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Effects of Indigenous Cultivation Practices on Soil Conservation in the Hilly Semiarid Areas of Western Sudan

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Abstract: In dry regions, it is customary for farmers to use soil water conservation and/or water harvesting techniques. These practices have now become applicable to agriculturalists combating the adverse effects of drought on food production. In the semiarid areas of Zalingei in western Sudan, we quantified the soil erosion using traditional conservation measures, and conducted experiments in two consecutive rainy seasons (2013 and 2014). A split-split plot design was used to quantify the respective influences of each variable on reducing soil erosion: A) three gentle gradients (Slope1 (0.98%), Slope2 (1.81%), and Slope3 (3.1%)); B) two cropping systems (mono-crop and mixed-crops); and C) five indigenous conservation tillage practices—chisel ploughing (CHP), cross slope tied bonding (CSTB), contour ridge with stone bonds (CRSB), cross slope bonding (CSB), and zero tillage (ZT). Our results showed that there were significant differences between the slopes in season 2 (2014); the soil eroded at Slope3 was more than that of Slope1 and Slope2 by 71% and 27%, respectively. Over two seasons, there were no significant differences between the cropping systems. Conversely, the erosion level observed with CHP was higher than with the other practices. However, the CSTB and CSB erosion levels were only higher in season 2 when compared with those of CRSB and ZT. The study concluded that under the above conditions, the rate of soil erosion was severe and exceeded the erosion tolerance. Based on these results, in western Sudan, CRSB and ZT may be the more effective indigenous conservation practices for the protection of agricultural soils and productivity.

Keywords: conservation tillage; soil conservation; farming systems; soil erosion

1. Introduction

The level of soil degradation is increasing globally and is linked to an increasing risk of drought [1]. The growing human population faces increased pressure on its food supply, which is compounded by the limited availability of agricultural lands. To address these issues, the productivity of existing arable lands must be increased via better water use efficiency and soil conservation practices. [2]. Moreover, climate change is also predicted to increase the incidence and severity of droughts in semiarid regions [3,4].

The erosion of agricultural soils has long been a global environmental concern [5–8]. Also, soil erosion is considered as one of the significant environmental problems worldwide due to its effects on water quality, soil productivity, and ecosystems [9]. Rain flood erosion in agricultural lands strips the fertile topsoil on-site in arid and semiarid regions.

Soil loss is often triggered and accelerated by poor or non-existing soil conservation practices promoting the transport of sediments and potentially hazardous pollutants via runoff to rivers and streams [9,10]. In rainfed areas, the on-farm management of soil and water plays a critical role in achieving the full potential of soil conservation and water use [11,12]. It is important to design conservation measures and strategies that are effective in controlling such soil losses on the Earth [5].

Reasonable cultivation patterns combined with rainwater harvesting techniques can improve the management of degraded lands, which eventually leads to the sustainability of production, greater certainty, and lower marginal inputs [13]. One type of soil conservation practices that are commonly used are conservation tillage practices (CTPs), which aim at no-tillage, little tillage, and cover crops [14]. Other traditional or modern agricultural operations are used in conjunction with CTPs to reduce farmland degradation and to increase land productivity [15,16]. In developing countries, the land is commonly fragile and degradable with poor vegetation as a result of the influence of frequent fires, tree logging, and free grazing [17,18].

On top of these challenges, the area may suffer from climatic changes [18], rainfall fluctuations and the rapid advancement of the Sahara Desert. As a climatic adaptation strategy, rainfed, smallholder cultivation of grain crops is the predominant agricultural system in the hilly areas, where the terrace system is an interesting practice among indigenous water harvesting systems [19]. However, the most effective method in conserving the soil surface is not well studied and reported so far in this area. Knowledge about the reduction in water and soil losses due to the practice of the terrace system is very limited in developing areas. Whether this traditional irrigation system helps in improving soil characteristics, crop production, and biodiversity richness in the area is also insufficiently quantified.

Arid and semiarid areas account for about 60% of the national land in Sudan and account for approximately 8% of the world's semiarid tropical regions [18]. They are usually characterized by an unprotected soil surface, especially in clay areas, through which high-intensity rainfall cannot be infiltrated and thereby discharged dominantly by the surface runoff process [20]. From these perspectives, this study aims to: (A) evaluate the effect of the cultivation practices on the soil erosion; (B) understand whether the cropping system affects water erosion, and (C) recommend suitable field operations.

2. Method and Materials

2.1. Study Site

The field experiments were carried out during two consecutive seasons (2013 and 2014) at the experimental field of the University of Zalingei, western Sudan (between latitudes 12°30′–13°30′ N and 23°30′–23°45′ E) in the semiarid zone of North Africa (Figure 1).

