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ORIGINAL ARTICLE

Integrated use of fertilizer micro-dosing and *Acacia tumida* mulching increases millet yield and water use efficiency in Sahelian semi-arid environment

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Abstract Limited availability of soil organic amendments and unpredictable rainfall, decrease crop yields drastically in the Sahel. There is, therefore, a need to develop an improved technology for conserving soil moisture and enhancing crop yields in the Sahelian semi-arid environment. A 2-year field experiment was conducted to investigate the mulching effects of *Acacia tumida* pruning relative to commonly applied organic materials in Niger on millet growth, yields and water use efficiency (WUE) under fertilizer micro-dosing technology. We hypothesized that (1) *A. tumida* pruning is a suitable mulching alternative for crop residues in the biomass-scarce areas of Niger and (2) combined application of *A. tumida* mulch and fertilizer micro-dosing increases millet yield and water use efficiency. Two fertilizer micro-dosing options (20 kg DAP ha^{-1}, 60 kg NPK ha^{-1}) and three types of organic mulches (millet straw, *A. tumida* mulch, and manure) and the relevant control treatments were arranged in factorial experiment organized in a randomized complete block design with four replications. Fertilizer micro-dosing increased millet grain yield on average by 28 %. This millet grain yield increased further by 37 % with combined application of fertilizer micro-dosing and organic mulch. Grain yield increases relative to the un-mulched control were 51 % for manure, 46 % for *A. tumida* mulch and 36 % for millet mulch. Leaf area index and root length density were also greater under mulched plots. Fertilizer micro-dosing increased WUE of millet on average by 24 %, while the addition of *A. tumida* pruning, manure and millet increased WUE on average 55, 49 and 25 %, respectively. We conclude that combined application of micro-dosing and organic mulch is an effective fertilization strategy to enhance millet yield and water use efficiency in low-input cropping systems and that *A. tumida* pruning could serve as an appropriate mulching alternative for further increasing crop yields and water use efficiency in the biomass-scarce and drought prone environment such as the Sahel. However, the economic and social implications and the long-term agronomic effects of this agroforestry tree in Sahelian millet based system have to be explored further.

Keywords Organic mulch · Fertilizer micro-dosing · *Acacia tumida* · Millet yield · Water use efficiency

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Introduction

Inadequate soil fertility management and irregular rainfall distribution are the most important limiting factors for agricultural production in Sahelian farming systems (Bationo et al. 1995; Schlecht et al. 2006). To meet the food requirements of the increasing population in the Sahelian areas there is, the need for enhancing soil fertility potential (Lal 2006). Accessibility to and affordability of external inputs such as mineral fertilizers limit their use by smallholder farmers (Abdoulaye and Sanders 2005). Therefore, Sahelian smallholder farmers tend to rely mainly on organic amendments such as crop residues and animal manure, which are the most accessible nutrient sources in the Sahelian cereal based-systems.

The positive contribution of crop residues in enhancing crop yields has received extensive consideration (Bationo et al. 1993; Rebafka et al. 1994; Buerkert et al. 2002; Yamoah et al. 2002; Turmel et al. 2014). For example, Yamoah et al. (2002) reported that return of crop residues into the soil significantly increased millet grain yields, water and fertilizer use efficiencies. Larbi et al. (2002) observed that grain yield in maize improved significantly with an increasing amount of crop residues applied as mulch. Larbi et al. (2002) also reported that soil organic carbon, total nitrogen and available soil phosphorus contents increased by crop residue amendments. The mechanisms underlying the positive effects of crop residue mulches in different agro-ecological West African zones have been explored by Buerkert et al. (2000). These authors support the statement that the positive crop residue effects on weakly buffered Sahelian soils were due to the enhanced P availability and to the protection of seedlings against wind erosion.

Although the contribution of crop residues in increasing yields and maintaining soil fertility is evident, the use of this material for agricultural purposes in the Sahelian zones is restricted due to the intense competition for use as animals feed, fuel and building material (Bationo et al. 1998; Valbuena et al. 2014). Furthermore, the rates of crop residues reported to achieve the beneficial effects are much higher than what is available to smallholder farms (Akponikpè et al. 2014). For instance, in Niger the recommended rate of crop residues is around 2000 kg ha^{-1} year^{-1} (Rebafka et al. 1994), while the quantity of millet straw in farmer fields is merely around 1200 kg ha^{-1} (Baidu-Forson 1995). The implication is that the recommended amount of crop residue is not accessible for incorporation into the soil or use as mulch, unless the straw production increases dramatically through the application of inorganic fertilizers and the straw is not being used as animal feed, fuel and building material (Bationo et al. 1995).

Fertilizer micro-dosing has been promoted to increase crop yield and residue production, and the additional crop residue production could be used as mulching material (Aune and Bationo 2008; Bagayoko et al. 2011). However, recent works on millet response to fertilizer micro-dosing technology indicated that low soil organic matter characterizing the Sahelian sandy soils contributes immensely to the low response of millet yields (Tabo et al. 2011). Generally very little organic amendment, including manure and crop residues, are put back into the soil which increases the risk of nutrient imbalances and thereby decreases crop yields. To enhance crop response to fertilizer micro-dosing technology, there is, therefore, a need to ensure that organic amendment is added to the Sahelian sandy soils to improve their capacity to store adequate moisture and nutrients. However, the competing uses of crop residues for instance make their use in agriculture difficult in the Sahel. Furthermore, it is well established that the economic benefits for feeding crop residue to livestock greatly exceeds the economic benefits derived from using crop residues as soil amendments (Opoku 2011). This makes the use of crop residues as a mulching in the Sahelian zones also a daunting challenge. Consequently a reliable option for resolving the problem of crop residues scarcity in the biomass-scarce dry areas is to identify other sources of organic amendment that can be easily adopted by Sahelian smallholder farmers.

