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Original Research Paper

The Effect of Different Soil Erosion Stages on Surface Roughness Under Simulated Rainfall

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ABSTRACT

Soil erosion is a complex and dynamic process. Correspondingly, as one of the main factors of soil erosion, Soil surface roughness (SSR) is also complex and dynamic in the process of soil erosion. Soil erosion process was divided into four stages: before the rain (S_0), splash erosion stage (S_1), sheet erosion stage (S_2), rill-gully erosion stage (S_3). The objective of this research is to make it clear how soil erosion affects SSR in detail through evaluating the changes of SSR in different soil erosion stages. Soil beds were operated by four different tillage systems to shape four different surface conditions: artificial shallow ploughing (ASP), artificial deep ploughing (ADP), contour ploughing (CT), and no tillage treatment as (CK). Thirty six experiments were conducted under simulated rainfall. Several indices including the standard deviation (S_d) of soil surface elevation, SSR, and the chain method index C_r' were measured before and after each rainstorm. The result shows that: For ASP, ADP, and CP tillage systems, in splash erosion stage, all the, S_d SSR, and C_r' decrease significantly; in sheet erosion stage, S_d, SSR, and C_r' continue to decrease but the quantity of change is small; in rill-gully erosion stage, S_d, SSR and C_r' increase obviously. For CK, all the S_d, SSR, and C_r' increase all the time. This means splash erosion and sheet erosion can decrease SSR, but the degree is different. Rill-gully erosion can increase SSR, make soil surface rougher than before.

INTRODUCTION

Soil surface roughness (SSR) describes the micro-invasion in the surface elevation which affects runoff, soil loss, surface depression storage, water infiltration, overland flow velocity and organization (Huang & Bradford 1990, Govers et al. 2000, Darboux et al. 2002). It is strongly affected by field management practices and mainly results from tillage practices and soil texture (Zobeck & Onstad 1987, Guzha 2004, Vázquez et al. 2005, Moreno et al. 2008, Moreno et al. 2011).

Soil roughness and canopy cover are important factors in preventing soil erosion (Eltz & Norton 1997). In cultivated areas, during the time of no residues, soil erosion mainly comes from tillage disturbance. During rainfall events, surface roughness affects runoff generation by providing water surface storage in the depressions and altering the flow direction on the surface, which influence soil erosion directly (Darboux et al. 2002).

At a small scale, SSR is an erodibility factor which determines the resistance or vulnerability of the soil to erosion. At a higher but contiguous scale, SSR becomes an erosivity factor, structurally mediating erosive energy of wind and water (Merrill et al. 2001). So, SSR is an important parameter of soil erosion. Many erosion factors relate to surface processes, such as depression water storage, raindrop or wind shear detachment, and sediment transport have characteristic lengths in millimetre scales (Huang & Bradford 1990). Therefore, soil roughness, which modifies the soil surface profile, is important to understand soil erosion mechanisms and its evolution.

The existing literature mainly focus on the measurement, calculation and mathematical description of soil roughness (Currence 1970, Linden & Van Doren 1986, Lehrsch et al. 1988, Borselli 1999, Hansen et al. 1999), or on the effect of soil roughness on runoff (Cogo et al. 1984, Katz et al. 1995, Darboux & Huang 2005), but rare studies research on the interaction of soil erosion process and surface roughness.

Surface roughness conditions affect soil erosion by determining the drainage network development. But the surface roughness-sediment concentration relationship was not monotonic in nature. Initially smooth, uniform surfaces may yield less soil loss than initially rough surfaces (Romkens et al. 2002).

Soil erosion is a very complex and dynamic process. Correspondingly, the changes of surface roughness are also complicated and variable. The purpose of this study was to evaluate the detail changes of SSR in the process of soil erosion, and make it clear that whether SSR is increased or decreased in each erosion stage to reveal the effect of soil erosion on surface roughness. Therefore, rainfall should be cut to a series of stages in order to study SSR changes in the processes of soil erosion step by step.

