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Optimizing yield of improved varieties of millet and sorghum under highly variable rainfall conditions using contour ridges in Cinzana, Mali

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Abstract

Background: Low productivity of cereals, the staple food, in Sahelian zone of Cinzana in Mali is caused by a range of factors including but not limited to inherent low soil fertility, and insufficient and inadequate distribution of the rainfall due to high climate variability. In addition, the small amount of rain falls as heavy storms in very short periods of time leading to water losses by runoff which in turn causes a lot of erosion. The two phenomena therefore call for a combination of both strategic (combating erosion) and tactical (coping with inter- and intra-annual rainfall variability) measures to cope with the production uncertainties in such risk-prone environment. As opposed to most farmers' practice of using the same variety, a tactical solution of using varieties of different cycles for different rainfall amounts/patterns was thought to be worth testing. Varieties of different cycles for different rainfall amounts/patterns were combined with a well-known soil and water conservation practice which is the contour ridge tillage (CRT). The combined effects of the two measures on the production of different varieties of sorghum and millet as well as on soil water content were assessed in on-farm participatory trials in five villages. The experiment was run during three consecutive years (2012, 2013 and 2014).

Results: A key finding of this research is that regardless of the yearly rainfall amount and provided CRT is used, there were large differences in yields between improved varieties and local ones. This is a result of higher soil water conservation and better response of the improved varieties.

Conclusion: The use of CRT increases considerably the yields of improved varieties of the most important staple crops of the Cinzana commune which are millet and sorghum. Thus, the use of these early maturing improved varieties, along with CRT, could be an accessible adaptation strategy to climate variability by farmers.

Keywords: Climate variability, Mitigation, Soil moisture, Improved varieties

Background

In sub-Saharan Africa region, 97% of the agricultural land is rainfed with crop yields of about 0.5–1 t ha^{-1} [1]. The most common crops in the Sahelian part of this region are cereals (millet, sorghum, maize, rice, etc.) as a staple food. For instance in 2008 in Mali, 1,615,450 ha were planted with pearl millet (*Pennisetum spp*) with an average yield of 768 kg ha^{-1}. Equivalent figures for sorghum (*Sorghum spp*) were 986,367 ha and 943 kg ha^{-1} [2]. Millet occupies a larger area than sorghum because of its higher plasticity. Average yields for millet and sorghum in Cinzana commune, Mali (Ségou region), were, respectively, 822 and 926 kg ha^{-1} reflecting national trends [3]. Obviously the yield values mentioned above are below the potential of most grown varieties of these staple crops [4, 5]. The low yields are attributed not only to climate change-related decreases in rainfall amount but also to variability of water availability related to the

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erratic rainfall patterns leading to water stress at some critical plant-growth stages [7] and inherent low soil fertility [6]. In addition, rain storms generate runoff and associated soil erosion [8–11]. This later phenomenon reduces top soil layer depth and soil organic matter content leading to weak soil water-holding capacity. The combined effects of all the above-mentioned factors will induce low water infiltration rates [12] with only 10–15% of rainfall that will be used by crops for transpiration [6, 13]. Thus, water availability to crop roots in the soil profile constitutes a major constraint for sustainable production systems [14–17]. Because of unpredictable rainfall [18] and decreased agricultural productivity, many soil and water conservation technologies such as stone lines, half-moons, contour hedgerows, rock bunds, filter walls, zaï, agroforestry, contour ridges, benches and no-tillage have been developed and are now widespread [19–23]. Tested technologies have shown that they can reduce runoff [16, 24–26] and soil erosion [27–29], improve water infiltration [12, 22, 30] and increase soil moisture [20, 23, 31–33]. However, their adoption did not always meet the expectations probably due to the promotion of a limited number of options everywhere as if "one size fits all." Actually, some analysis has revealed that the effects of such technologies depend on a number of factors such as rainfall (some performed better than others in drier areas, while others performed better in humid zones), soil productivity potential (some performed better in less fertile soils) and labor availability [31, 32]. All these observations call for local testing and adaptation of even the proven practices to make them context specific [34].

Because the farmers of Cinzana collaborate with the Climate Change Agriculture and Food Security (CCAFS) project and are therefore well aware of the advantages of soil and water conservation techniques and crop diversity to buffer climate change effects, a diagnosis including key stakeholders was realized in this village. Despite the awareness of the contour ridge tillage technique (CRT), there is a weak adoption of this practice and a need for training. The participatory selection of the technologies (the selection of technologies was done with the active participation of farmers) to be tested led to the choice of contour ridge tillage technique (CRT) and the use of improved sorghum and millet varieties among several adaptation strategies proposed to mitigate the observed erratic rainfall patterns. These improved varieties were chosen because of their performance on station trials, although local varieties are sometimes considered better adapted to high stress and low productivity conditions typical of smallholder farms. In Mali, CRT, referred to as "Aménagement en courbes de niveau" [12, 6, 35], is a water conservation technique locally developed in the early 1990s by Institut d'Economie Rurale (IER) and Centre de Coopération Internationale en Recherche Agronomique pour le Développement (CIRAD). According to Kablan et al. [12], the innovation of CRT resides in the fact that it is a holistic landscape level method for managing surface water on farmers' fields. Indeed, the contoured ridges decrease runoff, increase water infiltration and, therefore, capture rainfall close to the crop root system. The technology has been applied in the Sudanian area with rainfall varying from 600 to 1200 mm in southern Mali where runoff still occurs in fields with a slope as low as 1 to 2%, [6]. As a consequence of increased water infiltration due to CRT [8, 12], an increase in crop yields of 30–50% was reported for millet, sorghum, maize, groundnut and cotton [30, 36]. This is probably due to the fact that water availability is important for evapotranspiration, but also for releasing nutrients in the rooting zone of the crops. Without CRT, runoff varied from 25–55% (unavailable water for crops) while its implementation reduced runoff to 10% of annual rainfall. Although the CRT was introduced since early 1990s [35], its effects on crop yield in the Sahelian area of Mali are not well documented. Indeed, improved varieties along with CRT could help in addressing both the short- and long-term climate-related stresses and improve the resilience of the agro-ecosystems and farmers' income. We therefore hypothesized that improved crop varieties as opposed to the local ones will make a better use of a higher soil water storage using the CRT technique in the Sahelian zone of Cinzana in Mali.

