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Original Research Paper

Effects of Soil Crusts and Tillage Treatment on Soil Erosion in the Loess Plateau of China

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ABSTRACT

The objective of this laboratory study was to assess the effects of soil crusts and tillage treatments on soil erosion in the Loess Plateau of China. The simulated rainfall storms at 40 mm/h, 60 mm/h and 80 mm/h rates were applied to the soil boxes set to a 17.6% slope, two soil surface conditions (crusted and uncrusted soil surface) and two tillage types (contour tillage and straight slope) were used to investigate the resulting runoff rate and sediment yield. Results show that the runoff rates were greater and total soil loss was lower in crusted than uncrusted soils. Contour tillage treatment resulted in smaller runoff rate and total soil loss than straight slope treatment. Rainfall intensity, soil crusts and tillage treatments had very significant ($p < 0.001$) effects both on total runoff yield and soil loss. The combined effects of rainfall intensity and tillage treatment on total runoff yield and soil loss were much more significant ($p < 0.01$) than the other combined effects ($p < 0.05$). Rainfall intensity had a greatest correlation with the total runoff yield while tillage treatments had a greatest correlation with the total soil loss. As a result, the tillage treatments in the Loess Plateau can reduce the impact of soil crusts on soil erosion effectively.

INTRODUCTION

Soil crust formation is a common phenomenon in cultivated soils in arid and semiarid regions. A soil crust is a thin layer at the soil surface which has low porosity and is formed after rainfall or irrigation water application. Soil crusts increase runoff rates due to reduced soil infiltration rates. With a crust, there is greater bulk density of the soil surface, and the soil strength is greater than the non-crusted layer, which may reduce splash rates and influence the soil erosion process (McIntyre 1958a,b, Chen et al. 1980, Arshad & Mermut 1988, Moore & Singer 1990, Le Bissonnais & Singer 1993, Levy et al. 1994, Lado & Ben-Hur 2004).

Effects of soil crusts on the soil erosion process have been studied for many years, and it is clear that the formation of soil crust reduces the soil hydraulic conductivity. The lower the hydraulic conductivity of the crusts, the lower the soil infiltration rates go, and the greater the volume of runoff generated (Cerdan et al. 2002, Li et al. 2005, Cheng et al. 2007). Overland erosion process was affected by soil crusts in both splashing and washing processes. During the splashing process, the formation of soil crusts enhances the strength of the soil surface and decreases the amount of loose materials available for raindrop detachment, thus decreasing soil splash rates (Wu & Fan & Li 2001, Cheng et al. 2008a). During the washing process, there is currently a large controversy. On one hand, it is considered that there is a positive relationship between soil crust development and soil loss (Fox et al. 1998). The formation of soil crusts increases runoff rates and the flow shear stresses, resulting in an enhancement of soil loss (Neave & Rayburg 2007, Cheng et al. 2008b). On the other hand, it is considered that the formation of soil crusts increases soil strength and reduces loose debris (Zhu 2002, Wu & Fan 2005, Wang et al. 2008) resulting in diminished soil loss. Most likely, it is possible that either condition may occur, depending upon the specific soil type and conditions, moisture content and storm runoff rates.

The Loess Plateau of China is an area where soil erosion leads to considerable problems (Sun et al. 2013). The annual sediment flow into the Yellow River is approximately 16 billion tons, with approximately 50% to 70% coming from the sloping land of the Loess Plateau (Tang 2004). Tackett & Pearson (1965) reported that soils were more likely to form crusts when they had high silt content. The silt loam soil (USDA standard) used in this study was from Loess Plateau of China which contained 66.2% silt content. As a result, the soil was susceptible to form soil crusts. Meanwhile, the slope on the Loess Plateau ranged from 10°-35° which needed tillage treatments to prevent soil and water loss. Currently, zero tillage, shallow hoeing and contour ploughing were reported as the common tillage practices for agricultural production in Loess Plateau of China (Zhao et al. 2013).