Jester and Klik's study focused on only two roughness conditions: an initial and an ultimate roughness state (Jester & Klik 2005). They investigated two different aggregate sizes initial roughness conditions (aggregates <20 mm [0.78 in] and <63 mm [2.48 in]), each one suffered a 90 mm (3.54 in) of simulated rainfall. The surface roughness was measured before and after the rainstorm, and the results were compared. But only these two statuses cannot illustrate how roughness changed during the rainfall in detail.

Laura and Daniel operated two rainfall times (10 and 40 min) on two soil plots (deOro & Buschiazzo 2011). The total rain amounts were 7 and 28 mm (0.28 in and 1.1 in), respectively. The degradation rate of the oriented and the random roughness were comparative and analysed before and after the rainfall. But they did not state the reason why it should be 10 and 40 min.

Some scientists set a series of simulated rainfall, but they studied surface roughness due to a constant rainfall time or rain amount instead of water erosion evolution stages. Romkens and Helming applied successive storms of 0.3, 0.5, 0.7, 1.5, 3.0 and 6.0 h to each research plot (Romkens & Helming 1987). They described soil roughness as a function of the type-

$$R = C_1 + C_2 \cdot \exp(-C_3 \cdot r) \quad ...(1)$$

Where C_1, C_2 and C_3 are regression coefficients, representing the effect of rainfall, soil and soil antecedent conditions, r is the cumulative rainfall. They comparatively studied the changes of R among three tillage systems before and after six different rainfalls. But they did not explain why these durations were chosen. Meanwhile, all the rainfall were successive, so, the changes of R just showed the effect of duration of storms rather than erosion evolution on soil roughness.

Bertuzzi et al. (1990) also conducted a series of experiments to estimate soil roughness changes by testing roughness indices. They set three different rainfall periods, in which cumulative rains were 30, 64 and 100 mm (1.2, 2.5 and 3.9 in) respectively. These three stages were defined based on Boiffin's sealing processes theory (Boiffin 1986). Using visual criteria, the evolution of the soil surface structure can be classified in four typical stages. (1) S_0, initial soil surface resulting from tillage. (2) S_1, structural crust, soil aggregates, and clods disintegrate due to raindrop impact; continuous patches appear and expand due to interstitial infilling. (3) S_1^+, local appearance of depositional crusts. (4) S_2, depositional crust, the fragmented layer becomes continuous, depositional area is formed in small surface depressions where puddles appear during rainfall. These four stages were classified due to soil surface structure, especially sealing processes, not soil erosion evolution.

Daboux and Huang (2005) divided rainfall-runoff process into three stages to find whether SSR increase or decrease water and particle transfers on earth. Stage 1 is mainly for surface wetting and depression filling and ends when runoff starts at the point of observation. Time to runoff is usually used to characterize this stage. Stage 2 is mainly associated with the rising portion of the hydrograph as the runoff contributing area expands. At Stage 3, runoff reaches a plateau or an apparent steady state when the entire surface is contributing runoff. These three stages are reasonable for runoff development, but not appropriate for the entire soil erosion evolution, which is not just involve runoff, but detachment and transport of soil particles, depression storage, infiltration, topography, and crusting etc.

Erosion from water typically occurs in the following ways.

1. Raindrop splash: The first step in the erosion process begins as raindrops impact the soil surface. Splash erosion is the detachment and airborne movement of small soil particles. It can compact the upper layer of soil, creating a hard crust that inhibits plant establishment.
2. Sheet erosion: Sheet erosion is the process by which transportation of soil particles begins. Sheet erosion occurs when overland flows as a sheet over large areas down the slope washing away the top soil. One of the most important characteristics of sheet erosion is the detachment of soil particles and their removal down slope by water flowing overland as a sheet instead of in definite channels or rills. The process of sheet erosion is gradual, and difficult to detect until it develops into rill erosion.
3. Rill erosion: Rill erosion occurs as runoff begins to form small concentrated channels. It refers to the development of small, ephemeral concentrated flow paths, which function as both sediment source and sediment delivery systems for erosion on hill slopes. As rill erosion begins, erosion rates increase dramatically due to the resulting concentrated higher velocity flows.
4. Gully erosion. Gully erosion results from water moving in rills, which concentrate to form larger channels. When rill erosion can no longer be repaired by merely tilling, it is defined as gully erosion. Gully is sufficiently deep that it would not be routinely destroyed by tillage operations, whereas rill erosion is smoothed by ordinary farm tillage.

