Scale effect on runoff and soil loss control using rice straw mulch under laboratory conditions

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ABSTRACT
Amendments can control the runoff and soil loss by protecting soil surface. However, scale effects on runoff and soil loss control has not been considered yet. The present study has been formulated to determine the efficiency of two plot sizes of 6 and 0.25 m^2 covered by straw mulch with rate of 0.5 kg m^{-2} in changing the time to runoff, runoff coefficient, sediment concentration and soil loss under laboratory conditions. The study has been conducted for a sandy-loam soil taken from summer rangeland, Alborz Mountains, Northern Iran under simulated rainfall intensities of 50 and 90 mm h^{-1} and in 3 replicates. The results of the study showed that the straw mulch had more significant effect in in reducing runoff coefficient, sediment concentration and soil loss at 0.25 m^2-plot scale. The maximum effectiveness in time to runoff for both the scales, observed in rainfall intensity of 90 mm h^{-1}. The maximum increasing and decreasing rates in time to runoff and runoff coefficient observed in the rainfall intensity of 90 mm h^{-1} with the amounts of 367.92 and 96.71% for 0.25 m^2-plot and the amounts of 110.10 and 15.08% for 6 m^2-plot, respectively. The maximum reducing in runoff coefficient was in 0.25 m^2-plot for two rainfall intensities of 50 and 90 mm h^{-1} with rates of -89.34 and - 96.71%. The maximum change of soil loss in both the intensities of 50 and 90 mm h^{-1} occurred at 0.25 m^2-plot with the amount of 100% whereas at 6 m^2-plot, decreasing rates of soil loss for in both the intensities of 50 and 90 mm h^{-1} were 46.74 and 63.24%, respectively.

Key words Hydrology Response, Plot Size, Rainfall Simulation, Stubble Mulch, Sediment Yield

INTRODUCTION
The soil erosion rates are accelerated by tillage and the low vegetation cover (Cerdà et al., 2009 and 2010). The population increase and growing demand for agricultural products (Prokop and Poręba, 2012; Zhao et al., 2013) or intensive dry land (Biro et al., 2013) has generated changes in land use and resulted in erosion and land degradation. There are various methods for soil conservation but biological methods in bare and degraded slopes need long time for establishment (Adekalu et al., 2007; Smets et al., 2008a). In this context, various natural and organic mulches viz. crop residues, leaf litter, woodchips, bark chips, biological geotextiles, gravel and crushed stones (Ruy, 2006; Smets et al., 2008a; Ruiz-Sinoga et al., 2010) have been applied for soil conservation. Mulches have extraordinary potential in soil erosion control (Morgan, 1986) and runoff reduction (Poesen and Lavee, 1991). However, establishment of degraded areas and bare slopes by vegetation cover takes long time (Adekalu et al., 2007; Smets et al., 2008a). The effect of mulches depends on many factors including raindrops erosivity, soil condition, steepness and length of slope, and the mulch rate and type (Amimoto, 1981; Cogo et al., 1984; Poesen and Lavee, 1991; Morgan, 1995; Auerswald et al., 2003; Adekalu et al., 2007; Kukal and Sarkar, 2010; Jordán et al., 2010; Choi et al., 2012; Gholami et al., 2013). Straw mulch as an organic amendment reduce soil erosion but also recover the main soil properties lost due to the agriculture (García-Orenes et al., 2009 and 2010) this is also done by other materials (Giménez Morera et al., 2010).

