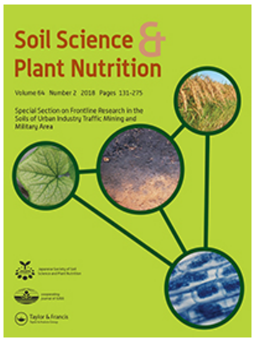

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ORIGINAL ARTICLE

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Are all three components of conservation agriculture necessary for soil conservation in the Sudan Savanna?

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ABSTRACT

Conservation agriculture (CA) as recommended by the Food and Agriculture Organization of the United Nations consists of three components: minimum soil disturbance, soil cover, and crop rotation/association. CA was expected to become an effective countermeasure against water erosion in the Sudan Savanna, but it has not been adopted by local smallholder farmers. As markets for grain legumes (including cowpea) have not been developed in the Sudan Savanna, crop rotation/association should be considered impractical for these farmers. Therefore, we examined whether legume intercropping as a crop rotation/association component is necessary for preventing soil erosion in the Sudan Savanna. Three-year field experiments were conducted in runoff plots at Institute of Environment and Agricultural Research Saria station. The four treatments were conventional practice (full tillage, no sorghum residue mulching, and no intercropping), two-component CA (minimum tillage (MT) and sorghum residue mulching without intercropping), and three-component CA with velvet bean (VB) or pigeon pea (PP) intercropping. It was revealed that: (1) MT and sorghum residue mulching (without intercropping) effectively reduced the annual soil loss by 54% mainly due to the improvement of soil permeability by the boring of termites and wolf spiders found under the sorghum stover mulch; (2) intercropping in combination with MT and crop residue mulching had no effect on soil erosion control mainly because: (a) PP did not survive the long dry season; (b) VB did not serve effectively as a cover crop since soil loss was concentrated at the beginning of the rainy season when VB was still too small; (c) unexpectedly, in combination with MT and crop residue mulching, intercropping with VB did not increase mulch biomass, especially sorghum biomass which prompts the boring of termites and wolf spiders. These results demonstrate that the third component of CA, namely legume intercropping, is not always necessary; rather, the two remaining components – minimum soil disturbance and soil cover – are sufficient for soil conservation in the Sudan Savanna. This finding lightens the burden of adopting CA and thus facilitates its future promotion to the smallholder farmers in the Sudan Savanna.

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Crop residue management; intercropping; minimum tillage; Sub-Saharan Africa; water erosion

1. Introduction

Soil erosion is a major threat to sustainable agriculture in Sub-Saharan Africa (SSA) since it depletes soil nutrient and productivity (Lal 1995; Stoorvogel and Smaling 1990) Conservation agriculture (CA) has been recommended by the Food and Agriculture Organization of the United Nations (FAO) as a soil and water conservation technique as well as a practice for improving crop yield and reducing labor requirements (FAO 2008). According to the FAO (FAO 2017), CA is a farming system with three principles: (1) continuous minimum mechanical soil disturbance (e.g., reduced, minimum, or no tillage); (2) permanent organic soil cover (with crop residues or cover crops); (3) diversification of crop species grown in sequence (e.g., crop rotation) and/or association (e.g., mixed farming or intercropping). Although CA has been widely adopted in North and South America, it has not been embraced in SSA (FAO 2017; Friedrich *et al*. 2012; Lal 2007) with certain exceptions as noted by Ekboir *et al*. (2002) and Haggblade and Tembo (2003). The primary reason for low CA implementation in SSA is considered to be a lack of access to input and output markets (Gowing and Palmer 2008). Giller *et al*. (2011) also emphasized that the development of better markets for grain legumes is needed to promote cereal-legume rotation in SSA.

In an alternative view, Tittonell *et al*. (2012) indicated that the reason behind the disinterest in CA is principally because CA has often been promoted as an indivisible package without proper adaptation to local circumstances. Giller *et al*. (2009) also argued that the promotion of the three-component CA program to the smallholder farmers in Africa was not realistic; they considered that it was imperative to determine which component(s) of the three contributes to the desired effects. Stevenson *et al*. (2014) agreed with Giller *et al*. (2009) and suggested that the high degree of flexibility in CA principles in southern Australian mixed farming systems may provide a more suitable model for the future promotion of CA in SSA.

