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Soil Erosion Control and Moisture Conservation Using Contour Ridge Tillage in Bougouni and Koutiala, Southern Mali

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Abstract

Soil erosion is among the critical environmental constraint for crop production in southern Mali. Contour ridge tillage (CRT), a water conservation technique had been locally applied since 1990. The objective of this study was to determine the effects of CRT compared with farmer conventional agriculture practice (NoCRT) on runoff, soil loss, nutrient loss, moisture conservation and cereals yields under rainfed conditions in two Southern Mali sites, in 2016 and 2017 in farmer fields. Measurements were performed on erosion plots composed of CRT and NoCRT plots from which water samples were collected to determine sedimentation levels, concentration and nutrients losses using pairwise comparison. Average runoff coefficient in NoCRT plots was 35.62% compared to 19.25% for the CRT plots explaining a runoff reduction of 46%. Mean soil losses of 12,095 $t \cdot ha^{-1}$ and 4970 $t \cdot ha^{-1}$ were respectively measured in NoCRT and CRT plots. Losses in calcium, magnesium and potassium nutrients in the NoCRT plots were 80%, 66%, 75% higher compared to CRT ones, respectively. Sorghum grain yield was at least two folds higher in CRT plots compared to the NoCRT plots. Maize average grain yield was 87% higher in CRT plots than in the NoCRT. For sustained soil productivity, CRT is advocated as a better soil and water management technique than the NoCRT one.

Keywords

Runoff and Erosion, Nutrients Loss, Yields

1. Introduction

Mali's economy is essentially based on the primary sector where agriculture accounts for more than 35 percent of gross domestic product (GDP) and 80 percent of livelihoods [1]. The predominantly rainfed nature of its agriculture remains problematic because of rainfall unreliability which threatens dangerously crop production and development strategy [2]. Water is one of the main constraints to crop production [3] [4] as it influences directly plants growth, therefore it's very important to minimize rain water runoff in rainfed agriculture [5].

Runoff is harmful to agricultural production. In one hand, it reduces water availability for crops and parkland trees, and on the other hand, it can lead to soil degradation by erosion of the upper soil layer [6]. Water erosion, which removes nutrients, thins the soil layer, reduces rooting depth and infiltration, damages soil structure, is the most common form of land degradation worldwide. Erosion usually increases with agricultural activity, particularly with annual cropping systems where the soil surface is seasonally exposed to rain with high intensities. This situation results in negative nutrient balances and lower crop yields in most farming systems in West Africa [7]. In Sub-Saharan Africa (SSA), rain comes as downpours under high anthropogenic (deforestation and population) pressure leading to over 50 tons·ha^{-1} soil losses in many situations [8]. Soil chemical properties that were most adversely influenced by erosion or topsoil removal in SSA include pH, organic matter content, total N, available P, exchangeable bases, and cation exchange capacity [9] [10].

Losses were estimated in cultivated soils of southern Mali [11] to 25 kg of N ha^{-1}·year^{-1} and 20 kg of K·ha^{-1}·year^{-1}. [11] concluded that 44% of farmer's agricultural incomes losses are due to soil depletion which is a major factor influencing food security in the area and finally the economy of the country since it affects the main rainfed staple crop. According to [12], the major staple crops grown in southern Mali are millet (*Pennisetum glaucum* (L.) R. Br.), sorghum (*Sorghum bicolor* (L) Moench), and maize (*Zea mays*) and these crops are becoming dominant southwards.

In southern Mali, erosion was emphasized by inadequate soil and crop management which could even jeopardize national food security goals, since impacting negatively directly on crop productivity [13] [14] [15]. So, because of unpredictable rainfall and decreased agricultural productivity, many soils and water conservation technologies such as stone lines, half-moons, contour hedgerows, rock bunds, filter walls, zaï, agroforestry, mulching, soil amendments, water harvesting, contour ridges, terraces, check dams, benches and no-tillage have been developed and are now widespread to improve soil quality, decrease runoff, erosion and nutrient losses, and increase infiltration and crop productivity [5] [16] [17] [18].

In Mali, contour ridge tillage (CRT), which is also referred to as "Aménagement en courbes de niveau" [19] [20] is a water conservation technique locally developed in the early 1990s by Institut d'Economie Rurale (IER) and the Agricultural Research Centre for International Development (CIRAD) [18]. It is a holistic landscape level method for managing surface water on farmers' fields, in which it decreases runoff, increases water infiltration and, therefore, captures rainfall close to the crop root system [21]. Placing a field under CRT requires the construction of permanent ridges (using a topographic equipment: automatic level, water level etc.), about 100 cm wide, prior to crops planting. Then, the annual small ridges will be constructed along these permanent ridges following contour lines. When necessary, waterways to evacuate excess water off the fields may also be added to the works. So, the furrows become rain water infiltration area which could be of great advantage for crop. Consequently, when applied in Sudanian area (rainfall varying from 800 to 1200 mm) in southern Mali, where runoff still occurs in fields with a slope as low as 1% to 2% leading to crops yields increase of 30% to 50% for maize, sorghum, millet, groundnut and cotton [22].

In the semi-arid zones of southern Mali where low inputs and low yields agriculture systems dominate, the development of soil and water conservation techniques such as CRT, is essential to ensure sustainable farming systems [18]. Thus, the need for integrated land and water resources management to reduce poverty and food insecurity especially in semi-arid Africa, where over 80% of rural livelihoods depend on land and water resources, cannot be overemphasized [23].

In the Soudanian area of southern Mali, although the effects of CRT on crop yield and infiltration were widely studied [5] [18] [19] [20] [21] [22] [24], influence of erosion and runoff of this area are not well documented. The objective of this study was to determine the effectiveness of CRT compared with farmer conventional agriculture on runoff, soil loss, nutrient loss, moisture conservation on cereals (maize and sorghum) yields under rainfed conditions. The hypothesis is that the use of CRT under natural rainfall conditions as opposed to farmer's practice will improve crop yields due to decreased soil, water, and nutrient losses from erosion.

2. Methodology

2.1. Study Sites

The experiment was conducted in two sites of southern Mali belonging to Soudanian Agro-ecological zone. The first one is located at a technology park in Flola village, district of Bougouni. The second site is at a technology park in Mpessoba village, district of Koutiala. The technology park of Flola is at 11˚42'N latitude, 7˚64'W longitude and 350 m altitude and the technology park of Mpessoba is at 12˚67'N latitude, 5˚71'W longitude and 346 m altitude. The two experimental sites are represented in **Figure 1**.

The average annual rainfall over the last 46 years (1971-2017), was 857 mm in Koutiala (40 km from Mpessoba village toward north) and 1095 mm for Bougouni (15 km from Flola village toward south) and has an irregular spatio-temporal distribution. Over 37 years (1971-2008), low temperatures occurred between December and February with monthly averages of 16.8˚C and 16˚C, and high temperatures between April and May, with monthly averages of 38˚C and 37˚C, respectively for Koutiala and Bougouni (**Figure 2(a)**). The daily evapotranspiration was 6 - 7 $mm \cdot day^{-1}$ in the dry season and 4 $mm \cdot day^{-1}$ during the rainy season.

Rainfall follows a uni-modal pattern with maximum events occurring in July and August. Enough rain for crop planting without prolonged dry spells that could hurt seedlings after sowing occurs in May and ends of rainy season in October [25]. Monthly rainfall, maximum and minimum temperatures and potential evapotranspiration (PET) were collected from the National Meteorological Service of Mali in Bougouni and Koutiala during the study period (**Figure 2(b)**).

