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RESEARCH ARTICLE

IMPROVING SOIL AND CROPS PRODUCTIVITY USING CONTOUR BUNDING TECHNOLOGY SOUTHERN-MALI

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ABSTRACT

Watershed encompassing the lands of the villages of Kani and Noumpinesso (Koutiala) is highly active. Soils are severely degraded, leading to reduced crop productivity; indeed, water erosion is the primary cause of this disastrous phenomenon. In this area, tillage methods are ineffective for managing rainfall runoff and conserving soil. Contour bunding technology (CBT) is one of the best soil and water conservation technology. It can reduce runoff and erosion, increase soil moisture and nutrients, and consequently boost crop yield. Subsistence crops in this area include sorghum, millet, maize and cotton. Infiltration rate was higher in CBT plots compared to those managed using farmer practices, ranging from 5.02 to 2.52 cm/h and from 0.87 to 0.69 cm/h, respectively. The respective percentage of runoff coefficient in farmer practice plots were 34.89 to 38.79 % and were decreased by CB to 17.46 to 21.48 %. CBT has annually reduced runoff and erosion by 37 to 75 %; it has increased soil volumetric moisture content by 2 to 20 % at depths of 0 to 100 cm. The same technology has raised the groundwater level by 1.95 m at Noumpinesso. CBT significantly increased soil pH, total nitrogen, available phosphorus, exchangeable potassium, organic carbon and ECEC by 24, 63, 46, 40, 59 and 42 % respectively. It also significantly increased the yields of sorghum, millet, maize and cotton, by 68, 37, 52 and 52 % respectively. CBT significantly improved the physical and chemical properties of soil and crop yields. Future studies will evaluate nutrient uptake by crops using CBT.

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INTRODUCTION

Mali is one of the countries in Sudano-Sahelian zone of West Africa where the general decline in soil fertility is the major constraint on agricultural productivity; for watershed areas, this is even worse due excessive runoff and erosion. Runoff is detrimental to agricultural production because, on the one hand, it reduces water retention for crops and trees in fields and on the other hand, it can lead to soil depletion by stripping away the topsoil. In low-input agriculture in semi-arid zones like those of Mali, the development or improvement of rainwater harvesting techniques is essential to ensure the sustainability of production systems (Dembele *et al.,* 2021). In recent years, erosion, poor rainfall distribution, and population pressures have severely impacted the environment of the villages of Kani and Noumpinesso. Vegetation cover (trees and grasses) has decreased, with disastrous consequences for the bare soil. This phenomenon has affected the natural environment of many areas in Mali. This is the case in the areas of Kani and Noumpinesso, located in Koutiala region.

Erosion and agricultural activities that extract nutrients from the soil have caused severe soil degradation in these villages, threatening both human and animal food security. With the presence of watershed in the area, erosion is stronger and its consequences are more pronounced. For watershed management, CBT is being developed locally by the Institute of Rural Economy (IER) and CIRAD (Traoré *et al.,* 2012, Dembele *et al.,* 2022). Dembele *et al.* (2021) reported that CBT retains rainwater and improves the availability of water and nutrients for crops. The application of CBT can increase groundwater levels, soil organic matter concentration and soil nutrients according to several results (Traoré *et al.,* 2012; Birhanu *et al.,* 2018). The implementation of CBT in this context could be of great interest for improved management and utilization of rainwater; it enhances water and nutrient retention and contribute to maintain food security. Although the area receives substantial rainfall, much is lost to significant runoff. Efforts to address these issues have focused on evaluating the impact of tillage and soil and water conservation amendments on increasing crop yields. The implementation of CBT in the fields is simple, requiring only an ox-drawn plow after contour lines (backs) have been marked with stakes whose locations were determined using a topographic or water level. The cultivated ridges follow the contour lines, which helps retain rainwater, top soil, nutrients and promote infiltration. With CBT, water balance is improved, and the soil profiles are more humid, which promotes the development of crops and associated trees in the fields (Dembele *et al.,* 2021). During this study, farmers in the villages of Kani and Noumpinesso appreciated this technology because it is a simple and less expensive method, and the results are visible in the fields (soil moisture and crop yield). At this watershed area, soils are characterized by declining land productivity due to decreased low soil fertility caused by the strong erosion. Crop growth and development were significantly influenced by same technology at same villages (Maiga, 2015; Samake, 2017; Dembele *et al.,* 2021). Crop yields in fields using CAT were 40% higher than those without CAT in Mali (Dembele *et al.,* 2022). The general objective of this study is to determine the effect of CBT on soil physical and chemical properties for watershed management at Kani and Noumpinesso villages.