This is a mountainous area, where there are different types of waterways due to the land undulation, and large water streams (valley/wadi), streaming through from the Jebel Marra massif (approximately 100 km east of Zalingei) carrying fertile alluvial and volcanic soils [21]. The agriculture consists exclusively of small-scale family farms. Miehe [17] classified the soils of the area as Andosols with a bulk density of 1.32 g/cm^3. The climate is hot and rainy in the summer and harsh and dry during the winter. The average annual rainfall in Zalingei is approximately 600 mm/yr.; however, approximately two-thirds of it falls during July and August and about 90% from June to September, and there is very little or no rain from October to March [22,23].

The major crops for food are mostly grown during the rainy seasons (June to October) and include sorghum (*Sorghum bicolor*), millet (*Pennisetum glaucum*), and groundnuts (*Arachis hypogaea*), with vegetables mostly cultivated alongside the wadis' lowland and flood plains during the winter.

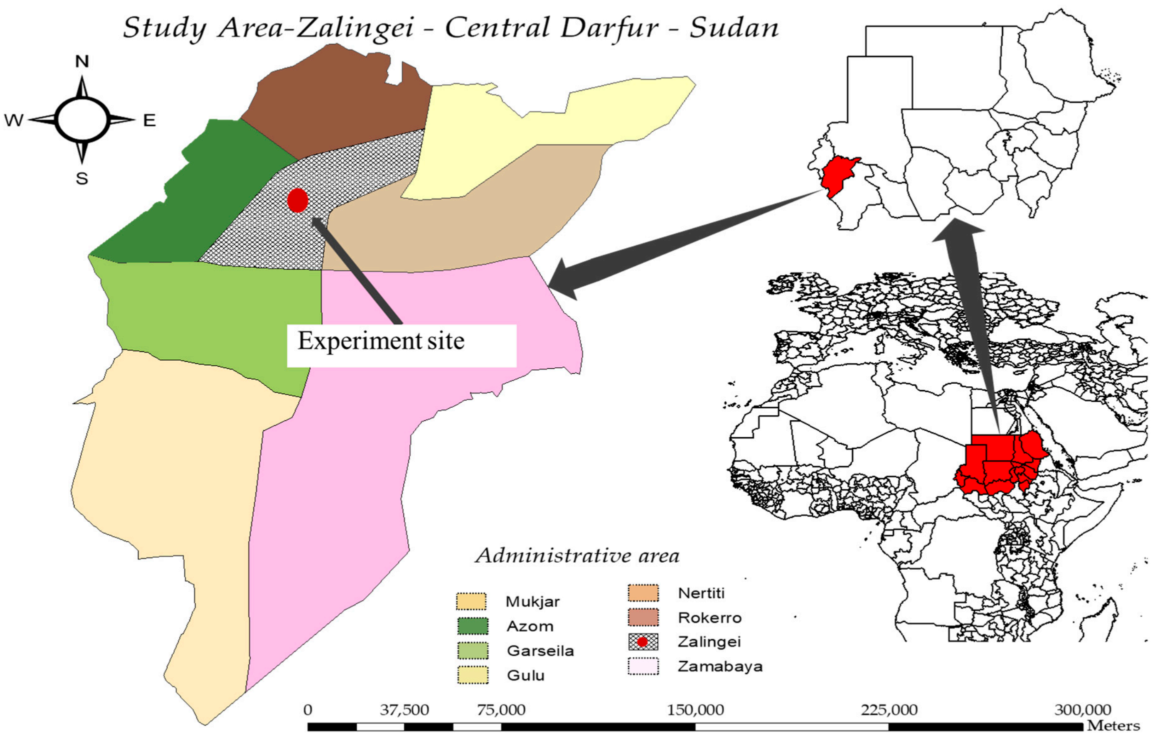

Figure 1. The study area, located in the semiarid zone of North Africa.

In the first rainy season (May–September 2013), the accumulation of rainfall was 542 mm, and it was 675 mm in the second season (June–October 2014); thus, the rainfall in the second season was 24.5% greater than in the first (Figure 2). The rain distributions were also varied, particularly during July and August of the second season, as a higher amount of rain precipitated, compared to that of the same period in the first season. To be exact, it was higher by 116.2% and 46% in July and August, respectively.