The use of agro-forestry trees for mulching is a possible option for the Sahel (Tilander and Bonzi 1997). However the contribution of existing agroforestry trees as mulching source is not well investigated in the Sahelian areas.

Acacia tumida, is one of the fast growing agroforestry Australian *Acacias* introduced and tested in Sahelian countries in the early 1980s with the aim to improve food security and combat hunger (Rinaudo et al. 2002). This species produces good seed yields and provides other products and services such as soil fertility improvement through nitrogen fixation and leaves for mulching. The pruning adds organic matter and nutrients to the soil (Rinaudo and Cunningham 2008). There is, however, limited information on the mulching effects of *A. tumida* pruning unlike other agro-forestry trees in low-input smallholder cereal based farming systems.

The current study is aimed at establishing the mulching effects of *A. tumida* pruning relative to commonly applied organic amendments (millet straw and manure) in Niger on millet growth, yields and water use efficiency under fertilizer micro-dosing technology. We hypothesized that (1) *A. tumida* pruning is a suitable mulching alternative for crop residues in the biomass-scarce dry areas of Niger and (2) combined application of *A. tumida* mulch and fertilizer micro-dosing increases further millet yield and water use efficiency.

Materials and methods

Experimental site

The experiment was set up in the 2013 and 2014 rainy seasons at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) Research Station located at Sadoré, Niger (13°15′N and 2°18′E, 240 m asl). The trial field had been left as natural fallow for 9 years. The soil is classified as a sandy Arenosol (West et al. 1984). The climatic conditions are characterized by a rainy season that takes place between June and September. A dry season dominates the rest of the year. The average annual rainfall for the last 30 years in Sadoré is 551 ± 110 mm (±SD) and the average temperature is 29 °C (ICRISAT Climate Database, 1983–2014).

Experimental design

The experiment was a 3 × 4 factorial experiment organized in a randomized complete block design with four replications. The treatments consisted of factorial combinations of two levels of fertilizer micro-dosing and three types of organic mulches. The relevant control treatments were adjoined to these treatments. The fertilizer micro-dosing treatments were (1) 20 kg ha^{-1} of di-ammonium phosphate (DAP, equivalent to 4 kg P ha^{-1} and 3.6 kg N ha^{-1}), and (2) 60 kg ha^{-1} of composite fertilizer NPK 15-15-15 (equivalent to 9 kg N ha^{-1}, 4 kg P ha^{-1}, and 7.47 kg K ha^{-1}). The application of these micro-dosing rates corresponded to 2 g DAP hill^{-1} and 6 g NPK hill^{-1}, respectively, which are the current fertilizer micro-dosing rates recommended in the study area (Tabo et al. 2011). Since P is the most limiting soil nutrient in the study area, the DAP and NPK rates applied were estimated to supply equal quantities of P (0.4 g P hill^{-1}). Hence these two sources of nutrient are used interchangeably because farmers did not have access to fertilizers at the due time. Thus, using different sources of nutrients that supplied equivalent quantities of P gave farmers alternatives. The types of organic mulch used were (1) millet straw (2) *A. tumida* mulch (3) cattle manure. All mulches were applied at the recommended rate of 2000 kg ha^{-1} for crop residue application (Muehlig-Versen et al. 2003). The inorganic fertilizer treatments were applied at sowing while the organic mulching materials were broadcasted after sowing in order to avoid losses through wind. Millet straw and *A. tumida* pruning were collected from the ICRISAT Research Station. *Acacia tumida* trees were pruned in May and the pruning was sun-dried before the onset of the rainy season. The manure was collected from a barn in Sadoré village. The initial chemical characteristics of these organic mulches are presented in Table 1.

The size of each treatment plot was 7 m × 7 m. Seeds of improved variety of millet, ICMV IS 89305 (110 maturity days) were sown on 27 June 2013 and 1 June 2014 based on the onset of the rainy season. The planting hills were spaced by 1 m × 1 m to attain a plant population of 10,000 hills ha^{-1} (current recommended plant density).

The millet was thinned to three plants per hill at 21 days after sowing followed by the first weeding. There were three weeding events during each cropping year. The millet panicles were harvested on 10 October in 2013 and 15 September in 2014 which coincided with the harvest maturity stage. To determine the millet grain yield and the dry matter yield (TDM), straw samples and millet panicles were harvested from the central 5 m × 5 m of each plot and dried at 65 °C for 48 h and hand threshed. Thereafter, the dried samples were weighed and stated in kg ha^{-1}.

Table 1 Initial organic amendment quality

	Total N (%)	Total P (%)	Total K (%)	C/N	Lignin (%)	Polyphenol (%)
2013						
Manure (n = 5)	1.0	0.4	1.6	23	nd	nd
Millet straw (n = 5)	1.7	0.14	1.3	43	nd	nd
Acacia tumida mulch (n = 5)	2.0	0.12	1.3	20	nd	nd
2014						
Manure (n = 5)	1.5	0.34	0.7	29	11.8	0.7
Millet straw (n = 5)	0.8	0.10	1.8	64	7.2	0.6
Acacia tumida mulch (n = 5)	2.3	0.14	1.5	22	22.1	1.3

nd not determined

Data collection and analysis

Growth parameters measurements

Leaf area (LA) was measured at tillering, elongation and flowering and dough stage. At each measurement stage, two pearl millet hills were randomly harvested in each treatment. The green leaves were taken to the laboratory for leaf length and width measurements. Leaf length and width were measured with a ruler and the LA was calculated from the formula used by Ma et al. (2013) as follows:

$$Leaf\ area\ (LA) = Leaf\ length \times maximum\ width \times k \tag{1}$$

where k is a shape factor with the value of 0.5 for partially unfolded leaves and 0.75 for completely unfolded leaves. The LAI was calculated as the ratio of LA to the surface area of the harvested plot.

