The impact of standard preparation practice on the runoff and soil erosion rates under laboratory conditions

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Abstract

The use of laboratory methods in soil erosion studies has been recently considered more and more because of many advantages in controlling rainfall properties and high accuracy of sampling and measurements. However, different stages of soil removal, transfer, preparation and placement in laboratory plots cause significant changes in soil structure and subsequently, the results of runoff, sediment concentration and soil loss. Knowing the rate of changes in sediment concentration and soil loss variables with respect to the soil preparation for laboratory studies is therefore inevitable to generalize the laboratory results to field conditions. However, there has been less attention to evaluate the effects of soil preparation on sediment variables. The present study was therefore conducted to compare sediment concentration and soil loss in natural and prepared soil. To achieve the study purposes, 18 field 1×1 m-plots were adopted in an 18% gradient slope with sandy-clay-loam soil in the Kojour watershed, Northern Iran. A portable rainfall simulator was then used to simulate rainfall events using one or two nozzles of BEX: 3/8 S24W for various rainfall intensities with a constant height of 3 m above the soil surface. Three rainfall intensities of 40, 60 and 80 mm h^{-1} were simulated on both prepared and natural soil treatments with three replications. The sediment concentration and soil loss at five three-minute intervals after time-to-runoff were then measured. The results showed the significant increasing effects of soil preparation ($p \leq 0.01$) on the average sediment concentration and soil loss. The increasing rates of runoff coefficient, sediment concentration and soil loss due to the study soil preparation method for laboratory soil erosion plots, were 179, 183 and 1050% (2.79, 2.83 and 11.50 times), respectively.

Keywords Erosion Plot, Rainfall Simulator, Runoff, Sediment, Soil Disturbance.

1 Introduction

Soil, as one of the valuable natural resources, is nonrenewable at short time scale and should be studied with a multidisciplinar perspective (Brevik et al., 2015). Soil erosion is a result of the interaction of several factors which vary in space and time (Cerdà, 1998; Le Bissonnias et al., 2002; García-Orenes, 2010). Study of soil erosion and sediment yield in the watershed is one of the basic necessities to achieve integrated land management and soil and water conservation. The identification and quantification of the hydrological properties and processes that induce runoff and soil erosion in necessary to determine the amount of soil erosion (Cerdà et al., 1997; Cerdà, 1999; Ramos et al., 2000; Iserloh et al., 2012; Iserloh et al., 2013; León et al., 2013; Martínez-Murillo et al., 2013). Although, the measurement of runoff and sediment using rainfall simulators can be performed in the laboratory (Gabarrón-Galeote et al., 2013; Moreno-Ramón et al., 2014; Gholami et al., 2014; Bochet, 2015; Sadeghi et al., 2015) and field conditions (Cerdà et al., 2009; Mandal and Sharda, 2013; Lieskovský and Kenderessy, 2014; Bochet, 2015), field measurements are usually costly and time consuming works. In addition, different methods of measuring runoff and erosion may lead to non-identical results that are not necessarily related to specific effects on studied variables (Bryan and Ploey, 1983; Boardman et al., 1990). Nowadays, the use of rainfall simulators in laboratory and field studies are considered more and more, because of ability to control the intensity and duration of rainfall which leads to increase the accuracy of data (Sadeghi, 2010). On the other hand, measuring runoff and soil loss at the plot scale have been of crucial importance from the beginning of the soil erosion research (Licznar and Nearing, 2003). The limitations of laboratory studies of soil erosion leads to lack of confidence especially when the aim of research is to study some important factors affecting erosion (Toy et al., 2002) which may because of soil disturbance in laboratory. Although various methods for soil preparation have been proposed to perform laboratory soil erosion research (Ekwue, 1991; Romkens et al., 2001; Hawke et al., 2006; Ekwue and Harrilal, 2010; Kukal and Sarkar, 2010), all these methods have one major goal that the soil samples were placed in the experimental plots as homogeneous as possible (Hawke et al., 2006). Changes in the soil during sampling, transportation and various stages of preparation include air-drying, passing through a sieve, soil moisture content during the preparation process and finally compacting to increase the bulk density of the soil surface by roller may influence the results of runoff and erosion. For example, the significant effect of soil characteristics such as small relief and aggregate shape on the amount and spatial pattern of runoff (Kirkby, 2001) and of surface roughness on runoff and erosion (Gomez and Nearing, 2005) that have been approved before, can all be created or weakened and intensified by rolling the soil surface. Tillage, as one of the most important human factors that leads to soil disturbance, is also a way to disturb the soil and will create higher erosion rates (Novara et al., 2011; Gabarrón-Galeote et al., 2013; Haregeweyn et al., 2013, Sadeghi et al., 2015) and this also occurs when the soil is disturbed by changes in crops (Zhang et al., 2015). Nevertheless, the textural and structural changes during soil preparation for experimental studies of erosion may not be the same with those in preparation for agriculture, forestry or gardening purposes, because of many differences in method of soil preparation. Despite the higher costs, effort, soil disturbances, etc., application of laboratory plots has been justified sometimes instead of natural plots because of advantages in controlling rainfall properties and high accuracy of sampling and measurements.