The specific objectives are

- Identify the effect of CBT on soil properties in watershed of Kani and Noumpinesso
- Determine the effect of CBT on crop yield in watershed of Kani and Noumpinesso

MATERIALS AND METHODS

Site Descriptions: The study area was Kani and Noumpinesso (Figure 1), Kani is closed Noumpinesso at 5 km. The geographic position of Kani is, at Latitude 12° 14' 43.23" North and longitude 5° 10' 57.94" West, the elevation is 384 m. They are located in Koutiala district in Sudanese zone. The essential characteristic is

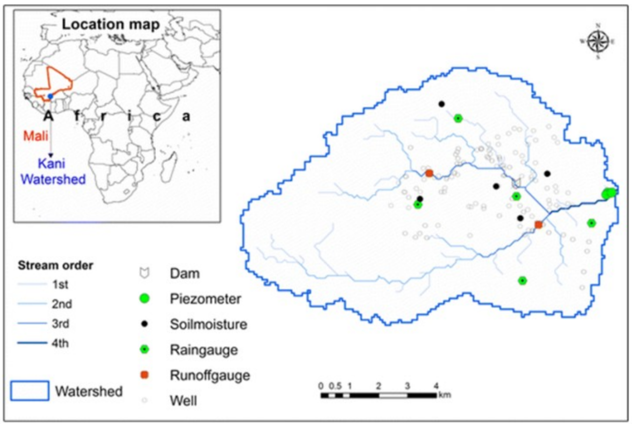

Figure 1. Watershed of Kani in southern zone of Mali at Koutiala Region (Birhanu *et al,* 2018)

Contour Bunding Technology (CBT) implementation: The topographic level allowed to fit out fields in contour bunding technology, marked by a graduated ruler and stakes. A field visit with each farmer helped identify watercourses and any erosion or excess water issues. The developed areas varied from one (1) to three (3) hectares per producer. The assessment with the farmers and the site level indicated the upstream edge of the field, from which we measured 25 meters into the field and marked the first stake. On the contour lines, we placed a stake approximately every 10 meters, and the distance between the ridges was approximately 50 meters. The ridges were made up with an ox-drawn plow after the first rains. The farmer made three or four passes with the plow to perform a main ridge (ado), lifting it with hoes. The ado is approximately 1 m wide and 0.5 m tall. Planting rows or ridges followed these main ridges for proper cultivation. Spontaneous grasses or shrub forage can be left grow on the top of ados to feed animals and strengthen the consistency of the system.

Measurement of bulk density and soil porosity: Cylinders of 100 cm³ density were used to collect soil samples from two pits previously described in Kani. Twenty-four soil samples were collected, twelve from each pit, and sent to the laboratory to determine the bulk density for each horizon. This activity was realized in two field at Kani before trials implementation.

Experimental design: The experimental design was paired with one part of field laid out in CBT and the other in farmer practice (control).