From visual perspective, there are three obvious phenomena in the process of soil erosion from water.

1. Runoff: When the soil is infiltrated to full capacity and excess water from rain, melt water, or other sources flows over the land, surface runoff occurs. Splash erosion occurs before and at the beginning of runoff occurs (Zheng & Gao 2003). Once a steady runoff is established, raindrops cannot hit soil directly. Raindrops fall on the surface of thin-layer runoff, and the lamellar runoff will greatly reduce the raindrops impact. The impact of the raindrop breaks apart the soil aggregate. Particles of clay, silt and sand fill the soil pores and reduce infiltration. After the surface pores are filled with sand, silt or clay, overland surface flow of water begins due to the lowering of infiltration rates. Once the rate of falling rain is faster than infiltration, runoff takes place.
2. Lamellar layer: When overland flow occurs, small soil particles, broken soil aggregates will be transported with surface runoff. There are two stages of sheet erosion. The first is rain splash, in which soil particles are knocked into the air by raindrop impact. In the second stage, the loose particles are moved down slope by broad sheets of rapidly flowing water filled with sediment known as sheet floods. This stage of sheet erosion is generally produced by cloudbursts, sheet floods commonly travel short distances and last only for a short time. At this stage, small size lamellar soil layers appear in large numbers distinctly.
3. Rill-gully: As sufficiently deep and wide washout by runoff, small concentrated flow paths will develop to rills gradually, and then rills will grow up to narrow channels, then to gullies at last.

Considering the four types of soil erosion combined with obvious visual changes present on soil surface, this study defined four stages to illustrate the process of soil erosion from water:

1. S_0, initial soil surface before rainfall events.
2. S_1, when the steady runoff takes place. In this stage, the only soil erosion type is splash erosion.
3. S_2, when plenty of lamellar soil layers appear. In this stage, although splash erosion still exists, the impact of which is relatively too weak to compute. Sheet erosion becomes to be the essential erosion type.
4. S_3, when major gully occurs and grows but the rest of soil surface tends to be steady. The steady means surface sealing, and crusting prevent runoff from washing away the soil particle and aggregates.

In 1986, Romkens and Wang defined four types of roughness: (1) Micro-relief variations due to individual grains, micro-aggregate or aggregate sizes, (2) random roughness, which represents surface variations due to soil clod, (3) oriented roughness, which describes the systematic variations in topography due to farm implements and (4) big-scale roughness, represents elevation variations at the field, basin or landscape level (Romkens & Wang 1986).

MATERIALS AND METHODS

Site description: From 2008 to 2009, 36 laboratory experiments were conducted at State Key Laboratory of Soil Erosion and Dryland Farming on Loess Plateau located at Yangling, Shaanxi province in China. The climate of the study area is warm-temperate, subhumid, continental monsoon climate. Farmers there still plough farmland by manpower because of the slope and poor economic condition.

The soil used in this experiment was top Lou soil, one of silty clay loam soils. The soil texture is 32% clay, 49% silt, 19% sand. The soil bulk density is 1.25 g/cm^3, field moisture capacity is 22%, soil water content is around 10%, and the organic matter content is 1%. The soil was taken from wheat/maize rotation arable land nearby the laboratory and was kept with the natural water content.

Experiment design: The experiments were conducted in laboratory under simulated rainfall. Natural and bare soil was filled in a manual 2 m × 1 m × 0.4 m (6.6 ft × 3.3 ft × 1.3 ft) slope-adjustable steel box to compose a soil bed. There were four different tillage treatments carried out on soil beds to imitate corresponding four types of soil surface conditions which were produced by different tillage systems. They are: (1) artificial shallow ploughing (ASP), (2) artificial deep ploughing (ADP), (3) contour ploughing (CT), and (4) no tillage treatment (CK). Fig. 1 shows the pictures of these four tillage systems and Table 1 lists the quantitative characteristics of them.

