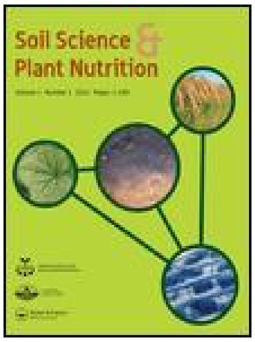

Soil Science and Plant Nutrition

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/tssp20

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To cite this article: Kenta Ikazaki , Fujio Nagumo , Saïdou Simporé , Kohtaro Iseki & Albert Barro (2020): Effects of intercropping component of conservation agriculture on sorghum yield in the Sudan Savanna, Soil Science and Plant Nutrition, DOI: 10.1080/00380768.2020.1816444

To link to this article: https://doi.org/10.1080/00380768.2020.1816444

SOIL SCIENCE AND PLANT NUTRITION
https://doi.org/10.1080/00380768.2020.1816444

ARTICLE

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Effects of intercropping component of conservation agriculture on sorghum yield in the Sudan Savanna

Kenta Ikazaki[a], Fujio Nagumo[a], Saïdou Simporé[b], Kohtaro Iseki[c] and Albert Barro[b]

[a]Crop, Livestock and Environment Division, Japan International Research Center for Agricultural Sciences (JIRCAS), Tsukuba, Ibaraki, Japan; [b]Gestion des Ressources Naturelles et Systèmes de Production, Institut De l'Environnement Et De Recherches Agricoles (INERA), Burkina Faso; [c]Biological Resources and Post-harvest Division, Japan International Research Center for Agricultural Sciences (JIRCAS), Tsukuba, Ibaraki, Japan

ABSTRACT

Conservation agriculture (CA), which consists of minimum soil disturbance, soil cover, and crop rotation/association, has been promoted as an indivisible three-component package to control water erosion in the Sudan Savanna. However, CA has not been adopted by local smallholder farmers, probably because the three-component package constitutes a large burden for the farmers. Our previous study revealed that two components – minimum tillage and crop residue mulching – are sufficient for soil conservation and intercropping, when used in combination with minimum tillage and crop residue mulching, had no effect on erosion control. In the present study, we conducted a 3-year field experiment in Burkina Faso to evaluate the effects of the intercropping component on sorghum yield. The four treatments employed were conventional practice (full tillage, no sorghum residue mulching, no intercropping), two-component CA (minimum tillage and sorghum residue mulching without intercropping), and three-component CA with velvet bean (VB) or pigeon pea (PP) intercropping. We found that sorghum yield was similar between treatments during the first 2 years but higher for CA with PP intercropping than for conventional practice in the third year. This increased yield was mainly attributed to higher soil nitrogen and carbon content as well as panicle mass and harvest index observed for CA with PP intercropping than for conventional practice. Unexpectedly, however, PP produced few seeds and did not survive the dry season. Therefore, we concluded that CA with PP intercropping is effective to increase sorghum yield but practical only for the prosperous farmers who can afford to purchase PP seeds every year and accept no increased yield during the first 2 years after its installation. For most smallholder farmers, it would be realistic to promote two-component CA without intercropping because it can effectively control water erosion and reduce the farmers' burden of its adoption in the Sudan Savanna.

ARTICLE HISTORY
Received 26 September 2019
Accepted 26 August 2020

KEY WORDS
Pigeon pea; semi-arid; soil carbon; soil nitrogen; sub-Saharan Africa

1. Introduction

Soil erosion is a major threat to sustainable agriculture in Sub-Saharan Africa (SSA) because it depletes soil nutrients and reduces productivity (Lal 1995; Stoorvogel and Smaling 1990). Conservation agriculture (CA), according to the Food and Agriculture Organization of the United Nations (FAO) (2008), is a farming system with three principles, i.e., minimum mechanical soil disturbance (reduced, minimum, or no tillage), permanent organic soil cover (with crop residues or cover crops), and diversification of crop species grown in sequence (rotation) and/or association (mixed farming or intercropping). The FAO has recommended CA as a soil and water conservation technique as well as a practice for improving crop yield and reducing labor requirements. However, it has been rarely adopted by local farmers in SSA (Friedrich, Derpsch, and Kassam 2012; Lal 2007). Tittonell et al. (2012) indicated that this low CA implementation in SSA is principally because CA has often been promoted as an indivisible three-component package without proper adaptation to local circumstances. Giller et al. (2009) also emphasized that promotion of the three-component CA package to the smallholder farmers in Africa is not realistic, and thus it is imperative to determine which component(s) of the three contributes to the desired effects.