Materials and methods

Study site

This on-farm trial was conducted in the Cinzana rural commune, which belongs to the Sahelian agroecological zone of Mali (Fig. 1). The trial area is located between 13°53′N and 13°14′N latitude and 5°63′W–6°15′W longitude. Participating villages are distributed within a radius of 30 km and are represented by the stars in Fig. 1. Rainfall was measured in Cinzana Research Station which is the closest meteorological weather station. Rainfall is uni-modal with the maximum of rain events occurring in July and August (Fig. 2) with a long-term average annual rainfall of 680 mm (Fig. 3b). The first useful rains (which provide enough soil moisture at time of planting without prolonged dry spells that could prevent the survival of seedlings after sowing [37]) occur in May and the rainy season ends in October. An analysis of rainfall patterns in Cinzana was performed using decadal (10-day) intervals in the month (Fig. 3b). Low temperatures occur in December through February (18 °C monthly average low), and high temperatures occur in April and May (40 °C monthly average high) (Fig. 2a). The daily evapotranspiration is 6–7 mm day^{-1} in the dry season and

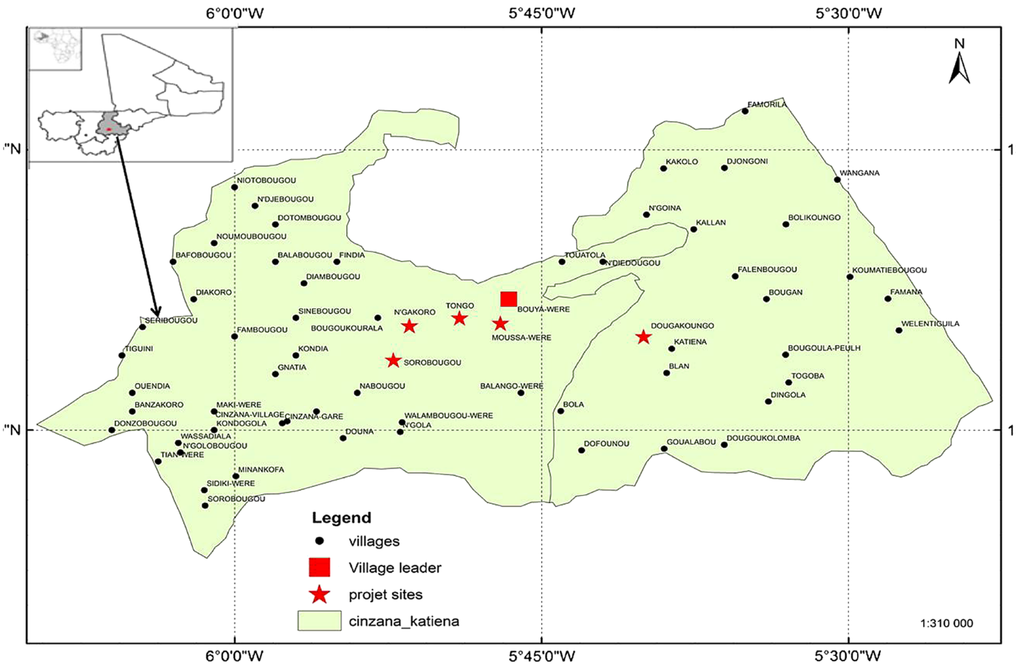

Fig. 1 The Cinzana commune and the location of the on-farm trial sites where the effects of contour ridge tillage on the production of local and improved millet and sorghum varieties were tested in 2012, 2013 and 2014 in Mali

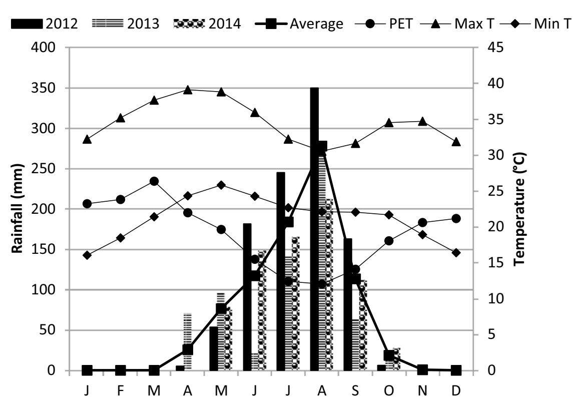

Fig. 2 Monthly rainfall average, maximum (Max *T*), minimum (Min *T*) temperatures and potential evapotranspiration (PET) of three consecutive years (2012, 2013 and 2014) in Cinzana commune, Mali

4 mm day^{-1} during the rainy season. The main soil types of the area are classified as leached tropical ferruginous soils with spots and concretions [38] and Alfisols according to U.S. Soil Taxonomy [39], with many Paleustalfs and frequent Plinthustalfs [12, 40]. Ustalfs are highly weathered and highly leached soils. Plinthustalfs are of special concern because they contain a plinthite layer of soft iron (Fe) and aluminum (Al) oxides that will harden irreversibly into lateritic stone if exposed.