Each soil bed was adjusted to 27% slope and was submitted to simulated rainfall of 120 mm/h (4.7 in/h) after tillage treatments. The rain would be stopped for three times during the process. The first time was when the steady runoff took place, the second time was when lamellar soil layers appear, and the final time was when major gully occurs. These three stops divided the whole soil erosion process into four stages as mentioned above: S_0,S_1,S_2, and S_3. SSR were measured before the rain and after each stop. At each stage, rain was stopped as soon as the typical characteristics occurred and measured soil roughness immediately, and then continue to the next stage.

Each soil bed was operated to one tillage treatment and would suffer three rain events. Each tillage treatment has three duplications. There were 36 rain events in total.

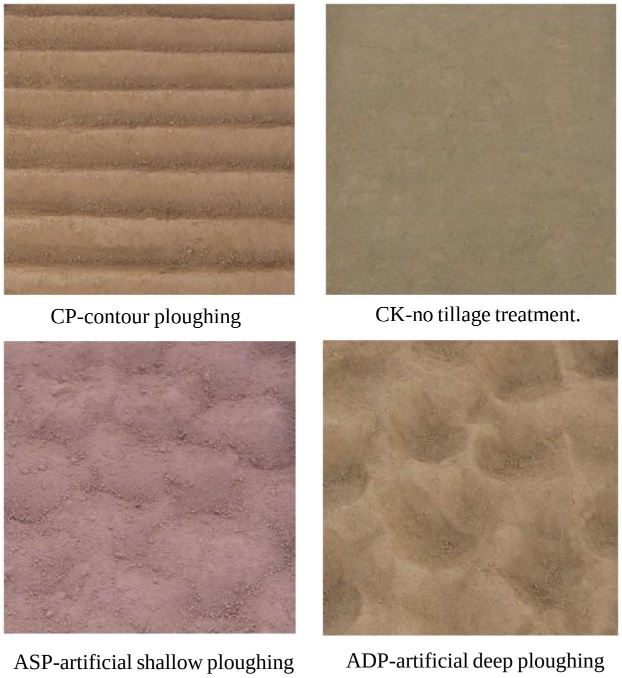

Fig. 1: Four types of tillage systems.

Fig. 2: Homemade laser scanner.

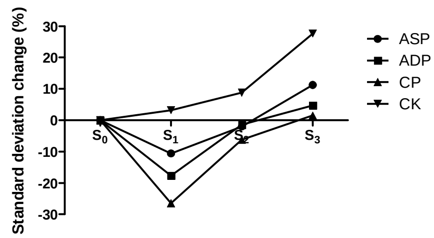

Fig. 3: The standard deviation changes of four tillage systems in different erosion stages.

Rainfall simulator device: The Rainfall simulation hall is the second largest one in the world and it is located in the key laboratory. The valid rainstorm area reaches up to 1,260 square meters. In this rainfall simulation hall, there are two types of rainfall simulation systems: lateral jets system and vertical jets system.

Lateral jets system was developed by Institute of Soil and Water Conservation, CAS. Rainfall intensity range from 40 mm/h (1.6 in/h) to 260 mm/h (10.2 in/h), the rainfall uniformity was over 80%. The maximum continuous rainfall time is 12 hours. Nozzles are 16 m (52 ft) high from floor which makes all raindrops reach the Raindrop terminal velocity to infinite approach the natural state.

Vertical jets system was imported from Japan. Rainfall intensity range from 30 mm/h (1.2 in/h) to 350 mm/h (13.8 in/h), the rainfall uniformity was also over 80%. The maximum continuous rainfall time is 12 hours. Rainfall height is 18 m (59 ft).

In this study, we used lateral jets system. The whole procedure of simulated rainfall is controlled automatically by a computer.

Roughness measurement technique and calculation: SSR was measured by both laser scanner and chain method.