Two millet hills were tagged from each plot at tillering for roots sampling. Root samples were collected with a metal frame measuring 15 × 10 × 10 cm from 0 to 20 cm in depth directly under the hill. Roots were subsequently collected at 20 cm depth increment with an access aluminium tube of 7.5 cm inner diameter following the first sampling depth of 0–20 cm. Sample cores were washed out separately by mixing the sample with tap-water within a plastic pail. The suspension was decanted and roots were sieved through a 0.63 mm mesh size. Root length (RL) for each sample core was calculated individually then the root length for the two hills in each plot were averaged to obtain root length for each plot. The root length was calculated by determining root intersections (N) using the grid counting method (Tennant 1975). The grid size of 2 × 2 cm was used for the coarse roots and the grid of 1 cm × 1 cm, for the fine roots. The coarse roots were counted on a sub-sample of 2 g taken from the main root 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. Root length was calculated using the following formula:

$$R = \frac{N \times total\ root\ fresh\ weight}{Root\ weight\ of\ sub\text{-}sample} \tag{2}$$

where N = number of intersections counted. Root length density (RLD) was determined by the following formula $RLD = R/V$, where R is Root length and V is soil volume of corresponding depth.

Soil moisture measurements

Daily rainfall data was recorded through a rain gauge placed at the experimental field. Access tubes were installed in each experimental plot (treatment) to monitor weekly soil moisture with a calibrated neutron probe from 0.15 to 2 m depth at 0.15 m intervals. The volumetric water content [θ_v (%)] was calculated with the formula used by Fatondji (2002) as follows:

$$\theta_V = a + b\left(\frac{C}{Cs}\right) \tag{3}$$

where, θ_v is volumetric water content expressed in %; a is the intercept of the equation of the neutron probe calibration curve; b is the slope of the equation; C is neutron count read with the probe in the field and Cs is a standard count reading from the access tube installed in pure water.

The change in soil water storage in the root zone was calculated from the equation used by Payne (1997) as follows:

$$dS = R - (ET + D) \quad (4)$$

where dS is the change in soil water storage in the root zone, R is rainfall, ET is evapo-transpiration and D is the root zone drainage. Drainage and ET were determined from the weekly neutron-probe data using the method developed by Klaij and Vachaud (1992). This method divides the water balance into two phases. "In the first phase, applicable early in the season, water flux across the maximum depth of probe measurement (Zm) is assumed negligible. Drainage (D) was calculated from the change in soil water content (θ) between the bottom of the root zone (Zr) and Zm, thus allowing calculation of unsaturated hydraulic conductivity, K (θ), from the flux across Zr. In the second phase, when soil water starts to percolate across Zm, D is calculated from K (θ), assuming a hydraulic head gradient of −1". The details of this method were given by Klaij and Vachaud (1992).

Water use efficiency (kg mm^{-1}) was calculated as a ratio of grain yield to evapo-transpiration (Wang et al. 2010).

Soil sampling and analysis

Soil samples were taken at the onset on the experiment before the rainy season from 0 to 20 cm in each plot. Each sample was analysed for pH (H_2O) using pH meter (with a 1:2.5 soil:water ratio), organic carbon, by Walkley and Black (1934); and total nitrogen (N) was determined using Kjeldahl method (Houba et al. 1995). Extractable phosphorus was determined using the Bray-1 method as described by van Reeuwijk (1993). Exchangeable bases (Na^+, K^+, Ca^{2+} and Mg^{2+}) were determined by the ammonium acetate (NH_4OAc) solution at pH 7 using the extraction method described by van Reeuwijk (1993). The exchangeable acidity (H^+ and Al^{3+}) was determined using the method described by van Reeuwijk (1993). The particle size distribution was determined using pipette method (Gee and Or 2002).

Statistical analysis

Before the statistical analysis, data were cautiously checked for variance homogeneity and normality. Square root transformation was applied merely to root length density data to ensure normal distribution of the residuals. Analysis of variance was performed with GENSTAT v.9 (Lawes Agricultural Trust, 2007) using a General Treatment Structure (in Randomized Blocks). Time series data was analysed based on repeated measures using the AREPMEASURES procedure of GENSTAT v.9. The differences among treatments were considered at an error probability ≤ 0.05. When necessary, means were separated using least significant difference (LSD).

Results

Soil properties of the experimental field

The initial physical and chemical characteristics of the experimental field within the top 20 cm are presented in Table 2. The texture of the soil was sand, with only 3.2 % clay. Soil pH (H_2O) and pH (KCl) were 5.4 and 4.4, respectively. The organic carbon level was low (2.2 g kg^{-1}). The nitrogen content of the soil was low (195 mg kg^{-1}). The extractable P contents and exchangeable bases were very low with 2.8 mg kg^{-1} and 1.9 $cmol^+$ kg^{-1}, respectively. The characteristics of this soil are representative of the soils in Niger characterized by sandy texture and low level of nutrients and organic matter.

