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Combined Traditional Water Harvesting (Zaï) and Mulching Techniques Increase Available Soil Phosphorus Content and Millet Yield

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Abstract

Mismanagement of soil fertility is one of the major challenges for farmers in the Sahelian zone of Niger. This study, conducted in 2012 and 2013 in western part of Niger, aimed at examining the effects of combined Zaï and Mulching techniques on soil fertility and millet productivity. The experimental design was a randomized Fischer block with four treatments (Zaï, mulching, Zaï + mulching and Control) and four replicates. In the Zaï treatment, 200 g cattle manure was added per Zaï hole (2.8 t/ha) and millet straw (2.0 t/ha) was spread in the mulching treatment. The control treatment did not receive cattle manure or millet straw. The measurements concerned grain and straw yield of millet (*Pennisetum glaucum* (L.) R. Br.) as well as physico-chemical soil characteristics. The results show that the Zaï + mulching treatment improved soil fertility parameters and grain yield significantly. The content of available phosphorus and clay in the soil was doubled after two years. The soil organic carbon content had increased from 0.45 to 2.1 $g \cdot kg^{-1}$. The cation exchange capacity and pH had increased by one compared to the control. The content of total nitrogen (0.1 to 0.2 $g \cdot kg^{-1}$) and total potassium (8.6 to 57.8 $mg \cdot kg^{-1}$) did not vary significantly between treatments. An increase of 250 $kg \cdot ha^{-1}$ grain of millet compared to the control was obtained. Concerning the straw yield, the highest values were obtained by Zaï treatment in both years (855±216 $kg \cdot ha^{-1}$ in 2012 and 843±313 $kg \cdot ha^{-1}$ in 2013) and Zaï + mulching in 2013 (888±251 $kg \cdot ha^{-1}$). The combination Zaï + mulching improved the soil fertility and millet productivity and can be used to restore degraded soils.

Keywords: Zaï, mulching, available phosphorus, millet productivity, agro-ecosystems

1. Introduction

In semi-arid West Africa, the total extent of severely degraded soils due to agricultural activities has been estimated to 1.1 million km^2 (Vågen et al., 2005). In this zone, soil infertility is the major constraint to increased agricultural productivity (Bationo et al., 2008). In the Sahel, partmost soils are sandy, acidic and have low contents of clay and organic matter (Bationo & Mokwunye, 1991), which are some of the conditions that lead to crusting (Pieri, 1989). These inherent constraints of soil fertility have been exacerbated by the mismanagement of agricultural land. Indeed, nutrient balances are negative for many cropping systems, indicating that nutrient inflows are less than outflows. According to Stoorvogel and Smaling (1990), removal of crop residues from the fields has contributed to the negative nutrient balance. Formerly, the best management of soil fertility was the use of fallow periods (Hiernaux, 1998), but the population growth makes fallow almost impossible for longer periods and promotes continuous cropping. Consequently, the annual depletion of nutrients such as nitrogen and phosphorus, which are the most limiting nutrients, is higher than the annual requirement (Bationo et al., 2008).

Various agricultural practices concerning organic matter management, such as mulching and mulching coupled with the traditional water harvesting techniques like "amended Zaï", have been used to restore soil fertility (Roose et al., 1993; Ambouta et al., 2000). Mulching reduces the impact of erosion on the physicochemical properties of the soil by improving the organic carbon content (Wezel & Boecker, 1998; Bationo & Buerkert, 2001) and contributing to increase pH, cation exchangeable capacity and improve phosphorus availability in the top soil (Buerkert et al., 2000; Iijima et al., 2004; Cong & Merckx, 2005). Many studies have shown that millet production could be increased by mulch application on sandy soil (Buerkert & Lamers, 1999; Akponikpe et al., 2008). Furthermore, the traditional water harvesting techniques, such as Zaï (Tassa), are another way of restoring the fertility of degraded soils (Bouzou & Dan Lamso, 2004). Decomposition of organic amendments and nutrient release is enhanced in the Zaï holes compared to surface application (Fatondji et al., 2009). According to Fatondji et al. (2006), millet grain yields of more than 1 $t \cdot ha^{-1}$ were obtained from fields with Zaï holes amended with cattle manure at a rate of 3 $t \cdot ha^{-1}$, and they reported that the effects of Zaï are not only due to water harvesting, but are also caused by the quality and quantity of amendments. However, the nutrients released from organic manure in Zaï holes can also be leached into deeper soil layers (Fatondji et al., 2011), and another problem is that biomass for mulching is scarce due to low overall production levels and the many uses of millet straw, e.g. as construction materiel and cooking fuel (Lamers & Feil, 1993). According to some authors, the solution may lie in developing a combination of various restoration techniques (Roose & Barthès, 2001; Zougmoré et al., 2004; Rezaei et al., 2014).