The Sudan Savanna (annual rainfall, 600–900 mm) in West Africa is a transition zone between the Sahel (annual rainfall, 200–600 mm) to the north and the Guinea Savanna (annual rainfall, 900–1200 mm) to the south. It stretches for ~3300 km from central Senegal and Gambia to northern Nigeria. The climate in the Sudan Savanna is mainly BSh in the Köppen climate classification, i.e., a steppe climate with an average

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annual temperature of 18°C or higher. Owing to the semi-arid conditions, pearl millet, sorghum, cowpea, and groundnut are the major crops and maize, root crops, and rice are also grown in fields rich in soil water (Matlon 1987; Callo-Concha *et al*. 2013). According to Callo-Concha *et al*. (2013), crop production in the Sudan Savanna is limited by several factors: low water availability (because of frequent droughts and high variability in the rainfall), poor soil fertility, farmers' limited technical, managerial and financial capacities, and the general structural, economic, and institutional weaknesses of the countries. All these influences are aggravated by ongoing water erosion. In the Sudan Savanna, soils with sandy topsoil having low organic matter content are dominant (Matlon 1987; Shehu *et al*. 2015) and thus, soil crusts/seals can be easily formed, which makes soils susceptive to water erosion (Valentin 1993). The United Nations Environment Program (UNEP 1997) reported that the risk of water erosion is high in the Sudan Savanna, particularly in the central plateau of Burkina Faso. Zougmoré (2003) showed that annual soil loss by water erosion in the Central plateau of Burkina Faso was as high as 32.7 Mg ha^{-1} yr^{-1} (corresponding to 2 mm of topsoil per year). This value is much higher than the tolerance limit (known as soil loss tolerance or T value, 2.2–11.2 Mg ha^{-1} yr^{-1}) proposed by the U.S. Department of Agriculture (Schertz 1983).

CA was expected to be an effective countermeasure against water erosion in the Sudan Savanna. However, as in the other regions of SSA, it is little-used by the smallholder farmers in the Sudan Savanna (FAO 2017). The three-component CA package is a heavy burden for the farmers who have meager cash and labor resources (Nagy *et al*. 1988). Then, a high probability that the crop rotation/association component of CA is not always necessary for reducing water erosion is noteworthy. Thierfelder and Wall (2009) reported a case in which intercropping with legumes was not effective for soil and water conservation; moreover, high competition for soil water between the main crop and the legume reduced crop yield and the efficiency of rainfall use on loamy sand soil in Zimbabwe. Giller *et al*. (2011) suggested that a major benefit of CA, i.e., the reduction of water erosion, is principally achieved by surface mulching. Therefore, the objective of this study was to examine whether all three components of CA are required for reducing water erosion in the Sudan Savanna, with the assumption that the crop rotation/association component may not be necessary. A lessening of the burden of its adoption could facilitate the promotion of CA to the smallholder farmers in the Sudan Savanna.

2. Materials and methods

2.1. Site description

Field experiments were conducted at the Institute of Environment and Agricultural Research (Institut de l'Environnement et de Recherches Agricoles: INERA) Saria station (N 12°16′, W 2°09′; 300 m above sea level). The station is located in the central plateau of Burkina Faso where the water erosion is even more severe than the other areas in the Sudan Savanna (UNEP 1997). The climate is BSh with a mean annual rainfall of 800 mm and mean annual temperature of 28°C. The rainfall is concentrated between June and September when the intertropical convergence zone is at its furthest north, and almost no rain falls between November and March when the intertropical convergence zone is in its southern position. The mean annual potential evaporation is between 1700 and 2000 mm (Ouattara *et al*. 2006). Soil in the experimental field is classified as Ferric Petroplinthic Lixisols (IUSS Working Group WRB, 2015). As in other areas of the Sudan Savanna (Matlon 1987; Shehu *et al*. 2015), topsoil with high sand content and low organic carbon content (4.4 g kg^{-1}) is structurally inert. Detailed soil chemical and physical properties are shown in Tables 1 and 2. The petroplinthic horizon (Bmv; Tables 1 and 2) starts from a depth of 73 cm, which limits root elongation in crops.

2.2. Experimental setting

Twelve runoff plots, 14.0 m long in the slope direction and 4.2 m wide, were created in 2012. The slope of the plots was 0.7%, which is the average in a watershed (192 km^2) including the INERA Saria station. The plots were delimited with 20-cm-high iron sheets to prevent runoff water from entering or exiting. An apron in the shape of an isosceles triangle was set up at the lowest edge of each plot to concentrate runoff water and eroded soil. The four following treatments were assigned to the plots using a randomized block design with three replicates. (1). CNTRL: Conventional methods as a control (full tillage, removal of crop residue, and no intercrop). (2). MT+CRM: Minimum tillage (MT) with crop residue mulch (CRM) without intercropping. (3). CA_VB: MT+CRM and intercropping with velvet bean (VB; *Mucuna pruriens* (L.) DC). (4). CA_PP: MT+CRM and intercropping with pigeon pea (PP; *Cajanus cajan* (L.) Millsp.).

The hypothesis that the crop rotation/association component is not necessary for soil and water conservation in the Sudan Savanna determined the treatments. Crop rotation was not selected because intercropping is more common in the Sudan Savanna (Mason *et al*. 2015). VB (annual) and PP

Table 1. Physical properties of the soil from the experimental site.