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. Owing to the semi-arid conditions, the major crops are sorghum, pearl millet, cowpea, and groundnut, although maize, root crops, and rice are also grown in fields in which the soil has adequate moisture (Callo-Concha et al. 2013; Matlon 1987). According to the United Nations Environment Program (UNEP 1997), water erosion is severe in the Sudan Savanna, particularly in the Central Plateau of Burkina Faso. As in the other regions of SSA, however, CA is not implemented by the majority of smallholder farmers in the Sudan Savanna (Friedrich, Derpsch, and Kassam 2012). This is likely because the three-component CA package is a substantial burden for the farmers who have meager cash and labor resources (Nagy, Sanders, and Ohm 1988). Therefore, we examined which component(s) of CA contributes to the reduction of water erosion and revealed that two components, namely minimum soil disturbance and soil cover, are sufficient for

CONTACT Kenta Ikazaki ikazaki@affrc.go.jp Crop, Livestock and Environment Division, Japan International Research Center for Agricultural Sciences (JIRCAS), Tsukuba, Ibaraki 305-8686, Japan

controlling water erosion and intercropping component, when used in combination with minimum tillage and crop residue mulching, had no effect on erosion control in the Sudan Savanna (Ikazaki et al. 2018a). Thierfelder and Wall (2009) also reported that intercropping with legumes was not effective for soil and water conservation. Our finding may lighten the burden of CA adoption by the majority of smallholder farmers in the Sudan Savanna.

Even if two-component CA is effective for reducing water erosion, this result does not by itself ensure future promotion of two-component CA because the short-term yield benefit largely determines whether a farming system will be implemented by smallholder farmers (Giller et al. 2009). If CA negatively affects crop yield, then it inevitably discourages the farmers from adopting CA. In previous studies, the effects of CA components on short-term crop yield are variable (Giller et al. 2009). Nicou, Charreau, and Chopart (1993) stressed the importance of tillage for improving soil physical properties and crop yield in the semi-arid regions of West Africa. Similarly, Ouédraogo et al. (2007) and Naudin et al. (2010) reported that no-tillage (NT) reduced sorghum yield in the Sudan Savanna and cotton yield in the semi-arid region of Cameroon, respectively. Kusuma Grace et al. (2013) also reported that minimum tillage (MT) diminished sorghum yield in the semi-arid region of India. In their review, Brouder and Gomez-Macpherson (2014) concluded that NT generally resulted in lower crop yield than did conventional tillage in the short term. Regarding mulching, Bayala et al. (2012) reviewed that it commonly improved crop yield in the semi-arid regions of West Africa, although Coulibaly et al. (2000) observed no difference in sorghum yield between fields with/without crop-residue mulching (CRM) in the Sudan Savanna. Taken together, these studies suggest that NT and MT would, in the short term, negatively affect crop yield, and CRM would neutrally or positively affect crop yield in the Sudan Savanna.

When NT or MT is combined with CRM, the negative effects of NT or MT may be offset by the beneficial effects of CRM. Nicou, Charreau, and Chopart (1993), however, concluded that crop yields for MT+CRM were lower than for conventional tillage in the Sudan Savanna. Results greatly differed when sufficient fertilizer, especially nitrogen (N), was applied. Vogel (1993) and Mupangwa, Twomlow, and Walker (2012) reported that maize yields for MT+CRM were higher in some dry years than for conventional tillage in the semi-arid region of Zimbabwe, although Mashingaidze, Twomlow, and Hove (2009) did not observe any positive effects of MT+CRM on maize and sorghum yields in a similar region. Thus, it appears that both CRM and fertilizer application are necessary to offset the short-term negative effects of NT or MT on crop yield in the Sudan Savanna.

The effects of crop rotation/association as a third CA component are also variable. In the Sudan Savanna, Bagayoko et al. (2000), Kouyate et al. (2000), and Bado et al. (2006) reported increased cereal yields owing to cereal-legume rotation. On the other hand, Bayala (2012) concluded that rotation/association reduced crop yield in West Africa when annual rainfall was <800 mm.

Previous studies have shown that the effects of the CA components on short-term crop yield are difficult to disentangle and predict. Therefore, we examined, in this study, the effects of two-component CA without intercropping (i.e., MT+CRM) and three-component CA package (i.e., MT+CRM with intercropping) on sorghum production and discussed the practicality of intercropping component in the Sudan Savanna.

2. Materials and methods

2.1. Site description

Field experiments were conducted at the Saria station of Institute of Environment and Agricultural Research (Institut de l'Environnement et de Recherches Agricoles: INERA). The Saria station is located at the Central Plateau of Burkina Faso (N 12° 16′, W 2°09′; 300 m above sea level), where water erosion is more severe than at other locations in the Sudan Savanna (UNEP 1997). The climate is BSh (Köppen classification system) with a mean annual rainfall of 800 mm and mean annual temperature of 28°C. The rainfall is concentrated between June and September, and almost no rain falls between November and March. The mean annual potential evaporation is between 1700 and 2000 mm according to Ouattara et al. (2006). Soil in the experimental field is classified as Ferric Petroplinthic Lixisols (IUSS Working Group WRB 2015), which have a petroplinthic horizon starting from a depth of 73 cm (Ikazaki et al. 2018b). As in the other areas of the Sudan Savanna (Matlon 1987; Shehu, Jibrin, and Samndi 2015), topsoil with high sand content (81.3%) and low organic carbon (C) content (4.4 g kg^{-1}) is structurally inert. Detailed soil morphological, chemical, and physical properties have been described by Ikazaki et al. (2018b; see soil group 2).