Table 2 Initial soil properties of the experimental site (n = 16)

Parameters	0–20 cm
Soil texture (%)	
Sand (particles >0.05 mm)	94.6 ± 0.1
Silt (0.002–0.05 mm)	2.2 ± 0.1
Clay (particles <0.002 mm)	3.2 ± 0.2
Soil chemical properties	
pH-H_2O (1:2.5)	5.4 ± 0.0
pH-KCl (1:2.5)	4.4 ± 0.1
Organic C (g kg^{-1})	2.2 ± 0.0
Total-N (mg kg^{-1})	195 ± 10
P-Bray (mg kg^{-1})	2.8 ± 0.1
Exchangeable base ($cmol^+$ kg^{-1})	1.9 ± 0.1
Exchangeable acidity ($cmol^+$ kg^{-1})	0.03 ± 0.04

± SE

Rainfall distribution during the cropping period

The rainfall distribution during the cropping periods of 2013 and 2014 is shown in Fig. 1. The total rainfall recorded in 2013 was 475 mm, which is less than the long-term (1983–2014) rainfall average at the site of 551 mm year^{-1}. Most of the rains occurred during August (from 40 to 60 DAS) accounting for 75 % of the total rainfall recorded during the cropping period. There was, a dry spell of 27 days in September–October, which coincided with the flowering and grain filling stages. In 2014, rainfall was evenly distributed with 689 mm recorded throughout the growing season (Fig. 1).

Root length density

The root length density were highest within the topsoil (0–10 cm) and reduced drastically below 10 cm depth (Fig. 2). There were significant differences in root length density between mulching materials ($P < 0.001$). In both years (Fig. 2a, b), the RLD in the topsoil (0–10 cm) was significantly higher in *A. tumida* plots. Below 10 cm depth, the root length density was greater in the plots that received manure treatment particularly in 2014 (Fig. 2b). The lowest RLD was produced in both years under un-mulched plots.

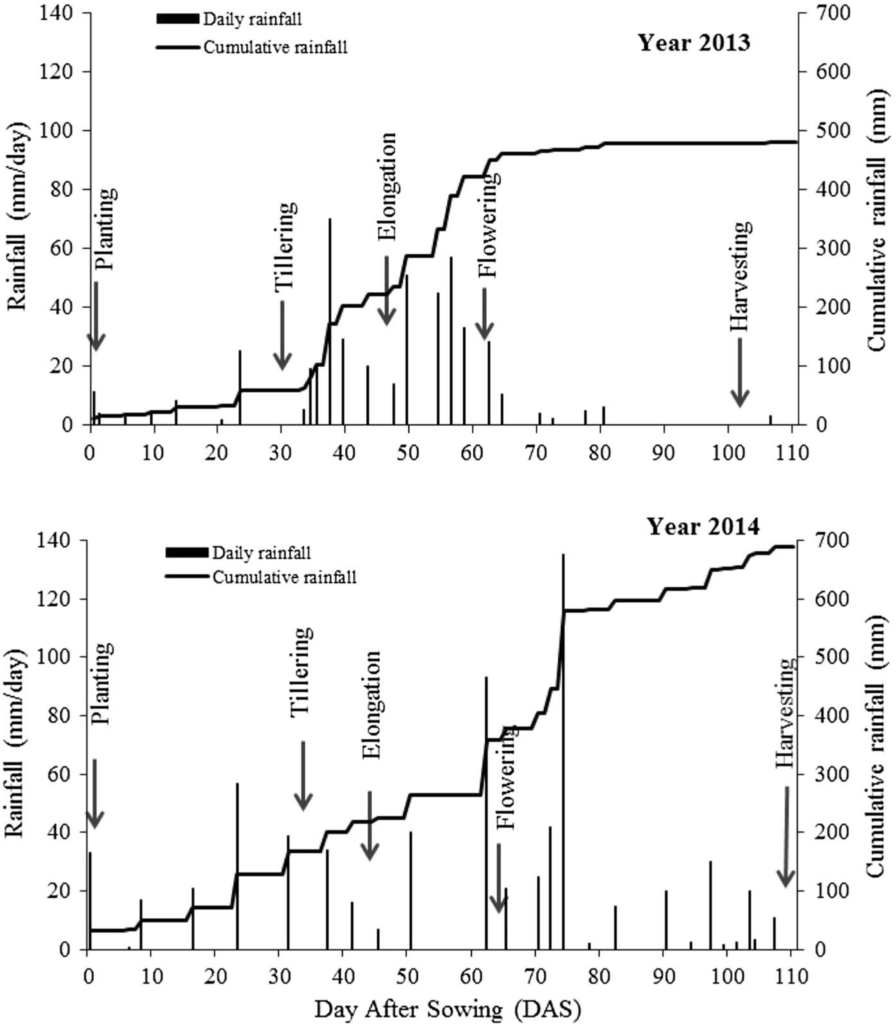

Fig. 1 Rainfall distribution in 2013 (*upper panel*) and 2014 (*lower panel*)