Horizon	Depth (cm)	Coarse fragment >2 mm (% weight)	Particle size distribution (% weight of fine earth): C. Sand 0.2–2	F. Sand 0.02–0.2	Silt 0.002–0.02	Clay < 0.002	Bulk density (Mg m^{-3})	Volumetric water content (%): pF 1.6	pF 2.0	pF 2.5	pF 3.0	pF 3.2	pF 3.8	PF 4.2
Ap	0–5	7.3	31.5	49.8	8.5	10.2	1.6	24.2	19.5	15.9	12.3	10.7	6.9	5.4
A	5–25	16.4	30.5	44.0	6.9	18.6	1.7	23.3	20.3	16.7	14.0	13.0	10.2	8.8
Btw	25–58	23.6	20.5	36.0	9.9	33.7	1.4	28.6	25.2	21.6	18.5	17.5	14.3	12.9
Btwc	58–73	44.1	22.3	39.5	7.2	31.1	1.5	28.4	25.3	21.4	17.5	16.3	13.2	11.8
Bmv	73–95+	–	–	–	–	–	–	–	–	–	–	–	–	–

C: coarse; F: fine. – : Soil sample could not be taken from Bmv horizon because it was consolidated.

Table 2. Chemical properties of the soil from the experimental site.

Horizon	Depth (cm)	pH (H_2O, 1:5)	pH (KCl, 1:5)	EC (mS m^{-1})	OC (g kg^{-1})	TN (g kg^{-1})	C/N[a]	Exchangeable bases Ca (cmol$_c$ kg^{-1})	Mg	K	Na	Al	CEC	EBS[b] (%)	Bray-1 P (mgP kg^{-1})
Ap	0–5	5.5	4.3	2.8	4.4	0.5	9.8	1.2	0.4	0.0	0.0	0.0	1.5	100	1.8
A	5–25	5.1	4.1	4.2	2.7	0.3	8.6	1.3	0.4	0.0	0.0	0.2	2.0	92	1.0
Btw	25–58	5.2	4.2	2.5	2.5	0.4	7.1	1.7	0.6	0.0	0.0	0.4	5.0	86	0.5
Btwc	58–73	5.2	4.2	2.9	2.2	0.3	6.9	1.5	0.6	0.1	0.0	0.3	4.6	88	0.7
Bmv	73–95+	–	–	–	–	–	–	–	–	–	–	–	–	–	–

EC: electrical conductivity; OC: organic carbon content; TN: total nitrogen content; CEC: cation exchange capacity; EBS: effective base saturation.
[a]Ratio of OC to TN; [b]ratio of exchangeable (Ca + Mg + K + Na) to exchangeable (Ca + Mg + K + Na + Al) defined in IUSS Working Group WRB (2015). – : Soil sample could not be taken from Bmv horizon because it was consolidated.

(perennial) were chosen as intercrops because they were expected to produce a large biomass and thus retain more crop residue in the field as mulch (Baudron *et al*. 2012). Contrary to expectations, however, PP did not survive (20% survival) the dry season during the experimental period; thus, three treatments excluding CA_PP were mainly used in the following section.

For all treatments, sorghum (*Sorghum bicolor* (L.) Moench, var. Kapelga) was planted by hand as a main crop at a rate of 3.125 pockets m^{-2}; the intervals between rows and pockets were 80 cm and 40 cm, respectively, and the average date of sowing was July 1. Two weeks after sowing, the number of plants in each pocket was reduced to three (thinning). Minimal chemical fertilizer was applied to avoid experimental failure owing to high heterogeneity in crop growth. In 2012–2015, the mineral levels were phosphorus, 23 kg P_2O_5 ha^{-1}; potassium, 14 kg K_2O ha^{-1}; and in 2012, nitrogen, first at 37 kg ha^{-1}, then in 2013–2015, at 25 kg ha^{-1}. Before sowing in 2012, the land was plowed with a moldboard (up to 10 cm deep) with animal traction in all the treatments to make soil conditions as uniform as possible. Weeds were controlled twice per cropping season by hand hoe in CNTRL and by hand in MT+CRM and CA_VB in 2012. From 2013 to 2015, the land was tilled by hand hoe (up to 5 cm deep) before sowing, and weeds were controlled by hand hoe 2–3 times per cropping season for CNTRL (full tillage). For the MT treatments (MT+CRM and CA_VB), planting rows were made using a chisel plow (depth 7–8 cm) with animal traction, and weeds were controlled by hand 2–3 times per cropping season. For mulching, residues from crops grown in the same plot in the previous year were used. Two weeks after the sowing of sorghum (average date, July 15), VB was planted between the sorghum rows with an 80-cm interval between VB rows. The interval between VB hills was 40 cm in 2012 and 80 cm in 2013–2015. The distance was increased because competition between sorghum and VB in 2012 appeared to be severe. To reduce competition, VB shoots were pruned when necessary (average date of first pruning, August 6).