2.2. Experimental setting

The same experimental settings as reported in Ikazaki et al. (2018a) were employed. In June 2012, 6- to 7-year fallow was cleared, and 12 runoff plots were established that were 14.0 m long in the slope direction and 4.2 m wide. The four following treatments were assigned to the plots using a randomized block design with three replicates. 1. CNTRL: Conventional practice as a control (full tillage, removal of crop residue, no intercropping). 2. MT+CRM: MT with CRM but without intercropping. 3. CA_VB: MT+CRM with velvet bean intercropping (VB; *Mucuna pruriens* (L.) DC). 4. CA_PP: MT+CRM with pigeon pea intercropping (PP; *Cajanus cajan* (L.) Millsp.). Crop rotation was not undertaken because intercropping is more common in the Sudan Savanna (Mason et al. 2015). Velvet bean (annual) and PP (perennial) were chosen as intercrops because they are expected to produce larger biomass, and consequently retain more crop residue in the field as mulch than cowpea (Baudron et al. 2012).

For all treatments, sorghum (*Sorghum bicolor* (L.) Moench, var. Kapelga) was planted as the main crop by hand at a rate of 3.1 hills m^{-2}; the distances between rows and hills were 80 cm and 40 cm, respectively. In 2012, the land for all treatments was plowed using a moldboard (depth 10 cm) with animal traction before sowing to make soil conditions as uniform as possible. Because in 2011 the plots were fallow (no crop residue in 2011) and full tillage was conducted in 2012, MT+CRM treatment could not be practiced in 2012; hence, the results obtained in 2013–2015 were used in the Results and Discussion sections. From 2013 to 2015, the land was prepared by hand hoe before sowing in CNTRL, whereas rows for planting were made using a chisel plow (depth 7–8 cm) with animal traction for MT+CRM, CA_VB, and CA_PP plots as the MT treatment. The sowing dates were June 28, June 28, and July 6 in 2013, 2014, and 2015, respectively. Two weeks after sowing (WAS), the number of plants in each hill was thinned to three. Every year, 100 kg ha^{-1} of 14–23-14 NPK compound fertilizer was applied at 2 WAS, and 25 kg ha^{-1} of urea (46% N) was applied at 4 WAS as a top-dressing to avoid experimental failure caused by high heterogeneity in crop growth. If not, the effects of main factors, i.e., tillage and intercropping methods, on sorghum yield could be masked by the high heterogeneity observed in the field. Weeds were controlled 2–3 times per cropping season by hand hoe in CNTRL and by hand in MT+CRM, CA_VB, and CA_PP. Every year at 2 WAS, VB was planted between the sorghum rows at a rate of 1.6 hills m^{-2}; the distances between rows and hills were 80 cm and 80 cm, respectively. Pigeon pea was planted between the sorghum rows on July 10 in 2012 at a rate of 0.8 hills m^{-2}; the distances between rows and hills were 160 cm and 80 cm, respectively. Contrary to expectations, PP did not survive (ca., 20% survival) the dry season during the experimental period. Therefore, PP was replanted on June 28 in 2013 or transplanted on June 6 and 19 in 2014 and June 21–22 in 2015 to maintain the intercropping treatment. To reduce competition between sorghum and intercrops, shoots of VB and PP were pruned when necessary during the cropping season. Sorghum was harvested on October 27, October 29, and October 27 in 2013, 2014, and 2015, respectively. Then, harvested sorghum stover (stem and leaf) grown *in situ* were used as mulch except in CNTRL, where sorghum stover was removed. At harvest time, haulm and leaves of VB were also cut and harvested VB grown *in situ* were used as mulch in CA_VB.

2.3. Measurements

2.3.1. Weather and soil

Wind speed and direction, air temperature, relative humidity, solar radiation, and rainfall were recorded in the field at 10-min intervals by an automatic weather station (U-30 station, Hobo). Annual rainfall amounts were as follows: 570 (2013), 787 (2014), and 800 (2015); the respective rainfall amounts during the cropping season were as follows: 468, 657, and 699 mm. The annual rainfall in 2013 was less than the average and in 2014–2015 was almost the same as the average. The mean daily temperature during the cropping season was 27 °C in 2013–2015.