Dominant soil types in the study areas are classified as leached tropical ferruginous soils with spots and concretions [26]; Arenosols, Lixisols and Acrisols [27] and Alfisols according to Soil Taxonomy [28], with many Paleustalfs and frequent Plinthustalfs. The Alfisol soil order indicates that the soils are constrained by both small amounts of nutrients and a low capacity to retain nutrients due to the chemical constituents [21]. Soils are characterized by light textured sandy loam topsoil (0 - 20 cm) with 8% clay covering heavy textured subsoil of 20% - 28% clay. Average bulk density is 1.5 $g \cdot cm^3$ at 0 - 20 cm soil horizon. These soils are inherently fragile with weak water retention capacity and poor in plant nutrients [12]. Soil pH varied from moderately acid (pH_2O = 6.5) to acid (pH_2O = 5.5), Organic Carbon (5 - 6 $g \cdot kg^{-1}$), Nitrogen (<0.5 $g \cdot kg^{-1}$), available P (<0.07 $g \cdot kg^{-1}$), exchangeable K (<72 $mg \cdot kg^{-1}$), Cation Exchange Capacity (CEC) (4 - 6 $cmol \cdot kg^{-1}$) and a base saturation ratio 75%.

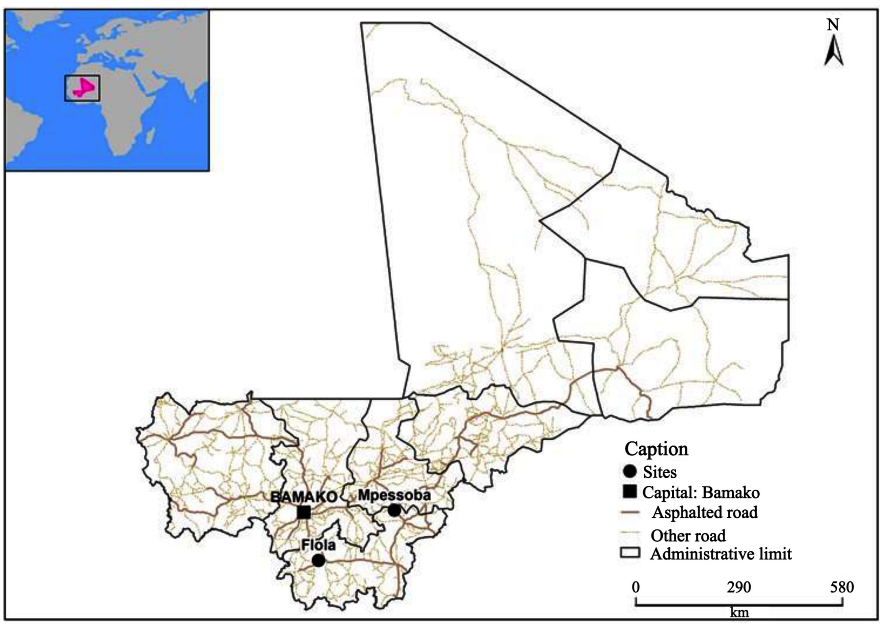
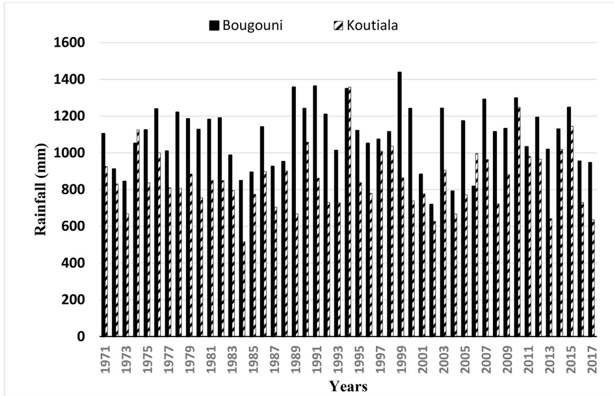
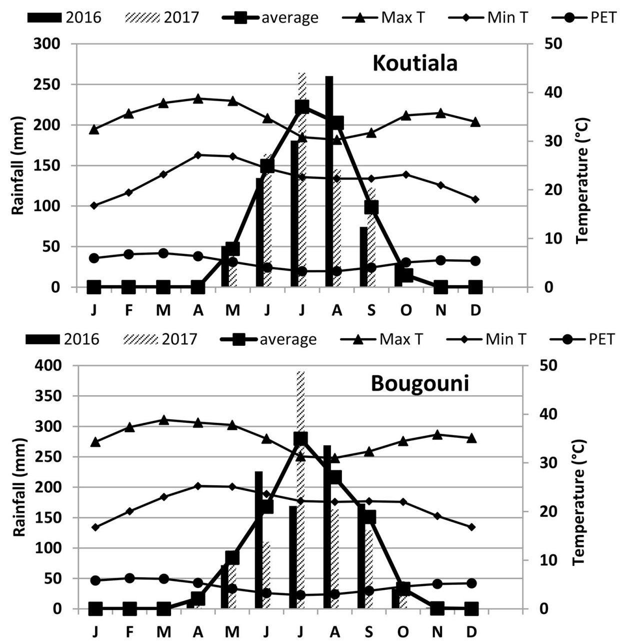


Figure 1. Location of the experimental sites where the effects of contour ridge tillage (CRT) on runoff; erosion; nutrient loss; water dynamics and cereals productivity were measured in 2016 and 2017 in southern Mali.



(a)



(b)

Figure 2. Long-term annual rainfall for Koutiala and Bougouni (a) and monthly rainfall average, maximum (Max *T*), minimum (Min *T*) temperatures and potential evapotranspiration (PET) of two consecutive years (2016 and 2017) (b) in Koutiala (Mpessoba) and Bougouni (Flola), Southern Mali.

Farming System in the Study Areas

The main farming system in Bougouni and Koutiala is a crop-livestock based rotation system of Cotton (*Gossypium hirsutum*, L.), Maize (*Zea mais*), and Sorghum (*Sorghum bicolor*).

Tested varieties were *Sotubaka* (improved maize variety) and *Pablo* (sorghum hybrid).

Rotation head is cotton followed by maize and sorghum allowing cereals to benefit from the cotton residual fertilizer effects. Annual staple crops, sorghum and maize, were planted in the middle and bottom of the catena. Cotton was also planted in the bottom while grazing area was in the top of the catena. Smallholder farmers used extensively animal manure collected in farmyard or sometime compost to improve crop productivity for food (grain) and straw for feed. The rainy season covers May to November for the main cropping period. Income from cash crops and livestock sales was partially used to cover farm inputs and other household needs [29].

2.2. Agronomic Practices for Yield Data

For both sites, maize and sorghum were planted from 15-25 June in 2016 and from 18-30 June in 2017 respectively in CRT and NoCRT plots. Planting density was 0.40 m within hills on the row and 0.75 m between rows for maize. For sorghum, density was 0.5 m within hills on the row and 0.75 m between rows. Elementary plot sizes were 34 m length and 7.5 m width for 255 m^2. One row at each border of the plot was discarded to determine the net plot sizes leading to 34 m length and 6 m width *i.e.* 204 m^2. Seedlings were thinned to two plants per hill 15 days after emergence for targeted populations of 66,666 (Maize) and 53,333 (Sorghum) plants·ha^{-1} which are the density advised by extension services for the area. Thinning was done two weeks after emergence. Base fertilizer was uniformly applied to each treatment (CRT and NoCRT plots) at the rate of 100 kg·ha^{-1} of NPK (15–15–15) at planting time for both crops. Thirty days after germination, 75 kg·ha^{-1} of urea for Maize and 50 kg·ha^{-1} of urea (46% of nitrogen) for sorghum were applied followed by hand hoeing. A second dose of 75 kg·ha^{-1} of urea was applied 45 days after germination on maize. Fertilizer was buried 5 cm below and 5 cm away from plants on the row banks.