2.3. Measurements

2.3.1. Runoff and soil loss measurement

Wind speed and direction, air temperature, relative humidity, solar radiation, and rainfall were recorded by an automatic weather station (U-30 station, Hobo) at 10-min intervals in the field. As an indicator of rainfall erosivity, EI_{30} [MJ mm ha^{-1} hr^{-1}] (Wishmeier and Smith 1978) was calculated in each erosion event with reference to Foster *et al*. (1981). The automatic weather station was malfunctioning from 30 July 2014 to 24 September 2014. Therefore, missing daily rainfall values were complemented using data recorded by the weather station in the INEAR Saria station and EI_{30} during that period was estimated by the following formula:

$$EI_{30} = 9.62 \bullet r - 59.68 \quad (1)$$

where r [mm] is the daily rainfall. This formula was derived from the relationship between EI_{30} and r from the beginning of August to the middle of September in 2013 and 2015 (n = 19, r = 0.82***).

A sedimentation container was connected to the apron in each plot to collect runoff water and eroded soil. For every erosive rainfall event, the amount of runoff and eroded soil (settled sediments as coarse particles + suspended solids as fine particles) were measured. The amount of runoff [L or mm] was determined from the quantity of water collected in the container. The amount of eroded coarse soil particles [g] was determined by collecting settled sediments on the apron and in the container and then measuring the mass after oven-drying at 70°C for 48 h. The amount of eroded fine soil particles [g] was determined by multiplying the concentration of suspended solids in the water of the container (SS_c) [mg L^{-1}] by the amount of runoff water. SS_c was estimated from the turbidity of the collected water using the following formula:

$$SS_c = 0.0011 \bullet x^2 + 0.833 \bullet x + 63.731 \quad (2)$$

where x is the reading of a turbidity meter (TU-2016, Lutron) in Nephelometric Turbidity Units.

Soil loss [g] can be factored into the amount of runoff [L] and sediment concentration [g L^{-1}]. To examine the factors that reduce water erosion in the Sudan Savanna, we calculated sediment concentration by dividing the annual soil loss by the amount of runoff with reference to Erenstein (2002).

We measured the mass of sorghum stover in each plot of MT+CRM and CA_VB at harvesting time after oven-drying at 70°C for 48 h. For VB, we measured the mass of haulm and leaves at harvest in each plot of CA_VB after oven-drying. Then, the sorghum stover in MT+CRM and CA_VB and VB haulm and leaves in CA_VB were returned to each plot and placed along the planted rows as mulch.

2.3.2. Infiltration measurement

We measured soil permeability of matrix soils (defined in this study as the soil for which galleries or holes made by insects was not found on the surface) in the CNTRL and MT+CRM plots and of soils with termite and wolf spider holes (Fig. 1) in the MT+CRM plots. This is because, as in Mando *et al.* (1996), (1999)), galleries or holes made by insects which were often found under the sorghum stover can greatly improve soil permeability. The measurements were conducted with three replicates before the rainy season in 2015 using a double ring infiltrometer (09.04, Eijkelkamp), which consisted of three pairs of inner and outer rings. The diameters of the inner ring/outer rings were 28/53, 30/55, and 32/57 cm. The inner and outer rings were inserted 10 cm into the soil and then filled with water to 5 cm above ground. The water level in the inner ring was measured at a specific interval (2 or 10 min), and when the water level dropped to lower than 3 cm, water was added to 5 cm. During the measurements, the water level in the outer ring was kept similar to that in the inner ring to ensure that the water in the inner ring infiltrated vertically (to prevent lateral spreading or narrowing of the water). Cumulative infiltration I [mm] was plotted against the square root of time t [$s^{-1/2}$] and fitted to Philip's equation (Philip 1957):

$$I = St + At^2 \tag{3}$$

where S [mm $s^{-1/2}$] and A [mm s^{-1}] are coefficients. S is the parameter called sorptivity that governs the early stage of water infiltration. According to Shaver *et al.* (2003), soil sorptivity is a critical factor in water capture in semi-arid dryland systems. Nishigaki et al. (2017a, 2017b) also argued that soil sorptivity greatly affects the runoff coefficient on the basis of field experiments in Tanzania and Cameroon.

Figure 1. Photos of a wolf spider (top) and soil surfaces with the holes made by termites (center) and a wolf spider (bottom).
Bars represent 2 cm.