Nevertheless, to date no research has been undertaken to study the combined effect of Zaï and mulching on the available phosphorus content, which is the major constraint of millet production in western Niger. The objective of this work is therefore to study the effect of combining Zaï and mulching techniques on available phosphorus content and pearl millet yields under field conditions.

2. Materials and Methods

2.1 Site Description

The study area is located in the Municipality of Simiri (13°50′ to 14°17′ northern latitude and 01°50′ to 02°40′ western longitude) in the western part of Niger. The climate is Sahelian semi-arid type (Mahamane et al., 2012). The mean rainfall (1983-2013) at Simiri is 390.6±100 mm and the monthly temperature mean varies between 24.2 °C and 34 °C. The soil type is tropical ferruginous and the soil surface state is crusted glacis with a gentle 2% slope. The main activities of the local population are agriculture and livestock. Millet, cowpea, and sorghum are the most cultivated crops (Moussa et al., 2015b).

2.2 Rainfall

Rainfall data originated from the national institute of statistics in Niger. The rainy season in 2012 began on June 15, and in 2013 on April 25, and the latest rains were recorded October 1st and August 10th in 2012 and 2013, respectively (Figure 1). The cumulated rainfall was 613 mm in 2012, and 380 mm in 2013 with 27 and 24 rain events in the two years, respectively. Rainy events higher than 20 mm represent 75% of total rainfall recorded in 2012 and 66% in 2013. However, a dry spell lasting about 15 days in 2013 occurred after the first more important rain occurred on June 27 compared to the rainy season of 2012, where the distribution of rainfall was more regular.

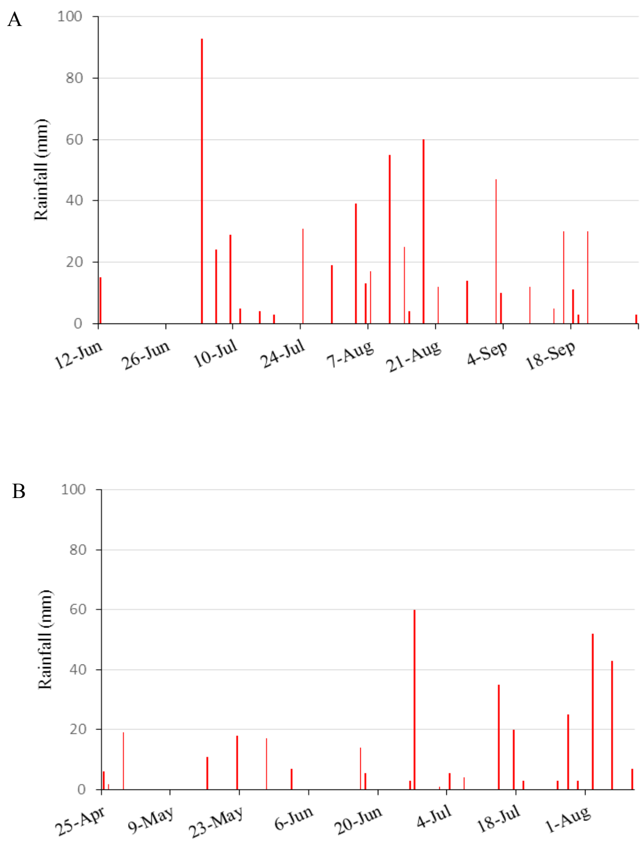

Figure 1. Rainfall (mm) at the experimental site in both rainy seasons of 2012 (A) and 2013 (B)

2.3 Experimental Design

The experimental design was a Fischer randomized design with 4 treatments and 4 replicates (Figure 2). The basic plots were arranged in staggered rows in an 87 m long and 46 m wide research area, summing up to 4002 m^2. Within the plot, the blocks were separated by 2 m while the basic plots of the same block were separated by 12 m. Treatments were allocated randomly to the basic plots that each one covered an area of 100 m^2 (10 m × 10 m).

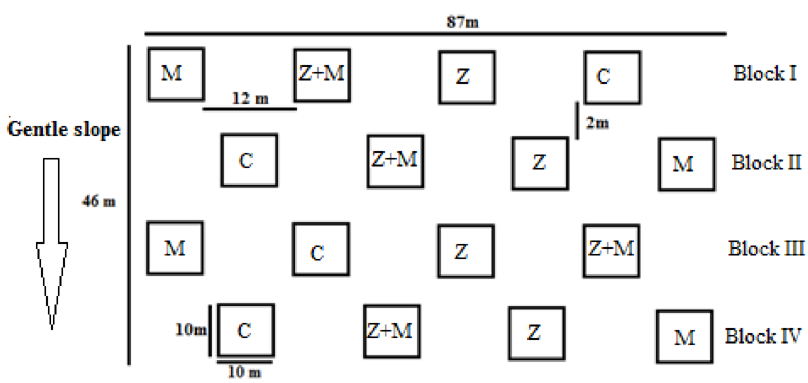

Figure 2. A diagram of the Fischer randomized block design. M: Mulching; Z: Zaï; Z+M: Zaï + mulching; C: control