In CRT and NoCRT plots, harvest was done from 2-30 October and from 7-27 October in 2016 and 2017, respectively for maize and sorghum, followed by 20 days of sun drying.

2.3. Experimental Design for Runoff and Erosion Measurement

The erosion study was conducted in 2016 and 2017 in the technology park of Flola and Mpessoba, in Mali. Experiment plot was divided in two parts: the first one was under contour ridge tillage (CRT) and the second one with farmer's practice (NoCRT) as a control. There were 4 experimental plots with 0.75 m width and 34 m length surrounded by an oblique galvanized iron sheets of 55 cm height inserted to a depth of 15 cm to prevent runoff to seep in or out from the plot, corresponding to four replicates for both in CRT and NoCRT plots.

In the paired CRT and NoCRT erosion plots, the surface runoff from each experimental plot was 1/10 diverted by a channel into a collection barrel of 200 liters capacity and an additional barrel for collecting another 1/10 of total runoff water. These barrels were placed in a pit of 1.5 m × 0.7 m × 1.3 m, covered by a metal sheet of 1.8 m × 1.0 m.

Runoff coefficient (Rco) was used to compare the influence of CRT and NoCRT and expressed as follow:

$$\mathrm{Rco} = \frac{\mathrm{Rw}(\mathrm{mm})}{\mathrm{Ra}(\mathrm{mm})} \tag{1}$$

where Rw = Runoff water; Ra = Rainfall received;

$$Rw = \frac{Vw(m^3)}{S(m^2)} \quad (2)$$

where Vw = Volume of water generated; S = Water measurement area.

To measure the average sediment concentration in the runoff water and estimate soil loss in each of the four replicates of the CRT and NoCRT plots. Three water samples of one-liter each were taken in each collecting barrel to maximize accuracy of the operation. These samples were taken after runoff water has been stirred vigorously to better capture sediments in the barrel. Sediments and nutrients concentrations were measured by oven drying at 40˚C for 7 days to constant weight and chemical analysis (organic carbon, N, P, K) whereas concentrations were determined in the Soil Plant and Water Laboratory of Institut d'Economie Rurale (IER). Runoff, soil loss by erosion, and nutrients contents were compared between CRT and NoCRT plots using pairwise t test at 0.05 significant levels. Two rain gauges were installed in each research site. Time-domain refractometry probes were installed, 100 cm deep below soil surface at the middle of CRT and NoCRT plots to measure soil moisture during the whole cropping season. Before rain onset, dry soil moisture content was recorded immediately after trials installation. In order to characterize soil moisture during the cropping season, CRT and NoCRT plots were represented by soil moisture daily measured, at the months of July (beginning of the rainy season), August (at the middle of the rainy season) and September (at the end of the rainy season) in 2016 and 2017.

In each site (CRT and NoCRT) plots were treated the same way in sowing dates, crop species and other cropping operations, except ridging mode.

Soil Water Storage calculation was performed to quantify the water stored in each soil profile,

In each profile it was calculated as the sum of the soil water per depth interval through the profile.

2.4. Data Collection and Analysis

On each site, 40 samples from horizon 0 - 20 cm were randomly collected in May 2016, on 1ha, using an Edelman Combination Auger (4 cm core) of 1.2 m length, mixed to form composite soil samples. Samples were air dried by spreading them on a plastic sheet at room temperature. Composite samples were made from the ones taken in an asterisk shape pattern in each site. Samples were analyzed for both physical and chemical properties. Particle size (soil texture) analysis was performed by the hydrometer method [30], pH was determined by the electrometric method in a soil solution with a soil/water ratio of 1:2.5. Soil organic was determined by the modified Walkley-Black wet oxidation method as outlined by [31]. Total nitrogen was determined by the modified Kjeldahl digestion method of [32], while bases, CEC and available P were determined as described in [33].

Crop yields were measured in central rows while discarding the two border rows on each side of the plot. At harvest, total panicles and cobs, grain and stems dry weights were recorded in the central rows and data extrapolated from the subplot size to hectare. Paired CRT and NoCRT plots data were analyzed as a simple trial in a four-block experimental design to determine the global significance of runoff volume, soil erosion, nutrient losses and crops yields using STATBOX 7.4.4. Newman-Keuls test was used to separate means for significant differences between treatments. Treatments effects were considered significant at $P < 0.05$.

3. Results

3.1. Rainfall Trend

Total cropping season rainfalls were 730 and 954 mm in 2016 and 635 and 945 mm in 2017 for Koutiala and Bougouni, respectively. Maximum rainfalls of 264 and 391 mm were received in July in 2017, while 260 and 269 mm were observed in August 2016, for Koutiala and Bougouni, respectively. July 2017 accounted for 42% and 41% of the total amount of rainfall in Koutiala and Bougouni, respectively. In August 2016, rain amount was +79 and +65% higher than those of 2017 for the same month, for Koutiala and Bougouni respectively. These increases represented 36% for Koutiala and 28% for Bougouni. In May, at the beginning of the rainy season, on both sites, rainfall was less than 85 mm (Figure 2(b)).

The mean annual minimum temperature was 16˚C and 15.5˚C and maximum temperature was 38.8˚C and 39.5˚C, for Koutiala and Bougouni, respectively.

Lowest mean annual potential evapotranspiration (PET) of 3.65 and 3.20 was recorded from June to September for Koutiala and Bougouni, respectively, while the other months of the year showed values varying from 5 to 6 mm.

3.2. Soil Characteristics

Table 1 presents surface soil horizon data on granulometry and chemical properties. Granulometric composition of Bougouni and Koutiala soils was closer. However, soil in Koutiala was slightly sandy than that of Bougouni (+8%), less silty (−2%) and less clayed (−6%). Soil pH (water and KCl) of the study sites were globally slightly acid. The Ca, K and CEC values in Bougouni were at least +40% higher than those of Koutiala while Mg value was +20% higher, compared to the same site. Phosphorus level was low but slightly higher in Bougouni (+7%) than Koutiala. Soil of both sites showed very low values in organic matter and nitrogen.

3.3. Runoff, Erosion and Soil Moisture Dynamics

3.3.1. Effects of CRT and NoCRT on Runoff

Monthly rainfall distribution, runoff and soil loss in 2016 and 2017 is given in Figure 3 for Koutiala (Mpessoba) and Figure 4 for Bougouni (Flola). Results showed that severe individual runoff and soil loss events occurred during heavy rainfalls of July and August. Highest runoff peaks curves were observed on NoCRT plots under farmer's practice conditions in both sites. Figure 3 and Figure 4 show evidence that the runoff coefficient for the CRT plots was always lower than that of the NoCRT ones. In 2016 and 2017, the mean runoff coefficient was highly significant and lower ($P = 0.004$) on the CRT plot than the control (Table 2). Also, the average runoff coefficient in the NoCRT plots in the two sites was 35.62% compared to 19.25% for the CRT plots explaining a runoff reduction of 46%. Runoff was 31% higher ($p = 0.03$) in Bougouni (Flola) than in Koutiala (Mpessoba) and varied across year. Mean runoff coefficient of 2016 (+30%) was greater than that of 2017 (24%) at the 5% probability level.

3.3.2. Effects of CRT NoCRT on Erosion

Figure 3 and Figure 4 showed erosion patterns in Koutiala and Bougouni, respectively. It appears that erosion peaks corresponded to runoff peaks and they were high-pitched in Bougouni than in Koutiala. Also, the highest erosion peak was always observed with NoCRT plot.