2.4. Statistical analysis

Statistical analysis was performed using statistical software (SPSS Statistics ver. 21, IBM). A normal distribution was assumed for each group and each measurement because the number of replications was not high. The significance of the difference between means of two samples was examined by the Student's *t*-test when the variances of the groups were equivalent or by the Welch's *t*-test when the variances of the groups were not. The significance of the differences between means of three or more samples was examined by one-way analysis of variance. When a significant difference was detected, a post-hoc test was conducted by the Tukey Honestly Significant Difference test. Significance was defined as $P < 0.05$ for all tests.

3. Results

3.1. Rainfall

The annual rainfall and sum of EI_{30} in 2013, 2014, and 2015 was 570, 787, and 800 mm and 3298, 6341, and 5474 MJ mm ha^{-1} hr^{-1} yr^{-1}, respectively. The annual rainfall in 2013 was less than the average, and those in 2014 and 2015 were almost the same as the average. Although the annual rainfall in 2014 was 2% less than that in 2015, the sum of EI_{30} in 2014 was 16% higher.

3.2. Soil loss

As observed for the rainfall data, annual soil loss in CNTRL in 2013 (3.1 Mg ha^{-1} yr^{-1}) was less than in 2014 and 2015 (6.5 and 5.1 Mg ha^{-1} yr^{-1}, respectively), but the difference was not significant. We compared our results with those of a study by Zougmoré (2003) in which soil loss caused by water erosion was measured at the INERA Saria station, although the reported slope in those experiments (1.5%) was slightly greater than in our study (0.7%). Soil loss in CNTRL in our current study was greater than that observed by Zougmoré for control plots in 2000 and 2001 (0.2 Mg ha^{-1} yr^{-1}, both years) but much less than that recorded in 2002 (32.7 Mg ha^{-1} yr^{-1}).

The temporal distributions of rainfall and the cumulative soil losses in 2013–2015 are shown in Fig. 2. Soil loss was concentrated at the beginning of the rainy season when soil surface was minimally covered by the crops and not protected from raindrops. The cumulative loss of soil in MT+CRM and in CA_VB was less than that in CNTRL during all 3 years of observation. The 3-year averages of soil loss are shown in Table 3. Whereas there was no significant difference between MT+CRM and CA_VB, the average soil loss for CNTRL was significantly greater than the value for either mulched plot.

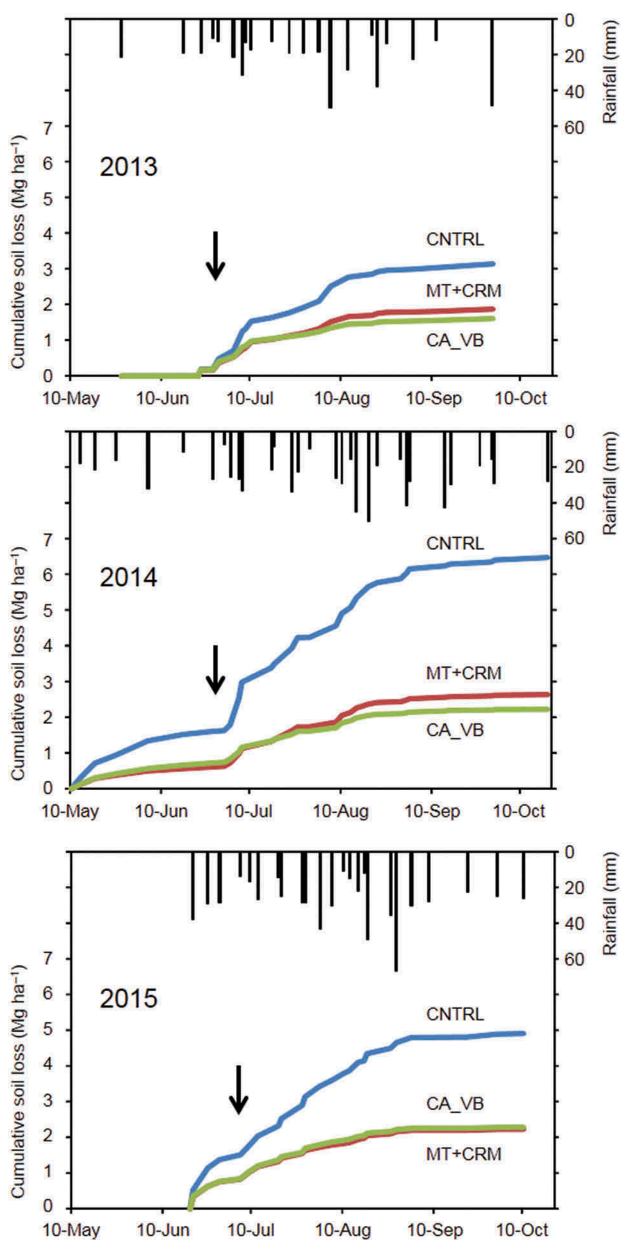

Figure 2. Temporal distribution of rainfall and cumulative soil losses for 2013–2015.