Cultural operations

For both millet and sorghum, planting dates were 2–3, 11–12 and 3–4 July in 2012, 2013 and 2014, respectively. Sorghum and millet seeds were placed at 0.5-m intervals within rows and 0.8-m intervals between rows, and seedlings were thinned to two plants per hill 15 days after emergence to ensure the targeted population of 50,000 plants ha^{-1} which is the density advised by extension services in Cinzana area. Immediately after thinning (i.e., the same day), the trials were hand-weeded using a hoe and again 30 days after crop germination.

Fertilizer was uniformly applied to the trial at the rate of 37.5 kg ha^{-1} of NPK (15–15–15) and 37.5 kg ha^{-1} of urea (46% of nitrogen), respectively, 15 and 30 days after germination. Fertilizer was buried in microdoses (1.5 g per hole) 5 cm below and 5 cm away the plant rows.

Sorghum and millet grains were harvested on 20–21 October, 5–6 November and 25–26 October in 2012, 2013 and 2014, respectively, and sun-dried straw measured 21 days after.

Experimental design

The field of each farmer was divided into two parts: one with contour ridges and the second part without contour ridge. The trial was established as a randomized complete block design with farmer fields or sites as replicates. This disposal allows a first examination of the global trend of the results for the control and the CRT plots. This pair

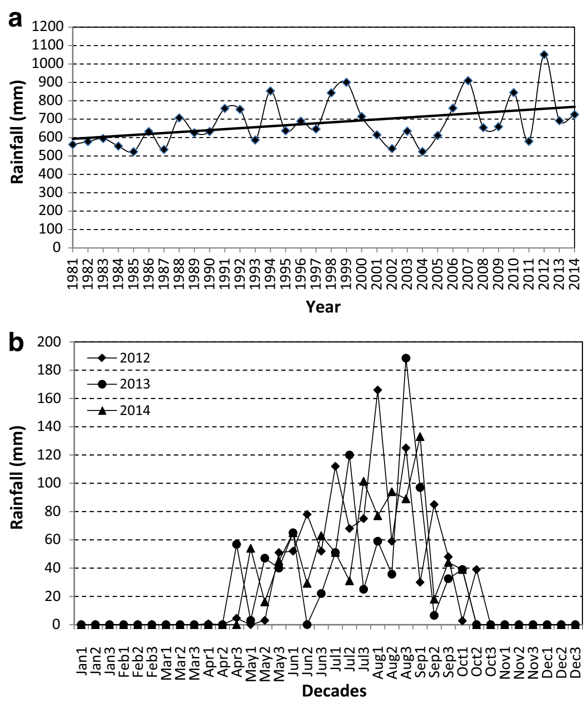

Fig. 3 Long-term annual rainfall **a** and decadal (10-day interval) rainfall (*Month1* first decade, *Month2* second decade, *Month3* third decade) of three consecutive years (2012, 2013 and 2014), **b** in Cinzana commune, Mali

of plots was treated the same way with regard to sowing dates, crop species and other cropping operations, except the ridging mode which was tested. Varieties were randomly distributed in each part of the experimental field. Plot sizes were 42 m^2 in 2012 and 2013 and 98 m^2 in 2014 for demonstrative purpose.

The trial started in 2012 with three farmers in each village (Moussawere, Sorobougou and Ngakoro), and two factors were studied which are field preparation (contour ridging and control) and varieties for each crop. Two varieties were tried in 2012 for both sorghum (local Jacumbe and Seguifa) and millet (local Toronion and Syn 0006) and the trial replicated three times. These varieties were chosen by farmers during a field visit in Cinzana research station. In 2013, two more villages (Tongo and Dougakoungo) were included in the trial as well as two more fodder crop "stay green" varieties, i.e., they remain green as fodder after harvesting the panicles (Seguifa and Tiandougou). The trial was therefore replicated five times for three varieties of sorghum (local Jacumbe, Seguifa and Tiandougou) and three varieties of millet (local Toronion, Syn 0006 and Soxat). Based on the outcomes of the first two years of trial and to facilitate the monitoring, the experience was conducted in two villages (Tongo and Ngakoro) in the third year, but was expanded to ten farmers for each of the two crop species (millet and sorghum), giving a total 20 farmers involved. Tested varieties were local Boboni, Soxat, improved Toroniou and HKD for millet and local Kenikeni, CSM 219, Seguifa and Sangatigui for sorghum.

Data collection and analysis

Composite soil samples were collected only in May 2012 at 0–20 cm soil depth before establishing the trials on each site. Composite samples were made of 20 soil samples taken in an asterisk shape pattern in the field. Samples were analyzed for both physical and chemical properties. Particle size (soil texture) analysis was performed by the hydrometer method [41]; pH was determined by the electrometric method in a soil solution with a soil/water ratio of 1:2.5; soil organic C was determined by the modified Walkley–Black wet oxidation method as outlined by Nelson and Sommers [42]; total nitrogen was determined by the modified Kjeldahl digestion method [43]; bases, effective cation exchange capacity (CEC) and available P were determined as described in Page et al. [44].

In 2012 and 2013, soil moisture was measured first in the dry season (mean dry soil) and in the rainy season at 15-day interval period in Sorobougou village to illustrate water conservation related to the use of CRT. Soil was sampled using an Edelman Combination Auger (4 cm core) of 1.2 m length at three locations in both plots in each field. Soil was sampled at four depths (0–10, 10–20, 20–40 and 40–60 cm) until a hardpan layer was reached, which in general was at about 60 cm depth. Soil samples were sent to the laboratory after securing them in a double plastic bag to avoid moisture loss. Gravimetric soil water content was determined at the same soil depths by weighing soil samples to obtain their wet mass, followed by oven-drying at 105 °C during 24 h until constant mass and weighing them again for their dry mass. Gravimetric soil water content was calculated as:

$$\text{Gravimetric soil water content (GSW)} \left(\text{g g}^{-1}\right) = \left(\text{wet mass} - \text{dry mass}\right)/\text{dry mass}$$

From the data collected throughout the rainy season, dates were chosen to represent the beginning, the middle and the end of the rainy season and are plotted in Fig. 4.