For the two years experiments, a mean of 12,095 $t \cdot ha^{-1}$ of soil was lost from the NoCRT plots, compared to a mean of 4970 $t \cdot ha^{-1}$ from the CRT plots. It appeared clearly that the use of CRT contributed to a significant decline in soil loss from cultivated lands. Thus, erosion was 2.4 times greater in NoCRT plots than those of CRT ones and the difference was statistically significant ($p = 0.02$). Erosion varied greatly among sites ($p = 0.04$) and was 97% greater in Bougouni, where average rainfall on the two years was also 39% higher than in Koutiala. Erosion varied among years ($p = 0.04$) with the highest values in 2016 (+92%) which was also the rainiest year.

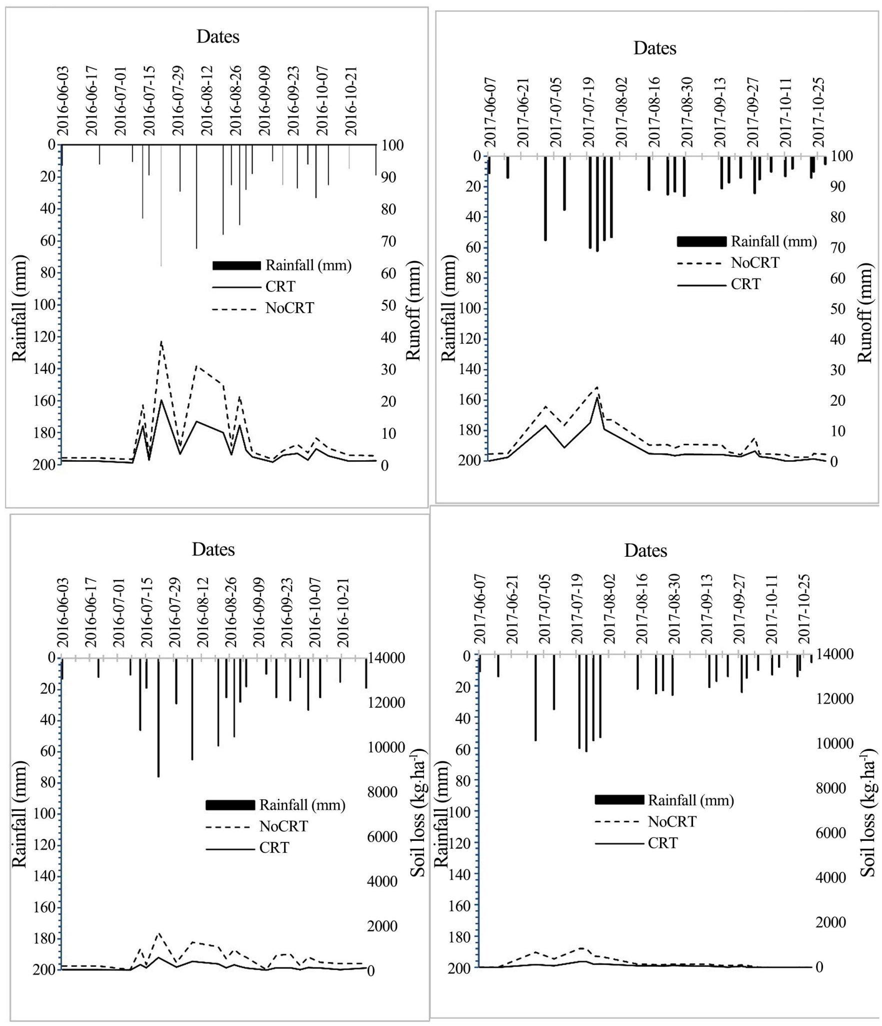
Table 1. Soils characteristics in the 0 - 20 cm soil depth of Bougouni and Koutiala experimental sites in 2016 in southern Mali.

Sites	Koutiala (Mpessoba)	Bougouni (Flola)
pH (water)	5.7	6.3
pH (KCl)	4.9	5.5
OC ($g \cdot kg^{-1}$)	4.1	5
Azote total ($g \cdot kg^{-1}$)	0.33	0.42
P Available ($mg \cdot kg^{-1}$)	5.71	6.12
CEC $cmol \cdot kg^{-1}$	3.69	5.18
Ca $cmol \cdot kg^{-1}$	2.63	3.85
Mg $cmol \cdot kg^{-1}$	0.81	0.98
K $cmol \cdot kg^{-1}$	0.22	0.31
Na $cmol \cdot kg^{-1}$	0.03	0.03
Sand% > 0.05 mm	76	70
Silt% 0.05 - 0.002 mm	19	23
Clay% < 0.002 mm	5	8

Table 2. Runoff coefficient and soil loss in Koutiala (Mpessoba) and Bougouni (Flola) during 2016 and 2017 cropping season in Mali.

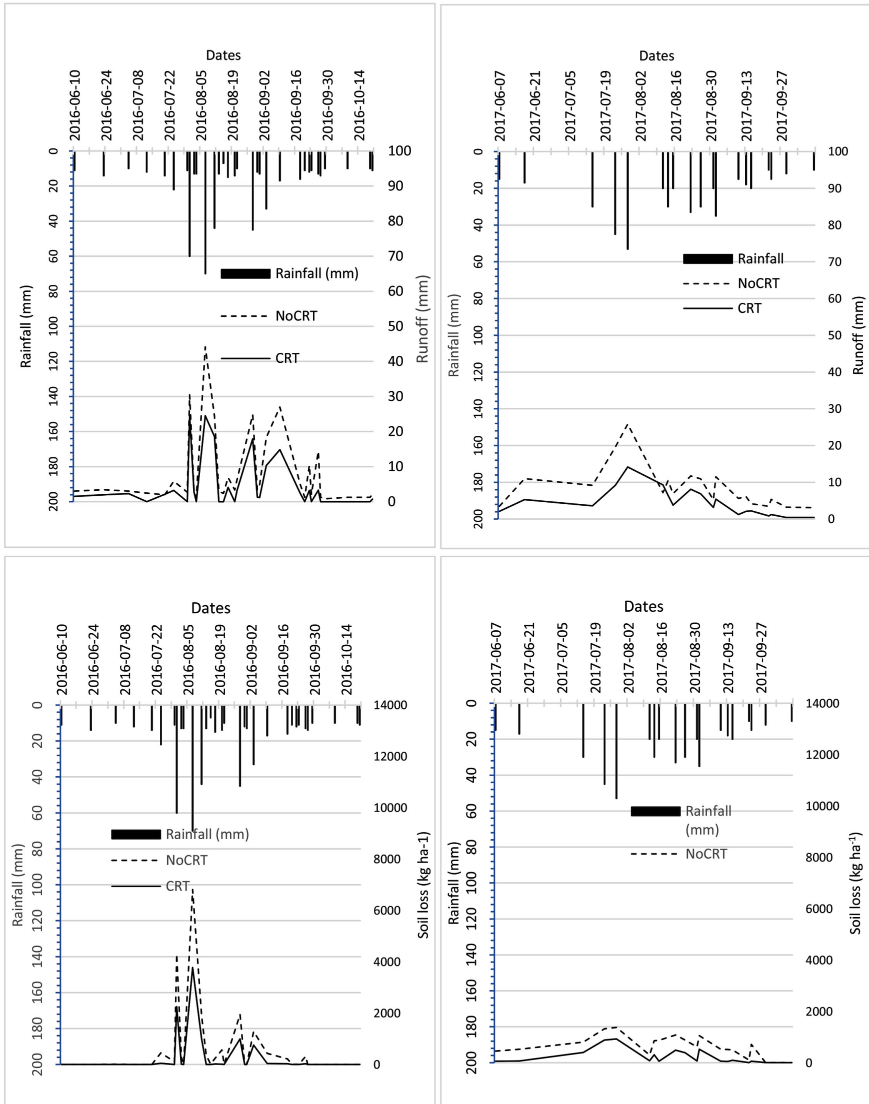
		Runoff coefficient (%)	Soil loss kg·ha^{-1}·year^{-1}
	CRT	19.25 b	4970 b
Technique	NoCRT	35.62 a	12,095 a
	P value	0.004	0.02
	Mpessoba	23.75 b	5733 b
Sites	Flola	31.12 a	11,332 a
	P value	0.03	0.04
	2016	30.87 a	11,228 a
Year	2017	24.00 b	5837 b
	P value	0.05	0.04

Values with different letters are statistically different at $P = 0.05$. Column means represent runoff coefficient and soil loss; row means are for techniques, sites and years.



