05	28.8	16.7	24.5	>0.05	97.2	53.1	82.9	>0.05

F.prob = F probability; $LSD_{0.05}$ = least significant difference at 0.05 probability level

* On a TDM basis

3.1.5 Millet N, P, and K utilization efficiency, nutrient agronomic efficiency and apparent recovery fraction

Under the 30 mm weekly irrigation, a better utilization of P under flat planting was observed at harvest (P=0.038). For K utilization, a positive effect of flat planting was observed already after 44 days of cropping (Table 3.3).

No statistically significant effect was observed between the planting techniques with regards to nutrient agronomic efficiency (Table 3.4). Nonetheless, throughout the cropping period, slightly higher values were observed in the zai compared to flat planting under both water regimes.

Under both water regimes, after 65 days of cropping, N, P and K recovery in the zai was slightly higher compared to flat planting (Table 3.5), although the differences were statistically significant only for K recovery under the 20 mm irrigation regime.

Table 3.3: Effect of planting techniques (zai vs flat) on millet N, P and K utilization efficiency; Sadore, dry season 1999

	23 Days after planting				44 Days after planting				65 Days after planting			
	Zai	Flat	$LSD_{0.05}$	F.prob.	Zai	Flat	$LSD_{0.05}$	F.prob.	Zai	Flat	$LSD_{0.05}$	F.prob.
	20 mm irrigation weekly											
N	35	35	3	>0.05	35	35	7	>0.05	38	41	10	>0.05
P	203	174	61	>0.05	342	391	236	>0.05	822	1080	736	>0.05
K	18	19	1	0.027	20	23	8	>0.05	31	44	19	>0.05
	30 mm irrigation weekly											
N	33	33	2	>0.05	35	36	9	>0.06	39	43	19	>0.05
P	181	166	76	>0.05	351	441	123	0.09	640	1171	457	0.038
K	15	18	4	>0.05	18	23	1	0.003	26	39	6	0.012

F.prob = F probability; $LSD_{0.05}$ = least significant difference at 0.05 probability level

Table 3.4: Effect of planting techniques (zai vs flat) on millet N, P and K agronomic efficiency; Sadore, dry season 1999

	23 Days after planting				44 Days after planting				65 Days after planting			
	Zai	Flat	$LSD_{0.05}$	F.prob.	Zai	Flat	$LSD_{0.05}$	F.prob.	Zai	Flat	$LSD_{0.05}$	F.prob.
	20 mm irrigation weekly											
N	0.2	0.1	0.5	>0.05	13	7	8	>0.05	85	28	61	>0.05
P	0.4	0.3	1.0	>0.05	27	15	17	>0.05	179	58	129	>0.05
K	1.1	0.8	2.5	>0.05	70	39	43	>0.05	460	150	332	0.06
	30 mm irrigation weekly											
N	0.1	0.2	0.1	>0.05	13	9	14.3	>0.05	61	49	61	>0.05
P	0.2	0.4	0.3	>0.05	27	19	30.2	>0.05	129	103	128	>0.05
K	0.6	1.0	0.8	>0.05	69	48	77.8	>0.05	124	99	124	>0.05

NB: F.prob = F probability; $LSD_{0.05}$ = least significant difference at 0.05 probability level

Δ TDM = Total Dry Matter yield difference between amended and non-amended plots

In most cases, no statistically significant differences were observed between the planting techniques. Nevertheless, slightly higher Figures were observed under flat planting compared to zai in terms of N, P and K utilization. This suggests that even though total dry matter production was high in the zai compared to flat planting, the crop could make better use of nutrients absorbed on flat planting. Figures related to the agronomic efficiency and recovery fraction show higher recovery and efficient use of all nutrients but significantly for K only. This might be due good growing conditions in the zai and maybe the effect of water collection.

Table 3.5: Effect of zai and water regime on millet N, P and K apparent recovery fraction; Sadore, dry season 1999

	Nutrient apparent recovery fraction											
	23 Days after planting				44 Days after planting				65 Days after planting			
	Zai	Flat	$LSD_{0.05}$	F.prob.	Zai	Flat	$LSD_{0.05}$	F.prob.	Zai	Flat	$LSD_{0.05}$	F.prob.
	20 mm irrigation weekly											
N	0.006	0.003	0.015	>0.05	0.37	0.21	0.28	>0.05	1.91	0.60	1.44	>0.05
P	0.002	0.002	0.004	>0.05	0.08	0.04	0.05	>0.05	0.19	0.04	0.16	>0.05
K	0.020	0.020	0.054	>0.05	1.34	0.66	0.94	>0.05	4.67	1.13	2.28	0.02
	30 mm irrigation weekly											
N	0.003	0.005	0.005	>0.05	0.36	0.25	0.36	>0.05	1.61	1.11	1.53	>0.05
P	0.002	0.003	0.002	>0.05	0.08	0.04	0.04	>0.05	0.20	0.08	0.23	>0.05
K	0.020	0.020	0.019	>0.05	1.4	0.82	1.23	>0.05	4.77	2.63	4.21	>0.05

F.prob = F probability; $LSD_{0.05}$ = least significant difference at 0.05 probability level

3.1.6 Soil chemical status 44 DAS (days after sowing)

No significant differences were observed between the amended zai and amended flat planting; but all the soil chemical parameters except for N were improved compared to the initial status following manure application (Table 3.6). The soil chemical status in the control plot under 30 mm irrigation regime was not reported in the Table because the samples were accidentally destroyed. Under the 20 mm irrigation regime, except for organic carbon, slight changes were observed in the other parameters compared to the status prior to the experiment.

Table 3.6: Soil chemical status after 44 days of cropping; Sadore, dry season 1999 (20 cm soil depth)

	Prior to experiment layout	44 DAS				
		20 mm irrigation regime			30 mm irrigation	
		Zai	Flat	Control	Zai	Flat
pH (KCl)	3.9	4.3	4.4	4.1	4.8	4.4
Exchangeable base (cmol+/kg)	0.3	0.6	0.5	0.2	1.0	0.6
Exchangeable Acidity (cmol+/kg)	0.7	0.3	0.4	0.5	0.1	0.3
ECEC (cmol+/kg)	1.0	0.9	0.8	0.7	1.1	0.9
Al saturation (%)	53	24	32	56	5	27
Base saturation (%)	29	67	58	28	90	63
P-Bray (mg-P/kg)	2.1	21.6	7.4	2.7	19.9	15.4
C org (%)	0.1	0.2	0.2	0.1	0.2	0.1
Total N (mg-N/kg)	119.4	94.0	73.8	66.7	99.4	79.8

3.1.7 Root development

Under both water regimes, root length density (RLD), root radius and root dry matter were high in the zai compared to flat planting in the soil layer of 10 to 40 cm (Table 3.7), while the reverse tendency was observed in the layer 0 to 10 cm. Most of the roots were concentrated in the upper 40cm of the soil layers at harvest, regardless of the planting technique and the water regime.

Table 3.7: Effect of water regimes and planting techniques (zai vs flat) on millet root distribution at harvest; Sadore, dry season 1999

Soil	Root length density (cm cm^{-3})			Root radius (µm)			Root total dry matter per		
Depth	Zai	Flat	$LSD_{0.05}$	Zai	Flat	$LSD_{0.05}$	Zai	Flat	$LSD_{0.05}$
				Twenty (20) mm irrigation weekly					
0-10cm	6.96	10.63	3.99	524	405	286	731	827	841
10-20cm	1.56	1.07	2.82	322	233	2	22	6	14
20-40cm	0.83	0.16	0.52	241	191	31	5	4	5
40-60cm	0.29	0.2	0.31	212	184	43	8	5	10
60-80cm	0.22	0.15	0.10	213	212	52	8	4	4
80-100cm	0.19	0.17	0.05	196	172	3	5	3	0.2
				Thirty (30) mm irrigation weekly					
0-10cm	4.78	10.51	6.23	555	500	106	487	1014	589
10-20cm	3.74	3.02	3.02	278	276	27	20	9	12
20-40cm	0.7	0.28	0.32	279	250	111	10	10	6
40-60cm	0.3	0.23	0.12	230	258	81	9	8	7
60-80cm	0.07	0.2	0.06	184	261	96	2	16	26
80-100cm	0.15	0.18	0.15	200	232	51	4	6	13

$LSD_{0.05}$ = least significant difference

Roots were concentrated in the upper 40 cm soil depth, which is supported by the study of Zaongo et al. (1994), who also reported a concentration of millet roots in the 0 - 40 cm soil layer at Kala Pate in Niger and related that to Al and Mn toxicity and low pH. But in the present study, nutrient concentration might be the most possible cause as reported in the studies of Kapur et al. (1985), and Singh (1999).

3.1.8 Nitrate leaching

An increase in the nitrate content in the soil layers was observed and more so in the zai compared to flat planting, regardless of the water regimes (Figure 3.4). At harvest, nitrate content was below the initial level at more than 50 cm depth under the 20 mm irrigation regime (Figure 3.4 a and b), while under the 30 mm water regime it remained above the initial level at the same depth under both planting techniques (Figure 3.4 c and d).

The dynamics in nitrate content throughout the soil profiles suggests higher leaching in the zai compared to flat planting in the early stage of the plant growth under both water regimes.

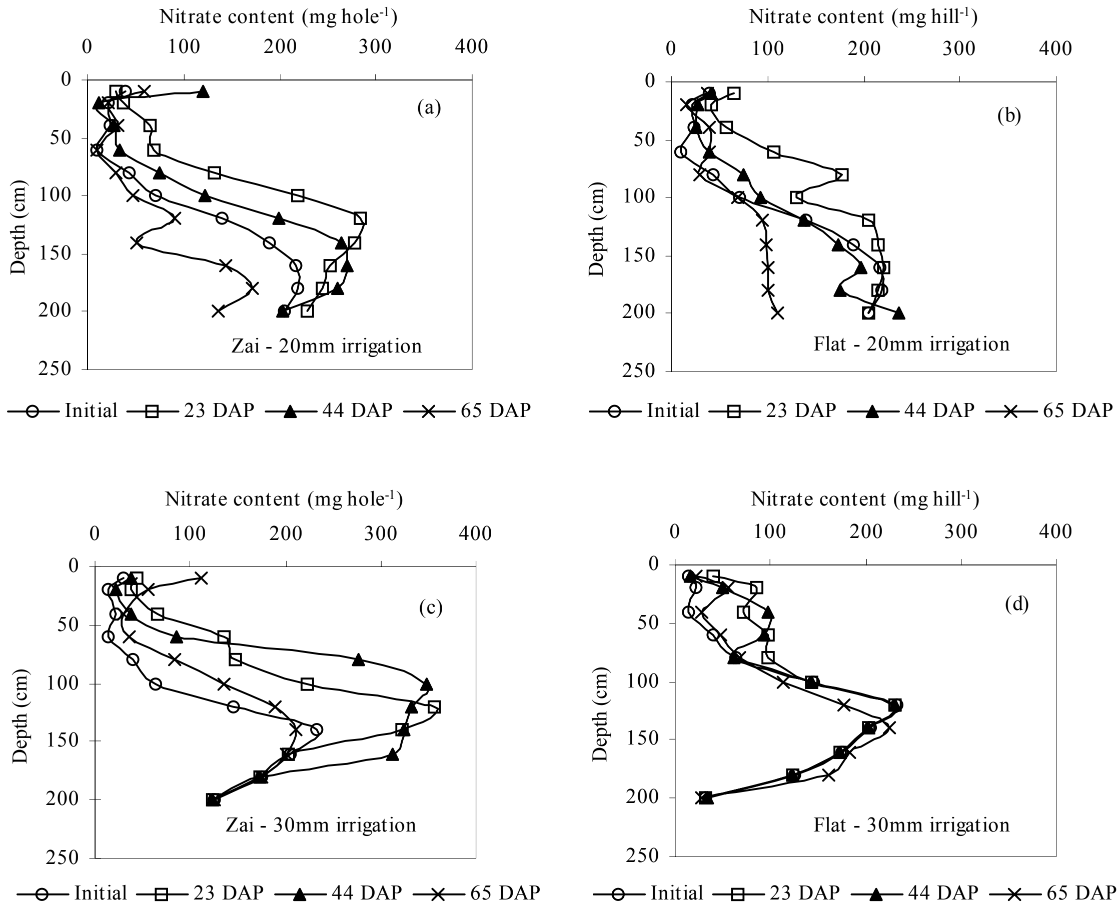


Figure 3.4: Effect of planting techniques (zai vs flat) on nitrate leaching; Sadore, dry season 1999 (DAS stands for days after sowing; a and b - 20 mm water regime; c and d - 30 mm water regime) - The values reported in the graphs are quantity of nitrate. To obtain the nitrate N the values must be multiplied by 0.226

3.1.9 Water balance

- **Volumetric soil water content**

The progress of the wetting front was more rapid in the zai compared to flat planting under both water regimes (Figure 3.5). There was a more rapid progress of the wetting front under the 30 mm water regime in both planting techniques compared to the 20 mm water regime, where the front never went beyond 150 cm except for the control non-amended flat. It was below 200 cm after 23 days of cropping under the 30 mm irrigation regime in contrast with the 20 mm water regime. At harvest, the volumetric water content below 80 cm depth in the amended plots was lower than prior to the trial layout except for zai under the 30 mm water regime. In the control plots the volumetric water content was still higher than the initial level at harvest (Figure 3.5 e and f).

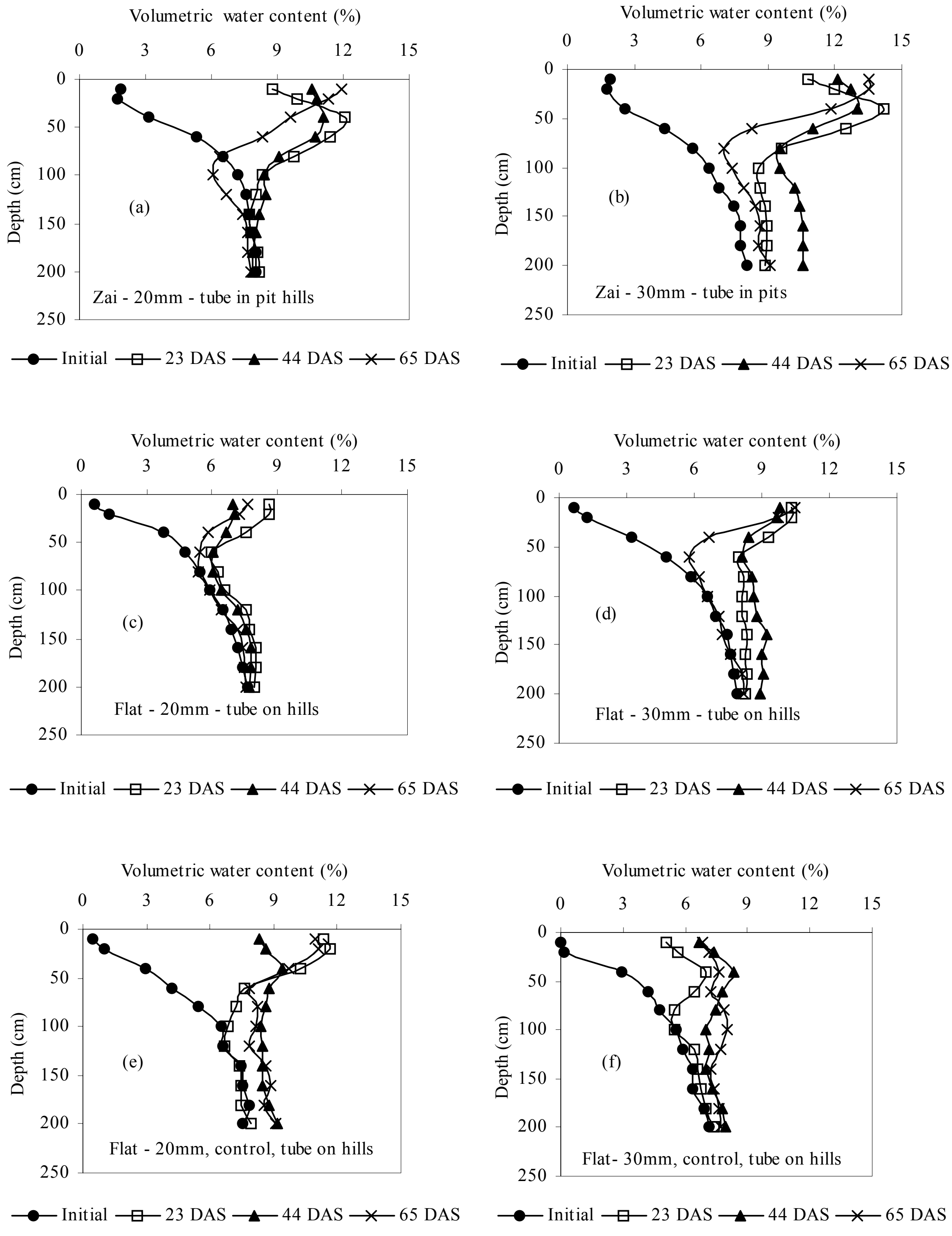


Figure 3.5: Volumetric water content as affected by planting techniques (zai vs flat) and irrigation regimes; Sadore, dry season 1999 (measured after irrigation except for the initial, which was measured before the experiment started)

- **Plant available water**

Under the 20 mm water regimes, no significant differences between the zai and the flat planting were observed in terms of plant available water throughout the cropping period (Figure 3.6a). Toward the end of the cropping period, the plant available water increased in the control non-amended plots, while it decreased in the amended plots. The plant available water almost reached zero in the rooting zone in the amended plots at harvest. Under the 30 mm weekly irrigation, towards the end of the cropping period, a slight increase in plant available water was observed in the zai pits compared to flat planting. At harvest, 30 mm remained in the control non-amended plots whereas 10 mm remained in the amended zai (Figure 3.6b).

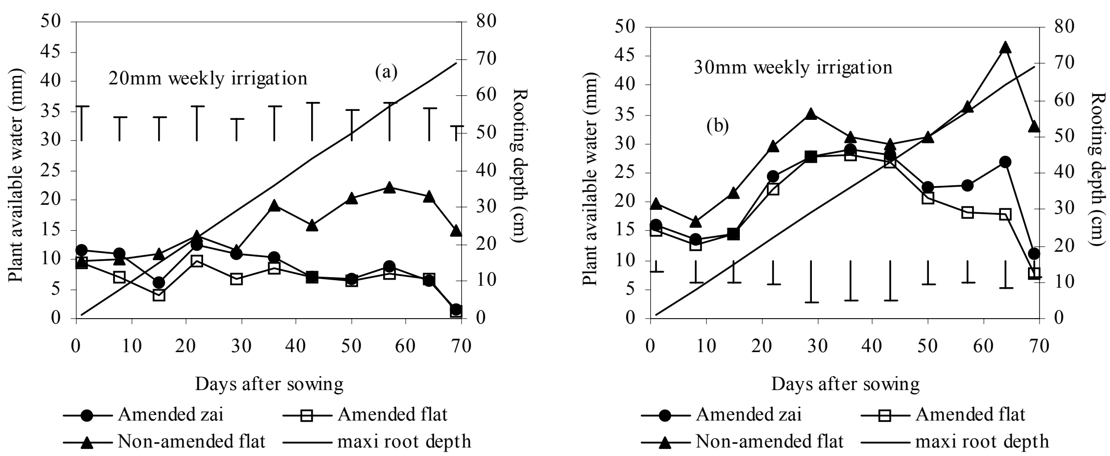


Figure 3.6: Plant available water as affected by planting techniques (zai vs flat); Sadore, dry season 1999 - error bars are standard error of differences between means (rooting depth in the course of the growing period used for the calculation)

- **Drainage**

Increased water loss through drainage was observed in the zai pit compared to flat planting under both water regimes (Figure 3.7). The cumulative drainage at maximum rooting depth (70 cm) was 140 mm at 65 DAS in the zai under 20 mm water regime, whereas it was 170 mm under the 30 mm irrigation regime (Figure 3.7). Drainage in flat planting was similar for amended and non-amended plots.

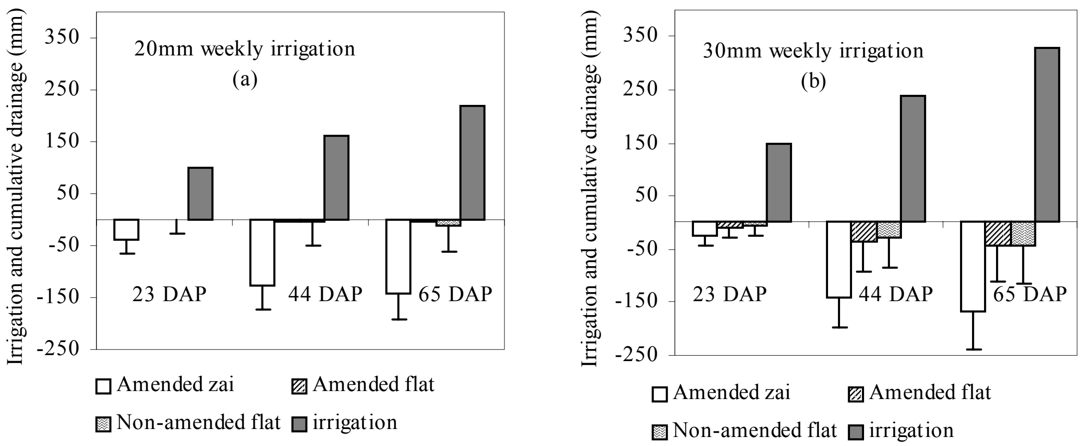


Figure 3.7 Water loss by drainage as affected by planting techniques (zai vs flat); Sadore, dry season 1999 - error bars are standard error of differences between means

The changes in the volumetric soil water content in the zai were different from that of the flat planting, which was due to the water-harvesting feature of the zai. In fact, the run-off water that collected in the zai during the irrigations enhanced the progress of the wetting front at the beginning of the cropping period. But later on, due to increased biomass and increased transpiration toward the end of the cropping period, the volumetric water content decreased markedly, even in the zai. The decrease in the volumetric water content was also reflected in the plant available water, as it was below 10 mm under the 20 mm irrigation regime between the irrigation dates. At harvest, almost all of the plant available water was used in the zai as well as in the flat planting.

Apart from transpiration, the decrease in plant available water could also be due to high evaporation related to the high air temperature (35^{o}C to 40^{o}C) during the period of experimentation. This would particularly be true for the flat planting. Sivakumar et al. (1999) reported 5% increase of total evaporation on bare soil compared to cropped and fertilized soil even during the rainy season when the air temperature is much lower (Figure 2.3).

The pattern of cumulative drainage at the maximum rooting depth suggests that adequate conditions were created for water loss through drainage in the zai. Under the 20 mm irrigation regime, 65% of the total irrigation was drained at harvest, whereas in the amended flat only 2% of this irrigation water was lost beyond the maximum rooting zone. On the non-amended flat, 5% drainage was observed. Under the 30 mm irrigation regime, 50% was drained in the zai and 13% in the amended and non-amended flat. Considering the low organic content (organic C = 0.11%) of the experimental soil and the low water holding capacity of these soils, the higher drainage could be expected in the zai where the breakage of the soil crust improves water infiltration. In addition, the hole allows collection of more run-off water, which, if not lost by evaporation or transpired, would be subjected to loss below the rooting zone.

3.1.10 Resume of experiment S1

From this study the following conclusions can be drawn. Under the 20 mm irrigation, the water harvested in the zai allowed for high TDM yield compared to flat planting. Under the 30 mm irrigation regime, the additional water supply was beneficial to the crop in flat planting. This resulted in a relatively high TDM in flat planting (1929 kg ha^{-1}) under this water regime. The plant available water under the 30 mm irrigation regime throughout the cropping period was higher in both planting techniques compared to the 20 mm irrigation regime, which is in support of this explanation.

Manure decomposition was not affected by the water regime, but it was faster with soil surface placement than in the zai. The same trend was observed for nutrient release. Termites were very active in the experimental plots and might have influenced the manure weight loss in both planting techniques. The difference between the planting techniques might be due to the effect of run-off water. After the comminution of the manure it can easily be washed away from the soil surface, which could not be the case in the zai.

In general, the planting technique effect on nutrient uptake and utilization was not consistent but seemed to be in line with TDM production. Nevertheless, K uptake, agronomic efficiency and recovery fraction were higher in the zai compared to flat planting.

The trend in nitrate movement across the soil profile, as well as the movement of the wetting front in the zai pit, point out one of the risks related to the zai: nitrogen loss through leaching due to the water collected in the zai. In the sandy soils of the Sahel with low water holding capacity, this problem is especially important. It is crucial when easily decomposed organic amendments like manure are used, and particularly with adequate rainfall. In such rainfall years, the advantage of the zai is lost, though no disadvantage emerged under the conditions of this experiment. Zai thus serves as labor-intensive crop insurance.

3.2 Effect of amendment type and rate on the performance of millet in zai technique (S2)

Millet growth and yield in the zai were studied under 2 amendments types and 4 rates of application.

3.2.1 Total dry matter (TDM) production

Millet grown in the non-amended zai pit, or the non-amended flat planting produced very low total dry matter (TDM) (52 vs 20 kg ha^{-1} – Figure 3.8). On average, a 6-fold TDM production increase was obtained with manure application compared to crop residues (Figure 3.8). Manure or crop residues application at the rate of 3 t ha^{-1} double the TDM yield compared to 1t ha^{-1} application rate (756 vs 293 kg ha^{-1} for crop residues and 3957 vs 1836 kg ha^{-1} for manure). Increasing the rate of manure application from 3 to 5 t ha^{-1} produced 12% TDM yield increase compared to 115% TDM increase following a manure application rate increase from 1 to 3 t ha^{-1}.

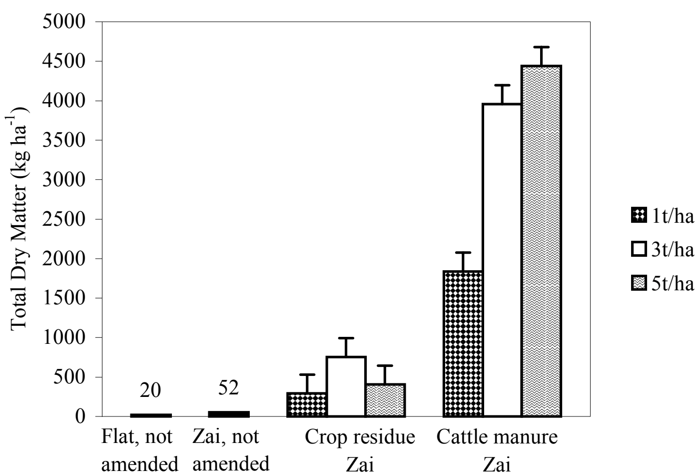


Figure 3.8: Millet total dry matter production as affected by organic amendments type and rate of application and planting technique (zai vs flat); Sadore, dry season 1999 - error bars are error of difference between means

The crop residues amendment rate significantly affected the crop establishment as only 4% emergence was recorded 6 days after sowing in plots amended with 5 t ha^{-1} crop residues (Table 3.8). At 13 DAS, the emergence improved under crop residues treatment compared to the first observation, but it was still low for 5 t ha^{-1} application rates. With manure no application rate effect on millet emergence was observed. At 13 DAS, the crop establishment was better in the non-amended zai than in the control flat (Table 3.8). Between 13 DAS and harvest, hill survival was close to 100% of emergence in all treatments except for the non-amended flat and the zai receiving crop residues (Table 3.9).

Table 3.8: Effect of planting techniques (zai vs flat), amendment type and rate of application on hill emergence 6 and 13 DAS; Sadore, dry season 1999

	Percentage of hills emerged (%)							
	6 days after sowing				13 days after sowing			
	Zai			Flat	Zai			Flat
Rate	CR	Manure	Control	Control	CR	Manure	Control	Control
0 t ha^{-1}	-	-	51	40	-	-	94	78
1 t ha^{-1}	60	44	-	-	97	89	-	-
3 t ha^{-1}	24	35	-	-	94	94	-	-
5 t ha^{-1}	4	35	-	-	66	94	-	-
$LSD_{0.05}$	20	41	78		27	10	16	

$LSD_{0.05}$ = least significant difference at 0.05 probability level; CR = crop residues

Table 3.9: Percentage of hills harvested and total dry matter per hill as affected by amendment type and rate under zai and flat planting conditions; Sadore, dry season 1999

	Percentage of hills at harvested (%)				Total Dry Matter per hill (g)			
	Zai			Flat	Zai			Flat
Rate	CR	Manure	Control	Control	CR	Manure	Control	Control
0 t ha^{-1}	-	-	69	59	-	-	9	0.4
1 t ha^{-1}	98	82	-	-	30	237	-	-
3 t ha^{-1}	94	94	-	-	81	422	-	-
5 t ha^{-1}	69	95	-	-	63	467	-	-
$LSD_{0.05}$	19	9	13		33	48	25	

$LSD_{0.05}$ = least significant difference at 0.05 probability level; CR = crop residues

3.2.2 Growth parameters

In general, under zai, manure application improved plant growth more than crop residues application. Both types of amendment gave better results as compared to the non-amended pit and the control flat planting. The final plant height was 110 cm with 5 t ha^{-1} manure compared to 12 cm in control flat (Figure 3.9). The performance of the crop was poor in the control plots with regards to all growth parameters. In the control zai the plant height was 32 cm at harvest. Significantly increased plant height and tiller formation was obtained with 3 t ha^{-1} crop residues application compared with 1 and 5 t ha^{-1} application rates (Figure 3.9 a and d).

The manure application rate affected all parameters from one month after sowing. A high rate of growth was induced by manure application compared to a slow growth for the plants in the control plots.

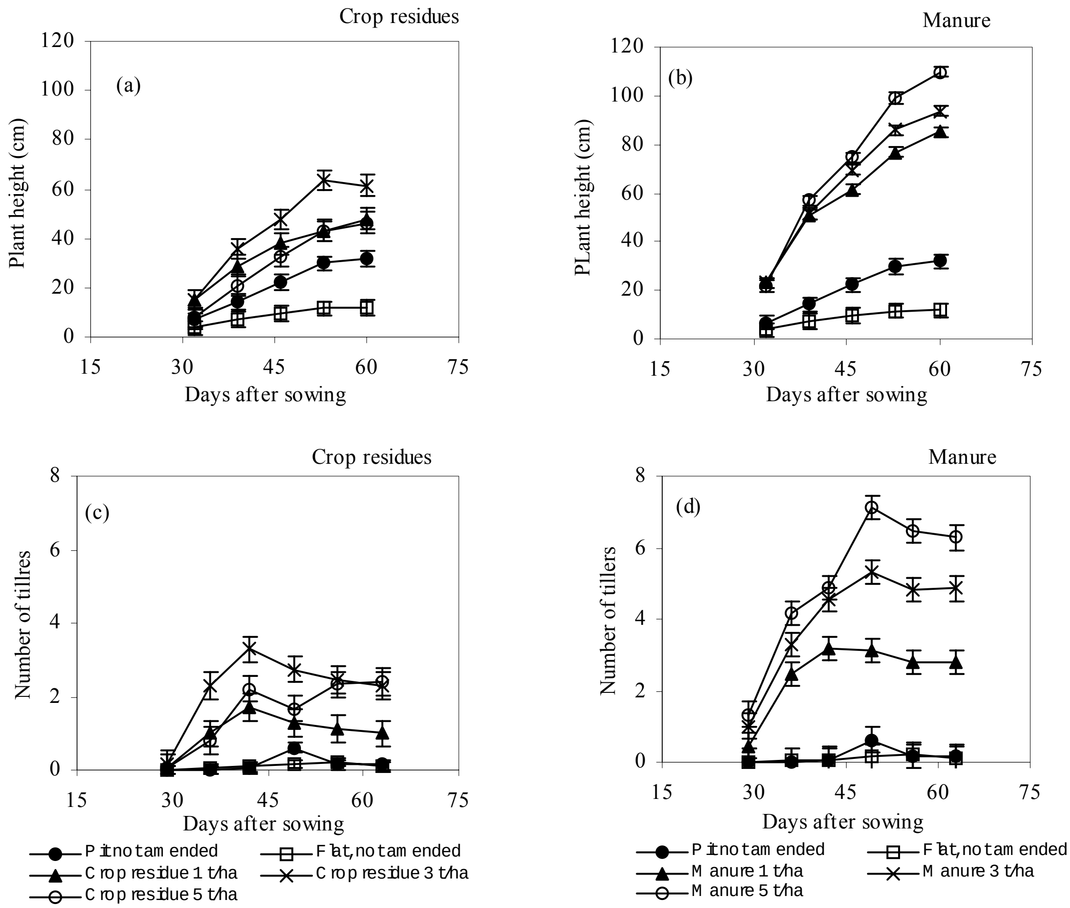


Figure 3.9: Effect of planting techniques (zai vs flat) amendment type and rates on millet growth; Sadore, dry season 1999 – error bars are error of difference between means (a, c, e) plant height, number of leaves, number tillers – crop residues (b, d, f) plant height, number of leaves, number tillers – cattle manure

In the Sahelian agricultural system, where farmers hardly use any inorganic fertilizer (McIntire 1986), organic amendments are an important source of nutrients to meet the nutritional requirements of the crops and also to sustain the fertility of the soil. The role of these amendments is even more important for resource-poor farmers who use them in their effort to rehabilitate their lands with the zai technique. As described earlier, crop residues and cattle manure were the two sources of nutrient used in the present study. At a rate of 5 t ha^{-1}, the crop residues entirely filled the zai pits and inhibited plant establishment due to a lack of contact of the seeds with the soil (Table 3.15). Plant growth was delayed and hills survival was low (Table 3.15). This explains the relatively low yield (632 kg ha^{-1}) with 5 t ha^{-1} compared to 3 t ha^{-1} crop residues (815 kg ha^{-1} - Figure 3.8).

Organic amendment application otherwise induced a better growth and development of the plant, which resulted in production of high TDM at harvest. The beneficial effect of crop residues and cattle manure application on millet yield and growth has been well documented

(Bationo et al. 1991, Michel et al. 1995, Pichot et al. 1981, Pieri 1986). Cisse (1988) also reported that manure application to millet on sandy soil in Northern Senegal improved plant height and tiller formation, which resulted in TDM increases compared to the control. These previous results are similar to those with cattle manure in the present study, where 3957 kg ha^{-1} was produced with 3 t ha^{-1} of this amendment. The 815 kg ha^{-1} total dry matter obtained with 3 t ha^{-1} crop residues application was far below the 3673 kg ha^{-1} reported by Buerkert et al. (2001) obtained at Sadore Niger, in 1998 when crop residues were applied as mulch at the rate of 500 kg ha^{-1}. In the above-mentioned references, crop residues were used in most cases as surface mulch. In this form, apart from the role of nutrient recycling, it has other effects. It reduces the mass of soil carried away by wind erosion as well as protects the young millet seedlings against sand blasting and seedling burial (Michel et al. 1995). It also helps to reduce the soil surface daily peak temperature by 8^{o}C (Buerkert et al. 1996).

Increasing the rate of manure application from 3 to 5 t ha^{-1} did not produce a proportional yield increase. This suggests that it would be optimal for the farmer to apply the manure at the rate of 3 t ha^{-1} rather than 5 t ha^{-1}. The optimal rate may be between 1 and 3 t ha^{-1}, but further investigations are needed to determine this.

3.2.3 Organic amendment decomposition and nutrient release

Statistically significant differences were observed between the decomposition patterns of the 2 types of organic amendment after 32 days of litter exposure, regardless of the rate of application (Figure 3.10 a). The manure weight loss was faster than crop residues weight loss. After 32 days of litter exposure, the weight loss from the crop residues was 18% for both application rates, whereas it was 59% for the manure. At the end of the period of litter exposure (74 days), almost all of the crop residues and the manure exposed were decomposed.

The N, P and K release followed the trend in amendment decomposition. However, after 32 days of litter exposure, no significant differences were observed between the amendments in terms of percentage P released (Figure 3.10 c). On average, K release was faster than N and P release (Table 3.10). At the end of the period of litter exposure, on average 99% of K had been released from the amendments, and 95% of N and P were released (Figure 3.10 b, c and d).