Tillage treatment or soil surface management to prepare a desired seedbed is a major input in agricultural production which is powerful to alleviate some soil-related constraints to crop production, e.g. compaction, crusting, low infiltration, poor drainage, unfavourable soil moisture and temperature regimes (Lal 1991). On cultivated soils, tillage operations produce abrupt changes in soil surface roughness. A number of studies have demonstrated the different soil surface roughness states influence runoff generation and formation due to soil sealing and crusting effects (Govers et al. 2000, Kamphorst et al. 2000). Helming et al. (1993) investigated how the interactions between rainfall energy and micro-relief affect soil surface sealing and runoff. The kinetic energy of drop impacting on the soil surface leads to sealing, which is the actual trigger mechanism for runoff formation. The relationship between infiltration and runoff will have to take the micro-relief dependent energy dissipation into consideration when basing infiltration and runoff on kinetic rainfall energy. Zhao et al. (2013) found that the seal and crust formation on the soil surface was also an important factor that decreased SSR's effect on runoff. However, no studies have investigated tillage treatments with soil crusts in the Loess Plateau of China. In this study, the objective was to assess the interactions between soil crusts and tillage treatment on soil erosion.

MATERIALS AND METHODS

This study was conducted in the artificial rainfall simulation hall in the Soil and Water Conservation Engineering Laboratory at Northwest A & F University, Yangling, Shaanxi, China. The experiments were performed on crusted and uncrusted surface under two tillage treatments (contour tillage and straight slope) with three rainfall intensity (40 mm/h, 60 mm/h, 80 mm/h).

Study area and soil materials: Soil samples were collected in Yan'an County, Shaanxi province, China (36°40'39" N, 109°31'37" E). This area is located in the central region of the Loess Plateau. Yan'an County has a temperate, semi-humid to semi-arid monsoon climate with an annual mean temperature of 8.5-9.5°C. The mean annual precipitation is 450-650 mm. Rainfall distribution is not uniform throughout the year, particularly in the summer when sudden storms are common. The winter wheat/summer maize rotation represents the main cropping system in this area.

Topsoil (0-10 cm) was excavated from a field under winter wheat/summer maize rotation system. Soil texture compositions (silt loam, USDA standard) were 20.5% sand, 66.2% silt, 13.3% clay, and organic matter content was 11.84 g/kg. The soil was air-dried and passed through a 4.0 mm sieve to remove debris. The soil boxes used were 200 cm long by 100 cm wide by 40 cm deep. Soil was packed into the boxes by pouring a known mass of soil (120 kg per layer) into a marked volume (5 cm layer thickness in the box) and then compressing to the mark with a wooden board to achieve a bulk density of 1.10 to 1.20 g/cm^3. The slope of the soil box was set at 17.6% (10°).

Additionally, two tillage treatments were simulated inside the soil boxes with a hoe. The tillage treatments included contour tillage (CT) and straight slope (SS), which are common tillage treatments used in the Loess Plateau of China. Photographs of two boxes with different types of tillage treatments are shown in Fig. 1. Contour tillage consisted of horizontal tillage perpendicular to the slope to form ridges and depressions (Fig. 1a). The height of the ridges was 7-10 cm, with the distance between two ridges at 30 cm. The Straight slope had a uniform flat soil surface which was made smoothly (Fig. 1b).

Soil crusts formation and measurement: Soil crusts formation and measurement: the rainfall event was at a rainfall intensity of 80 mm/h and lasted for 30 min. This was formed to create crusted and uncrusted soil surface. In one event of the rainfall, three soil boxes were used. One box was covered with fabric to avoid directly rainfall hitting on the soil surface in order to form uncrusted surface. The other two boxes were uncovered for the formation of crusted soil surface. One of the boxes with crusted soil surface was used for soil crust characteristics measurement. The other was used in the following rainfall event.