Soil infiltration measurement (double ring method): Infiltration allows us to determine and classify soils according to their permeability. Permeability is expressed as the amount of water that passes through the soil by percolation and is given by Darcy's Law. Large cylinder was driven 10 cm into the ground to allow for deep vertical infiltration of water and to maintain soil structure intact. Next, small cylinder was driven 5 cm into the center of the large one. A hammer was used to tap on the hard iron lid. A wooden board placed on the rings was also used to drive them vertically into the ground. After cylinders were positioned, water was poured into the large cylinder until it was full. Then, the small cylinder was filled in turn, and a graduated ruler was placed against its inner wall to measure the change in the water level. The infiltration time was timed, and each time the small cylinder emptied, it was immediately refilled. These infiltration measurements were carried out in both contour bunding field and control plots in two fields (replications). The collected data were analyzed and processed.

Runoff measurement device: Runoff device consisted of a diverter with 1/10 perforations and the following characteristics: a 40 cm long angled iron sheet to prevent diverted water from entering the reservoir, another 33 cm wide sheet, and a 60 cm long water supply pipe. Two graduated tanks (0 to 200 liters) and a 1.8 x 1 m cover sheet were also included, all placed in a pit 1.5 m x 0.7 m x 1.3 m deep. Data was collected over an area of 24 m². Runoff and erosion measurement equipment was installed in two fields (replication) located within the same landscape unit. For each replication, one device was installed in CBT plot and one in the plot of farmer practice. Both areas were managed uniformly with regard to all field operations and cultivated species. Data were collected after each rainfall event that caused runoff during two years. For erosion measurement, after each rain that has produced runoff, water collected in the tank is carefully mixed and three samples of 1 liter was taken. These samples are then sent to the laboratory for oven drying and sediment weighing.

Moisture measurement device: Moisture data was collected using a TDR probe at 10-day intervals. Data was collected in both developed and control plots and are displayed directly as volumetric moisture with four replications, two at Kani and two at Noumpinesso. Tubes of device were protected against children with padlocks.

Principle: Access tubes were installed in CBT and farmer practice plots for each replication, DELTA-T Devices "HH2 moisture meter" were used to read volumetric moisture with a PR2 profile probe and its protective base.

Moisture profile probe includes

Cables: HH2 meter is a cable that connects PR2 profile probe to HH2 moisture meter; DL6 is data logger and extension cable.

A connector: Fully waterproof, but protected with a cap when not in use.

Access tubes: (1m) exceptionally robust, thin-walled GRP tubes that can be reused multiple times.

Sensors: highly sensitive to soil moisture, but unaffected by temperature or conductivity (salinity). A detection field: a 60 mm extended tube is buried in the ground and tightly sealed with soil. The tubes are carefully installed to avoid air gaps.

A centering spring: an innovative combination ensures that the probe is perfectly centered for accurate readings.

Groundwater Dynamics measurement device: Groundwater level measurement devices were installed at Noumpinesso next the outlet of watershed. The PVC tubes of 6 m long and 10 cm diameter PVC uniformly perforated around their entire circumference were installed at downstream side in both CBT and control plots. A manual piezometer with an audible and visual signal, coupled with a 50 m graduated tape was used to collect groundwater data each week. The PVC tubes were protected from children by iron covers and secured with padlocks.

Crops (Maize, cotton, millet, sorghum): For cultivated data was collected in eight fields (replication) in which four at Kani and four at Noumpinesso. For each replication, four yield squares are placed in the CBT plots and four others in the control plots. The average of these yields is extrapolated to hectare for each plot to determine crops grain yield.

Collect of soil samples: Soil samples were collected after two years of experimentation. An auger was used to take samples from a depth of 20 cm. For each replicate, in both the CBT plots and the peasant farming plots, five samples were taken diagonally across the plot. The five samples were thoroughly mixed in a basin and placed in plastic bags. The plastic bags were labeled and taken to the laboratory for soil analysis. Cylinders of 100 cm^3 density were used to collect soil samples from two pits of 20 cm in which one in CBT plot and one in the control at Kani. For this purpose, 10 soil samples were taken, 5 from each pit, and sent to the laboratory to determine the bulk density for each horizon.