Arrows represent the sowing date in each year.

Table 3. Three-year average of annual soil loss, runoff coefficient, and sediment concentration for each treatment.

	Soil loss (Mg ha^{-1} yr^{-1})	Runoff coefficient (%)	Sediment concentration (g L^{-1})
CNTRL	4.9^a	27.9^a	3.0^a
MT+CRM	2.3^b	18.8^b	2.2^a
CA_VB	2.0^b	17.5^b	2.1^a

Mean values with different letters are significantly different between treatments ($P < 0.05$).

3.3. Runoff coefficient and sediment concentration

The 3-year average of runoff coefficient in CNTRL (27.9%) was greater than that reported by Zougmoré (2003; 15.2%) and significantly greater than in MT+CRM or CA_VB (Table 3). The 3-year average of sediment concentration in CNTRL (3.0 g L^{-1}) was also greater than that measured in either 2000 or 2001 (0.2 and 0.3 g L^{-1}, respectively) but less than that for 2002 (25.4 g L^{-1}). In the current study, although this parameter showed a tendency toward a greater value than those recorded for MT+CRM (2.2 g L^{-1}) and CA_VB (2.1 g L^{-1}), the difference was not significant (Table 3).

3.4. Amount of crop residue retained as mulch

The biomass of crop residues retained in the field as mulch after harvesting is shown in Table 4. The residues retained were: sorghum stover in MT+CRM, and sorghum stover and VB haulm and leaves in CA_VB (no residue was retained in CNTRL). Contrary to expectations, for all 3 years, the biomass retained as mulch in CA_VB (2.5–3.0 Mg ha^{-1}) was not significantly greater than that in MT+CRM (2.0–2.4 Mg ha^{-1}).

3.5. Soil permeability

Soil permeability data for matrix soils in the CNTRL or MT+CRM plots and of soils with holes or galleries made by termites and wolf spiders are shown in Fig. 3. Cumulative infiltration in the matrix soils of CNTRL and MT+CRM plots was not different, whereas that in the soils with insect holes was much greater. As shown in Fig. 4, the sorptivity (S) of the soils with insect holes was significantly greater than that of the matrix soils in CNTRL and MT+CRM plots.

4. Discussion

4.1. Is the crop association component of CA necessary for the reduction of water erosion?

PP did not survive the dry season during the experimental period, although the rainfall in 2014–2015 was similar to the annual average. The relatively shallow soil in the experimental

Table 4. Biomass of crop residues retained in the field after harvesting.

	MT+CRM	CA_VB		
	Sorghum stover (Mg ha^{-1})	Sorghum stover	Velvet bean residue (Mg ha^{-1})	Total
2012	2.4^a	1.7	1.3	3.0^a
2013	2.0^a	1.8	0.7	2.5^a
2014	2.3^a	2.0	1.0	3.0^a

Mean values with the same superscript letter are not significantly different between treatments ($P \geq 0.05$).

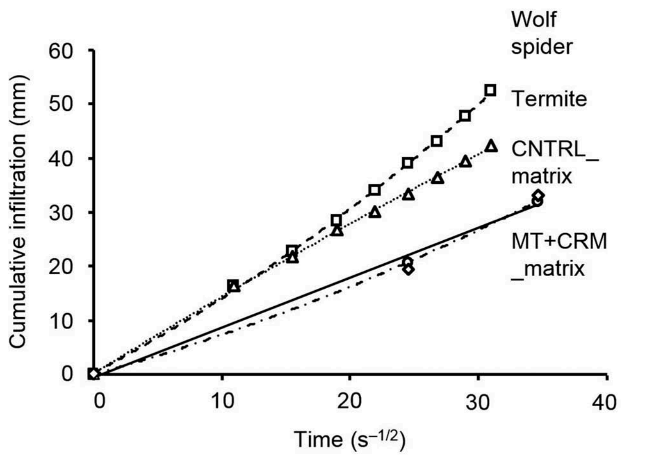

Figure 3. Soil permeability of matrix soils in the CNTRL and MT+CRM plots and of soils with holes made by termites and wolf spiders in the MT+CRM plots.