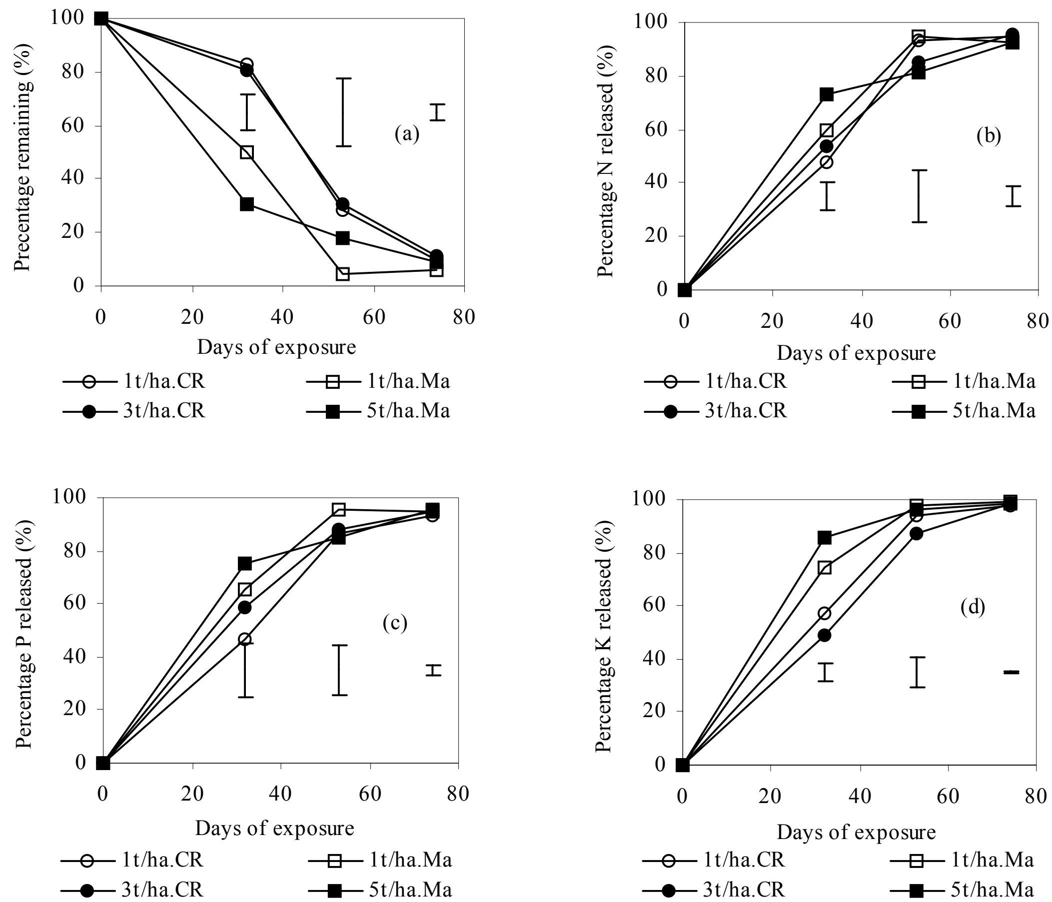


Figure 3.10: Effect of amendment type and rate on decomposition and nutrient release under zai technique conditions; Sadore, dry season 1999 (a - amendment decomposition; b, c and d - N, P and K release; CR = Crop residues, Ma = manure; error bars are error of difference between means

Table 3.10: Quantity of nutrient released as affected by amendment type; Sadore, dry season 1999

		Nutrient released from applied amended (kg ha^{-1})								
		27 Days after planting			47 Days after planting			67 Days after planting		
Organic amendment	Rates	N	P	K	N	P	K	N	P	K
Crop residues	1t ha^{-1}	3.8	0.4	5.3	7.3	0.8	8.7	7.4	0.9	9.0
	3t ha^{-1}	12.6	1.6	13.5	19.9	2.4	24.1	22.4	2.6	27.2
Cattle manure	1t ha^{-1}	8.1	4.2	5.0	12.9	6.2	6.6	12.6	6.2	6.6
	5t ha^{-1}	49.8	24.4	28.8	55.7	27.4	32.2	62.9	31.0	33.1
	$LSD_{0.05}$	5.2	1.5	2.4	12.6	4.9	4.2	5.0	1.4	0.4

$LSD_{0.05}$ = least significant difference at 0.05 probability level

- **Amendment applied**

The quantity of N and K applied with 3 t ha^{-1} crop residues was higher than the amount of N and K applied with 1 t ha^{-1} manure (Table 3.11). Even the quantity of P applied with 5 t ha^{-1} crop residues was lower than with 1 t ha^{-1} manure.

Table 3. 11: Nutrients applied in the experiment with the respective amendments in 1999

Amendment	Rate (t ha^{-1})	Nutrients (kg ha^{-1})		
		N	P	K
Crop residues	1	8	1	9
	3	23	3	28
	5	39	5	46
Manure	1	14	7	7
	3	41	19	20
	5	68	32	34

The chemical composition of the litter governs the decomposition rate and nutrient release. This finding has been well documented (Thomas et al. 1993, Lehmann et al. 1995, Tian et al. 1992, Azam et al. 1993, Palm et al. 1991). The C:N ratio of the crop residues was higher (50) than that of cattle manure (20). However, Palm et al. (1991) in a study on N release from leaves of some tropical legumes reported that the polyphenolic to N ratio was more important. In the literature it appears that there is no consensus on which characteristics are most important in governing the decomposition and nutrient release. In the present study, manure decomposition was faster than crop residues, which shows the importance of the C:N ratio. During the first 32 days of litter exposure, 80% of the K was released, which confirms the high mobility of this element (Tian et al. 1992). This suggests that in the zai pits, leaching of K as well as N could occur because of run-off water harvesting.

3.2.4 Millet N, P and K uptake

More than 4-fold N, P and K were taken up in manure-amended plots compared to crop residues application throughout the cropping period (Table 3.12). Nitrogen, P and K uptake increased by factor 3 to 8 throughout the cropping period in plots amended with 1 t ha^{-1} manure compared to 1 t ha^{-1} crop residues, and by factor 2 compared to plots amended with 3 t ha^{-1} of crop residues. No differences in N, P and K uptake were observed between the individual rates of crop residues application throughout the cropping period except for a slight increase in K uptake with 3 t ha^{-1} crop residues compare to 1 t ha^{-1} application rate at final harvest (Table 3.12).

Increased N, P and K uptake due to manure application was observed. Even though the P content of the manure was low, its relatively rapid release from the manure might have promoted rapid root growth. This might have resulted in increased nutrient uptake and consequent increased growth and TDM production. Payne et al. (1990), Bagayoko et al. (2000) reported similar results.

Table 3.12: Millet straw N, P and K uptake as affected by planting techniques (zai vs flat), organic amendment type and rate; Sadore, dry season 1999

Planting technique	Organic amendment Type	Rate	27 Days after planting N	P	K	47 Days after planting N	P	K	67 Days after planting N	P	K
			Nutrient uptake kg ha^{-1}								
Zai	Crop residues	1t/ha	0.19 C	0.01 C	0.31 B	2.9 B	0.1 B	4.2 C	8.1 D	0.3 D	8.0 E
		3t/ha	0.27 C	0.02 BC	0.52 B	5.2 B	0.3 B	8.8 C	20.6 D	0.7 D	24.9 D
		5t/ha	0.17 C	0.01 C	0.31 B	3.4 B	0.2 B	6.5 C	15.9 D	0.7 D	22.6 DE
	Cattle manure	1t/ha	0.49 BC	0.06 B	1.03 B	10.5 B	0.7 B	17.7 BC	46.6 C	1.9 C	62.2 C
		3t/ha	0.83 AB	0.14 A	2.05 A	25.4 A	1.9 B	47.3 B	93.3 B	4.9 B	127.3 B
		5t/ha	1.12 A	0.17 A	2.67 A	37.4 A	3.6 A	81.8 A	113.8 A	7.1 A	161.1 A
		$LSD_{0.05}$	0.43	0.04	0.96	14.0	1.2	30.6	13.1	0.6	15.0
Zai	control	0t/ha	0.05 A	0.00 A	0.08 A	0.44 A	0.02 A	0.66 A	0.98 A	0.04 A	1.21 A
flat	control	0t/ha	0.08 A	0.01 A	0.07 A	0.11 B	0.003 B	0.10 B	0.31 A	0.01 A	0.19 A
		$LSD_{0.05}$	0.13	0.01	0.11	0.32	0.01	0.35	2.12	0.09	2.41

NB: Letters A, B, C and D indicate significance of differences between means
$LSD_{0.05}$ = least significant difference at 0.05 probability level

Nutrient uptake in the control plot was very low, which reflects the advanced stage of degradation of the experimental field. This was also expressed in the very low TDM obtained with the control zai and the control flat.

3.2.5 Millet N, P and K utilization efficiency, agronomic efficiency and apparent recovery fraction

TDM produced with a unit of P and K absorbed was higher in plots amended with crop residues than with the manure throughout the cropping period and, particularly, at final harvest. A similar tendency was observed on N only at final harvest ($P<0.05$) (Table 3.13). This tendency was also observed between the lowest rate of manure application and the others. A possible reason could be that the rate of manure and, consequently, the rate of nutrient applied was very high, particularly on plots receiving 3 or 5 t ha^{-1}. The Figures also show a better use of the absorbed K by the plant on the control flat than in the control zai throughout the cropping period ($P<0.05$).

- **Nitrogen and K agronomic efficiency (AE)**

The chemical analysis was restricted to two rates for each amendment type with regards to the apparent nutrient recovery fraction and agronomic efficiency.

Increased N and K agronomic efficiency (AE) due to manure application was observed throughout the cropping period even though the effect on N AE was significant only at harvest 67 DAS ($P<0.05$ - Table 3.14). The TDM produced with a unit of N or K applied with 1 t ha^{-1}

manure was almost 2 times higher than that produced with a unit of N or K applied with 5 t ha^{-1} manure. Excessive nutrient application with that high rate of manure in the zai could be the possible explanation of that response.

Table 3.13: Millet straw N, P and K utilization efficiency as affected by planting techniques (zai vs flat), organic amendment type and rate; Sadore, dry season 1999

Planting technique	Organic amendment Type	Rate	Nutrient utilization efficiency (TDM/unit nutrient absorbed kg/kg) 27 Days after N	P	K	47 Days after N	P	K	67 Days after N	P	K
Zai	Crop residues	1t/ha	37 ^{A}	568 ^{A}	22 ^{A}	38 ^{AB}	893 ^{A}	25 ^{A}	37 ^{C}	1028 ^{AB}	38 ^{A}
		3t/ha	40 ^{A}	625 ^{A}	20 ^{AB}	35 ^{C}	685 ^{AB}	21 ^{B}	40 ^{ABC}	1118 ^{A}	34 ^{AB}
		5t/ha	37 ^{A}	695 ^{A}	21 ^{A}	39 ^{A}	609 ^{BC}	21 ^{B}	37 ^{C}	847 ^{BC}	26 ^{C}
	Cattle	1t/ha	38 ^{A}	289 ^{B}	18 ^{BC}	38 ^{AB}	539 ^{BC}	22 ^{AB}	43 ^{A}	1028 ^{AB}	32 ^{ABC}
		3t/ha	41 ^{A}	230 ^{B}	16 ^{C}	38 ^{AB}	506 ^{BC}	20 ^{BC}	42 ^{AB}	787 ^{CD}	30 ^{BC}
		5t/ha	37 ^{A}	251 ^{B}	16 ^{C}	36 ^{BC}	376 ^{C}	17 ^{C}	39 ^{BC}	636 ^{D}	28 ^{BC}
		$LSD_{0.05}$	4	199	2	3	265	4	4	183	6
Zai	control	0t/ha	37 ^{A}	702 ^{A}	26 ^{B}	36 ^{A}	755 ^{B}	24 ^{B}	36 ^{A}	736 ^{A}	29 ^{B}
Flat	control	0t/ha	42 ^{A}	533 ^{A}	48 ^{A}	39 ^{A}	1010 ^{A}	45 ^{A}	39 ^{A}	1119 ^{A}	64 ^{A}
		$LSD_{0.05}$	9	478	6	7	160	11	3	718	13

NB: Letters A, B, C and D indicate significance of differences between means
$LSD_{0.05}$ = least significant difference at 0.05 probability level

- **Phosphorus agronomic efficiency**

In contrast with N agronomic efficiency, the total dry matter produced with a unit P applied with crop residues was 2 times higher than that with manure throughout the cropping period ($P<0.05$) (Table 3.14). The improvement effect was observed mainly with the lower rate of crop residues application.

Table 3.14: Millet N, P and K agronomic efficiency as affected by amendment type and rates; Sadore, dry season 1999 (kg/kg)

Amendment	Rate	Nutrient agronomic efficiency (TDM/unit nutrient applied kg/kg) 27 Days after sowing N	P	K	47 Days after sowing N	P	K	67 Days after sowing N	P	K
Crop residues	1t ha-1	0.7	5.5	0.8	12	101	10	34	290	29
	3t ha-1	0.4	3.1	0.3	7	60	6	31	261	26
Cattle manure	1t ha-1	1.2	2.6	2.5	28	59	57	119	251	242
	5t ha-1	0.6	1.3	1.2	20	41	40	64	134	130
	LSD0.05	0.6	2.1	1.2	23	117	39	24	94	47

All the parameters in this table are expressed on total dry matter basis

- **Millet apparent N, P and K recovery**

Increased N recovery (2-fold) with manure application compared to crop residues was observed only at harvest ($P<0.05$ - Table 3.15). No differences were observed between the amendments in terms of P recovery.

At harvest, K recovery under manure application was as much as 87% higher than with crop residues (Table 3.15). Potassium recovery at the lower rate of manure application (1 t ha^{-1}) was 38% higher than with the higher rate of application (5 t ha^{-1}).

Table 3.15: Millet N, P and K apparent recovery fraction as affected by amendment type and rates; Sadore, dry season 1999

		Nutrient apparent recovery fraction (kg/kg)								
		27 Days after sowing			47 Days after sowing			67 Days after sowing		
Amendment	Rate	N	P	K	N	P	K	N	P	K
Crop residues	1t ha^{-1}	0.02	0.01	0.04	0.3	0	0.44	0.94	0.28	0.76
Ü	3t ha^{-1}	0.01	0.01	0.02	0.2	0	0.31	0.78	0.24	0.79
Cattle manure	1t ha^{-1}	0.03	0.01	0.14	0.73	0.07	2.61	2.8	0.24	7.6
	5t ha^{-1}	0.02	0.01	0.08	0.54	0.1	2.43	1.63	0.21	4.68
	$LSD_{0.05}$	0.02	0.003	0.07	0.61	0.44	1.96	0.42	0.11	1.03

All the parameters in this table are expressed on total dry matter basis

$LSD_{0.05}$ = least significant difference at 0.05 probability level

The high N, P and K utilization efficiency observed with crop residues application compared to manure is associated with lower nutrient uptake in the plant. The nutrient content (mainly P) of the straw in these treatments was very low. Manure application increased nutrient uptake and accumulation, which was expressed in subsequent yield. As water was not a limiting factor (see plant available water below), the plant might have been fertilized more than required, especially with the 5 t ha^{-1} manure application rate.

Nitrogen and K agronomic efficiency and apparent recovery fraction were best with manure application. The plant used the N and K from 1 t ha^{-1} manure more effectively compared to 5 t ha^{-1}. This is another indication that this high rate of manure application in this study might not be optimal. It is also a positive signal for the resource poor farmers. Rani-Perumal (1988), in his study with finger millet, found that nutrient recovery increased with the rate of organic amendment application. Nevertheless, there is a need to determine the limit to which increasing the rate of application can result in increased recovery.

3.2.6 Soil chemical status 47 DAS

After 47 days of cropping, which correspond to 61 days after amendment application, soil pH increased more in the hills, which received 5 t ha^{-1} cattle manure (Table 3.16). The Al saturation was reduced considerably in all treatments except for the plots receiving 1 t ha^{-1} crop residues. The total N and extractable P have increased considerably in plots receiving 3 and 5 t ha^{-1} of cattle manure. Bationo et al. (1989), and Kretzschrmar et al. (1991) reported a similar effect of cattle manure application, which on acid soil helps to fix free Al, which might immobilize P and therefore make it unavailable the for plant.

Table 3.16: Selected soil chemical parameters of the experimental plots 47 days after sowing; Sadore, dry season 1999

	Before	47 Days after sowing							
	Experiment	Crop residues			Cattle manure			Control	
	layout	1t/ha	3t/ha	5t/ha	1t/ha	3t/ha	5t/ha	zai	flat
pH (KCl)	3.9	4.2	4.4	4.4	4.2	4.5	4.9	4.1	4.2
Exchangeable base (cmol+/kg)	0.5	0.3	0.7	0.6	0.3	0.8	1.2	0.3	0.2
Exchangeable acidity (cmol+/kg)	0.6	0.6	0.3	0.3	0.6	0.2	0.2	0.7	0.5
ECEC (cmol+/kg)	1.1	1.0	1.0	1.0	0.9	1.0	1.4	1.0	0.8
Al saturation (%)	41	46	19	23	33	13	8	49	51
Base saturation (%)	43	35	70	65	45	80	85	29	30
P-Bray (mg-P/kg)	2.5	1.3	2.5	3.4	6.5	28.0	30.5	1.3	2.2
C org (%)	0.1	0.1	0.2	0.2	0.1	0.2	0.3	0.1	0.1
Total N (mg-N/kg)	123.3	72.0	79.2	91.7	65.4	139.9	141.7	67.3	64.9

3.2.7 Root development

- **Root length density**

In the early stages of the plant growth – 27 DAS, no significant differences were observed between the treatments in terms of the root length density (RLD) in the upper 10 cm soil layer (Table 3.17). But in the soil layer of 10-20 cm and 20-40 cm, the RLD of millet grown with manure was higher than the RLD of millet grown with crop residues and that of the controls ($P=0.009$). No application rate effect was observed at this time for either amendment. Later, the millet rooting system increased rapidly so that at harvest 67 DAS, it was larger with manure application than with crop residues as well as in the control plots throughout the soil profile ($P<0.001$ - Table 3.17).

- **Root radius**

In the early stage of the plant growth (27 DAS) root radius was higher with manure application compared to crop residues and the controls in the layer 10-20 cm. At 47 DAS, as well as at 67 DAS, increased radius due to manure application compared to crop residues application and the controls was observed up to 60 cm depth ($P<0.001$) (Appendix 1). At 67 DAS, millet root radius in the upper (0 – 10 cm) soil layer under manure was 35% higher than with crop residues and

70% higher than in the control zai. The millet root radius under crop residues amendment was 2-fold that of the controls.

Table 3.17: Effect of planting techniques (zai vs flat) amendment type and rate on millet root length density (cm*cm^{-3}) distribution; Sadore, dry season 1999 – all amended plots are treated with zai

	Crop residues			Manure			Control		
Depth	1t ha^{-1}	3t ha^{-1}	5t ha^{-1}	1t ha^{-1}	3t ha^{-1}	5t ha^{-1}	Zai	Flat	$LSD_{0.05}$
Twenty-seven days after sowing									
0-10cm	1.29	1.29	0.64	0.80	1.10	0.79	0.94	1.16	0.69
10-20cm	0.28	0.32	0.22	0.15	0.66	0.49	0.31	0.34	0.22
20-40cm	0.03	0.03	0.02	0.03	0.07	0.06	0.01	0.03	0.03
40-60cm	0.03	0.02	0.01	0.003	0.02	0.05	0.01	0.01	0.03
Forty-seven days after sowing									
0-10cm	2.41	2.62	1.18	2.09	4.37	4.08	1.54	0.92	1.28
10-20cm	0.36	0.53	0.67	0.51	1.33	1.05	0.37	0.16	0.51
20-40cm	0.06	0.11	0.12	0.12	0.31	0.30	0.04	0.05	0.08
40-60cm	0.02	0.09	0.05	0.08	0.12	0.17	0.04	0.04	0.07
60-80cm	0.03	0.06	0.02	0.05	0.13	0.14	0.01	0.03	0.06
Sixty-seven days after sowing									
0-10cm	1.74	5.18	6.34	5.53	10.78	10.27	0.94	2.69	6.02
10-20cm	1.23	2.12	0.77	2.07	3.34	4.10	1.18	0.47	1.74
20-40cm	0.32	0.39	0.19	0.20	0.69	1.05	0.14	0.13	0.47
40-60cm	0.09	0.13	0.14	0.18	0.38	0.36	0.07	0.03	0.21
60-80cm	0.07	0.12	0.09	0.16	0.15	0.22	0.03	0.07	0.13
80-100cm	0.06	0.14	0.11	0.11	0.12	0.23	0.06	0.04	0.14

$LSD_{0.05}$ = least significant difference at 0.05 probability level

In the present study, root growth was improved by manure application compared to crop residues application as well as to the control. This is probably due to improved nutrient availability. However, as observed in Section 3.2.6, manure application increased soil pH and also reduced the Al saturation, 2 factors, restricting cereal root growth and proliferation (Zaongo 1988, Scott-Wendt et al. 1988). Phosphorus enhances root development (Payne et al. 1996) and subsequently increases the soil volume explored by the plant. The rapid increase in N, P and K uptake under manure application suggests that optimal conditions for root development were created, whereas the rooting system was weak under all rates of crop residues application compared to manure, because of the lower nutrient availability. Most of the root mass was confined to the upper 40 cm soil depth.

3.2.8 Nitrate leaching

In all treatments, a slight increase in NO_3^- was observed at 47 DAS in the upper 30 cm soil layer. At harvest, the nitrate content along the soil profile was similar to that prior to the installation of the experiment in the non-amended pits (Figure 3.11 a). In plots amended with manure at 45 cm and below, depth nitrate content was lower than the initial level (Figures 3.11 c and d).

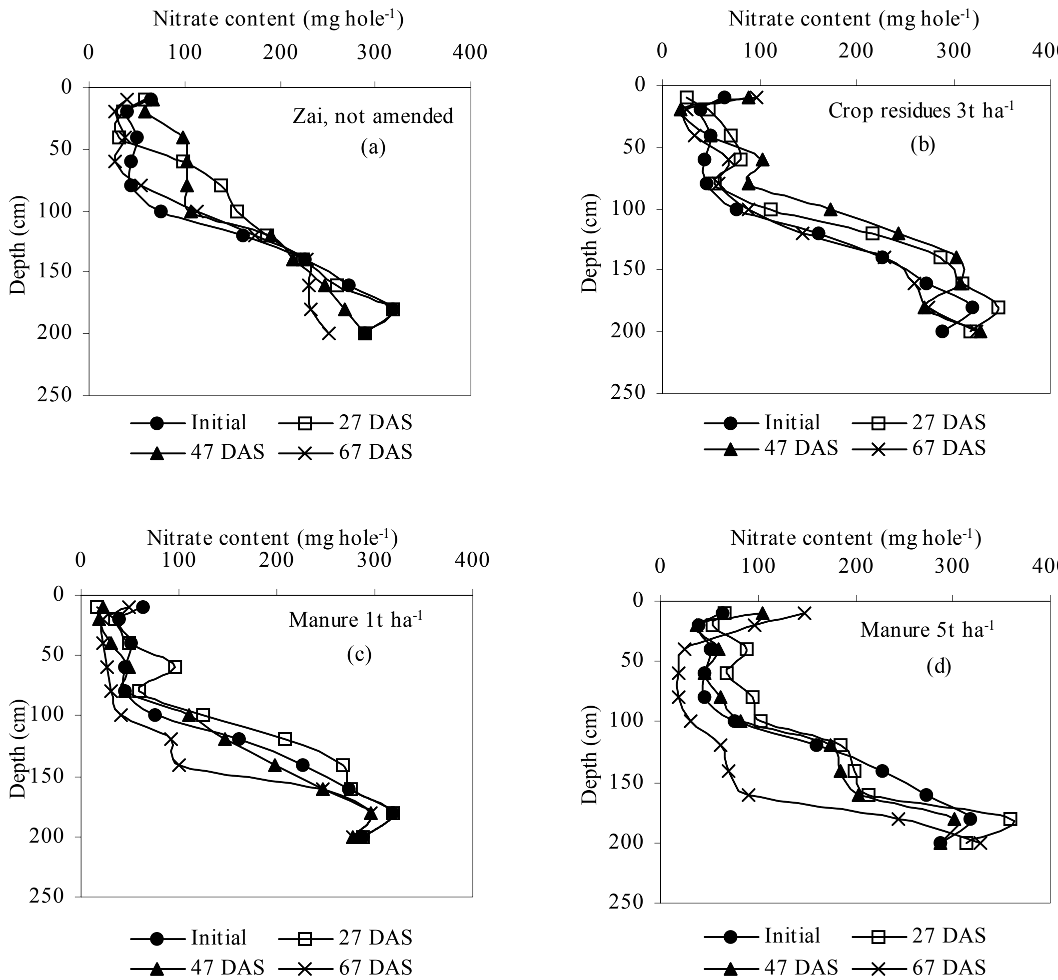


Figure 3.11: Nitrate content as affected by amendment type and rate; Sadore, dry season 1999 (a – non-amended zai; b - 3 t ha^{-1} of crop residues; c and d – 1 t and 5 t ha^{-1} manure, all plots were treated with zai)

A significant reduction in total nitrate content under manure treatment was observed at final harvest, compared to the other treatments (Table 3.18). This trend was more prominent with the 5t ha^{-1} cattle manure application.

Table 3.18: Total nitrate content (mg hole^{-1}) in soil profile as affected by amendment type and rate; Sadore, dry season 1999

Treatment	Initial	27 DAS	47 DAS	67 DAS	F.prob
Zai not amended	1.6	1.8	1.8	1.4	P=0.033
Zai, 3t ha^{-1} CR	1.6	1.9	2.0	1.6	
Zai, 1t ha^{-1} manure	1.6	1.7	1.4	1.2	
Zai, 5t ha^{-1} manure	1.6	1.6	1.5	1.2	
$LSD_{0.05}$	1.6	1.4	1.5	1.0	

CR = crop residues; F.prob = F probability
$LSD_{0.05}$ = least significant difference at 0.05 probability level

The nitrate content of the soil profile suggests more NO_3^- leaching under crop residues than manure application. This could be explained by a higher uptake under manure application. However, Shrestha et al. (2000) reported low NO_3^- in the soil profile due to crop residues incorporation, which they relate to N immobilization in the residue.

3.2.9 Water balance

- **Volumetric water content**

The progress of the wetting front was more rapid on plots amended with crop residues and those with 1t ha^{-1} manure (Figure 3.12 b and c) than the control zai and the pit amended with 5 t ha^{-1} manure (Figure 3.12 a and d).

On May 5 (8 weeks after irrigation started), the wetting front was beyond 200 cm in all treatments except for the pits with 5 t ha^{-1} manure. On May 25 (11 weeks after irrigation started), the volumetric water content in plots amended with 5 t ha^{-1} of manure was lower below 60 cm depth than before the start of the irrigation (Figure 3.12 d).

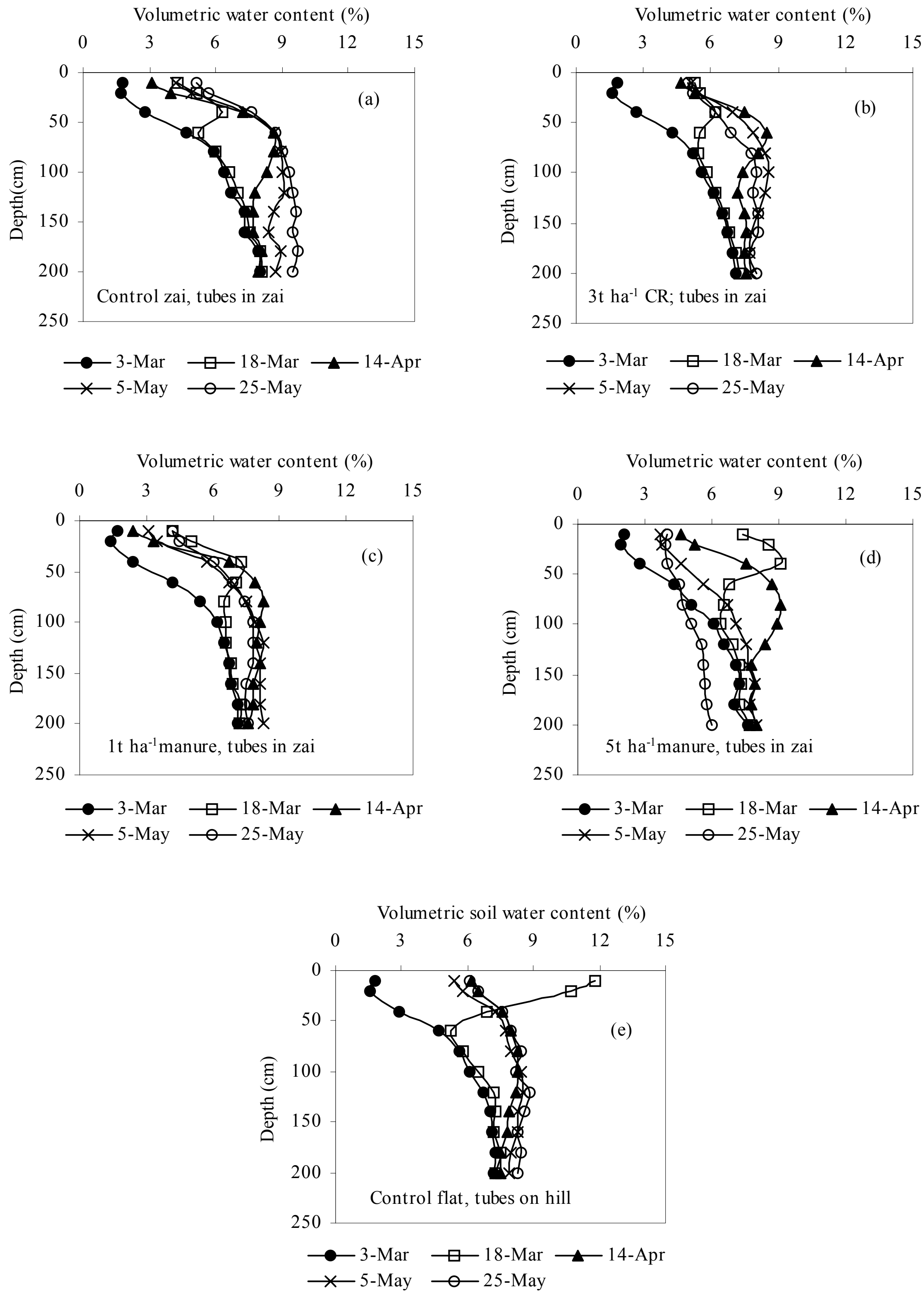


Figure 3.12: Volumetric soil water content as affected by amendment type and rate of application and planting technique (zai vs flat); Sadore, dry season 1999 – CR = crop residues

- **Plant available water**

Plant available water increased during the cropping period regardless of the treatments (Figure 3.13). But at harvest, PAW decreased consistently in all treatments. With crop residues amendment, on average 25 mm water was still available at harvest in the rooting zone (Figure

3.13 a). In the control plots, the available water was 18 mm. With manure amendment, on average 10 mm of water still remained in the rooting zone under the 3 t and 5 t ha^{-1} application rates, whereas 15mm remained under the 1 t ha^{-1} application rate (Figure 3.13 b). A strong negative correlation (R^2 = 0.73) was observed between plant available water remaining at harvest (67 DAS) and the TDM production (Figure 3.14).

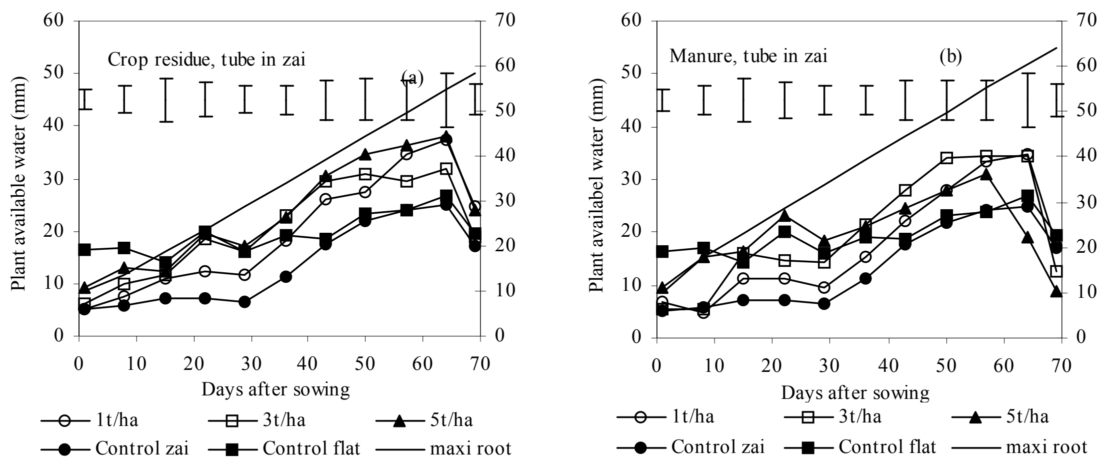


Figure 3.13: Plant available water as affected by amendment type and planting techniques (zai vs flat); Sadore, dry season 1999 – error bars are error of difference between means

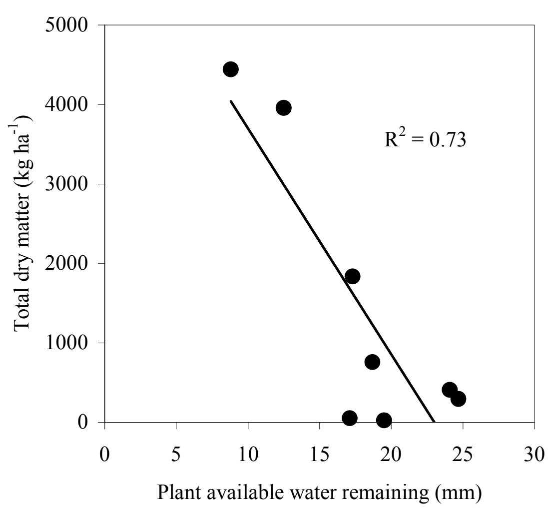


Figure 3.14: Plant available water remaining at harvest as a function of TDM; Sadore, dry season 1999

- **Drainage**

Throughout the cropping period, drainage was higher in plots amended with crop residues than those amended with manure (Figure 3.15). At 67 DAS, 70% of the irrigation water was lost by drainage in the plots amended with 1 t ha^{-1} crop residues, whereas 10% was lost in the plots amended with 3 t ha^{-1} manure (data reported in Appendix 2). A strong negative correlation (R^2=0.72) was observed between the cumulative drainage in the zai pits and the total dry matter production (Figure 3.16)

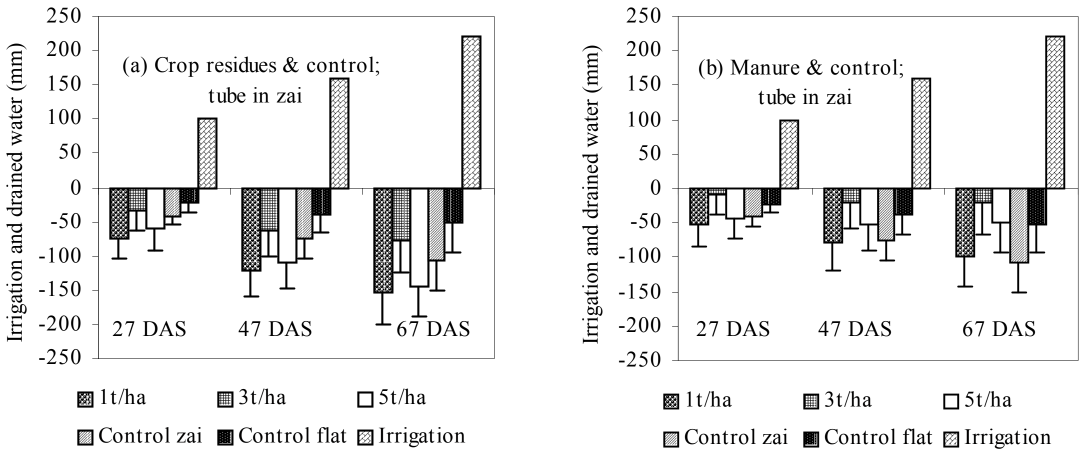


Figure 3.15: Water losses by drainage as affected by amendment type and rate of application and planting techniques (zai vs flat); Sadore, dry season 1999 - error bars are error of difference between means

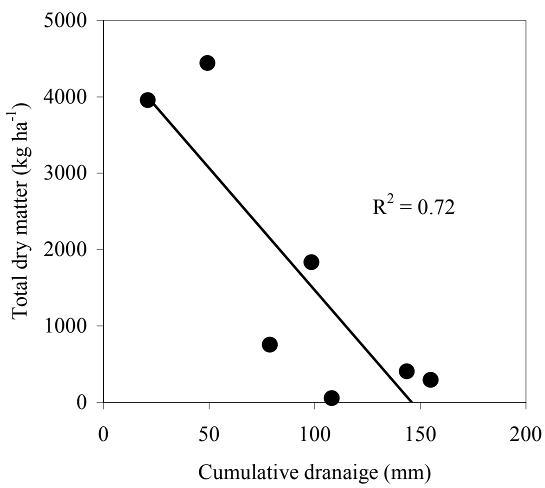


Figure 3.16: Cumulative drainage as a function of TDM; Sadore, dry season 1999

The rapid progress of the wetting front under zai was an indication of increased irrigation water collection in the zai pit. Due to the low water holding capacity of the soil, the water might be subjected to drainage. Plant available water as well as drainage was low under manure application compared to the other treatment. All this together with the high RLD obtained under manure application suggests intensive water and nutrient use by the plant in plots treated with manure, which is supported by the findings of Payne et al. (1996) and Zaongo et al. (1997). This resulted in use of most of the plant available water and less loss of water through drainage. This was consistent with the strong negative correlation observed between the remaining plant available water at harvest and the TDM on the one hand, and the cumulative drainage and the TDM on the other hand. Thus, a good soil nutritional status is a prerequisite for improved water use efficiency.