The characteristics of soil crusts on soil surface were measured before the second simulated rainfall started. The thicknesses of soil crusts were measured as the average of 10 different points using a Vernier calliper. The bulk density of soil crusts was measured by the method of coating a thin film (Fan 2001), and the shear strength of soil crusts was measured by fall-cone device. The porosity of soil crusts was calculated through soil bulk density using the equation as below:

$$\text{Soil Porosity} = \left(1-\frac{\text{Bulk Density}}{\text{Specific Gravity}}\right) \times 100 \qquad ...(1)$$

Where specific gravity = 2.65 g/cm^3

The thickness of the soil crusts ranged from 1.85 mm to 2.52 mm; the bulk density of the soil crusts from 1.39 g/cm^3 to 1.55 g/cm3; the shear strength of the soil crusts from 27.0 kPa to 35.0 kPa; and the porosity of the soil crusts from 41.51% to 47.92%.

Rainfall application: A rainfall simulator system designed by the Institute of Soil and Water Conservation, CAS & MWR was used in this study. Two programmable rainfall simulator troughs were erected opposite to each other which were supplied with inflow water from the same pipe. The rainfall intensity was adjusted by controlling the pressure of water in the pipe. The height of the equipment was 7 m above the soil surface to ensure that terminal velocity of the raindrops was reached. The rainfall kinetic energy was 27.0 J m^2/mm. The effective rainfall area was 4 m × 9 m which was enough to cover the area above the box. The uniformity of rainfall simulator was nearly 75% and the raindrop distribution and size is similar to that of natural rainfall (Zheng & Zhao 2004). In this study, the second rainfall was designated with 40, 60 and 80 mm/h rainfall intensity, which lasted for 30 minutes. Before rainfall application, eight gauges were placed throughout the rainfall area to calibrate rainfall intensity.

Sampling and data analysis: The second simulated rainfall event for crusted and uncrusted surface started at the same time. Runoff and sediment samples were taken at 3-min intervals. Sediment samples were immediately weighed after the simulated rainfall and then oven-dried at 105°C. Runoff (L) and sediment yield (g) were determined gravimetrically. After the experiment, the runoff rate (L/m^2/min) and total soil loss (g) were calculated using the runoff and sediment samples collected in the rainfall process. Each treatment was replicated 3 times. Statistical analysis was carried out using SPSS 13.0 software and the paired *t*-test at 5% significance level was used to test significant differences about total soil loss among soil surface conditions. Multivariate analysis and partial correlation analysis were used to test main effects and interactions among the factors.

RESULTS

Effect of soil crusts on runoff rate and total soil loss: The runoff rate measured in crusted and uncrusted soil surface is shown in Fig. 2. The runoff rate was low at the beginning, increased gradually, and then approached a steady-state stage. The runoff rates at all rainfall intensities were significantly greater in crusted than that in uncrusted soils. In addition, there is an increasing trend of runoff rates with increasing rainfall intensity.

In the contour tillage treatment (Fig. 1a,b,c), the runoff rates were maintained at 0.42, 0.76 and 1.18 L/m^2/min in crusted soil for different rainfall intensities, while 0.31, 0.53 and 0.91 L/m^2/min in uncrusted soil. In the straight slope treatment (Fig. 1d,e,f), the runoff rates were maintained at 0.58, 0.91 and 1.22 L/m^2/min in crusted soil for different rainfall intensities, while 0.42, 0.91 and 1.15 L/m^2/min in uncrusted soil. Steady-state under both tillage treatments was reached at 3 min in crusted soil while at 18 min in uncrusted soil.

Total soil loss measured both in crusted and uncrusted soil is displayed in Fig. 3. For all the rainfall intensities and both the tillage treatments, the similar result was found: total soil loss was significantly (α=0.05) smaller in crusted than that in uncrusted soil. The amount of total soil loss in uncrusted soil is 1.98-2.12 times as high as crusted soil under CT treatments, and correspondingly, 2.10-2.23 times under SS treatments. Total soil loss increased for both the soil surface conditions with an increase in rainfall intensity.