As soil bulk density changes very little with time, we decided to use values obtained in a previous study in 2011 along the 0–60 cm profile which includes most of the root system of cereals [45, 46]. The values for soil bulk density were 1.67 ± 0.02, 1.61 ± 0.01, 1.48 ± 0.01 and 1.45 ± 0.00 g cm^{-3} for 0–10, 10–20, 20–40 and 40–60 cm depths, respectively [46]. Soil moisture storage (SMS, mm) for each layer was calculated from gravimetric soil

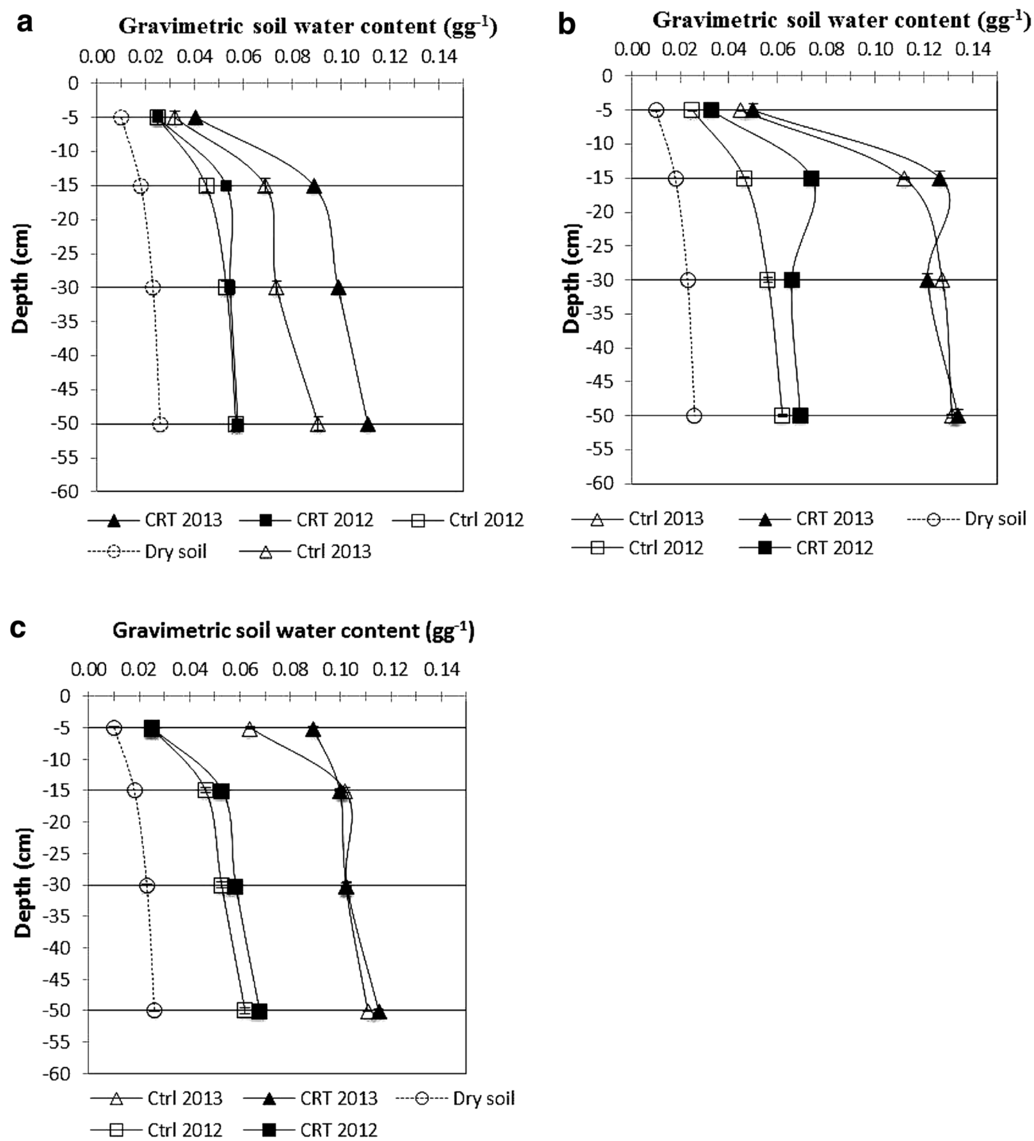

Fig. 4 Vertical distribution of gravimetric soil water content in the 0–60 cm depth in Contour ridge tillage plots (CRT) and plots without CRT (Ctrl) in Sorobougou village in Cinzana commune in 2012 and 2013; **a** beginning of the growing season (July 22, 2012; July 20, 2013); **b** middle of the growing season (August 7, 2012; August 5, 2013); **c** end of the growing season (September 7, 2012; September 4, 2013); *dry soil* soil during the dry season (May 5, 2012); *bars* indicate standard errors of the means

water content (GSW), soil bulk density (Db) and soil layer depth (H) as follows:

$$\text{SMS}i = \text{SGW}i \times \text{Db}i \times \text{H}\ (i = 1, 2, 3 \ldots n)$$

where SMSi is the soil moisture storage for a certain soil layer depth (mm), SGWi is the gravimetric soil water content (g g^{-1}) at such soil depth, Dbi is the soil bulk density (g cm^{-3}) at such depth, H is the soil layer depth (mm), i is the soil sequence and n is the number of measured layers.

Crop yields were measured in central rows of each plot by discarding two rows along the border of each side of the plot. At harvest, total panicles, grain and stems dry weight were recorded in the central subplot as indicated above and data extrapolated from the subplot size to ha.