3.2.10 Resume of experiment S2

The present study showed that as much as 3 t ha^{-1} cattle manure was the best treatment for relatively high (3957 kg ha^{-1}) millet TDM production on highly degraded soils. The high increase in TDM when the manure rate of application was increased from 1 to 3 t ha^{-1}, suggests that the optimal rate of manure application in the zai technique may need further study. The incorporation of crop residues in the zai pit did not improve TDM production, indicating that high quality amendment is needed for the success of the zai technique.

The lower quality of the crop residues, especially the high C:N ratio, probably lead to nutrient immobilization. This resulted in lower nutrient uptake in plots amended with crop residues and consequently lower yield. Although almost all of the nutrients were released from the crop residues at the end of the period of exposure, the slow release and low quantity of nutrients added with the crop residues might not meet the requirements of the crop. The consequence was a low TDM yield. In contrast, the nutrient-rich manure decomposed and released nutrients faster than the crop residues, which resulted in better nutritional conditions, and better nutrient uptake and plant growth. In consequence, nutrient agronomic efficiency and recovery were also improved.

Due to the better nutritional conditions created in the zai amended with manure, higher plant water consumption was observed, which possibly resulted in less water and nitrate percolation below the rooting zone. Less residual water remained in the plots amended with manure, which also reduced the risk of residual water loss.

3.3 Recovery from drought and growth of millet in zai technique (S3)

3.3.1 Yield and yield parameters

Zai planting produced significantly higher yield for all irrigation regimes (Figure 3.17). Imposed dry spells induced a considerable total dry matter yield loss compared to the continuous irrigation regardless of the planting techniques (34% yield loss for 3-week dry spell and 49% for 4-week dry spell in the zai; 34% and 59% in flat planting) (Figure 3.17). The total dry matter (TDM) production in zai after the 4-week dry spell was similar to that of flat planting under continuous irrigation (2225 vs 2148 kg ha^{-1}). No interaction effect was observed between the treatments.

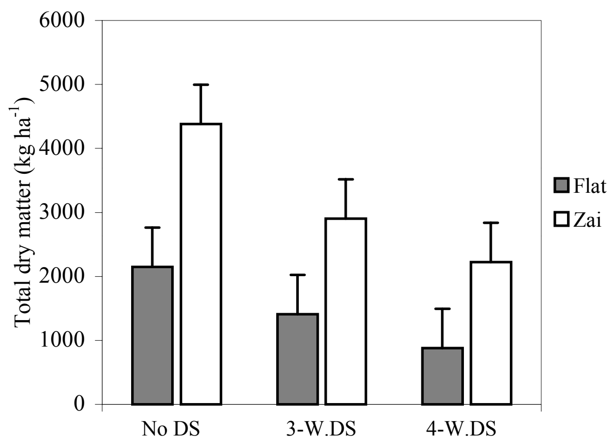


Figure 3.17: Millet total dry matter production as affected by dry spells, and planting techniques (zai vs flat); Sadore, dry season 2000 – W = week; DS = dry spell; error bars are error of difference between means

Millet emergence was poor in the zai compared to flat planting 5 and 15 DAS (Table 3.19). The 3-week and 4-week dry spells delayed node formation by 9 days and 15 days, respectively, in flat planting compared to continuous irrigation. In the zai, only the 4-week dry spell delayed the node formation by 7 days compared to continuous irrigation. The hill survival was higher under flat planting than in zai (P=0.011) (Table 3.19).

Under all water regimes, the TDM per hill was higher (e.g. 60% with the 3-week dry spell) in the zai than in flat planting (P<0.001; Table 3.19). This parameter was also negatively affected by the dry spells (e.g. 55% lower under the 4-week dry spell than under continuous irrigation; P=0.004).

3.3.2 Growth parameters

- **Tillers formation**

Three groups were formed with respect to tiller formation in response to the treatments (Figure 3.18): (1) More tillers (7) in the flat planting under continuous irrigation, where the number of tillers increased until 51 DAS and remained constant afterwards; (2) zai with continuous irrigation and zai with 3-week dry spell, where fewer (5) tillers were formed; (3) the rest of the treatment combinations, where the final number of tillers was 3. In the last group, no new tillers were formed after 44 days of growth.

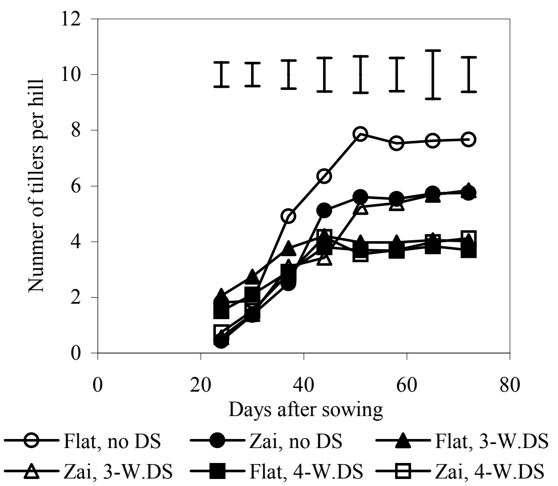


Figure 3.18: Effect of dry spells and planting techniques (zai vs flat) on millet tillers formation; Sadore, dry season 2000 - W = week; DS = dry spell; error bars are error of difference between means

Table 3.19: Millet yield parameters as affected by planting techniques (zai vs flat) and dry spells; Sadore, dry season 2000

Water regime	Planting technique	Percentage hills emerged 5 DAS	15 DAS	23 DAS	Days to 5 leaves	Days to first node	Hill survival	Total dry matter per hill (g)
No DS	Flat	51	74	91	19	51	86	215
	Zai	25	66	88	19	51	61	438
3-W.DS	Flat	57	84	94	17	60	81	141
	Zai	34	72	78	20	51	70	290
4-W.DS	Flat	71	94	97	18	66	95	88
	Zai	62	94	92	20	58	78	222
	$LSD_{0.05}$	17	13	17	2	7	22	131

W = week, DS = dry spell, DAS = days after sowing

In the Sahel in general and particularly in Niger, rainfall patterns are characterized by high variation in space and time. The reason for water being a major constraint to agricultural production is more this high variation than the low annual rainfall (Sivakumar et al. 1993).

Recurrent dry spells are one of the major problems for millet production in the country. The above results suggest a strong effect of dry spells on the yield and yield parameters under both planting techniques. This effect was more damaging in flat planting than in the zai. The dry spells were imposed from 20 DAS and continued until 44 DAS and 51 DAS for 3-week and 4-week dry spell, respectively. These periods cover parts of the millet growth phase I (vegetative growth) and the beginning of growth phase II (panicle initiation flowering) (Ong and Montheith 1984). Dry spell during this period affect mainly the hill survival and tiller formation. Both parameters determine the final total dry matter (Fussel et al. 1980). In the present study, no effect of the dry spell on hill survival was observed, but the number of tillers was affected. Tiller formation stopped earlier in plants under drought stress. This is in agreement with the finding of Rockstrom (1997), who reported negative impacts of dry spells during millet growth phase I on tiller formation in farmer fields. To better understand why the plants performed better in the zai compared to flat planting, data were collected on plant available water during the dry spell (see below).

3.3.3 Amendment decomposition and nutrient release

Cattle manure decomposition was not effected by dry spells or planting techniques. The decomposition was rapid in all treatments. After 39 days of litter exposure, on average 37% of the manure remained. At the end of the period of litter exposure (98 days), almost all of the manure was decomposed (Figure 3.19 a) and only 3% remained.

Nitrogen, P and K release followed the trend of amendment decomposition. High variation among the treatments was observed in N release after 39 days of litter exposure, which was consistent with the observed manure decomposition (Figure 3.19 b). Potassium release was faster in all treatments compared to N and P.

According to Agbim et al. (1997), Andren et al. (1993), Arunachalam (1998) and Bryant et al. (1998), soil moisture plays an important role in litter decomposition. In the present study, it appeared that dry spells did not affect manure weight loss. However, these above-cited studies mostly concerned leaves and wood litter rather than manure.

The nutrient release generally followed the trend of manure decomposition. The rapid release of K compared with the other nutrients makes this nutrient susceptible to leaching as mentioned earlier in Section 3.2.3. However, the soils of Sadore are rich in K (West et al. 1984) and this nutrient should not be a limiting factor for plant growth.

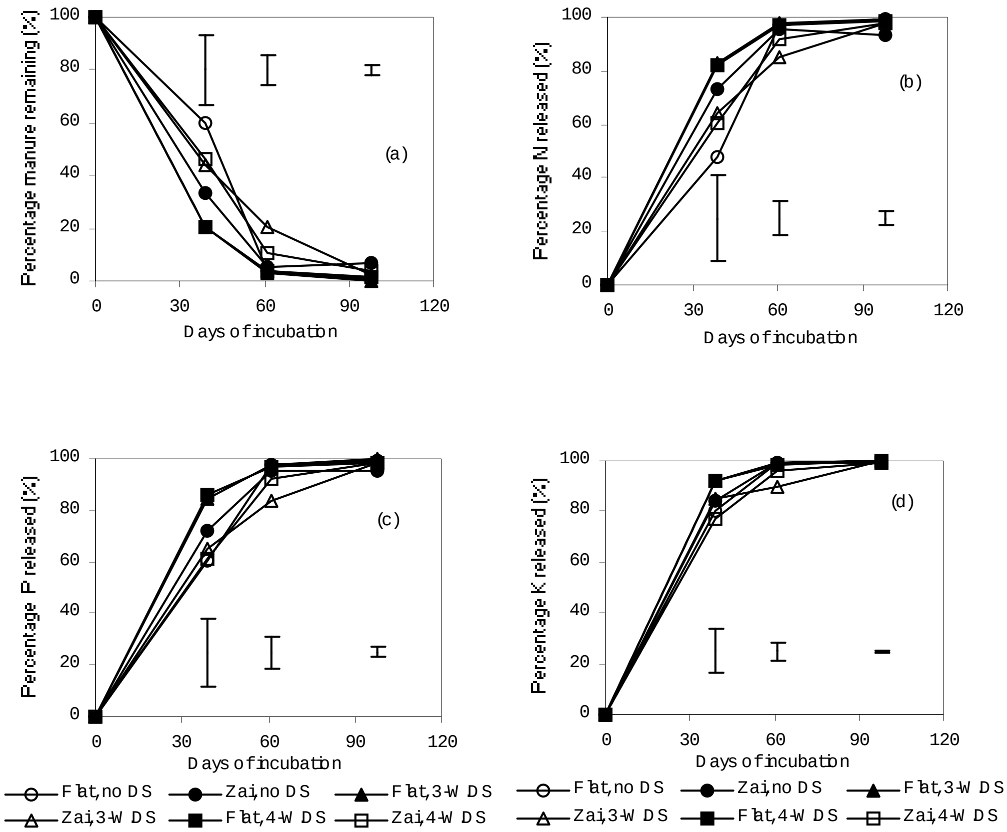


Figure 3.19: Effect of dry spells and planting techniques (zai vs flat) on manure decomposition and nutrient release; Sadore, dry season 2000 – error bars are error of difference between means - W = week, DS = dry spell

3.3.4 Millet N, P and K uptake, and utilization efficiency

- **Nutrient uptake**

Imposed dry spells induced a decrease in nutrient uptake at 44 DAS compared to continuous irrigation (Table 3.20). This difference was less pronounced at final harvest. The zai increased N, P and K uptake at harvest 78 DAS by 33%, 42% and 36%, respectively, compared to flat planting (P=0.018 for N, P=0.009 for P and P=0.019 for K) (Table 3.21). No interaction effect was observed between the treatments with regard to this parameter.

Table 3.20: Effect of dry spells on millet N, P and K uptake; Sadore, dry season 2000

	Nutrient uptake (kg ha^{-1})								
Water	20 DAS			44 DAS			78 DAS		
regime	N	P	K	N	P	K	N	P	K
No DS	0.07	0.02	0.14	6.08	0.53	9.80	76.8	6.9	95.2
3-W.DS	0.07	0.02	0.14	3.79	0.24	4.54	60.9	4.7	83.2
4-W.DS	0.07	0.02	0.14	4.00	0.23	4.66	51.0	4.1	63.0
$LSD_{0.05}$	0.05	0.01	0.11	2.95	0.20	4.27	23.9	2.3	34.7

W = week, DS = dry spell, DAS = days after sowing, $LSD_{0.05}$ = least significant difference at 0.05 probability level

Table 3.21: Effect of planting techniques (zai vs flat) on millet N, P and K uptake; Sadore, dry season 2000

Planting technique	Nutrient uptake (kg ha^{-1}) 20 DAS			44 DAS			78 DAS		
	N	P	K	N	P	K	N	P	K
Flat	0.09	0.02	0.17	4.27	0.23	4.89	50.5	3.8	62.8
Zai	0.05	0.01	0.11	4.97	0.44	7.77	75.3	6.6	98.1
$LSD_{0.05}$	0.04	0.01	0.09	2.41	0.16	3.49	19.5	1.9	28.3

- **Nitrogen, P and K utilization efficiency (UE)**

The 4-week dry spell decreased N UE by 20% at harvest (P=0.042) (Table 3.22). In general, the P and K utilization efficient was higher when the plant experienced drought stress (period corresponding to 44 DAS) than when it did not experience any. Phosphorus UE was increased by 36% under dry spells compared to continuous irrigation 44 DAS (P<0.001) (Table 3.22). Zai increased P UE by 19% compared to flat planting 20 DAS (P=0.014), but the reverse tendency was observed 44 DAS (47% increase in flat planting compared to zai P<0.001) (Table 3.23). Potassium UE increased by 24% under dry spells compared to continuous irrigation (P=0.007) (Table 3.22) and by 31% in flat planting compared to zai at 44 DAS (Table 3.23) (P<0.001). This tendency may be related to the reduction of nutrient uptake and cell growth induced by the effect of the drought stress (Mengel et al. 1987), whereas under the continuous irrigation, active nutrient uptake and cell growth might have resulted in the excessive accumulation of these nutrients at that stage of plant growth.

Table 3.22: Effect of dry spells on millet N, P and K utilization efficiency; Sadore, dry season 2000

Water regime	Nutrient utilization efficiency (kg TDM per unit nutrient absorbed) 20 DAS			44 DAS			78 DAS		
	N	P	K	N	P	K	N	P	K
No DS	31	147	15	39	464	25	49	574	40
3-W.DS	33	138	16	35	692	33	44	596	35
4-W.DS	31	131	16	38	720	33	39	486	31
$LSD_{0.05}$	6	27	1	6	102	5	8	80	8

Table 3.23: Effect of planting techniques (zai vs flat) on millet N, P and K utilization efficiency; Sadore, dry season 2000

Planting technique	Nutrient utilization efficiency (kg TDM per unit nutrient absorbed) 20 DAS			44 DAS			78 DAS		
	N	P	K	N	P	K	N	P	K
Flat	31	124	16	37	819	36	42	563	36
Zai	32	153	16	37	432	25	46	541	36
$LSD_{0.05}$	5	22	1	5	83	4	6	65	7

Nutrient uptake 44 DAS was affected mostly by dry spells, suggesting that despite increased nutrient availability shown by the nutrient release, during dry spells the plants may not have been able to take advantage of the nutrients. During the dry spells, the upper soil layer, which is the most fertile especially with the localised application of the manure, dried first. Consequently, the transport to the roots by diffusion of nutrients like P was probably reduced drastically (Bhadoria et al. 1991). This would lead to low P uptake by the plant and consequent yield reduction. Data on available water in the soil will help to evaluate this idea. The increased utilization efficiency under dry spells compared to continuous irrigation suggests that, despite the low nutrient uptake the plant utilized the nutrient it had taken up efficiently. It also suggests that excessive nutrient accumulation in the non-stressed plants might have occurred.

3.3.5 Root development

The trend in root dry matter distribution in the soil profile showed that most of the roots were concentrated in the upper 40cm soil layer (Table 3.24). But no statistically significant differences were observed between the treatments, and the plant developed similar rooting systems under all water regimes. However, from 0 cm to 60 cm depth, total root dry matter was high in the zai compared to flat planting (Table 3.25).

Table 3.24: Total root dry matter and percentage of total root dry matter per soil layer at harvest as affected by dry spells; Sadore, dry season 2000

Sampling	Total root dry matter (g m^{-2})				Percentage total root dry matter (%)			
Depth	No DS	3-W.DS	4-W.DS	$LSD_{0.05}$	NDS	3-W.DS	4-W.DS	$LSD_{0.05}$
0-10cm	973	850	690	428	72	70	65	9
10-20cm	318	301	316	192	23	32	30	20
20-40cm	40	50	44	21	5	5	4	3
40-60cm	14	12	13	8	1	1	2	1
60-80cm	6	6	4	4	1	1	1	0.3
80-100cm	4	4	6	3	0.4	0.4	1	0.3
100-120cm	4	5	6	3	0.4	0.5	1	0.2
120-140cm	6	6	5	4	2	1	9	14
140-160cm	5	5	5	3.1	0.4	0.6	0.5	0.5

W = week, .DS = dry spell, No DS = no dry spell; $LSD_{0.05}$ = least significant difference at 0.05 probability level

A Strong rooting system is important for efficient nutrient and water uptake (Payne et at 1995, Payne et al. 1996, Hamblin et al. 1987). The high total root dry weight recorded in the zai in the 0 – 60 cm soil layer compared to flat planting, and the run-off water collected in the zai (see below) might have played an important role in the observed differences between the treatments in terms of nutrient uptake and TDM production. The roots were concentrated in the upper soil layer, which might have affected the plants in the plots subjected to the dry spells.

Table 3.25: Total root dry matter and percentage of total root matter per soil layer at harvest as affected by planting techniques (zai vs flat); Sadore, dry season 2000

Planting depth	Total root dry matter			Percentage total root dry matter (%)		
	Flat	Zai	$LSD_{0.05}$	Flat	Zai	$LSD_{0.05}$
0-10cm	728	947	349.7	76.1	62.2	6.94
10-20cm	164	460	156.6	20.8	35.9	16.24
20-40cm	36	53	16.8	4.4	5.5	2.73
40-60cm	9	17	6.8	1.1	1.6	0.68
60-80cm	5	7	3.2	0.5	0.5	0.26
80-100cm	4	5	2.1	0.5	0.4	0.27
100-120cm	5	5	2.4	0.6	0.4	0.20
120-140cm	7	4	3.3	7.7	0.3	11.27
140-160cm	3	7	2.5	0.3	0.7	0.42

$LSD_{0.05}$ = least significant difference at 0.05 probability level

3.3.6 Nitrate leaching

Significant changes in the nitrate content in the soil profile throughout the cropping period were observed in all treatments (Figure 3.20). In the course of the cropping period, nitrate content decreased in all treatments below 50 cm depth compared to prior to the experiment. This decrease was pronounced under continuous irrigation (Figure 3.20 a and b). This suggests active plant uptake, which may not necessarily exclude nitrate loss beyond the rooting zone.

3.3.7 Water balance

- **Volumetric soil water content**

In the zai, the wetting front was beyond 200 cm depth within 28 days after irrigation started (Figure 3.21). After a 3-week dry spell, the wetting front was still beyond 200 cm in the zai pits, whereas with flat planting it was at 150 cm (Figure 3.21 c). At harvest, below 100 cm depth it was lower than the initial level in the zai with continuous irrigation, while it was similar or above the initial level in the other treatments. This could be attributed to active uptake induced by intensive vegetative growth of the non-stressed plants.

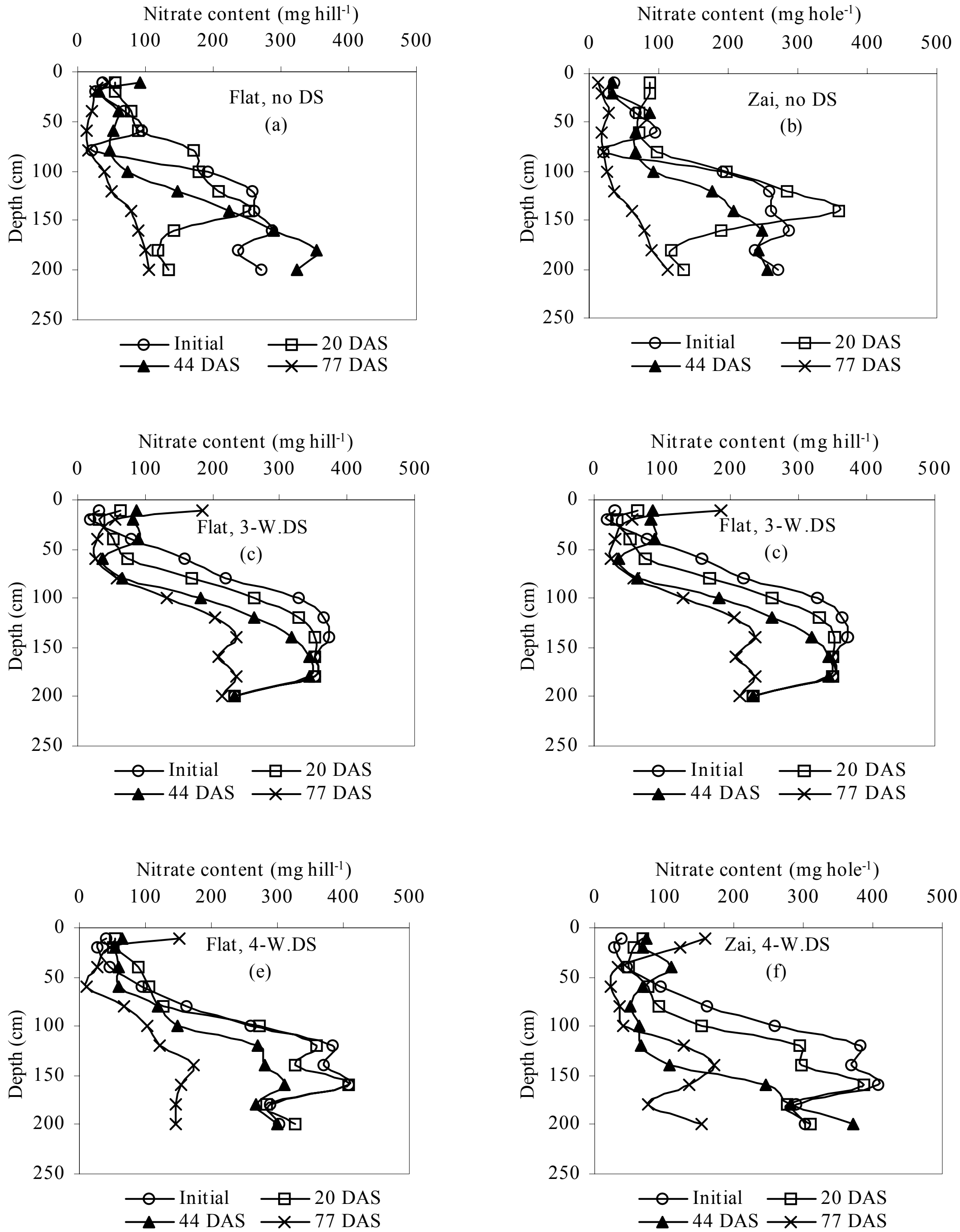


Figure 3.20: Effect of dry spells and planting techniques (zai vs flat) on nitrate content along the soil profile; Sadore, 2000 - DAS = days after sowing, W = week, DS = dry spell

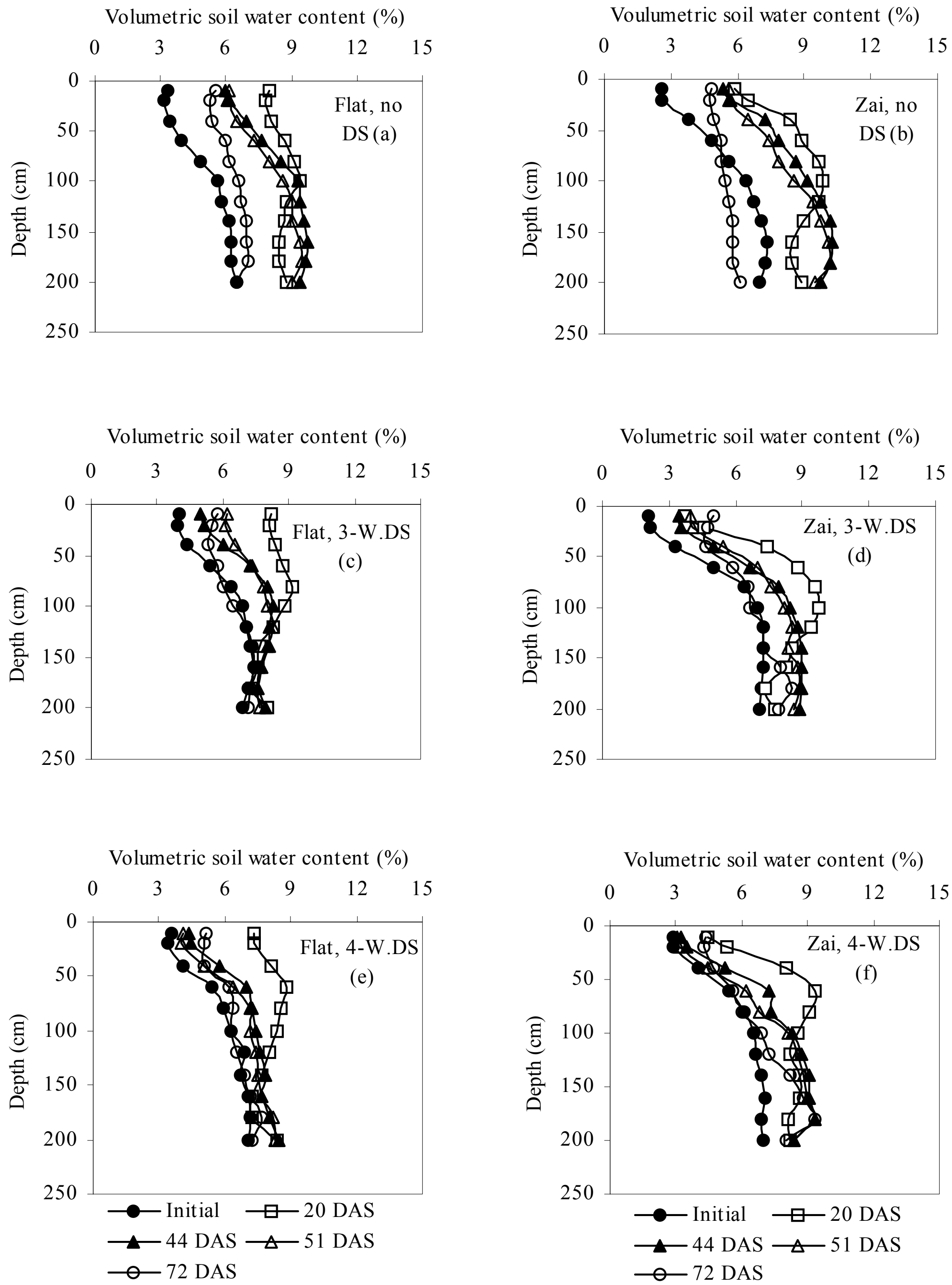


Figure 3.21: Volumetric soil water content as affected by dry spells and planting techniques (zai vs flat); Sadore, dry season 2000 – W = week, DS = dry spell, DAS = days after sowing

- **Plant available water (PAW)**

Data on plant available water were calculated based on depth containing 98% of the roots at final harvest (50 to 80 cm depending upon the treatment). A considerable amount (40 mm) of water was available down to the maximum rooting depth in all treatments at sowing according to data recorded with the tube installed on the hills (Figure 3.22 b). After a 3-week dry spell, the PAW fell to 30 mm in the flat planting compared to 20 mm in the zai (Figures 3.22 a and b). After a 4-week dry spell the PAW dropped to 17 mm on average with both planting techniques (Figures 3.22 a and b). At harvest, the PAW was 15 mm on average in all treatments.

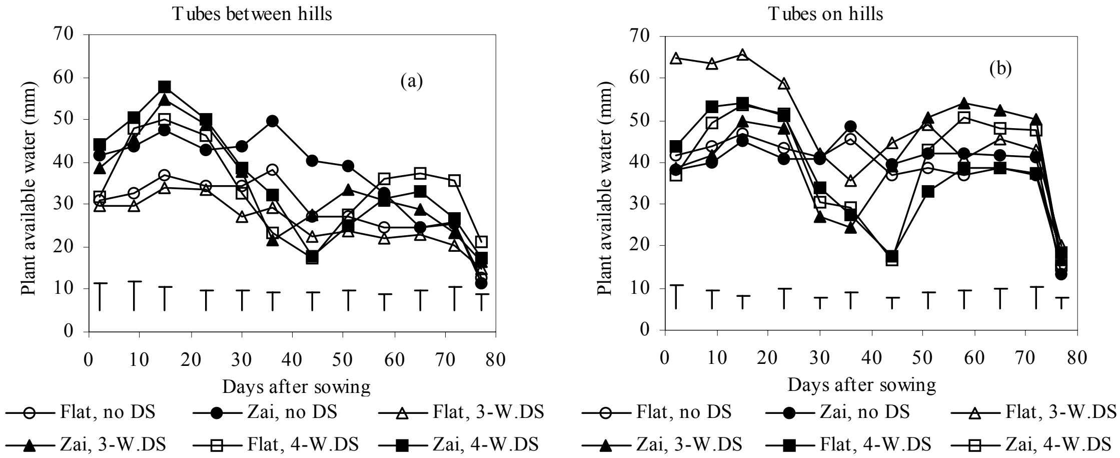


Figure 3.22: Plant available water as affected by dry spells and planting techniques (zai vs flat); Sadore, dry season 2000 - No DS = no dry spell, W = week, DS = dry spell (rooting depth at harvest - 50 to 80 cm depending on the treatment)

- **Drainage**

Water loss through drainage was more important in the zai pits compared to flat planting (Figure 3.23 a). Despite the dry spells, water loss below the maximum rooting depth was observed. The variability in drainage observed with the measurements using the tube installed on the hill might be due to non-uniformity in the irrigation, or water percolation along the tubes.

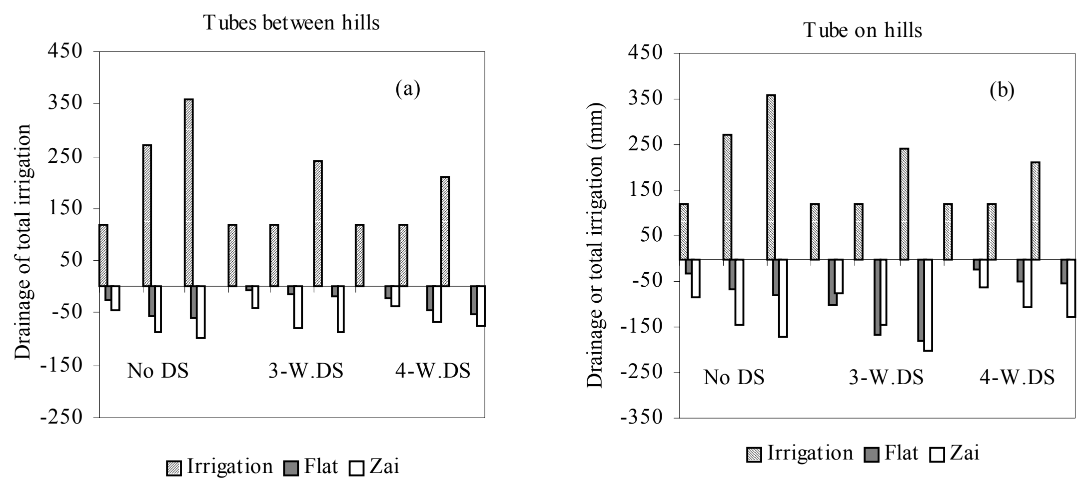


Figure 3.23: Water loss by drainage as affected by dry spells and planting techniques (zai vs flat); Sadore, dry season 2000 – No DS = No dry spell, DS = dry spell, W = week

The rapid progress of the wetting front the first month after irrigation started is consistent with the low water retention capacity of the soil. Volumetric water content decreased in all treatments, which suggests intensive transpiration and evaporation during this period of the year when air temperature can reach 40°C (Sivakumar et al. 1986). Root data were not collected during the cropping period, so the PAW was calculated based on the rooting depth at harvest. The roots might not be active to that depth during the dry spells. Plant available water decreased rapidly in flat planting compared to zai. When irrigation was restored, the PAW increased rapidly in the zai. As all the experimental plots received the same amount of organic amendment, water could be the most likely differential constraint for the plant growth. So the low PAW observed in the flat planting compared to the zai throughout the cropping period could be the reason why, under continuous irrigation, the TDM produced in the zai was double that in flat planting. Payne et al. (1992) reported a strong relationship between soil water content and millet P utilization, and drew the conclusion that in the Sahel, the water supply cannot be effectively managed for improved crop production without addressing soil fertility constraints. Rockstrom (1997) reported that drought affects those parts of the plant that are growing rapidly when the dry spell occurs, which might be the case in the present study.

3.3.8 Resume of experiment S3

The general finding of this study was that the dry spells affected the plant under both planting techniques. But zai showed benefits over flat planting that were proportionally greater when dry spell were imposed. The results also showed that despite the yield loss after the 4-week spell, the total dry matter produced by the crop in zai under this treatment was similar to that produced in flat planting under continuous irrigation. This reflects the importance of the water-harvesting component of the technique when dry spells occur during the cropping period. As shown in Figure 3.22 a, the PAW in the zai during the 4-week dry spell was less than the PAW in flat planting under continuous irrigation only at the end of the dry spell and one week later. This suggests a similar water supply during most of the cropping period.

The trend in manure decomposition and nutrient release was similar in all treatments. The nutrients might not be available to the plants subjected to dry spells, as the upper soil layer dried first. The result of this was the low nutrient uptake and consequent high yield loss from the plots subjected to dry spells. Nutrient utilization efficiency was improved in stressed plants compared to non-stressed ones, which was probably a result of the reduction of nutrient uptake in plots under dry spells, whereas active uptake might have continued in non-stressed plots leading to excessive accumulation.

3.4 Effect of catchment area and amendment type on the development of millet (D1 and K1)

This experiment was conducted at Damari and Kakassi in 1999 and 2000. In both years, the rain started at the end of June at Damari (Figure 3.24 a and c), with a cumulative rainfall of 499 mm in 1999 and 425 mm in 2000, which was below the long-term average (550 mm). At Kakassi it was 397 mm in 1999 and 490 mm in 2000, compared to the long-term average of 450 mm. Despite a small amount of rain in early June at Kakassi in both years, rainfall adequate for planting was received only at the end of June (Figure 3.24 b and d). In both years and particularly in 2000, frequent dry spells (more than one week without rain) occurred (Figure 3.25 a and b).