The laser instrument in this experiment is homemade laser scanner (Fig. 2). It is used for automated measurement of surface elevations by a point laser probe. It consists of three major parts: (1) Transmitting and receiving device. An optical transducer for the detection of surface elevation and a laser probe used to project a laser spot onto soil surface meanwhile receive the return elevation data. (2) Framework. This is a computer-controlled, motor-driven and two-dimensional traversing framework and orbit. (3) Data processing device. It consists of a computer and software. The computer is used to control the motion of the laser probe carriage and to record and process elevation data. The software is used for analysing and processing data. In this experiment, surface relief was measured with the laser probe point by point in 20 mm × 20 mm (0.79 in × 0.79 in) spaced grid. The maximum scanning area was 1 m × 1 m (3.3 ft × 3.3 ft).

Linden and Van Doren (1986) defined two parameters Limiting Elevation Difference (LD) and Limiting Slope (LS). The spatial variation of surface roughness can be well described by LD and LS. They obtained a roughness index which is a modified spatial variability procedure termed the mean absolute-elevation-difference analysis. The mean absolute-elevation-difference is defined as:

$$\Delta Z_h = \sum_{i=1}^{n} \left| Z_i - Z_{i+h} \right| / n , \quad ...(2)$$

Where ΔZ_h is the mean absolute-elevation-difference, Z_i is the elevation of point i, Z_{i+h} is the elevation of the point $i+h$ which is lag number h from point i, and n is the number of pairs of elevation data that occur in the data set at a lag inter-

Table 1: The quantitative characteristics of four tillage systems.

Tillage systems	Depth (cm)	Distance (cm) Between furrows	Within a furrow
Contour Ploughing (CP)	7-10	30	Continuous
Artificial Shallow Ploughing (ASP)	4-5	15	10
Artificial Deep Ploughing (ADP)	5-8	20	25
No tillage treatment (CK)	-	-	-

Table 2: Statistical features of elevation.

Tillage System	Stage	Elevation/m Range	Mean	S_d*	C_v†
ASP	S_0	0.0700	0.2269	0.0115	0.0507
	S_1	0.0630	0.2292	0.0104	0.0454
	S_2	0.0620	0.2264	0.0102	0.0451
	S_3	0.0740	0.2254	0.0115	0.0510
ADP	S_0	0.0800	0.2192	0.0167	0.0762
	S_1	0.0650	0.2166	0.0142	0.0656
	S_2	0.0800	0.2141	0.0140	0.0654
	S_3	0.0930	0.2148	0.0147	0.0684
CP	S_0	0.0800	0.2085	0.0172	0.0825
	S_1	0.0700	0.2043	0.0136	0.0666
	S_2	0.0680	0.2084	0.0128	0.0614
	S_3	0.2320	0.2057	0.0130	0.0632
CK	S_0	0.0080	0.2176	0.0030	0.0138
	S_1	0.0110	0.2165	0.0031	0.0143
	S_2	0.0280	0.2150	0.0034	0.0158
	S_3	0.0480	0.2095	0.0047	0.0224

*: Standard deviation of elevation
†: Coefficient of correlation of elevation

val. Linear regression analysis was used to relate mean elevation differences ΔZ_h to a lag distance ΔZ_h. This relationship was described by the equation:

$$\Delta Z_h = 1/[(b(1/\Delta X_h)) + a], \quad ...(3)$$

Where ΔZ_h is the mean absolute-elevation-difference at a horizontal spacing of ΔZ_h, and a and b are fitted parameters. The reciprocal of parameters a and b, which are the intercept and slope, respectively, of the linear regressional fit of the reciprocal form of eq. (3), are for convenience defined as:

$$LD = 1/a, \quad ...(4)$$

$$LS = 1/b, \quad ...(5)$$

Where a and b are parameters from eq. (3). Linden and Van Doren (1986) also researched the goodness of fit of the relationship between LD, LS and RR. They indicated that LD is a sensitive index of the roughness condition which is the asymptote value of the first-order variance (i.e., the sill) and it is related to RR. The parameter LS is not associated with RR. The optimal parameter of soil roughness is:

$$SSR = (LD \times LS)^{1/2} \quad ...(6)$$

Laser technique is a three dimensional (3D) and noncontact way, meanwhile, chain method is a two dimensional (2D) profile and a contact measurement technique. 3D digital technique is far more accurate and veracious than 2D technique. What is more, noncontact measurement way can make the micro-geomorphology keep natural and without disturbance which is the critical defect of 2D measurement way.