The treatments were: Mulching (M), Zaï (Z), Zaï + mulching (Z+M) and Control (C). The mulching treatment consisted of spreading 20 kg (2.0 t/ha) millet straw right after harvest. The Zaï technique consisted of sowing the crop (in this case millet) in holes having a diameter of 20 to 30 cm and a depth of 30 cm. The excavated soil was placed on the downstream side of the hole to help capture as much rain water as possible to the benefit of the millet seedlings. The holes were dug three months prior to the rainy season and were staggered with a spacing of 80 x 80 cm. The mean density was 144 Zaï-holes per plot, or 14400 Zaï-holes per hectare. An amount of 200 g (2.8 t/ha) of cattle manure was added to each hole shortly after the establishment. For Zaï + mulching treatment, it combines the treatments of Zaï and Mulching. No mulch and no cattle manure were applied to the controls. Millet seeds were buried in the ground in seed holes dug with sticks after a first rain above 20 mm. The seed holes were placed in rows and were separated by 80 cm, and the distance between rows was also 80 cm. Pearl millet was the test crop. The experiments were carried out in 2012 and 2013, and the main cultivation operations were spreading straw (10/15/2012 and 09/21/2013), making holes Zaï (05/03/2012 and 05/07/2013), sowing (07/05/2012 and 06/27/2013) and harvest (09/20/2012 and 10/20/2013).

2.4 Data Collection

Data concerning millet growth, yield and soil physico-chemical parameters were collected during both rainy seasons.

The measurements of millet height were done at a 10 days interval starting 20 days after sowing and the total plant height was measured. For yield parameter measurements, all millet plants from basic plots were cut at harvest time and pooled with the exception of border plants to avoid the edge effect. Thus, the area harvested per plot was 70.56 m^2 (8.4 m × 8.4 m).

The grain yield (Rg) was evaluated through the following formula:

$$Rg(Kg/ha)\frac{(DW_{p,s} \times FW_{p,t} \times 10)}{FW_{p,t} \times 70.56} \tag{1}$$

Where, DWp,s = grain dry weight, panicle, sample (g); FWp,s = fresh weight, panicle, sample (g), and FWp,t = fresh weight, panicle, total (g).

Straw yield (Rp) was calculated through the following formula:

$$Rp(Kg/ha)\frac{(DW_{s,s} \times FW_{s,t} \times 10)}{FW_{s,t} \times 70.56} \tag{2}$$

Where, DWs,s = dry weight, straw, sample (g); FWs,s = fresh weight, straw, sample (g) and FWs,t = fresh weight, straw, total (g). 10, indicate the quantity of kg·ha^{-1} which correspond to 1 g·m^2 and 70.56, the value of area harvested for each plot.

A diviner tube was installed in the center of each basic plot to measure the soil water storage. From the 20th days after the sowing date, measurements were taken at 10 day intervals. An amount of 500 g of soil samples were also collected in the center of basic plots at 0-20 cm depth on October 29, 2013. However, a reference sample (initial control) was taken on June 19, 2012, before sowing. The samples were analyzed for soil physico-chemical parameters at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT). Particle size analysis was carried out using the Robinson pipette method to separate clay (< 2 µm), fine silt (2-20 µm), coarse silt (20-50 µm), fine sand (50-200 µm) and coarse sand (200-2000 µm). The organic carbon was quantified by the Walkley and Black (1934) method, while total phosphorus and total nitrogen were determined using the Kjeldahl method (Houba et al., 1988). Available phosphorus was assessed by the Bray-I procedure (Olsen & Sommers, 1982). Soil pH was determined in soil-water ratio of 1/2.5 using a glass electrode pH meter (Mathieu & Pieltain, 2003). Cation Exchange Capacity and exchangeable cations were determined by silver-Thiourea (AgTU) method.

2.5 Statistical Analysis

In order to compare soil physicochemical parameters and yield parameters as influenced by restoration techniques, a one-way analysis of variance with treatment as factor was performed using R software (R Development Core Team, 2010). In case of non-normality and heteroscedasticity, the nonparametric Kruskal-Wallis test was applied. A linear regression test was carried out between rainfall amount, plant height and water content in the soil using the same software.

