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Effects of Ridge Tillage and Straw Returning on Runoff and Soil Loss under Simulated Rainfall in the Mollisol Region of Northeast China

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Abstract: Ridge tillage and straw returning are tillage practices widely used in the Chinese Mollisol region. However, the effects of ridge tillage combined with straw returning on runoff and soil loss control are still unclear. The objective of this study was to compare the effects of ridge tillage practices (contour ridge (CR)) and longitudinal ridge (LR), straw returning practices (straw on the furrow surface (SS)) and straw below the furrow (SB)), and their interactions on the runoff and soil loss by using simulated rainfall experiment. Two rainfall intensities (45 and 60 mm h^{-1}) were applied to six combinations of ridge tillage and straw returning (contour ridge treatment, contour ridge with straw on the furrow surface treatment, contour ridge with straw below the furrow treatment, longitudinal ridge treatment, longitudinal ridge with straw on the furrow surface treatment, and longitudinal ridge with straw below the furrow treatment) on a 5° slope. The results showed that the phenomenon of ridge failure was common in the treatments with contour ridge. The average runoff rate and soil loss rate after ridge failure for treatments with contour ridge were separated 2.8 and 3.5 times greater than those of before failure at 60 mm h^{-1}. However, the corresponding values were only 68.6% and 43.3% of the average value of longitudinal ridge treatment and longitudinal ridge with straw below the furrow treatment at 60 mm h^{-1}. The water storage capacities of treatments with contour ridge remained constant when the rainfall intensity varied. The water storage capacities of contour ridge with straw on and below the furrow treatments were separate 3.0 and 1.0 mm less than that of contour ridge. However, longitudinal ridge with straw on the furrow surface treatment increased the runoff rate by 7.4% but reduced the soil loss rate by 72.6% when compared with longitudinal ridge treatment and longitudinal ridge with straw below the furrow treatment under the two rainfall intensities. Longitudinal with straw on the furrow surface treatment was more conducive to the stability of ridges, and there was no significant difference in total soil loss between longitudinal ridge with straw on the furrow surface treatment and treatments with contour ridge. This study was based on simulated rainfall conditions, and its adaptability under long-term positioning monitor in the field should be added in future.

Keywords: runoff; soil loss; water storage capacity; ridge tillage; straw returning

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1. Introduction

The Mollisol region is an important source of commodity grain in China [1]. Long-term cultivation with few soil and water conservation measures causes severe soil erosion in this area. The soil and water loss mainly occurs on the sloping farmland. Currently, the soil erosion area is expanding, and the soil layer thickness is becoming thinner [2]. The topsoil thickness declined from 50–80 cm in the 1950s to 20–40 cm at present with 3–10 mm of soil loss per year [3]. Severe soil loss greatly decreases crop yield and arable land area [4] and becomes a main problem of agriculture production [5]. Thus, studies of soil erosion in the Mollisol region need to be conducted deeply.

The studies of tillage and crop management can help to identify methods for determining sustainable agriculture production [6]. Tillage measurements affect the soil erosion process to a certain extent [7] and water-use efficiency [8]. Ridge tillage, as a traditional method of seedbed preparation and fertilizer application [9], is widely used in Northeast China [10] for regulating soil temperature, soil depth, changing water patterns, soil fertility, and controlling pest management [11]. Contour ridge is a popular agronomic practice [12] with the objective of increasing soil infiltration and controlling soil erosion [13]. Contour ridge has a good effect on reducing soil erosion [14]. However, under higher rainfall intensity, ephemeral gully erosion occurs after ridge failure, leading to serious soil erosion [15] which was a common phenomenon in northern China [15,16]. Longitudinal tillage is a common tillage practice in Northeast China. Ridge furrow converges the flow from ridge side-slopes, which cause serious soil erosion [14], as in the United States and Brazil [17]. For the long slope in Northeast China, a large amount of surface runoff is confluent at the bottom of the longitudinal ridge, resulting in serious soil erosion. However, the influence on crop growth on the ridges is not harmful [14]. Therefore it is necessary to further discuss the effect of longitudinal ridge and contour ridge on runoff and soil loss and to provide reference for selecting appropriate tillage practices in the Mollisol region of Northeast China.