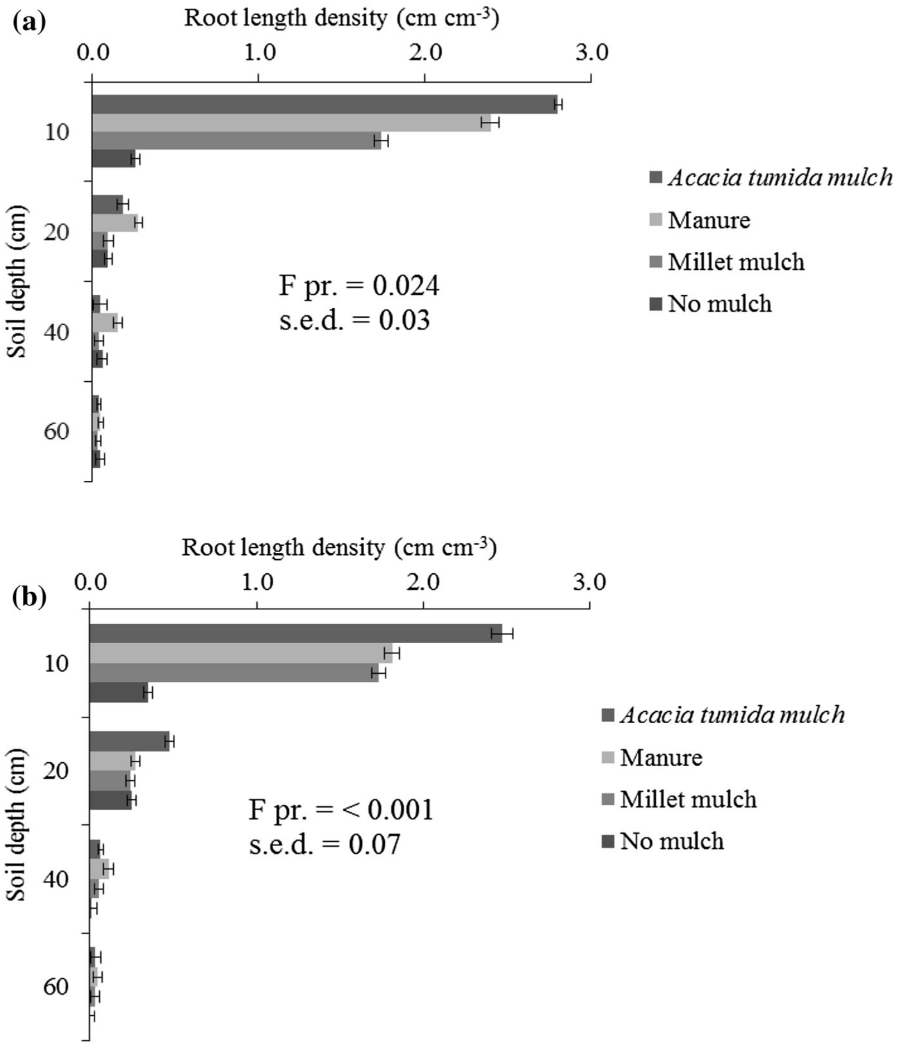

Fig. 2 Root length density of millet in **a** 2013 and **b** 2014. *Bars* indicate SE. Anova was performed on square root transformed yield data. Back-transformed data are reported here

Leaf area index

Leaf area index (LAI) increased significantly with millet growing stages (Fig. 3). LAI values were significantly higher ($P < 0.001$) in the plots receiving mulches than under the un-mulched plots. However, differences in LAI between plots that received mulching treatments were not significant. Combined application of fertilizer micro-dosing and organic mulches did not significantly affect LAI (data not presented, only significant interactions have been presented in the current paper). In 2013 (Fig. 3a), the highest LAI (1.6 m^2 m^{-2}) was observed in *A. tumida* mulching plots at the flowering stage followed by millet straw mulch (1.4 m^2 m^{-2}). In 2014 (Fig. 3b), the highest LAI (1.8 m^2 m^{-2}) was recorded in manure plots followed by *A. tumida* mulched (1.7 m^2 m^{-2}).

Grain and straw yields

Mean millet grain and straw yields as affected by fertilizer micro-dosing and mulching are presented in Table 3. Fertilizer micro-dosing increased yields significantly ($P < 0.001$) regardless of the type of organic mulch applied. Application of 2 g DAP $hill^{-1}$ and 6 g NPK $hill^{-1}$ increased grain yield on average by 39 and 16 %, respectively compared with the unfertilized control (Table 4). The addition of organic