Calculation

Infiltration Rate: The average infiltration rate V = Q x 10 / ST where Q = water expenditure per cm^2, S = cross-sectional area in cm^2, T = time in minutes or hours.

Porosity

ad = Ms/Vc;

Where da = apparent density, Ms = mass of dry soil; Vc = volume of cylinder. Then, the porosity (P) as a percentage (%) was calculated using following formula:

P (%) = (dr – ad/ad) * 100

Where, ad = actual density (=2.65), da = apparent density

Runoff Coefficient (RC)

RC= (Runoff Depth) / (Precipitation Depth) * 100

Rainfall and runoff volume measurements taken on the plots for each rainfall event of the season allow us to calculate:

- runoff depth, denoted RD, expressed in millimeters, corresponds to the amount of rain that did not infiltrate the soil. Its value is calculated from the runoff volume measured in barrels.

RD = (V (m^3) x 10,000 m^2) / (Plot Area)

The runoff coefficient, denoted RC, is expressed as a percentage and represents the proportion of rainfall (P in mm) that did not infiltrate the soil.

RC = RD / (Rainfall (mm)) x 100

From the total rainfall measured during the season and the sum of all RD values, an average annual runoff coefficient (KRAM) is calculated.

TRM = RD * 100 / Annual P
Annual P and RD are in mm, TRM is in %
The highest measured RC value during the season is noted as RC max.
Furthermore, examining the runoff depths from the beginning to the end of the season allows us to determine the critical rainfall depth that triggers runoff.

Data Analysis: Data were analyzed using GENSTAT software version 12 (GenStat Release 12.1 (PC/Windows Vista) Copyright (2009)). Analysis of variance was used to evaluate the agronomic performance of treatments, and comparisons of means were performed using the smallest significant difference (SSD). Excel was used for intermediate calculations and graphs.

RESULTS AND DISCUSSIONS

Bulk Density and Porosity: Density is 1.86 in the control plot and 1.56 in CBT plot. The average porosity of soil horizons is 31.13 % in control plot profile and 41.13% in CBT plot. These results show that density and porosity varied according to the horizons in different soil profiles, depending on their position within tillage system. Density is higher in 0-20 cm profile of control plot than in CBT plot. In the control plots, soil is more compacted due to significant erosion; whereas in the CBT plots, water is stored and infiltrated into the soil, resulting in less compaction. CBT technology increases soil moisture and may promote microbial activity, which increases soil porosity. Microorganism activities in soil were increased responding positively to soil moisture contents (Luis *et al.,* 2020)

Tableau 1. Density and porosity measured in the experimental plots at Kani

Soil pits	Density		Porosity (%)	
Horizons	Profile Control	Profile CBT	Profile Control	Profile CBT
1	1,86	1,56	31,13	41,13

Soil infiltration rate: Analysis of data collected in the experimental plots shows that infiltration is greater in CBT plots compared to those treated in farmer practice, at approximately 2.52 cm/h and 0.69 cm/h, respectively. The low permeability observed in control plot is due to a massive, compact structure with high overall porosity. Permeability is also linked to soil structure, which has been improved by CBT technology.