At the beginning of data processing, each part of the experiment plot was analyzed as a simple trial and the means and residual values used to pool the trial following two hierarchized factors (CRT-Ctrl; varieties) to just determine the global significance of data using

STATBOX 7.4.4. Then, data were analyzed using Genstat statistical software (Release 14 for Windows) where crop data were subjected to a factorial analysis considering the individual effects of CRT and crop variety as well as their interaction. Because the numbers of replications and crop varieties varied from year to year, the data were analyzed separately per year. Finally, the three years were pooled to statistically assess the interaction between CRT and varieties. The effects of the treatments were considered significant at the probability threshold of $P < 0.05$. Newman–Keuls test was used to separate means for significant differences between treatments.

Results

Rainfall pattern in the study area

Maximum amount of 166 mm of rain was received in the first decadal (10-day) interval of August in 2012, where July and August represented 77% of the total amount of rainfall (Fig. 3b), with no significant dry spell during this period. Dry spell of 6 days occurred once in the second decade of June. In September, dry spells of 7 and 8 days occurred in the second and third decades, respectively. The dry spells coincided with the development of reproductive organs of millet and sorghum. In 2013, the longest dry spell lasted 14 days and occurred in second and third decades of June, before crop sowing. A 9-day dry spell also occurred in July (second and third decades) and a 11-day one in September (second and third decades). In 2014, the longest dry spell was 5 days and occurred in the second decade of September, suggesting that rainfall was evenly distributed throughout the cropping season. This relatively short dry spell was adequate to allow weeding, mounding and other crop management operations.

Soil characteristics

The soils of Ngakoro and Tongo sites displayed more silt content and less clay than those of other villages, whereas mean sand content was less variable between villages with a value around 90% (Table 1). Soil pH (water) of the study sites was generally slightly acid, but more acid at the Sorobougou village site. The Ca and Mg contents at this latter site had double the values observed on the other sites. However, considering other physicochemical characteristics, Moussawere village appeared to have the poorest soil with phosphorus content at least twice lower compared to other sites. The CEC was also higher in all sites in comparison with Moussawere, except Tongo. All soils showed very low values in organic matter, nitrogen and phosphorus (Table 1).

Figure 4 shows that gravimetric soil water content (GSW) was frequently greater in CRT than in the control ($P = 0.04$). In general, soil was drier in 2012 compared to 2013. Rainfall was more abundant in 2012 but less well distributed compared to 2013 because of two heavy rain events of 70 and 80 mm in less than two hours (Fig. 3b). In July at the beginning of the rainy season, CRT exhibited greater differences from control in 2013 compared to 2012. Differences were only noticeable at the 10–20 cm soil depth in 2012 but were noticeable in the whole soil profile in 2013. CRT differences from control were also more noticeable at the 10 to 20 cm soil depth in early August 2012 and 2013 when rainfall events were still frequent and differences were more pronounced at the 10–20 cm soil depth in 2012 when soils were drier compared to 2013. This difference appeared at 10 cm and was maintained up to 60 cm in 2012. In 2013, when rainfall was much lower, CRT displayed only higher soil water content in the 10–20 cm depth.

Table 1 Soils characteristics in the 0–20 cm soil depth of five sites under trial in 2012 in Cinzana commune, Mali

Sites	Sorobougou	N'Gakoro	Moussawere	Tongo	Dougakoungo
pH (water)	5.75	6.54	6.44	6.50	6.48
pH (KCl)	4.04	5.10	4.44	5.37	5.34
OC (g kg^{-1})	3	4	4	5	6
Total N (g kg^{-1})	0.2	0.03	0.2	0.4	0.05
P av (ppm)	5.32	4.20	1.96	3,75	3,67
CEC meq 100 g^{-1}	5.80	5.80	4.35	4.40	4,65
Ca meq 100 g^{-1}	3.86	1.58	1.58	1.41	1.18
Mg meq 100 g^{-1}	1.80	0.95	0.84	0.81	0.77
K meq 100 g^{-1}	0.41	0.13	0.15	0.16	0.18
Na meq 100 g^{-1}	0.03	0.03	0.03	0.02	0.04
Sand % 0.05 mm	92	89	92	90	92
Silt % 0.05–0.002 mm	4	9	4	8	6
Clay % 0.002 mm	4	2	4	2	2

Water storage reached a maximum of 42 mm in August 2012 and a maximum of 68 mm in August 2013 (Fig. 5). Water storage decreased regularly until November when both CRT plot and control displayed similar values of 13.4 mm in 2012 and 21.8 mm in 2013. Water storage was always higher in CRT plot compared to control plot with a surplus of 0.23 mm day^{-1} in 2012 and 0.43 mm day $^{-1}$ in 2013 in the CRT plots over the monitoring period.

Millet and sorghum yield

Average millet grain yield was 783 kg ha^{-1} in 2012, 1424 kg ha^{-1} in 2013 and 1301 kg ha^{-1} in 2014 (Table 2a). Millet grain yield in 2012, 2013 and 2014 was statistically higher in CRT plots compared to the control (all $P < 0.01$) with yield difference ranging from 301 kg ha^{-1} in 2012 to 622 kg ha^{-1} in 2013. These values correspond to an increase of 60 and 56%, respectively. Improved varieties produced more than the local ones, and the average increase was +25% in 2012 and +35% in 2014 (Table 2a). There were significant interactions between variety and tillage mode in 2012 and 2014 ($P < 0.029$ in 2012 and $P < 0.002$ in 2014).

Millet straw production differed statistically according to varieties only in 2014 ($P = 0.01$) during the three years (Table 2b). Straw production was statistically greater in CRT plots compared to control plots in 2013 and 2014, but not in 2012. The effect of CRT on straw yield varied from 881 kg ha^{-1} in 2012 to 2654 kg ha^{-1} in 2014 corresponding to an increase of 32–61%.