3. Results

3.1 Soil Physico-Chemical Parameters

The Zaï + mulching treatment had a significantly higher content of clay and clay + fine silt compared to the other treatments, whereas the highest content of sand particles was found in the mulching treatment (Table 1). In addition, the Zaï + mulching treatment showed two times higher organic carbon content (2.1±0.4 g·kg^{-1}) than the Zaï and mulching single treatments. The content of available phosphorus (4.8±0.5 mg·kg^{-1}) and cation exchange capacity (2.5±0.2 cmol^{+}·kg^{-1}) for the Zaï + mulching treatment were two times higher than those of the initial control. Concerning soil pH, the values obtained by the Zaï + mulching (5.1±0.1) and Zaï treatments (5±0.1) were not significantly different from the control, but had increased by one unit compared to the initial control value. However, the content of total nitrogen (0.1 to 0.2 g·kg^{-1}) and total potassium (8.6 to 57.8 mg·kg^{-1}) did not vary significantly between treatments.

Table 1. Mean (m) and standard deviation (σ) of soil physico-chemical parameters for treatments of Mulching (M), Zaï (Z), Zaï + mulching (Z+M), final control (fC) and initial control (iC)

Physico-chemical parameters	M		Z		Z+M		fC		iC		Probability
	m	σ	m	σ	m	σ	m	σ	m	σ	
Clay (%)	7.2 (a)	2.6	11.7 (a)	0.8	22.1 (b)	1.1	10.2 (a)	3.2	11.7 (a)	3.7	0.032
Silt (%)	2.8 (a)	1.0	3.9 (a)	0.1	3.4 (a)	0.1	3.5 (a)	0.7	3.4 (a)	0.5	0.328
Sand (%)	91.9 (c)	3.7	84.3 (b)	0.7	74.4 (a)	1.0	86.2 (b)	3.8	84.8 (b)	4.2	0.000
Clay+fine silt (%)	6.3 (a)	3.2	13.1 (b)	0.8	24.5 (c)	1	11.5 (b)	3.3	12.9 (b)	3.9	0.000
C (g·kg^{-1})	1.1 (a)	0.2	0.9 (a)	0.02	2.1 (b)	0.4	0.8 (a)	0.01	0.45(a)	0.2	0.017
N (g·kg^{-1})	0.1 (a)	0.02	0.1 (a)	0.001	0.2 (a)	0.1	0.1 (a)	0.02	0.1 (a)	0.04	0.653
C N^{-1}	7.9 (a)	0.1	9 (a)	0.03	10 (a)	4	12.4 (a)	4.5	14.4 (a)	8.5	0.424
K (mg·kg^{-1})	8.6 (a)	3.4	57.8 (a)	51	28.7 (a)	1.3	40.5 (a)	9	32.6 (a)	29.6	0.301
P_ avail (mg·kg^{-1})	1.7 (a)	0.2	1.5 (a)	0.2	4.8 (b)	0.5	1.3 (a)	0.1	1.7 (a)	0.4	0.041
pH_water	4 (a)	0.1	5 (b)	0.1	5.4 (b)	0.1	4.1 (a)	0.01	4.2 (a)	0.3	0.025
CEC (cmol^{+}·kg^{-1})	1.5 (a)	0.1	1.4 (a)	0.1	2.5 (b)	0.2	1.3 (a)	0.01	1.2 (a)	0.02	0.04
S (cmol^{+}·kg^{-1})	1.04 (a)	0.4	0.7 (a)	0.1	1.47 (a)	0.01	0.73 (a)	0.12	0.94 (a)	0.1	0.245

Note. C: Organic carbon; N: total nitrogen; C N^{-1}: Carbon/Nitrogen; K: total potassium; P_avail: available phosphorus; CEC: cation exchange capacity; S: exchangeable bases. Within the same line the values with different letters are significantly different (ANOVA or Kruskal-Wallis test) at probability of level (0.05).

3.2 Water Content in the Soil

The water content is significantly higher in the treatments than in the control at most dates (Figure 3). In both years and 50 days after sowing, the Zaï treatment recorded the highest value of water storage (147 mm/50 cm in 2012 and 174 mm/50 cm in 2013) followed by the Zaï + mulching (136 mm/50 cm in 2012 and 168 mm/50 cm in 2013) and mulching (132 mm/50 cm in 2012 and 136 mm/50 cm in 2013) treatments. The control recorded the lowest values in both years.