Effect of tillage treatments on runoff rate and total soil loss: The runoff rate measured with CT and SS treatments is shown in Fig. 4. The runoff tendency was the similar to each other which was low at the beginning, increased gradually, and then approached a steady-state stage. The drop in infiltration capacity of soil may be responsible for the increases in the runoff rates (Magunda et al. 1997). The runoff rates at all rainfall intensities were greater under SS treatment than that under CT treatment, especially for the steady-state runoff rates. SS treatments resulted in 1.28-1.87 times greater steady-state runoff rate than CT treatments. Total soil loss measured from both the treatments is displayed in Fig. 5. Total soil loss was significant (α=0.05) under CT treatment than that under SS treatment. The total soil loss was measured during the whole stage at 186.57 g (CT) vs 278.90 g (SS), 246.23 g (CT) vs 614.23 g (SS), and 319.53 g (CT) vs 1254.70 g (SS) under 40 mm/h, 60 mm/h and 80 mm/h rainfall intensity, respectively.

Analysis of the main effects and interactions of rainfall intensity, soil crusts and tillage treatment on total runoff yield and total soil loss: Table 1 presents multivariate analysis results for the total runoff yield and total soil loss. Each of the main factors (rainfall intensity, soil crusts and tillage treatments) had highly significant ($p < 0.001$) effects on both total runoff yield and total soil loss (Table 1). Interactions among the main factors were also significant. However, the interactions between rainfall intensity and tillage treatment on total runoff yield and total soil loss were more significant ($p < 0.01$) than the other interactions ($p < 0.05$).

Table 2 shows the results of partial correlation analysis of the data for the total runoff yield and total soil loss. Rainfall intensity had positive correlation while tillage treatments had the negative correlation with total runoff yield and total soil loss; soil crusts had a positive correlation with total runoff yield while a negative correlation with total soil loss. Rainfall intensity had the greatest correlation (0.600 by Person Correlation Coefficient analysis and 0.900 by Partial Correlation Coefficient analysis) with the total runoff yield after eliminating the effects of soil crusts and tillage treatments. Tillage treatments had the greatest correlation (0.511 by Person Correlation Coefficient analysis and 0.688 by

Partial Correlation Coefficient analysis) with the total soil loss after eliminating the effects of rainfall intensity and soil crusts.

DISCUSSION AND CONCLUSION

Surface sealing has been mentioned several times as the process responsible for runoff rate (Assouline & Ben-Hur 2006, Ben-Hur & Lado 2008, Zhang et al. 1998). Our results showed that the steady-state was earlier happened in crusted soil than uncrusted soil. Chen et al. (1980) commented that steady state runoff indicated that seal resistance to infiltration reached equilibrium with erosive forces acting on the seal. However, the fresh soil surface needed time to surface sealing formation, so the soil surface with the antecedent soil crust was easy to reach the steady state. Neave & Rayburg (2007) found that the initial crusts development was an important contributor to runoff. Under the same rainfall intensity and tillage treatment the runoff discharge rate measured in crusted soil were always significantly higher than those in uncrusted soil. The soil crusts reduced infiltration rate and increased runoff volume. In the case of an uncrusted surface, the soil was loose and soil permeability was high. Thus, runoff volume was low. Runoff rates in crusted soil were high.

Uncrusted soil is usually considered to be the most erodible condition, and in the results from these experiments the total soil loss was lower in crusted soils under the same rainfall intensities and tillage treatments than in uncrusted soils. This was because the soil particles on the uncrusted soil surfaces could be easily removed or flushed away at the early stages of runoff generation (Zhu 2002). In field trials, Fox et al. (2004) also concluded that breaking the surface crust increased erosion considerably since the freshly tilled condition resulted in abundant loose sediments.

In an agricultural environment, tillage operations produce abrupt changes in roughness. Soil roughness describes the micro-variation in soil elevations across and it is another important highly suited to the study of soil susceptibility to the processes like infiltration, evaporation, wind and water erosion (Moreno et al. 2008). Soil roughness has been noted to affect runoff and erosion in some field and laboratory experiments which were small plots or had slope lengths less than 1 m (Renard et al. 1997). In this study, the runoff rates were significantly higher under the SS treatments compared with those under the CT treatments. These results are in agreement with the studies of Romokens et al. (2001), who reported that soil roughness increased the length of the flow path and flow time, and it also decreased runoff velocity.