(a) (b)

Figure 3. Rainfalls, runoffs and soil losses in 2016 (a) and 2017 (b), in Koutiala (Mpessoba), southern Mali.



(a) (b)

Figure 4. Rainfalls, runoffs and soil losses in 2016 (a) and 2017 (b), in Bougouni (Flola), Southern Mali.

3.3.3. Effects of CRT and NoCRT on Nutrient Losses

Table 3 shows carbon and other nutrients losses in eroded soil of Mpessoba and Flola technology parks. Nutrient loss was not significantly different between the two sites (p = 0.06 - 0.98). However, nutrient losses between CRT and NoCRT plots were significantly different in all cases, and the highest nutrient loss was always recorded from the NoCRT plots. Carbon, nitrogen and phosphorous quantities were at least two folds greater in NoCRT plot than the CRT one. Losses of calcium, magnesium and potassium in the NoCRT plots, were 80%, 66%, 75% higher compared to CRT ones, respectively.

Except for phosphorous (p = 0.12), nutrient loss was significantly higher in 2016 than 2017 (P values varying from 0.003 to 0.02). Carbon, nitrogen, phosphorous, calcium, magnesium and potassium losses in total nutrients eroded from the fields were 74%, 6.6%, 5.0%, 6.6%, 3.3% and 5.0% in 2016 compared to 66%, 8.0%, 7%, 8.0%, 5.0% and 5.0% in 2017, respectively.

3.3.4. Effects of CRT and NoCRT on Soil Moisture

Figure 5 showed that along the profile, that soil water content was always higher in CRT compared to the NoCRT, plots in both sites. Deeper soil layers water content was also higher. Soil water content was higher in CRT plots in 2017 compared to 2016 except in Flola which had less rain at the beginning of the cropping season.

At the beginning of the rainy season (June), in the 10 cm of soil surface layer, differences of soil water content between CRT plots in 2016 and 2017 and NoCRT plots were +33% and +37% respectively for Flola and Mpessoba. Also, in all cases, a global moisture decrease was observed in the 10 - 20 cm depth. Soils moisture mean differences of 21% and 27% were observed at 100 cm depth, respectively at Mpessoba and Flola. In the upper 60 cm soil layer, soil moisture was not greater than 20% in both sites.

August, the middle of the growing season, had frequent rainfalls with deep drainage, where mean soil moisture content along the profile was about 30% in Flola while this value was rather observed in the 60 - 100 cm soil layers in Mpessoba. Here also, soil water content was always higher in CRT plots compared to the NoCRT plots. The difference between CRT and NoCRT was visible along the profile where, at the deepest 100 cm soil layer, mean soil moisture was +40 and +31% greater in the CRT plots (32.68 and 23.27) compared to the NoCRT plots (32.57 and 24.80), respectively for Flola and Koutiala.

At the end of the growing season (October), the drainage was deep with less water, but at 100 cm, mean soil moisture in CRT plots was 31% in both sites. Soil moisture remained always greater in CRT plots than the NoCRT ones. Also, mean differences of 24% and 33% were observed between CRT and NoCRT plots at 100 cm depth, respectively in Flola and Mpessoba.

Table 3. Nutrient losses in eroded soil ($kg \cdot ha^{-1} \cdot year^{-1}$) under farmers' practice (NoCRT) compared to contour ridge tillage technology (CRT) in Mpessoba and Flola, Southern Mali, in 2016 and 2017.

		C	N	P	Ca	Mg	K
Technique	CRT	45b	5b	4b	5b	3b	4b
	NoCRT	106a	11a	8a	9a	5a	7a
	P value	0.04	0.006	0.02	0.01	0.01	0.02
Sites	Mpessoba	75	7	4	8	4	5
	Flola	76	8	6	7	4	6
	P value	0.97	0.98	0.06	0.6	0.62	0.76
Year	2016	112a	10a	7	10a	5a	7a
	2017	39b	5b	4	5b	3b	3b
	P value	0.02	0.01	0.12	0.008	0.003	0.01

Values with different letters are statistically different at $P = 0.05$.

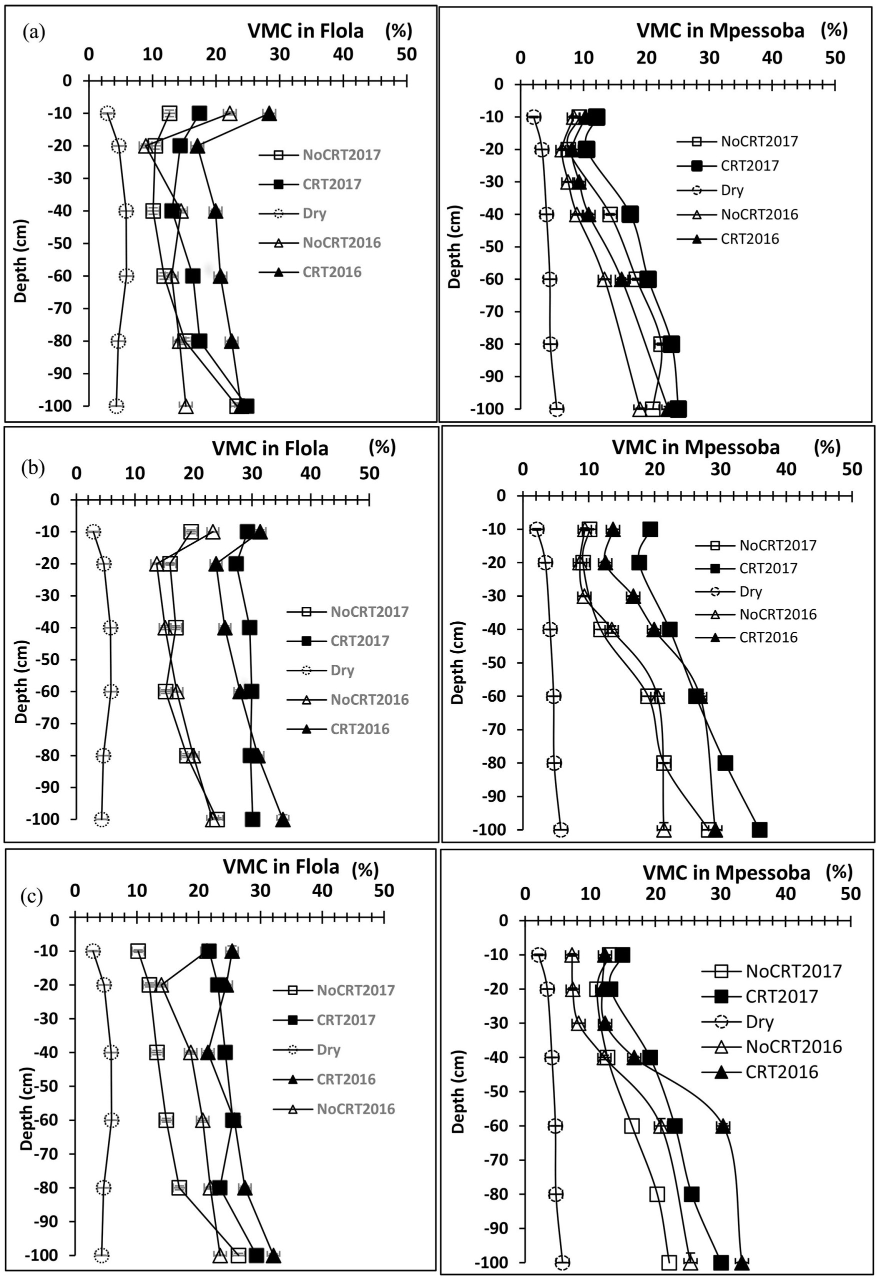
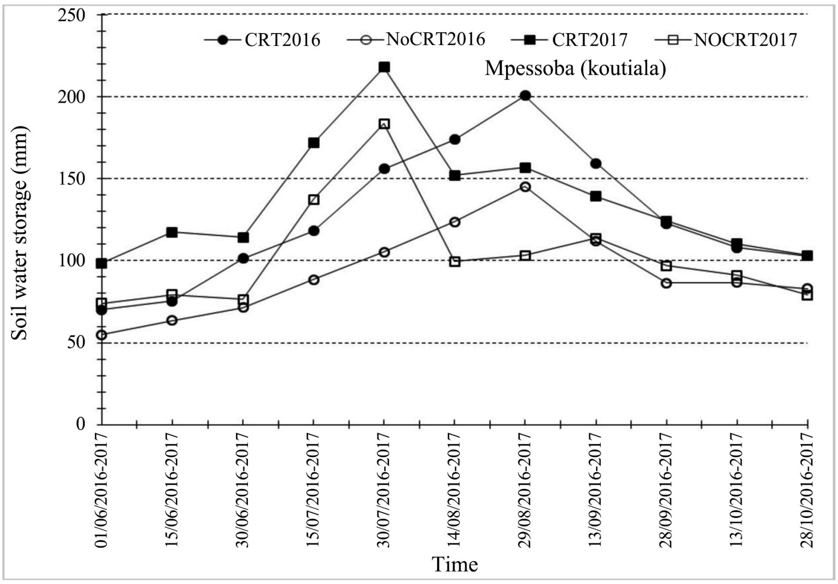


