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Effects of gravel-sand mulch on the runoff, erosion, and nutrient losses in the Loess Plateau of north-western China under simulated rainfall

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Abstract: Gravel mulching is a characteristic agricultural technique that has been used for hundreds of years in the north-western Loess Plateau of China. However, the effects of the gravel-sand mulch on the processes of the runoff, soil erosion, and nutrient losses are neither fully distinguished nor even known in many parts of the world. This study investigated how different gravel particle sizes in the mulch affected the runoff, erosion as well as the extent of the nutrient losses in the surface runoff. The laboratory experiments were conducted using a rainfall simulator with three gravel mulch treatments: (1) fine gravel mulch (FG); (2) medium gravel mulch (MG); (3) coarse gravel mulch (CG) and a control group, bare soil (BS). The results of these rainfall simulation experiments gave estimates on how the grain size influences the runoff and losses of the soil and its nutrients. Applying the gravel mulch significantly delayed the runoff's starting time when compared with the bare soil. Both the total runoff and soil loss increased with the grain size of the gravel mulch. Compared with the bare soil, the lowest surface runoff and soil loss was observed from the fine gravel treatment. These results clearly show that gravel mulch plays an important role in the runoff and sediment generation processes, and that it significantly reduces the surface runoff and soil loss. The losses of the total nitrogen (TN), total phosphorus (TP), and total organic carbon (TOC) from the bare soil were much higher than those under the gravel mulching. The fluctuations in these nutrient-loss processes were the most intense in the CG treatment, while the TC content, in initial runoff, was significantly higher in the FG than the other treatments. Our findings suggest gravel mulch is a useful water and soil conservation technique in the loess area of north-western China, and these results can inform one on the theoretical principles for properly utilising gravel-mulched fields.

Keywords: gravel mulch; rainfall simulation; sediment; soil erosion; surface runoff

Gravel mulch is a typical water and soil conservation technique that has been used for centuries in the north-western Loess Plateau of China. In this region, the mean annual precipitation ranges between 250 and 350 mm, and over 70% of which occurs during the monsoon months from June to September, when most precipitation events consist of heavy precipitation (Xie et al. 2006a, b). Gravel-sand mulch is a mixture of particles ≥ 2 mm in diameter, about 10 cm thick, that is used to reduce the risk of crop failure, which frequently occurs due to the low rainfall and high rates of evaporation in this region. Applying gravel-sand mulch effectively reduces the evaporation, but also increases the soil temperature and retains the soil moisture level (Nachtergaele et al. 1998; Xie et al. 2010; Ma & Li 2011). This technique

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has been promoted and widely adopted in China due to insufficient water resources and high irrigation costs or to enhance the efficiency of soil conservation. By the late 1990s, ca. 118 000 ha of fields with gravel mulch were distributed in the semiarid region of the Loess Plateau in China's Gansu Province alone.

Soil erosion is a serious environmental and ecological problem in China. About five billion tonnes of soil is lost every year in China (Li et al. 2008), and the total eroded area of the Loess Plateau is 454 000 km^2 (YRCC 2002). The most important reasons why the soil erosion occurs on the Loess Plateau are its irrational land-use and low vegetation coverage (Jiang 1997). Runoff and sediment transport are complex hydrological phenomena. Many experiments on runoff and erosion dynamics have been carried out in China (You & Li 2011) and internationally (Boer & Puigdefábregas 2005), and this body of research proves the importance of retaining vegetation to control water-driven soil erosion. Antecedent soil moisture conditions, soil cover, and rainfall intensity all play an important role in the rainfall-runoff process and the resulting water and soil losses (e.g., Römkens et al. 2001). Several investigations of mulching's impact upon the runoff have been conducted, addressing the effect of the cover densities on the surface flow, soil moisture, and soil temperature (e.g., Cook et al. 2006), and several researchers have found that conservation tillage practices can mitigate erosion-driven losses in the soil and organic carbon (SOC) (e.g., Puustinen et al. 2005).