In this study, we used chain method to test and verify the results of laser scanner and the way of calculating SSR.

In 1993, Ali Saleh used a roller chain to measure SSR (Saleh 1993). The roller chain was given length L_1, and was carefully placed on the soil surface following aggregates and depressions along a shorter horizontal length L_2. The difference between L_1 and L_2 is related to the degree of roughness.

$$C_r = (1 - L_2 / L_1) \cdot 100 \quad ...(7)$$

In this study, we improved a little different way. The horizontal length L_2' was given, which is the length of the measure zone (180cm or 5.9 ft). A much more precise chain placed following the roughness surface in the measure zone to measure the surface length L_1' other than a roller chain. The computing method of parameter C_r' is the same as C_r.

$$C_r' = (1 - L_2' / L_1') \cdot 100 \quad ...(8)$$

L_1' was measured every 10cm (3.9 in) width, so each roughness surface has 10 data of C_r'. Then average of C_r' was computed as the parameter of chain method.

RESULTS AND DISCUSSION

Elevation changes in different erosion stages: Some statistic parameters of soil surface elevation are listed in Table 2 as Yvonne et al. (2008) presented that the statistic features of soil surface elevation can describe the topographic relief if the effect of slope is removed.

For ASP, from S_0 to S_1, the standard deviation S_d of elevation decreases 10% and the range decreases from 0.07 m to 0.063 m (2.8 in to 2.5 in) which implies that the dispersion degree of elevation value is declined. The coefficient of variation C_v declines 10% and the mean increases from 0.2269 m to 0.2292 m (8.9 in to 9.0 in). This demonstrates that soil surface becomes a little smoother than the initial state. This change can be explained by the splash erosion mechanism easily. At the beginning of rainfall, raindrop hit the loose soil surface, making surface soil wetted and the soil aggregation detached and removed. Thus, loose soil becomes tighter and granular soil particle or aggregation becomes dispergated. From S_1 to S_2, S_d decreases 2%, range decreases 0.001 m (0.04 in), and C_v declines 1%. The variation tendency is the same as last stage, but all of the variation amounts are much less than the first stage. In the sheet erosion stage, sheet floods flow over soil and make soil surface present lamellar sheets. Overland flow cuts down the ridge and fills the depression with sediment on its way, which makes the S_d less than before. From S_2 to S_3, both S_d and C_v increase 13%. Range increase 1.2 cm (0.5 in), which is a sharp increase. All of the changes of these parameters show that rill or gully occurred in this stage.

The ADP and CP tillage systems have the same variation trend of S_d and C_v in every stage as ASP. They go down in the first stage, turn to rise in the second stage, and then keep rising in the last stage. However, quantity of the change is different. According to Fig. 3, S_d of CP declined the most in stage S_1 and rise the least in stage S_3, while ASP declined the least in stage to S_1 and rise the most in stage S_3. The change of ADP is always gentle.

But elevation change of CK is totally different from the above three types. As a control sample, the initial surface roughness of CK was assumed to be zero. Any disturbance of the soil surface will increase soil roughness. So, from stage S_0 to S_2, C_v increases as the decreases of mean and increases of S_d. Soil roughness goes up in this stage, which is opposite to ASP, ADP and CP. From stage S_1 to S_2, the increasing trend of all range, S_d and C_v suggest that soil surface of CK becomes rougher. In the last stage, all the above-mentioned statistical indices increase further. So, for CK, as rainfall time accumulated, S_d of elevation increase continuously in every stage. Specially, it increase significantly in stage S_3, which means the rill or gully disturbed soil surface seriously.

The change of SSR in different erosion stages: SSR was measured vertical to the direction of tillage. Fig. 4 shows the SSR of different tillage systems before and after each rainfall events.