Although, there are a lot of studies about soil amendments as soil conservation e.g. Fernández et al. (2012), Jiménez et al. (2012), García-Moreno et al. (2013), Robichaud et al. (2013) Lieskovský and Kenderessy, (2014) and Martins et al. (2014) but the effects of study scale on effectiveness of various mulch covers has been rarely considered. There are a few studies about spatial scale variations mulches on runoff and soil loss. Poesen et al. (1994) reviewed the effects of rock fragments on soil erosion and stated the spatial scale has an important impact on the soil erosion. They showed that at the microplot scale, 4 mm^2 to 1 m^2, sediment yield reached a maximum value with 0% rock fragment cover and reached minimum value with 100% rock fragment cover. At the mesoplot scale (i.e. interrill areas), negative, positive as well as convex upward relationships with cover percentages have been observed, depending on the fine earth structure, on the vertical position in the topsoil, on the size of rock fragments and on the surface slope. Finally, at the macroplot scale (i.e. interrill and rill areas), 10-10000 m^2, sediment yield decreased exponentially with rock fragment cover. Cerdan et al. (2002) investigated scale effect (plot to catchment) on runoff in agricultural areas of Normandy, France. Three database of 450 m^2 plots, a 90 ha catchment and an 1100 ha catchment were selected to collect runoff data. Between the three scales, a significant decrease in the runoff coefficient was observed as the area increased. Mingguo et al. (2007) also studied the effect of vegetation on runoff-sediment yield relationship at different spatial scales (plot to watershed) in hilly areas of the Loess Plateau, North China and found that the vegetation could reduce runoff and soil loss in both scales but the reduction rate of sediment was more than runoff at plot scale. Smets et al. (2008a) reviewed the impact of plot length on the effectiveness of different soil-surface covers in reducing runoff and soil loss. The results indicated that for plot lengths <11 m, there was a large variation in the runoff and erosion-reducing effectiveness of each soil cover, depending on various factors. Smets et al. (2008b) also examined the spatial scale effects on the effectiveness of organic mulches in reducing soil erosion at field and laboratory experiments (plot length ranges between 0.1 and 30.5 m). Results verified the effectiveness of mulches in reducing soil erosion by water in various scales. In addition, they reported a positive linear relation between the erosion-reducing effectiveness of an organic mulch cover and plot length. On short plots, the response of a soil surface cover on runoff and soil loss was immediately observed. Nevertheless, on longer plots, the runoff and soil loss response could be compensated due to the longer plot length. Fernández et al. (2012) studied the seeding and mulching + seeding effects on post-fire runoff and soil erosion in Galicia (NW Spain) with rainfall rate of 67 mm h^{-1} and plot scale. Ther showed that the conserved treatments did not significantly increase soil cover or affect runoff but soil losses were low in all cases. García-Orenes et al. (2012) demonstrated that the use of a cover (plants or straw) contributes to increases in soil quality and reduces the risk of erosion. Liu et al. (2012) evaluated the effects of rice straw mulch and plastic film mulching at plot scale and 2 years in the Xiaofuling watershed in the Danjiangkou Reservoir area, China. The straw mulch treatment significantly decreased the sediment yield from 18 to 22%. The results showed that the straw mulch was beneficial for controlling runoff and sediment.

Scrutinizing the available literatures showed that although there are lots of references on using straw as mulch for runoff and soil erosion control, but there was no literature in regards to report the effectiveness of straw mulch in various plot scales. The present study was therefore planned to determine the efficiency of two plot sizes covered by straw mulch changing the important runoff and soil loss components under laboratory conditions.

MATERIALS AND METHODS

The laboratory experiments were conducted by using two sets of 6 × 1 m and 0.5 × 0.5 m plots installed in the rainfall simulator laboratory, Faculty of Natural Resources of Tarbiat

Modares University (TMU), located in Noor Mazandaran Province, Northern Iran. The experiments were carried out to study the effect of rice straw mulch on runoff and soil loss processes by using simulated rainfall in intensities of 50 and 90 mm h^{-1} and in 3 replicates (all of experiments were 24, 12 experiments for rainfall intensity of 50 mm h^{-1}, 6 experiments for control treatments and 6 experiments for conservation treatments, and another 12 treatments for rainfall intensity of 90 mm h^{-1} , 6 experiments for control treatments and 6 experiments for conservation treatments). The entire number of eight treatments in three replicates was formulated as a factorial design as shown following:

2 plot sizes (0.25m^2 and 6m^2) × 2 rainfall intensities (50 and 90 mm h^{-1}) × 2 treatment (control and straw mulch) = 8 treatments and 3 replicates = total of 24 rainfall simulations

The rainfall simulator consists of a 4000-L water tank and 27 precalibrated nozzles in three parallel lines designed to simulate raindrops of 1.3 mm average size. The drops fall from a height between 4 and 6 m at the upper and lower parts of the plot, respectively, reaching a 7 m s^{-1} speed (Duiker et al., 2001) the study plot.