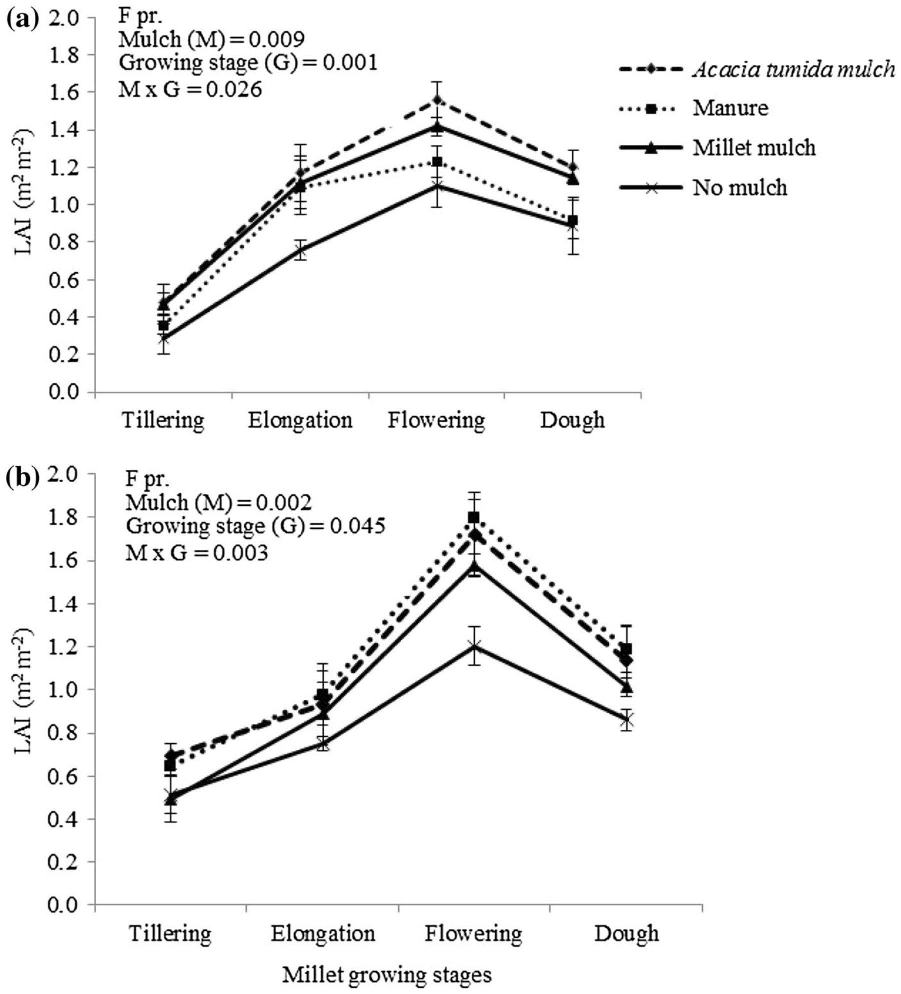

Fig. 3 Leaf area index (LAI) in **a** 2013 and b 2014 under mulches. *Bars* indicate SE

mulch to fertilizer micro-dosing treatments caused a marked improvement in millet grain yield over fertilizer micro-dosing treatments alone. Mulching increased grain yield by 38 and 35 %, respectively, with 2 g DAP hill^{-1} and 6 g NPK hill^{-1} over the un-mulching micro-dosing treatment. The millet grain yields were significantly different among the mulching materials. The average increase in millet grain yield was recorded to be 43, 38 and 26 %, respectively for manure, *A. tumida* and millet mulch over the un-mulched control (Table 4). The addition of organic mulch to fertilizer micro-dosing led to an increase in straw yield of 15–27 %, depending on the type of mulching materials; straw yields decreased in the following order: *A. tumida* > manure > millet straw (Table 4).

Soil moisture and water use efficiency

Soil volumetric water content (VWC) in the different soil layers responded to mulching treatments (Fig. 4). Throughout the cropping periods, the VWC was significantly higher within 0–15 cm under the plots that received *A. tumida* mulch followed by the plots with millet straw mulch (Fig. 4a, b). The same trend was observed within 15–30 cm depth (Fig. 4c, d). There was, however, no significant difference in VWC between the plots that received manure application and un-mulching plots.

Fertilizer micro-dosing and organic mulches did not change millet evapotranspiration (ET) significantly (Table 5). However, there was, a significant variation in ET among the cropping seasons. The evapotranspi-

Table 3 Grain and straw yields in 2013 and 2014 growing seasons

Fertilizer micro-dosing	Mulching	Grain yield (kg ha^{-1})		Straw yield (kg ha^{-1})	
		2013	2014	2013	2014
Control	No mulch	402 ± 25	695 ± 147	861 ± 100	1750 ± 121
	Manure	507 ± 33	1386 ± 159	1556 ± 309	2694 ± 149
	Millet mulch	570 ± 72	1107 ± 213	1500 ± 210	1944 ± 227
	Acacia tumida mulch	597 ± 65	1117 ± 70	1806 ± 338	2167 ± 173
2 g DAP hill^{-1}	No mulch	780 ± 24	1011 ± 92	1986 ± 141	2194 ± 290
	Manure	742 ± 33	1661 ± 147	1611 ± 169	2917 ± 146
	Millet mulch	843 ± 124	1590 ± 437	2083 ± 250	2639 ± 226
	Acacia tumida mulch	980 ± 121	1611 ± 65	2278 ± 150	2722 ± 200
6 g NPK hill^{-1}	No mulch	611 ± 48	901 ± 49	1667 ± 106	2028 ± 227
	Manure	638 ± 48	1647 ± 185	1639 ± 126	2778 ± 194
	Millet mulch	759 ± 96	1032 ± 145	1750 ± 148	2167 ± 145
	Acacia tumida mulch	910 ± 83	1126 ± 149	2083 ± 189	2222 ± 168
Year (Y)		<0.001		<0.001	
Mineral fertilizer (F)		<0.001		<0.001	
Mulch (M)		0.001		0.004	
F × M		NS		NS	
F × Y		NS		NS	
M × Y		0.006		0.01	
F × M × Y		NS		NS	
CV (%)		26		29.8	

± SE, *NS* not significant

Table 4 Increase in grain yield, straw yield and WUE over the control

	Grain yield (kg ha^{-1})	Increased in grain yield as compared to control (%)	Straw yield (kg ha^{-1})	Increased in straw yield as compared to control (%)	WUE in grain (kg mm^{-1})	Increased in WUE as compared to control (%)
Micro-dosing						
Control	823^{b}		1785^{b}		2.7^{b}	
2 g DAP hill^{-1}	1152^{a}	39	2304^{a}	29	3.7^{a}	38
6 g NPK hill^{-1}	953^{b}	16	2042^{a}	14	2.9^{b}	9
Mulching material						
No mulch	767^{b}		1748^{b}		2.3^{b}	
Millet straw	984^{a}	26	2014a^{b}	15	2.9^{b}	25
Manure	1097^{a}	43	2199^{ab}	26	3.5^{a}	49
Acacia tumida mulch	1057^{a}	38	2213^{a}	27	3.6^{a}	55
LSD (0.05) for:						
Micro-dosing	147		235		0.48	
Mulching material	171		271		0.55	

Values affected by the same letter in the same column are not significantly different