Straw returning is an important method of straw utilization, which has been greatly recommended in China [18]. Straw mulching restrains runoff, increases soil infiltration, reduces soil evaporation, improves soil moisture, benefits the environment, and improves crop growth [19–22]. Straw mulching has a good effect on soil and water conservation on gentle hillslopes in the Mollisol region of Northeast China [23]. However, the traditional full straw mulching practice often leads to a significant decrease in soil temperature [2], makes tillage difficult, and leads to unfavorable root penetration [18]. Straw mulching strips in the furrow improve water-use efficiency and yield [24]. There is another method where the straw is incorporated below the surface about 20–40 cm. This method has little impact on farming and shows good effects on the soil aggregate and yield [25]. However, the effects on runoff and soil loss of the two straw returning methods are still scarce.

In order to improve the soil temperature, ridge tillage is a common farming method in Northeast China. Straw returning also needs to further research and assessment [18]. Typical farming land in the Mollisol region of Northeast China was shown in Figure 1. Many studies have separately characterized the effectiveness of straw returning and ridge tillage practices on soil erosion [2,9,12,14–16,21,26–28], water-use efficiency [29], yield [30], and soil structure and soil quality [25]. Some studies were conducted on the characteristics of soil loss [31], soil organic carbon [32], and crop yield [8] by combining ridge tillage (zero, minimum, and conventional tillage) with straw returning. However, contour ridge and longitudinal ridge combined with straw returning (straw on the furrow surface and straw below the furrow) were rarely involved. Thus, 6 combinations (CR for contour ridge treatment, CRSS for contour ridge with straw on the furrow surface treatment, CRSB for contour ridge with straw below the furrow treatment, LR for longitudinal ridge treatment, LRSS for longitudinal ridge with straw on the furrow surface treatment, and LRSB for longitudinal ridge with straw below the furrow treatment) and 24 rainfall simulations were conducted. This study aimed to quantify the effects of combinations of ridge tillage and straw returning on runoff and soil loss.

Figure 1. Typical farming land in the Mollisol region of Northeast China. (**a**) Contour ridge; (**b**) longitudinal ridge; (**c**) contour failure; and (**d**) straw returning.

2. Materials and Methods

2.1. Experimental Equipment and Materials

This study was conducted in the rainfall simulation laboratory of the Scientific Research Base of Soil and Water Conservation (43°52′ N, 125°21′ E) at Jilin Agricultural University. A downward-facing sprinkler rainfall simulator system was fixed at 6 m from the ground and the adjustable rainfall intensity ranging from 30 to 200 mm/h. The system contained 9 separate nozzles with 3 nozzles in a group distributed at 3 lines above the soil pan, and the coverage area was 36 m^2 with rainfall uniformity >90%.

Two soil pans (2.0 m long, 1.0 m wide, and 0.6 m deep) were used with 2 cm aperture holes at the bottom to drain water smoothly. The tested soil was collected from a depth of 0–20 cm from the surface in a corn field at Jilin Agricultural University. The soil was classified as a Mollisol with 10.2% sand (>50 μm), 80.2% silt (50–2 μm), and 9.6% clay (<2 μm) in the US Soil Taxonomy [33]. The soil organic matter content was 25.6 g kg^{-1} obtained by the potassium dichromate oxidation-external heating method. The soil properties were shown in Table 1. To keep its natural state, the soil was not sieved but was air-dried, organic crop residues were removed, and the soil was crushed into small pieces of less than 8 mm [23].

Table 1. Soil properties in the experiment.

Soil Type	Particle Size (%)			Soil Texture	PH	Organic C (g kg^{-1})	Bulk Density of the Tilth Layer (g cm^{-3})	Bulk Density of the Plow Pan Layer (g cm^{-3})
	Sand	Silt	Clay					
Mollisol	10.2	80.2	9.6	silty loam	6.22	25.6	1.2	1.35

2.2. Experimental Design

When the instantaneous rainfall intensity was greater than ≥42.6 mm h^{-1}, it could cause moderate-intensity soil erosion [34]. The 1 h maximum recorded precipitation for twenty years recurrence period was close to 60 mm h^{-1}, which was from the national benchmark meteorological stations of Changchun [35]. Thus, two rainfall intensities (45 and 60 mm h^{-1}) were used in this study. The slopes were mainly less than 7° in the Chinese Mollisol region [13], and 5° was the representative slope of the seriously eroded farmland in this region [36]; thus, the designed slope gradient was 5°. The rainfall duration of each experiment was 60 min. Two replications were designed for each experimental treatment.