A sandy-loam (14% clay, 24% silt and 62% sand) topsoil was collected 0–20 cm (Kukal and Sarkar, 2010) the Alborz Mountains, Northern Iran. The soil was transport to the lab and air-dried up to optimum moisture content to maintain the relative stability of soil aggregates and decrease breaking down the aggregates in sieving process (Khaledi Darvishan et al., 2013). The coarse rock fragments and plant residues were removed from the soil through passing from 8 mm sieve to obtain maximum homogeneity in soil profile (Hawke et al., 2006). The pH, EC and organic matter of experimental soil were 7.95, 75.5 µmohs cm^{-1} and 2.167%, respectively.

Three layers of mineral pumice grains with different sizes and total thickness of 15 cm were used as a filter layer and placed at the bottom of the plots in order to simulate natural drainage condition and decreasing plot weight (Defersha et al. 2011). A 15 cm-thick soil layer was then placed on the top and separated from the mineral pumice by a sheet of porous jute (Defersha et al., 2011). The soil was ultimately compacted by a small PVC roller (a hand-made roller and filled with cement and sand) to achieve the bulk density of 1.38 g cm^{-3} almost equal to that measure for the soil under natural conditions (Romkens et al., 2001; Saedghi et al., 2010; Gholami et al., 2013). Each experiment was also spanned using new soil and straw mulch cover (Adekalu et al., 2007). The rainfall intensities of 50 and 90 mm h^{-1} with duration of 15 min were considered corresponded with climatological condition in the origin of the soil obtained though IDF curves analysis for data collected from the nearest synoptic station (Kojour with longitude 51° 44´, altitude 36° 23´ and height 1550 m) with the return period less than 20 years.

The air-dried rice straw mulch was ultimately spread on the soil surface 5 days before treatments with the cover, thickness and dry weight of about 90% (Das and Agrawal, 2002; Adekalu et al., 2007; Kukal and Sarkar, 2010), ~ 8 cm and 0.5 kg m^{-2}, respectively. A general view of the experimental plots and setups has been shown in Fig. 1. The control plots subjected to the study rain storms were monitored under identical lab conditions on bare soils and just before applying the straw mulch.

Time to runoff, runoff coefficient and soil loss were measured at the outlet of each plot for control (before mulching) and treated plots (after mulching) in intervals of 2 min (Ruiz-Sinoga et al., 2010). To know the runoff and sediment fluxes in all experiments, the 2 min intervals was considered because of the short whole duration of the experiments (15 min). The amounts of soil loss were then measured using decantation procedure and oven dried at 105ºC for 24 h and weighed by means of high-precision scales (Kukal and Sarkar, 2011; Gholami et al., 2013).

The General Linear Model (GLM) using the SPSS 17 software (SPSS Inc. Released 2009) was applied to statistically analyze the main (individual) and interaction effects of spatial scale (plot size), conservation treatments and rainfall intensity on the quantitative characteristics of runoff, sediment concentration and soil loss. The necessary prerequisites were also fulfilled before applying the GLM.

RESULTS AND DISCUSSION

The amounts of time to runoff and runoff coefficient before and after conservation treatment in each plot output and each scale are shown in Table 1. The percentage of changes in study variables in treated plots and in comparison with control plots have been summarized in Table 2.

Tables 1 and 2 showed that the straw mulch increased time to runoff compared to untreated plots except in rainfall intensity of 50 mm h^{-1} for 0.25 m^2-plot and also decreased runoff coefficient in both the scales. It might be due to water storing effects of straw and also increasing ponding time on the plot surface. This finding is in the same line with that reported by Poesen and Lavee (1991), Mingguo et al. (2007) and Smets et al. (2008a and b). Though the maximum change effectiveness in time to runoff, for two scales, could be found in rainfall intensity of 90 mm h^{-1}. These effects were more serious in 0.25 m^2-plot with rate of + 367.92%. While, 6 m^2-plot compared to 0.25 m^2-plot could reduce the time to runoff in rainfall intensity of 50 mm h^{-1} with rate of + 106.15%.

Figs. 2 and 3 also show the average rates of time to runoff and coefficient in the both scales.