Sorghum yield did not differ significantly under the CRT technique in 2012 as opposed to the two following years during which CRT displayed statistically higher values compared to the control plot (all $P < 0.05$). Yield increases related to the CRT technique were 613 kg ha^{-1} in 2013 and 616 kg ha^{-1} in 2014 or, respectively, 85 and 58% yield increases compared to the control plot (Table 3a). In the overall, average sorghum grain yield increased consistently from 461 kg ha^{-1} in 2012 to 1378 kg ha^{-1} in 2014. Improved varieties produced on average 55% more yield than the local ones (Fig. 6). There were significant effects of CRT on sorghum grain production in 2013 ($P < 0.04$) and 2014 ($P < 0.001$). There was, also, significant interaction in 2014 between variety and tillage mode ($P = 0.001$).

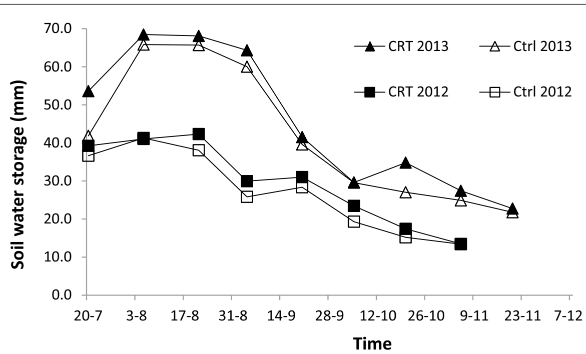

Fig. 5 Soil water storage in the 60 cm profile in the Sorobougou village of the Cinzana commune in 2012 and 2013. *CRT* contour ridge tillage plots; *Ctrl* plots without Contour ridge tillage

Table 3b shows sorghum straw production for which significant differences were only observed in 2014 for both varieties and the tillage modes but the interaction between these two factors was not significant ($P > 0.05$). Straw biomass increase due to CRT was 3363 kg ha^{-1} in 2014, representing 61% more biomass, while increase due to improved varieties was much lower (17%).

For both crops, the statistical analysis showed inconsistent interactions between variety and tillage mode each year which is characteristic of on-farm trials. However, when plotting grain yield against the tillage modes, another interaction is revealed, which is an interaction between CRT mode and improved varieties. In general, without CRT there were no much differences between local and improved varieties of both millet (Table 2a) and sorghum (Table 3a). However, improved varieties produced better under CRT compared to the local ones. Moreover, such difference is larger in sorghum compared to millet, particularly for Sangatigui (Fig. 6) which outyielded the other sorghum varieties.

Discussion

An increasing but non-consistent trend in both grain and straw biomass yields was observed for millet (Table 2) and sorghum (Table 3) from the first to the third year. Such trend cannot be easily related to the amount of rainfall recorded during the three years of testing. Indeed, the amount of rainfall recorded in 2013 (692 mm) and in 2014 (725 mm) was almost half of the volume in 2012 (1051 mm), yet better yields were recorded in 2014. Better production in 2014 might therefore be due to better rainfall distribution during the rainy season of that year. Decadal rainfall analysis revealed the occurrence of several dry spells in September during the grain filling period which might have affected the yields in both 2012 and 2013 (two very contrasting years in terms of rainfall amount) independently of the total amount of rainfall received in a given year. These observations are supported by Sivakumar [18] who widely reported similar trends when studying the relation between climate and soil productivity in Sudanian and Sahelian zones of Africa. Indeed, high inter-annual rainfall and within-season variability of rainfall typify the West Africa Sahel climate [47–49]. A supplementary explanation may be the cumulative effect of fertilization which would make the

Table 2 Effects of contour ridge tillage on the production of millet varieties in Cinzana commune, Mali

Year	Conservation technique	Variety	Mean values and comparisons		
			Variety	Technique	Variety × technique
a. Grain yield (kg ha^{-1})					
2012	CRT	Syn 006	1094a	963a	
		Toronion (local)	831b		
	Control	Syn 006	641c	602b	
		Toronion (local)	563c		
SE			45.6		
Probability value			0.002	0.001	0.029
CRT yield increase				301	
2013	CRT	Syn 006	1837a	1735a	
		Toronion (local)	1497a		
		Soxat	1871a		
	Control	Syn 006	1063a	1113b	
		Toronion (local)	1280a		
		Soxat	997a		
SE			309.4		
Probability value			0.97	0.002	0.125
CRT yield increase				622	
2014	CRT	Toroniou	1716a	1585a	
		Soxat	1646a		
		Boboni (local)	1166b		
		HKP	1811a		
	Control	Toroniou	1064b	1017b	
		Soxat	1009b		
		HKP	1105b		
		Boboni (local)	891b		
SE			102.9		
Probability value			0.001	0.001	0.002
CRT yield increase				568	

Year	Technique	Varieties	Mean values and comparisons		
			Variety	Technique	Variety × technique
b. Straw dry mass (kg ha^{-1})					
2012	CRT	Syn 006	4048a	a	
		Toronion (local)	3238a		
	Control	Syn 006	3048a	a	
		Toronion (local)	2476a		
SE			404		
Probability			0.611	0.641	0.691
CRT yield increase				881	
2013	CRT	Syn 006	3514a	a	
		Toronion (local)	2886a		
		Soxat	4314a		
	Control	Syn 006	2200a	b	
		Toronion (local)	2657a		
		Soxat	2514a		
SE			524		
Probability			0.270	0.001	0.148

Table 2 continued

Year	Technique	Varieties	Mean values and comparisons		
			Variety	Technique	Variety × technique
CRT yield increase				1114	
2014	CRT	Toroniou	7389a	a	
		Soxat	7034ab		
		Boboni (local)	6112b		
		HKP	7563a		
	Control	Toroniou	4460c	b	
		Soxat	4530c		
		HKP	4588c		
		Boboni (local)	4460c		
SE			312		
Probability			0.01	0.001	0.001
CRT yield increase				2654	

NB For a given year, values with different letters are statistically different at $P = 0.05$. Column means represent tillage techniques and row means the varieties. *SE* standard error of the mean

comparison between years inappropriate in the absence of soil data for each year.