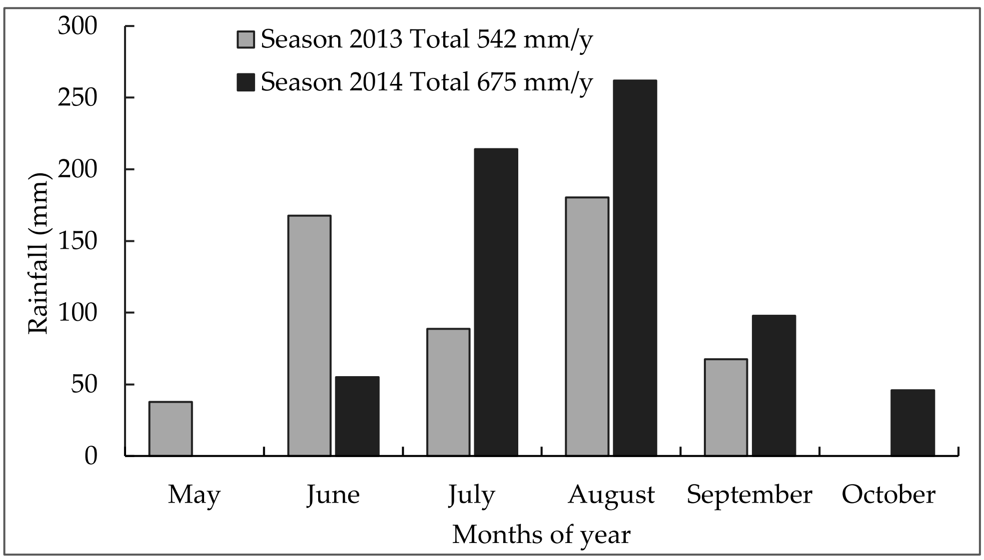

Figure 2. The distribution of the rainwater per month (mm/m) and the accumulation of rainfall in each of the growing seasons, Season 1 (2013) and Season 2 (2014).

2.2. Experimental Design:

In three-factor field trials, split-split plots, each with 3 replicates, were used to quantify the influence of the following factors on soil erosion control: slope, cropping systems, and indigenous conservation tillage practices. Thus, the field trial layout consisted of 90 plots, i.e., 3 whole plots × 2 subplots × 5 sub-subplots × 3 replicates. Three whole plots (each 35 m × 10 m), each with a different slope (S): S1 = 0.98%, S2 = 1.81%, and S3 = 3.1% (gradient measured by manual clinometer), were subdivided into 3 subplots (each 11 m × 10 m), each with a different cropping system (CS): mono-crop; sorghum and mixed crop; sorghum + groundnut. Each cropping type subplot was further subdivided into 5 sub-subplots (each 2 m × 5 m), each cultivated with a different conservation tillage practice (CTP): chisel ploughing (CHP), cross slope tied bonding (CSTB), contour ridge with stone bonds (CRSB), cross slope bonding (CSB), and zero tillage (ZT) (Figures 3A and 4).

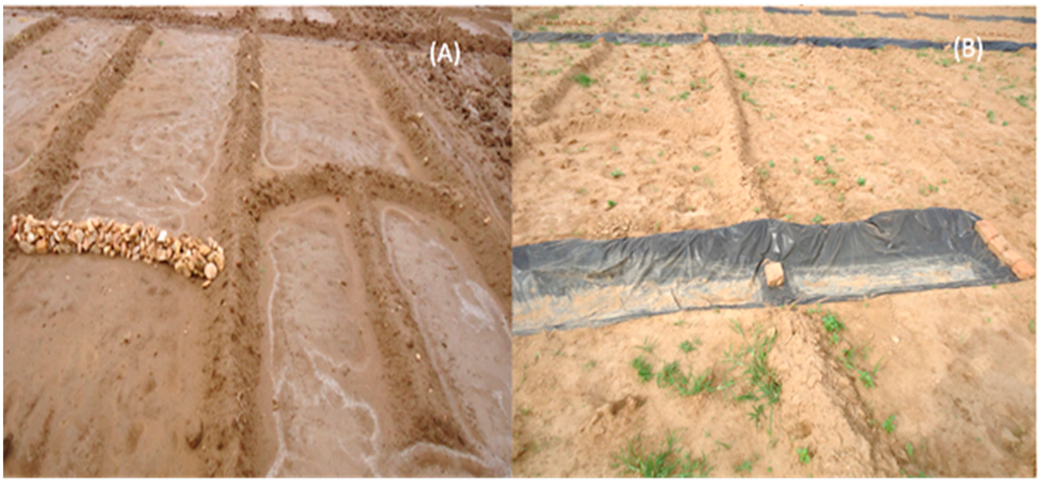

Figure 3. View of the prepared land of the experiment: (**A**) conservation tillage techniques; (**B**) collectors of soil particle deposits.