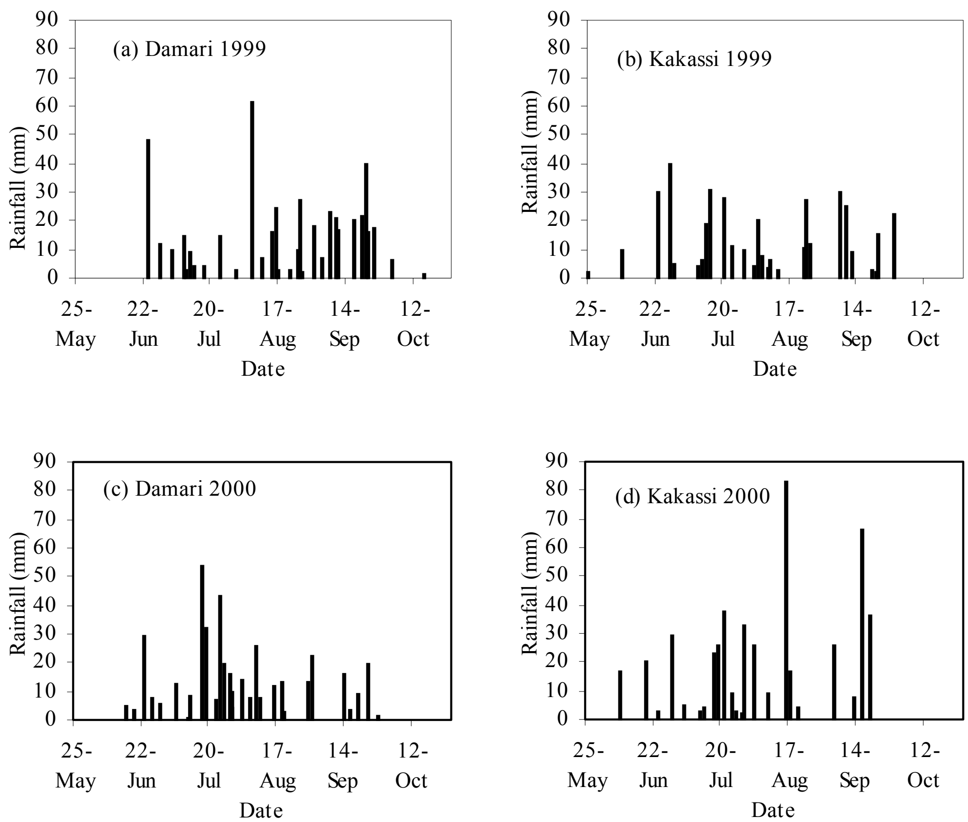


Figure 3.24: Daily rainfall distribution; Damari and Kakassi, rainy seasons 1999 and 2000

3.4.1 Yield and yield parameters

- **Total dry matter (TDM)**

No interaction effect was observed between the main treatments with regards to TDM. So only the results of the main treatments are presented below.

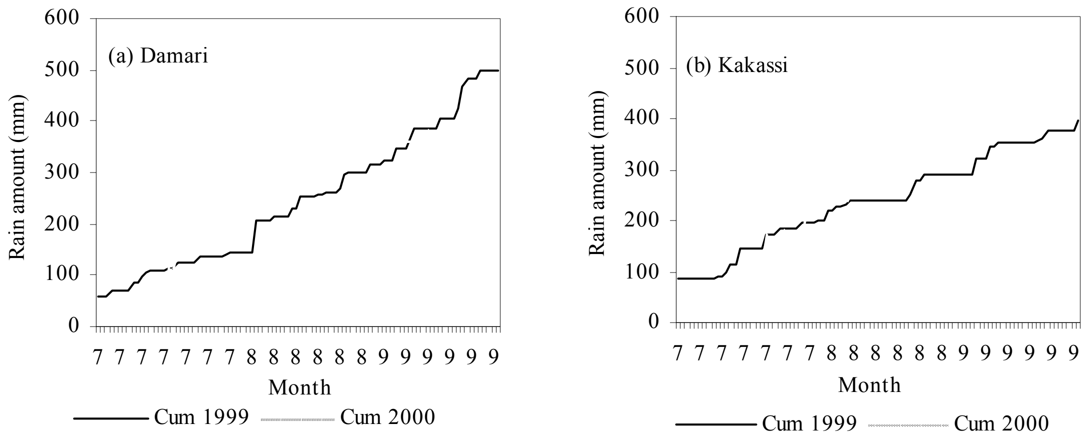


Figure 3.25: Cumulative rainfall; Damari and Kakassi, rainy seasons 1999 and 2000 (Dry spells are visible as horizontal lines)

At both sites in both years, manure application increased TDM considerably compared to the control and the other amendments (Figure 3.26).

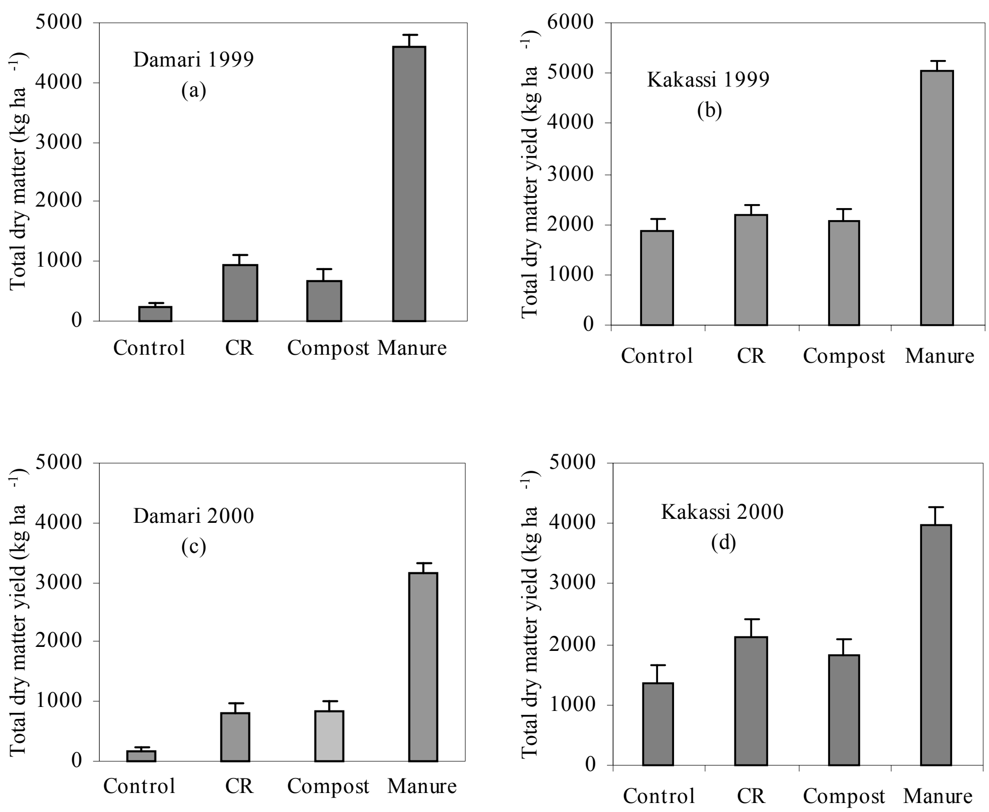


Figure 3.26: Millet total dry matter as affected by amendment type; Damari and Kakassi, rainy seasons 1999 and 2000 – CR = crop residues error bars are standard error of difference between means

On average, 4600 kg ha^{-1} of dry matter was produced in plots treated with manure compared to 226 kg ha^{-1} in the control plots in 1999 at Damari (Figure 3.26 a). In the same year at Kakassi, the respective yields with manure and the controls were 5030 and 1884 kg ha^{-1} (Figure 3.26 b). The TDM produced with manure in 2000 amounted to 3148 and 3900 kg ha^{-1} at Damari and Kakassi, respectively (Figures 3.26 c and d).

The total dry matter produced with compost and crop residues at Kakassi was higher than that produced at Damari in both years. The TDM in the control plots at Kakassi was 8-fold the TDM at Damari in 1999 and 2000. This shows that the native fertility of the soil at Kakassi was better than at Damari.

At both sites in 1999, the zai increased TDM production compared to flat planting (50% at Damari and 93% at Kakassi) (Figures 3.27 a and b). However, this effect was less pronounced in 2000 (Figure 3.27 c and d).

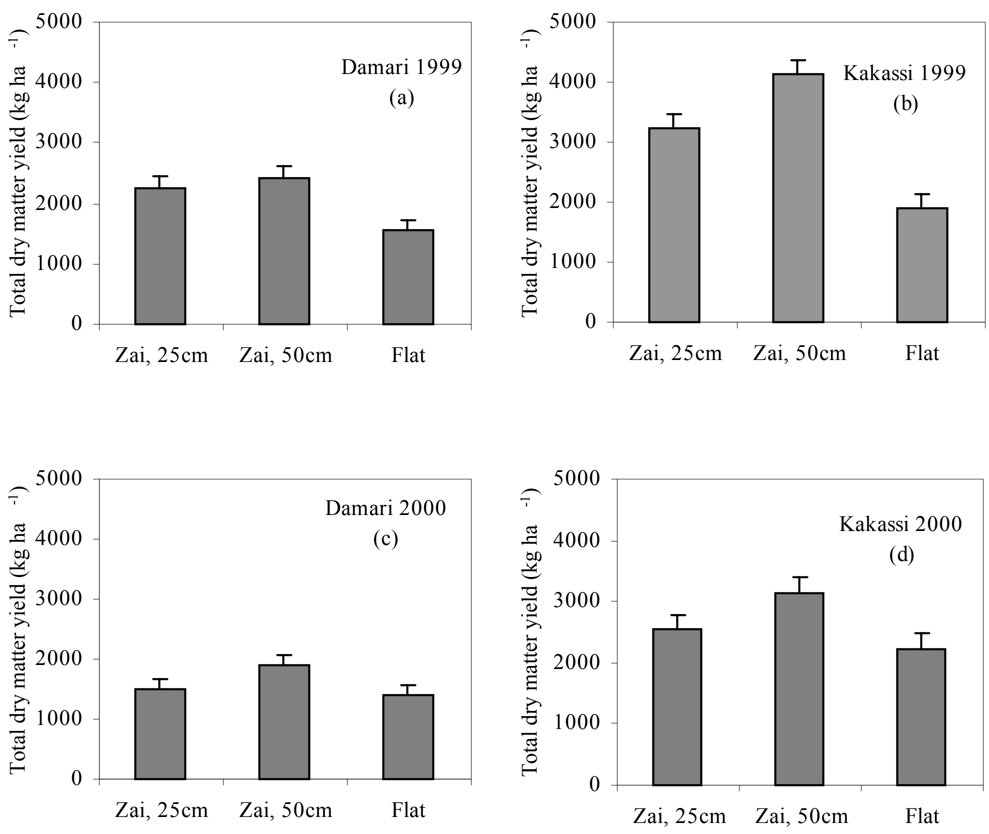


Figure 3.27: Millet total dry matter as affected by planting techniques (zai vs flat); Damari and Kakassi, rainy seasons 1999 and 2000 - error bars are standard error of difference between means

Zai pit size effect on TDM was observed only in 1999 at Kakassi, which was due to higher straw yield (2020 and 2680 kg ha^{-1} for 25 cm and 50 cm pit size, respectively). In both years, the TDM produced in the control zai at Kakassi was considerably higher than the production in the control flat (3-fold in 1999 and 2-fold in 2000 - Table 3.26). In this case, water could be considered the determining factor. However, a considerable amount of soil particles and plant residue were collected in the pits, which might have increased the soil nutritional status in the non-amended pits. At Damari, TDM in the control zai was also higher than in flat planting, but it was very low.

Table 3.26: Effect of planting techniques (zai vs flat) on millet total dry matter yield in control plots; Damari and Kakassi, rainy seasons 1999 and 2000

		Total dry matter (kg ha^{-1})			
Organic	Planting	1999		2000	
amendment	technique	Damari	Kakassi	Damari	Kakassi
Control	Zai, 25cm	303	2125	213	1938
	Zai, 50cm	280	2775	193	1415
	Flat	96	752	101	768
	$LSD_{0.05}$	221	795	172	855

- **Grain yield**

No interaction effect between the main treatments was observed, but all treatment combinations are presented to show the effect of advanced soil degradation on grain yield.

At both sites in both years, manure application increased grain yield compared to the other treatments (Table 3.27). It appears that under the conditions of Damari, millet grain production would not have been possible without amendment (1 kg ha^{-1} of grain from flat control plots in 1999 and 6 kg ha^{-1} in 2000 - Table 3.27). Manure application increased the seed yield 11 and 7-fold in 1999, 4 and 6-fold in 2000 compared to crop residues and compost at Damari. At Kakassi, the grain yield increase was 2-fold in 1999 and 2 and 3-fold in 2000 compared to crop residues and compost.

At both sites in both years, the effect of planting techniques (zai vs flat) was most prominent when zai was combined with manure application. On average, more than 1 t ha^{-1} grain yield was produced in the zai amended with manure at Damari in both years, whereas 0.7 t and 0.45 t ha^{-1} were produced with flat planting amended with manure in 1999 and 2000 (Table 3.27).

The good performance of the crop in the control plots at Kakassi compared to Damari (Table 3.28) probably results from the better fertility level at that location (Table 3.2). Almost no grain was produced on the control flat at Damari (Table 3.27). No significant pit size effect was observed in both years and at both sites.

Table 3.27: Effect of amendment and planting techniques (zai vs flat) on millet grain yield; Damari and Kakassi, rainy seasons 1999 and 2000

		Grain yield (kg ha^{-1})			
Planting	Organic	1999		2000	
technique	amendment	Damari	Kakassi	Damari	Kakassi
Zai, 25cm	CR	168	384	154	358
	Compost	115	440	196	253
	Manure	1157	872	821	915
Zai, 50cm	CR	157	518	219	522
	Compost	85	435	101	471
	Manure	1100	1008	1005	894
Flat	CR	127	279	133	287
	Compost	64	186	105	166
	Manure	705	454	450	490
	$LSD_{0.05}$	307	280	185	347
		Control			
	Zai, 25cm	17	434	19	388
	Zai, 50cm	8	526	19	260
	Flat	1	118	6	94
	$LSD_{0.05}$	12	203	27	262

NB: CR = Crop residues

- **Grain yield per hill and grain yield per tiller**

Manure application increased grain yield per hill, in both years at both sites compared to the other treatments ($P<0.001$). Zai with manure increased this parameter by 38% and 50% in 1999 compared to flat planting with manure at Damari and Kakassi. Manure application increased grain yield per tillers only in 1999 at Damari and 2000 at Kakassi ($P<0.05$) (data are reported in Appendices 4 and 5).

Hill survival, harvest index and 1000 seeds weight

Amendment application increased the harvest index only at Damari in both years ($P<0.001$ Table 3.28). At this site, manure was also better than crop residues and compost. The amended zai increased the harvest index only in 2000 at both sites ($P<0.001$) (Table 3.29).

Table 3.28: Effect of amendment type on millet harvest index and hill survival; Damari and Kakassi, rainy seasons 1999 and 2000

Organic	Harvest index				Hill survival (%)			
	1999		2000		1999		2000	
amendment	Damari	Kakassi	Damari	Kakassi	Damari	Kakassi	Damari	Kakassi
Control	0.03	0.19	0.07	0.15	88	88	72	85
CR	0.15	0.18	0.2	0.18	95	90	82	78
Compost	0.13	0.18	0.15	0.14	93	95	89	94
Manure	0.21	0.15	0.24	0.19	94	95	97	96
$LSD_{0.05}$	0.05	0.03	0.04	0.04	4	6	10	10

CR = crop residues

In 2000, the hill survival with manure was better than with crop residues (P<0.001) (Table 3.29) at both sites. In the same year, hill survival in flat planting was higher than in the zai pits at Damari (P<0.001) (Table 3.29).

Hill survival is a critical parameter in the zai system under the experimental conditions of this study. The zai pits collect a large amount of soil with run-off water, which covers the young millet seedlings. As mentioned earlier, repeated resowing filling was done at the early stage of plant growth. This can be considered a major constraint for the use of zai on sandy soils. Nevertheless, there is an important pay-off from the techniques despite these constraints. No zai pit size effect was observed on both parameters.

Table 3.29: Effect of planting techniques (zai vs flat) on millet harvest index and hill survival; Damari and Kakassi, rainy seasons 1999 and 2000

Planting	Harvest index				Hill survival (%)			
	1999		2000		1999		2000	
technique	Damari	Kakassi	Damari	Kakassi	Damari	Kakassi	Damari	Kakassi
Zai, 25cm	0.18	0.18	0.24	0.20	93	94	83	90
Zai, 50cm	0.17	0.16	0.20	0.19	94	93	86	83
Flat	0.15	0.17	0.16	0.12	96	92	98	94
$LSD_{0.05}$	0.05	0.03	0.04	0.04	4	6	10	10
	Control							
Zai, 25cm	0.05	0.20	0.07	0.20	89	98	67	90
Zai, 50cm	0.02	0.19	0.07	0.16	89	89	53	67
Flat	0.01	0.17	0.07	0.11	87	77	96	100
$LSD_{0.05}$	0.03	0.07	0.12	0.10	12	21	42	16

In both years at both sites, manure increased the seed size compared to crop residues, compost and the control (P<0.05); except for Kakassi in 2000 (Table 3.30).

On the amended plots, in both years and at both sites, smaller seeds were formed in flat planting compared to zai, even though the difference was significant only in 2000 (P<0.001) for Damari and (P=0.039) for Kakassi (Table 3.31).

Table 3.30: Effect of amendment type on millet 1000 seeds weight; Damari and Kakassi, rainy seasons 1999 and 2000

Organic amendment	1000 seed weight 1999 Damari	1999 Kakassi	2000 Damari	2000 Kakassi
Control	2.58	5.82	3.91	6.00
CR	5.59	5.99	5.78	6.60
Compost	4.85	5.65	5.43	5.64
Manure	6.74	6.06	6.97	6.24
$LSD_{0.05}$	0.79	0.54	0.71	0.89

CR = crop residues

Table 3.31: Effect of planting techniques (zai vs flat) on millet 1000 seeds weight; Damari and Kakassi, rainy seasons 1999 and 2000

Planting technique	1000 seed weight 1999 Damari	1999 Kakassi	2000 Damari	2000 Kakassi
Zai, 25cm	5.91	5.98	6.80	6.53
Zai, 50cm	6.03	6.25	6.12	6.47
Flat	5.23	5.47	5.26	5.49
$LSD_{0.05}$	0.79	0.54	0.71	0.89
Control				
Zai, 25cm	3.68	5.65	3.64	7.02
Zai, 50cm	3.1	6.28	3.86	5.62
Flat	0.96	5.52	4.24	5.37
$LSD_{0.05}$	2.65	1.46	4.76	1.46

At both sites and in both years, TDM production and grain yield were increased by manure application. This shows that even on soils at an advanced stage of degradation like the ones used in the present study, high quality organic amendment can provide good yields. Ganry et al. (1994) reported a total dry matter yield of 3500 kg ha^{-1} on a sandy soil in Senegal with manure application. Pichot et al. (1974), Cisse (1988 II), Rani (1988), Bationo et al. (1991), and Duivenbooden et al. (1993) also reported a millet yield increase due to manure application. Zai treatment, when used in combination with manure, significantly increased grain yield (900 - 1100 kg ha^{-1} were obtained at both sites). Zai significantly increased the effectiveness of manure and resulted in grain yield increases of 60 and 100% on average in 1999, and 100 and 85% in 2000 at Damari and Kakassi, respectively. There was no significant effect of pit size on millet grain yield at either location in the presence of manure. The better relative response to manure application at Damari than at Kakassi may be explained by the soil characteristics (Table 3.2). In the acidic soils of Damari, the organic amendment may have helped to bind the aluminium and other metals in the soil that reduce P availability, and that may have certain toxicity for millet

(Bationo et al. 1989, Kretzschmar et al. 1991). Thus, the mobility of the native P that can be expected to be the most limiting nutrient at Damari (Bationo et al. 1990), may have increased.

The second experimental year was characterized by intermittent dry spells, typical to the rainy season in Niger (Sivakumar 1986), which affected the grain yield at both sites. Data on plant available water throughout the cropping period will help us to better understand the impact of the dry spells. The effect of crop residues and compost on millet yield was not as prominent as that of manure application. Michel et al. (1995), Bationo et al. (1991), and Hafner et al. (1993) have reported a positive effect of crop residues application on millet grain and TDM, yield, but the residues were applied as mulch. Incorporation of material with a high C:N ratio like crop residues leads to N and P immobilization (Thomas et al. 1993, Tian et al. 1992, Seligman et al. 1986, Bationo et al. 1991, Watkins et al. 1996, Budelman 1988, Hood et al. 1999). This makes these nutrients unavailable to the plant in most of the growing period until they become released to the soil in the process of immobilization mobilization turn over. This asynchrony between plant nutrient requirement and nutrient release may have produced the low yield recorded applying crop residues and compost in both years. This was also expressed in the yield parameters.

3.4.2 Growth parameters

Manure application most effectively increased plant height, leave and tiller formation, and stem elongation (Figure 3.28). With manure, the height reached 250 cm 3 months after planting. The increase in plant height was similar for crop residues and compost (100 cm). The final height in the control plots was less than 50 cm.

The plants in the control plots hardly formed any tillers and nodes at Damari. On average, one tiller and one node were formed in the control plots throughout the cropping period (Figure 3.28 c and d). These results show that the effect of manure application on the growth parameters was more pronounced compared to the effect of the planting techniques, which was not evident and was not reported. The results are also in line with the improved effect of manure on millet yield.

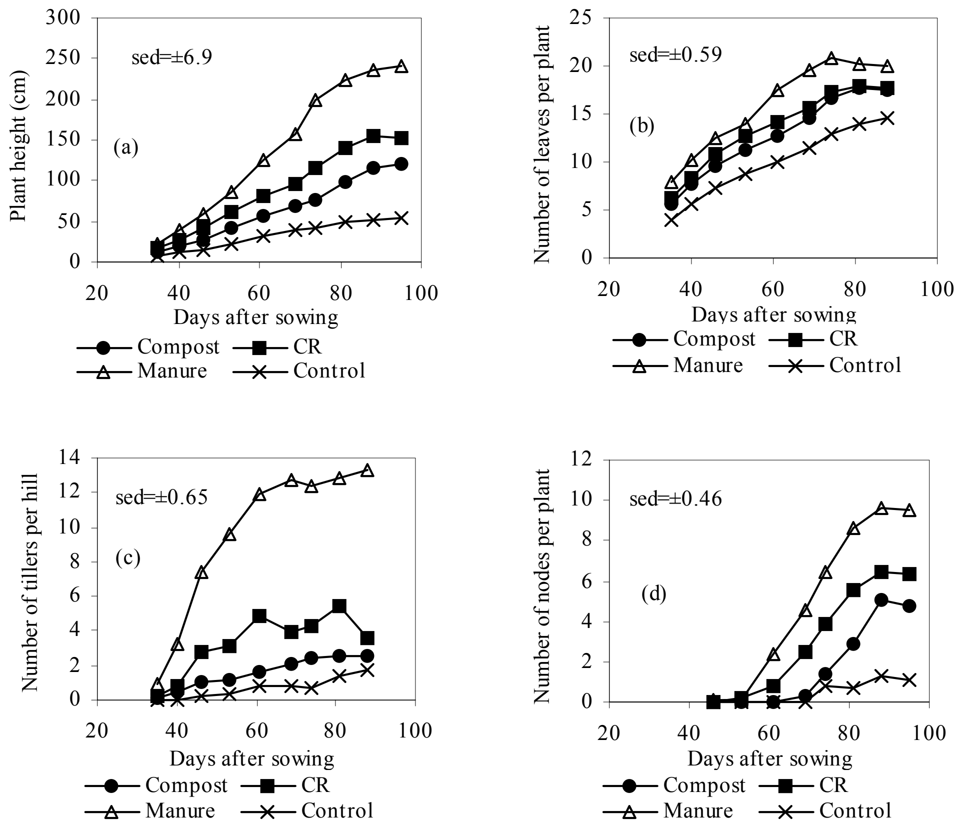


Figure 3.28: Effect of amendment type on selected millet growth parameters; Damari, rainy season 1999 (CR = crop residues)

3.4.3 Amendment decomposition

In both years at both sites, no significant differences were observed with regards to crop residues, compost and manure decomposition between the planting techniques (Figures 3.29 and 3.30. The manure weight loss on soil surface exposure was lower than that in the zai only at the fourth sampling at Kakassi (Figures 3.29 f and 3.30 f).

In both years, decomposition of the manure tended to be faster than that of the crop residues and compost at Damari ($P<0.05$) (Figures 3.29 and 3.30 a, b and c), whereas at Kakassi no differences were observed (Figures 3.29 and 3.30 d, e and f). For example in 1999, after 73 days of litter exposure at Damari, only 20% of the manure remained, whereas 50% of the crop residues remained.

The weight loss of all amendments was faster at Damari than at Kakassi. In both years, almost all of the manure was decomposed at the end of the period of litter exposure at Damari, whereas on average 40% remained at Kakassi except for manure decomposition in 1999, which was more complete.

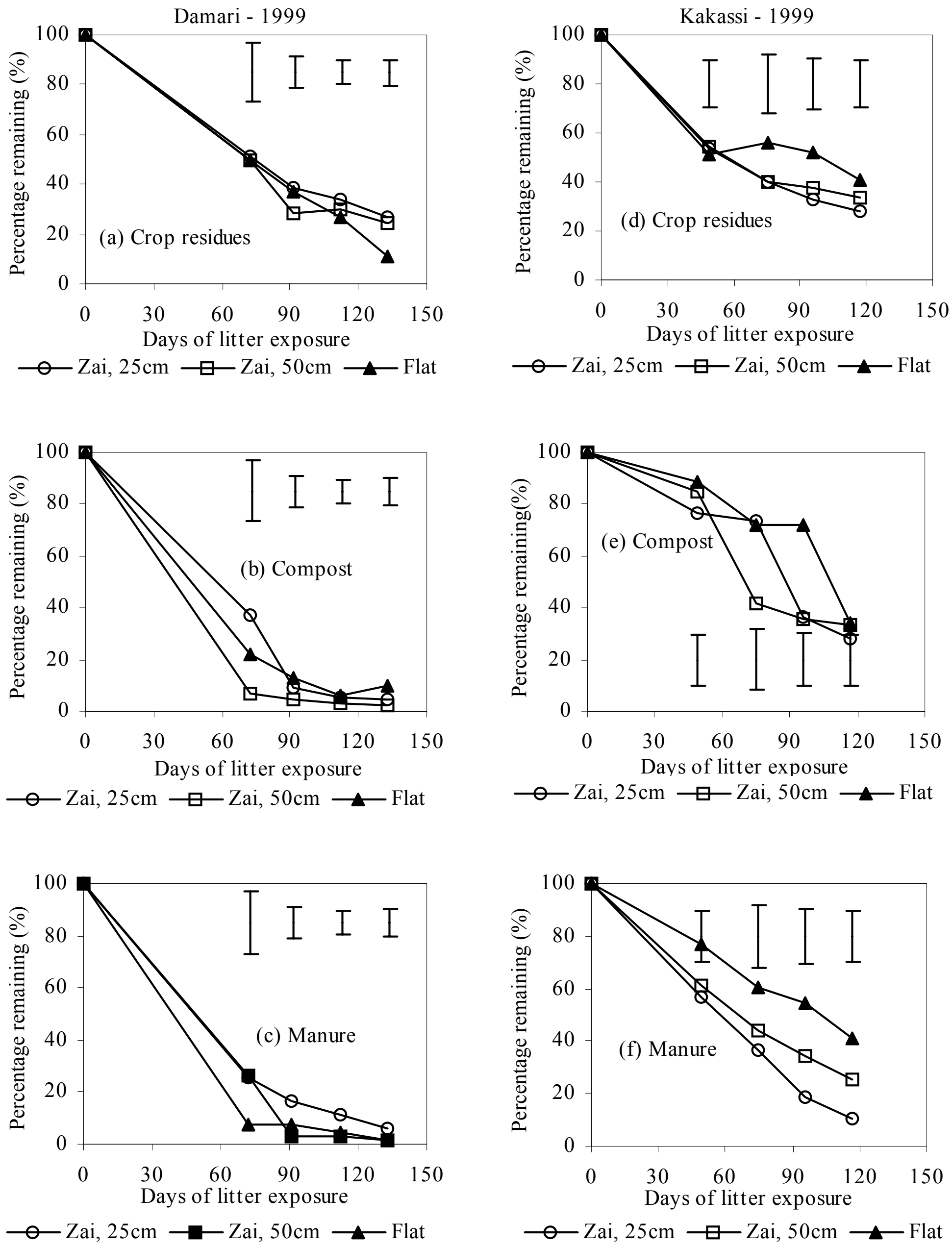


Figure 3.29: Effect of planting techniques (zai vs flat) on amendment decomposition; Damari and Kakassi , rainy season 1999 – error bars are error of difference between means

Thus, amendment quality was the main factor governing the decomposition. No planting technique effect was observed on the pattern of decomposition. Thomas et al. (1993), Lehmann et al. (1995), Tian et al. (1992), Azam et al. (1993), and Palm et al. (1991) reported a similar effect of amendment characteristics on their decomposition. A faster amendment weight loss was observed at Damari in both years, which might be due to termite activities. Termites were very active especially at Damari, but not at Kakassi as will be reported later Section 3.5.2. The influence of termites and other arthropods (Mando et al. 1997, Mando et al. 1999, Anderson et al. 1983a, Edwards and Heath 1963) was reported to increased litter decomposition as the arthropods contribute to the comminution of the litter and make it more accessible to microorganisms.

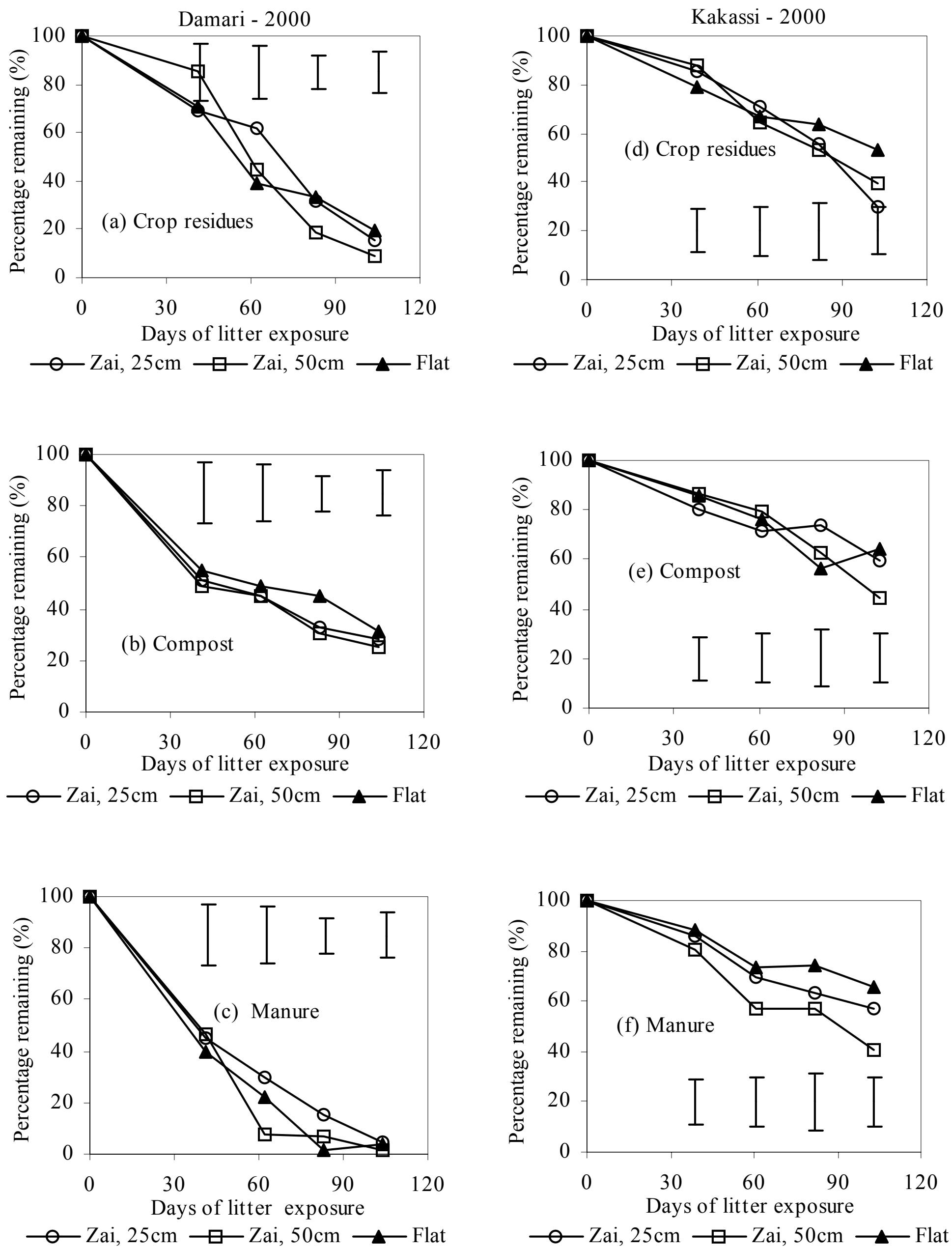


Figure 3.30: Effect of planting technique (zai vs flat) on amendment decomposition; Damari and Kakassi, rainy season 2000 – error bars are error of difference between means

3.4.4 Nutrient release

No planting technique effect was observed on the nutrient released at either sites in both years (Figures 3.31, 3.32, 3.33 and 3.34), except for N and P release from manure at Kakassi in 1999, which was faster in the zai than on the soil surface (Figures 3.32 g and h).

Nitrogen and P release followed the amendment decomposition in both years at Damari, but it was faster and more complete than the amendment decomposition at Kakassi. At the end of the period of litter exposure, on average 80% of N and P nutrients were released at both sites in both years, whereas on average 40% of amendment still remained.

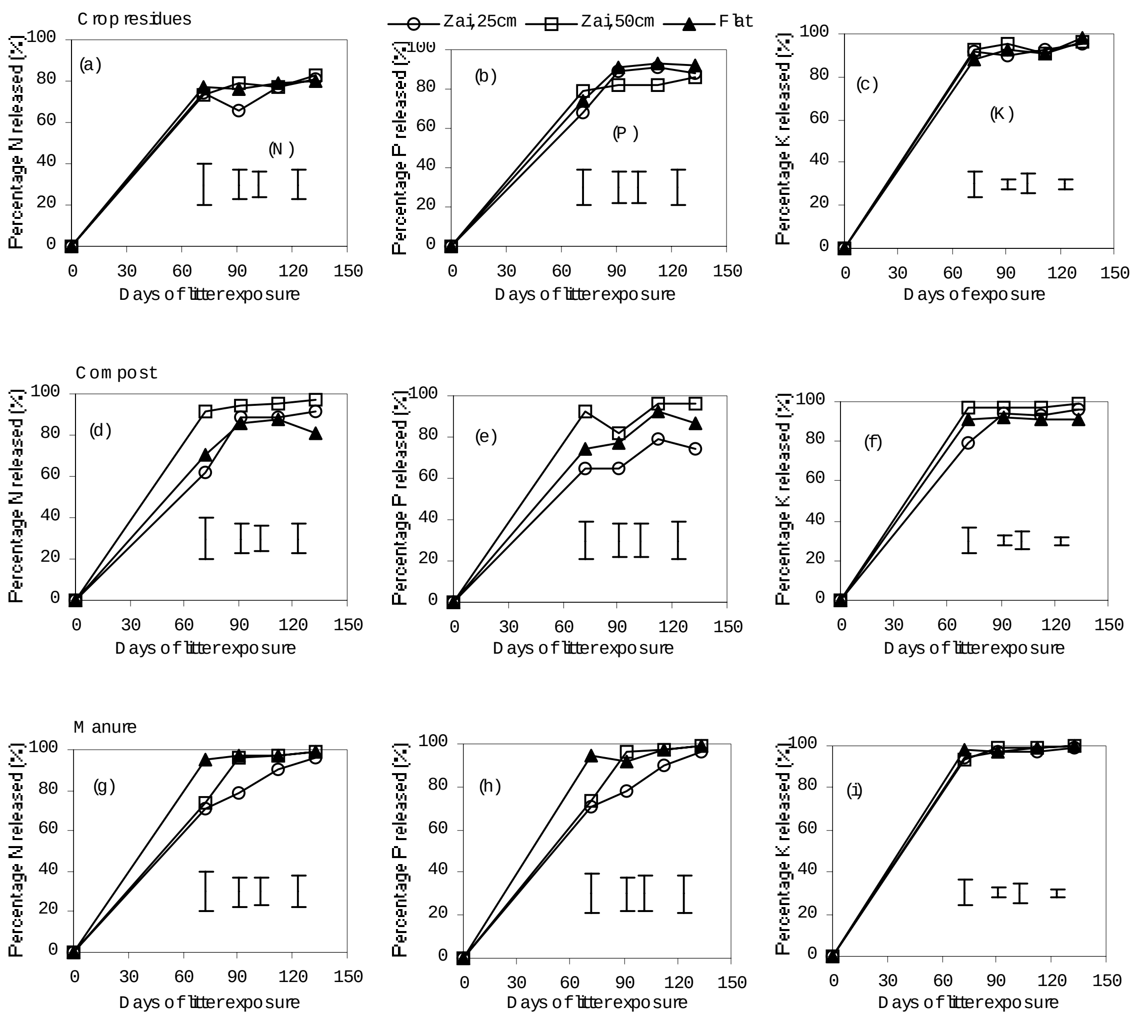


Figure 3.31: Effect of planting techniques (zai vs flat) on N, P, and K release from various organic amendments; Damari, rainy season 1999 – error bars are error of difference between means

Potassium release was faster and more complete with crop residues and manure regardless of site and year. Compost at both sites in both years released its K more slowly, with an average 30% K remaining at the end of the period of litter exposure (Figures 3.31, 3.32, 3.33, 3.34 d, e and f).