Soil roughness increases the surface storage capacity of rain and reduces runoff rate and thus erosive power of runoff (Hairsine et al. 1992, Onstad 1984, Huang & Bradford 1990). Total sediment yield for the initially smooth surfaces was generally appreciably greater than that for the initially rough surface conditions. The same trend was observed in this study that sediment yield followed as CT treatment < SS treatment in crusted and uncrusted soils due to the impacts of the oriented roughness elements of the treatments. The findings are also completely consistent with those findings reported by Gómez & Nearing (2005) and Zhao et al. (2013). Zhao et al. (2013) who believed that depressions on the surface played a decisive role in reducing total sediments, as more sediment was deposited in these areas following rainfall. CT treatment which had more distinct

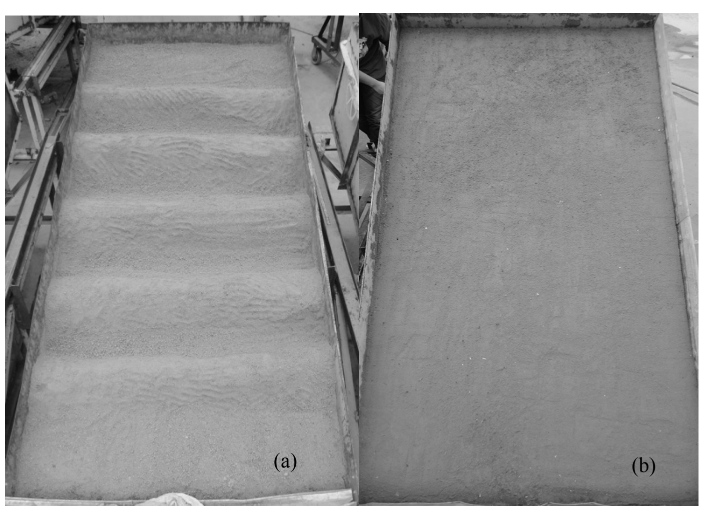

Fig. 1: Photographs of two boxes with different types of tillage treatments (a) Contour tillage (CT), (b) Straight slope.

Table 1: Multivariate analysis of rainfall intensity, soil crusts and tillage treatments on total runoff yield and total soil loss.

Source	Num DF	Total runoff yield	Total soil loss
Rainfall intensity	2	***	***
Soil crusts	1	***	***
Tillage treatment	1	***	***
Rainfall intensity × Soil crusts	2	*	*
Rainfall intensity × Tillage treatment	2	**	**
Soil crusts × Tillage treatment	1	*	*
Rainfall intensity × Soil crusts × Tillage treatment	2	*	*

* = p< 0.05; ** = p<0.01; *** = p<0.001

Table 2: Partial correlation analysis of rainfall intensity, soil crusts and tillage treatments on total runoff yield and total soil loss.

Rainfall intensity	Soil crusts	Tillage treatment	Notes	
Total runoff yield	0.600	0.583	-0.465	Person Correlation Coefficient
Total soil loss	0.504	-0.442	-0.511	
Total runoff yield	0.900	0.896	-0.848	Partial Correlation Coefficient
Total soil loss	0.683	-0.634	-0.688	

depressions than SS treatment was easy for net deposition occurred during rainfall, as depressions acted as temporary puddles before the retained water overflowed and flowpath connectivity occurred across the surface (Darboux et al. 2001).