Soil erosion is the main cause of nutrient loss in many soils. Previous studies have shown that the loss of key nutrients, such as nitrogen and phosphorus, from the surface soil due to the serious soil erosion of sloping land is an important cause of soil quality degradation (e.g., Douglas et al. 1998). Work by Jia et al. (2004) demonstrated that as well, and also that the erosion intensity is linearly related to the degree of the SOC loss. Straw mulching can significantly reduce the runoff and sediment loss, thereby significantly reducing the losses of nitrogen, phosphorus, and potassium (Lin et al. 2010). It is generally recognised that mulching practices have a pronounced impact on the soil hydrological process; however, most previous research has focused on the vegetation cover, and empirical studies testing the effects of gravel-sand mulch on both the runoff and soil loss dynamics are scanty. Here, we investigated the influence of three types of gravel mulch differing in grain size on the runoff, soil erosion and nutrient losses. The purpose of this study was to determine in what ways gravel-sand mulch affected the runoff, soil erosion, and nutrient losses on the Loess Plateau, and to discern some theoretical principles that could be applied for properly utilising a gravel-mulched field.

MATERIAL AND METHODS

Experimental site. This study was conducted at the Gaolan Research Station of Ecology and Agriculture (GRSEA), Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences. The station is located in the north-west Loess Plateau (Gaolan County, Lanzhou, Gansu Province; 36°13'N, 103°47'E), at an elevation of ca. 1 800 m a.s.l. Based on 30 years of station records, the mean annual rainfall totals of 263 mm, of which nearly 70% falls between June and September. The region's mean annual temperature is 8.4 °C, with a maximum of 20.7 °C in July and a minimum of –9.1 °C in January.

Methods and experimental design. The gravel-mulched fields, known locally as 'sandy fields', have been widely used by farmers here for over 300 years and the types of gravel used are fluvial materials from the Yellow River. The soil used in this study was collected from the top layer (0–20 cm) of a field in GRSEA. The soil is a silt loam of loess origin, which belongs to the Haplic Orthic Aridisols (Table 1); the bulk density of the repacked soil was 1.31 g/cm^3, which was similar to that of the top layer under conventional tillage in the field. Rainfall simulation experiments were conducted indoors under laboratory conditions. A 2 × 3 m steel tank with its longer sides parallel to the slope (15%) was used in this study. We put a 30-cm thick soil layer into the tank

Table 1. The properties of the loessian soil and aeolian sand at the sampling site on the Loess Plateau

Soil type	Particle size content (%)			BD	Soil moisture	TC	TN	SOC
	sand	silt	clay	(mg/m^3)	(%)	(g/kg)		
Silt loam of loess origin	15.3 ± 0.78	66.9 ± 2.67	17.8 ± 1.25	1.31 ± 0.03	15.46 ± 0.17	22.68 ± 0.024	0.66 ± 0.011	6.39 ± 0.091

BD – bulk density; TC – total carbon; TN – total nitrogen; SOC – soil organic carbon

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Figure 1. The experimental setup used in this study

and then mulched it with different types of gravel (applied above the soil surface). A rainfall simulator (QYJY-501, Qingyuan Measurement and Control Technology Co., Ltd. China) was used to produce the rainfall (Figure 1). The rainfall process can be run fully automatically by computer control. The type of nozzle is a rotary down spray type; it has an initial speed when spraying water, which can ensure that the raindrops reach a terminal speed. The effective rainfall uniformity of the QYJY artificial rainfall simulation system was over 80%. The kinetic energy and rainfall intensity had a good linear relationship: E = 0.0042I-0.021, suggesting that it is feasible to achieve the kinetic energy of natural rainfall through controlling the simulated rainfall intensity. The raindrops produced are composed of different diameters, which are similar to the raindrops of natural rainfall. The relationship between the raindrop and the stain diameters followed the function $d = 0.3839D^{0.709}$ when the raindrops were at their terminal velocity. In recent years, the QYJY rainfall simulation system has been widely used in many research institutions in China (Huo et al. 2015).

Table 2. Some characteristics of the selected gravel treatments

Gravel type	Grain size distribution D_{97}	Thickness (cm)	Total porosity (%)
FG	2 mm ≤ D_{97} ≤ 5 mm	10	42.15[a]
MG	5 mm ≤ D_{97} ≤20 mm	10	43.07[a]
CG	20 mm≤ D_{97} ≤40 mm	10	45.76[a]

D_{97} – the gravel grains in each specific mesh size range by a 97% confidence; FG – fine gravel; MG – medium gravel; CG – coarse gravel; different letters within the same column indicate significant differences at $P < 0.05$

To evaluate the influence of the gravel mulch on the runoff and nutrient losses, we used three types of gravel mulch obtained via differing mesh size (Table 2): fine gravel (FG, 2–5 mm), medium gravel (MG, 5–20 mm), and coarse gravel (CG, 20–60 mm). For all three treatments, the thickness of the mulch layer was fixed at 10 cm and, likewise, the rainfall intensity at 30 mm/h. Such rainfall intensities can often occur in the study area during natural rainfall events. There were three replications for each rainfall event. The duration of each rainfall is 150 min.