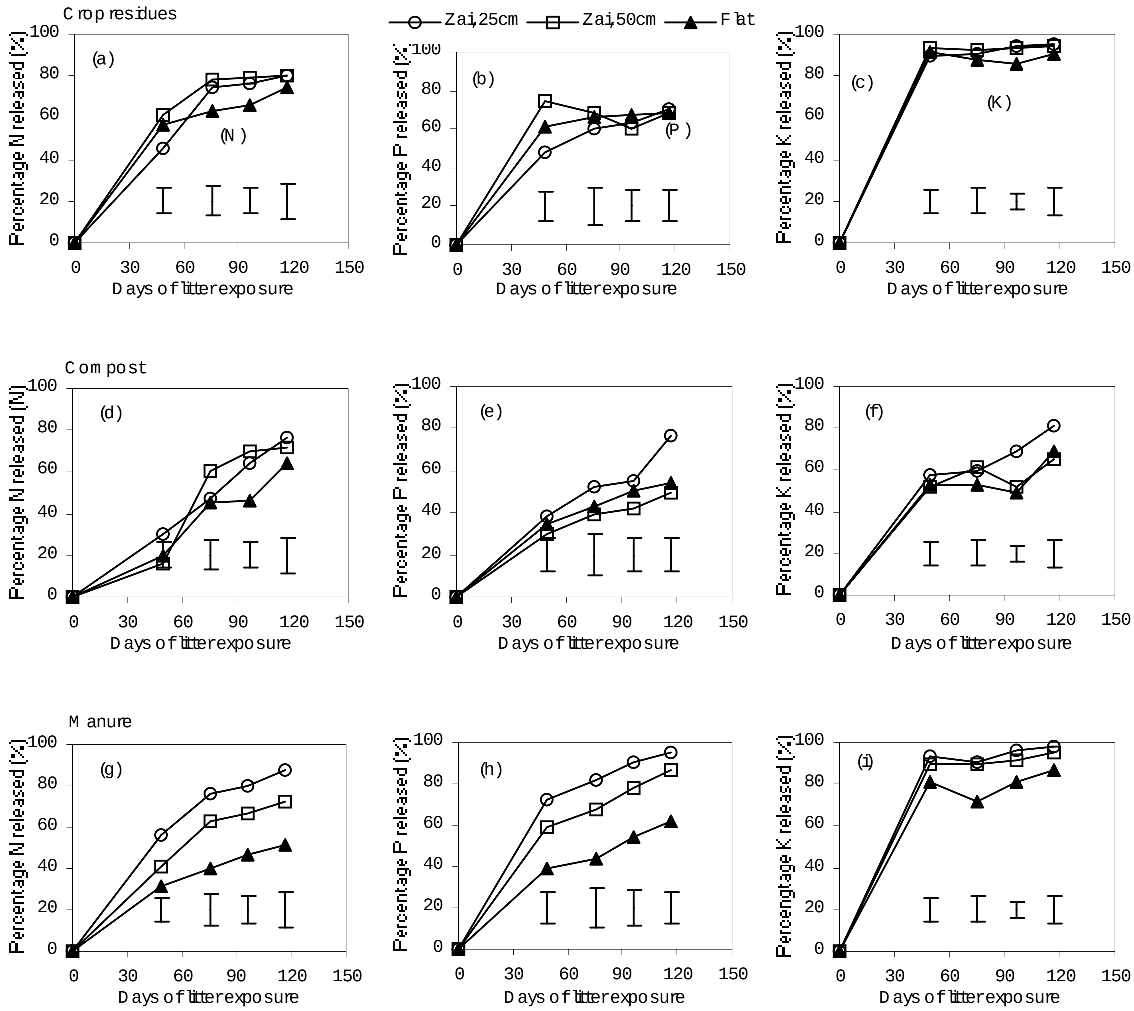


Figure 3.32: Effect of planting techniques (zai vs flat) on N, P and K release from various organic amendments; Kakassi, rainy season 1999 – error bars are error of difference between means

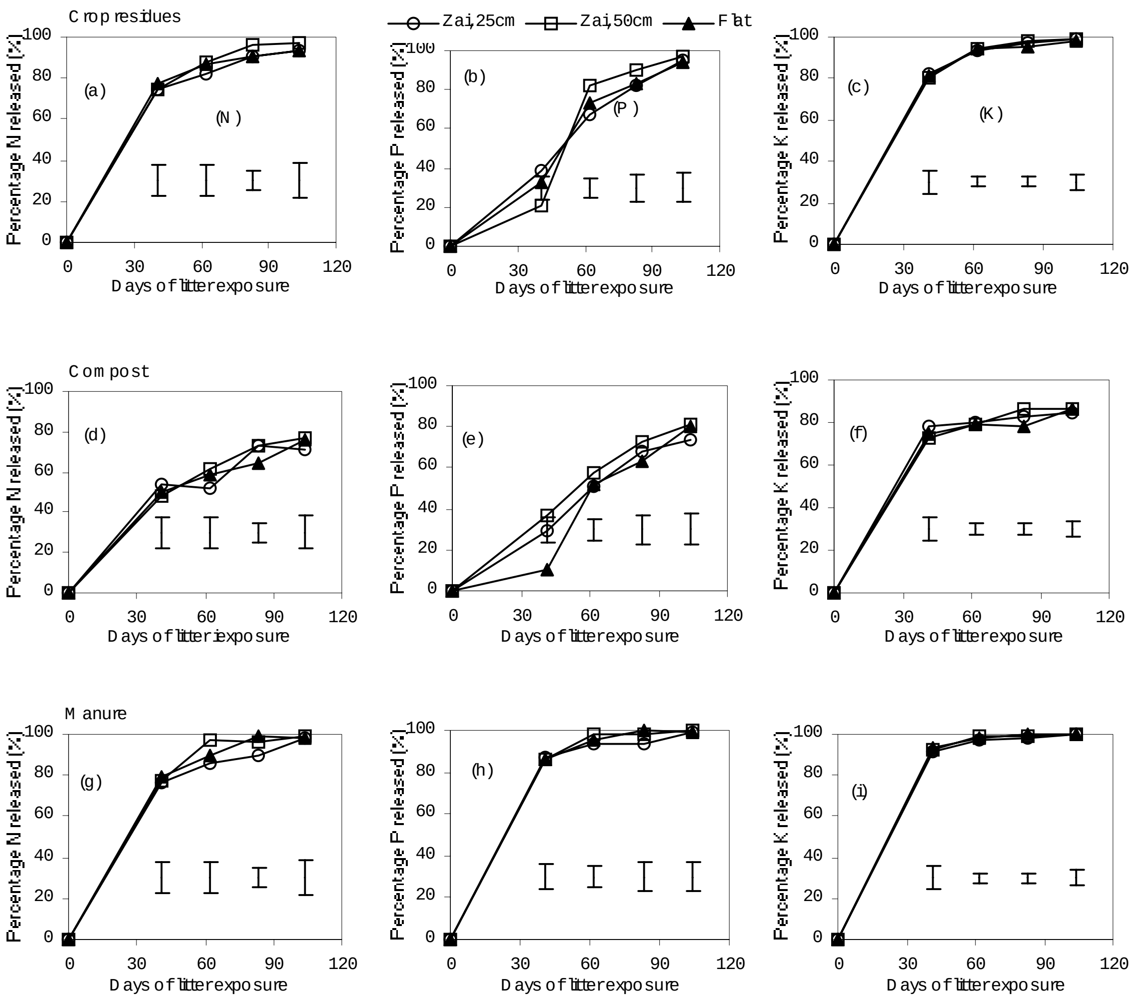


Figure 3.33: Effect of planting techniques (zai vs flat) on N, P and K release from various organic amendments; Damari, rainy season 2000 – error bars are error of difference between means

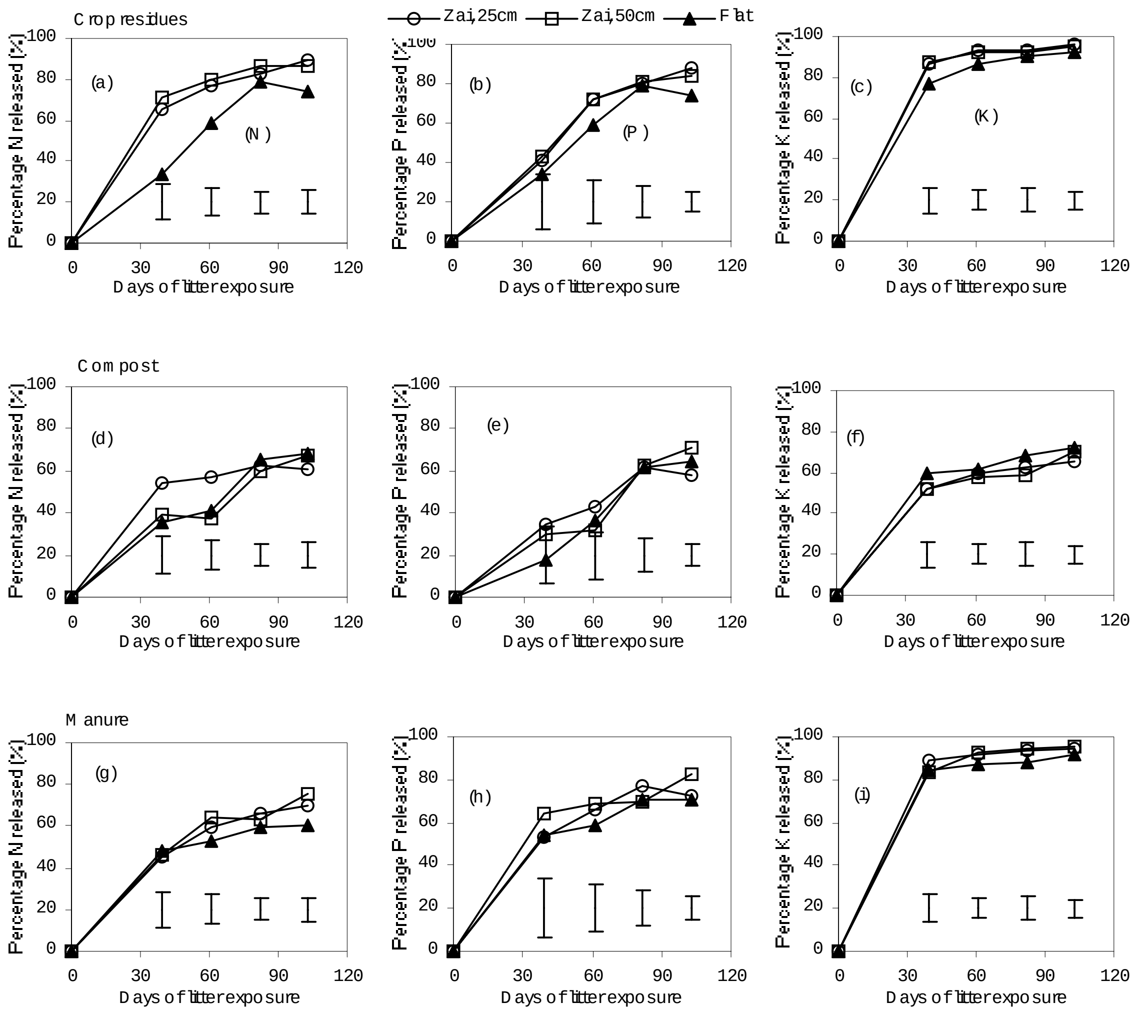


Figure 3.34: Effect of planting techniques (zai vs flat) on N, P and K release from various organic amendments; Kakassi, rainy season 2000 – error bars are error of difference between means

3.4.5 Nutrient uptake

No significant interaction effect between the main treatments was observed except for nutrient uptake at harvest, although slightly higher values were recorded on the amended plots under zai compared to the controls.

Zai improved plant nutrient uptake mainly at harvest at both sites and in both years ($P<0.05$). In most cases N, P and K uptake was 2-fold the uptake in flat planting (Tables 3.32 - 3.35). This was observed, for example, at Damari in 1999 and at Kakassi in 1999 and 2000. In 1999, zai increased N, P and K uptake even in the two sampling dates before harvest at Kakassi.

Table 3.32: Effect of planting techniques (zai vs flat) on Millet N, P, and K uptake; Damari, rainy season 1999

Planting technique	36 DAS N	36 DAS P	36 DAS K	76 DAS N	76 DAS P	76 DAS K	119 DAS (Stover) N	119 DAS (Stover) P	119 DAS (Stover) K	119 DAS (Grain) N	119 DAS (Grain) P	119 DAS (Grain) K
	Millet nutrient uptake during the cropping period (kg ha^{-1})											
Zai, 25cm	1.21	0.11	1.8	19.90	4.25	23.83	14.01	3.26	23.6	7.75	1.04	2.19
Zai, 50cm	1.45	0.11	2.15	17.46	3.12	18.81	18.48	3.65	27.09	8.6	1.05	2.25
Flat	1.55	0.08	2.09	21.45	5.00	27.12	10.99	2.34	17.38	4.92	0.63	1.25
$LSD_{0.05}$	0.48	0.03	0.72	12.28	3.21	15.0	4.61	1.04	9.18	3.75	0.52	0.97

DAS= days after sowing

Table 3.33: Effect of planting techniques (zai vs flat) on Millet N, P, and K uptake; Damari, rainy season 2000

Planting technique	25 DAS N	25 DAS P	25 DAS K	67 DAS N	67 DAS P	67 DAS K	122 DAS (Stover) N	122 DAS (Stover) P	122 DAS (Stover) K	122 DAS (Grain) N	122 DAS (Grain) P	122 DAS (Grain) K
	Millet nutrient uptake during the cropping period (kg ha^{-1})											
Zai, 25cm	0.23	0.03	0.45	10.33	0.79	12.96	7.16	0.44	12.11	5.31	0.81	1.71
Zai, 50cm	0.17	0.02	0.3	12.42	0.85	15.18	10.92	0.7	17.01	5.89	0.78	1.85
Flat	0.21	0.03	0.38	15.52	0.92	20.48	8.53	0.4	11.57	3.13	0.41	0.99
$LSD_{0.05}$	0.07	0.01	0.13	7.45	0.65	8.94	2.89	0.24	4.58	1.64	0.29	0.67

Table 3.34: Effect of planting techniques (zai vs flat) on millet N, P and K uptake; Kakassi, rainy season 1999

Planting technique	22 DAS N	22 DAS P	22 DAS K	65 DAS N	65 DAS P	65 DAS K	113 DAS (Stover) N	113 DAS (Stover) P	113 DAS (Stover) K	113 DAS (Grain) N	113 DAS (Grain) P	113 DAS (Grain) K
	Millet nutrient uptake during the cropping period (kg ha^{-1})											
Zai, 25cm	0.77	0.08	1.18	42.9	7.3	57.2	22.1	9.1	45.1	14.1	2.7	3.5
Zai, 50cm	0.59	0.05	0.93	33.1	5.4	42.9	29.3	11.8	57.7	15.4	2.8	3.8
Flat	0.28	0.03	0.45	20.4	3.3	26.3	14.4	5.3	26.3	7.2	1.3	1.8
$LSD_{0.05}$	0.33	0.04	0.50	14.4	2.5	20.6	6.9	2.1	9.9	3.6	0.7	0.9

Table 3.35: Effect of planting techniques (zai vs flat) on millet N, P and K uptake; Kakassi, rainy season 2000

Planting technique	20 DAS N	20 DAS P	20 DAS K	62 DAS N	62 DAS P	62 DAS K	123 DAS (Stover) N	123 DAS (Stover) P	123 DAS (Stover) K	123 DAS (Grain) N	123 DAS (Grain) P	123 DAS (Grain) K
	Millet nutrient uptake during the cropping period (kg ha^{-1})											
Zai, 25cm	0.27	0.02	0.28	26.6	1.7	31.6	18.7	1.0	28.9	10.5	1.4	2.8
Zai, 50cm	0.26	0.02	0.3	33.9	2.4	45.3	22.1	1.3	34.2	10.7	1.3	2.9
Flat	0.2	0.02	0.22	30.5	1.8	34.3	17.2	0.9	26.7	5.7	0.7	1.4
$LSD_{0.05}$	0.12	0.01	0.13	16.9	1.4	25.0	9.1	0.6	11.6	3.9	0.6	1.1

At both sites and in both years, manure application increased N, P and K uptake compared to the other treatments throughout the cropping period (Tables 3.36 - 3.39). In most cases N, P and K uptake was increased by factor 3 due to manure application. At both sites and years, N, P and K uptake of millet amended with crop residues and compost was higher than the uptake in the control plots.

Table 3.36: Effect of organic amendment type on millet N, P and K uptake; Damari, rainy season 1999

Organic	Millet uptake during the cropping period (kg ha^{-1})											
	36 DAS			76 DAS			119 DAS (Stover)			119 DAS (Grain)		
Amendment	N	P	K	N	P	K	N	P	K	N	P	K
Control	0.60	0.03	0.64	3.62	0.5	3.28	3.6	0.53	3.21	0.23	0.02	0.06
CR	1.38	0.07	1.88	15.77	2.95	18.8	8.64	1.74	13.22	3.11	0.39	0.76
Compost	0.79	0.03	0.96	6.01	0.96	6.10	7.61	1.50	10.97	2.14	0.27	0.57
Manure	2.86	0.27	4.57	53.01	12.09	64.84	38.12	8.56	63.38	22.87	2.95	6.19
$LSD_{0.05}$	0.56	0.04	0.83	14.18	3.71	17.31	5.32	1.20	10.60	4.33	0.60	1.12

CR = crop residues; DAS = days after sowing

Table 3.37: Effect of organic amendment type on millet N, P and K uptake; Kakassi, rainy season 1999

Organic	Millet nutrient uptake during the cropping period (kg ha^{-1})											
	22 DAS			65 DAS			113 DAS (Stover)			113 DAS (Grain)		
amendment	N	P	K	N	P	K	N	P	K	N	P	K
Control	0.24	0.02	0.35	20.8	3.2	27.4	15.4	5.4	29.7	9.4	1.7	2.3
CR	0.44	0.04	0.64	20.7	2.9	28.9	17.3	6.5	32.4	9.9	1.9	2.5
Compost	0.52	0.03	0.78	24.1	4.0	33.4	15.6	6.4	33.0	8.3	1.5	2.0
Manure	0.97	0.12	1.64	62.9	11.2	78.9	39.6	16.6	77.1	21.4	3.9	5.4
$LSD_{0.05}$	0.37	0.05	0.58	16.6	2.9	23.7	8.0	2.4	11.4	4.1	0.8	1.0

CR = crop residues; DAS = day after sowing

Table 3.38: Effect of organic amendment type on millet N, P and K uptake; Damari, rainy season 2000

Organic	Millet nutrient uptake during the cropping period (kg ha^{-1})											
	25 DAS			67 DAS			122 DAS (Stover)			122 DAS (Grain)		
amendment	N	P	K	N	P	K	N	P	K	N	P	K
Control	0.15	0.02	0.23	2.38	0.09	2.05	0.3	0.02	0.08	3.06	0.24	0.83
CR	0.14	0.02	0.29	7.03	0.36	9.98	2.56	0.25	0.76	4.71	0.44	1.42
Compost	0.16	0.02	0.27	9.31	0.38	9.12	2.59	0.23	0.72	2.59	0.23	0.72
Manure	0.36	0.06	0.72	32.3	2.57	43.67	13.67	2.16	4.49	14.44	2.3	4.74
$LSD_{0.05}$	0.08	0.01	0.15	8.61	0.75	10.32	1.89	0.33	0.77	3.37	0.37	1.08

CR = crop residues; DAS = days after sowing

Table 3.39: Effect of amendment type on millet N, P and K uptake; Kakassi, rainy season 2000

Organic	Millet nutrient uptake during the cropping period (kg ha^{-1})											
	20 DAS			62 DAS			123 DAS (Stover)			123 DAS (Grain)		
amendment	N	P	K	N	P	K	N	P	K	N	P	K
Control	0.18	0.01	0.17	12.98	0.64	14.54	11.34	0.56	18.09	4.81	0.56	1.25
CR	0.17	0.02	0.2	21.25	1.63	34.40	16.86	0.89	30.61	7.16	0.86	1.74
Compost	0.22	0.02	0.25	34.38	1.90	39.09	14.06	0.78	20.70	6.10	0.81	1.68
Manure	0.41	0.04	0.46	52.79	3.76	60.34	34.96	2.01	50.24	17.74	2.29	4.88
$LSD_{0.05}$	0.14	0.01	0.15	19.54	1.56	28.89	10.48	0.686	13.34	4.48	0.64	1.28

CR = crop residues, DAS = days after sowing

Zai increased nutrient uptake particularly in plots amended with manure, resulting from the better timing of nutrient release and the higher nutrient content of the manure. It might have favoured the development of a strong rooting system and a consequent increase in the volume of soil explored; this was an effect not observed with the other amendments. The initial N and P level of crop residues and compost was low. Even though most of the nutrients from these sources were released as shown with the litterbag data, the amount released might not meet the requirements of the plant. The slower release might have also brought about asynchrony between the need of the plant and the nutrient release at both sites.

3.4.6 Nutrient utilization efficiency

In 2000 at Damari zai increased the straw P utilization efficiency ($P<0.05$) at 67 DAS and at final harvest (Table 3.40). Organic amendment application increased the grain N, P and K utilization efficiency by a factor 2 compared to the control at Damari in both years (Tables 3.41 and 3.42). The reverse tendency was observed with regard to straw N, P and K utilization efficiency.

Table 3.40: Effect of planting techniques (zai vs flat) on millet N, P and K utilization efficiency; Damari, rainy season 2000

Planting technique	Millet nutrient utilization efficiency during the cropping period (kg/kg)											
	25 DAS			67 DAS			122 DAS (Stover)			122 DAS (Grain)		
	N	P	K	N	P	K	N	P	K	N	P	K
Zai, 25cm	35	282	19	45	812	39	99	1689	59	52	512	178
Zai, 50cm	36	320	21	45	678	33	87	1693	57	45	418	148
Flat	35	288	20	43	1125	40	79	2179	69	45	470	154
$LSD_{0.05}$	4	43	3	8	130	5	26	455	8	9	117	35

DAS = days after sowing

Table 3.41: Effect of amendment type on millet N, P, and K utilization efficiency; Damari, rainy season 1999

Organic amendment	Millet nutrient utilization efficiency during the cropping period (kg/kg)											
	36 DAS			76 DAS			119 DAS (Stover)			119 DAS (Grain)		
	N	P	K	N	P	K	N	P	K	N	P	K
Control	37	987	39	35	257	44	46	309	55	17	162	67
CR	38	771	28	54	278	45	70	355	51	41	329	168
Compost	38	926	31	41	258	41	66	329	54	40	332	157
Manure	35	406	22	56	261	46	81	347	47	42	332	157
$LSD_{0.05}$	1	208	3	9	15	9	14	50	16	9	80	34

Table 3.42: Effect of amendment type on millet N, P and K utilization efficiency; Damari, rainy season 2000

Organic amendment	Millet nutrient utilization efficiency during the cropping period (kg/kg)											
	25 DAS			67 DAS			122 DAS (Stover)			122 DAS (Grain)		
	N	P	K	N	P	K	N	P	K	N	P	K
Control	35	345	25	40	934	41	63	1628	66	36	439	135
CR	37	301	19	49	905	32	101	2263	61	51	539	172
Compost	36	318	21	41	1019	40	87	1975	62	48	547	170
Manure	33	222	17	48	629	36	103	1549	57	53	343	163
$LSD_{0.05}$	4	49	3	10	150	6	30	525	10	2	135	40

CR = crop residues; DAS = days after sowing

3.4.7 Nutrient apparent recovery fraction and agronomic efficiency

On average the grain N, P and K apparent recovery and agronomic efficiency were higher in the zai compared to flat planting at Damari in both years at harvest, but the differences were not statistically significant (Tables 3.43 - 3.46). The reverse tendency was observed with regard to straw N, P and K recovery. No consistent trend was observed with regard to grain and straw nutrient apparent recovery and agronomic efficiency at Kakassi in 1999 (data in Appendices 10 - 13).

Table 3.43: Effect of planting techniques (zai vs flat) on millet N, P and K apparent recovery fraction; Damari, rainy season 1999

Planting technique	Millet nutrient recovery fraction during the cropping period											
	36 DAS			76 DAS			119 DAS (Stover)			119 DAS (Grain)		
	N	P	K	N	P	K	N	P	K	N	P	K
Zai, 25cm	-0.001	-0.005	-0.003	0.50	0.38	0.92	0.15	0.17	0.59	0.33	0.24	0.26
Zai, 50cm	0.035	0.014	0.139	0.58	0.62	1.59	0.22	0.22	0.93	0.33	0.18	0.21
Flat	0.070	0.023	0.255	0.86	0.92	2.44	0.27	0.44	1.83	0.19	0.10	0.11
$LSD_{0.05}$	0.028	0.015	0.133	0.40	0.28	1.16	0.16	0.34	1.45	0.16	0.18	0.20

DAS = days after sowing

Table 3.44: Effect of planting techniques (zai vs flat) on millet N, P and K apparent recovery fraction; Damari, rainy season 2000

Planting technique	Millet nutrient recovery fraction during the cropping period											
	25 DAS			67 DAS			122 DAS (Stover)			122 DAS (Grain)		
	N	P	K	N	P	K	N	P	K	N	P	K
Zai, 25cm	0.003	0.003	0.019	0.19	0.10	0.62	0.17	0.10	1.03	0.07	0.06	0.05
Zai, 50cm	-0.001	-0.001	-0.003	0.36	0.14	0.99	0.25	0.09	0.91	0.15	0.09	0.08
Flat	0.002	0.002	0.006	0.43	0.12	1.21	0.23	0.06	0.76	0.09	0.06	0.06
$LSD_{0.05}$	0.003	0.004	0.020	0.22	0.07	0.58	0.14	0.10	0.83	0.08	0.07	0.07

DAS = days after sowing

Table 3.45: Effect of planting techniques (zai vs flat) on millet N, P and K agronomic efficiency; Damari, rainy season 1999

Planting technique	Millet nutrient agronomic efficiency (yield per unit of nutrient applied)											
	36 DAS			76 DAS			119 DAS (Stover)			119 DAS (Grain)		
	N	P	K	N	P	K	N	P	K	N	P	K
Zai, 25cm	0.0	-3.4	-0.9	32	99	49	69	341	51	14	73	38
Zai, 50cm	1.3	7.2	2.5	30	168	70	68	348	49	13	58	32
Flat	2.7	19.0	7.2	53	250	114	60	313	54	8	33	18
$LSD_{0.05}$	1.1	8.9	4.0	28	78	61	12	47	14	7	51	27

DAS = days after sowing

Table 3.46: Effect of planting techniques (zai vs flat) on millet N, P and K agronomic efficiency; Damari, rainy season 2000

Planting technique	Millet nutrient agronomic efficiency (yield per unit of nutrient applied)											
	25 DAS			67 DAS			122 DAS (Stover)			122 DAS (Grain)		
	N	P	K	N	P	K	N	P	K	N	P	K
Zai, 25cm	0.09	0.57	0.28	11	79	26	19	167	58	9	64	22
Zai, 50cm	-0.05	-0.62	-0.15	15	94	35	22	134	50	7	40	13
Flat	0.06	0.29	0.04	20	140	47	21	148	48	5	32	10
$LSD_{0.05}$	0.11	1.21	0.43	9	68	26	10	99	39	4	32	13

In both years at Damari, manure application increased the grain N and K recovery and agronomic efficiency ($P<0.05$) (Table 3.47 - 3.49). In general, manure application increased straw N, P and K recovery and agronomic efficiency at Damari compared to compost and crop residues in both years ($P<0.05$) (Tables 3.47 - 3.49).

In both years at Kakassi, straw K recovery was higher with compost application than with the other amendment (data reported in Appendices 15 - 18). Apart from this, there was no consistent pattern in P and N recovery in both years at Kakassi.

Table 3.47: Effect of amendment type on millet N, P and K apparent recovery fraction; Damari, rainy season 1999

Organic amendment	Millet nutrient recovery fraction during the cropping period											
	36 DAS			76 DAS			119 DAS (Stover)			119 DAS (Grain)		
	N	P	K	N	P	K	N	P	K	N	P	K
CR	0.033	0.015	0.045	0.52	0.89	0.56	0.09	0.18	0.16	0.12	0.13	0.03
Compost	0.017	0.005	0.150	0.21	0.43	1.33	0.20	0.47	1.91	0.17	0.23	0.24
Manure	0.055	0.012	0.196	1.21	0.60	3.06	0.36	0.18	1.29	0.55	0.15	0.31
$LSD_{0.05}$	0.028	0.015	0.133	0.40	0.28	1.16	0.16	0.34	1.45	0.16	0.18	0.20

CR = crop residues; DAS = days after sowing

Table 3.48: Effect of amendment type on millet N, P and K apparent recovery fraction; Damari, rainy season 2000

ORGANIC AMENDMENT	MILLET NUTRIENT RECOVERY FRACTION DURING THE CROPPING PERIOD											
	25 DAS			67 DAS			122 DAS (STOVER)			122 DAS (GRAIN)		
	N	P	K	N	P	K	N	P	K	N	P	K
CR	3E-04	0.001	0.001	0.145	0.097	0.185	0.088	0.054	0.130	0.04	0.049	0.009
COMPOST	1E-04	0.001	0.009	0.363	0.164	1.661	0.263	0.138	1.807	0.067	0.070	0.081
MANURE	0.003	0.002	0.012	0.476	0.106	0.975	0.302	0.055	0.757	0.196	0.088	0.097
$LSD_{0.05}$	0.003	0.004	0.020	0.224	0.074	0.584	0.140	0.098	0.829	0.075	0.067	0.069

CR = crop residues; DAS = days after sowing

Table 3.49: Effect of amendment type on millet N, P and K agronomic efficiency; Damari, rainy season 1999

ORGANIC AMENDMENT	MILLET NUTRIENT AGRONOMIC EFFICIENCY DURING THE CROPPING PERIOD (KG/KG)											
	36 DAS			76 DAS			119 DAS (STOVER)			119 DAS (GRAIN)		
	N	P	K	N	P	K	N	P	K	N	P	K
CR	1.3	11.3	1.1	29	250	25	20	167	17	5	43	4
COMPOST	0.7	7.4	3.7	10	108	54	31	330	165	7	72	36
MANURE	2.0	4.1	4.0	76	159	154	69	146	141	23	49	48
$LSD_{0.05}$	1.1	8.9	4.0	28	78	61	28	286	142	7	51	27

CR = crop residues; DAS = days after sowing

The grain yield per unit nutrient absorbed was higher in the zai compared to the flat planting, while the reverse tendency was observed with straw nutrient utilization efficiency. This suggests that on plots not treated with zai, nutrient accumulation increased in the grain compared to the shoot. It might be due to the frequent water stress the plant experienced in flat planting (see water balance data below) resulting in the effect of haying-off, as the plants might have run out of water before the grain was able to develop (Russell, 1967). Seligman et al. (1986) observed a similar nutrient content increase in wheat in dry years.

The effect of zai as well as that of manure application on N, P and K recovery and agronomic efficiency was more prominent at Damari, which suggests that zai was more effective on the highly degraded soils.

3.4.8 Soil chemical status 76 DAS at Damari and 65 DAS at Kakassi

Mid term soil chemical status data for 2000 was not assessed (destruction of samples). Nonetheless, the information from the data of 1999 shows that all parameters were affected by the organic amendment application. The effect of manure was strongly expressed in extractable P and total N at both sites (values expressed in unit per kg of dry soil). Total N increased as much as 2 times in all treatments compared to prior to the trial (Tables 3.50 and 3.51).

Table 3.50: Effect of organic amendment application on soil chemical status 76 DAS; Damari, rainy season 1999

Parameters	Soil initial status	Treatments				LSD$_{0.05}$
		Control	CR	Compost	Manure	
pH (KCl)	3.9	3.6	3.8	3.7	3.9	0.2
Exch. base (cmol+/kg)	1.7	0.4	0.7	0.8	1.0	0.3
Exch. acidity (cmol+/kg)	1.1	0.7	0.6	0.6	0.5	0.2
ECEC (cmol+/kg)	2.8	1.1	1.3	1.4	1.6	0.2
Al saturation (%)	29	42	28	29	25	13
Base saturation.(%)	61	39	56	54	62	18
P-Bray (mg-P/kg)	2.0	1.9	2.1	2.2	17.2	9.8
C org (%)	0.2	0.1	0.2	0.2	0.2	0.1
Total N (mg-N/kg)	116.1	195.5	243.0	301.7	261.7	64.7

ECEC = Effective Cation Exchange Capacity; CR = crop residues

Table 3.51: Effect of organic amendment application on soil chemical status 65 DAS; Kakassi, rainy season 1999

Parameters	Soil status	Treatments				LSD$_{0.05}$
		Control	CR	Compost	Manure	
pH (KCl	5.4	5.5	5.5	5.5	5.6	0.2
Exch. base (cmol+/kg)	7.9	7.0	7.8	7.0	7.5	0.7
Exch. acidity (cmol+/kg)	0.0	0.0	0.0	0.0	0.1	0.01
ECEC (cmol+/kg)	7.9	7.0	7.8	7.1	7.5	0.7
Al saturation (%)	0.0	0.0	0.0	0.0	0.0	-
Base saturation (%)	99.6	99.7	99.7	99.5	99.1	0.1
P-Bray (mg-P/kg)	0.8	0.9	1.1	1.8	32.5	10.2
C org (%)	0.2	0.2	0.3	0.4	0.4	0.1
Total N (mg-N/kg)	168.7	246.7	352.3	460.6	519.0	127.8

ECEC = Effective Cation Exchange Capacity; CR = crop residues

3.4.9 Soil respiration and microbial biomass

A limited number of soil samples collected at both sites in 2000 were subjected to measurement of substrate-induced respiration (SIR) using the method suggested by Anderson and Domsch (1978). The SIR curve showed low CO_2 production in all treatments after 1 hour of incubation of the sample taken 41 days after amendment application at Damari. A sharp increase in CO_2 production occurred in soil amended with manure after 13 hours of incubation reaching 16µL h^{-1} g^{-1} of soil (Figure 3.35 a), whereas at Kakassi it reached only 5 µL h^{-1} g^{-1} of soil (Figure 3.35 b).

In the soils of control zai plots, CO_2 production was almost constant and low throughout the incubation period for both sites and for both sampling dates. This shows the advanced stage of degradation of these soils.