Scrutinizing Table 2 and Figs. 2 and 3 also verified the varying effect of straw mulch on runoff coefficient from -10.43 to - 96.71% in two scales. The minimum and the maximum effects were also in rainfall intensities of 50 in 6 m^2-plot with rate of -10.43% and 90 in 0.25 m^2-plot with rate of 96.71% mm h^{-1}, respectively. The 0.25 m^2-plot had the maximum reduction in runoff coefficient for rainfall intensities of 50 and 90 mm h^{-1}. These results showed that the 0.25 m^2-plot had the maximum impact on decreasing runoff coefficient and increasing time to runoff except in case of rainfall intensity of 50 mm h^{-1}. It verified that the straw mulch pieces could store more runoff leading to more infiltration as already reported by Poesen and Lavee (1991), Choi et al. (2012) and Liu et al. (2012). The results showed that there were large variation in the runoff coefficient (Smets et al., 2008a) and time to runoff on 0.25 m^2-plots compared to those recoded for 6 m^2-plots in various rainfall intensities. In this study the effectiveness of mulch in reducing runoff was influenced by the plot size. So that, with increasing plot size the runoff amount increased while the Poesen et al. (1994), Cerdan et al. (2002) and Smets et al. (2008a and b) showed that runoff amount decreased with increasing plot size. The differences between mulch type, application manner and density as well as soil type and rainfall intensity could be supposed as potential reasons behind the disagreement. But, according to McGregor et al. (1988), plot border effects on runoff rates were much more important in small plots compared to large ones.

Tables 3 and 4 showed that the conservation treatment essentially reduced soil loss which is consistent with Poesen and Lavee (1991), Fernández et al. (2012), García-Orenes et al. (2014) and Fernández and Vega (2014). Sediment concentration also decreased in treated plots as similarly reported by Poesen and Lavee (1991) and Smets et al. (2008a and b). This indicated that the flow could not get enough power to detach particles. A similar finding has been reported by Poesen and Lavee (1991).

The sediment concentration and soil loss amounts before and after conservation treatment in each scale have been shown in Table 3. The relative effectiveness of straw mulch on sediment concentration and soil loss for two scales has also been summarized in Table 4. Figs. 4 and 5 accordingly show the average rates of sediment concentration and soil loss in two study plots.

Table 4 and Figs. 4 and 5 also showed that the amounts of sediment concentration at two study scales changed from -43.47 to -100%. The maximum change occurred at 0.25 m^2-plot in both the intensities of 50 and 90 mm h^{-1}. So that, the soil loss was found negligible after mulching in small plot of 0.25 m^2 (Poesen et al., 1994). The results also showed that the soil loss reduced at 0.25 and 6 m^2-plots and also the variation ranged from -58.69 to -100%. Poesen et al. (1994) found that the soil loss reduced by 100% in small plots 1 m^2 of with cover 100%. It was also observed that both the study variables got the maximum effect in small plot of 0.25 m^2 in view point of decreasing sediment concentration and soil loss. It has also been verified by Mingguo et al. (2007) that the soil loss by water erosion in laboratory condition reduced as plot size decreased. Poesen and Lavee (1994) and Smets et al. (2008a and b) also stated that the soil loss by water erosion was influenced by the plot length. They showed that the small plots with mulch cover were significantly less effective in reducing relative soil loss compared to longer plots. Whereas, this study stated that the small plot with straw mulch was more effective in reducing runoff and soil loss amounts (Mingguo et al., 2007). Therefore, effectiveness of mulch cover in reducing runoff and soil loss by water erosion decreased with increasing plot size. These results were not consistent with Poesen et al. (1994) and Smets et al. (2008a and b), whereas it agreed Mingguo et al. (2007).

Poesen et al. (1994), Cerdan et al. (2002), Boix-Fayos et al. (2006) and Smets et al. (2008a and b) showed that plot length (or spatial scale) can be important in variations of runoff or soil loss rates and in the effectiveness of surface covers. These results were found to be important in designing runoff production and erosion plots and modeling runoff and soil loss rates (Smets et al., 2008a).

Also the results of statistical analysis based on the GLM has been summarized in Table 5.

According to Table 5, changing plot size could have significant effect ($P>0.01$) on time to runoff and coefficient, sediment concentration and soil loss. The runoff coefficient ($p=0.00$), sediment concentration ($p=0.00$) and soil loss ($p=0.02$) were significantly influenced by plot size as well as conservation treatment of rice straw mulch. The interaction effect of plot size and conservation treatment on runoff coefficient, sediment concentration and soil loss were also significant with respective p-values of 0.001, 0.002 and 0.02. However time to runoff was only influenced by plot size.