Twelve soil samples were taken from 0 to 5 cm deep using a 100-ml metal core in June 2012. Then, three soil samples were taken for each plot in the same manner and mixed to make a composite sample in December 2012, June and November 2014, and June and October 2015. All soil samples were air-dried and passed through a 2-mm sieve. Total C and N content were determined using the dry combustion method with an elemental analyzer (SUMIGRAPH NC-220 F, Sumika Chemical Analysis Service).

2.3.2. Sorghum and intercrop

Every 2 weeks from the end of July (ca., 4 WAS), the number of leaves per plant (plant^{-1}), plant height (m), and stem diameter (mm) were measured for six plants per plot as growth parameters, and soil plant analysis development (SPAD) readings were recorded at the youngest fully expanded leaf with a chlorophyll meter (SPAD-502 plus, Konica Minolta) for six plants per plot. At harvest time, all sorghum plants in each plot except the ones at the borders were harvested and subjected to yield and yield component survey. The mass of stover, panicle (including grain), and grain was determined after oven-drying at 70°C for 48 h. The harvest index was calculated as a ratio of grain mass to total above-ground biomass (stover + panicle). For yield components, hill number per unit area (m^{-2}), panicle number per hill (hill^{-1}), and grain weight per panicle (g panicle^{-1}) were determined.

The biomass of pruned VB (haulm and leaf) and PP (branch and leaf) as well as above-ground biomass of VB (haulm and leaf) cut at sorghum harvest time were weighed fresh in the field. Then, sub-samples were taken to the laboratory and oven-dried at 70°C for 48 h to obtain oven-dried weight. Root biomass was not examined because root extraction conflicts with the MT treatment. To assess N and C accumulation by sorghum and intercrops, total N and C content of each plant part of the harvested sorghum, pruned VB and PP, and VB cut at sorghum harvest time were determined using the dry combustion method (described in section *2.3.1*). Nitrogen translocation index, defined as grain N mass divided by whole-plant N mass, was calculated for sorghum.

2.4. Statistical analysis

Statistical analysis was performed using statistical softwares (SPSS Statistics ver. 21, IBM and JMP ver. 14, SAS Institute). A normal distribution was assumed for each group and measurement because the number of replicates was not high. In most cases – with the exception of temporal changes in total soil N and C content – the significance of the difference between means was examined by the Tukey honestly significant difference test. Temporal changes in total soil N and C content for each treatment were assessed by repeated analysis of variance (ANOVA) followed by the Bonferroni post-hoc test. Significance was defined as $P < 0.05$ for all tests.

3. Results

3.1. Soil

Repeated ANOVA revealed that the total soil N and C content for CNTRL, MT+ CRM, and CA_VB decreased significantly with time, and similar decreasing trends were observed for CA_PP; by contrast, these values did not decrease significantly for CA_PP (Figure 1; statistical results are not shown). The rates of decrease of total soil N and C content for CNTRL, MT+CRM, CA_VB, and CA_VB were 7.1, 4.8, 4.3, and 3.2 × 10^{-3} g kg^{-1} month^{-1} for N and 76.3, 49.2, 49.7, and 33.2 × 10^{-3} g kg^{-1} month^{-1} for C, respectively, and those were significantly higher for CNTRL than for CA_PP. Total soil N and C content did not differ significantly between treatments up to June 2015, but the

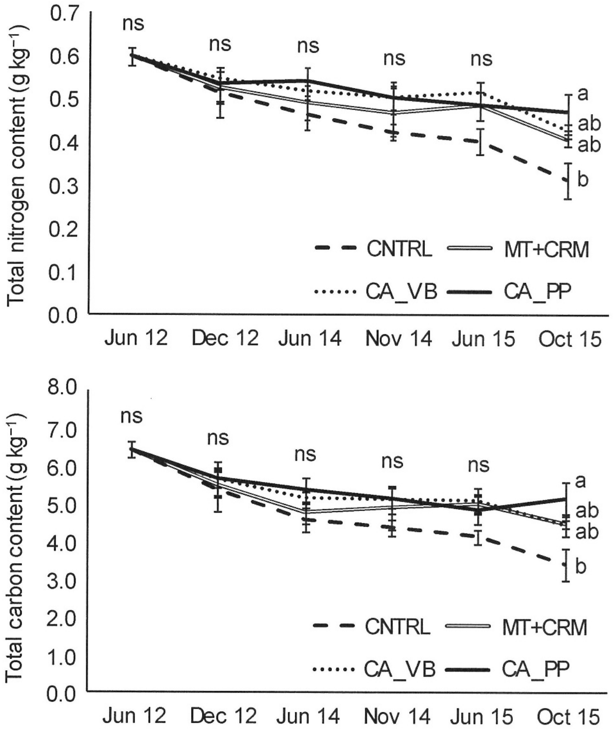

Figure 1. Temporal changes in total nitrogen (top) and carbon (bottom) content of the topsoil for each treatment form June 2012 to October 2015. CNTRL, control; MT +CRM, minimum tillage + crop residue mulching; CA_VB, MT+CRM with velvet bean intercropping; CA_PP, MT+CRM with pigeon pea intercropping. Mean values with different letters are significantly different between treatments ($P < 0.05$). ns, not significant. The data for June 2012 represent the initial content of total nitrogen and carbon.

values were significantly different in October 2015 (Figure 1). In October 2015, total soil N and C contents were significantly higher for CA_PP than for CNTRL.