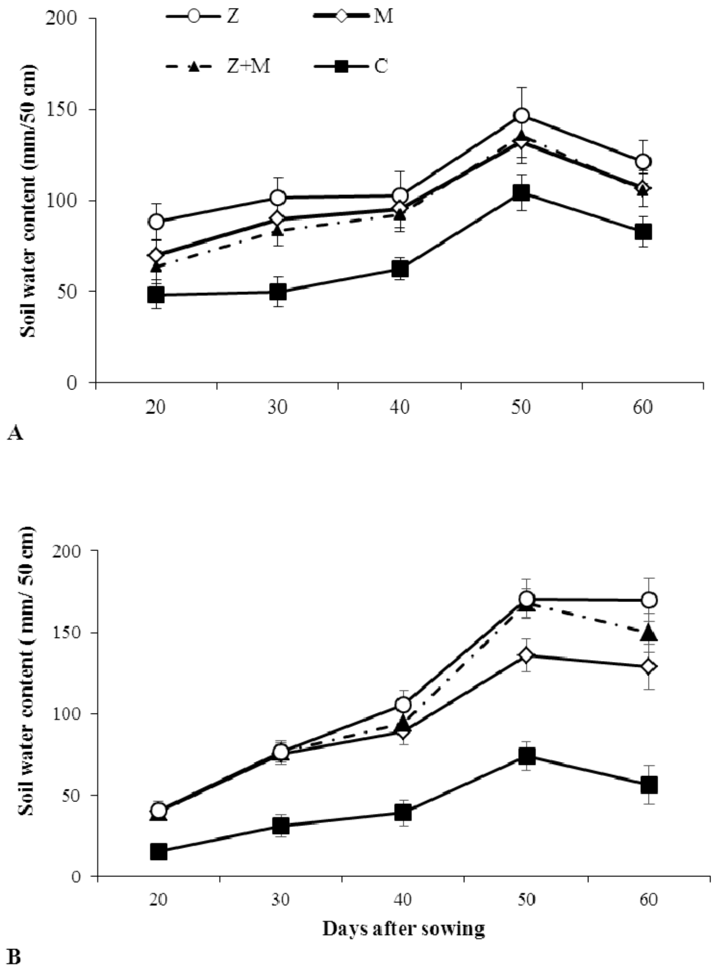

Figure 3. Change of water content in the soil according to treatments of Zaï (Z), Mulching (M), Zaï + mulching (Z+M) and Control (C) at different days after sowing in 2012 (A) and 2013 (B). Error bars are standard error of difference between means

3.3 Relation between Water Content and Rainfall

There was a correlation between accumulated rainfall and soil water content during both rainy seasons (Figure 4). For 2012, the lowest correlation coefficients were obtained by the Zaï treatment (R^2 = 0.60), while the highest correlation coefficient was found in the control (R^2 = 0.69). Nevertheless, a variation of accumulated rainfall between 200 to 500 mm was followed by a variation in soil water content from 40 to 100 mm for control treatment and from 80 to 160 mm for the Zaï. In 2013, the Zaï treatment showed the highest correlation coefficient (R^2 = 0.92), while the control had the lowest values (R^2 = 0.80). For this year, the change of accumulated rainfall from 200 to 400 mm improved the soil water content from 20 to 80 mm in the control and from 40 to 180 mm in the Zaï.