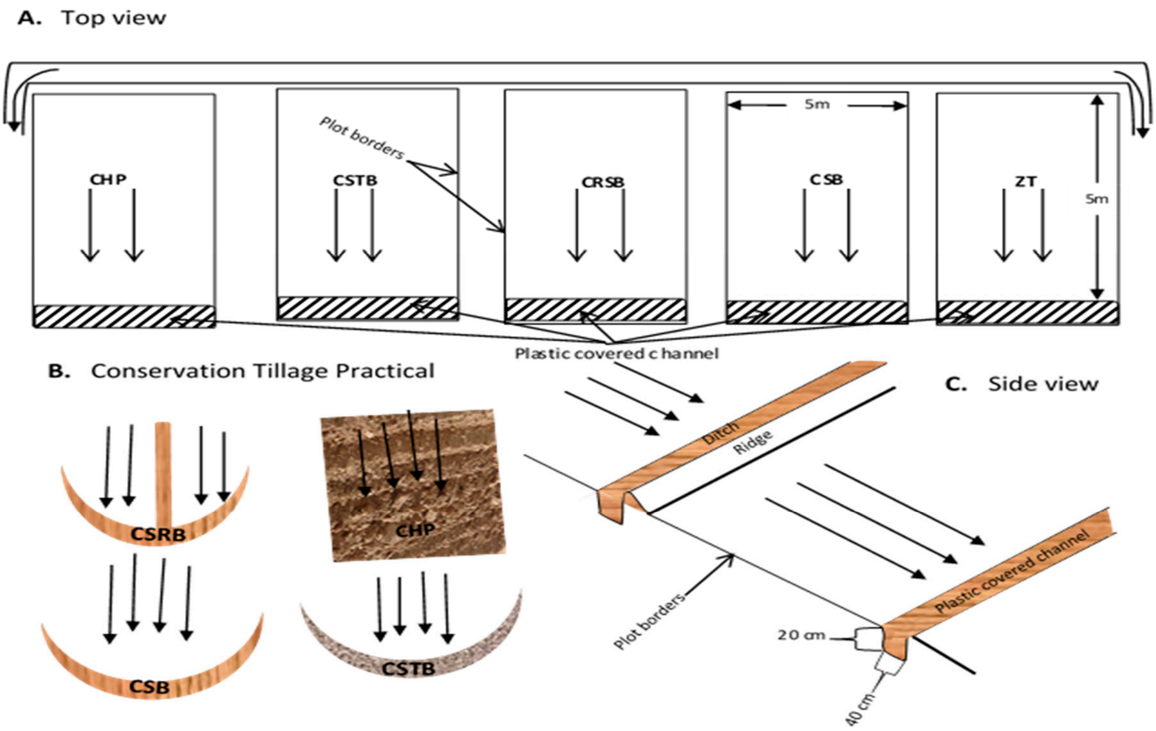

Figure 4. The field layout of the simple methodology to determine the effect of conservation tillage on soil erosion. Chisel ploughing, CHP; cross slope tied bonding, CSTB; contour ridge with stone bonds, CRSB; cross slope bonding, CSB; and zero tillage, ZT. Arrows are in the flow direction.

2.3. Measurement of Soil Losses:

A small ditch (40 cm wide and 20 cm deep) was prepared, covered with a plastic sheet at the bottom end of each plot to receive the deposit of soil eroded, and transported by rain force out of the plot (Figures 3B and 4). After at least one day of rain events, the soil deposit was carefully taken from the field to the lab, where the samples were dried in an oven at 70 °C until a constant weight was obtained. At the rainy season's end, the samples were weighed and the eroded soil mass per plot area was estimated.

2.4. Data Analysis

The procedure in Gomez and Gomez [24] was used for the analysis of variance (ANOVA) and all statistical analyses were performed using the SAS 9.4 software package (SAS Institute Inc., Cary, NC, USA). A least significant difference (LSD) of 5% probability was used in comparing the means of soil erosion for different treatment: (S), (CS), (CTP) (S × CS), (S × CTP), (CS × CTP) and (S × CS × CTP).

3. Results

3.1. Soil Erosion

There were significant differences in the mass of eroded soils among treatments with different land slopes in the second season (Figure 5A). However, the slope levels did not significantly affect the soil erosion in the first season. The cropping system factor also did not exhibit any significant variances among the treatment means over the two consecutive seasons (Figure 5B). The results showed differences as a result of the interaction between the land slope and the cropping system only in the first season (Figure 6A). The conservation tillage also significantly ($p \leq 5\%$) affected the soil erosion. There were no significant differences among treatments due to factor interactions over the two seasons: slope (S) × cropping system (CS) × conservation tillage practices (CTPs) (Table 1).