The present research has been therefore conducted to evaluate the effects of soil preparation for experimental studies on runoff and soil erosion. The results of present research can hopefully be used to generalize the results of laboratory studies of soil erosion to natural conditions more accurately.

2 Materials and methods

2.1 Study area

The field experiments were conducted in a south slope with sandy-clay-loam soil located in the longitude and latitude of 36˚ 27′ 15″ N and 51˚46′ 27″ E and the altitude of 1665 m in the vicinity of Kodir village in Educational and Research Forest Watershed of Tarbiat Modares

University, in the north of Iran (Fig. 1). The degree of the slope at the experiments site was about 18%. The amount of organic matter, pH and EC of the studied soil were 2.2 %, 7.9 and 157.6 dS mm^{-1} respectively.

Fig. 1

2.2 Installation and preparation of plots

The top 20 cm layer of the soil was collected for soil preparation using Kukal and Sarkar method (2011) with some modifications to maintain aggregate structure (Khaledi Darvishan et al., 2012 and 2014). The collected soil was air dried to the optimum soil moisture sontent (Fox and Bryan, 1999). All plant residues and pebbles were removed from the soil (Agassi and Bradford, 1999) and finally, the soil was passed through 8.0 mm sieve (Ekwue and Harrilal, 2010; Defersha et al., 2011; Khaledi Darvishan et al., 2014). The prepared soil was then transferred into the 9 plots with the depth of about 15 cm. Because of the effects of soil bulk density on soil resistance against rain drops and runoff (Luk, 1985; Cerdà, 2002), a PVC pipe with diameter of 10 cm and filled with a mixture of sand and cement as a roller was used to compact the soil to achieve the natural bulk density of the soil. The other 9 plots were placed on the soil in natural condition and all plant tissues above the soil surface were removed using a small secateur. The initial soil moisture content is also among the factors affecting soil hydrological responses (Chow et al., 1988) that was about 29 volumetric % and relatively the same in all 18 plots. A view of the plots in both before and after soil preparation is shown in Fig. 2.

Fig. 2

2.3 Rainfall simulation

According to Kojour synoptic rain gauge data and IDF curves, which is the nearest station to the study slope, three rainfall intensities of 40, 60 and 80 mm h^{-1} were selected with a constant duration of 15 min after time-to-runoff. These range of rainfall intensities are among the most erosive ranifalls in the study area because they have erosive intensities and as well as enogh durations and return periods (20 years). According to the IDF curves, all three intensities of 40, 60 and 80 mm h^{-1} had a duration equal or longer than 15 min in return period of 20 years. A portable rainfall simulator was then used to simulate rainfall events using one or two nozzles of BEX: 3/8 S24W for various rainfall intensities with a constant height of 3 m above the soil surface. The median diameter and velocity of simulated raindrops were determined using processing the images of a high speed camera (Canon EOS 550D). The median diameter of raindrops were 1.11, 1.05 and 1.03 mm and the mean velocity of raindrops were 4.38, 4.08 and 4.03 m s^{-1} for three studied rainfall intensities respectively. The kinetic energy of simulated rainfalls were then calculated using the main kinetic energy formula ($E=1/2\ mv^2$) and the average volume and number of raindrops per mm depth of rainfall. The kinetic energy of simulated rainfalls were 9.59, 8.32 and 8.12 J m^{-2} mm^{-1} for three studied rainfall intensities respectively.