Tableau 2. Effect of CBT on soil infiltration rate

Tillage	**CBT**	2.52 cm /h	Medium
	Control	0.69 cm /h	Low

Runoff and Runoff Coefficient: The amount of runoff was consistently higher in CBT plots than in farmer practice plots during both years of research. The highest runoff was observed after heavy, frequent, and intense rainfall, due to soil saturation by rainwater and its low infiltration rate. The highest runoff was measured in July and August during both years of research. During this period, rainfall was more frequent and intense, while soil was saturated, thus reducing the infiltration rate. CBT reduced runoff by 37.5 % at the first year of the research in Kani watershed. During the second year of the research, CBT was even more effective, reducing runoff by 48.5 %. CBT not only reduces erosion but also reduces runoff by storing rainwater between ridges that follow contour lines. CBT technology has been adopted and has demonstrated soil conservation through its ability to reduce surface water. This significant rainwater retention is partly due to ridge placement system, which helps ridges effectively reduce runoff velocity. Our results corroborate those of Farahani *et al.* (2016), who reported that CBT technology reduced runoff by 32 %. Maiga (2015) measured the highest runoff rates in plots using traditional farming practices compared to those using CBT. In the first year, runoff coefficient was 37 % in the control plots and 21 % in CBT plots. In the second year, it was 35 % in control plots and 17 % in CBT plots. Runoff coefficient is directly related to the amount of water runoff following a given rainfall amount, CBT technology appears to significantly reduce runoff coefficient. Our results are similar to those of Traore and Birhanu (2019), who noted that the average runoff coefficient in the control plots was 35.62 % compared to 19.25 % for CBT plots at Bougouni and Koutiala.

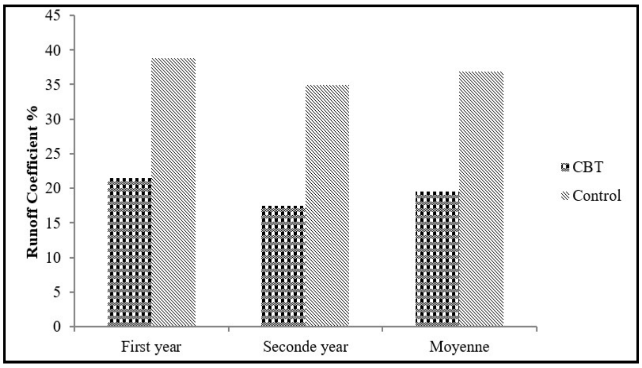

Figure 2. Effect of CBT on runoff coefficient at Kani, 2022 and 2023

Effect of CBT on Erosion: The same trend observed for runoff was observed for erosion. CBT technology reduced soil loss compared to farmer practices for all the experimental fields during the two years of research. CBT reduces soil erosion in cultivated fields by decreasing the erosive power of runoff and its acceleration rate (Birhanu *et al.,* 2018). This technology is effective in reducing runoff in fields and also contributes to reducing gullies and rills. Soil erosion rates of 53,078 kg ha^{-1}/year and 16,702 kg ha^{-1}/year were observed in the control plots and CBT plots respectively. In CBT plots, erosion was on average two to three times lower than in farmer practices plots; it was reduced by 67 %. Our results corroborate those of recent findings by Traore *et al.* (2017) and Birhanu *et al.* (2020), which confirmed that the application of contour tillage significantly reduced runoff in fields and consequently decreased erosion by 73 %. Containment strips (ados) act as filters that slow flow velocity, reducing runoff competence and thus the deposition of coarse sands and organic matter, while allowing for increased infiltration. Our results corroborate those of FAO (2017), which reported that CBT is twice as effective as simple contour plowing; it reduces erosion by approximately 30 % compared to the control plot worked on flat terrain for slopes of 1 to 8 %.