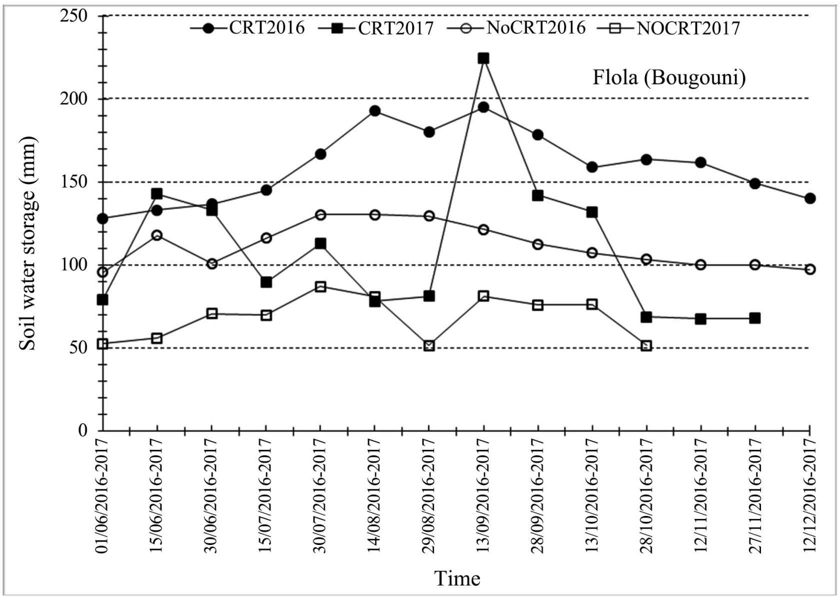
Figure 5. Vertical distribution of soil moisture 0 - 100 cm depth in Contour ridge tillage plots (CRT) and no contour tillage (NoCRT) plots in Flola (Bougouni) and Mpessoba (Koutiala) villages in 2016 and 2017; (a) beginning of the growing season (June 10, 2016 and 2017); (b) middle of the growing season (August 20, 2016 and 2017); (c) end of the growing season (October 30, 2016 and 2017); *dry is* dry soil during the dry season (May 10-11, 2016 and 2017); *bars* indicate standard errors of the means; VMC Volumetric moisture content.

3.3.5. Effects of CRT and No CRT on Soil Moisture Storage

Water storage in CRT plots reached a maximum of 218 mm end of July 2017 and 200 mm end of August 2016 in Mpessoba (Figure 6). The corresponding values observed in Flola were 225 and 195 mm in mid-September for 2017 and 2016, respectively. Globally, from end of August, water storage decreased regularly until end of October, both on CRT and NoCRT plots in Mpessoba, while the same pattern was observed from mid-September in Flola for the two techniques. At the end of the growing season in October, mean water storage for the two years was 30% higher in CRT plots compared to that of the NoCRT plots in Mpessoba while this advantage was 50% for the CRT plots over the NoCRT plots in Flola. Water storage was always higher in CRT compared to the NoCRT, plots with a surplus of 11.86 mm·day^{-1} in 2016- and 8.56-mm·day $^{-1}$ in 2017 resulting from 150 days (June 1st to 28 October) monitoring period in both sites.



(a)



(b)

Figure 6. soil water storage in the 100 cm profile in the Mpessoba (a) and Flola (b) village in 2016 and 2017 performed on CRT contour ridge tillage plots and NoCRT plots without contour ridge tillage.

3.3.6. Effects on Crop Yields

Average maize grain yields in Mpessoba were 2296 kg·ha^{-1} and 1729 kg·ha^{-1} in 2016 and 2017, respectively (Table 4). The corresponding values for Flola were 2732 and 2475 kg·ha^{-1} for 2016 and 2017 respectively. Averages maize straw yields in Mpessoba were 5184 and 3334 kg·ha^{-1} in 2016 and 2017 and 6673 and 5150 kg·ha^{-1} for the same years in Flola. Average sorghum grain yields were 1709 and 2312 in 2016 and 2017 and 1879 and 1334 in 2016 and 2017, respectively for Mpessoba and Flola. Sorghum straw average yields in 2016 and 2017 were 10,156 and 13,665 kg·ha^{-1} in Mpessoba and 7798 and 6650 kg·ha^{-1} in Flola during the same years.

Table 4. Effects of contour ridge tillage (CRT) and without contour ridge tillage (NCRT) on sorghum and maize yields (kg/ha^{-1}) in Mpessoba and Flola during the 2016 and 2017 cropping season in Mali.

Sites	Year	Technique	Maize Grain	Maize Straw	Sorghum Grain	Sorghum Straw
Mpessoba	2016	CRT	3017 a	6567 a	2350 a	12,150 a
		NoCRT	1575 b	3800 b	1068 b	8163 b
		Mean	2296	5184	1709	10,156
		Probability	0.007	0.002	0.008	0.01
		MSD	428	577	359	1432
		CV (%)	17.8	9.9	17.8	14.1
	2017	CRT	2233 a	4167 a	3267 a	19,768 a
		NoCRT	1225 b	2500 b	1358 b	7563 b
		Mena	1729	3334	2312	13,665
		Probability	0.0002	0.003	0.004	0.005
		MSD	139	414	483	3476
		CV (%)	8.5	12.7	19.8	27.5
Flola	2016	CRT	3823 a	8384 a	2836 a	11,329 a
		NoCRT	1641 b	4961 b	922 b	4267 b
		Mena	2732	6673	1879	7798
		Probability	<0.0001	<0.0001	<0.0001	<0.0001
		MSD	368	670	480	1569
		CV (%)	15.3	11.7	27.8	22.9
	2017	CRT	2950 a	6500 a	1825 a	9100 a
		NoCRT	2000 b	3800 b	842 b	4200 b
		Mean	2475	5150	1334	6650
		Probability	0.01	0.01	0.005	0.01
		MSD	206	562	144	917
		CV (%)	8.5	12.4	9.1	16.3

MSD = mean standard deviation; **CV** = coefficient of variation; $CV(\%) = \frac{MSD}{M} \times 100$.