2.4 Measuring Runoff, Sediment Concentration and Soil Loss

During each experiment, runoff was collected in the outlet of plots and sampled in five 3-min intervals after runoff commencement time. The time of fifth sample was exactly coincident with the time the rain had stopped and then, all the remained runoff was collected as the final sixth sample. The samples were transferred to the laboratory and sediment concentration was measured using decantation procedure, oven dried at 105°C for 24 h (Walling et al., 2001; Gholami et al., 2013; Ziadat and Taimeh, 2013).

2.5 Statistical analysis

The effect of soil preparation practice on the variables of time-to-runoff, runoff volume and coefficient, sediment concentration and soil loss were analyzed. The statistical tests were performed under experimental design of spilt plots and factorial experiments with two soil conditions (before and after soil preparation) and three rainfall intensities. The normality test was done for all variables of runoff, sediment concentration and soil loss. Based on the results of normality test, the runoff volume and soil loss datasets were transformed to logarithmic form to achieve normality distribution, because parametric tests on normal data seems to be more powerful to detect the differences than the nonparametric tests on non-normal data (Townend, 2002).

The ANOVA tests with considering the split plots design (Bihamta and Zare Chahouki, 2011) were finally used to evaluate the statistical differences between studied variables before and after soil preparing.

3 Results and Discussion

The results of average runoff variables, sediment concentration and soil loss for three replicates of both before and after soil preparation in three studied rainfall intensities are shown in Tables 1 to 3 respectively.

Table 1

Table 2

Table 3

The statistical analysis of the effects of rainfall intensity and soil preparation on sediment concentration and soil loss are shown in Table 4.

Table 4

Mean temporal variation of sediment concentrations in three replications of before and after soil preparation are shown in Fig. 3 and increasing ratios (%) of runoff variables, sediment concentration and soil loss after preparing soil are shown in Fig. 4.

Fig. 3

Fig. 4

According to Table 1, weighted mean runoff coefficient of the average values of various time intervals were varied from 6.82 to 25.70 before soil preparing condition and from 25.08 to 57.17 after soil preparing condition. The results revealed that soil preparation leads to significantly ($p \leq 0.01$) increase runoff coefficient (Table 4).

According to Table 2, weighted mean sediment concentrations of the average values of various time intervals were varied from 2.7 to 7.57 and from 10.38 to 12.41 before and after soil preparing respectively. According to Tables 2 and 4, the sediment concentration was significantly ($p \leq 0.01$) increased after soil preparation for laboratory erosion plots. One of the reasons of more sediment concentration before soil preparing is the longer time-to-runoff which leads to more splash and particle separation before the flow of surface runoff. Consequently, in the first sampling after runoff commencement time, the available source of soil particles to be transport is more and leads to increse sediment concentration. But a few minutes after runoff commencement time, the available sediment source and consequently, the sediment concentration decreases. The effects of soil preparation practice for laboratory erosion plots on runoff or soil loss was in agreement with previous studies which revealed the same effects of soil preparation for agriculture and gardening purposes (Harold et al., 1945; Choudhary et al., 1997; Layon et al., 1999; Erkossa et al., 2005; Gomez and Nearing, 2005; Ziadat and Taimeh, 2013). The results was in agreement with Cao et al., (2013) who studied and modelled the interrill erosion on unpaved roads and Villarreal et al., (2014) who studied the effects of vehicle-based soil disturbance and compaction on soil erosion potential. Soil surface disturbance and compaction because of grazing can increase soil erosion (Palacio et al., 2014). In other words, soil preparation -for any purposes especially for laboratory erosion plots- could decrease soil resistance against raindrops because of aggregates breakdown which respectively leads to more detachment, less infiltration, more runoff and more sediment concentration. Concentrations of runoff sediment after soil preparation confirmed that erosion depended directly on the sediment available on the soil surface that was in agreement with Ceballos et al., (2002). The presence of pebbles and gravels on soil surface as well as inside soil profile has been considered as an affective factor against the kinetic energy of raindrops (Jomaa et al., 2012). The presence of stones at the soil surface not always decrease soil erosion but on the contrary, if stones are embedded in crusted surfaces, they can increase runoff and thus soil erosion. The roots and other plant residues can also play a significant role to physically decrease the kinetic energy of raindrops and improve aggregates stability (Monroe and Kladivko, 1987; Ghidey and Alberts, 1997; Martens, 2002). Removing all pebbles, gravels and plant residues could also been considered as another significant reason which leads to more sediment concentration in prepared soil for laboratory studies. All these results mean that more splash in prepared soil is one the main results of increasing sediment concentration.