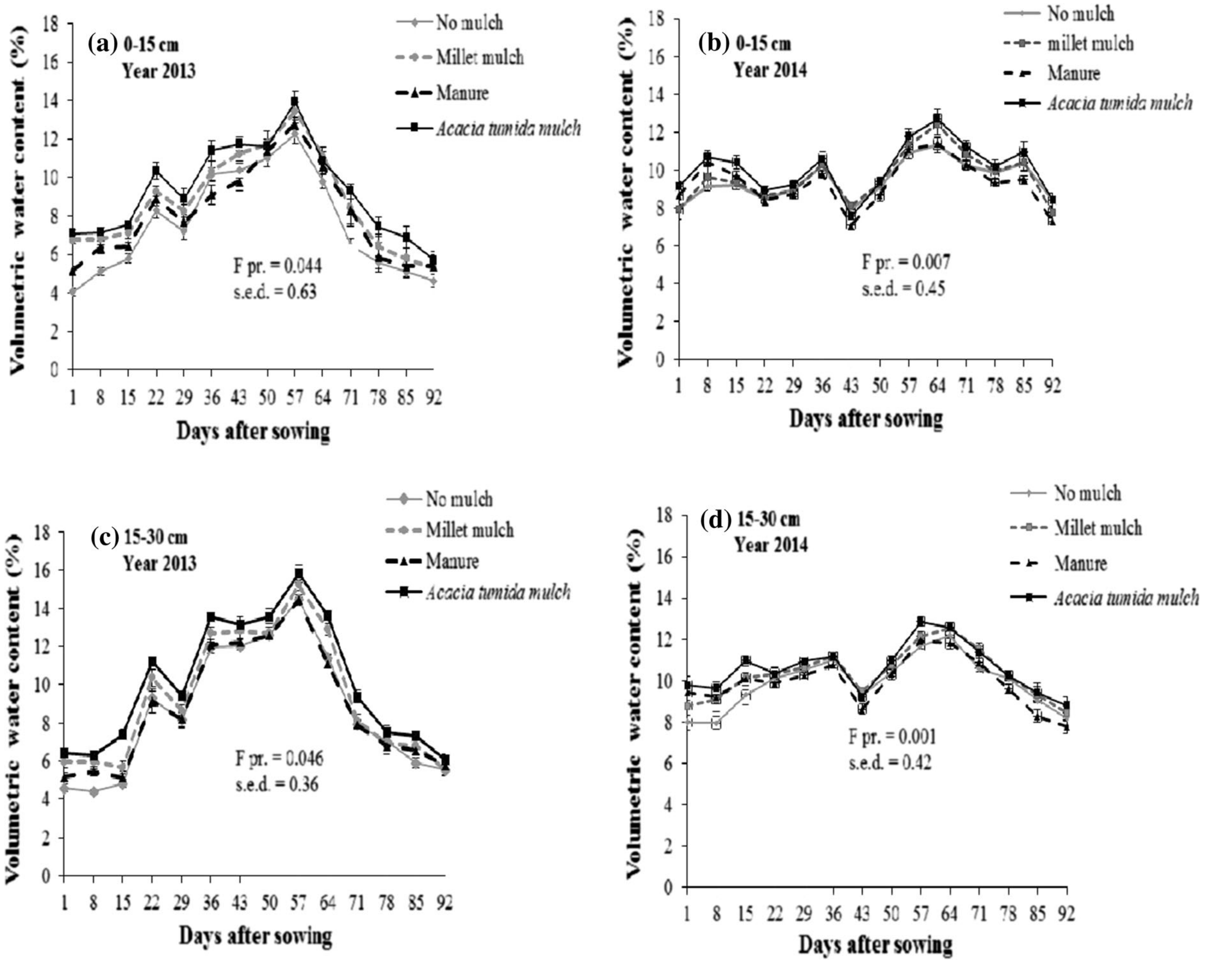

Fig. 4 Volumetric water content in 2013 and 2014. *Vertical line* indicate SE

ration was higher in 2014 (375 ± 12 mm) than in 2013 (268 ± 4 mm).

Combined application of fertilizer micro-dosing with organic mulch increased water use efficiency (WUE) on average by 31 % compared with lone application of fertilizer micro-dosing. Mulches *of A. tumida*, manure and millet mulch increased WUE by on average 55, 49 and 25 %, respectively (Table 4), while WUE increased by on average 38 % with 2 g DAP hill^{-1} and by 9 % with 6 g NPK hill^{-1}.

Discussion

The results showed that fertilizer micro-dosing significantly increased millet yield compared to no application of fertilizer (Table 3). The current results reinforce the earlier reports on micro-dosing regarding the effectiveness of the technology in improving crop yield under a low-input millet based system (Bagayoko et al. 2011; Bielders and Gérard 2014; Ibrahim et al. 2014).

There was, a significant seasonal difference in millet yields recorded in the current study; yields were higher in 2014 than in 2013. The seasonal yield variability could be attributed to the larger amount and better rainfall distribution observed throughout the growing period in 2014 (Fig. 1) which ultimately favoured better plant growth and biomass production (Ibrahim et al. 2015). The differences in yields recorded in 2013 and 2014 may also be attributed to the residual effect of the organic mulches applied.