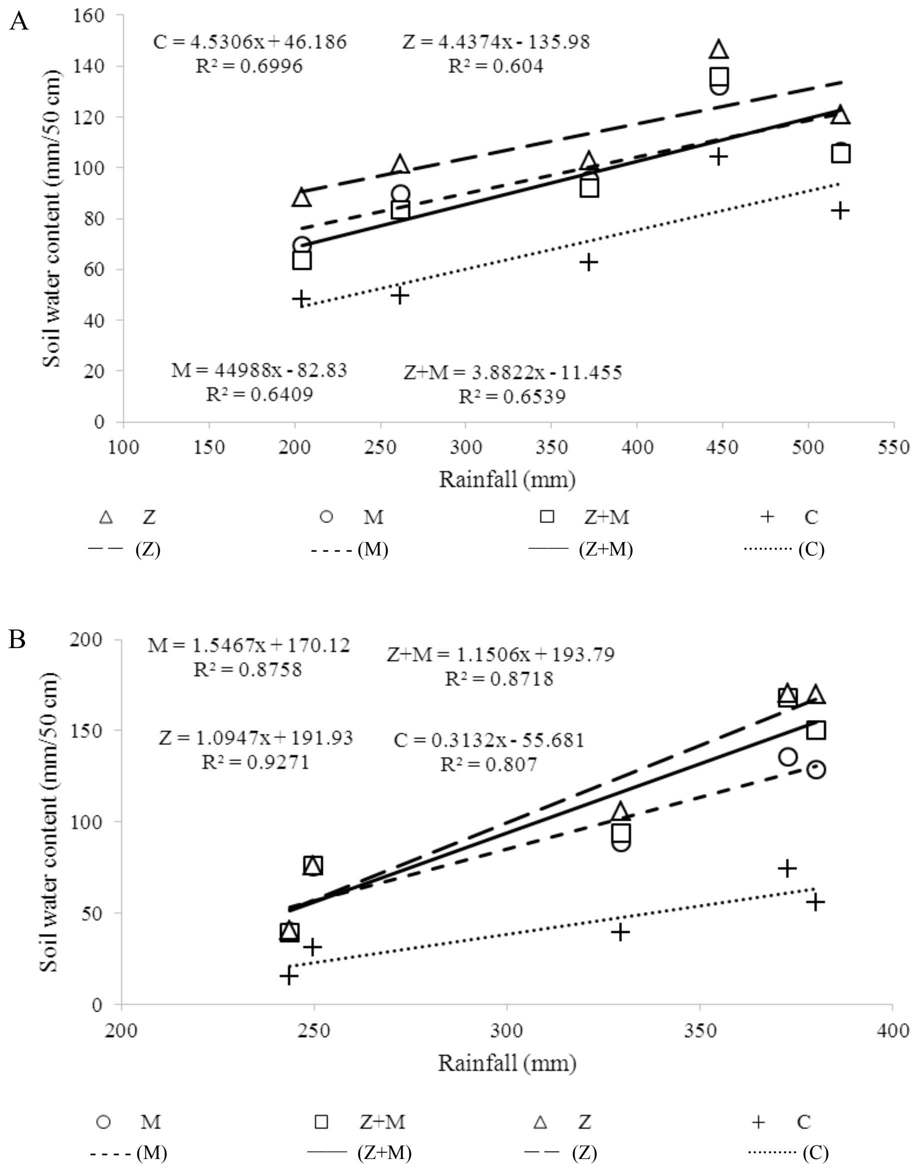

Figure 4. Relation between soil water content and accumulated rainfall for treatments of Zaï (Z), Mulching (M), Zaï + mulching (Z+M) and Control (C) in 2012 (A) and 2013 (B)

3.4 Millet Plants Height

The mean height of millet plants of all treatments for both rainy seasons varied significantly during the measurement dates (Figure 5). In 2012, the significant highest values of plant height were recorded for the Zaï + mulching and the mulching treatments 60 days after sowing. In 2013, the Zaï + mulching and Zaï treatments showed the highest values at the same date. However, the highest values for these two treatments were found 50 days after sowing.

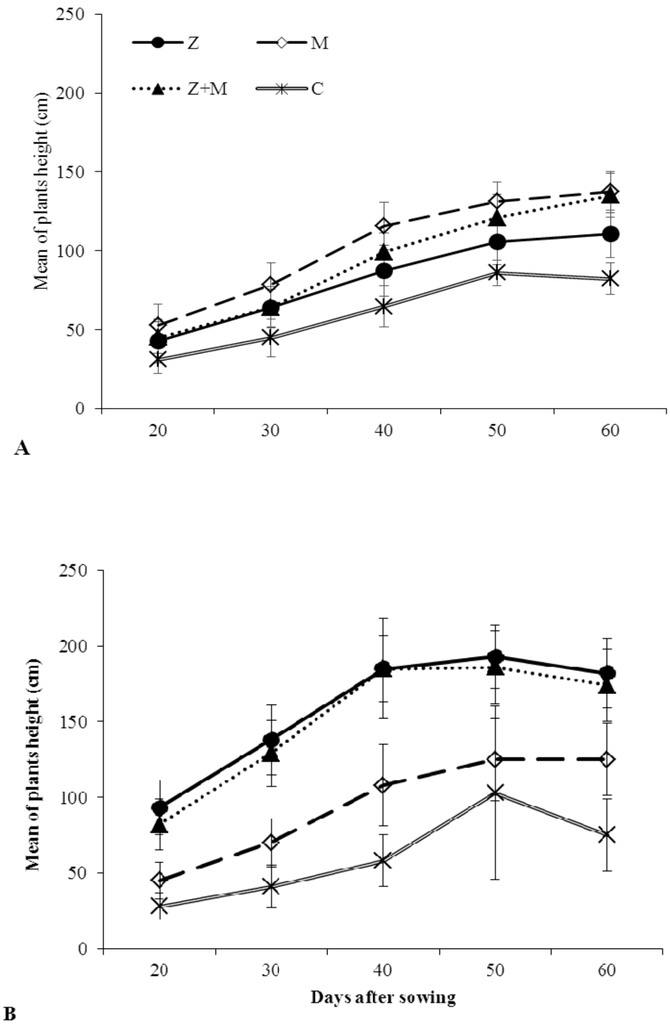

Figure 5. Change of plants height according to treatments of Zaï (Z), mulching (M), Zaï + mulching (Z+M) and control (C) at different days after sowing in 2012 (A) and 2013 (B). Error bars are standard error

3.5 Relation between Plant Height and Soil Water Content

In the Zaï ($R^2 = 0.78$) and control ($R^2 = 0.79$), there was a clear correlation between plant height and soil water content (Figure 6). For Zaï, the variation of the water content in the soil of between 80 to 140 mm led to an increase in plant height from 40 to 120 cm, whereas in the control a fluctuation in soil moisture of between 40 to 100 mm caused a lower increase in plant height (20 to 80 cm).