All the steps of soil preparation vis. sampling, transporting, spreading to be air-dried, passing through 8 mm sieve, packing into the plots and compacting again are the reasons to damage soil structure and aggregates breakdown even without removing any parts of the soil materials.

Using a sieve with larger mesh number (8 mm) may decrease the negative effects of soil preparing (Khaleidi Darvishan et al., 2014), but a significant part of effects which is connected with sampling, transporting and especially compacting the soil remains yet.

Longer Time to runoff before soil preparation revealed that preparing soil, even with compacting again, can cause a temporary increase in infiltration which itself leads to longer time-to-runoff (Table 1). But the main note is that the increasing infiltration is a temporary effect of preparing soil and after a few minutes, more detachment can decrease the infiltration rate and leads to more runoff volume in the first 3-minute sampling interval after runoff commencement time (Fig. 3). The results showed that in all three rainfall intensities, sediment concentration in both before and after soil preparation treatments reached to the peak in the first sample of runoff and then gradually decreased. This result was in agreement with many other laboratory soil erosion researches (Assouline and Ben-Hur, 2006).

The significant effect of soil preparation practice on soil loss may be due to eliminated surface gravel during sieving the soil. This may be because of the ability of gravel surface to reduce total amount of available sediment (Tailong et al., 2010) and also to decrease power erosivity of surface flow (Rieke-Zap et al., 2007; Tailong et al., 2010). Rock fragments, roots and plants debris on the soil surface and within the soil profile in soil surface before any preparation practice could protect the aggregate against raindrops or runoff flow. In this regard, Li et al., (1991), Ghidey and Alberts (1997) and Mamo and Bubenzer (2001a and 2001b) showed that root system helps the soil resistance and thus reduces the amount of soil loss.

According to Table 4, the increasing effects of rainfall intensity on runoff coefficient, sediment concentration and soil loss were significant. The significant effects of rainfall intensity on various runoff, sediment and soil loss variables have been emphasized by Romkens et al., (2001), Chaplot and Le Bissonnais (2003), Assouline and Ben-Hur (2006), Ahmed et al., (2012) and Defersha and Melesse (2012) too.

The results of statistical analysis (Table 4) showed that the interaction between rainfall intensity and soil preparation treatment on sediment concentration was not significant that may be due to the limited studied levels of rainfall intensity (40, 60 and 80 mm h^{-1}). All rainfall intensities may also high enough to seal the soil surface. In other word, for lower rainfall intensities (for example 20 mm h^{-1}), probably it would have found an interaction between rainfall intensity and soil preparation treatment.

4 Conclusion

It can be generally concluded that the average and peak values and variation gradient of runoff and sediment concentration increased due to soil preparation practice. The increasing rates of runoff coefficient, sediment concentration and soil loss due to the study soil preparation method for laboratory soil erosion plots, were 179, 183 and 1050% (2.79, 2.83 and 11.50 times), respectively. The observed differences indicated that the use of laboratory plots are not appropriate to predict soil erosion of natural conditions, while their results can be used to compare soil erosion rates in various treatments and conditions. It is highly recommended to leave the prepared soil inside the plots at least for a few weeks before rainfall simulation instead of using roller, to increase the bulk density and improve structural condition of the soil. It may decrease the negative effects of soil preparing process caused by rolling the soil surface. The soil moisture content during the process especially after packing the prepared soil inside the plots is also very important and can leads to increase the bulk density in a shorter time. The results of this research are valid only for a natural cover (rangeland) on specific soil and could not be extended to any other land use and soil conditions. In addition, the slope length was not long enough to produce rills and therefore, the resuls are valid only when splash and sheet erosion are dominant erosion processes.