The time to the initial runoff was recorded during each rainfall event. The runoff from each tank-plot was continually collected in 6-L calibrated barrels, covered with a close-fitting plastic sheet to prevent the entry of the precipitation and to prevent the evaporation of the collected runoff water. When a barrel was filled to capacity, the time was noted and the full barrel was replaced with an empty one. The total runoff was measured after each rainfall. To measure the respective content of the nutrient elements in the runoff, the samples were collected using 200-cm^3 polyethylene bottles, at 10-min intervals, until the runoff was too small to monitor. The total carbon (TC), total nitrogen (TN), total phosphorus (TP), and total organic carbon (TOC) contents were measured by a water quality analyser (DR3900, Hach Water Quality Analysis Instrument Co., Ltd. USA). The collected samples of the surface runoff were filtered and oven-dried at 105 °C for 24 h, to measure their total soil loss.

RESULTS

Runoff. The generation of the surface runoff depended largely on the gravel's characteristics. The results presented in Figure 2 show that the runoff starting time of the gravel mulch treatments increased by 13–25 min under the rainfall intensity of 30 mm/h when compared to the bare soil. In particular, the runoff starting time of the FG treatment at the rainfall intensity of 30 mm/h was significantly delayed (by 89%) relative to that of the bare soil. The delays in the runoff start times incurred in the MG and CG treatments were 46% and 71%, respectively. Figure 3 presents the runoff processes of the different treatments under the rainfall intensity of 30 mm/h over the entire 150-min period of testing: the lowest surface runoff was observed from the FG treatment. All the mulched treatments, irrespective of the grain size, had a significant reduction in the surface runoff

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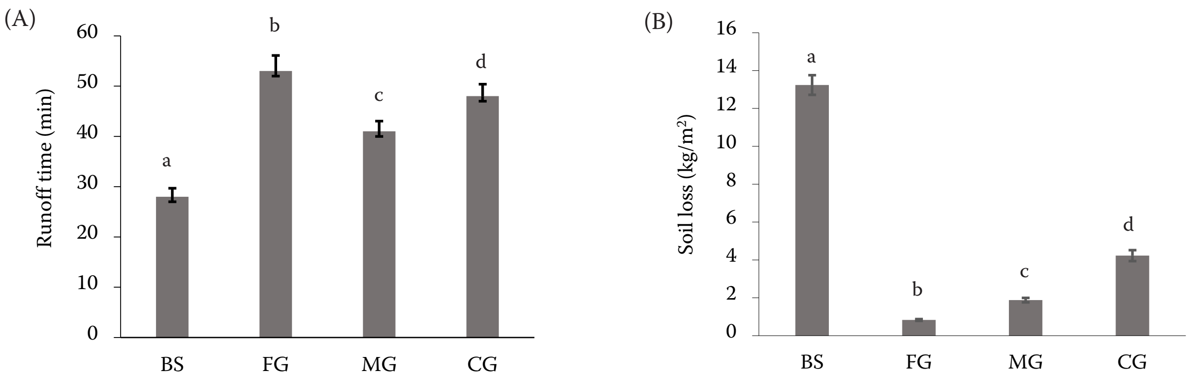

Figure 2. The runoff starting time (A) and soil loss (B) of the different mulch treatments at the rainfall intensity of 30 mm/h
BS – bare soil; FG – fine gravel; MG – medium gravel; CG – coarse gravel; the bars are the mean ± SE, n = 3; different letters indicate significant differences at $P < 0.05$