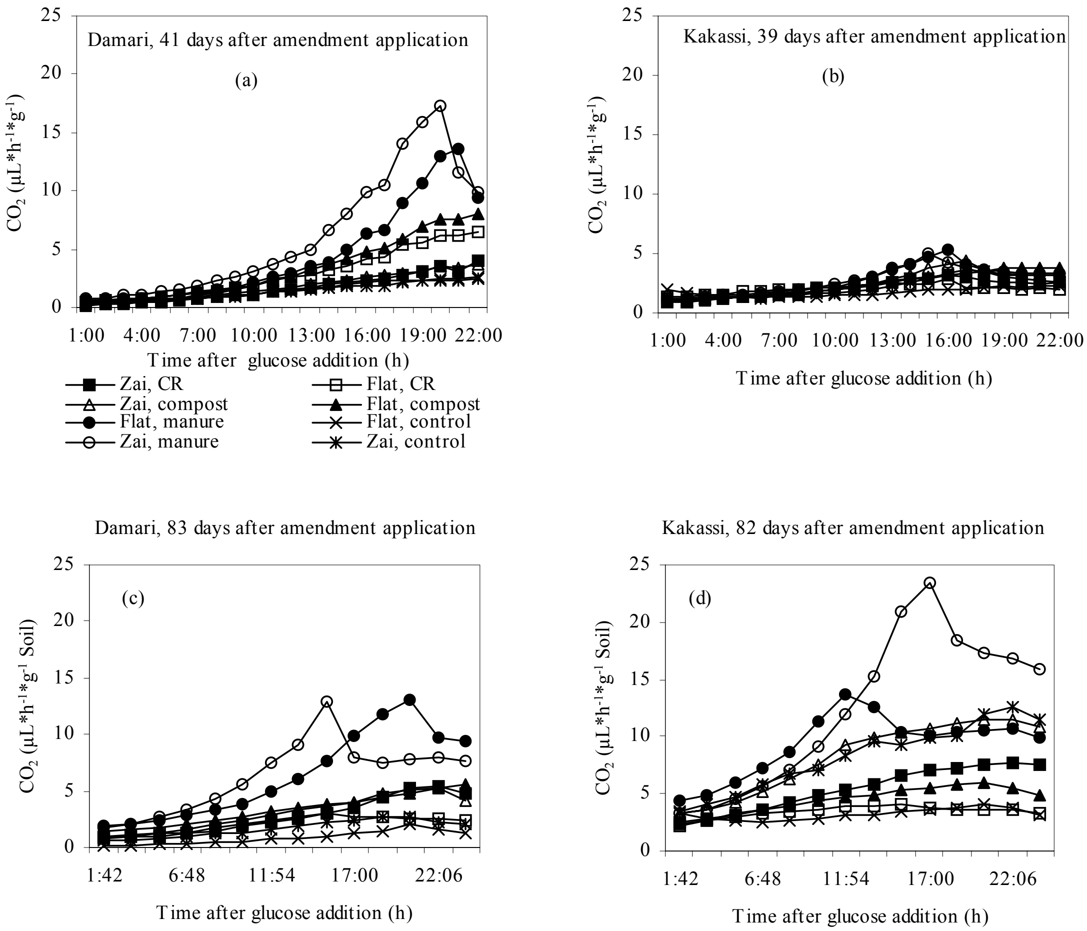


Figure 3.35: Effect of amendment type and planting techniques (zai vs flat) on substrate-induced soil respiration; Damari and Kakassi, rainy season 2000 – samples collected during the cropping period; (CR = crop residues)

It is also an indication that an easily available carbon source (glucose) does not necessarily lead to strong growth of the soil microbial biomass. Other readily available nutrients were limiting, e.g. N and/or P. The addition of such nutrients might induce microbial activity development as reported by Förster et al. (1995), who showed that adding nitrate to glucose-amended soil caused a sharp increase in soil respiration.

The CO_2 production of the soil samples taken later during the cropping period shows that manure application considerably stimulated the microbial activity in the soil (2µL h^{-1} g^{-1} CO_2 was produced after 1:42 of incubation) (figure 3.35 c and d). These results are supported by the study of Torben et al. (1988), who reported increased mineralization of soil N due to manure application and a consequent increase of available N. At Kakassi, CO_2 production from soil treated with millet straw and compost at this stage was more important than that of the samples taken 41 days after amendment application. These results coupled with the high microbial biomass C (Table 3.52) suggest that nutrients were released slowly at Kakassi compared to Damari.

Table 3.52: Effect of organic amendment type and planting techniques (zai vs flat) on soil microbial biomass; Damari and Kakassi, rainy season 2000 (soil samples taken under the hill)

		Microbial biomass C (µg/g soil)			
Organic	Planting	Damari		Kakassi	
amendment	technique	25 DAS	67 DAS	22 DAS	65 DAS
Control	Flat	17	8	54	118
	Zai	17	26	51	164
CR	Flat	22	43	68	105
	Zai	14	36	54	114
Compost	Flat	10	66	51	112
	Zai	19	41	51	149
Manure	Flat	26	86	54	204
	Zai	34	88	60	154

CR = crop residues

The results indicate that manure application stimulated the microbial activity of the soil of both sites. In the control zai at Kakassi, considerable CO_2 production was observed, which proves that the native soil fertility was relatively better than at Damari. This explains the relatively good yield obtained in the non-amended zai at this site.

3.4.10 Root development

- **Root dry matter**

No interaction effect was observed between the treatments. Therefore only the effect of the main treatments are presented and discussed below.

At both sites in 1999, millet root dry matter was higher in zai compared to flat planting in the 10 - 40 cm soil layer (Tables 3.53 and 3.54). As already observed, most of the root dry matter was concentrated in the upper 40 cm of the soil regardless of the planting technique.

Table 3.53: Root total dry matter (g m^{-2}) at harvest as affected by planting techniques (zai vs flat); Damari, rainy season 1999

	Planting technique			
Depth (cm)	Zai, 25cm	Zai, 50cm	Flat	$LSD_{0.05}$
0-10	140.8	134.0	143.0	74.5
10-20	306.1	348.7	145.9	97.2
20-40	20.5	11.2	11.3	9.7
40-60	3.5	3.5	5.2	2.7
60-80	2.7	1.7	3.3	2.7
80-100	2.5	1.2	1.9	1.7
100-120	1.9	1.2	1.3	1.7
120-150	2.3	0.8	0.9	1.7

$LSD_{0.05}$ = least significant difference at 0.05 probability level

Table 3.54: Root total dry matter (g m^{-2}) at harvest as affected by planting techniques (zai vs flat); Kakassi, rainy season 1999

	Planting technique			
Depth (cm)	Zai, 25cm	Zai, 50cm	Flat	$LSD_{0.05}$
0-10	268.2	260.5	188.0	59.9
10-20	130.0	113.7	24.6	84.7
20-40	19.6	10.3	6.5	15.2
40-60	3.2	4.2	2.5	2.5
60-80	1.3	2.0	1.5	1.3
80-100	0.7	0.8	0.3	0.7

$LSD_{0.05}$ = least significant difference at 0.05 probability level

Manure application increased the root dry matter considerably at both sites in both years compared to the other treatments (Tables 3.55 - 3.58). The rooting depth was also higher with manure application. In both years, the root mass was higher at Kakassi compared to Damari.

Table 3.55: Root total dry matter (g m^{-2}) at harvest as affected by amendment type; Damari rainy season 1999

	Organic amendment				
Depth (cm)	Control	CR	Compost	Manure	$LSD_{0.05}$
0-10	30.8	97.1	58.6	370.6	86.1
10-20	113.2	164.8	129.2	660.4	112.3
20-40	3.5	7.1	6.1	40.6	11.2
40-60	1.3	1.7	1.7	11.6	3.1
60-80	0.8	1.3	1.3	7.0	3.1
80-100	0.7	1.4	1.0	4.3	1.9
100-120	0.7	0.6	0.7	3.7	1.9
120-150	0.4	0.7	0.7	3.5	2.0

CR = crop residues; $LSD_{0.05}$ = least significant difference at 0.05 probability level

Table 3.56: Root total dry matter (g m^{-2}) at harvest as affected by amendment type; Kakassi, rainy season 1999

	Organic amendment				
Depth (cm)	Control	CR	Compost	Manure	$LSD_{0.05}$
0-10	131.8	238.0	179.8	406.0	69.2
10-20	47.2	72.1	65.3	173.6	97.8
20-40	4.9	6.5	10.4	26.7	17.6
40-60	2.0	2.3	3.6	5.2	2.9
60-80	0.6	1.3	1.5	3.1	1.5
80-100	0.7	0.5	0.5	0.7	0.8

CR = crop residues; $LSD_{0.05}$ = least significant difference at 0.05 probability level

- **Root length density**

Root length density was evaluated only in 2000. Manure application increased root length density in the soil layer of 10 - 40 cm at both sites (Tables 3.58, 3.59).

Table 3.57: Root length density and total dry matter at harvest as affected by amendment type; Damari, rainy season 2000

	Root length density (cm cm^{-3})					Root dry matter (g cm^{-2})				
Depth	Contro	CR	Compost	Manure	$LSD_{0.05}$	Contro	CR	Compost	Manure	$LSD_{0.05}$
0-10	13.79	0.42	0.42	0.95	19.99	20.45	46.70	54.70	186.04	40.61
10-20	0.25	0.21	0.29	0.43	0.15	10.06	15.02	21.57	44.25	15.38
20-40	0.21	0.22	0.26	0.88	0.21	10.82	16.73	11.07	45.04	14.00
40-60	0.05	0.62	0.22	0.32	0.86	3.40	4.15	6.67	13.21	7.45
60-80	0.04	0.03	0.05	0.13	0.05	2.90	2.27	2.90	19.00	18.57
80-100	0.03	0.04	0.03	0.09	0.03	1.64	2.39	1.76	5.41	1.56
100-120	0.04	0.03	0.03	0.10	0.05	2.77	1.89	1.76	4.41	1.76
120-140	0.02	0.03	0.04	0.09	0.05	1.51	1.89	4.66	4.28	4.50

CR = crop residues; $LSD_{0.05}$ = least significant difference at 0.05 probability level

Table 3.58: Root length density and total dry matter at harvest as affected by amendment type; Kakassi, rainy season 2000

Depth	Root length density (cm cm^{-3})					Root total dry matter (g cm^{-2})				
(cm)	Contro	CR	Compost	Manur	$LSD_{0.05}$	Contro	CR	Compost	Manure	$LSD_{0.05}$
0-10	0.99	1.22	1.10	2.33	0.53	124.61	201.07	150.36	336.39	91.60
10-20	0.67	0.58	0.82	1.26	0.27	24.24	23.78	43.24	69.00	20.50
20-40	0.13	0.07	0.26	0.56	0.29	5.66	4.91	9.56	16.99	8.61
40-60	0.07	0.05	0.12	0.24	0.16	5.03	3.02	5.54	16.86	16.02
60-80	0.04	0.02	0.06	0.18	0.16	2.52	2.02	15.98	4.66	19.33
80-100	0.02	0.03	0.01	0.07	0.07	1.14	1.39	1.01	1.51	1.53
100-120	0.03	0.03	0.02	0.05	0.05	1.01	1.51	1.14	1.89	1.56
120-140	0.01	0.01	0.01	0.02	0.02	0.13	0.51	0.88	1.01	1.15

CR = crop residues; $LSD_{0.05}$ = least significant difference at 0.05 probability level

3.4.11 Water balance

- **Volumetric water content**

Only data on the wetting front in zai (25 cm pits size) are presented because the tendencies in both pit sizes were similar. At both sites in both years, the wetting front proceeded rapidly in the zai compared to flat planting. However, it was more pronounced at Damari, where on the day of sowing in 1999, the wetting front was below 150 cm depth (figure 3.36). For technical reasons, soil water content was not measured at Kakassi in 1999 before the rain started. Here, almost no wetting front progress was observed in plots not treated with zai amended with manure (figures 3.36 h and 3.37 h). The same tendency was observed in 2000. The soil volumetric water content of 2000 is reported in Appendices 22 and 23).

- **Plant available water (PAW)**

In both years and at both sites, almost the total plant available water was consumed at harvest. This situation was more prominent on plots amended with manure (figure 3.38). At Kakassi in both years, the PAW was regularly totally depleted (more prominent in 2000). At this site, both seasons started with a short period of water shortage, which occurred again in the period between 60 and 80 DAS in 2000, when the soil almost dried out. Data on the PAW at both sites in 1999 are reported in Appendix 24.

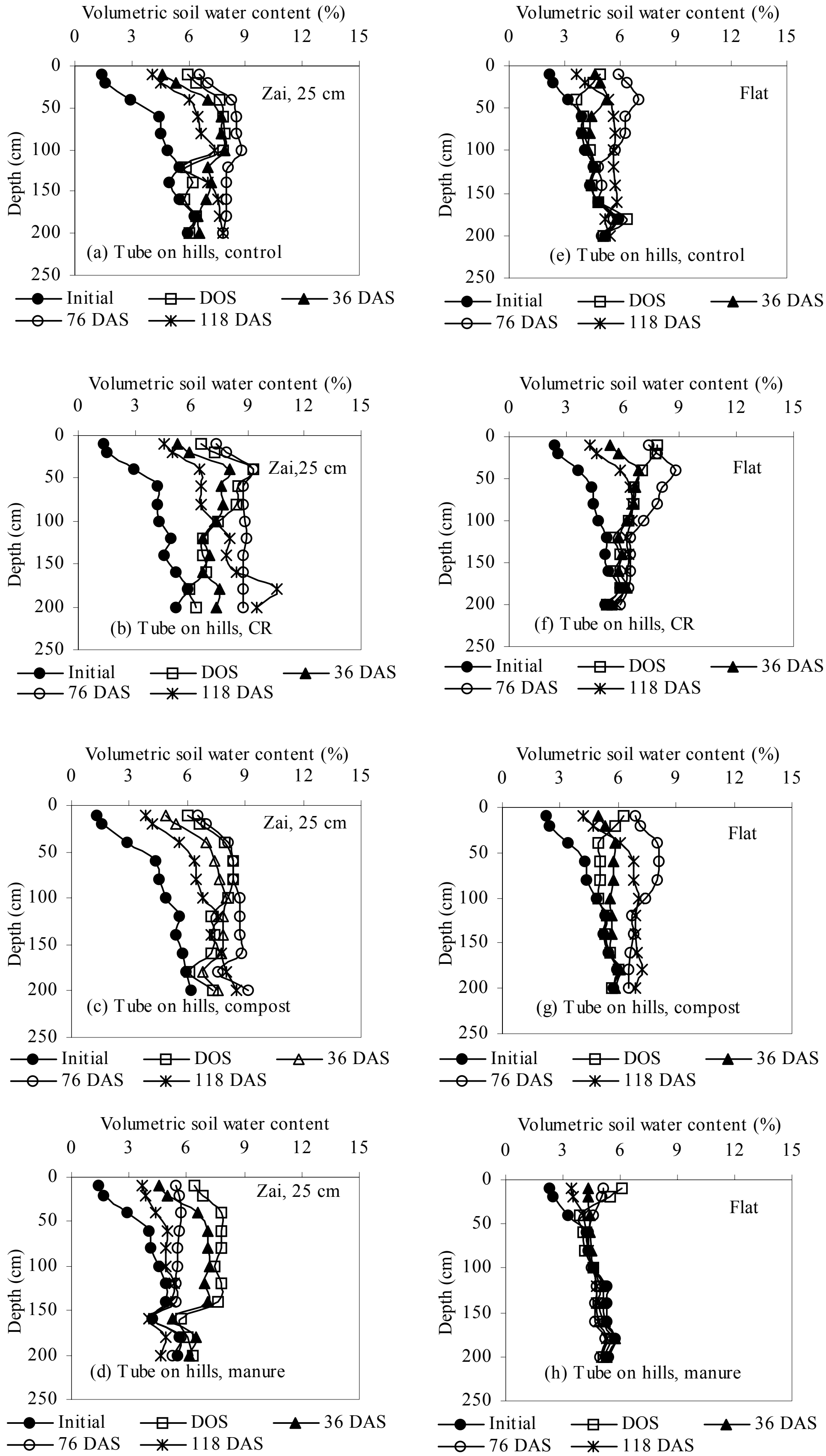


Figure 3.36: Effect of planting techniques (zai vs flat) and amendment type on volumetric water content in the soil profile; Damari, rainy season 1999 – CR = crop residues, DOS = day of sowing, DAS = days after sowing

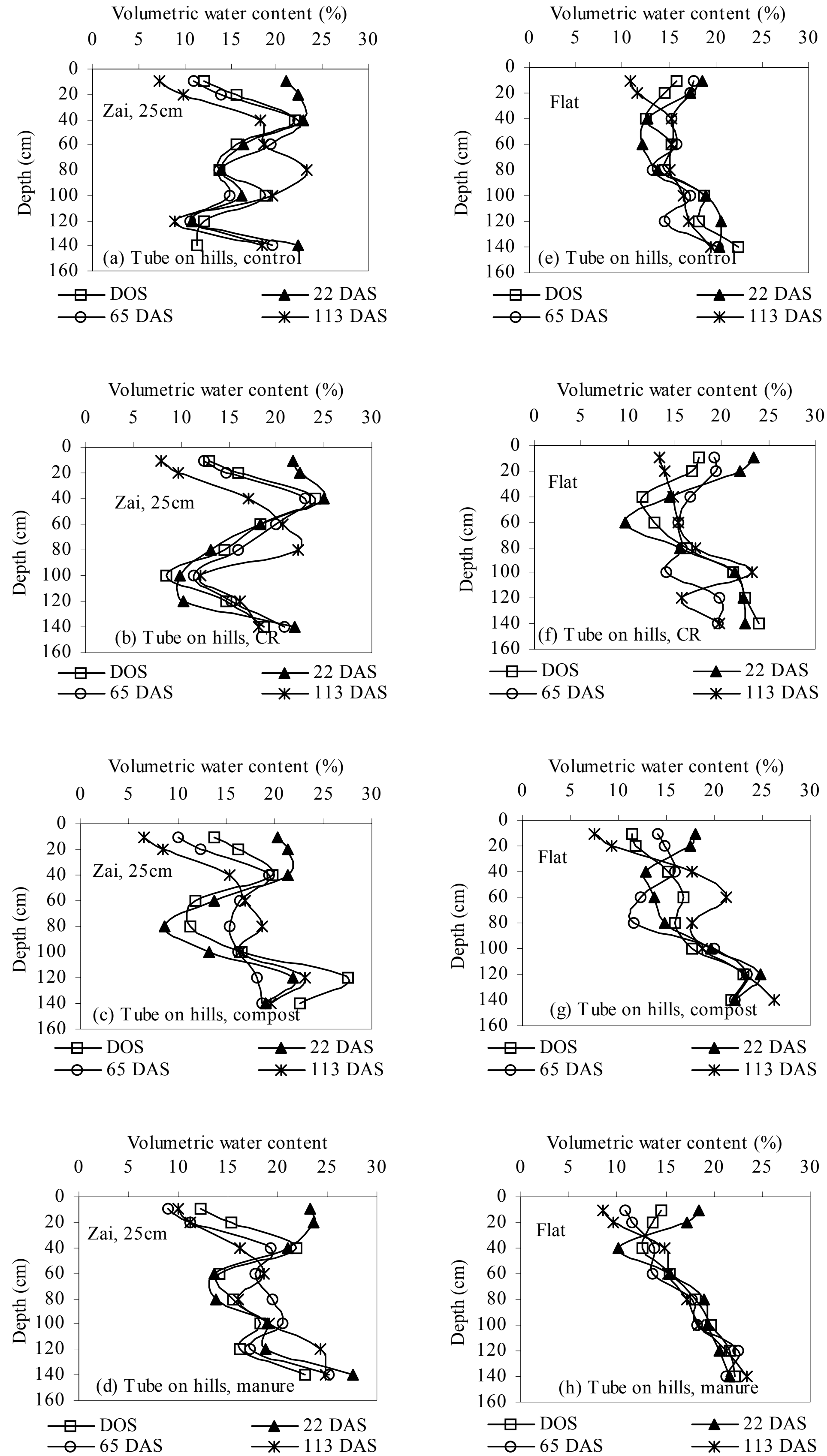


Figure 3.37: Effect of planting techniques (zai vs flat) and amendment type on volumetric water content in the soil profile; Kakassi, rainy season 1999 – CR = crop residues, DOS = day of sowing, DAS = days after sowing

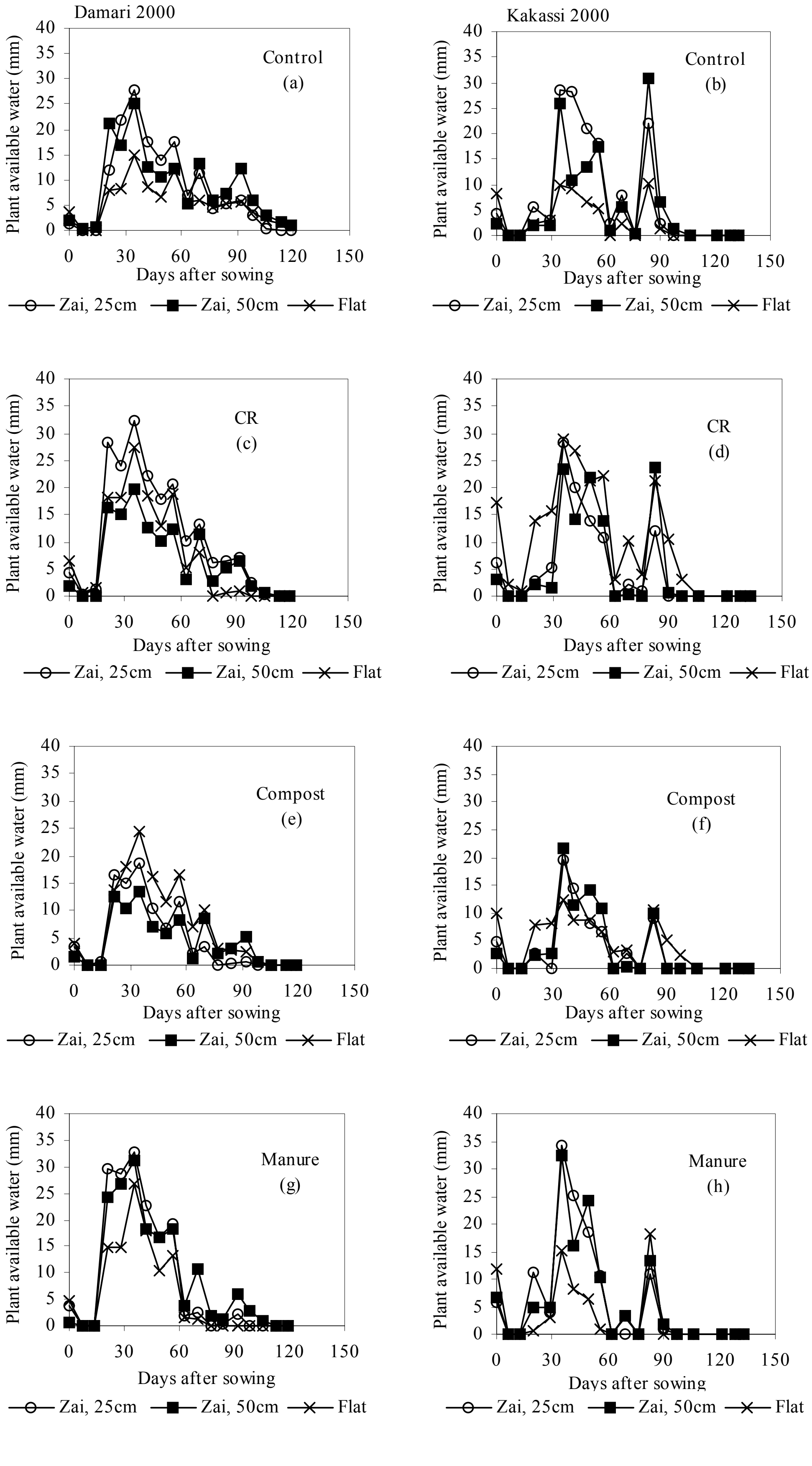


Figure 3.38: Plant available water as affected by planting techniques (zai vs flat) and amendment type; Damari and Kakassi, rainy season 2000 – CR = crop residues

The progress of the wetting front suggests that in both years at both sites zai favored water percolation in the soil; this was more pronounced at Damari, probably due to the lower water holding capacity and low organic matter content of this soil. Soil water content was reduced considerably in the profile at harvest, which suggests important transpirational and evaporational use. Some residual water still remained in the zai at harvest even though at both sites and in both years all of the PAW was used. This situation was worse at Kakassi where from 90 DAS to harvest the PAW was exhausted in both years resulting in haying-off effect in plots not treated with zai. However, water shortage in that period less affects the millet grain yield compared to the period of flowering and grain filling when grain yield is more affected (Fussel et al. 1980). The PAW was totally consumed between the period 60 and 80 DAS in 2000 at Kakassi. This affected the grain yield of a second experiment, which was conducted on the same site but sown one week before the first experiment.

Except for some cases, the PAW in flat planting was lower than in zai, which suggests that even with the risk of water loss that exists in the zai, the plant could be provided with water more easly in the zai and the probability of water stress was reduced.

3.4.12 Resume of experiments D1 and K1

The tendency observed on-station during the dry season under controlled water provision conditions was confirmed again on farm during the rainy season in the 2 years of experimentation. The water collection feature of the zai combined with cattle manure assured a good rooting system development and subsequent high nutrient and water uptake as a result of exploration of a larger volume of soil if high quality organic amendment was used.

Despite this, a question remains concerning the ability of the zai to assure subtantial yields if severe dry spells occur in the critical periods of plant growth. Frequent and long dry spells occurred in 2000, which reduced the TDM yield at both sites. The grain yield reduction was greater at Damari on plots amended with manure, which shows that the plant transpirational need could not be fully covered. In plots amended with manure and especially on plots not treated with zai, the PAW was zero from 80 DAS to harvest, resulting in the effect of haying-off in these plots.

Despite the high rate of decomposition of the organic amendment, loss due to run-off water could be avoided with zai. At Kakassi, good moisture conditions in the zai might have enhanced the amendment decomposition and nutrient release as a result of possibly lower termite activity. The decomposition was lower, and nutrient release could possibly match the requirement of the plant. The following crop on this site might also benefit from the residual effect of this amendment.

One important aspect in this technique is the ready availability of the organic amendment as soon as it is applied as a result of the localized application and good moisture conditions which enhanced the decomposition and nutrient release. The trend in volumetric water content and PAW shows that the zai improves the water requirements for the plant growth. At Kakassi in 2000, for example, from 50 DAS to 78 DAS only a cumulative rainfall of 38 mm was received 26 mm being received 67 DAS. Despite this, no water shortage was observed in the zai in the rooting zone until 60 DAS.

3.5 Effect of termite exclusion and zai technique on cattle manure decomposition and millet growth (D2 and K2)

3.5.1 Total dry matter, grain yield and yield parameters

At Damari, no effect of pesticide treatment was observed on straw yield as well as 1000 seed weight and total biomass production (P>0.05) (Figure 3.39 a). At Kakassi, total dry matter (TDM) production increased by 18% in plots treated with pesticide compared to non-pesticide treated plots (P=0.011) (Figure 3.39 b). Zai treatment increased the TDM production as compared to flat planting (P<0.001) (Figure 3.39 b). The TDM production in the zai at Damari was low (2 t ha^{-1}) compared to Kakassi (3.8 t ha^{-1}).

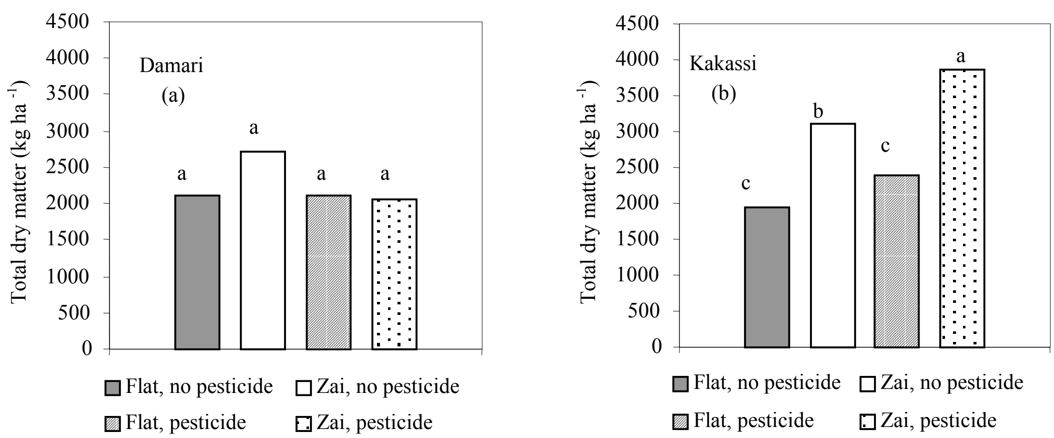


Figure 3.39: Millet total dry matter production as affected by planting techniques (zai vs flat) and pesticide treatment; Damari and Kakassi, rainy season 2000 (letters a, b and c indicate difference between means)

At both sites, zai increased the grain yield considerably (almost 3 times at Damari) regardless of pesticide application (Figure 3.40 a). Pesticide treatment had no effect on the grain yield (P>0.05). In contrast with total biomass, the grain yield at Kakassi was very low in both zai and flat planting compared to Damari. This might be due to the 3-week dry spell that occurred during the period of flowering and pollination causing flower abortion.

The harvest index was higher in the zai (30%) than in the flat planting (10%) at Damari. There was no treatment effect on the harvest index at Kakassi, where the harvest index was low (5% and 7% for flat planting and zai, respectively) possibly due to sterility induced by dry spell during the period of pollination.

At both sites, zai treatment increased millet seed yield per hill, seed yield per tiller as well as seed yield per head ($P<0.05$) (Table 3.59). Hill survival at Damari was lower in the zai as compared to flat planting, while at Kakassi the reverse was observed. Due to the sandy structure of the soil at Damari, the young seedlings were often covered by sand after each rain event. This negatively affected the plant establishment.

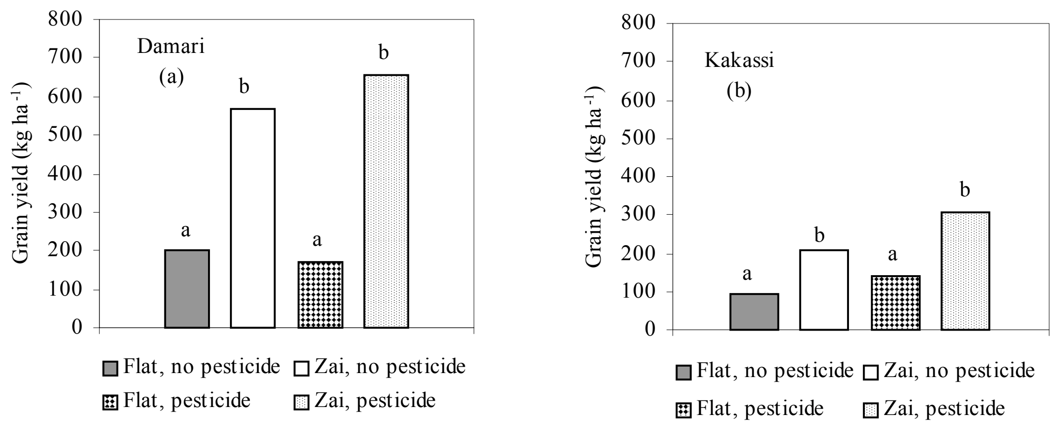


Figure 3.40: Effect of planting techniques (zai vs flat) and pesticide treatment on millet grain yield; Damari and Kakassi, rainy season 2000 (letters a and b indicate differences between means)

Table 3.59: Effect of planting technique (zai vs flat) on selected millet yield parameters; Damari and Kakassi, rainy season 2000

PLANTING TECHNIQUE	SEED YIELD PER HILL (G)	SEED YIELD PER TILLER (G)	SEED YIELD PER HEAD (G)	HILL SURVIVAL %	1000 SEEDS WEIGHT (G)	HARVEST INDEX
			DAMARI			
FLAT	19.3	2.3	2.2	98	5.7	0.1
ZAI	67.8	11.9	6.6	91	6.0	0.3
$LSD_{0.05}$	22.3	5.8	2.2	7	1.2	0.1
			KAKASSI			
FLAT	12.3	1.0	1.2	94	4.0	0.05
ZAI	25.9	3.0	1.9	99	4.8	0.07
$LSD_{0.05}$	9.0	1.4	0.6	3	0.9	0.02

$LSD_{0.05}$ = least significant difference at 0.05 probability level

Zai also increased the 1000 seeds mass compared to flat planting at Damari but not at Kakassi. The percentage of non-matured heads was also very high in the flat planting as compared to the zai pits at Damari (Table 3.60), whereas the reverse tendency was observed with regard to head length. At Kakassi, the number of tillers was higher in flat planting compared to the zai. At both sites, plant height was higher in the zai compared to flat planting (Table 3.60).

Table 3.60: Effect of planting technique and pesticide treatment on selected millet yield parameters; Damari and Kakassi, rainy season 2000

		Damari				Kakassi			
Pesticide treatment	Planting technique	Percentage non-matured heads (%)	Number of tillers per hill	Head length (cm)	Plant height (cm)	Percentage non-matured heads (%)	Number of tillers per hill	Head length (cm)	Plant height (cm)
No	Flat	20	9	45	198	10	12	43	192
	Zai	5	6	52	214	5	9	42	207
Pesticide	Flat	14	8	42	195	9	12	40	189
	Zai	2	7	53	230	15	9	45	225
	$LSD_{0.05}$	14	2	8	23	10	2	7	28

$LSD_{0.05}$ = least significant difference at 0.05 probability level

The plants grown in plots of flat planting formed slightly more tillers compared to those grown in the zai pits, but this did not compensate for the reduction of the other yield components at both sites. No significant effect of pesticide treatment on the above-mentioned parameters was observed. No interaction effect was observed between the main factors under study.

In general, the grain yield at both sites was very low compared to the grain yield obtained with cattle manure in 2000 and reported in Section 3.4.1 of experiments D1 and K1 at Damari and Kakassi. Millet sowing was done in experiments D2 and K2 on 23 June at Damari and on 20 June at Kakassi. At both sites, a 3-week dry spell occurred from mid August to the beginning of September, the period of flowering and pollination of the plants. This might be the main raison for the low grain yield obtained, while the straw yield was less affected. Fussel (1980) and Rockstrom (1997) also observed significant grain yield loss due to drought stress during the period of panicle initiation and development of the reproductive organs of the millet plants.

3.5.2 Amendment decomposition and nutrient release

At Damari, a pesticide application effect was observed on the rate of manure decomposition when the manure was exposed on the soil surface, whereas no significant pesticide treatment effect was observed when the manure was exposed in the zai pits (Figure 3.41 a).

After 47 days of litter exposure, 43% of manure was decomposed in soil surface exposure without pesticide treatment and 18% with pesticide treatment. At the end of the period of manure exposure, almost all of the manure exposed on the soil surface in the plots not treated with pesticide was decomposed, while about 70% of it remained on the soil surface in plots treated with pesticide. For the same period, on average 50% of manure exposed remained in the zai plot treated with pesticide. At Kakassi, no treatment effect was observed on manure decomposition.

After 47 days of manure exposure only a 12% weight loss was observed (Figure 3.42 a). At the end of the exposure period, 64% remained in soil surface exposure, while 51% remained in the zai.

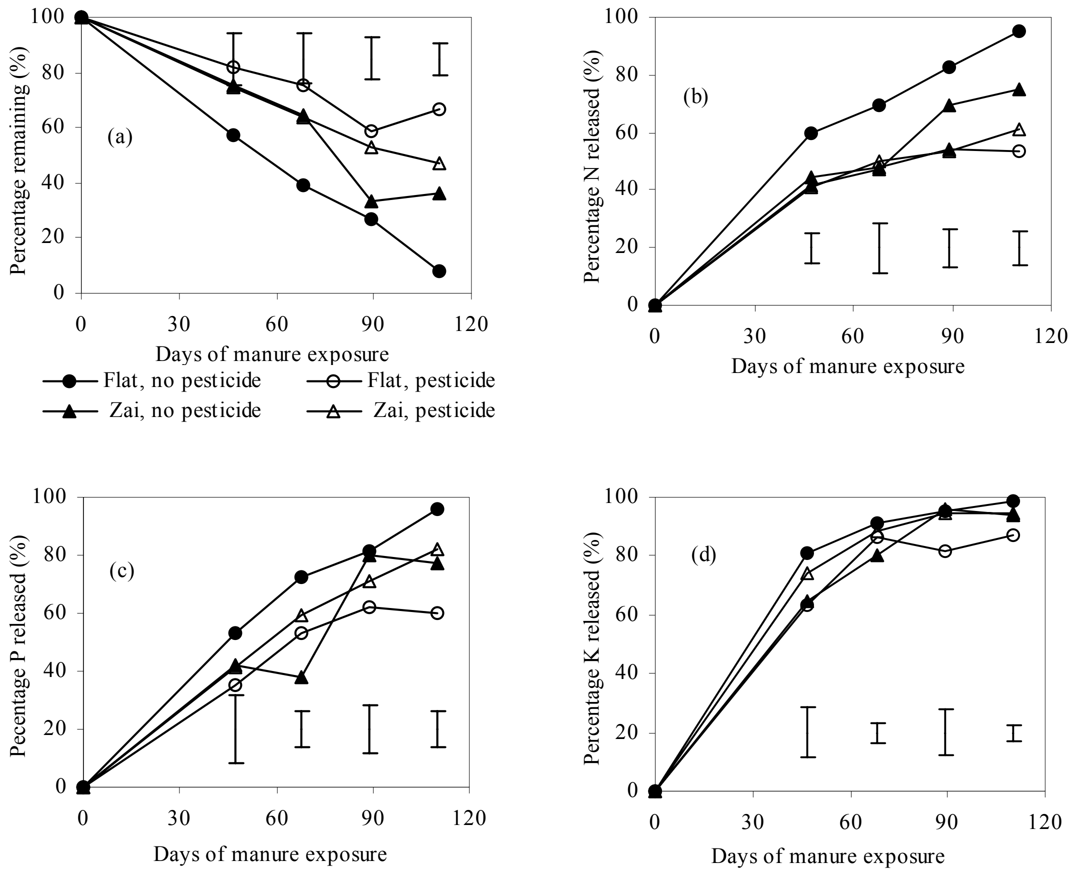


Figure 3.41: Cattle manure decomposition and nutrient release as affect by planting techniques (zai vs flat) and pesticide treatment; Damari, rainy season 2000

Nitrogen and P release closely followed the pattern of manure decomposition both at Damari and Kakassi (Figure 3.44 b and c and Figure 3.45 b and c). Potassium release was similar for all treatments at both sites but it was faster than the manure decomposition (Figures 3.44 d and 3.45 d), suggesting leaching of K. After 47 days of manure exposure at Damari, K released was 60% in soil surface exposure with pesticide treatment and 80% without pesticide treatment; however, this difference was not statistically significant. At Kakassi, 80% on average was released for the same period. At both sites, almost all of K was released at the end of the period of manure exposure.