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Table 1 The average time-to-runoff and runoff volume for three replicates of both before and after soil preparation treatments in three studied rainfall intensities

Rainfall intensity (mm h^{-1})	Soil treatment	Time-to-runoff (min)	Runoff volume (l)							Rainfall volume (l)	Runoff coefficient (%)
			Time after runoff commencement (min)					After the rain stop	Total		
			3	6	9	12	15				
40	Before soil preparation	8.54	0.12	0.22	0.20	0.23	0.22	0.07	1.06	15.54	6.82
	After soil preparation	11.36	0.19	0.53	0.95	1.15	1.26	0.20	4.29	17.11	25.08
60	Before soil preparation	3.99	0.21	0.41	0.52	0.62	0.73	0.13	2.62	18.82	13.92
	After soil preparation	15.74	0.70	1.51	2.12	2.73	2.85	0.26	10.17	29.70	34.24
80	Before soil preparation	2.99	0.47	1.03	1.31	1.49	1.62	0.28	6.20	24.12	25.70
	After soil preparation	4.73	1.20	2.81	3.49	3.44	3.64	0.39	14.96	26.17	57.17

Table 2 The average sediment concentration for three replicates of both before and after soil preparation treatments in three studied rainfall intensities

Rainfall intensity (mm h^{-1})	Soil treatment	Sediment concentration (g l^{-1})						
		Time after runoff commencement (min)					After the rain stop	Weighted mean
		3	6	9	12	15		
40	Before soil preparation	2.59	2.78	2.73	2.82	2.04	2.78	3.49
	After soil preparation	10.56	9.92	9.00	7.59	6.68	4.78	10.44
60	Before soil preparation	3.45	2.37	2.56	2.74	2.68	2.26	2.70
	After soil preparation	10.35	10.99	9.62	10.48	9.98	8.95	10.38
80	Before soil preparation	6.76	5.56	6.06	6.00	5.06	2.86	7.57
	After soil preparation	12.06	10.89	10.15	8.56	7.51	4.32	12.41

Table 3 The average soil loss for three replicates of both before and after soil preparation treatments in three studied rainfall intensities

Rainfall intensity (mm h^{-1})	Soil treatment	Soil loss (g)						
		Time after runoff commencement (min)					After the rain stop	Total soil loss
		3	6	9	12	15		
40	Before soil preparation	0.28	0.50	0.50	0.61	0.39	0.12	3.19
	After soil preparation	2.12	5.36	8.69	8.97	8.72	0.96	46.42
60	Before soil preparation	0.79	0.79	1.42	1.87	2.00	0.27	7.15
	After soil preparation	8.12	18.39	22.84	33.30	30.10	2.50	115.25
80	Before soil preparation	4.07	8.18	12.32	12.20	11.62	1.05	49.45
	After soil preparation	20.04	41.99	47.06	39.76	36.96	2.20	188.02

Table 4 Statistical analysis of the effects of soil preparation treatment and rainfall intensity on sediment concentration and soil loss

Source	Dependent variable	Sum of squares	df	Mean squares	F	P value
Treatment	Runoff Coefficient (%)	2425.56	1	2425.56	15.963	0.005**
	Sediment Concentration (g l^{-1})	189.67		189.67	26.794	0.003**
	Log_Soil_Loss (g)	4.56		4.56	49.192	0.000**
Treatment × Repetition	Runoff Coefficient (%)	607.61	4	151.90	0940	0.488
	Sediment Concentration (g l^{-1})	28.33		7.08	1.579	0.269
	Log_Soil_Loss (g)	0.37		0.09	0.861	0.526
Rainfall intensity	Runoff Coefficient (%)	2043.90	2	1021.95	6.322	0.023*
	Sediment Concentration (g l^{-1})	42.52		21.26	4.742	0.044*
	Log_Soil_Loss (g)	2.54		1.27	11.820	0.004**
Rainfall intensity × Treatment	Runoff Coefficient (%)	15.41	2	77.71	0.481	0.635
	Sediment Concentration (g l^{-1})	6.54		3.27	0.729	0.512
	Log_Soil_Loss (g)	0.30		0.15	1.410	0.299
Error	Runoff Coefficient (%)	1293.20	8	161.65		
	Sediment Concentration (g l^{-1})	35.87		4.48		
	Log_Soil_Loss (g)	0.86		0.11		

* and ** are the significant levels of 95 and 99%, respectively.