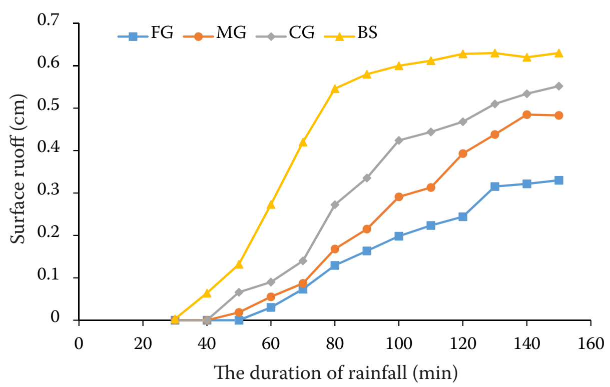

Figure 3. The runoff processes of the different mulch treatments under the rainfall intensity of 30 mm/h
FG – fine gravel; MG – medium gravel; CG – coarse gravel; BS – bare soil

compared to the bare soil during the 150 min of the simulated rainfall. The total runoff increased with a greater grain size of the gravel mulch and the FG treatment tended to be more effective in reducing the runoff when compared to bare soil.

Soil loss. Figure 2 shows the variation in the soil loss on the artificial loess slopes under the different gravel grain sizes during the simulated rainstorms. In the FG treatment, the total soil loss was 0.43 kg/m^2, followed by 0.88 and 4.23 kg/m^2 in the MG and CG treatments, respectively, under the rainfall intensity used (30 mm/h). The total soil loss during the 150 min of the simulated rainfall increased with the larger grain size of the gravel mulch. Compared with the bare soil, all the mulched treatments presented a significant reduction in the soil loss, but among them,

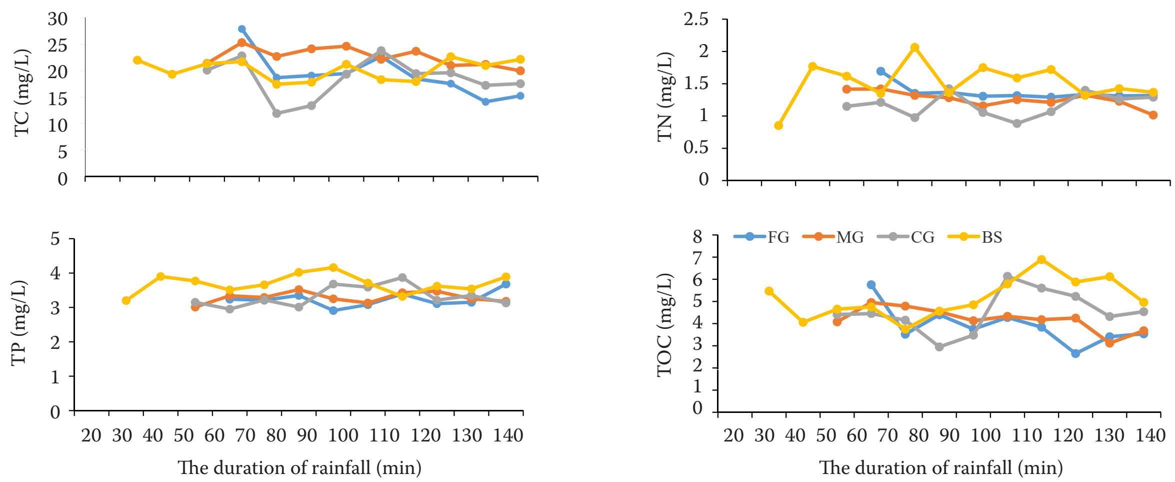

Figure 4. The total carbon (TC), total nitrogen (TN), total phosphorus (TP) and total organic carbon (TOC) content of the runoff in the different mulch treatments under the rainfall intensity of 30 mm/h
FG – fine gravel; MG – medium gravel; CG – coarse gravel; BS – bare soil

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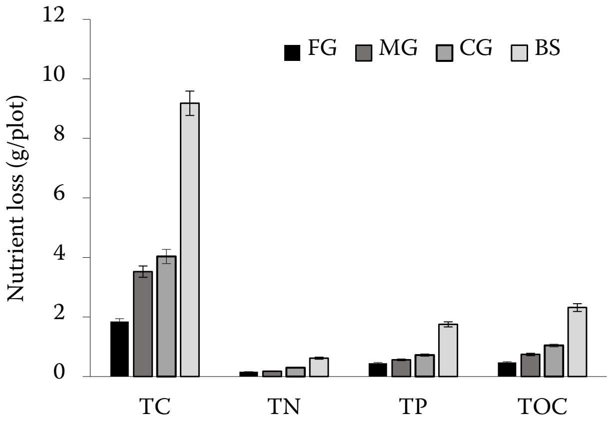

Figure 5. The cumulative nutrient losses in the runoff water for the different mulch treatments under the rainfall intensity of 30 mm/h

TC – total carbon; TN – total nitrogen; TP – total phosphorus; TOC – total organic carbon; FG – fine gravel; MG – medium gravel; CG – coarse gravel; BS – bare soil

the FG treatment was most effective for minimising the soil losses to the water-driven erosion.