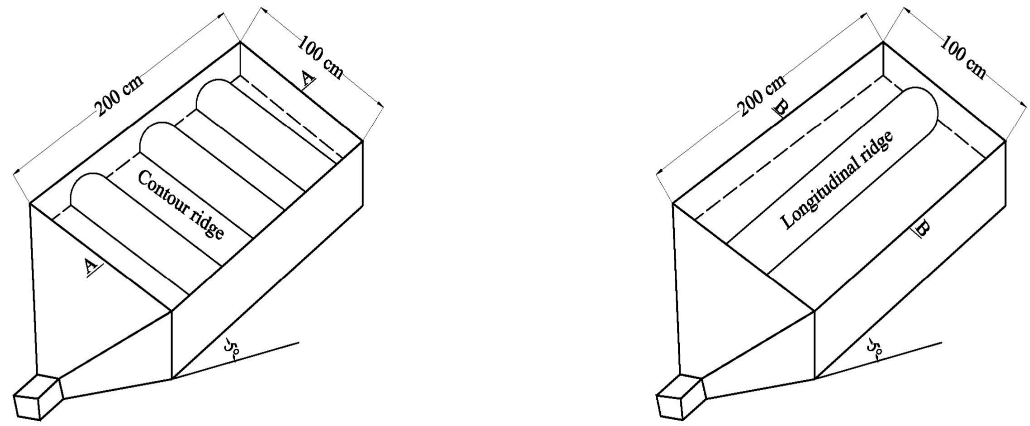
Agricultural tillage practices should adapt to mechanized operation and at the same time, should reduce the procedures, not affect sowing and conforming to farmers' production habits. In the cold Northeast China, improving soil temperature was helpful to increase the crop productivity [11]. Ridge tillage was the conventional method to improve soil temperature in this region. Straw on the furrow surface and straw below the furrow did not affect the sowing, seed penetration, and soil temperature. Then, 6 combinations were conducted: contour ridge (CR), contour ridge with straw below the furrow (CRSB), contour ridge with straw on the furrow surface (CRSS), longitudinal ridge (LR), longitudinal ridge with straw below the furrow (LRSB), and longitudinal ridge with straw on the furrow surface (LRSS). Each treatment was conducted with two same soil pans at the same time. After each rainfall simulation, soil bed and ridges were reconstructed for next treatments.

2.3. Establishment of Soil Bed and Ridge System

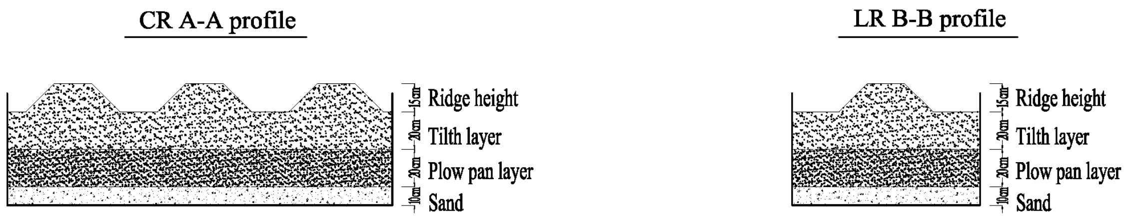
First, 10 cm fine sand was filled with the soil pan at the bottom to drain excess water. Second, the soil was packed with a 20 cm plow pan layer and a 20 cm tilth layer, and the bulk densities were separate 1.35 and 1.20 g cm^{-3}. Third, contour ridge and longitudinal ridge systems were built on the tilth layer. For the CR, 2 furrows and 3 ridge tops were constructed parallel to the contour. The length, width and height of each ridge were 1, 0.65, and 0.15 m [10], which was consistent with the local mechanized ridge planting specifications. For the LR, 2 furrows and 1 ridge top were constructed perpendicular to the contour. The length, width, and height of each ridge were 2, 0.65, and 0.15 m. At the tail end of the soil pan is a triangular conveyer to collect the runoff and sediment, and the top of conveyer is closed to prevent rainwater from entering. In CRSS and LRSS, the straw was put on the furrow surface. In CRSB and LRSB, the straw was put on the plow pan layer, which was the position of the furrow. The amount of straw returning to the soil was 7500 kg ha^{-1}, based on the corn straw output in this region. The length of the straw was approximately 12–17 cm, based on the straw length harvested by the machines. The experimental schematic was shown in Figure 2. After making the furrows and ridges, the soil pan was stationary for 48 h before the rainfall experiments.