Table 5 Evapotranspiration (ET) and water use efficiency (WUE)

Fertilizer micro-dosing	Mulch	ET (mm)		WUE (kg mm^{-1})	
		2013	2014	2013	2014
Control	No mulch	278 ± 24	362 ± 16	1.5 ± 0.1	1.8 ± 0.3
	Manure	281 ± 17	366 ± 28	1.8 ± 0.2	3.9 ± 0.6
	Millet mulch	247 ± 5	321 ± 19	2.4 ± 0.1	3.5 ± 0.4
	Acacia tumida mulch	255 ± 10	311 ± 27	2.3 ± 0.2	3.6 ± 0.1
2 g DAP hill^{-1}	No mulch	266 ± 7	349 ± 47	2.9 ± 0.1	3.1 ± 0.1
	Manure	272 ± 8	379 ± 23	2.7 ± 0.1	4.5 ± 0.5
	Millet mulch	292 ± 22	427 ± 38	2.9 ± 0.2	3.6 ± 0.6
	Acacia tumida mulch	259 ± 10	338 ± 13	3.8 ± 0.4	4.8 ± 0.1
6 g NPK hill^{-1}	No mulch	263 ± 13	391 ± 33	2.7 ± 0.2	2.3 ± 0.6
	Manure	276 ± 16	405 ± 30	2.3 ± 0.1	4.1 ± 0.4
	Millet mulch	263 ± 11	440 ± 36	2.3 ± 0.1	2.4 ± 0.3
	Acacia tumida mulch	266 ± 4	405 ± 43	3.4 ± 0.2	2.8 ± 0.1
Year (Y)		<0.001		<0.001	
Mineral fertilizer (F)		NS		<0.001	
Mulch (M)		NS		<0.001	
F × M		NS		NS	
F × Y		NS		NS	
M × Y		NS		0.002	
F × M × Y		NS		NS	
CV (%)		20.3		26.4	

± SE, *NS* not significant

Bationo et al. (1993) had earlier reported similar significant millet yield responses in the second year of crop residue application. The probable explanation of the residual effect of mulching to the following year could be the enhanced supply of nutrients and water through nutrient recycling, wind-blown dust trapping, and reduced evaporation (Movahedi Naeni and Cook 2000; Ram et al. 2003; Schlecht et al. 2006). This residual effect may also explain the significant interaction between mulch and year on yields (Table 3).

Our results also showed that millet yields may be increased further by organic mulches (Table 3). Increases in yields under mulch have been attributed to the higher water retention capacity of soil and efficient use of available rainfall which encourage root proliferation and thereby favour better crop growth in early season under an arid and semiarid environment (Chakraborty et al. 2008). This was demonstrated in the highest root length density (Fig. 2) and LAI (Fig. 3) recorded in mulched plots at the early stage of millet development. The current study produced results which corroborate the findings of Vial et al. (2015) who showed an early-season effect of mulch on crop growth. Furthermore, the greater root length density observed in the topsoil under mulched plots (Fig. 2) could improve P mobility and more importantly water availability thereby improving the grain yield (Li et al. 1999).

A positive effect of mulching in combination with mineral fertilizer on millet yield in the Sahel has also been reported by Bationo et al. (1993) and Yamoah et al. (2002). However, the response of millet yields to mulching depends on mulching material applied. In 2013, *A. tumida* mulch was the best in producing high millet grain and straw yields followed by the millet mulch. Conversely, in 2014, the highest yields (Table 3) were documented in manure plots, followed by *A. tumida* and millet mulches, respectively. The high yield recorded with *A. tumida* in 2013 season could be explained by the improvement of soil moisture content as a result of the reduction in soil evaporation rate. This was less the case with manure, because soil volumetric water content was lower with manure than with *A. tumida* and millet straw mulches (Fig. 4). The present observation is consistent with that of Cook et al. (2006) who found significant evaporation loss under farmyard manure compost compared to wheat and soybean straw. Yet, the higher yields in manure plots in 2014 suggest that in a relatively wet season, the mulching effect could be enhanced by improved nutrient supply from the mulch (Ram et al. 2003). In addition, the relatively high lignin content of *A. tumida* pruning (Table 1), hampers the nutrient release from this mulching material. Yet, the slow decomposition rate of *A. tumida* mulch (data not presented) could be an advantage because it stays in the soil for a longer period of time, and therefore restricts soil water from evaporative loss and also protects the soil against wind erosion losses. This result indicates that application of *A. tumida* prunings as mulch could improve crop water availability and allow better use of limited rainwater particularly in high drought risk areas such as the Sahel.

The evapotranspiration (ET) was not affected by any treatment in the current study. However, there was, a significant seasonal variation in evapotranspiration (Table 4). The variation in evapotranspiration between the cropping years can be attributed to the difference in rainfall recorded between the two experimental years (Fig. 1). Application of mulches significantly increased WUE compared with the no-mulch treatment (Table 4). About 50 % increase in WUE was noted in *A. tumida* plots followed by manure (46 %) and millet much (26 %) in comparison to the no-mulch plots (Table 5). This observation conforms with reports from previous studies which demonstrated the effectiveness of organic mulch in reducing soil evaporative rate and increasing WUE (Huang et al. 2005; Chakraborty et al. 2008). However, the current study further shows that the mulching effect on improved water use efficiency depends on the type of mulching material applied. The application of *A. tumida* mulch more significantly increased WUE compared to the millet mulch (Table 5). It appears that the potential of *A. tumida* in increasing WUE is attributable to its capacity to conserve soil water in upper soil layers (Fig. 4). This is in accordance with the results from previous studies that have demonstrated that any practice that leads to an increase in soil water availability in the upper portion of the root may have a positive impact on WUE and improve nutrient uptake (Payne 1997; Hatfield et al. 2001).

Conclusion

Organic mulches had an evident effect on millet yield and WUE. Combined application of fertilizer microdosing and organic mulches is an effective fertilization strategy for improved millet production in the Sahelian semi-arid environment. *A. tumida* pruning could serve as an appropriate mulching alternative for further increasing crop yield and water use efficiency in the biomass-scarce and drought prone environment such as the Sahel. However, the economic and social implications and the long-term agronomic effects of this agro-forestry tree in Sahelian millet based system have to be explored.

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