3.2. *Input of organic N and C from intercrops and retained sorghum residue*

Table 1 presents the amounts of organic N and C returned to the soil from the intercrops and/or retained sorghum stover. For CNTRL, input was considered negligible because sorghum was not intercropped and sorghum stover was removed. For CA_VB and CA_PP, not only sorghum stover having a high C:N ratio (>100) but also the pruned intercrop (and for CA_VB, also VB cut at sorghum harvest time) having a low C:N ratio (12–14 and 10–15 for VB and PP, respectively), were returned to the soil. Therefore, the amounts of returned organic N for CA_VB and CA_PP were significantly greater than for MT+CRM, where sorghum was not intercropped and only sorghum stover was retuned (Table 1). In contrast, the amounts of returned organic C for CA_VB and CA_PP were not always greater than for MT +CRM (Table 1) because total C content of sorghum and intercrops were similar. It is also worth noting that the inputs of organic N and C for CA_VB and CA_PP were not significantly different (Table 1). This is because both the returned biomass and C:N ratio of sorghum stover and intercrops were similar for CA_VB and CA_PP in each year.

3.3. *Sorghum yield, growth parameters, and yield components*

Although grain yields did not differ significantly between treatments in 2013–2014, the yield was significantly higher for CA_PP than for CNTRL in 2015 (Table 2). Consistent with the rainfall data, grain yields for CA_VB and CA_PP tended to be

Table 1. Input of organic nitrogen and carbon from intercrops and/or retained sorghum stover.

	Nitrogen (kg ha^{-1})			Carbon (kg ha^{-1})		
	2013	2014	2015	2013	2014	2015
CNTRL	-	-	-	-	-	-
MT+CRM	8.9 ± 1.0 a	10.4 ± 0.3 a	4.9 ± 0.5 a	970.1 ± 111.1 a	1126.4 ± 30.5 a	544.9 ± 110.7 a
CA_VB	33.6 ± 0.8 b	97.6 ± 7.1 b	40.9 ± 6.0 b	1211.2 ± 126.8 a	2156.3 ± 220.3 b	1073.9 ± 26.3 b
CA_PP	31.9 ± 4.1 b	106.9 ± 9.6 b	33.1 ± 3.5 b	990.7 ± 77.7 a	2444.0 ± 247.0 b	850.5 ± 25.7 ab

CNTRL, control; MT+CRM, minimum tillage + crop residue mulching; CA_VB, MT+CRM with velvet bean intercropping; CA_PP, MT+CRM with pigeon pea intercropping. Mean ± standard error.

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

In CNTRL, input was considered negligible because sorghum was not intercropped and sorghum stover was removed from the plot.

Table 2. Sorghum yield for each treatment and year.

	Grain yield (kg ha^{-1})		
	2013	2014	2015
CNTRL	853 ± 70 a	909 ± 106 a	657 ± 65 a
MT+CRM	791 ± 148 a	994 ± 31 a	737 ± 47 ab
CA_VB	787 ± 144 a	874 ± 153 a	899 ± 181 ab
CA_PP	594 ± 42 a	1190 ± 177 a	1161 ± 40 b

CNTRL, control; MT+CRM, minimum tillage + crop residue mulching; CA_VB, MT +CRM with velvet bean intercropping; CA_PP, MT+CRM with pigeon pea intercropping.
Mean ± standard error.
Mean values with different letters are significantly different between treatments ($P < 0.05$).

higher in 2014–2015 than in 2013. In contrast, grain yields for CNTRL and MT+CRM did not show a similar trend, and the lowest yields were recorded in 2015.

Table 3 presents data for the temporal changes in growth parameters for sorghum in 2015. There was no difference in leaf number, plant height, stem diameter, or SPAD reading between treatments. As in 2015, growth parameters did not differ significantly between treatments in 2013–2014 (data not shown).

Yield components in 2015 are shown in Table 4. The panicle biomass was significantly greater for CA_PP than for CNTRL; however, stover and total biomass did not differ significantly between treatments. Similar to the panicle biomass data, the harvest index and grain weight per panicle were significantly higher for CA_PP than for CNTRL. Hill number per unit area for CNTRL was significantly lower than for the other three treatments, but the difference was slight. In 2013–2014, as for the growth parameters, there was no difference in yield components between treatments (data not shown).