ASP and ADP have the similar variation trend as follows: From S_0 to S_1, the SSR declines obviously, it keeps going down a little to S_2, and then it has a slight rise in the last stage. Although they have the same trend, the SSR value is actually different. SSR value of ASP in each stage is always around 0.001 less than ADP. Before the rain, both the depth and distance between furrows of ASP tillage system are less than that of ADP. The spacing distribution of tillage treatments of ASP and ADP are similar: ridges and furrows scattered randomly with no rules. The only difference is the size of ridges and furrows. So, during the rain, SSR change trends of ASP and ADP are similar too.

The SSR change of CP is remarkable. From S_0 to S_1, it declines significantly from 0.063 to 0.037, then it decreases only 0.001 during S_2, but it increases dramatically to 0.083 in the last stage. CP has the largest depth from ridge to furrow and the range of the elevation is the most, so the initial SSR of CP is the highest and it will decrease most in stage S_1. Once rill or gully occurs, the range will increase rapidly. Accordingly, SSR in stage S_3 will rise up dramatically.

CK is special. Other than remarkable, the change of CK is very slight. From S_0 to S_1, it increases a little bit, only 0.0003. And it keeps increasing even less to S_2, 0.0002. From S_2 to S_3, SSR of CK increases the most of all the stages, 0.0033. Before the rain, CK was supposed to be smooth. So, in the first stage, although the absolute elevation of CK descends, SSR will just change rarely. In the second stage, sheet layer will make soil surface a little rough, but not obvious. Till the last stage, rill or gully makes the elevation present significant decrease. That is the essential factor to rise up SSR.

The change of C_r' in different erosion stages: As Fig. 5 shows, C_r' decreases from S_0 to S_1 distinctly, then continue to go down slightly from S_1 to S_2, in the last stage S_3, C_r' increases relatively significantly. This rule is universal for all ASP, ADP and CP. The differences among them are the quantity of change also.

For ASP, C_r' changes from 5.62 to 3.93, to 3.89, and to 5.52 at last. For ADP, C_r' decreases from 7.25 in S_0 to 4.31 in S_1, then down to 4.04 in S_2, and at last, it rise up to 9.00 in stage S_3. For CP, C_r' decreases from 15.92 to 9.68 in stage S_1; then declines only 0.12 in S_2 from 9.68 to 9.56; in stage S_3, C_r' increases 1.93 to 11.49. Variation of CP is the most significant one and ASP is the slightest.

C_r' change trend of CK is similar to SSR change trend. It grows gently in the first and second stage, and then gets a relatively rapid increase in the last stage.

Soil roughness changes in splash erosion stage: In splash erosion stage, force of raindrops represents in two ways. One is hit, which means raindrops dripped down to soil surface and hit the soil particles to make loose surface to become tighter than before the rain. The other is splash. Besides hit, raindrops can splash the small or micro particles in all directions. Under this force, soil particles on the ridge would be splashed to the furrow; particles in the furrow would be splashed up, but would be splashed down finally. So, there would be slight settlement occurring in the furrow.

Under these two forces, the ridge elevation of shallow surface soil would decrease obviously; meanwhile, the furrow would be filled a little. So, soil roughness would be decreased significantly. ASP, ADP and CP obey the rules in

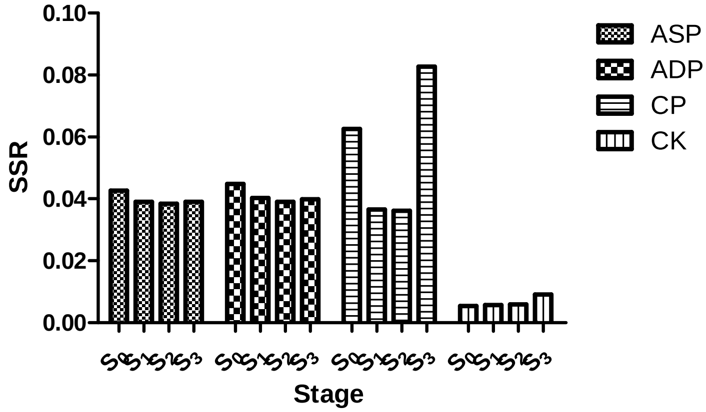

Fig. 4: The soil surface roughness of different tillage systems in erosion stages.