CONCLUSIONS

The present study was conducted to study the effects of plot size treated by rice straw mulch at rate of 0.5 kg m^{-2} and two plot scales of 0.25 and 6 m^2 on runoff and soil loss control under two rainfall intensities of 50 and 90 mm h^{-1}. The straw mulch increased time to runoff compared to untreated plots except in rainfall intensity of 50 mm h^{-1} for 0.25 m^2-plot and also decreased runoff coefficient in both the scales. The maximum change effectiveness in time to runoff, for two scales, could be found in rainfall intensity of 90 mm h^{-1}. The maximum change of soil loss occurred at 0.25 m^2-plot in both the intensities of 50 and 90 mm h^{-1}. The results showed that the 0.25 m^2-plot had the better effectiveness in reducing runoff coefficient, sediment concentration and soil loss. The results of the study clearly proved the different responses of the plots in regards to runoff soil loss components which can be practically applied at time of setting up experimental studies. The results further showed that the plots are mainly advised to be used for comparative studies rather those leading to accurate data on larger scale outcomes.

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Fig. 1 A general view of treated plots of 6 m^2 (a), the runoff collection system at 6 m^2-plot outlet (b) and 0.25 m^2 (c) with rice straw mulch under the lab condition

Fig. 2 Average time to runoff for two study scales and two rainfall intensities

Fig. 3 Average runoff coefficient for two study scales and two rainfall intensities

Fig. 4 Average sediment concentration for two study scales and two rainfall intensities