3.4. N accumulation and N translocation by sorghum

Data for the amount of total N accumulated in sorghum stover and panicle as well as the N translocation index in 2015 are shown in Table 5. Total N in stover was lower and that in panicles was higher for CA_VB and CA_PP than for CNTRL and MT+CRM, but the differences were not significant. In contrast, the N translocation index was significantly higher for CA_VB and CA_PP than for CNTRL and MT+CRM, suggesting that N was more effectively translocated from leaves and stem to panicle for CA_VB and CA_PP than for CNTRL and MT+CRM.

4. Discussion

4.1. Effects of the intercropping components on soil N and C content

The rates of decrease of total soil N and C content were significantly greater for CNTRL than for CA_PP (Figure 1; statistical data not shown), which is consistent with Mando et al. (2005), who showed that full tillage without any organic input greatly reduced soil organic matter at the Saria research station. Lower contents of total soil N and C in CNTRL are reasonable because the amounts of organic N and C returned to the soil were negligible in CNTRL (Table 1). Moreover, annual soil loss by water erosion in CNTRL was 4.9 Mg ha^{-1} yr^{-1} (3-year average; Ikazaki et al. 2018a), which is greater than soil loss tolerance, i.e., the amount of soil loss that can be tolerated without decreasing its productivity (4.5 Mg ha^{-1} yr^{-1} in this study site according to Schertz 1983). Severe water erosion should have reduced soil N and C in CNTRL, as has been frequently reported (e.g., Lal 1995; Stoorvogel and Smaling 1990). In MT+CRM, CA_VB, and CA_PP, annual soil losses were 2.3, 2.0, and 1.8 Mg ha^{-1} yr^{-1}, respectively, and they are not significantly different (3-year average; Ikazaki et al. 2018a).

The total soil N and C content for CNTRL, MT+ CRM, and CA_VB decreased significantly with time, whereas those for CA_PP did not (Figure 1; statistical data not shown). Although the total soil N and C content for CA_PP will become significantly lower than the initial values over a longer period given that decreasing trends were also found in CA_PP, this result suggests that PP intercropping is effective for conserving soil N and C in the short term. Pigeon pea, however, produced few seeds and mostly died during the dry season, and therefore we had to purchase new seeds and replant/transplant them every year, even though the annual rainfall in 2014–2015 was the same as the average. The relatively shallow soil in the experimental plot, which has a petroplinthic horizon that starts from 73-cm deep, likely did not supply enough water to PP during

Table 3. Growth parameters for sorghum in 2015.

	Leaf number (plant^{-1})					Height (m)				
	30 Jul	13 Aug	27 Aug	10 Sep	24 Sep	30 Jul	13 Aug	27 Aug	10 Sep	24 Sep
CNTRL	4.1 ± 0.3	7.5 ± 0.3	10.6 ± 0.2	13.8 ± 0.2	15.2 ± 0.5	0.1 ± 0.0	0.3 ± 0.0	0.5 ± 0.0	0.7 ± 0.1	1.4 ± 0.2
MT+CRM	3.9 ± 0.1	6.7 ± 0.1	9.9 ± 0.5	13.3 ± 0.7	15.1 ± 0.7	0.1 ± 0.0	0.3 ± 0.0	0.4 ± 0.0	0.6 ± 0.0	1.4 ± 0.1
CA_VB	4.4 ± 0.5	7.8 ± 0.8	11.4 ± 1.2	14.6 ± 1.0	15.4 ± 0.6	0.1 ± 0.0	0.4 ± 0.1	0.6 ± 0.2	1.1 ± 0.3	2.0 ± 0.3
CA_PP	4.2 ± 0.4	7.2 ± 0.3	10.9 ± 0.6	13.6 ± 0.3	14.9 ± 0.1	0.1 ± 0.0	0.3 ± 0.0	0.5 ± 0.0	0.8 ± 0.1	1.6 ± 0.2

	Stem diameter (mm)					SPAD reading				
	30 Jul	13 Aug	27 Aug	10 Sep	24 Sep	30 Jul	13 Aug	27 Aug	10 Sep	24 Sep
CNTRL	1.4 ± 0.1	2.1 ± 0.5	7.0 ± 1.5	10.7 ± 1.1	12.3 ± 0.8	26.3 ± 3.4	29.6 ± 1.6	28.3 ± 2.5	38.7 ± 2.8	41.4 ± 2.6
MT+CRM	1.2 ± 0.1	2.4 ± 0.3	7.4 ± 0.4	12.2 ± 0.1	12.7 ± 0.4	20.2 ± 1.8	24.3 ± 0.1	26.0 ± 0.8	35.1 ± 1.5	43.0 ± 2.4
CA_VB	1.2 ± 0.2	2.6 ± 0.5	7.8 ± 1.4	11.9 ± 0.6	12.9 ± 0.5	25.2 ± 3.1	29.4 ± 1.1	29.3 ± 1.1	38.8 ± 1.8	43.9 ± 0.7
CA_PP	1.1 ± 0.0	2.2 ± 0.1	6.9 ± 1.0	11.3 ± 1.0	12.4 ± 1.1	22.3 ± 3.0	27.0 ± 1.4	27.6 ± 1.4	35.6 ± 4.0	38.9 ± 2.7

CNTRL, control; MT+CRM, minimum tillage + crop residue mulching; CA_VB, MT+CRM with velvet bean intercropping; CA_PP, MT+CRM with pigeon pea intercropping.
Mean ± standard error.
All mean values are not significantly different between treatments ($P > 0.05$).