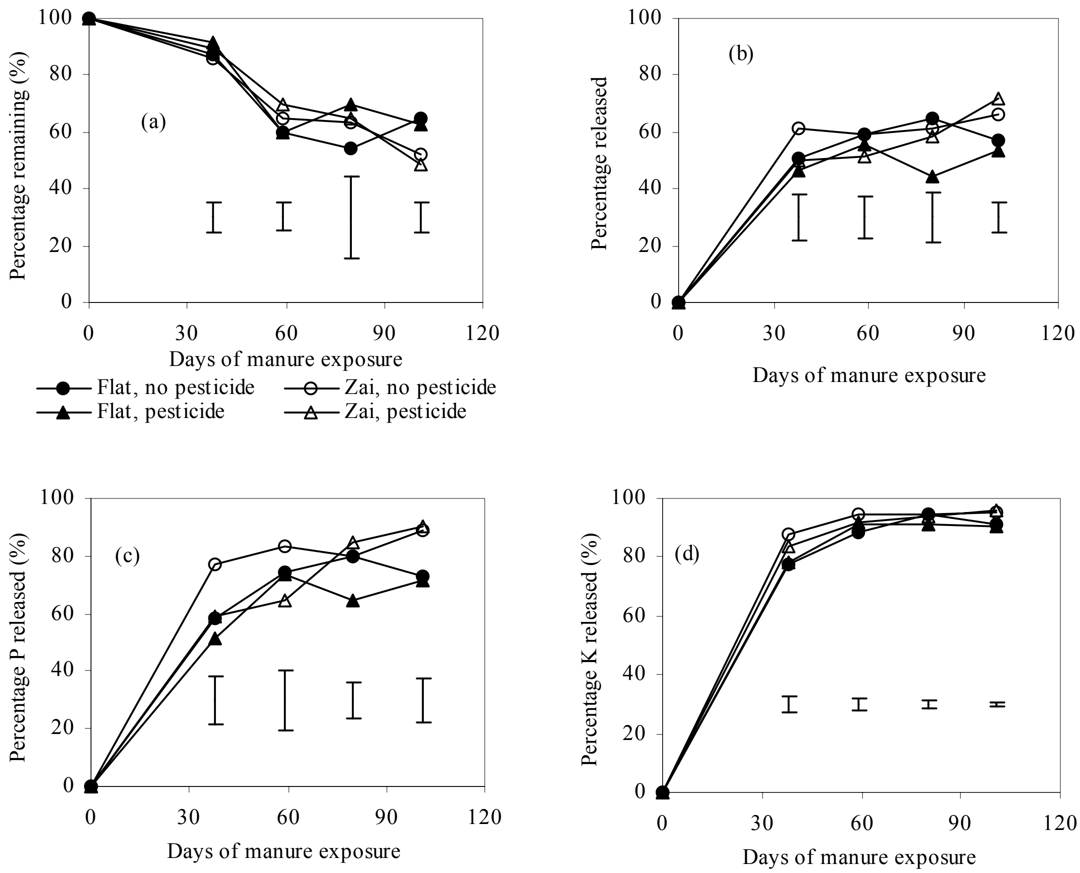


Figure 3.42: Cattle manure decomposition and nutrient release as affected by planting techniques (zai vs flat) and pesticide treatment; Kakassi, rainy season 2000

Soil fauna and macro flora play an important role in the comminution and subsequent decomposition of organic residues as well as of green or cattle manure. These soil animals, while feeding on these substrates, break them into pieces accessible to microoganisms (fragmentation or primary decomposition). The results of the pesticide experiments show that the faster decomposition of manure at Damari was due to the intensive activities of the termites on that site. Tian et al. (1992) reported similar findings. Almost the same amount of manure remained in the zai at both sites regardless of the pesticide treatment.

The faster decomposition in the zai at Kakassi could be due to better moisture conditions in the zai as shown in paragraph 3.4.12. Soil moisture content regulates the activities of the decomposer microorganisms (Runge 1983) and might have played an important role in the weight loss of manure.

The slow rate of manure weight loss at Kakassi suggests that a succeeding crop might still benefit from this manure. This idea is supported by the relatively lower percentage of N and P released at the end of the manure exposure period. The fast and almost complete release of K at both sites confirms the high mobility of this component of the manure nutrient pool as reported in Section 3.1.3.

3.5.3 Millet N, P and K uptake and utilization efficiency

Millet nutrition was mainly affected by the planting technique, but no effect of pesticide treatment was observed at both sites. No interaction effect was observed either. Zai slightly increased straw N uptake compared to flat planting at both sites at harvest, and straw P uptake was slightly higher in flat planting compared to zai at Damari (Table 4.62) even though the differences were not significant at Damari. The effect of zai on grain nutrient uptake was more pronounced as N, P and K uptake in the grains was increased by at least factor 2 as compared to flat planting at Damari (P<0.05 - Table 3.62) and Kakassi (Table 3.63). Nutrient uptake was very low compared to 104, 16 and 104 ka ha^{-1} reported by Duivenbooden et al. (1993) from a control non-amended plot in Senegal, which reflects the harsh condition for plant growth in this study.

Table 3.61: Millet N, P and K uptake as affected by planting techniques (zai vs flat); Damari, rainy season 2000

	Millet nutrient uptake during the cropping period (kg ha^{-1})											
Planting	25 DAP			67 DAP			111 DAP (Stover)			111 DAP (grain)		
technique	N	P	K	N	P	K	N	P	K	N	P	K
Flat	0.28	0.04	0.44	89.1	3.7	78.1	187.2	11.2	303.3	56.0	7.1	14.9
Zai	0.39	0.04	0.76	75.2	4.5	74.4	161.2	4.0	244.7	139.5	18.9	38.8
$LSD_{0.05}$	0.17	0.02	0.41	27.7	2.2	37.7	189.5	10.8	307.9	55.9	5.1	14.6

$LSD_{0.05}$ = least significant difference at 0.05 probability level

Table 3.62: Millet N, P and K uptake as affected by planting techniques (zai vs flat); Kakassi, rainy season 2000

	Millet nutrient uptake during the cropping period (kg ha^{-1})											
Planting	23 DAP			65 DAP			122 DAP (Stover)			122 DAP (grain)		
technique	N	P	K	N	P	K	N	P	K	N	P	K
Flat	0.39	0.03	0.35	47.1	3.2	66.2	137.4	12.7	319.3	24.7	3.7	7.1
Zai	0.54	0.06	0.82	69.1	4.5	77.7	280.6	20.7	496.5	59.2	8.3	14.9
$LSD_{0.05}$	0.30	0.03	0.43	11.2	0.9	16.8	83.0	9.0	88.7	28.7	3.9	7.5

$LSD_{0.05}$ = least significant difference at 0.05 probability level

Neither pesticide nor an interaction effect was observed on N, P and K utilization efficiency. Both at Damari and Kakassi, a more efficient utilization of P and K in flat planting compared to zai was observed in the early stages of the plant growth (25 DAS and 23 DAS P<0.05; Tables 3.64 and 3.65). No significant treatment effect was observed on N utilization. Nonetheless, slightly higher values of N and P utilization efficiency for grain production were observed in the zai compared to flat planting at Damari and at Kakassi.

Table 3.63: Millet N, P and K utilization efficiency as affected by planting techniques (zai vs flat); Damari, rainy season 2000

	Millet nutrient utilization efficiency (Yield per unit nutrient absorbed)											
Planting	25 DAP			67 DAP			111 DAP Stover			111 DAP Grain		
technique	N	P	K	N	P	K	N	P	K	N	P	K
Flat	28	204	17	35	831	40	88	2339	58	42	338	163
Zai	29	259	15	34	608	34	112	5030	60	45	329	160
$LSD_{0.05}$	4	34	2	8	267	7	30	1973	16	4	55	11

$LSD_{0.05}$ = least significant difference at 0.05 probability level

Table 3.64: Millet N, P and K utilisation efficiency as affected by planting techniques (zai vs flat); Kakassi, rainy season 2000

	Millet nutrient utilization efficiency (Yield per unit nutrient absorbed)											
Planting	23 DAP			65 DAP			122 DAP (Stover)			122 DAP (grain)		
technique	N	P	K	N	P	K	N	P	K	N	P	K
Flat	27	313	30	48	662	32	129	1240	48	39	254	132
Zai	26	248	18	43	630	37	95	1448	53	38	263	147
$LSD_{0.05}$	3	63	6	11	71	4	50	794	4	3	57	21

$LSD_{0.05}$ = least significant difference at 0.05 probability level

3.5.4 Resume of experiment D2 and K2

At both sites, millet grain and TDM were not affected by pesticide treatment except for increased TDM in zai treated with pesticide compared to non-treated zai and flat planting at Kakassi. As no effect was observed on amendment decomposition and nutrient release on this site, additional investigation might be needed to draw a conclusion on this result. Again, a positive effect of the planting technique was observed on grain yield. This effect was more prominent at Damari than at Kakassi, which might be due to the severity of the dry spells at Kakassi. As reported in many studies (Payne et al. 1995, Vetterlein 1994), dry spells affect plant growth and nutrient uptake as they limit nutrient and water uptake.

Grain N, P and K uptake was higher in the zai compared to the flat planting, but no effect of planting technique was observed on nutrient utilization efficiency. This suggests an accumulation of the nutrient in millet grown on plots not treated with zai, which was not subsequently translated into higher grain production at Damari. This is similar to the results of Payne et al. (1995) and Bennett et al. (1964). However, Gregory (1979) observed a decrease in nutrient content in water-stressed pearl millet.

Most of the rooting system in the zai as well as in flat planting was confined to the upper 40 cm of soil. Kapur et al. (1985) reported that roots tend to concentrate in soil layers with a higher fertility level. In the case of drought, the upper layers dry quickly. Under these conditions, the plant might starve even though nutrients could be near the roots.

Pesticide application reduced the rate of manure weight loss at Damari, whereas it had no effect at Kakassi, which suggests that the activities of termites enhanced the manure breakdown at Damari. At Kakassi, such faunal activities could hardly be observed, and here manure took longer to decompose. This, in fact, could be profitable to the plant as it might allow nutrient release to match the requirement of the plant during the growing period better than fast decomposition rates.

4 GENERAL DISCUSSION

The objectives of this study were (1) test the effectiveness of the zai compared to flat planting with regard to millet plant establishment, total dry matter and grain yield production. One of the questions to be answered was whether the considerable investment by the farmer into digging the zai pits is compensated by an increased return in grain and stover yield. (2) Find optimal combination of pit size with amendment type and rate to optimise the investment in labour in the technique.

All investigations were done in the light of understanding the process of amendment decomposition, nutrient release and nutrient uptake by the millet crop in the technique.

The following hypothesis was then formulated:

> The zai technique benefits from both the water catchment area and the organic fertilizer input. Optimizing the ratio of water catchment to quantity for various sources (quality) of organic amendment will provide the best return on investments of organic matter and labor.

An overview of our findings are discussed below.

4.1 Zai improved millet growth and yield compared to flat planting

The zai technique assured substantial total dry matter (TDM) increase (3086 kg ha^{-1}) compared to flat planting (991 kg ha^{-1}) with cattle manure application under the 20 mm irrigation regime. The additional water added with the 30mm irrigation regime (as shown in the plant available water) boosted plant growth in the traditionally planted plots (1929 kg ha^{-1}). Consequently, at harvest the TDM in both planting techniques was similar under this higher water regime. Zai thus proves valuable as a risk-minimizing technology in drought prone areas. The quality of the amendment played a key role, as low TDM as well as grain yield was produced with crop residues or compost of low quality. The TDM produced on average with crop residues application was 756 at Sadore; 925 at Damari and 2185 kg ha^{-1} at Kakassi in 1999; compared to 3957, 4600 and 5030 kg ha^{-1}, respectively, with the same rate of manure application. The grain yield was 151 kg ha^{-1} at Damari and 393 kg ha^{-1} at Kakassi with crop residues application, while it was 987 and 778 with manure application. The readily available nutrient from the manure promoted rapid root growth and increased the volume of soil the roots could explore. This resulted in high nutrient uptake, and consequently, high TDM and grain yield. The initial nutrient content and especially N was very low under crop residues application. Nutrient immobilisation following their incorporation into the soil, and other additional losses of N might have occurred following the process of remineralization. The effect of Al toxicity reduction and increase in P mobility following millet residue application reported by Kretschmar et al. (1991) was not evident in this study. This was consistent with the low TDM and grain yield obtained with their incorporation into the soil as applied in the zai technique. TDM yield increased by 115% when manure application rate was raised from 1 to 3 t ha^{-1}, but a further increase of the application rate from 3 to 5 t ha^{-1} only increased TDM by 12%. Therefore, the optimal application rate is to be expected to be between 1 and 3 t ha^{-1}. However, further studies might be needed to determine the optimal rate of manure application in the zai technique. Nevertheless, the manure amendment rate of 3 t ha^{-1} used in this study and which produced a substantial yield increase, was far below the 10 t ha^{-1} farmers applied with corralling as reported by Powell and Williams (1993) and Powell (1996).

Zai significantly increased the effectiveness of manure and resulted in grain yield increases of 60 and 100% on average in 1999 and 100 and 85% in 2000 at Damari and Kakassi, respectively, compared to flat planting amended with manure. There was no significant effect of pit size on millet grain yield at either location in the presence of manure, suggesting that doubling the pit size might not be a prerequisite for improving the technique. The relatively better response to manure application at Damari than at Kakassi (additional 100 kg ha^{-1} of grain at Damari compared to Kakassi) may be explained by the possible binding effect of manure application on the soil aluminium and other metals that reduce P availability and may have certain toxicity for millet. Thus, the mobility of the native P that can be expected to be the most limiting nutrient at Damari may have increased resulting in higher yield. With the natural soil fertility at Kakassi being better, this shows that the zai technique can overcome the effect of severely degraded soils. The better fertility of the heavy soil at Kakassi was evident from the 480 kg ha^{-1} grain yield (yield similar to the average yield of Niger) obtained with the non-amended zai compared to 19 kg ha^{-1} at Damari in a good rainfall year. The TDM in the non-amended zai pit at the same site was relatively high (on average 2500 kg ha^{-1}) compared to 290 kg ha^{-1} TDM on the highly degraded sandy soil at Damari. At Kakassi, TDM as well as grain yield produced in the control zai was 2 to 3-fold that produced in the control flat, reflecting the importance of the water harvesting in the zai pit here. However, in both years at this site most of the pits were filled with wind-blown sand and plant debris before planting. It might be necessary to evaluate the additional nutrient input in the zai with the soil particles and plant debris to assess their contribution to improving the nutritional status in the pits.

The limited availability of high quality cattle manure can be regarded as a constraint for the implementation of the technique, because farmers in Niger can apply manure only to 10 to 40%

of the total cultivated household fields in a year, if they rely on their household livestock alone (Timothy et al. 1995). The possibility of using organic wastes of different origins to prepare good quality compost, however, may help to overcome this constraint, although such quality compost was not readily available for the present studies.

The dry spells affected the plant under both planting techniques. But zai showed benefit over flat, that was proportionally greater when dry spells were imposed. The total dry matter production under the 4-week dry spell with zai was similar to that in flat planting under continuous irrigation, demonstrating the ability of the zai to secure the plant in case of dry spells. Wendum et al. (1996) reported similar results. They observed a crops survival of up to 10 - 14 days during dry spell during the rainy season. Longer dry spells occurring during the period of flowering and pollination can cause a drastic grain yield reduction. The grain yield produced in the zai amended with manure when 3-week dry spell occurred at Kakassi in 2000 during the period of pollination was 300 kg ha^{-1} compared 900 kg ha^{-1} with the same treatment in a second experiment which flowered later. However, even then the grain yield in the zai was 50% higher than that in flat planting.

4.2 Zai enhanced amendment decomposition and nutrient release in the absence of termites

The faster weight loss in cattle manure than in crop residues (30% of manure vs 80% of crop residues remained after 30 days of litter exposure) points to the importance of the amendment's chemical characteristics in controlling the rate of decomposition and nutrient release. These results were in line with the high C:N ratio and the low N content of the crop residues and the compost used in the study.

The moisture in the pits was determinant in the decomposition mainly at Kakassi, where decomposition was faster in the pit than the surface exposure. Soil moisture content regulates the activities of the decomposer microorganisms (Runge 1983) and might have contributed to the amendment decomposition in the zai.

Excluding the termites with pesticide application reduced the rate and the amount of amendment decomposed at the end of the period of litter exposure only at Damari, where termites were very active as opposed to Kakassi. Termites not only increase the porosity of the soil but also transport nutrients from their nest to the top and back again (Ouedraogo et al. 1996). Considering the influence of the termites on amendment decomposition observed in this study and the yield recorded in manured plots, further investigations might be necessary to clarify their effect on crop yield. In fact, the present study showed that termite exclusion did not affect grain yield.

Nutrient release was related to the rate of litter decomposition except for K, which was released faster and more completely than N and P. In all experiments, and particularly at Sadore and Damari, at least 50% of all nutrients were released one month after sowing when the plants had not reached the stage of panicle initiation. In flat planting, most of these nutrients could be lost to the system because of run-off water, as the plants might not have grown enough to make use of them efficiently.

In the study, it appeared that manure application stimulated the soil microbial activities as high CO_2 production was recorded with soil samples taken from hills amended with this amendment. This was in line with the high yield produced in these plots. The low and constant CO_2 production during the incubation of soils samples taken from the control plots, particularly at Damari is an indication of the advanced stage of degradation of the soil used in the study. The relatively high CO_2 production recorded with the incubation of the soil samples taken 82 days after litter application from the control zai at Kakassi is another indication that considerable nutrient input occurs in the zai pits from soil and debris collection.

4.3 Zai and nutrient uptake and utilization

The present study revealed an increased nutrient uptake in the zai, especially when good quality amendment was applied. Nutrient uptake was low in plots amended with crop residues and compost. Dry spells reduced millet nutrient uptake under both planting techniques, but the effect was more prominent in plots traditionally planted (flat). Most of the plant roots (95% of the root total dry matter) were concentrated in the upper 40 cm in all planting techniques and mainly in the soil layer of 0 to 20 cm in the plots traditionally planted (flat). Due to the localized application of the amendment this was the most fertile soil layer. However, it is the layer that dries first during dry spells. Consequently, the movement of nutrients with low mobility (like P) might have been restricted under drought conditions, resulting in lower plant uptake and consequently lower growth.

Zai increased nutrient agronomic efficiency as well as nutrient apparent recovery for grain yield compared to flat planting, if cattle manure was applied. This shows that the plants in the zai made better use of the readily available nutrient from the manure, possibly due to the combined effect of water harvesting and nutrient uptake from the manure in the zai. This does not occur in flat planting, where a drastic reduction of the plant available water took place due to recurrent dry spells particularly in the on-farm experiments. Under flat planting there was an accumulation of nutrients in the grains, which was not converted into increased grain yield. All this is possibly due to the effect of 'haying-off'. The plant may have run out of water before the seeds were totally matured. When stover yield was considered, the nutrient agronomic efficiency in the traditional flat planting was higher than in the zai. Similar tendency was observed with the plants under imposed dry spell at Sadore in dry season 2000. This might result from the reduction of nutrient uptake from the water stressed plants, which might not be the same with non-stressed plants.

4.4 Zai and water harvesting

Penning de Vries and Djiteye (1982), and Breman and de Witt (1983) reported that nutrient but not water availability was the most important limiting factor for agricultural production in the Sahel. However, Bationo et al. (1990) reported a poor response of millet to N application in dry years, and Payne et al. (1995) argue that the nutritional aspect of agriculture in the Sahel could not be considered without including the water component. Many studies have shown that a strong interaction exists between the availability of water and plant nutrients, and that changing one of these factors can greatly affect responses to the others. An increased available water supply not only directly enhances fertilizer responses by eliminating water as a growth-limiting factor, but, in many cases, may also affect native nutrient availability and efficiency of utilization. Campbell et al. (1977), Campbell and Paul (1978); Wright et al. (1978) and Payne et al. (1995) reported that plants grown with an adequate nutrient supply extend roots to deeper depths than the same plants grown in soil that is deficient in one or more nutrient. Increased root proliferation increases the volume of soil colonized, thereby increasing the potential for water use and thus reducing the probability of plant growth being restricted by intermittent periods of drought (Brown 1971). Therefore, it is imperative to promote technologies that combine both factors and consequently help rehabilitate degraded lands. The study showed that zai enhanced soil water storage and increased plant available water, but on soils with low water holding capacity like at Sadore and Damari, most of this water could be drained out. As much as 74% of the irrigation water was drained out in plots amended with 1 t ha^{-1} crop residues at Sadore. The use of high-quality organic amendment, which could promote rapid and deep root growth, could help limit this loss as well as the nutrient loss associated with it. Dry spells affected water storage in both planting techniques but the effect was particularly severe in plots not treated with zai.

In the study, at the end of the growing period, most of the plant available water was consumed in all planting techniques and at all sites, particularly in plots amended with manure. This was possibly a result of increased shoot development, which increased the plants' need for transpiration. On the other plots, where the TDM and the grain yield were not as high as in plots treated with manure, a large fraction of this water might be evaporated, but a sizable part of it could also have percolated in deeper layers to recharge the under ground water stock. In order to make better use of the water collected in the pits, it is necessary to use high quality organic amendment, which would promote rapid plant growth and consequently reduce water loss through evaporation or underground percolation. In the present study, drainage and plant available water are reduced in plots with high TDM production.

The zai with a larger pit size (50 cm) increased water collection but did not affect any of the parameters studied except for TDM at Kakassi in 1999. Apparently, increasing the pit size to 50 cm is not necessary.

5 CONCLUSION

In the light of the present study the following conclusions can be drawn:

Good TDM and grain yield far above the average yield is possible when using the zai technique in the Sahel, particularly on highly degraded sandy soils, where more than 1 t ha^{-1} millet grain yield was obtained when the zai pit was amended with cattle manure at a rate of 3t ha^{-1}. An additional 500 kg ha^{-1} of grain was obtained by planting in zai compared to flat planting, which is an important gain to the farmers.

A good-quality organic amendment is essential on highly degraded soils. The scarcity of animal dung might be a constraint to the use of the zai technology. However, farmers are able to prepare good quality compost using all kinds of domestic wastes, weeds and leguminous residues before and during the onset of the rainy season. In this study, such quality compost was not available, which resulted in the low grain and straw yields recorded with this amendment.

The considerable increase in total dry matter yield (115%) resulting from increasing the manure application rate from 1 to 3 t ha^{-1}, and the minor yield increase (12%) following a further increase of the manure application rate from 3 to 5 t ha^{-1} shows that the optimum application rate could be around 3 t ha^{-1}, but the exact optimum rate should still be investigated.

The present study also shows that, on heavy soils with relatively high native fertility, the grain yield was much lower (900 kg ha^{-1}) than the sandy soil (1100 kg ha^{-1}). Water logging was also observed on this site in the zai resulting from low soil permeability.

Nutrients released from the organic amendment in combination with the water collected in the zai favor the development of the rooting system leading to better use of this water and the nutrients. This can explain the good performance of the crop in terms of TDM in the dry season experiments at Sadore and the grain yield at Damari and Kakassi with the zai.

High CO_2 production (substrate induced respiration – SIR) from soil samples taken on the planting hills amended with manure was observed, whereas CO_2 production from the control plots was low and constant throughout the incubation period. This suggests that manure application stimulated the microbial activities in the treated plots.

The zai technique can secure consistent grain and TDM yield even during dry spells. This was achieved as the result reserve of water available in the zai during the period of dry spell as recorded at Sadore in 2000 under controlled irrigation. A TDM of 2225 kg ha^{-1} was produced in the zai compared to 880 kg ha^{-1} in flat planting. At Kakassi a dry spell that occurred during the millet flowering period induced a drastic grain yield loss (300 kg ha^{-1} grain was produced in the zai compared to 200 kg ha^{-1} on flat). In the same experiment, 3500 kg ha^{-1} TDM was produced against 2000 kg ha^{-1} in flat suggesting a “haying-off” .

The present study shows that increasing the diameter of the zai pit from 25 cm to 50 cm did not influence the studied parameters. Consequently doubling the diameter of the pit might not be necessary to improve the technique.

The zai technique is simple but requires hard work. However, as the pits are dug during the dry season when farmers are not engage in other field activities, this need not be considered as a constraint.

6 SUMMARY

In the Sahelian zone, soil fertility restoration through the fallow system is becoming increasingly inefficient due to population pressure, which leads to shorter fallow periods. In some cases, a fallow period is no longer maintained.

The zai technique is used to rehabilitate degraded land. For the implementation of this technique, locally available material is used and the zai therefore has the potential to be adopted by small-scale farmers, who are the major food producers in the region. In this technique, small pits are dug in the soil, and about 2 handfuls of organic amendment such as crop residues, manure or their composted form are placed in the pits. The technique combines water harvesting aspects as well as nutrient management practices. To study the resource-use efficiency in the zai in the context of the Sahelian zone of Niger, studies were conducted both on-station with a controlled water supply and on-farm. During the dry season 1999 and 2000, to study the effect of water availability on nutrient release and availability to the crop in the zai compared with classical flat planting, different water regimes were applied, and all plots were amended with cattle manure except for the control. The effect of type and rate of different amendments on the performance of millet under zai conditions was also studied. Millet recovery from dry spell and their effect on millet total dry matter yield was studied under zai and flat-planting conditions as 3-week and 4-week dry spells were compared to continuous irrigation. The experiments were conducted at the ICRISAT experimental station at Sadore. During the rainy season 1999 and 2000, the effect of different designs and combinations of the water catchment area and nutrient management techniques on the performance of the millet crop was studied as two pit sizes plus flat planting and 3 types amendment plus a control were tested. During the rainy season of 2000, the influence of termite activity on organic amendment decomposition was studied through experiments with pesticide application. These rainy season experiments were conducted on-farm at Damari and Kakassi. The sites have contrasting soil characteristics and rainfall regimes. At Damari, the long-term average annual rainfall is 550 mm. The soil is acidic (pH H_2O = 4.2), with low effective cation exchange capacity (ECEC = 2.8 $cmol_+ \ kg^{-1}$) with a relatively high aluminum saturation (29%) and 61% base saturation. The sand and clay content of the soils is 84% and 13%, respectively, the Bray-1 extractable P is 2 mg kg^{-1} and the total N is 116 mg kg^{-1}. At Kakassi, the long-term average annual rainfall is 450 mm. The reaction of the soil is almost neutral (pH H_2O = 6.4), with relatively high ECEC of 7.9 $cmol_+ \ kg^{-1}$ and a 99% base saturation. The sand and clay content was 69% and 29%, respectively, the extractable P is 0.2 mg kg^{-1} and the total N is 169 mg kg^{-1}.

Zai treatment, when used in combination with good quality amendment applied at the rate of 3 t ha^{-1}, significantly increased total dry matter (TDM) as well as grain yield. In the zai, 4000 to 6500 kg ha^{-1} TDM was achieved compared to 990 - 3000 with flat planting when cattle manure was applied. On farmer fields, 900 - 1100 kg ha^{-1} grain yield were produced in the zai compared to 450 to 700 kg ha^{-1} with traditional flat planting with the same amendment. There was no pit size effect on grain yield or on TDM. Dry spells induced yield loss in all planting techniques. However, zai yielded substantial TDM despite the imposed dry spell. TDM in the zai after the 4-week dry spell (2225 kg ha^{-1}) was similar to TDM in flat planting under continuous irrigation (2148 kg ha^{-1}). At Kakassi, TDM as well as grain yield in the control zai was 2 to 3-fold that produced in the control flat, reflecting the importance of the water harvesting in the zai pit here. However, in both years at this site most of the pits were filled with wind-blown sand and plant debris before planting, which might have improved the nutritional status of the soil in the pit.

Manure decomposition was slower in the zai compared to soil surface exposure. Termite activity enhanced weight loss mainly with soil surface exposure. Even in the presence of termites, manure weight loss was faster than crop residues weight loss. Experimental termite exclusion through pesticide application reduced the rate of manure weight loss at Damari, where termites played the key role in the amendment decomposition, but it had no effect on grain yield at either sites.

Nutrient release followed the rate of amendment decomposition in all experiments except for K, which was released faster than the rate of amendment decomposition. At the end of the period of amendment exposure, 80% or more of all nutrients were released. Manure nutrient release was faster than crop residues and compost nutrient release.

Manure application revived the soil-microbial activity in both on-farm experiments.

Zai increased N, P and K uptake by factor 2 to 3 compared to flat planting, especially in plots amended with manure. Plant uptake in the zai was higher than the amount applied, consequently nutrient uptake from the soil pool must have occurred. Nutrient uptake was low in plots subjected to a dry spell resulting possibly from drying of the most fertile soil layer.

Higher P and K utilization efficiency in crop-residues amended plots compared to manure-amended plots was observed when millet stover was considered. Higher N utilization efficiency was also observed in plots with dry spells compared to plots with continuous irrigation when millet stover yield was considered. Nitrogen utilization efficiency of grain was higher in the zai compared to the flat, whereas the reverse was observed with N use efficiency of millet stover. These tendencies suggest accumulation of nutrients in the grain which was not converted in subsequent yield due to haying-off, as the plant might have run out of water before the grain was able to develop.

The zai technique increased N, P and K agronomic efficiency and apparent recovery. Manure application also increased grain and stover N and K agronomic efficiency and apparent recovery compared to crop residues application, particularly at Damari.

Increased nitrate content was observed in deeper layers in the zai, which could be due to in-depth water percolation. More NO_3^- leaching was observed with crop residues than manure application, which could be explained by possible higher uptake by plants in the manured plots.

Strong rooting systems developed in plots amended with cattle manure. In all cases, the roots (95% or more) were concentrated in the upper 40 cm soil layer. In the zai, most of the roots were in the soil layer of 10 to 40 cm. In the on-farm experiments in 2000 for example, manure application increased root length density in the layer 0 – 60 cm by factor 2.

Rapid progress of the wetting front in the zai was observed at the beginning of the cropping period in all cases. But towards the period of harvest, the volumetric water content decreased especially in plots amended with manure, due to increased plant uptake. Water evaporation may have played a role in the irrigated experiments, which were carried out in a period of the year when air temperature could reach 40^{o}C.

In the on-farm experiments, in both years plant available water (PAW) was less in flat plots than in those treated with zai. At Kakassi from 90 days after sowing to harvest in both years, the PAW was exhausted. A strong negative correlation was observed between TDM and PAW. After the 3-week dry spell, the PAW was 30 mm in plots treated with zai whereas it was less than 20 mm in the flat plots.

Drainage was observed in plots treated with zai, but it was less in plots amended with manure. A strong negative correlation was observed between TDM and drainage.

In conclusion, a good TDM and grain yield far above the average yield is possible when using the zai technique in the Sahel even in rather dry years. However, a good-quality organic amendment is essential on highly degraded soils.

7 RESÜMEE

In der Sahelzone wird die Wiederherstellung der Bodenfruchtbarkeit aufgrund des steigenden Bevölkerungsdrucks zunehmend ineffizient, da immer kürzere Bracheperioden eingeführt werden. In manchen Fällen wird überhaupt keine Bracheperiode mehr eingehalten.

Die Zai-Technik wird benutzt, um degradiertes Land zu rehabilitieren. Bei dieser Technik werden kleine Vertiefungen in den Boden gegraben und ca. 2 Handvoll organisches Material, wie, z.B. Ernterückstände, Dung oder Kompost aus diesen Materialien, eingebracht. Die Technik verbindet wassersammelnde Aspekte mit Nährstoffmanagementverfahren. Zai nutzt örtlich vorhandenes Material und kann von Kleinbauern, den Hauptnahrungsmittelproduzenten der Region, problemlos eingesetzt zu werden. Um die Effizienz der Ressourcennutzung beim Zai in der Sahelzone im Niger zu untersuchen, wurden Untersuchungen sowohl auf einer Forschungsstation - mit kontrollierter Wasserzufuhr - als auch auf Farmen durchgeführt. Die beiden ausgewählten Farmstandorte Damari und Kakassi unterscheiden sich insbesondere durch ihre Böden: Während in Damari sandige, hoch degradierte Böden vorherrschen, sind die Böden in Kakassi durch eine hohe natürliche Fruchtbarkeit und einen höheren Tonanteil gekennzeichnet. In den Stationsversuchen während der Trockenzeiten 1999 und 2000 wurden verschiedene Wasserzufuhrmengen getestet, um die Auswirkung der Wasserverfügbarkeit auf die Nährstofffreisetzung und -verfügbarkeit im Zai im Vergleich zum traditionellen Anbau auf flachem Boden zu vergleichen. Auf allen Flächen außer der Kontrollfläche wurde Viehdung dem Boden zugesetzt. Die Wirkung der verschiedenen Arten organischer Zusätze sowie deren Mengen auf die Leistungsfähigkeit von Hirse unter Zai-Bedingungen wurde ebenfalls untersucht. Die Erholung der Hirsepflanzen von den Trockenperioden und die Auswirkung dieser Trockenzeiten auf die Gesamttrockenmasse der Hirse wurden unter Zai- und Flachanbaubedingungen untersucht, indem 3- und 4-wöchige Trockenzeiten mit Dauerbewässerung verglichen wurden. Während der Regenzeiten 1999 und 2000 wurden die Auswirkungen unterschiedlicher Bauarten und Kombinationen des Wassereinzugsgebietes und der Nährstoffmanagementverfahren auf die Leistungsfähigkeit des Hirseanbaus untersucht, indem 2 verschiedene Zai-Größen plus Flachanbau sowie 3 verschiedene Bodenzusätze plus einer Kontrollfläche untersucht wurden. Während der Regenzeit 2000 wurde der Einfluß der Termitenaktivität auf den Abbau der organischen Bodenzusätze durch einen experimentellen Ausschluss dieser Tiere mit Hilfe von Insektiziden untersucht.

Wenn Zai unter Verwendung organischer Zusätzen hoher Qualität in einer Menge von 3 t ha^{-1} eingesetzt wurde, führte die Technik zu einer signifikanten Erhöhung der Gesamttrockenmasse

(GTM) sowie des Körnerertrags bei den untersuchten Hirsepflanzen. Beim Zai wurden 4000-6000 kg ha^{-1} erreicht; im Vergleich zu 990-3000 kg ha^{-1} beim Flachanbau mit Viehdung. Auf den Farmfeldern wurde ein Hirseertrag von 900-1100 kg ha^{-1} beim Zai erreicht, im Vergleich zu 450-700 kg ha^{-1} beim traditionellen Flachanbau mit dem gleichen Bodenzusatz. Die Größe der Zai-Vertiefungen zeigte keine Auswirkung auf den Hirseertrag oder auf die GTM. Trockenperioden führten zu Ertragsverlusten bei allen Anbautechniken. Beim Zai jedoch war die GTM trotz der auferlegten Trockenperiode beträchtlich: Die GTM im Zai nach der 4-wöchigen Trockenperiode (2225 kg ha^{-1}) war vergleichbar mit der GTM beim Flachanbau mit Dauerbewässerung (2148 kg ha^{-1}). In Kakassi waren die GTM und der Gesamthirseertrag in der Zai-Kontrollfläche 2-3x so hoch wie die entsprechenden Werte der Flachanbaukontrollfläche. Dies zeigt die Bedeutung des wassersammelnden und - konzentrierenden Aspekts der Zai-Technik in Kakassi. In beiden Jahren jedoch waren an diesem Standort die meisten Zai-Löcher mit Sand und Pflanzenresten gefüllt, die vor der Aussaat durch den Wind dorthin transportiert worden waren, und dies könnte möglicherweise den Nährstoffzustand des Bodens im Zai verbessert haben.