Fig. 5 Average soil loss for two study scales and two rainfall intensities

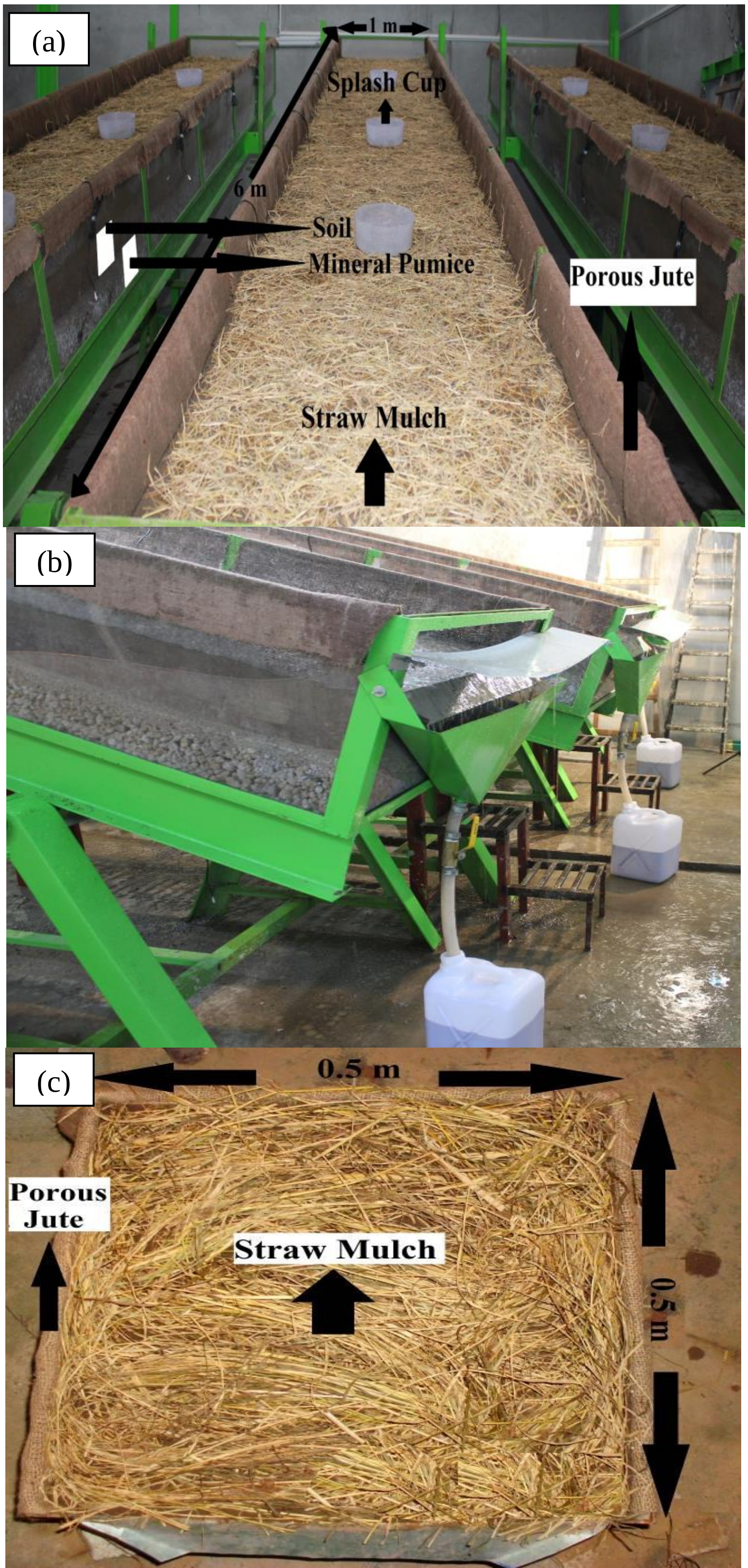

Fig. 1 A general view of treated plots of 6 m^2 (a), the runoff collection system at 6 m^2-plot outlet (b) and 0.25 m^2 (c) with rice straw mulch under the lab condition