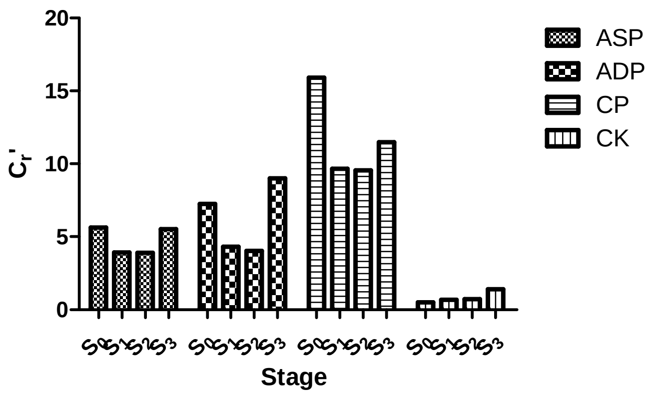

Fig. 5: C_r' of different tillage systems in erosion stages.

this stage, but CK is opposite. Roughness of CK increases in this stage. All the three parameters analysed in this study, S_d, SSR and C_r' can prove this decrease rule for ASP, ADP, and CP and the increase rule for CK.

The order of the decline amount is: CP>ADP>ASP. Before the rain, initial soil roughness state order is CP>ADP>ASP, that means CP is the roughest tillage treatment and the force of raindrop can influence it strongly. ASP is relatively smooth, so the effect of raindrop is not as much as that on CP and ADP. That is why ASP changes the least of all.

Soil roughness changes in sheet erosion stage: In sheet erosion stage, for ASP, ADP, and CP tillage systems, runoff plays a very important role in erosion and roughness variation. There are also two ways of runoff to affect soil. First, runoff flow over the surface soil, flush away soil particles of ridges and slope to makes the absolute elevation fallen down seriously. Second, runoff carries a large amount of bedload to flow away, and if it experiences a furrow, it will be deposited.

These two impacts make soil tend to become flat, though these impacts are not very strong. Therefore, in sheet erosion stage, soil erosion continues to decrease surface roughness marginally except CK.

Soil roughness changes in rill-gully erosion stage: In rill-gully erosion stage, for ASP, ADP and CP tillage systems, the roughness condition becomes complicated. Sheet erosion still been existing, even many rills or streams will turn up, and it will decrease soil roughness as usual. But once the rill comes into being, the down-cut effect will make the microtopography changed a lot. Intensifying soil fluctuation will lead to increase in soil roughness.

In this stage, soil surface is under the combination effect of these two opposite forces. So, increase and decrease exist simultaneously. It is hard to say which effect can gain the upper hand.

But as time goes on, the crusts and seals on top soil will prevent runoff from taking away soil particles. Meanwhile, the rill grows deeper and wider, and finally, it will become a gully. This kind of impact will increase roughness remarkably. Consequently, the increase of roughness will be strengthened but the decrease of roughness will be controlled. This means when gully grows big enough, SSR would be increased at last.

Soil roughness changes on CK: CK is the control treatment. It is supposed to be absolutely smooth initially. This is totally difference from the surface which has primary soil surface ups and downs. For smooth surface, no matter what effect it is, it will cause roughness to increase. Whether splash erosion, sheet erosion or rill-gully erosion, every force would make the smooth surface become rough. Thereby, the roughness of CK will increase all the time, especially when rill or gully occurs.

SUMMARY AND CONCLUSIONS

For ASP, ADP and CP tillage systems, the changes of C_d, SSR and C_r' in each stage reveal that in splash erosion stage, soil erosion decreases surface roughness significantly. After runoff occurs and before the rills take shape, sheet erosion is the main type of erosion. In this stage, soil erosion continues to decrease surface roughness with a small quantity. That means both splash and sheet erosion will decrease SSR, but with different degree. In rill-gully erosion stage, when rills grow mature enough, steady runoff cannot decrease roughness obviously any more, meanwhile, the undercutting and lateral shearing force of growing rills will make soil surface rougher significantly. That indicates rill-gully erosion will increase SSR because of the rill degradation.

For CK, soil erosion increases SSR all the time. That means rainfall will make a smooth surface to be rough, no matter what erosion stage it is.

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