Table 4. Yield components for sorghum in 2015.

	Biomass (Mg ha^{-1})			Harvest index (%)	Hill number (m^{-2})	Panicle number (hill^{-1})	Grain weight (g panicle^{-1})
	Stover	Panicle	Total				
CNTRL	1.3 ± 0.1 a	0.8 ± 0.0 a	2.1 ± 0.1 a	32.0 ± 3.3 a	2.9 ± 0.0 a	2.2 ± 0.1 a	10.4 ± 0.7 a
MT+CRM	1.2 ± 0.1 a	1.0 ± 0.1 ab	2.1 ± 0.1 a	34.4 ± 1.1 a	3.1 ± 0.0 b	2.2 ± 0.1 a	10.7 ± 0.1 a
CA_VB	1.2 ± 0.3 a	1.1 ± 0.2 ab	2.3 ± 0.5 a	39.1 ± 0.5 ab	3.1 ± 0.0 b	2.1 ± 0.1 a	13.3 ± 1.9 ab
CA_PP	1.2 ± 0.0 a	1.3 ± 0.0 b	2.5 ± 0.1 a	46.0 ± 1.3 b	3.1 ± 0.0 b	2.3 ± 0.1 a	16.3 ± 0.1 b

CNTRL, control; MT+CRM, minimum tillage + crop residue mulching; CA_VB, MT+CRM with velvet bean intercropping; CA_PP, MT+CRM with pigeon pea intercropping.
Mean ± standard error.
Mean values with different letters are significantly different between treatments ($P < 0.05$).

the dry season. Barro (1999) reported that a petroplinthic horizon at 70-cm deep limits root growth of crops. Because plinthosols that have a petroplinthic horizon starting < 50 cm deep are widely distributed in the Sudan Savanna (EU 2013), PP planted on the dominant soils of this region is unlikely to survive the dry season. In addition, markets for grain legumes such as PP have not been developed in this region (Callo-Concha et al. 2013). Therefore, we conclude that three-component CA with PP intercropping can maintain soil N and C levels in the short term but is not practical for the farmers who do not have access to the markets or cannot afford to buy PP seeds every year. This system might be a good option in more humid areas such as the Guinea Savanna, where annual rainfall is between 900 and 1200 mm and PP could survive the dry season, as suggested by Kassam et al. (2010).

The total soil N and C contents for CA_PP were relatively higher than for CA_VB in October 2015, though the amounts of returned organic N and C (Table 1) as well as C:N ratio of returned biomass (27 and 26 for CA_PP and CA_VB, respectively) were similar. This could be due to the slower decomposition rate of PP than VB as reported by Carvalho et al. (2011) and Mhlanga et al. (2015). Carvalho et al. (2011) described that the higher lignin content of PP resulted in the slower decomposition rate of PP than VB.

4.2. Factors affecting sorghum yield

The results for total soil N and C content (Figure 1) were remarkably similar to those for grain yield (Table 2); there was no difference between treatments in 2013–2014, whereas higher soil N and C content and sorghum yield were observed for CA_PP than for CNTRL in 2015. This association suggests that total soil N and C content, i.e., soil organic matter content, affects sorghum yield. Many studies (e.g., Brock et al. 2011; Lal 2004; Oldfield, Bradford, and Wood 2019) have reported that higher soil N content or organic matter content leads to higher crop yield unless the content is too high.

Even though sorghum yields in 2015 were significantly different between treatments, growth parameters were not (Table 3). This is consistent with the data for stover and total biomass (Table 4). It was also reported by van Oosterom and Hammer (2008) that the biomass of mature sorghum stems for treatments that produced a greater yield was not always greater than for CNTRL, which was a less fertile plot. As shown in Table 4, the higher sorghum yield observed for CA_PP than for CNTRL in 2015 was attributed to the higher panicle mass, harvest index, and grain weight per panicle. Similarly, Ezeaku and Mohammed (2006) found a strong positive correlation between sorghum yield and panicle mass in the Sudan Savanna, and Lafitte and Loomis (1988) found a lower harvest index under N stress conditions. Then, the higher panicle mass and harvest index for CA_PP than for CNTRL in 2015 could be due to the higher whole-plant N (though not significant) and higher efficiency of N translocation (Table 5). This is supported by the results of Lafitte and Loomis (1988) and Alagarswamy and Seetharama (1983). The former group reported that the panicle growth rate was dependent on the amount of N translocated from leaves and stem for sorghum probably because lower N translocation results in lower structural carbohydrate content of the panicles which restricts grain growth and starch formation. The latter reported that both whole-plant N and N translocation index significantly correlated with sorghum yield.