The effects of rainfall intensity, soil crusts and tillage treatments on soil erosion were complementary to each other. Helming et al. (1993) found that both rainfall intensity and micro-relief affected runoff significantly. The kinetic energy of drops impacting on the soil surface leads to sealing, which is the actual trigger mechanism for runoff formation. Higher rainfall intensity led to an earlier start and to an initially steeper rise in runoff curves. Our results confirmed this report that the rainfall intensity had the greatest correlation (0.600 by Person Correlation Coefficient analysis and 0.900 by Partial Correlation Coefficient analysis) with the total runoff yield after eliminating the effects of soil crusts and tillage treatments. Bielders et al. (1996) believe that surface topography is an essential factor contributing to crust development. Chen et al. (1980) and Bodna´r & Hulshof (2006) found that depositional crusts could develop in surface depressions in field situations which led to reduction in the hydraulic conductivity of soils and increased runoff (Ndiaye et al. 2005). It was found in this study that the soil crusts resulted in a greater correlation on runoff than tillage treatment, because the function of depositional crusts. As a result, the correlation of soil crusts on total runoff yield was 0.583 by Person Correlation Coefficient analysis and 0.896 by Partial Correlation Coefficient analysis, which was greater than the correlation of tillage treatments (0.465 by Person Correlation Coefficient analysis and 0.848 by Partial Correlation Coefficient analysis). Morin (1993) mentioned that in many cases, but not always, limited soil infiltration ability was caused by surface crusting rather than by deeper profile properties. Fox et al. (1998) concluded that initial surface roughness influenced the thickness and spatial distribution of the depositional crusts and may influence the rates of mound erosion and of infilling of depressions. Surface roughness decreased as depressions filled with sediments from thick depositional crusts and micro-aggregates detached from the mounds. Consequently, tillage treatments had a greatest correlation (0.511 by Person Correlation Coefficient analysis and 0.688 by Partial Correlation Coefficient analysis) with the total soil loss.

This study explored the effects of soil crusts and tillage treatments on runoff rate and soil loss. The runoff rates were always measured greater in crusted soils than those in uncrusted soils. The opposite phenomenon was observed for soil loss. In all the cases, total soil loss was lower in crusted soils than that in uncrusted soils. When rainfall intensity increased, the runoff rates and soil loss both increased. Runoff rates under the CT treatment were smaller than those under the SS treatment. The same trend was also observed for soil loss because of the soil surface microtopography. Rainfall intensity, soil crusts and tillage treatments had very significant ($p < 0.001$) effects on both total runoff yield and total soil loss. The interactions between rainfall intensity and tillage treatment on total runoff yield and total soil loss were highly significant ($p < 0.01$) than the other interactions ($p < 0.05$). Rainfall intensity had positive correlation while tillage treatments had the nega-