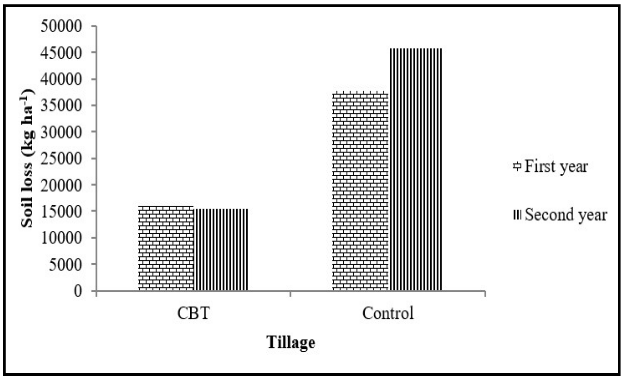

Figure 3. Effect of CBT on the variation of soil loss at Kani, 2022 and 2023

Soil moisture: For soil moisture analysis, the dates were chosen to represent the beginning, the middle and the end of rain season at the second year of research. At Kani and Noupinesso soil moisture was always higher in the CBT plots than the control plots and the difference was higher from August to the end of October when the rain was frequent and heavy. At August at Noumpinesso, the maximum moisture of 37.7 % in CBT and 34 % in farmer practice was observed in the 100 last cm of soil deep. For the other levels (10 to 90 cm) water content increased from the beginning at the end of the season and attain 19.8 % for CBT and 15.5% for Control. At the end of the rainy season (10^{th} October), CBT increased soil water content in the soil profile at 100 cm from 21 to 36 % (figure 5). After the retention and concentration of rainwater by ridges and ados, CBT increased water infiltration, resulting in deeper percolation and greater moisture retention. Our observations corroborate those of Maïga. (2015), Dembele *et al.* (2022), who reported that, soil moisture was significantly greater in CBT plots than control plots at the horizons of 1 m.

Effect of CBT on groundwater dynamic at Noumpinesso: With two groundwater level measurements taken in a CBT plot, two in the control plot, and one at the outlet; in the second year of research, the distance from groundwater to soil surface varied.