Taken together, we conclude that the higher soil N and C content as well as higher panicle mass and harvest index possibly caused by higher whole-plant N and efficiency of N translocation observed in CA_PP than in CNTRL brought in a higher grain yield for CA_PP than for CNTRL in 2015.

Table 5. Total nitrogen accumulated in each plant part of sorghum, and nitrogen translocation index for sorghum in 2015.

	Total nitrogen (kg ha^{-1})			NTI[†] (%)
	Stover	Panicle	Whole plant	
CNTRL	4.9 ± 0.3 a	14.5 ± 0.1 a	19.4 ± 0.1 a	71.6 ± 3.3 a
MT+CRM	4.9 ± 0.5 a	15.7 ± 0.1 a	20.6 ± 0.1 a	71.2 ± 1.1 a
CA_VB	3.1 ± 0.8 a	18.4 ± 0.5 a	21.6 ± 0.5 a	83.2 ± 0.5 b
CA_PP	3.4 ± 0.1 a	22.8 ± 0.1 a	26.2 ± 0.1 a	84.8 ± 1.3 b

CNTRL, control; MT+CRM, minimum tillage + crop residue mulching; CA_VB, MT+CRM with velvet bean intercropping; CA_PP, MT+CRM with pigeon pea intercropping.
[†] Nitrogen translocation index: The ratio of grain N mass to whole plant N mass.
Mean ± standard error.
Mean values with different letters are significantly different between treatments ($P < 0.05$).

4.3. Effects of the intercropping components on sorghum yield

Grain yield was not significantly lower for MT+CRM than for CNTRL (Table 2), suggesting that the negative effects of MT (e.g., Kusuma Grace et al. 2013) on sorghum yield were offset by CRM and minimal chemical fertilizer application. In the third year, we observed higher grain yield for CA_PP than for CNTRL (Table 2). Baudron et al. (2012) also reported that CA with legume intercropping increased sorghum yield in the last year of the 3-year study conducted in semi-arid region of Zimbabwe. The positive effect in our present study will last for some time since the rates of decrease of total soil N and C content were much greater for CNTRL than for CA_PP (Figure 1). Giller et al. (2009)

reported that the effects of CA generally become more apparent as the implementation time increases. These results indicate that PP intercropping can be used for increasing sorghum yield, though increased yield would not be observed during the first 2 years and the purchase of PP seeds every year will add a burden to the farmers. Therefore, we conclude that three-component CA with PP intercropping is effective and a good option for the prosperous farmers who can accept both no increased yield during the first 2 years and the purchase of PP seeds every year. For the majority of smallholder farmers in the Sudan Savanna, however, it would be realistic to promote two-component CA without intercropping (MT+CRM), which is sufficient for controlling water erosion (Ikazaki et al. 2018a), for reducing their burden of adoption. Stevenson, Serraj, and Cassman (2014) also suggested that two-component CA is more readily adopted by smallholder farmers in SSA (see also the Nebraska Declaration on CA in Stevenson 2013). Another key to improve sorghum yield might be increased fertilization, especially with N (Kusuma Grace et al. 2013; Rockstrom et al. 2009; Rusinamhodzi et al. 2011). Valbuena et al. (2012) argued that agricultural intensification is necessary to make CA easier and more viable.

Although the long-term effects of three-component CA with VB intercropping are difficult to predict from our study, we did not observe short-term yield benefit for CA_VB (Table 2) probably because VB intercropping did not increase total soil N and C as well as panicle mass and harvest index compared with CNTRL. This indicates that promotion of three-component CA with VB intercropping would be risky in the Sudan Savanna.

5. Conclusion

It was found that CA with PP intercropping is effective for both conserving soil N and C and improving sorghum yield in the short term but would not be practical for the majority of smallholder farmers and therefore, promotion of two-component CA without intercropping could be realistic under the current circumstances in the Sudan Savanna. We anticipate that this conclusion will lighten the burden of CA adoption and facilitate the future promotion of CA to smallholder farmers in the Sudan Savanna. To improve sorghum yield, agricultural intensification – mainly through the increased use of chemical fertilizer – would offer a possible solution.

Acknowledgments

This study was conducted under the JIRCAS-INERA collaborative project entitled” Development of technologies for sustainable agricultural production in the African savanna (2011–2015).” We thank Dr. Lamien Niéyidouba, Dr. Korodjouma Ouattara, Dr. Adama Kaboré, and Mr. Simporé Kouka for their support.

Disclosure statement

No potential conflict of interest was reported by the authors.

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