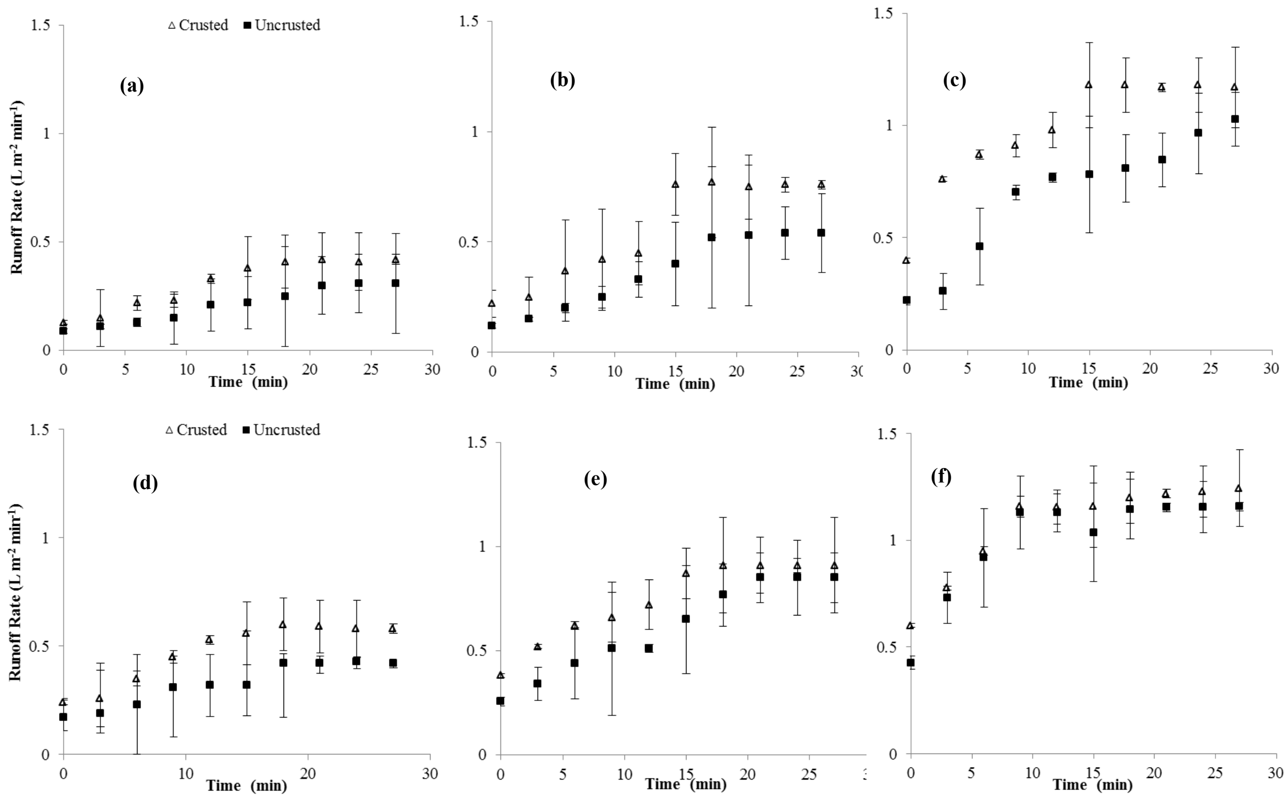

Fig. 2: Runoff rate measured during the rainfall simulation. (a) contour tillage - 40 mm/h; (b) contour tillage - 60 mm/h; (c) contour tillage - 80 mm/h; (d) straight slope - 40 mm/h; (e) straight slope - 60 mm/h; (f) straight slope - 80 mm/h

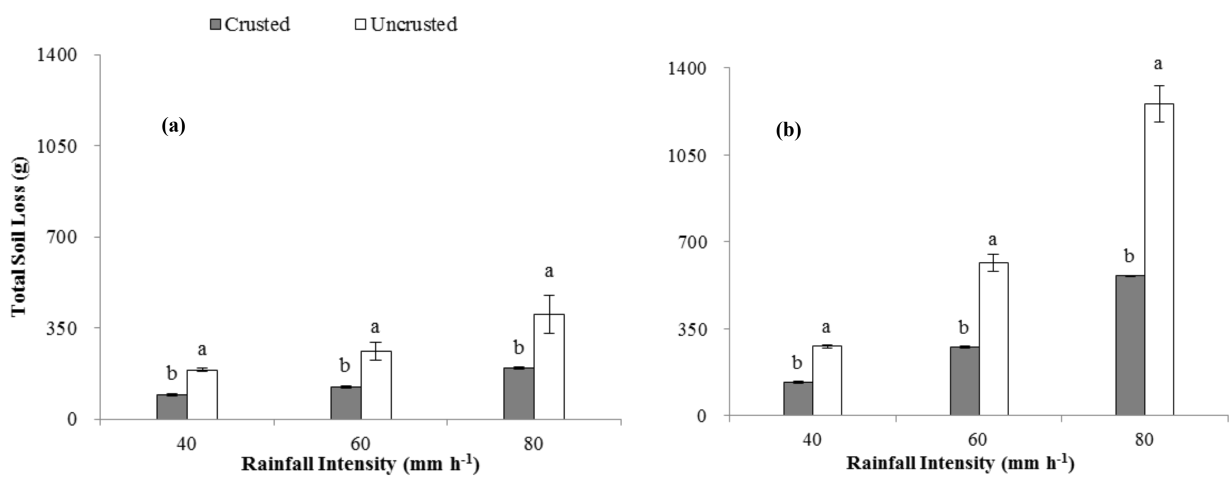

Fig. 3: Total soil loss measured during the rainfall simulation. (a) contour tillage; (b) straight slope. The different letters means the significant difference between crusted and uncrusted soil surface by paired *t*-test (α=0.05).