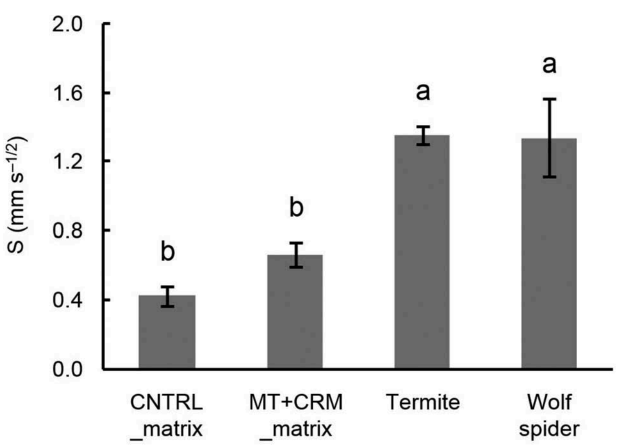

Figure 4. S in matrix soils of the CNTRL and MT+CRM plots and in soils with wolf spider and termite holes. S is the parameter called sorptivity that governs the early stage of water infiltration – an important parameter for water capture in semi-arid dryland systems.

Error bars indicate standard error. Mean values with different letters are significantly different ($P < 0.05$).

plot, at an effective soil depth of 73 cm because of the Bmv horizon, likely did not supply enough water to PP during the long dry season. Barro (1999) reported that the Bmv at 70-cm deep limits root growth of crops at the INERA Saria station. According to the European Commission (EU 2013), plinthosols with effective soil depth <50 cm are widely distributed in the Sudan Savanna, and therefore we concluded that CA with PP intercropping would not be practical in most of the Sudan Savanna.

Soil loss caused by water erosion was reduced on average by 54% in MT+CRM and by 58% in CA_VB (Table 3), and the runoff coefficient decreased on average by 32% in MT+CRM and by 37% in CA_VB (Table 3). These data indicate that both management strategies are effective for soil and water conservation in the Sudan Savanna. These results are consistent with those of Scopel *et al*. (2005), who concluded that a CRM of 1.5 Mg ha^{-1} effectively reduces the soil loss and runoff coefficient on sandy loam soil in the semi-arid region of Mexico. Soil loss in our present study was more efficiently controlled than the runoff coefficient, as was the case in a study by Harrold and Edwards (1972). However, the soil losses in MT+CRM and CA_VB were not significantly different, which indicated that intercropping with VB in combination with MT+CRM did not help reduce soil loss. Therefore, we conclude that two CA components, namely minimum soil disturbance and soil cover, would be sufficient for soil conservation in the Sudan Savanna. As described in Callo-Concha *et al*. (2013), markets for grain legumes (including cowpea) have not been developed in the Sudan Savanna, and thus the promotion of intercropping with leguminous crops will not increase smallholder farmers' incomes or resilience but will impose additional expense and labor requirements. We anticipate that the conclusion supported by our study will lighten the burden of CA adoption and facilitate the promotion of CA to smallholder farmers in the Sudan Savanna. Stevenson *et al*. (2014) also suggested that two-component CA is more readily adopted by smallholder farmers (see also the Nebraska Declaration on CA in Stevenson (2013)).

4.2. Reasonability of little contribution of VB intercropping to the reduction of water erosion

To discuss the reasonability of the result that VB intercropping did not contribute to the reduction of water erosion, we first considered what factors reduced soil loss. Soil loss can be factored into the amount of runoff and sediment concentration. The runoff coefficient for each of MT+CRM and CA_VB was significantly smaller than that for CNTRL (Table 3). In contrast, the sediment concentration for CNTRL, MT+CRM, and CA_VB did not differ significantly (Table 3), which suggests that soil structure or aggregate stability was not greatly improved in MT+CRM and CA_VB during the period of this study (long-term effects were not evaluated and are not known). These results showed that the reduced soil loss in each of MT+CRM and CA_VB was mainly attributable to the reduction in the runoff coefficient. Buerkert *et al*. (2000) reported that a CRM of 2.0 Mg ha^{-1} improved the rain infiltration on sandy soil in semi-arid West Africa. In the present study, however, soil permeability of the matrix soils in CNTRL and MT+CRM did not differ (Figs. 3 and 4), which suggests that the reduction in runoff coefficient was not caused by the change in soil permeability of the matrix soils. On the other hand, soils around galleries or holes made by termites and wolf spiders showed greater sorptivity (1.3 mm s$^{-1/2}$) and consequently infiltration than the matrix soils (0.4–0.7 mm s$^{-1/2}$; Figs. 3 and 4). This result is consistent with that of Mando *et al*. (1996) who reported that, in northern Burkina Faso, the cumulative infiltration in Ferric Lixisol with macropores made by termites was 2.2 times greater than that without macropores. Mando *et al*. (1999) also demonstrated that mulching with pearl millet straw of 3 Mg ha^{-1} significantly increased the number of termite-made macropores.