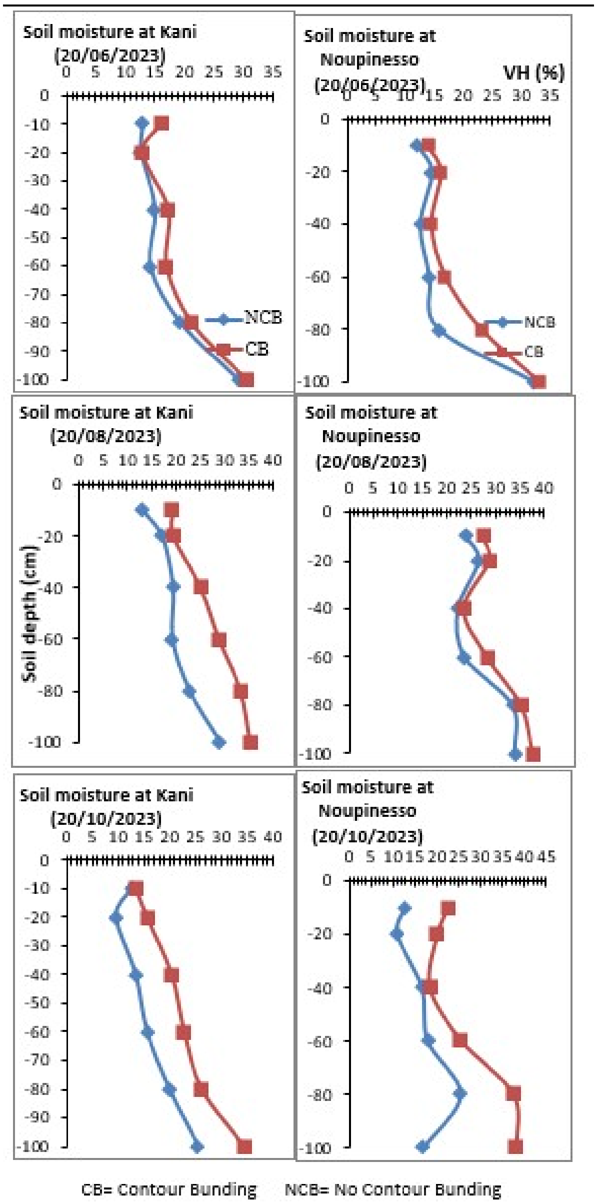

Figure 4. Vertical distribution of soil moisture at Kani and Noumpinesso, 2023

A minimum of 1.52 m in the tube near outlet, 3.11 m in CBT plot, and 5.08 m in the farmer-managed plot at the beginning of September and October. After this period, groundwater level gradually decreased, reaching 1.62 m in outlet, 3.36 m in CBT plots and 5.13 m in farmer practice plot at November (Figure 18). Over the two years of research, groundwater level was high from August to October, and thereafter the level gradually decreased at all monitoring points. During this period of year, rainfall is more abundant and frequent, leading to increased water infiltration to recharge groundwater. In this area, the maximum rainfall is observed in August, which increases infiltration and groundwater level. Futura (2019) reported that groundwater level varies according to infiltration and rainfall. Infiltrated water increases soil moisture and consequently recharges the groundwater. If rainfall is not continuous or another source of recharge is not available, groundwater level gradually decreases due to strong percolation and evapotranspiration. The USGS (2019) observed that groundwater levels depend primarily on recharge through rainfall infiltration and that drought negatively impacts groundwater levels. CBT is a system for significantly reducing runoff in fields, increasing infiltration and percolation. The application of CBT leads to the accumulation of rainwater in furrows by the strips, which reduces runoff velocity and increases infiltration (Liu *et al.,* 2014). Groundwater recharge is mainly linked to surface water infiltration, the extent of which varies depending on tillage practices. The use of simple technologies can increase infiltration, temporarily maintain water at the soil surface, and enhance infiltration (Rao and Singh, 2016) and groundwater recharge. Rao and Singh (2016) observed that soil and water conservation practices improve soil porosity, increase infiltration and hydraulic conductivity, and consequently increase soil water storage.

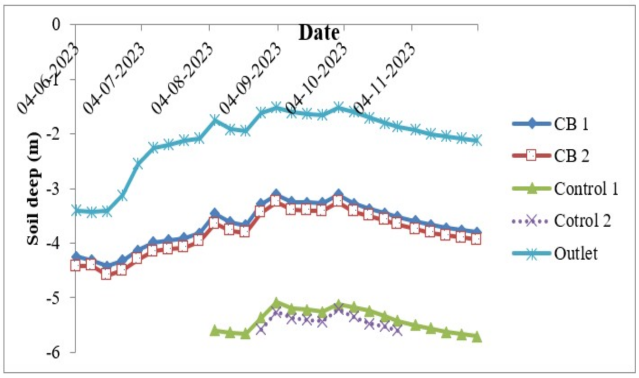

Figure 5. Effect of CBT on water table dynamic in 2023

Effect of CBT on soil chemical properties at Kani and Noumpinesso: Soil chemical parameters were significantly improved by CBT in watershed management at Kani and Noumpinesso. Soil Ph, assimilable phosphorus, exchangeable potassium, total carbon, total nitrogen and ECEC were 6.08, 4.12 ppm, 2.160 100mq/g, 0.4920 %, 0.0520 % and 4.100 cmolc kg-1respectively in CBT plots, the same parameters were 4.92, 2.82 ppm, 1.540 100mq/g, 0.3100 %, 0.0320 % and 2.880 cmolc kg respectively in farmer practice plots. CBT allow to increase topsoil in the fields, increase soil moisture and microbial activities. That contribute to mineralize structural organic and nutrients. Soil conservation tillage preserve topsoil in the field and mitigates the loss of essential nutrients contents into soil (Sairam *et al.,* 2023). Our results corroborate with which of Masri *et al.* (2026) when contour technology moderate increase soil chemical properties at 0-15 cm depth in northwest Syria.

Effect of CBT on the main crops (Millet, sorghum, maize and cotton) at Kani and Noumpinesso: In ten (10) fields at Kani and Noumpinesso during the two seasons of research, CBT technology significantly ($p<0.05$) increased crops yields. Millet, sorghum, maize and cotton grain yields were 2185, 2136, 2929 and 2657 kg ha^{-1} respectively in CBT plots and 1301, 1405, 2131 and 1753 kg ha^{-1} in the control. For crops straw yield 7857, 6254, 6254 and 4083 kg ha^{-1} were observed in CBT plots; also 5036, 4231, 4231 and 2663 kg ha^{-1} respectively were weighed in farmer practice plots (Table 6). For sustainable soil productivity, CBT is recommended as one of the best soil and water conservation techniques. The technology is adopted in Mali due to its effects of increasing crop yields through water retention efficiency and nutrients availability to crops (Traoré and Birhanu, 2019). ACN technology was adopted for improving soil moisture in the root zone and increasing crop productivity by 15-20 % (Rao and Singh, 2016). According to Traoré and Birhanu (2019), runoff and sediment loss was significantly reduced in CB fields.