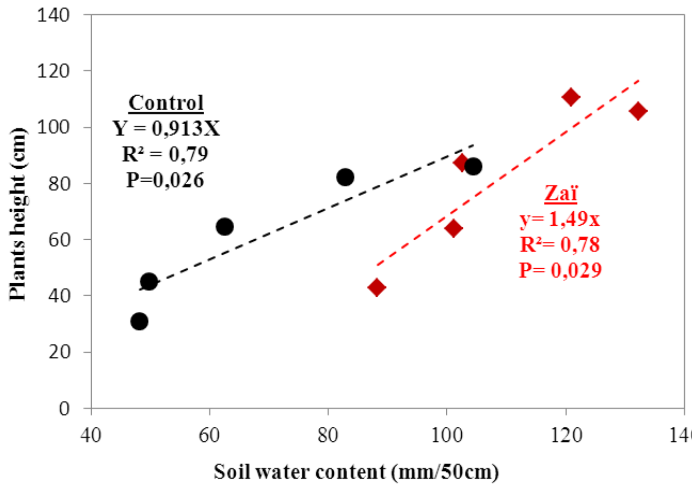

Figure 6. Relation between plant height and water content in the soil for the Zaï and control treatments

3.6 Straw and Grain Yield

Straw and grain yields varied significantly among treatments and between years (Figure 7). For the grain yield, the Zaï + mulching treatment produced significantly higher yields both years (305±78 kg·ha^{-1} in 2012 and 277±49 kg·ha^{-1} in 2013) followed by the Zaï treatment (173±52 kg·ha^{-1} in 2012 and 212±68 kg·ha^{-1} in 2013). Furthermore, in 2013 the grain yield from the Zaï + mulching treatment was not significantly different form that of the Zaï treatment. Concerning the straw yield in 2012, the Zaï treatment showed a significantly higher value (855±216 kg·ha^{-1}) than the other treatments, whereas in 2013 the higher values were obtained in both the Zaï + mulching (888±251 kg·ha^{-1}) and Zaï (843±313 kg·ha^{-1}) treatments.

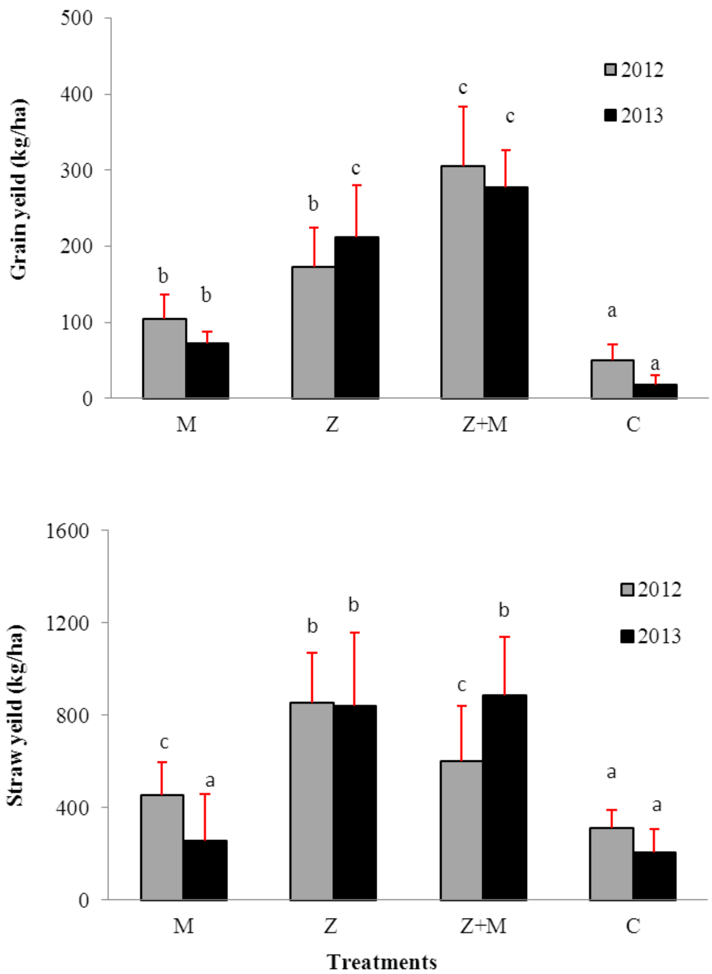

Figure 7. Mean yields of grain (kg·ha^{-1}) and straw (kg·ha^{-1}) for of the Zaï (Z), mulching (M), Zaï + mulching (Z+M) treatments and the control (C) in 2012 and 2013. Error bars are standard errors ½