3.2. Effect of the Land Slopes and Cropping System

The slope factor clearly affected the magnitude of soil erosion, as we expected (Figure 5A). Only in the second season, S3 (3.1%) had significantly more eroded soil than S2 (1.81%); moreover, the masses of the eroded soil at the slopes were in the following order: S3 > S2 (by 27%), S2 > S1 (by 35%), and S3 > S1 (by 71%). However, there were no significant differences between S1 (0.98%) and S2 or S3 in the first season. The first season was unlike the second; the slope factor did not show any significant differences. The results did not show any significant differences between the mono- and mixed-crop systems (Figure 5B). Therefore, the two systems had no effects on soil erosion.

3.3. Effect of the Conservation Tillage Practices

The results in Figure 5C showed that the conservation tillage techniques in both seasons affected the soil water erosion significantly: in the first season, the CHP treatment differed significantly from CSTB and CRSB/CSB/ZT, whereas CRSB, CSB, and ZT were not markedly dissimilar from each other. In season 2, the soil loss measured in CRSB and ZT was significantly smaller than in the other three techniques. At the same time, the soil loss measured in CHP did not significantly differ from that in ZT; moreover, CSTB did not significantly differ from CSB. However, CHP and Z were not different from CRSB, but smaller than CSTB and CSB.

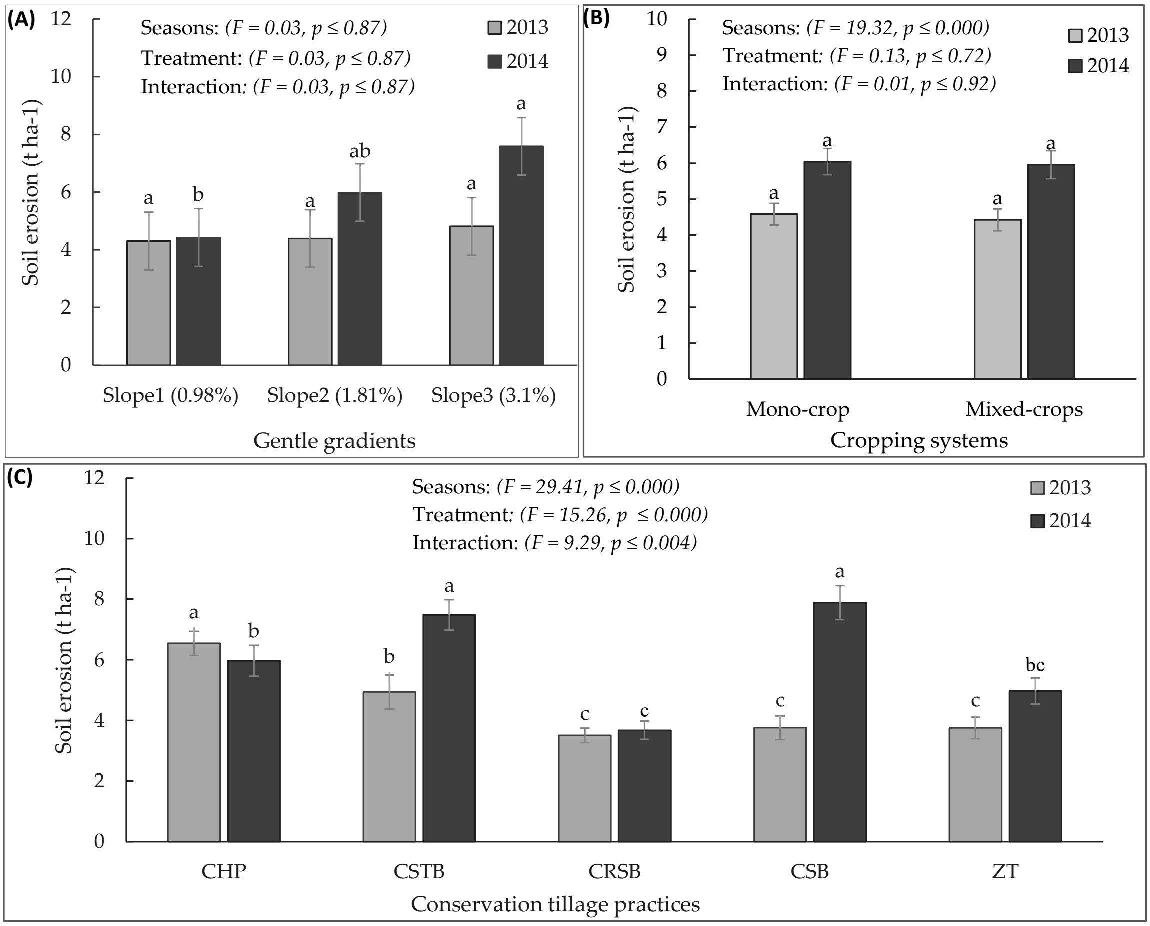

Figure 5. Effect of the slope (**A**), cropping systems (**B**), and conservation tillage practices (**C**), on eroded soil (t ha-1) for both seasons 2013 and 2014. Means followed by the different latter in same latter do not differ significantly at (LSD; $p \leq 0.05$).