Table 3. CBT on soil chemical properties in watershed management

Soil chemical parameters	Tillage		Statistic information			
	CBT	Control	F. Pro	CV	Standard deviation	General average
Ph	6.08	4.92	<.001	6.2	0.214	5.50
Assimilable phosphorus (ppm)	4.12	2.82	<.001	9.9	0.216	3.47
Exchangeable potassium 100mq/g	2.160	1.540	0.004	13.0	0.1523	1.850
Total Carbon (%)	0.4920	0.3100	<.001	6.5	0.03817	0.4010
Total Nitrogen (%)	0.0520	0.0320	0.005	19.9	0.00529	0.0420
ECEC (cmolc kg^{-1}	4.100	2.880	<.001	8.3	0.1292	3.490

Table 4. Effect of CB on sorghum, millet, maize and cotton grain yield and economic profitability

Crops grain yield (kg ha^{-1})				
	Sorghum	Millet	Maize	Cotton
Tillage				
CBT	2185	2136	2929	2657
Control	1301	1405	2131	1753
F.pr (0.05)	0,001	0,014	0,004	<,001
Standard deviation	246,9	272,2	223,5	176,5
Mean	1743	1771	2530	2205
CV %	37,5	36,0	16,5	20,4

Tableau 5. Effect of CB on sorghum, millet, maize and cotton straw yield

Crops straw yield (kg ha^{-1})				
	Sorghum	Millet	Maize	Cotton
Tillage				
CBT	7857	6254	6254	4083
Control	5036	4231	4231	2663
F.pr (0.05)	0,007	0,003	0,003	<,001
Standard deviation	956,8	595,5	595,5	302,4
Mean	6446	5242	5242	3373
CV %	39,3	26,6	26,6	22,9

It is one of the effective and vital soil moisture conservation techniques for small cropping systems (Birhanu *et al.,* 2018; Traoré and Birhanu 2019; Dembele *et al.,* 2021). The moisture retained by the technologies provides water to crops at the end of the rainy season when at crops flowering and grains formation stage.

CONCLUSION

This study demonstrated that contour bunding technology (CBT) is an effective soil and water conservation practice for watershed management in the degraded agricultural landscapes of Kani and Noumpinesso in southern Mali. The technology significantly improved soil physical properties by reducing bulk density, increasing porosity and infiltration rate, and enhancing soil moisture throughout the soil profile. It also substantially reduced runoff, runoff coefficient, and soil erosion, while contributing to groundwater recharge. Beyond its hydrological benefits, CBT significantly improved soil fertility by increasing soil pH, organic carbon, total nitrogen, available phosphorus, exchangeable potassium, and effective cation exchange capacity. These improvements translated into significant increases in the grain and straw yields of the main crops cultivated in the area, namely sorghum, millet, maize, and cotton, demonstrating the agronomic and economic potential of the technology for smallholder farming systems.

Overall, contour bunding technology represents a practical, low-cost, and sustainable solution for restoring degraded watersheds, improving soil health, enhancing water use efficiency, and increasing crop productivity under rainfed conditions in southern Mali. Its wider dissemination and adoption could contribute substantially to strengthening climate resilience, improving farmers' livelihoods, and enhancing food security in the Sudano-Sahelian region. Future research should investigate the long-term impacts of CBT on soil carbon sequestration, nutrient dynamics, groundwater recharge, and its economic performance under different agroecological conditions.

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