The overall low grain yield of the tested varieties for both millet and sorghum, with highest grain yield inferior to 1500 kg ha^{-1}, might stem from a combination of limited water availability (due to poor within-season distribution) and poor soil fertility. The laboratory analyses have revealed that the soils of the study sites have a low fertility and are slightly acid. They all showed a very high proportion of sand of about 90% and very low nitrogen and soil organic matter contents as well as low CEC values (Table 1). Tropical ferruginous soils are characterized by a high water infiltration rate (leading to high drainage) in sandy soils and a low water-holding capacity unless soil organic matter content is improved [9, 11]. In fact, low activity of kaolinite (1:1 clay type) which is the dominant clay in these soils suggests that other fine elements (e.g., silt) intervene in complexes with soil organic matter and play a certain role in soil chemical (CEC) properties by influencing its capacity for storage and exchange of nutrients as reported by previous workers [9, 50]. In such sandy soils, an increase of 1 g kg^{-1} of organic carbon leads to an increase of 4.3 mol kg^{-1} of CEC [51]. Improved varieties as expected performed better than the local ones for both crops (Tables 2 and 3). Indeed, Fig. 6 shows that a marginal difference was found between improved varieties and local ones with the control tillage mode and a much larger difference was found between these two types of varieties under CRT. Improved varieties with a higher yield potential likely took advantage of the higher available water under CRT to produce higher yield. Accumulated water in CRT may delay water stress [6, 30, 52] while being more available for the crop to accomplish its physiological processes of biomass accumulation and grain filling [53, 54]. This finding corroborates Gigou et al. [36] who estimated water supply through modeling and concluded that more significant water was available in CRT field when compared to the control in South Mali. The use of CRT can result in reducing soil erosion by reducing precipitation water runoff. It allows more time than the control for rainwater to infiltrate, therefore increasing water storage. This leads to better growth and higher yield during cropping seasons with unpredictable rainfall or low total rainfall as reported by many authors [12, 29, 30, 52].

The higher grain and straw biomass yields could also be attributed to growth and genetic characteristics of the crop. Improved varieties have a greater ability to convert assimilates to grain and biomass. In fact, genetic characteristics could explain variability of sensitivity of crop to water deficit or availability. There is a very large plant genetic variability of growth sensitivity related to water deficit as reported by Tardieu [55], who mentioned that sensitivity of leaf growth to evaporative demand and soil water deficit can be translated into biomass accumulation in the field. The different responses of improved vs local varieties to water availability could be attributed to this difference in biomass accumulation both in grain and straw.

The substantial response of millet and sorghum to the use of CRT indicated that in Sahelian area such as the Cinzana zone, this soil and water conservation technique

Table 3 Effects of contour ridge tillage on the production of sorghum varieties in Cinzana commune, Mali

			Mean values and comparisons		
Year	**Technique**	**Varieties**	**Variety**	**Technique**	**Variety × technique**
a. Grain yield (kg ha^{-1})					
2012	CRT	Seguifa	621a	a	
		Jacumbe (local)	381b		
	Control	Seguifa	545a	a	
		Jacumbe (local)	297b		
SE			43.5		
Probability			0.01	0.56	0.97
CRT yield increase				96	
2013	CRT	Jacumbe(local)	1174a	a	
		Seguifa	1231a		
		Tiandougou	1600a		
	Control	Jacumbe(local)	677b	b	
		Seguifa	704b		
		Tiandougou	786b		
SE			287		
Probability			0.39	0.04	0.62
CRT yield increase				613	
2014	CRT	Seguifa	1957b	a	
		CSM 219	1353c		
		Sangatigi	2300a		
		Kenikeni (local)	1134cd		
	Control	Seguifa	1200cd	b	
		CSM 219	928de		
		Sangatigi	1333c		
		Kenikeni (local)	819e		
SE			81.6		
Probability			0.001	0.001	0.001
CRT yield increase				616	

			Mean values and comparisons		
Year	**Technique**	**Varieties**	**Variety**	**Technique**	**Variety × technique**
Straw dry biomass (kg ha^{-1})					
2012	CRT	Jacumbe	3524a	a	
		Seguifa (local)	6857a		
	Control	Jacumbe	3943a	a	
		Seguifa (local)	5000a		
SE			1407		
Probability			0.08	0.49	0.29
CRT yield increase				−167	
2013	CRT	Jacumbe	5057a	a	
		Seguifa (local)	4457a		
		Tiandougou	4143a		
	Control	Jacumbe	3314a	a	
		Seguifa(local)	3429a		
		Tiandougou	3486a		
SE			958		
Probability			0.92	0.06	0.88

Table 3 continued

			Mean values and comparisons		
Year	**Technique**	**Varieties**	**Variety**	**Technique**	**Variety × technique**
CRT yield increase				1142	
2014	CRT	Seguifa	10452a	a	
		CSM 219	8007a		
		Sangatigi	9543a		
		Kenikeni (local)	7558a		
	Control	Seguifa	6027b	b	
		CSM 219	4937b		
		Sangatigi	5873b		
		Kenikeni (local)	5273b		
SE			445		
Probability			<0.001	<0.001	0.97
CRT yield increase				3363	

NB For a given year, values with different letters are statistically different at $P = 0.05$. Column means represent tillage techniques and row means the varieties. *SE* standard error of the mean