3.4. Interaction of the Slope and Cropping System

There was a significant difference in the soil erosion due to the interaction between the slopes and cropping systems on the soil erosion (Figure 6A) in the two seasons. This difference was only significant between the cropping system and the 3.11% slope (S3). Other interaction differences were not significant. For the second season, unlike the first one, the results show considerable differences among all interactions between the two systems. the interaction with the 3.11% slope was higher than with the others.

3.5. Interactions between Cropping Systems and Conservation Tillage Practices

The mass of the soil erosion was significant affected by the interactions of the cropping system and conservation tillage techniques in the two seasons (Figure 6B). The interaction of the slope was highest with CSB and CSTB interaction and lowest with CRSB.

3.6. Effects of the Slope Combined with Conservation Tillage Techniques

Figure 6C shows the treatments with slopes and conservation tillage techniques together. Significant differences among means were seen over the two seasons. CSTP and CSB interaction with slope were the highest and CRSB was the lowest.

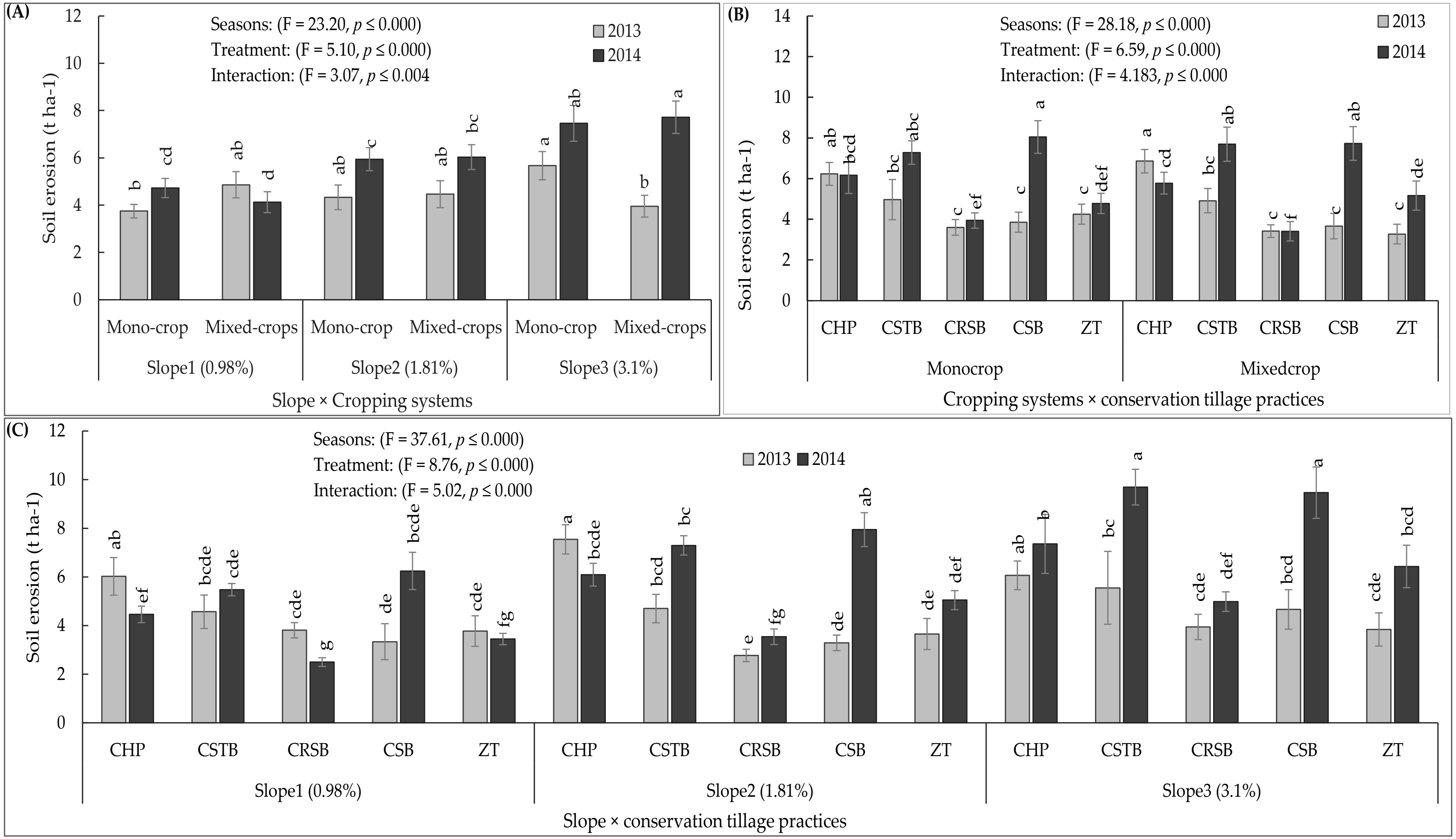

Figure 6. Interaction effects of (slope × cropping systems), (cropping systems conservation tillage practices), and (slope × cropping systems × conservation tillage practices) on eroded soil (t ha-1) for both seasons 2013 and 2014. Chisel ploughing, CHP; cross slope tied bonding, CSTB; contour ridge with stone bonds, CRSB; cross slope bonding, CSB; and zero tillage, ZT. Means followed by the different latter in same latter do not differ significantly at (LSD; $p \leq 0.05$).

3.7. Interactions of Slope (S), Cropping Systems (CS), Conservation Tillage Practice (CTP)

Table 1 shows that the effects of various levels of the three factors (i.e., the mixture of S, CS, and CTP) were insignificant.

Table 1. The combination of effects of slope, cropping systems, and conservation tillage practices on eroded soil (t ha-1) for both seasons 2013 and 2014.