Other factors may have reduced the runoff coefficient in MT+CRM and CA_VB. Unger *et al*. (1991) argued that CRM can increase soil permeability by dissipating the energy of raindrops and by retarding the flow of runoff water. In their view, the reduced impact minimizes soil crusting and retarded water flow provides more time for infiltration. Whereas the retardation of water flow may have improved rain penetration into the soil in the current study, the dissipation of raindrop energy by CRM could not have contributed to infiltration. Table 3 shows that the sediment concentration in each of MT+CRM and CA_VB was not significantly smaller than that observed in CNTRL, which indicates that CRM did not effectively dissipate raindrop energy (perhaps because of the low coverage ratio). These data reinforce our conclusion that the reduction in runoff coefficients in MT +CRM and CA_VB was mainly attributable to the improvement of soil permeability caused by the boring of termites and wolf spiders found under sorghum stover mulch and, to some degree, by the retardation of runoff water flow.

Then, we considered the reasonability of the result that VB intercropping did not contribute to the reduction of water erosion. Intercropping with VB was expected to decrease the runoff coefficient, but this effect was not observed when VB intercropping was combined with MT+CRM (Table 3). This is reasonable because VB intercropping did not increase the biomass of crop residues retained in the field after harvesting (Table 4), especially the biomass of sorghum stover that prompts the boring of termites and wolf spiders and improves soil permeability. Competition between the VB and the sorghum probably reduced the growth of the sorghum.

Intercropping with VB was also expected to decrease the sediment concentration by protecting soil from raindrops as a cover crop. This prediction was likewise not validated in CA_VB (Table 3), probably because soil loss every year was concentrated in the period before VB growth was sufficient to provide adequate cover. The average date of VB planting was July 15, and the first pruning was September 6. The majority of the annual soil loss, i.e., >75% on average, occurred before September 6 (Fig. 2). From these observations, we conclude that, under the soil and climate conditions of this study, it is reasonable that VB Intercropping is not effective for reducing water erosion in the Sudan Savanna when employed with MT+CRM. Although Kassam *et al*. (2010) concluded that VB worked effectively as a cover crop in Burkina Faso, it is possible that VB is not applicable to the Sudan Savanna.

4.3. Future challenge for promoting two-component CA

The individual contributions of MT and CRM to the reduced runoff coefficient and soil loss are probably not the same. Nicou *et al*. (1993) reported that plowing significantly increased soil porosity and decreased runoff coefficients in the INERA Saria station, which suggests that full tillage in CNTRL is more favorable than MT. Therefore, CRM may be considered the major contributor in MT+CRM to water conservation as was suggested by Giller *et al*. (2011).

CRM, however, is generally not easily implemented by smallholder farmers under the present circumstances in SSA. Large quantities of crop residues are used as fuel, fodder, and construction materials; thus, little is retained in the field as mulch (Giller *et al*. 2009; Valbuena *et al*. 2012; Baudron *et al*. 2014). This is also true in the Sudan Savanna. According to Senayah *et al*. (2005) and Valbuena *et al*. (2012), the residue retained in the field as mulch may be less than 10% of total. Some measures or scenarios to secure sufficient amounts of crop residue on the land as mulch have been proposed by Unger *et al*. (1991), Lal (2007), Valbuena *et al*. (2012), and Baudron *et al*. (2014). Valbuena *et al*. (2012) argued that CRM can be made somewhat easier and more viable through agricultural intensification, particularly by the increased use of chemical fertilizers. Therefore, we are establishing a method to produce low-priced chemical fertilizers from the local phosphate rocks, e.g., Kodjari phosphate rocks, in Burkina Faso, and the product will be available to smallholder farmers. If these low-priced chemical fertilizers are popularized, the biomass of crop residues that can be retained in the field as mulch will increase, and CRM will become practical for the farmers in the Sudan Savanna. The significance of the popularization of low-priced chemical fertilizers is also supported by Giller *et al*. (2009) and Rockstrom *et al*. (2009) who concluded that CA cannot improve crop yield without application of adequate doses of chemical fertilizer in SSA.

5. Conclusion

Three-year field experiments at the INERA Saria station revealed that water erosion in the Sudan Savanna can be controlled by CA mainly through the reduction in runoff water by CRM. CRM stimulates the boring of termites and wolf spiders, and this activity increases soil permeability. This study also demonstrated that the CA component of crop association (intercropping with VB and PP) did not contribute to the reduction in runoff and thus had no effect on soil erosion control when employed with MT +CRM. These data suggest that the promotion of the full CA package is not reasonable, but rather that two-component CA, i.e., MT+ CRM, is a more viable approach in terms of water erosion control in the Sudan Savanna. However, the retention of sufficient crop residue in the field as mulch remains a challenge under the current situation in the Sudan Savanna because crop residue is used by smallholder farmers for multiple purposes. Agricultural intensification offers a possible solution to this problem, mainly through the increased use of chemical fertilizer. Studies aimed at establishing methods for the production of low-priced chemical fertilizer from local resources (e.g., phosphate rocks) and the determination of optimal product dosage for the major crops and soils should be accelerated.

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