Nutrient losses. Figure 4 presents the loss processes of TN, TC, TP, and TOC on the loess slopes with the different grain size of the gravel mulch under the rainfall intensity of 30 mm/h. Evidently, the processes of nutrient loss in all the treatments fluctuated and were complex. For the TC, its fluctuation under the gravel mulch treatments was more intense than that of the bare soil, and the fluctuation in the CG treatment was the most intense. The TC content in the initial runoff of the FG treatment was significantly higher than that of the other treatments. The cumulative losses of the TN, TP, and TOC in the bare soil were all much higher than those incurred under the three mulching treatments (Figure 5). Moreover, the TN, TP, and TOC contents of the surface runoff were higher in the BS treatment than the mulching treatments for most of the time during the simulated rainfall events (Figure 4). Greater fluctuations in the TN, TP, and TOC contents occurred in the BS treatment than the mulching treatments, and the TN and TP contents in the runoff were less at the beginning of runoff in the BS treatment.

DISCUSSION

Runoff and soil loss. The runoff starting time of the gravel mulch treatments increased by 13 to 25 min compared to the bare soil under the rainfall intensity of 30 mm/h. These results indicate that the gravel mulch postpones the timing of the initial runoff, which is consistent with previous findings (Xu et al. 2015). Furthermore, Mamedov et al. (2006) reported that the antecedent soil moisture content is the one of the most influential factors in generating the runoff over time. The soil used in this study was collected from the same field, so the antecedent soil moisture content in the treatments did not differ significantly among them. The effect of delaying the runoff starting time may be due to the improved soil infiltration that ensues under gravel mulch (Li 2003), and the critical shear stress protective effect provided to soil by the gravel mulch. More recently, Zhang et al. (2017) reported that a sand layer covering could change the runoff production mode; they believed the runoff produced on the sand-covered loess slopes was mainly subsurface saturation excess runoff, or subsurface flow produced at the sand-loess interface due to the sharp change in the permeability between the top sand layer and the underlying loess. Moreover, the process of rainfall interception may also play a role in this. El Boushi and Davis (1969) investigated the water retention characteristics of coarse rock particles in the laboratory. They reported that rainwater intercepted by rock fragments will be retained (1) as a thin film on the stone surface, (2) in the capillary openings at the contact points between the stones, and (3) in small puddles on the upper side of the stones, finding that the number of contact points per unit volume decreases as the particles' diameter increases. So, small rock fragments are able to retain larger quantities of water per unit of rock mass. Thus, the storage capacity of fine gravel would be far greater than other mulch types because it provides more contact points and a larger specific surface area; hence, the runoff generation time of the FG treatment is much higher than that of bare soil. Yet at the same time, another contributing determinant of the runoff generation time in the gravel mulch treatments is the speed of the soil infiltration. According to our results (data not shown), the cumulative infiltration of the rainfall water is significantly lower under the small-sized than large-size gravel used for the mulching. This may be one reason why the runoff generation time was lower in the MG than the CG treatment. A previous study that investigated the effects of the gravel content and its particle size on the soil infiltration also found that the cumulative infiltration increases with an increased particle gravel much size (Lv et al. 2017).