Parameter			Conservation Tillage Practice (CTP)						
			CHP	CRSB	CSB	CSTB	ZT	*F*	*p*
Season 2013	S1	CS1	4.7 + 0.81	3.19 + 0.53	3.3 + 0.14	2.87 + 0.53	4.66 + 0.19	1.79	0.09
		CS2	7.35 + 0.78	5.94 + 0.46	4.32 + 0.46	3.8 + 1.5	2.89 + 1.07		
	S2	CS1	7.19 + 1.05	4.23 + 0.77	2.6 + 0.32	3.1 + 0.52	4.5 + 1.03		
		CS2	7.91 + 0.75	5.17 + 0.95	2.94 + 0.44	3.48 + 0.45	2.81 + 0.53		
	S3	CS1	6.8 + 0.47	7.47 + 2.39	4.91 + 0.5	5.6 + 0.34	3.57 + 1.21		
		CS2	5.32 + 0.99	3.63 + 1.33	2.99 + 0.39	3.73 + 1.51	4.11 + 0.91		
Season 2014	S1	CS1	5.16 + 0.09	5.78 + 0.39	2.87 + 0.07	6.25 + 1.16	3.55 + 0.37	0.52	0.83
		CS2	3.77 + 0.27	5.16 + 0.27	2.12 + 0.11	6.25 + 1.26	3.34 + 0.36		
	S2	CS1	5.55 + 0.75	7.42 + 0.64	3.91 + 0.52	7.92 + 1.08	4.9 + 0.46		
		CS2	6.63 + 0.5	7.17 + 0.61	3.17 + 0.33	7.97 + 1.13	5.2 + 0.73		
	S3	CS1	7.79 + 2.68	8.64 + 1.21	5.03 + 0.49	9.97 + 1.31	5.88 + 1.13		
		CS2	6.94 + 0.11	10.74 + 0.3	4.94 + 0.75	8.96 + 1.89	6.98 + 1.49		

Note: S1, S2 and S3: are 0.98%, 1.81% and 3.1% slope levels. Chisel ploughing (CHP), cross slope tied bonding (CSTB), contour ridge with stone bonds (CRSB), cross slope bonding (CSB), and zero tillage (ZT), mono-crop (CS1), mixed-crops (CS2).

3.8. Correlation Coefficients of Linear and Quadratic Relationships between Slope, Cropping System, Conservation Tillage Practical to the Soil Erosion.

The linear prediction equation of the slope, cropping systems, conservation tillage practices, and their interaction for the soil erosion (t ha^{-1}) results, in Table 2, showed that the R^2 value was very low. However, the lowest R^2 value of the linear prediction was recorded in the interaction of S × CS × CTP (0.23). The best fit in the regression was achieved when we used S, CS, CTP, and the interaction of S × CS, S × CTP, and CS × CTP in each linear relation (0.37).

Table 2. The linear prediction equation of soil erosion (t ha-1) using the land slope (S), cropping systems (CS), conservation tillage practices (CTP), and interactions (S × CS, S × CTP, CS × CTP, and S × CS × CTP) during the two growing seasons.