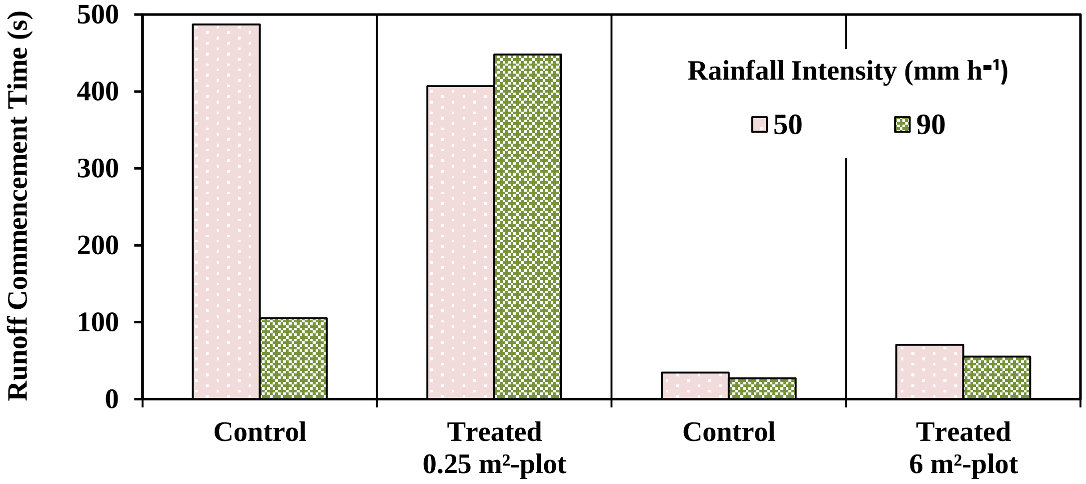

Fig. 2 Average time to runoff for two study scales and two rainfall intensities

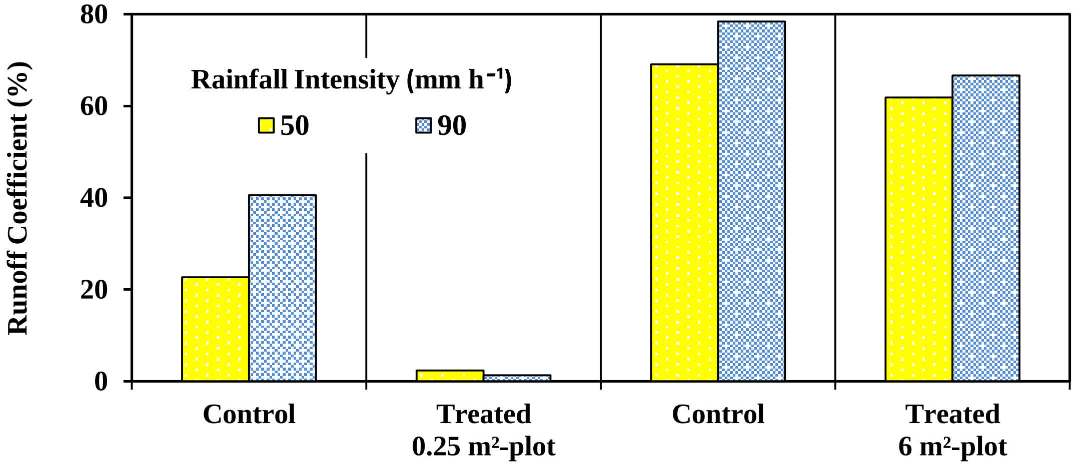

Fig. 3 Average runoff coefficient for two study scales and two rainfall intensities

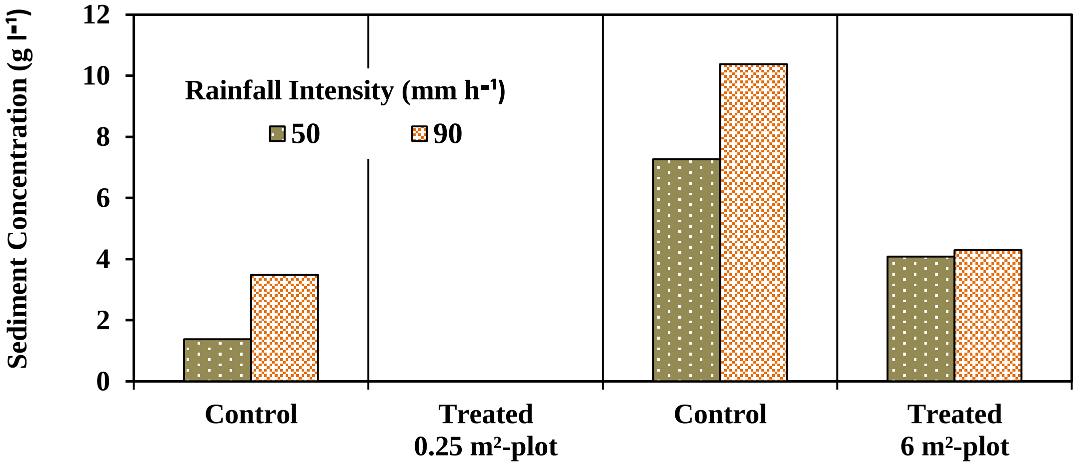

Fig. 4 Average sediment concentration for two study scales and two rainfall intensities

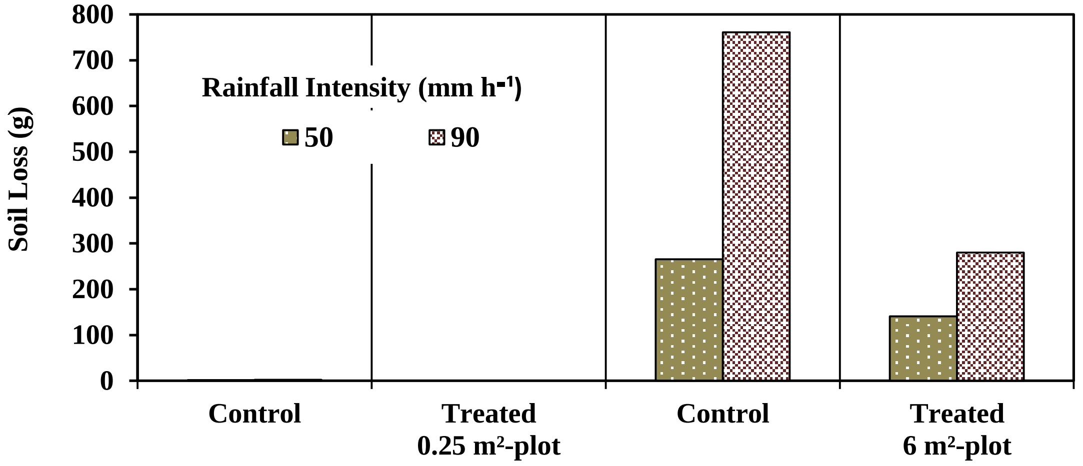

Fig. 5 Average soil loss for two study scales and two rainfall intensities

Table 1 Time to Runoff and coefficient before and after conservation treatment in study scales