The total soil loss during the 150 min of the simulated rainfall increased with the greater grain size of the gravel mulch. Although in all the mulched treat-

https://doi.org/10.17221/141/2019-SWR

ments, less soil was lost from them compared with rain's impact on the bare soil, this reduced soil loss was the most pronounced in the FG treatment. Our results suggest that the grain size of the gravel mulch is a reasonable and effective method for mitigating the soil loss. Bruce-Okine and Lal (1975) reported that the kinetic energy of raindrops breaks the soil aggregates into individual components, which hastens the rate of the soil loss. Hence, the amount of soil available for removal by the runoff depends on the total kinetic energy of the raindrops in the face of the strength of the aggregates to resist the disruptive force of the raindrops' impact. Zuazo and Pleguezuelo (2008) also reported that rainfall energy is the prime cause of erosion from tilled or bare land, occurring when the soil lacks a protective vegetative cover. In our study, the applied gravel mulch protected the soil by intercepting the raindrops and reducing their kinetic energy. The lower amount of soil loss that occurred in the mulched treatments indicates the soil beneath these gravel types was conserved, by diminishing the threshold raindrop energy required to detach the particles and cause the soil loss. The FG treatment's better protective effect afforded by more contact points and its bigger specific surface area may be a contributing factor to why the fine gravel mulch was also more effective at reducing soil loss than the other gravel types.

The total runoff increased with the grain size of the gravel mulch, but the FG treatment tended to be more effective for the runoff reduction when compared to the bare soil. Increasing the gravel particle size could change the runoff starting time and increase the soil shear strength that would result in the significant variations observed in the runoff during the simulated rainfall. The bare soil treatment generated the highest surface runoff under 75–80 min of simulated rainfall; however, compared with this, the mulched treatments were able to significantly delay the time when the highest surface runoff was generated. This may be due to the delay effect of the runoff starting time in the mulched treatments and the protecting effect of the gravel mulch on the soil. Besides, the process of rainfall interception may also play a role (Ma et al. 2011).

Nutrient losses. For the TC, it varied more intensely under the mulch treatments than the bare soil, with that of the CG treatment being the most intense. The latter may be explained by the weaker ability of the larger pores of the coarse gravel to intercept and store the incoming rainwater (Qiu et al. 2018). Raindrops with a reduced kinetic energy accumulate in the pores for a short time and then form the runoff, thus leading to stronger fluctuations. The TC content of the initial runoff from the FG treatment surpassed that of the other mulch treatments, most likely because the fine gravel significantly delayed the runoff starting time compared to the bare soil and this fine gravel layer retained larger quantities of water per unit of rock mass. This gives the runoff water more time to carry away the total carbon in the soil at the initial stage of the runoff generation.

More TN, TP, and TOC was lost from the bare soil than the mulch-treated soils (Figure 5); the main reason for this result might be that more runoff was generated in the BS treatment. Moreover, the runoff's TN, TP and TOC contents in the BS treatment were higher than that of mulching treatments for most of the time during the simulated rainfall (Figure 4). The results of the TN, TP and TOC content of the runoff varying more in the bare soil than the mulch treatments are consistent with the findings of Hahn et al. (2012). They reported substantial fluctuations in the nutrient concentrations in the bare soil, because of the runoff that is generated before the soil's internal voids are saturated and the lag of the extraction process between its surface and the internal nutrient concentrations. The TN and TP contents in the runoff were lower at the beginning of the runoff in the BS treatment; a plausible explanation for this result in the early stage of the rainfall–runoff process could be that an insufficient amount of time elapsed to extract the soil's internal TN and TP concentrations because the runoff began significantly sooner on the bare soil than in the mulching treatments. From the perspective of preserving nutrients, reducing runoff and soil loss, gravel mulching provides a more favourable environment for plant growth in the arid regions of north-western China, offering a novel approach to do this in the context of the degraded arable land and severe soil erosion currently characterising the Loess Plateau. Further research should focus on how gravel mulching may affect the crop growth, yield and mortality, for advancing the sustainable development of agriculture in these arid regions of north-western China.

CONCLUSION

The results of these rainfall simulation experiments give estimates of how the grain size influences the runoff as well as the soil and nutrient losses. The runoff starting time in the mulching treatment was significantly delayed compared to the bare soil. The total runoff increased with the grain size of the gravel mulch. The lowest surface runoff soil and nutrient losses were observed from the fine gravel treatment. The positive effect of the gravel mulch on reducing the soil erosion may be due to it delaying the runoff starting time in the mulched treatments and also due to its physical protection of the soil. Thus, concerning the latter, the process of rainfall interception by

https://doi.org/10.17221/141/2019-SWR

the gravel may play a key role. Our findings suggest that gravel mulching had a severe impact on reducing the soil erosion, making it a useful water and soil conservation technique for reducing the erosion of the soils in the loess area of north-western China.

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