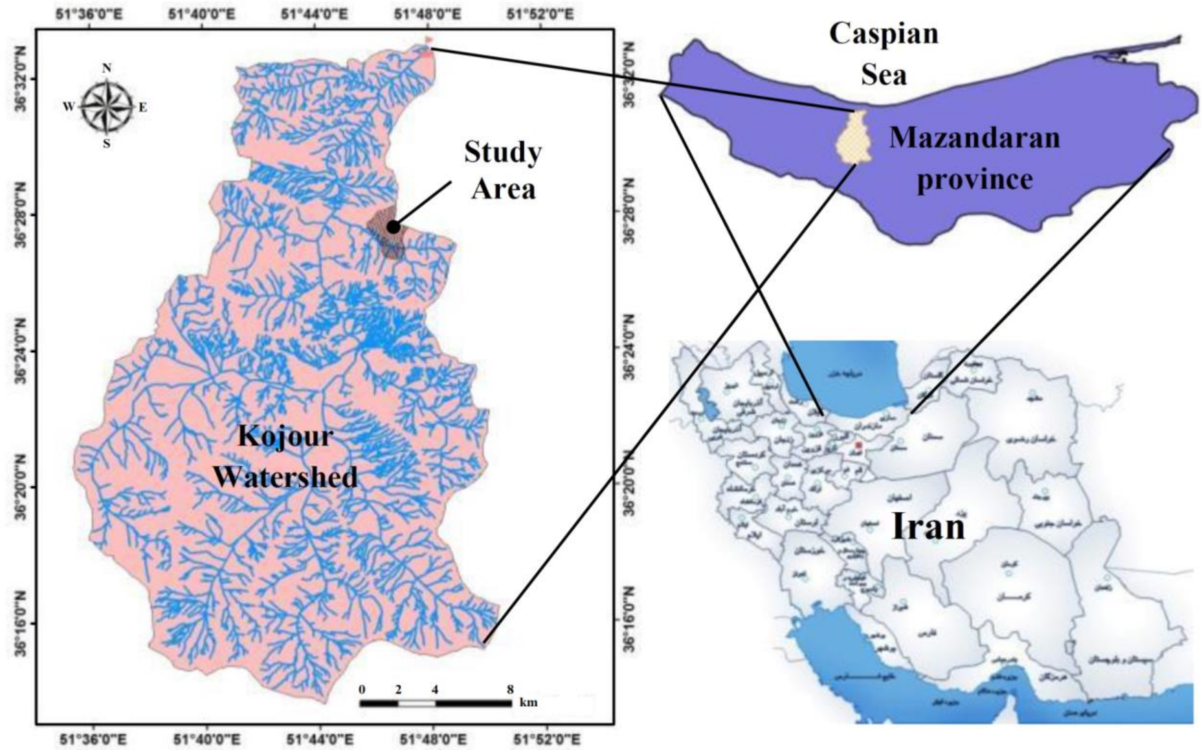

Fig. 1 Location of the study area in Kojour Watershed, Mazandaran Province, Iran

Fig. 2 Views of the plots in both soil treatments; before soil preparation (right) and after soil preparation (left)