Plot Area (m^2)	Rainfall Intensity ($mm\ h^{-1}$)	Kinetic Energy of Rainfall ($j\ m^{-2}$)	Time to Runoff (s)		Runoff Coefficient (%)	
			Control	Treated	Control	Treated
0.25	50	23.41	420.00	480.00	24.56	2.03
			609.6	368.4	19.60	2.94
			432.00	372.00	23.86	2.07
		SD	106.17	63.42	2.68	0.51
	90	24.10	69.00	480.00	34.18	1.30
			120.00	564.00	49.56	1.18
			126.00	300.00	37.91	1.39
		SD	31.32	134.88	8.02	0.11
6	50	23.22	38.51	72.52	69.35	60.20
			30.27	68.11	68.45	62.95
			34.34	70.44	69.48	62.48
		SD	4.12	2.21	0.56	1.47
	90	21.15	23.15	56.11	79.42	66.85
			30.32	52.27	78.32	72.18
			26.70	57.28	77.65	60.90
		SD	3.59	2.45	0.90	5.64

Table 2 Changes (%) in time to runoff and Runoff coefficient in treated plots with rice straw mulch

Plot Area (m^2)	Variable	Rainfall intensity (mm h^{-1})	
		50	**90**
0.25	Time to Runoff	- 13.06	+ 367.92
	Runoff Coefficient	- 89.34	- 96.71
6	Time to Runoff	+ 106.15	+ 110.10
	Runoff Coefficient	- 10.43	- 15.08

Table 3 Sediment concentration and soil loss measured at the outlet of the study plots before and after applying conservation treatment

Plot Area (m^2)	Rainfall Intensity ($mm\ h^{-1}$)	Sediment Concentration ($g\ l^{-1}$)		Soil Loss (g)	
		Control	Treated	Control	Treated
0.25	50	2.04	0.00	1.61	0.00
		1.13	0.00	0.98	0.00
		1.88	0.00	1.54	0.00
	SD	0.49	0.00	0.35	0.00
	90	2.69	0.00	3.78	0.00
		1.56	0.00	3.42	0.00
		2.00	0.00	3.27	0.00
	SD	0.57	0.00	0.26	0.00
6	50	6.13	3.87	226.27	131.38
		7.43	3.69	266.64	128.94
		8.27	4.70	302.82	161.62
	SD	1.08	0.54	38.29	18.20
	90	10.28	4.39	756.69	286.37
		10.71	4.47	787.94	315.10
		10.15	4.01	738.20	239.42
	SD	0.29	0.25	25.14	38.20

Table 4 Reduction rates (%) in average sediment concentration and soil loss in treated plots with rice straw mulch

Plot Area (m^2)	Variable	Rainfall intensity ($mm\ h^{-1}$)	
		50	**90**
0.25	Sediment Concentration	- 100	- 100
	Soil Loss	- 100	- 100
6	Sediment Concentration	- 43.47	- 58.69
	Soil Loss	- 46.74	- 63.24

Table 5 results of GLM test for plot size and conservation treatment effects on the quantitative characteristics of runoff and soil loss

Source	**Dependent Variable**	**Type III Sum of Squares**	**df**	**Mean Square**	**F**	**Significant level**
Plot	Time to Runoff (s)	595564.22	1	595564.22	40.92	0.00
	Runoff Coefficient (%)	16413.83	1	16413.83	381.42	0.00
	Sediment Concentration (g l^{-1})	185.59	1	185.59	194.67	0.00
	Soil Loss (g)	780024.69	1	780024.69	38.46	0.00
Treatment	Time to Runoff (s)	40142.53	1	40142.53	2.76	0.11
	Runoff Coefficient (%)	2317.91	1	2317.91	53.86	0.00
	Sediment Concentration (g l^{-1})	63.64	1	63.64	66.75	0.00
	Soil Loss (g)	139578.68	1	139578.68	6.88	0.02
Plot Treatment	Time to Runoff (s)	14704.47	1	14704.47	1.01	0.33
	Runoff Coefficient (%)	616.72	1	616.72	14.33	0.001
	Sediment Concentration (g l^{-1})	11.48	1	11.48	12.04	0.002
	Soil Loss (g)	135178.56	1	135178.56	6.67	0.02