Equation	R^2	*p*
Soil erosion = 2.599 + 1.497(season) + 0.985(S) − 0.119(CS) − 0.417(CTP)	0.37	***
Soil erosion = 2.437 + 1.497(season) + 0.985(S × CS) − 0.201(S × CTP) − 216(CS × CTP)	0.37	***
Soil erosion = 1.94 + 1.497(season) + 0.069(S × CS × CTP)	0.23	***

Note: *** = The probability of variance significant level.

4. Discussion

Soil erosion occurs due to soil particle detachment, transportation, and sedimentation by erosion, such as water or wind. The problems caused by soil erosion can be both onsite and offsite, including nutrient lessening and limiting of crop production. As the topography affects these processes, the practices of CTP and CS also affect the soil erosion and crop production as a result.

Not only is the quantity of annual rainfall essential to removing the soil particles from the original place, but the number of events, rain intensity in each event, and raindrop characteristics are also crucial factors. The mass of heavy rain with larger drops is more powerful for detaching and transporting the soil. Steep topography, coupled with a relatively high rainfall during a short time, is another factor that, in the absence of appropriate measures for sustainable natural resource management, contributes to soil erosion and other types of land degradation.

The slope factor exhibited significant differences among the means in season 2, and this might be strongly attributed to high precipitation, especially during July–August. On the other hand, rainfall during the peak (July and August) in season 1 was relatively low; consequently, there were insignificant differences among the means. Regarding the slopes, the steeper land is more soil surface erodible; thus, for that reason, the deposits of S3 were approximately double those of S1.

Conservation tillage practices (CTP) strongly affected the soil erosion. This indicates that some of the CTP treatments had less soil erosion. The soil eroded by chisel plow in the first season was absolutely higher compared to the other CTPs. However, cross slope tied bonding and cross slope bonding were markedly higher erosion measures compared with a chisel plow, contour ridge with stone bonds, and zero tillage, although the Chisel Plow yielded higher soil erosion measures compared to zero tillage.

Stone CTPs such as CRSB were more resistant to erosion due to their potential for reducing the effect of the splash, and thus of particle detachment. Indigenous cultivation practices can improve the vegetative cover of an area and help halt environmental degradation (Figure 5). This can be an individual or community response to an environmental limitation. Indigenous cultivation practices provide a sound basis for improved resource management, reduced costs, and can provide people with tools for improving the farmland, and therefore improving their income and livelihoods (Figure 5).

If we adopt the fact that erosion tolerance standards in soil conservation planning are equal to 2.43 t $ha^{-1}yr^{-1}$ [25], the means of soil erosion in all the treatments were beyond these standards. Thus, the cultivation of cropland in this area needs more care to conserve the top-soil surface. The stone bunds used in the study area reduced the erosion more effectively than other practical methods. However, these results support the assertion that soil and water conservation measures (SWCM) effectively reduced the rate of soil loss, with stone bunds and mulching reducing the soil loss by 95% and 45%, respectively [26].

In general, the implemented CTPs and CSs assisted in the rehabilitation of degraded lands and significantly improved the groundwater by resisting the water flow, which resulted in higher soil moisture.

The dry areas are a very fragile ecosystem and they receive inadequate annual rainfall for economical dry farming. Natural vegetation and plants undergo severe moisture stress periods and during rainfall a great deal of soil was transferred and removed from the topsoil, which significantly increased the soil erosion. Part of the rain which flows as runoff usually forms erosive streams and results in severe soil erosion and land degradation. In the study area, the long-term average of the annual rainfall was 561.83 mm/yr. The main problem is that the area is characterized by compacted soils, sloped lands, and soil surface sealing, which are conducive to runoff. Consequently, the water depletion is reduced. There were great declines and variability in the amount and distribution of rainfall during the last three decades. This imposed a degree of uncertainty and initiated a positive response to the effective utilization of rainwater through the collection and storage of the surface runoff and direct rainfall into the root zones of plants.

5. Conclusions

Our experiment provides a clear picture of how the conservation tillage practices (CTPs) affect the soil erosion of three slopes (S), and two cropping systems (CSs) in the hilly semiarid areas of the study area. According to the results of the experiment, we concluded that the conservation tillage practices (CTPs) strongly affected the soil erosion, such as the contour ridge with stone bonds and zero tillage.

We found that the cropping systems (CSs) did not have significant effects; therefore, farmers need to apply more practices (i.e., CRSB) beside the CSs to conserve their land from soil erosion. We confirmed that the steeper the land, the more erodible the soil surface. The soil erosion due to cultivation practices in the study area is severe; therefore, the cultivation of cropland requires extensive conservation considerations, and the awareness of soil degradation must be increased substantially following intensive extension programs.

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