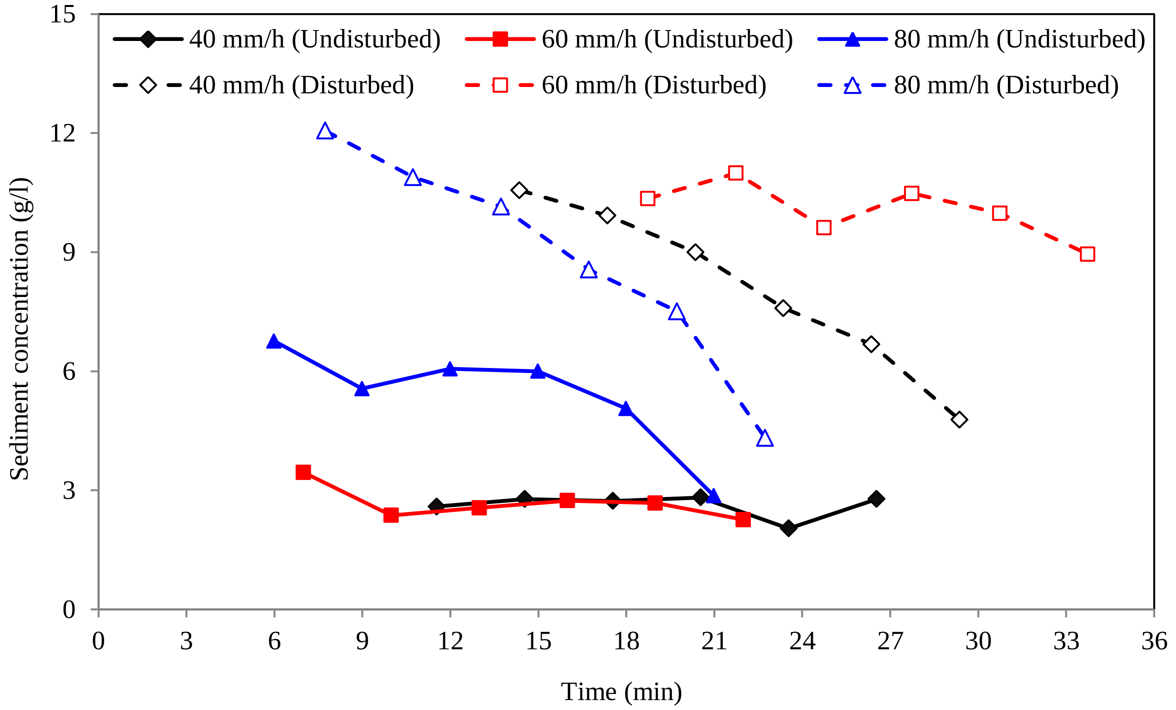

Fig. 3 Mean temporal variation of sediment concentrations in three replications before and after soil preparation treatments

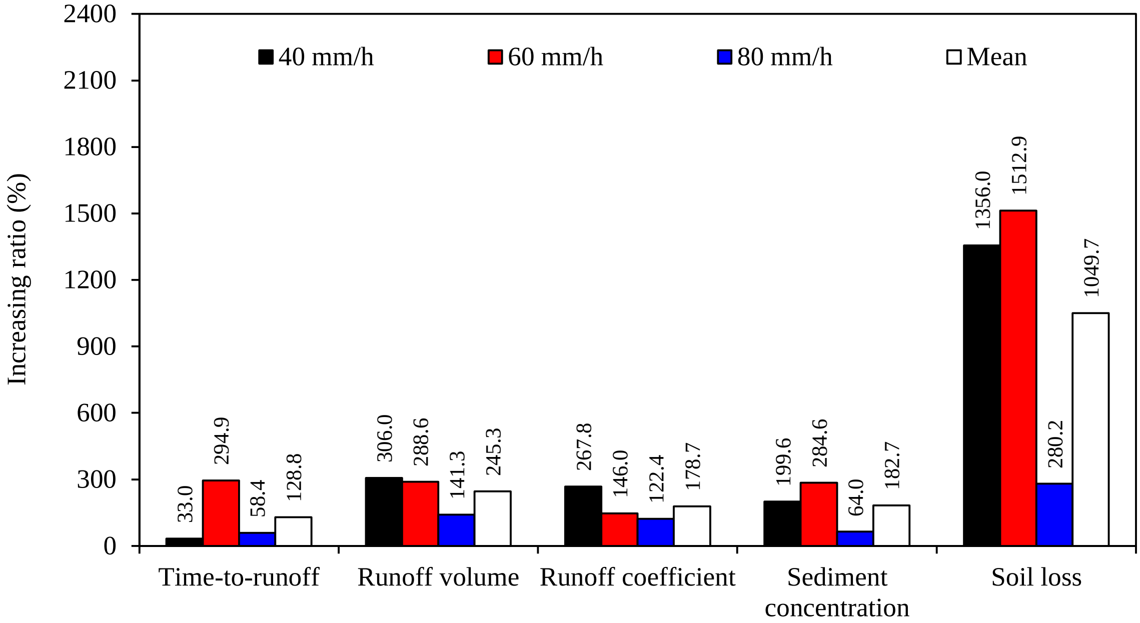

Fig. 4 Increasing ratios of runoff variables, sediment concentration and soil loss after preparing soil