The use of CRT significantly improved maize grain and straw yields in both sites. Maize grain yield in Mpessoba was 92% and 82% higher in the CRT compared to the NoCRT plots, respectively for 2016 and 2017. In Flola, maize average grain yield in CRT plots was more than two folds compared to that of NoCRT plots in 2016 and 48% in 2017 (**Table 4**).

Maize average straw yields in CRT plots were 73%, 67%, 67%, 71% higher in 2016 and 2017 than the ones of NoCRT plots, respectively for Mpessoba and Flola sites.

Sorghum average grain yield was at least two folds higher in CRT plots than in the NoCRT plots for both years in both sites. The same trend was observed for sorghum straw, except in Mpessoba, in 2016, where average CRT plot was only 49% higher than the NoCRT (**Table 4**).

4. Discussion

4.1. Rainfall Trend

Rainfall analysis revealed not only inter-annual rainfall variabilities (635 - 1437 mm) but also intra-annual rainfall distributions. This situation is likely to negatively impact crop production as reported by [34] when studying the relation between climate and soil productivity in Sudanian and Sahelian zones of Africa where amount of rainfall distribution in a given year determines crop productivity level [35] [36]. In the same way, [37] mentioned that climate variability was among the main impediment to the realization of the first Millennium Development Goal of reducing poverty and food insecurity through increase of agricultural production in developing countries. Mean temperatures and PET values during the study period were very close to those from 37 years data analysis.

4.2. Soil Characteristics

Soils were predominately loamy and sandy (**Table 1**) indicating a strong susceptibility of surface soil layers to compaction which can lead to severe runoff and erosion, mainly when combined with greater than average rainfall [38] [39]. In both sites, the highest organic carbon content was less than 6 $g \cdot kg^{-1} \cdot ha^{-1}$ and in line with the low values of nitrogen, phosphorus and CEC, indicating that they had low soil fertility and water-holding capacity. Findings reported in this study agree well with those claimed by several authors [6] [18] [40] [41] [42] for tropical ferruginous soils of West Africa. Findings of [42] showed that in soil surface layers of West Africa, organic carbon content is dependent on soil texture, explaining that the lower the clay and fine silt contents, the lower the soil carbon content. In the same way, the dominant clay type, although low in these soils is kaolinite (1:1 low activity clay) indicating the necessity to apply fine elements such organic matter to improve soils CEC and storage capacity for nutrients exchange [18] [42] [43]. This observation agrees with what of [44] for sandy soils who reported that an increase of 1 $g \cdot kg^{-1}$ of organic carbon leads to an increase of 4.3 mol·kg^{-1} of CEC.

4.3. Effect of CRT and NoCRT on Runoff

For all rainfall events measured, runoff was always greater in the NoCRT plots than the CRT ones. The greater rainwater loss was probably due to high runoff and low infiltration rates during intensive rainfall peaks (**Figure 3** and **Figure 4**). These peaks may be due to soil saturation leading to infiltration reduction rate. In assumption, a light rain event is associated with less runoff than a heavy rain event, which may release a greater volume of water over a short period of time. In this study, runoff peaks were observed in July and August, the rainiest period of the cropping season in both sites, explaining that conditions for runoff to occur are important. In fact, wet soils generally have lower infiltration rates than dry soils since pore spaces are already filled with water due to previous rain events. Soil type also, may play a role in runoff severity because number and pores sizes are reduced in a clay type soil which swells when wet. This situation results in weak infiltration rate and consequently to runoff. Soil in Bougouni has more clay and silt, when saturated and then receives considerable quantity of rainfall, may explain the highest runoff rate compared to Koutiala site. The sandy nature of the parent materials of the studied soils also emphasizes runoff, in agreement with [45] who reported that in most tropical soils in Africa, even not originally sandy, were intensively washed by runoff and leaching that transform their texture to coarse after heavy rainfalls. These observations agreed with those of several authors [5] [21] [46]-[52]. In agreement with findings of this study, it has been reported by many authors [20] [24] [53] that CRT was beneficial for reducing runoff and soil loss, as well as for increasing crop yield and was a holistic landscape approach to managing water and capturing precipitation in farmer's fields.

Mean runoff coefficient was significantly higher in the NoCRT plots cultivated up and down the slope which was farmer's practice compared to the CRT plots where ridges followed the contour line. This practice of up and down ridging does not create any kind of resistance to runoff flow, facilitating faster flow of excess water leading to high runoff amounts. This water loss is detrimental to agricultural production because, it reduces availability for crops and can result in severe moisture shortage during dry spells occurrences which are the cropping season characteristic in the area. These results agreed with other findings [5] [18] [53] who have pointed out significant water losses due to runoff in semi-arid lands. Runoff reduction was 46% in our study and agrees with the findings of [21] who reported that the main roles of CRT were capturing and recycling precipitations in treated fields. Also, CRT assists to the evacuation of excessive rainfall and surface fluxes destructive that can trickle into the fields as its application reduced rain runoff from 22% to 61%.

Mean runoff coefficient was higher in 2016 than 2017 for both sites. This situation can be attributed to rainfall difference between year and rain erosivity, in agreement with those reported by [53] when studying runoff in southern Mali.

4.4. Effect of CRT and NoCRT on Erosion

Mean soil loss was two folds greater in NoCRT plots than CRT ones where the difference was statistically significant ($p = 0.02$). Similar observations were reported [54] in Sri lanka and in southern Mali [5]. CRT reduced soil erosion in cultivated land by reducing the erosive power of runoff intercepting and its speed [55]. These results support CRT use in cultivated fields to ensure soil conservation. Erosion varied greatly between the two experimental sites. These findings agree with those of many scientists [56] [57] who have widely reported the spatial variation of erosion when studying soil erosion and restoration in Mali and Burkina watersheds, in the semi-arid areas of West Africa. The fact that erosion was greater in Bougouni than in Koutiala can be attributed to 39% higher rainfall amount obtained in Bougouni. Soil loss was also greater in 2016 than 2017 but no year showed erosion above the tolerable limit of 2.5 $t \cdot ha^{-1}$ and 12.5 $t \cdot ha^{-1}$ reported by several researchers [57] [58] [59] [60]. This can be attributed to rainfall amount and aggressivity for Koutiala and Bougouni as mentioned by [61] in similar agro-ecological zone of Burkina Faso. Also, soils of the studied area were both sandy and low in organic matter (**Table 1**) resulting to weak surface structure, then leading to runoff and erosion by surface sealing as similarly reported by [39] for sandy soil of United Kingdom. Our results support the recommendation of organic manure to improve soil surface structure for saving agricultural land from erosion. Globally, the use of CRT reduces runoff velocity and rainfall energy resulting in runoff and soil loss decrease in cultivated lands as supported by [62] who mentioned that a small reduction in runoff velocity can substantially reduce the amount of transported material. These results corroborated with the findings of many researchers [5] [21] [56] [57] [60] [63] [64].