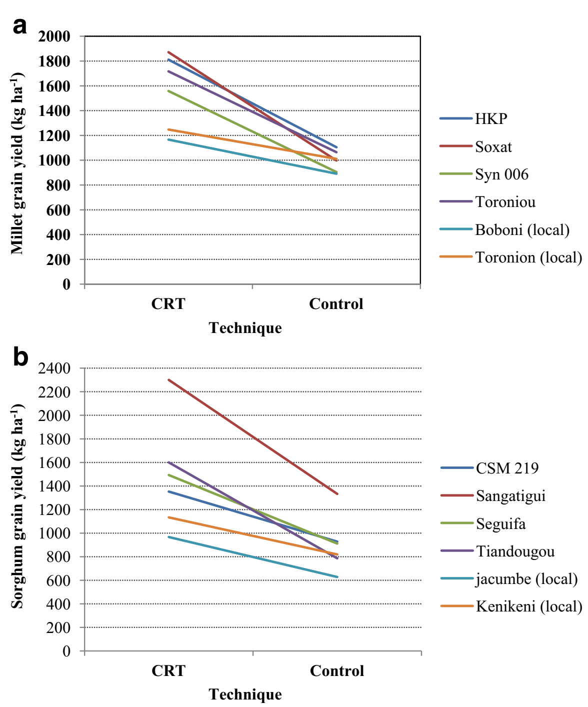

Fig. 6 Interactions between contour ridge tillage (CRT) and millet **a** varieties (improved: Soxat, Soxat1, HKP, Synthetic 006, Toroniou; local: Boboni, Toronion) and sorghum **b** varieties (improved: CSM219, Sangatigui, Seguifa, Tiandougou; local: Jacumbe, Kenikeni) observed from 2012 to 2014 in Cinzana commune, Mali. *CRT* contour ridge tillage plots; *Ctrl* plots without contour ridge tillage

should be largely recommended as a sustainable agronomic practice. Indeed, results clearly showed that realizing some of the increased potential of these new varieties requires improved water management. However, as mentioned by Mcauley et al. [56], additional support is required to strengthen production and delivery systems of improved seed varieties while encouraging farmers to better manage their natural resources with the CRT technique.

Conclusion

The current investigation highlighted the importance of rainfall variability during the cropping season in comparison with inter-annual variability of total rainfall. Fortunately, there are management practices like the CRT that can help buffering the effects of the uneven distribution of rainfall within a season. The results also showed that the effects of the efforts and resources put in realizing the CRT may be optimized by using improved varieties of the most important staple crops of the Cinzana rural commune and its region which are millet and sorghum. Thus, the use of the tested early maturing varieties of the two crops could be an accessible adaptation strategy to climate variability by farmers. Ridging being already traditionally practiced in different farmer communities, the additional step will be the implementation of ridge tilling in contour lines and mechanization of the operation to reduce human labor (otherwise this operation can be done by hand hoe but takes more time and effort in this case). This finding is very important but may gain more attention if the social acceptability of the tested practice (CRT) is assessed through a cost–benefit analysis. Such investigation also needs to be validated on a larger scale by involving more farmers of different wealth status and by including more agroecological zones.

Abbreviations
IER: Institut d'Economie Rurale; ICRAF: World Agroforestry Centre; CRT: contour ridge tillage; CCAFS: Climate Change, Agriculture and Food Security; CIRAD: Centre de Coopération Internationale en Recherche Agronomique pour le Développement; Fe: iron; Al: aluminum; NPK: nitrogen–phosphorus–potassium; ECEC: effective cation exchange capacity; SM: soil moisture content; SMS: soil moisture storage; Db: soil bulk density; H: soil depth; D1: first decade; D2: second decade; D3: third decade; Ca: calcium; Mg: magnesium; CGIAR: Consultative Group on International Agricultural Research; CIDA: Canadian International Development Agency; DANIDA: Danish International Development Agency; EU: European Union; IFAD: International Fund for Agricultural Development; PAR-CSA: participatory action research on climate smart agriculture; AMEDD: Association Malienne d'Eveil pour le Developpement Durable; ARCAD: Association pour le Renforcement des Capacités pour une Agriculture Durable; NGO: Non-Governmental Organization; ENSAM: Ecole Normale Supérieure Agronomique de Montpellier; FAO: Food and Agriculture Organization; SSAC: Sous-Secteur d'Agriculture de Cinzana; IRAT: Institut de Recherche en Agronomie Tropicale; IRD: Institut de Recherche pour le Développement; ORSTOM: Office de la Recherche Scientifique et Technique Outre-mer; USDA: United States Department of Agriculture; USA: United States of America; DC: District of Columbia.

Authors' contributions
KT, DKS and HC designed the experiments, the data collection instruments and gathered the data, and helped in analysis and write-up. JB provided guidance, corrections and supervision to the entire research and critically read and amended the manuscript. All authors read and approved the final manuscript.

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Competing interests
The authors declare that they have no competing interests.

Consent for publication
The Institut d'Economie Rurale and ICRAF, the researchers (Dr. Kalifa Traore, Dr. Daouda Kalifa Sidibe and Dr. Harouna Coulibaly, Dr. Jules Bayala) and farmers involved in this research gave their consent for this publication.

Ethical approval and consent to participate
Generating scientific knowledge, technological innovations and decision support tools for improving agricultural sector in Mali is part of the mandate and missions of Institut d'Economie Rurale (IER, http://www.ier.gouv.ml/), institution to which belong Dr. Kalifa Traore, Dr. Daouda Kalifa Sidibe and Dr. Harouna Coulibaly. Such research involves active participation of local stakeholders to help implementing trials. The protocol of the current study was submitted to the scientific and ethical committee of IER and was approved. Before starting the field work, farmers in the community were informed about the context of the study and the willingness to participate. They have all given their consent and participated to all field works.

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