4. Discussion

The content of available phosphorus of Zaï + mulching treatment (4.8±0.5 mg·kg^{-1}) was 2 to 3 times higher than that obtained by mulching and Zaï single treatments, respectively. This increase may be linked to the rate of organic amendment applied to these techniques. Indeed, combining millet straw and cattle manure amendments produced a supply of 4.8 t/ha organic matter per year in total. According to Schlecht et al. (2006), organic input, including animal manure and crop residues, serves as a reservoir of nutrients such as phosphorus. Haynes and Mokolobate (2001) found that the application of organic amendment to soil may increase the availability of phosphorus to plants. The Zaï + mulching treatment also increased some soil physico-chemical parameters such as clay, clay + fine silt, total carbon, cation exchange capacity and pH. The high contents of clay and clay + fine silt compared to the other treatments may be linked to the sedimentation of fine particles under Zaï pits. These increases may be explained the carbon content (2.1±0.4 g·kg^{-1}), which was 2 times higher than those obtained by Zaï and mulching single treatments. Indeed, the content of soil organic carbon depends on the mineralization rate (Roose & Barthès, 2001), which is low when the organic carbon is physically protected through silt and clay associations or soil microaggregate associations (Six et al., 2002). Moussa et al. (2015a) found low values of organic carbon (1.2±0.6 g·kg^{-1}) in the sandy soil of fields in the same study area. For cation exchange capacity and pH, the significant increases were probably due to the enhancement of soil organic carbon content. Bationo and Buerkert (2001) found a significant positive correlation between those parameters in Sudano-Sahelian West Africa soil. However, nitrogen and potassium contents were not significantly different between treatments, which may be assigned to the percentage of released absorbed nutrients by the millet plants, as Fatoundji et al. (2009) found that nitrogen and potassium plant uptake exceeded the amount released from cattle manure in Zaï pits at Sadoré in the western Niger.

Concerning soil water content, the highest values were recorded in the Zaï and Zaï + mulching treatments, which may be linked to macrofauna activities. Termites attracted by the organic matter dig galleries at the bottom of Zaï holes, allowing the infiltration of rainwater deeper into the soil. According to Mando and Brussaard (1999), the decomposition of organic amendment is strongly linked to the termites' activities in acid sandy soils in the Sahelian zone of Niger. Fatoundji et al. (2009) showed a faster decomposition of manure due to termites in the western Niger. Similar trends have been obtained in semi-arid degraded land of Burkina Faso and Niger (Roose et al., 1999; Bouzou & Dan Lamso, 2004). The Zaï + mulching and Zaï treatments also had the highest millet plants. The relationship between the height growth of millet plants and soil water storage under the Zaï treatment ($R^2 = 0.78$) revealed an efficient use of water. The plant heights of Zaï treatment had increased from 40 to 120 cm when the water content in the soil varied between 80 to 140 mm. According to Fatondji et al. (2006), the Zaï treatment can alleviate the effect of dry spells during plant growth and may improve water use efficiency by a factor of about 2 compared to the traditional flat planting. However, in 2012 the water contents in the soil (147 mm/50 cm) were lower than those found in 2013 (174 mm/50 cm) despite the fact that the rainfall of 2012 was higher. Under high rainfall such as in 2012, Zaï pits can be filled by fine sediments causing congestion and low termite activity, which affects the soil porosity that facilitates water infiltration and millet development.

In both years, the combined treatment of Zaï + mulching gave the highest grain yields with 305±78 kg·ha^{-1} in 2012 and 277±49 kg·ha^{-1} in 2013, which was 2-3 times better than the grain yield of Zaï and mulching treatments, respectively. Furthermore, the high straw yield was obtained by Zaï treatment in both years and Zaï + mulching in 2013 (888±251 kg·ha^{-1}) compared to the other treatments. The millet yield enhancement may be linked to the soil water use efficiency and some plant nutrient availabilities as described above. The increase in millet yield in the Sahelian zone through water harvesting techniques such as Zaï has been widely documented (Roose et al., 1993; Bouzou & Dan Lamso, 2004; Kabore & Reij, 2004). Wildemeersch et al. (2015), found that water and soil conservation techniques increases grain yields up to 0.7±0.2 Mg·ha^{-1} on degraded soils of Niger. However, for the Zaï technique, grain yields in 2012 were significantly lower than those obtained in 2013, which may be due to rainfall variability, which affects the water available to the plant. Many authors found that rainfall variability affects cereal productivity in the Sahelian part of Niger (Fatoundji et al., 2011; Ibrahim et al., 2015).

5. Conclusion

A significant increase in available phosphorus content could be obtained by combining Zaï and mulching with the amendment of 4.8 t/ha of organic matter compared to their single treatment. In addition, this treatment showed two times higher organic carbon content than Zaï or mulching alone, while cation exchange capacity and pH increased by one unit compared to the control. The Zaï treatment caused an increase in water content in the soil and the height of millet plants. Concerning millet yield, 2 and 3 times better grain yields were found by combining treatment of Zaï and mulching compared to their single treatments, respectively. For straw yield, the values obtained by Zaï + mulching treatment were 2 to 4 times higher than those found in the controls in 2012 and 2013, respectively. Soil water harvesting techniques such as Zaï combined with crop residue management such as mulching is a way to alleviate soil fertility constraints and thereby increase millet productivity in the semiarid zone of West Africa.

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