4.5. Effect of CRT and NoCRT on Nutrient Loss

In NoCRT plots, a large amount of organic carbon, nitrogen, phosphorous and exchangeable bases, vital plant nutrients, were annually lost through eroded sediments, compared to the CRT ones. This situation can be explained by the serial disposal of narrowly spaced ridges (0.6 - 0.70 m) and furrow between ridges, which allow rainwater to be retained where it falls, resulting in better infiltration and remarkable slowing down or stopping runoff, erosion and nutrients losses. Higher nutrient loss in farmer's practice (NoCRT) and reduced nutrient loss in CRT plots in the fields on gentle slope (1% - 3%) is in line with earlier similar studies on CRT [57] [60] [63]-[68]. Carbon, nitrogen and phosphorus were at least two folds greater in the NoCRT plots than the CRT ones. This can be explained through the work of [67] who reported that about 95% of the soil nitrogen and 25% to 50% of the phosphorus are contained in the soil organic matter and a large amount of it is found in the soil surface as decaying leaves, stems and other fine organic particles, facilitating erosion and nutrients losses. This relation among phosphorus, carbon and nitrogen were well explained [69] who mentioned that the loss of soil organic matter was often followed by a corresponding loss of nitrogen. This situation is detrimental for agriculture since several soil quality indicators such as infiltration, water retention capacity, aggregate stability, cation exchange capacity (CEC), nutrient availability to plants are tightly related to organic matter and well documented [6] [52] [70] [71] [72]. Moreover, organic carbon lost from agricultural land could be released as inorganic carbon and increase quantity of greenhouse in the atmosphere. Otherwise, concerning phosphorus, farmers in the area annually apply cotton complex fertilizer composed of nitrogen, phosphorus, potassium, sulfur and boron corresponding to NPKSB (14-22-12-8-1) at the rate of 150 $kg \cdot ha^{-1}$, buried in the soil surface using animal traction. Therefore, increasing runoff may increase phosphorus amount in eroded soil since the concentration is high in the upper soil layer as reported by [73] who concluded that 80 percent of eroded P were transported in surface runoff from most cultivated land during flow events. Similar findings were mentioned by several authors [74] [75] [76] [77] when reporting on factors affecting nutrient losses.

It was observed that higher quantities of carbon, nitrogen, calcium, potassium, phosphorus and magnesium were lost in eroded soil in 2016 compared to 2017. This could be attributed to higher and severe rainfall events in 2016, where, for instance, in Flola, 31 July and 07 August rains produced 60 mm and 70 mm corresponding to I_{30} of 67- and 75-$mm \cdot h^{-1}$, respectively. For Mpessoba, in 2016, 21 July and 07 August rains produced 76 and 65 mm corresponding to I_{30} of 80 and 72 $mm \cdot h^{-1}$, respectively. Additionally, in Flola, 32 rain events producing runoff were recorded in 2016 against 19 in 2017. For Mpessoba, the number of rain events was almost the same (21 in 2016 and 22 in 2017) but rain intensity and quantity were greater in 2016.

4.6. Soil Moisture Content and Storage

In Mpessoba and Flola, soil moisture was always higher in the CRT plots compared to the NoCRT ones. CRT technology is applied to reduce runoff, which therefore increases infiltration and soil moisture as demonstrated by the work of [18] who, for instance, reported an average moisture difference of 25% at 60 cm depth when comparing CRT and NoCRT, plots. In fact, CRT plots benefited from rain water captured as reported [21] who mentioned that CRT increased soil moisture in areas explored by plant roots by 16% to 64% compared to NoCRT plots. At the end of the season, soil moisture was at least 25% on CRT plots explaining a real water supply potential for the park land trees as reported by [21] when assessing the effects of CRT on soil water dynamic in Siguidolo and Fansirakoro, in Mali. This finding also corroborated with [78] regarding assessment of farmers' perception on the effect of CRT in Cinzana (Mali) who showed that with the use of CRT, soil moisture was found to be better conserved and allowed field operations for an extended 7 to 10 days.

Water storage was always higher in CRT plots than the NoCRT ones in both sites. These observations were supported by [20] who reported 17% of water storage in CRT plots in the 80 - 160 cm profile horizons and 12.7% in the first 80 cm. Similar trend was mentioned [18] when studying the effect of CRT on soil moisture in a 60 cm soil profile in Sahelian area of Mali. They concluded that, 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 [18]. [19] [22] Also, this situation can be important for crops sown late in the growing season but also for trees to continue surviving during the dry and hot season when the maximum temperature may reach 46˚C.

4.7. Effects of CRT and NoCRT on Crop Yields

Significantly lower maize and sorghum grain and straw yields were obtained under NoCRT plots, a traditional cropping system [79]. Part of this trend explanation was the high amounts of runoff and erosion, which resulted in low moisture and nutrient availability for plant growth. These observations corroborated with several researchers' findings who reported that CRT allowed water accumulation which became significantly available for crop to accomplish its physiological processes of biomass accumulation and grain filling compared to e NoCRT plots [4] [5] [20] [22]. In related studies [64] [80] reported that CRT increases soil nutrients and available soil moisture for crop uptake and enhances crop growth and dry matter yield compared to the NoCRT plots.

Higher grain and straw biomass sorghum yields compared to the national average yield of 1000 kg·ha^{-1} of grains, could be attributed to growth and genetic characteristics of hybrid crop. In fact, improved varieties have a greater ability to convert assimilates to grain and biomass as reported by [18] when studying the effect of CRT on improved and local cereals varieties in Sahelian area of Mali. However, sorghum hybrid grain yields obtained in this study were lower than those reported by [81] in Mali which averaged 3500 kg·ha^{-1}. One of the explanations of higher yield reported by [81] could be sites difference since their trials were implemented in the ICRISAT Research Center at Samanko where all fields operations were under control.

The average maize grain yield of 2600 kg·ha^{-1} for the same variety reported by [82] in southern Mali fell within the range of 1729 to 2732 kg·ha^{-1} obtained in this study.

4.8. Novelty and Importance of the Study

This study, besides what has been mainly reported in Mali, combines determination of runoff, erosion, nutrient losses and crop yields at the same time. These data on soil and yield are strong decision-making tools for agricultural policies under rainfall conditions in Sub-Saharan Africa. Thus, farmers can increase crops grain yield by 50% and up to 87% for maize grain. For draught and fattening animals, there are gains of 116% and 70% for sorghum and maize straw yields, respectively. All these advantages were obtained when CRT was applied. Consequently, this study pleads for training of farmers, NGOs and extension agents on the contour ridge tillage technique for wide up scaling, targeting sustainable crop production through more water and nutrient conservation to mitigate recurrent drought.

5. Conclusion

This research results updated erosion and runoff data performed since the 1990s in Mali. The study highlighted threats related to nutrient and crop yield losses. Scientists can use these current data to advocate policy and lawmakers in reorienting strategies and efforts for food security. Current findings clearly showed that NoCRT, a farmer traditional practice, does not only increase water, soil and nutrient losses from farm fields, but also results in low maize and sorghum yields subsequent to its higher erosion, runoff and soil nutrients depletion. CRT, a soil and water conservation technology, provides lower water and nutrients losses, thus increases crops yield. Therefore, it became very important to undertake awareness and proactive CRT training of stakeholders, mainly farmers, NGOs and extension agents of Malian Agricultural Ministry to change its traditional practice in order to reduce farm runoff, erosion, nutrient and crop yield losses from agricultural lands. The CRT technology could be a good option in similar ecologies in other West African countries. This could be a motivation source for CRT adoption for food security with a great advantage for draught and fattening animals in Mali and beyond; allowing a better integration between crop and livestock production, a key strategy to sustain agricultural production in a climatically volatile environment.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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