Der Dungabbau im Zai war langsamer als im Flachanbau. Die Termitenaktivität führte zu einem erhöhten Dung-Gewichtsverlust hauptsächlich im Flachanbau. In der Gegenwart von Termiten war der Gewichtsverlust des Dungs schneller als der von Ernterückständen. Der experimentelle Ausschluss der Termiten durch die Insektizide verringerte den Grad des Dung-Gewichtverlustes in Damari, wo hauptsächlich die für die Zersetzung des Bodenzusatzes verantwortlich waren. An beiden Standorten wurde jedoch keine Auswirkung auf den Hirseertrag beobachtet.

Der Grad der Nährstofffreigabe entsprach dem Abbau des organischen Zusatzes in allen Versuchen außer beim K, wo die Freigabe schneller war als der Abbau. Am Ende der Versuchsperiode war die Nährstofffreisetzung 80% oder höher. Die Nährstofffreisetzung beim Dung war höher als bei den Ernstrückständen und beim Kompost.

Die Zugabe von Dung führte in beiden Farmexperimenten zu einer Wiederbelebung der Bodenmikroben-Aktivität.

Beim Zai war die N-, P- und K-Aufnahme 2-3x höher als im Flachanbau, insbesondere auf den Flächen mit Dungzusatz. Die Nährstoffaufnahme durch die Pflanzen war unter Zai höher als die eingebrachte Menge, daher muß eine Nährstoffaufnahme aus den Nährstoffvorräten des Bodens erfolgt sein. Die Nährstoffaufnahme auf den Flächen, die einer Trockenperiode ausgesetzt waren, war niedrig, möglicherweise als Folge der Austrocknung der nährstoffreichsten obersten Bodenschicht.

Eine höhere P- und K-Nutzungseffizienz auf den Flächen mit Zusatz von Ernteresten im Vergleich zu denen mit Dungzusatz wurde im Zusammenhang mit Hirsestroh beobachtet. Hier wurde eine höhere N-Effizienz in Bezug auf Hirsestroh auch auf den Flächen mit Trockenperioden im Vergleich zu den Flächen mit Dauerbewässerung beobachtet. Die N-Nutzungseffizienz in Körnern im Zai war höher als im Flachanbau, Im Gegensatz zur N-Nutzungseffizienz des Hirsestrohs. Diese Tendenzen deuten auf eine Nährstoffakkumulation in den Körnern hin, die jedoch von den Pflanzen nicht in Ertrag umgesetzt wurde. Grund dafür war eine erhöhte Heubildung, die bewirkt, dass der Pflanze zum Zeitpunkt der Körnerreifung nicht mehr ausreichend Wasser zur Verfügung steht.

Die Zai-Technik erhöhte die agronomische Effizienz von N-, P- und K sowie deren „scheinbare Aufnahme“ (Differenz zwischen Nährstoffaufnahme in behandelten und Kontrollflächen, geteilt durch die Menge der Nährstoffzugabe). Der Zusatz von Dung erhöhte auch die agronomische Effizienz von N und K in Körnern und Stroh sowie die „scheinbare Aufnahme“ im Vergleich zum Zusatz von Ernterückständen, besonders in Damari.

Ein erhöhter Nitratgehalt wurde in den tieferen Bodenschichten unter Zai beobachtet, was an der tiefen Wasserversickerung liegen könnte. Bei Zusatz von Ernteresten kam es zu einer höheren NO_3^--Auslaugung als bei Dungzusatz, was durch eine höhere Aufnahme durch die Pflanzen in den mit Dung behandelten Flächen erklärt werden könnte.

Kräftige Wurzelsysteme entwickelten sich auf den Flächen mit Dungzusatz. In allen Fällen konzentrierten sich die Wurzeln (95% oder mehr) in den oberen 40 cm des Bodens. Beim Zai befanden sich die meisten Wurzeln in der 10 bis 40 cm tiefen Bodenschicht. In den Farmversuchen im Jahr 2000 zum Beispiel erhöhte Dungzusatz die Wurzellängendichte in der Schicht 0 - 60 cm um den Faktor 2.

Ein rasches Fortschreiten der Nässefront im Boden unter Zai wurde zu Beginn der Versuchsperiode auf allen Flächen beobachtet. Mit Näherrücken der Ernteperiode jedoch nahm der volumetrische Wassergehalt ab, besonders in den Flächen mit Dungzusatz, und zwar aufgrund einer höheren Aufnahme durch die Pflanzen. Möglicherweise spielte die Wasserverdunstung eine Rolle in den Bewässerungsversuchen, die in der Jahreszeit durchgeführt wurden, in der die Lufttemperaturen 40°C erreichen können.

In den Farmversuchen war in beiden Jahren die Menge des pflanzenverfügbaren Wassers (PVW) bei Flachanbau geringer als unter Zai. In Kakassi war das PVW 90 Tage nach der Aussaat bis zur Ernte in beiden Jahren verbraucht. Eine starke negative Korrelation zwischen der GTM und dem PVW wurde beobachtet. Nach der 3-wöchigen Trockenperiode betrug das PVW 30 mm in den Zai-Flächen, während es bei Flachanbau unter 20 mm lag.

Drainage kam in den Zai-Flächen vor, aber sie war auf den Flächen mit Dungzusatz geringer. Es gab eine starke negative Korrelation zwischen der GTM und der Drainage.

Zusammenfassend kann festgestellt werden, dass ein GTM- und Körner-Ertrag weit über dem durchschnittlichen Ertrag sogar dann möglich sind, wenn im Sahel die Zaitechnik in ziemlich trockenen Jahren angewandt wird. Jedoch ist auf stark degradierten Böden die Zugabe organischen Materials von sehr hoher Qualität unabdingbar.

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9 APPENDICES

Appendix 1: Effect of planting techniques (zai vs flat) amendment type and rate on millet root radius (µm) distribution; Sadore, dry season 1999

	Crop residues			Manure			Control		
Depth	1t ha^{-1}	3t ha^{-1}	5t ha^{-1}	1t ha^{-1}	3t ha^{-1}	5t ha^{-1}	Zai	Flat	$LSD_{0.05}$
Twenty seven days after sowing									
0-10cm	218	247	170	239	244	287	183	234	84
10-20cm	84	77	81	55	136	109	85	92	31
20-40cm	27	27	15	35	37	31	18	30	22
40-60cm	29	18	12	6	17	26	17	25	13
Forty seven days after sowing									
0-10cm	640	689	614	816	1173	1211	323	279	183
10-20cm	119	140	156	159	262	271	82	63	87
20-40cm	40	54	62	64	111	137	35	41	35
40-60cm	23	63	35	53	65	71	34	38	33
60-80cm	23	44	29	40	62	70	16	26	30
Sixty seven days after sowing									
0-10cm	711	1145	1142	1202	1714	1804	444	455	351
10-20cm	187	434	211	538	614	776	169	131	236
20-40cm	72	140	78	86	282	282	70	62	98
40-60cm	54	59	58	82	132	150	32	22	64
60-80cm	47	64	49	72	81	79	23	47	50
80-100cm	47	49	53	63	63	107	38	26	51

$LSD_{0.05}$ = least significant difference at 0.05 probability level

Appendix 2: Percentage of irrigation water drained throughout the irrigation period; Sadore dry season 1999

Planting	Treatments		Number of days after irrigation started		
technique	Amendment	Rates	34 days	55 days	75 days
Zai	Crop	1t ha^{-1}	73.6	76.5	70.4
		3t ha^{-1}	33.2	38.8	35.8
		5t ha^{-1}	61.0	69.0	65.3
	Manure	1t ha^{-1}	53.2	49.8	44.8
		3t ha^{-1}	7.9	12.7	9.5
		5t ha^{-1}	42.3	32.2	22.4
	Control	-	41.2	47.0	49.2
Flat	Control	-	22.3	24.0	23.9
		$LSD_{0.05}$	65.0	49.9	42.5

$LSD_{0.05}$ = least significant difference at 0.05 probability level

Appendix 3: Total nitrate content over 200 cm depth during the cropping period; Sadore, dry season 2000

		Nitrate content (kg ha^{-1})			
Watereg	Plantech	Initial	20 DAS	44 DAS	78 DAS
No DS	Flat	358	313	345	119
	Zai	358	346	308	103
3 W DS	Flat	511	462	416	323
	Zai	511	480	412	181
4 W DS	Flat	486	440	395	271
	Zai	486	421	309	235
	$LSD_{0.05}$		116	171	99

DAS = days after sowing
$LSD_{0.05}$ = least significant difference at 0.05 probability level

Appendix 4: Effect of amendment type on millet grain yield per hill and grain yield per tiller; Damari and Kakassi, rainy seasons 1999 and 2000

	Grain yield per hill (g)				Grain yield per tiller (g)			
Organic	1999		2000		1999		2000	
amendment	Damari	Kakassi	Damari	Kakassi	Damari	Kakassi	Damari	Kakassi
CR	15.9	44.6	10.1	54.1	2.2	8.4	5.7	7.7
Compost	9.2	37.2	7.6	31.6	1.5	7.4	1.9	4.5
Manure	104.6	82.9	39.8	81.3	8.8	10.4	6.4	10.9
$LSD_{0.05}$	18.21	18.62	24.83	23.23	1.92	3.28	9.23	3.91

$LSD_{0.05}$ = least significant difference at 0.05 probability level; CR = crop residues

Appendix 5: Effect of planting techniques (zai vs flat) on millet grain yield per hill and grain yield per tiller; Damari and Kakassi, rainy season 1999 and 2000

	Grain yield per hill (g)				Grain yield per tiller (g)			
Planting	1999		2000		1999		2000	
technique	Damari	Kakassi	Damari	Kakassi	Damari	Kakassi	Damari	Kakassi
Zai, 25cm	51.4	60.9	22.0	56.5	5.2	9.9	4.4	8.6
Zai, 50cm	47.5	70.0	23.8	75.7	4.3	10.4	7.7	10.5
Flat	30.8	33.9	11.7	34.9	2.9	5.9	1.8	4.1
$LSD_{0.05}$	18.21	18.62	24.83	23.23	1.92	3.28	9.23	3.91
	Control							
Zai, 25cm	1.9	44.6	1.2	44.7	0.4	12.3	0.3	9.7
Zai, 50cm	1.0	59.8	1.5	35.4	0.1	11.8	0.5	4.9
Flat	0.1	14.9	0.3	9.4	0.01	5.15	0.07	2.11
$LSD_{0.05}$	1.34	22.36	3.41	30.31	0.237	4.825	1.162	7.692

$LSD_{0.05}$ = least significant difference at 0.05 probability level

Appendix 6: Effect of planting techniques (zai vs flat) on millet N, P and K utilization efficiency; Damari, rainy season 1999

Planting technique	Millet nutrient utilization efficiency during the cropping period (kg/kg)											
	36 DAS			76 DAS			119 DAS (Stover)			119 DAS (Grain)		
	N	P	K	N	P	K	N	P	K	N	P	K
zai.25cm	37	618	27	46	269	43	69	341	51	38	303	145
zai.50cm	37	674	28	45	259	41	68	348	49	37	309	144
flat	38	1025	35	48	262	48	60	315	55	31	254	123
$LSD_{0.05}$	1	180	3	8	13	8	12	43	14	8	69	29

$LSD_{0.05}$ = least significant difference at 0.05 probability level; DAS = days after sowing

Appendix 7: Effect of planting techniques (zai vs flat) on millet N, P and K utilization efficiency; Kakassi, rainy season 1999

Planting technique	Millet nutrient utilization efficiency during the cropping period (kg/kg)											
	22 DAS			65 DAS			113 DAS (Stover)			113 DAS (Grain)		
	N	P	K	N	P	K	N	P	K	N	P	K
zai.25cm	32	438	22	48	297	36	96	230	46	39	204	156
zai.50cm	32	449	21	44	281	34	92	228	46	39	210	156
flat	32	468	22	49	292	34	87	240	45	38	217	153
$LSD_{0.05}$	2	85	2	9	26	4	13	10	4	2	13	7

$LSD_{0.05}$ = least significant difference at 0.05 probability level; DAS = days after sowing

Appendix 8: Effect of planting techniques (zai vs flat) on millet N, P and K utilization efficiency; Kakassi, rainy season 2000

Planting technique	Millet nutrient utilization efficiency during the cropping period (kg/kg)											
	20 DAS			62 DAS			123 DAS (Stover)			123 DAS (Grain)		
	N	P	K	N	P	K	N	P	K	N	P	K
zai.25cm	25	273	22	41	706	35	82	1596	51	44	371	174
zai.50cm	25	292	22	42	661	32	80	1472	50	44	380	164
flat	28	327	27	40	717	35	79	1594	49	42	364	181
$LSD_{0.05}$	6	62	6	6	104	4	11	344	4	2	73	45

$LSD_{0.05}$ = least significant difference at 0.05 probability level; DAS = days after sowing

Appendix 9: Effect of amendment type on millet N, P, and K utilization efficiency; Kakassi, rainy season 1999

Organic amendment	Millet nutrient utilization efficiency during the cropping period (kg/kg)											
	22 DAS			65 DAS			113 DAS (Stover)			113 DAS (Grain)		
	N	P	K	N	P	K	N	P	K	N	P	K
Control	32	502	23	42	297	34	84	242	44	39	220	158
CR	33	548	24	45	311	32	89	227	45	40	200	156
Compost	32	493	22	50	289	35	94	232	45	38	216	160
Manure	32	262	19	51	263	38	100	230	49	37	207	147
$LSD_{0.05}$	2	98	2	11	30	5	15	12	4	3	15	8

$LSD_{0.05}$ = least significant difference at 0.05 probability level; CR = crop residues

Appendix 10: Effect of amendment type on millet N, P and K utilization efficiency; Kakassi, rainy season 2000

	Millet nutrient utilization efficiency during the cropping period (kg/kg)											
Organic	20 DAS			62 DAS			123 DAS (Stover)			123 DAS (Grain)		
amendment	N	P	K	N	P	K	N	P	K	N	P	K
Control	26	381	28	40	768	34	76	1527	48	44	406	170
CR	26	266	22	47	716	33	81	1706	44	44	384	210
Compost	25	300	22	38	732	34	85	1616	55	42	363	156
Manure	27	242	23	39	564	35	78	1366	53	42	333	155
$LSD_{0.05}$	7	72	6	7	120	4	13	397	4	2	85	52

$LSD_{0.05}$ = least significant difference at 0.05 probability level; DAS = days after sowing

Appendix 11: Effect of planting techniques (zai vs flat) on millet N, P and K apparent recovery fraction; Kakassi, rainy season 1999

	Millet nutrient recovery fraction during the cropping period											
Planting	22 DAS			65 DAS			113 DAS (Stover)			113 DAS (Grain)		
technique	N	P	K	N	P	K	N	P	K	N	P	K
zai.25cm	0.016	0.013	0.065	0.73	0.54	2.83	0.21	0.38	0.93	0.03	-0.04	-0.01
zai.50cm	0.025	0.014	0.156	0.30	0.05	1.24	0.15	0.84	1.24	0.02	-0.08	-0.07
flat	0.011	0.005	0.056	0.28	0.49	1.37	0.14	0.29	0.55	0.16	0.13	0.08
$LSD_{0.05}$	0.018	0.016	0.079	0.70	0.92	4.37	0.33	1.37	3.02	0.321	0.60	0.39

$LSD_{0.05}$ = least significant difference at 0.05 probability level; DAS = days after sowing

Appendix 12: Effect of planting techniques (zai vs flat) on millet N, P and K apparent recovery fraction; Kakassi, rainy season 2000

	Millet nutrient recovery fraction during the cropping period											
Planting	20 DAS			62 DAS			123 DAS (Stover)			123 DAS (Grain)		
technique	N	P	K	N	P	K	N	P	K	N	P	K
zai.25cm	1E-04	0.001	0.008	0.37	0.14	1.15	-0.02	-0.04	-0.54	-0.02	-0.12	-0.06
zai.50cm	0.003	0.002	0.005	1.12	0.83	4.22	0.41	0.25	1.53	0.26	0.34	0.21
flat	0.004	0.004	0.015	0.52	0.24	1.93	0.29	0.12	0.77	0.11	0.09	0.05
$LSD_{0.05}$	0.004	0.003	0.018	0.82	0.65	3.70	0.36	0.22	1.23	0.19	0.36	0.22

$LSD_{0.05}$ = least significant difference at 0.05 probability level; DAS = days after sowing

Appendix 13: Effect of planting techniques (zai vs flat) on millet N, P and K agronomic efficiency; Kakassi, rainy season 1999

	Millet nutrient Agronomic efficiency (grain) yield per unit applied nutrient)											
Planting	22 DAS			65 DAS			113 DAS (Stover)			113 DAS (Grain)		
technique	N	P	K	N	P	K	N	P	K	N	P	K
zai.25cm	0.5	3.3	1.4	35	135	107	21	46	34	1	-21	-3
zai.50cm	0.8	6.3	3.1	13	51	51	31	123	81	0	-24	-11
flat	0.4	2.5	1.1	22	128	52	22	66	40	6	29	13
$LSD_{0.05}$	0.6	4.4	1.6	35	288	133	29	298	144	121	12.6	62

Appendix 14: Effect of planting techniques (zai vs flat) on millet N, P and K agronomic efficiency; Kakassi, rainy season 2000

PLANTING TECHNIQUE	MILLET NUTRIENT AGRONOMIC EFFICIENCY (GRAIN) YIELD PER UNIT APPLIED NUTRIENT)											
	20 DAS			62 DAS			123 DAS (STOVER)			123 DAS (GRAIN)		
	N	P	K	N	P	K	N	P	K	N	P	K
ZAI.25CM	-0.013	-0.379	0.007	11	43	29	-5	-110	-31	-2	-41	-12
ZAI.50CM	0.076	0.513	0.094	49	495	135	37	337	102	12	103	31
FLAT	0.098	0.861	0.276	24	182	71	25	177	47	5	27	8
$LSD_{0.05}$	0.092	0.877	0.218	39	412	130	23	211	75	9	97	37

$LSD_{0.05}$ = least significant difference at 0.05 probability level; DAS = days after sowing

Appendix 15: Effect of amendment type on millet N, P and K agronomic efficiency; Damari, rainy season 2000

ORGANIC AMENDMENT	MILLET NUTRIENT AGRONOMIC EFFICIENCY DURING THE CROPPING PERIOD (KG/KG)											
	25 DAS			67 DAS			122 DAS (STOVER)			122 DAS (GRAIN)		
	N	P	K	N	P	K	N	P	K	N	P	K
CR	-0.01	-0.12	-0.01	7	86	6	10	113	7	4	42	3
COMPOST	0.01	0.09	0.04	15	165	68	24	260	107	6	63	26
MANURE	0.10	0.27	0.15	23	62	34	28	76	42	11	31	17
$LSD_{0.05}$	0.11	1.21	0.43	9	68	26	10	99	39	4	32	13

$LSD_{0.05}$ = least significant difference at 0.05 probability level; CR = crop residues

Appendix 16: Effect of amendment type on millet N, P and K apparent recovery fraction; Kakassi, Rainy season 1999

ORGANIC AMENDMENT	MILLET NUTRIENT RECOVERY FRACTION DURING THE CROPPING PERIOD											
	22 DAS			65 DAS			113 DAS (STOVER)			113 DAS (GRAIN)		
	N	P	K	N	P	K	N	P	K	N	P	K
CR	0.009	0.009	0.010	-0.01	-0.10	0.05	0.08	0.42	0.10	0.02	0.09	0.01
COMPOST	0.025	0.018	0.202	0.29	0.77	2.84	-0.17	0.51	0.26	-0.10	-0.19	-0.16
MANURE	0.018	0.005	0.064	1.03	0.41	2.56	0.59	0.58	2.36	0.29	0.11	0.15
$LSD_{0.05}$	0.018	0.016	0.079	0.70	0.92	4.37	0.33	1.37	3.02	0.32	0.60	0.39

$LSD_{0.05}$ = least significant difference at 0.05 probability level; CR = crop residues

Appendix 17: Effect of amendment type on millet N, P and K apparent recovery fraction; Kakassi, rainy season 2000

ORGANIC AMENDMENT	MILLET NUTRIENT RECOVERY FRACTION DURING THE CROPPING PERIOD											
	20 DAS			62 DAS			123 DAS (STOVER)			123 DAS (GRAIN)		
	N	P	K	N	P	K	N	P	K	N	P	K
CR	0.001	0.002	0.002	0.25	0.35	0.46	0.19	0.15	0.40	0.07	0.10	0.01
COMPOST	0.002	0.003	0.020	1.12	0.72	5.77	0.12	0.12	0.39	0.07	0.14	0.10
MANURE	0.004	0.001	0.007	0.63	0.13	1.07	0.38	0.06	0.98	0.21	0.07	0.09
$LSD_{0.05}$	0.004	0.003	0.018	0.83	0.67	3.67	0.36	0.22	1.23	0.19	0.36	0.22

$LSD_{0.05}$ = least significant difference at 0.05 probability level; CR = crop residues

Appendix 18: Effect of amendment type on millet N, P and K agronomic efficiency; Kakassi, rainy season 1999

Organic amendment	Millet nutrient agonomic efficency during the cropping period											
	22 DAS			65 DAS			113 DAS (Stover)			113 DAS (Grain)		
	N	P	K	N	P	K	N	P	K	N	P	K
CR	0.29	2.42	0.24	-0.9	-7.9	-0.8	6.8	58.0	5.8	0.9	8.0	0.8
Compost	0.79	8.40	4.19	20.2	214.7	107.1	5.1	47.1	23.3	-4.4	-46.5	-23.2
Manure	0.58	1.21	1.17	51.2	107.8	104.0	61.9	130.6	125.9	10.5	22.1	21.3
$LSD_{0.05}$	0.55	4.44	1.62	35.0	287.8	133.0	29.3	298.2	143.5	12.1	125.6	62.4

$LSD_{0.05}$ = least significant difference at 0.05 probability level; CR = crop residues

Appendix 19: Effect of amendment type on millet N, P and K agronomic efficiency; Kakassi, rainy season 2000

Organic amendment	Millet nutrient agonomic efficency during the cropping period											
	20 DAS			62 DAS			123 DAS (Stover)			123 DAS (Grain)		
	N	P	K	N	P	K	N	P	K	N	P	K
CR	0.017	0.192	0.013	17.4	200.8	13.1	14.8	170.4	11.1	3.1	35.7	2.3
Compost	0.05	0.549	0.226	41.3	450.2	185.2	14.4	157.3	64.7	2.6	28.8	11.9
Manure	0.094	0.254	0.138	25.3	68.2	37.2	28.5	76.9	42.0	8.8	23.7	12.9
$LSD_{0.05}$	0.092	0.877	0.218	38.7	412.2	129.5	22.8	211.4	75.5	9.0	96.6	36.5

$LSD_{0.05}$ = least significant difference at 0.05 probability level; DAS = days after sowing

Appendix 20: Root length density and root total dry matter at harvest as affected by planting techniques (zai vs flat); Damari rainy season 2000

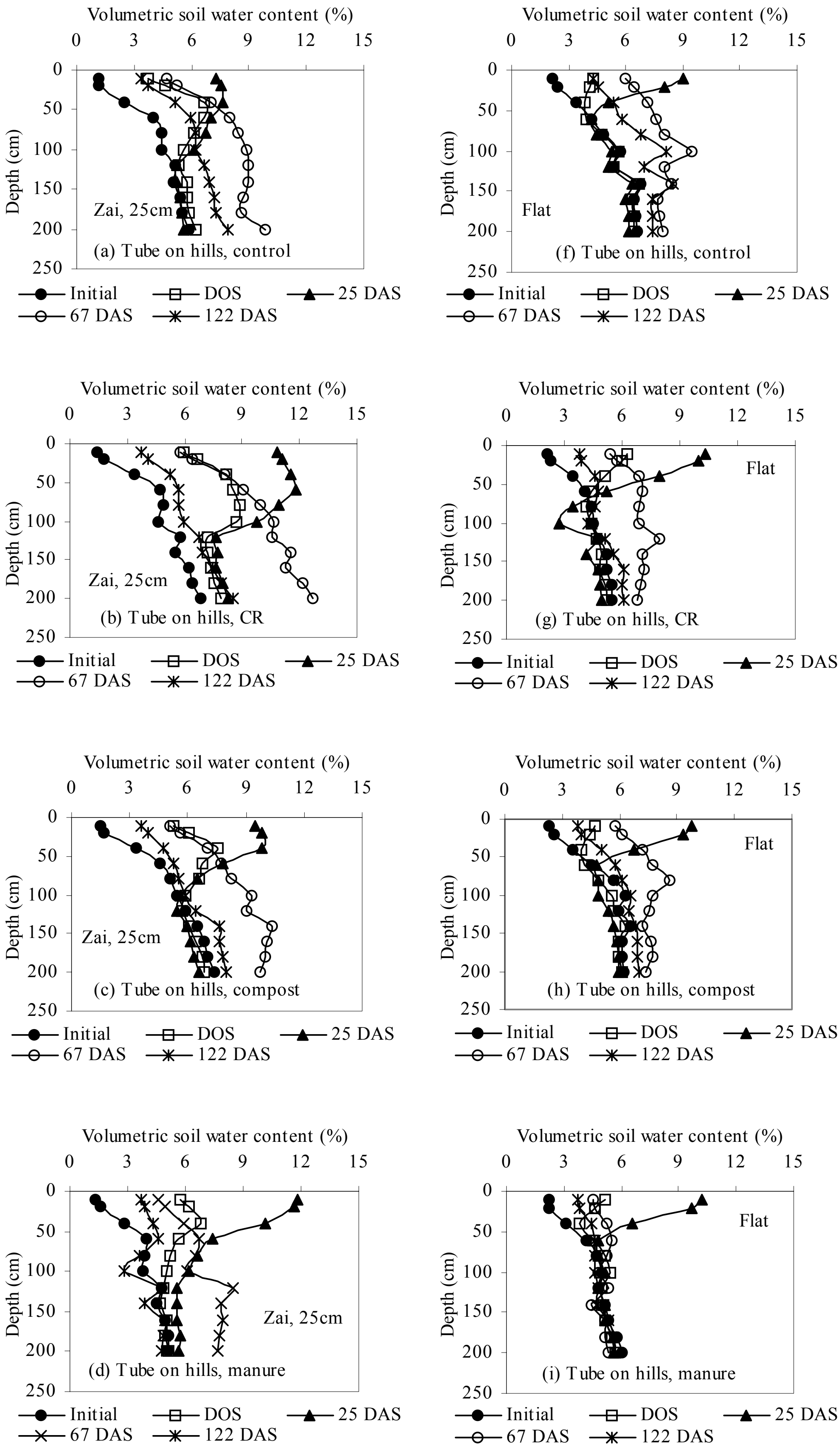
Depth (cm)	Root length density (cm cm^{-3})				Root dry mass (g m^{-2})			
	Zai, 25cm	Zai, 50cm	Flat	$LSD_{0.05}$	Zai, 25cm	Zai, 50cm	Flat	$LSD_{0.05}$
0-10	0.40	0.27	11.02	34.62	64.9	53.2	112.8	70.3
10-20	0.33	0.28	0.28	0.26	26.9	25.1	16.2	26.6
20-40	0.47	0.36	0.35	0.36	19.9	25.3	17.6	24.2
40-60	0.21	0.52	0.18	1.49	7.1	6.3	7.2	12.9
60-80	0.06	0.05	0.08	0.08	3.3	3.3	13.7	32.2
80-100	0.05	0.03	0.06	0.05	3.1	2.4	2.9	2.7
100-120	0.06	0.03	0.06	0.08	3.5	1.4	3.2	3.0
120-140	0.05	0.04	0.05	0.08	3.2	1.3	4.7	7.8

$LSD_{0.05}$ = least significant difference at 0.05 probability level

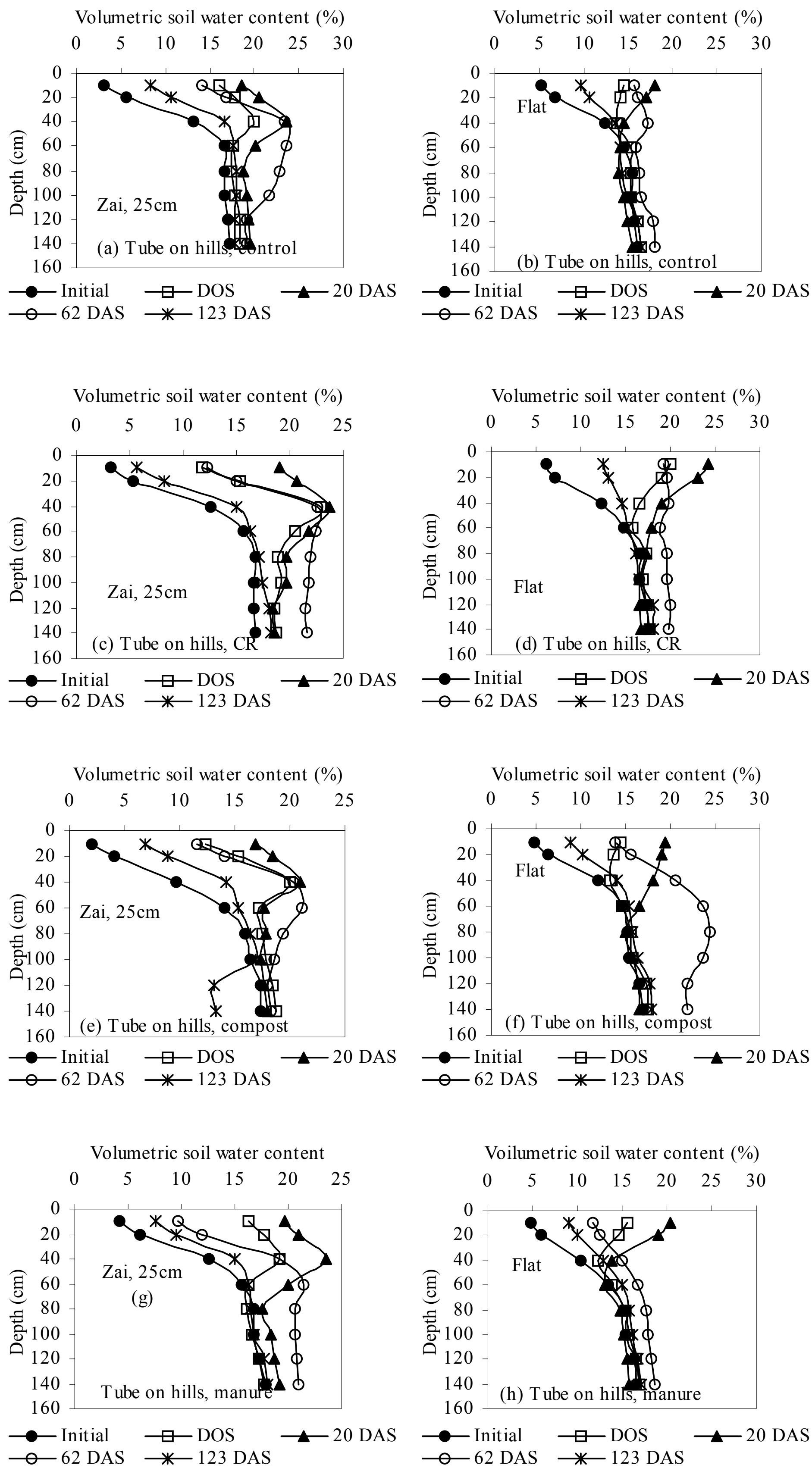
Appendix 21: Root length density and root total dry matter at harvest as affected by planting techniques (zai vs flat), Kakassi, rainy season 2000

	Root length density (cm cm^{-3})				Root total dry matters (g m^{-2})			
Depth (cm)	Zai, 25cm	Zai, 50cm	Flat	$LSD_{0.05}$	Zai, 25cm	Zai, 50cm	Flat	$LSD_{0.05}$
0-10	1.34	1.23	1.7	0.9	200.4	203.5	205.4	158.7
10-20	0.84	0.68	1.0	0.5	43.9	43.0	33.3	35.5
20-40	0.32	0.19	0.3	0.5	11.1	7.6	9.1	14.9
40-60	0.11	0.11	0.2	0.3	4.5	11.7	6.6	27.8
60-80	0.10	0.04	0.1	0.3	3.8	12.2	2.9	33.5
80-100	0.03	0.02	0.1	0.1	1.0	1.1	1.6	2.7
100-120	0.03	0.03	0.03	0.1	1.1	1.5	1.5	2.7
120-140	0.02	0.01	0.01	0.03	0.8	0.6	0.6	2.0

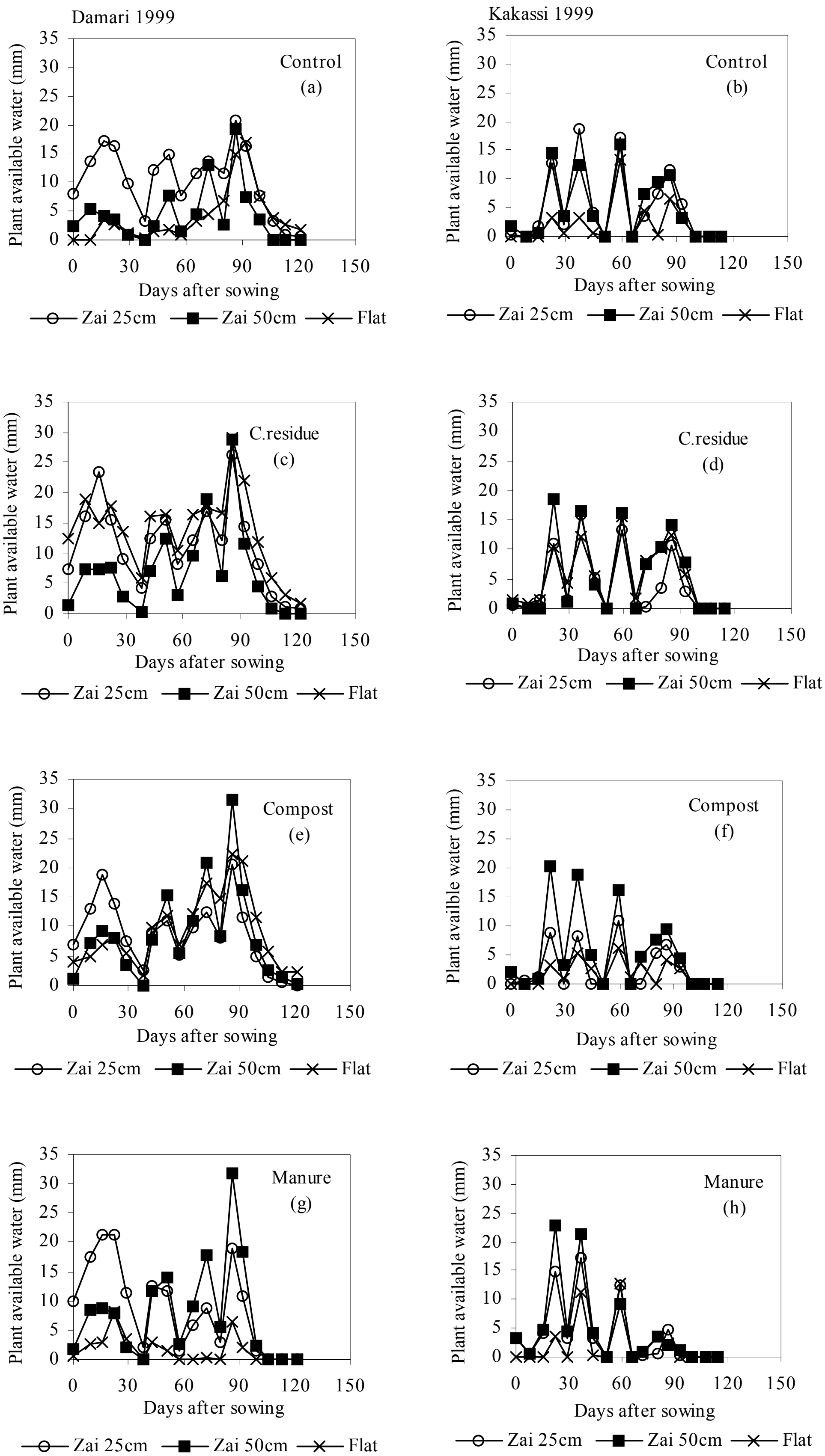
$LSD_{0.05}$ = least significant difference at 0.05 probability level



Appendix 22: Effect of planting techniques (zai vs flat) and amendment type on volumetric water content in the soil profile; Damari, rainy season 2000 - DOS = day of sowing; CR = crop residues; DAS = days after sowing



Appendix 23: Effect of planting techniques (zai vs flat) and amendment type on volumetric water content in the soil profile; Kakassi, rainy season 2000 – DOS = day of sowing; CR = crop residues; DAS = days after sowing



Appendix 24: Plant available water as affected by planting techniques (zai vs flat) and amendment type; Damari and Kakassi, rainy season 1999