tive correlation with total runoff yield and total soil loss; soil crusts had a positive correlation with total runoff yield while a negative correlation with total soil loss. Rainfall intensity had the greatest correlation with the total runoff yield after eliminating the effects of soil crusts and tillage treatments. Tillage treatments had the highest correlation with the total soil loss after eliminating the effects of rainfall intensity and soil crusts. As a result, the tillage treat-

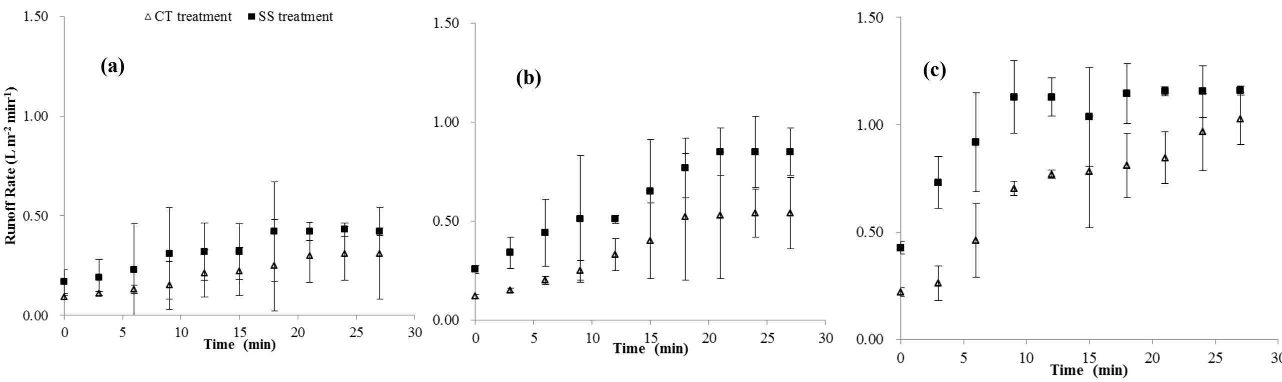

Fig. 4. Runoff rate measured during the rainfall simulation. (a) Rainfall intensity = 40 mm/h; (b) Rainfall intensity = 60 mm/h; (c) Rainfall intensity = 80 mm/h

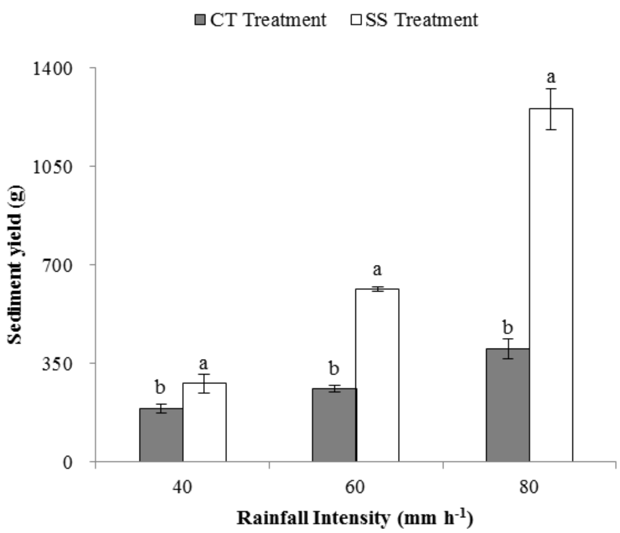

Fig. 5: Total soil loss measured during the rainfall simulation. The different letters mean the significant difference between CT and SS treatments by paired *t*-test (α=0.05).

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