2.4. Experiment Procedure

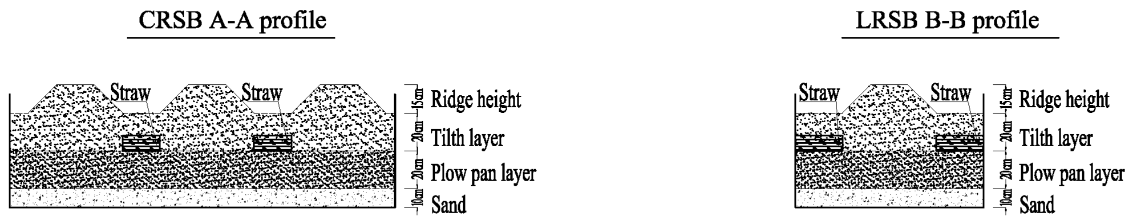
Before each rainfall experiment, a pre-rain with a 30 mm h^{-1} was applied until surface flow occurred. During the pre-rain, a nylon net with 1 mm aperture was placed over the soil pan to reduce the raindrop impacts on soil surface infiltration [34]. After pre-rain, the soil pan was covered with a plastic sheet to prevent evaporation before the experiment. Then 24 h later, the soil water content was tested before each experiment, and the average value was 24.5% ± 1.9%. The rainfall intensity was calibrated to achieve the target rainfall intensity before each experiment. Recording the time when stable runoff was generated, the runoff and sediment samples were collected at intervals of 2–5 min in the run time and weighed immediately. After the samples were fully precipitated, the supernatant was poured out slowly and then dried to a constant weight at 105 °C and weighed. Then, the runoff rate and soil loss rate were calculated. At last, the storage capacity of treatments with contour ridge was calculated by the rainfall amount minus the runoff in this period.



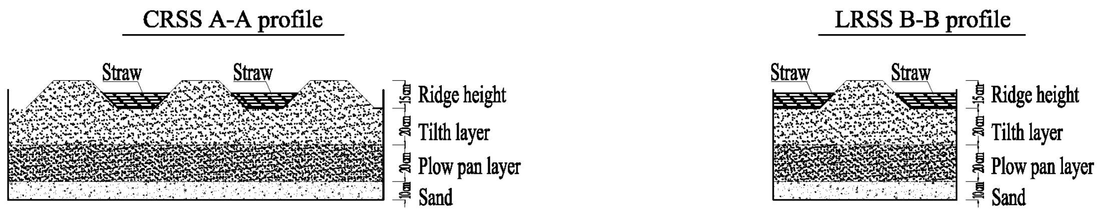
(**a**) Arrangement drawing of contour ridge and longitudinal ridge



(**b**) Contour ridge (A-A) profile and longitudinal ridge (B-B) profile



(**c**) Contour ridge with straw below the furrow profile (A-A) and longitudinal ridge with straw below the furrow profile(B-B)



(**d**) Contour ridge with straw on the furrow surface profile (A-A) and longitudinal ridge with straw on the furrow surface profile (B-B)

Figure 2. Schematic of the experimental set up.

2.5. Date Analysis

SPSS 19.0 software (SPSS Inc., Chicago, IL, USA) was used for statistical analysis. Analysis of variance (ANOVA) was carried out to test significant differences in total runoff, total soil loss, and water storage capacity. The least significant difference (LSD) method and Games-Howell were used for multiple comparisons at 95% confidence level. MANOVA was carried out for the analysis of the influence factors and their interactions on the average soil loss rate and runoff rate.

3. Results and Discussion

3.1. Runoff Responses

The runoff rate values of CR, CRSS, and CRSB were very close and exhibited a relatively stable state at 45 mm h^{-1}, but only CRSS showed a sharp rise at 54 min (Figure 3a). However, CRSB, CRSS, and CR all showed sharp upward trends separated at 42, 45, and 49 min at 60 mm h^{-1} (Figure 3b), which is for rainfall preserved in the furrows in the initial stage and concentrated in treatments with contour ridge. The runoff generated down the first ridge close to the outlet was removed, but when the furrow storage capacity was exceeded, a failure point occurred [15], and sharp rising runoff rate emerged. The average runoff rate of treatments with contour ridge after ridge failure was 2.8 times greater than that before the ridge failure. The phenomenon of ridge failure was common in the treatments with contour ridge [12,14–16,26,30].

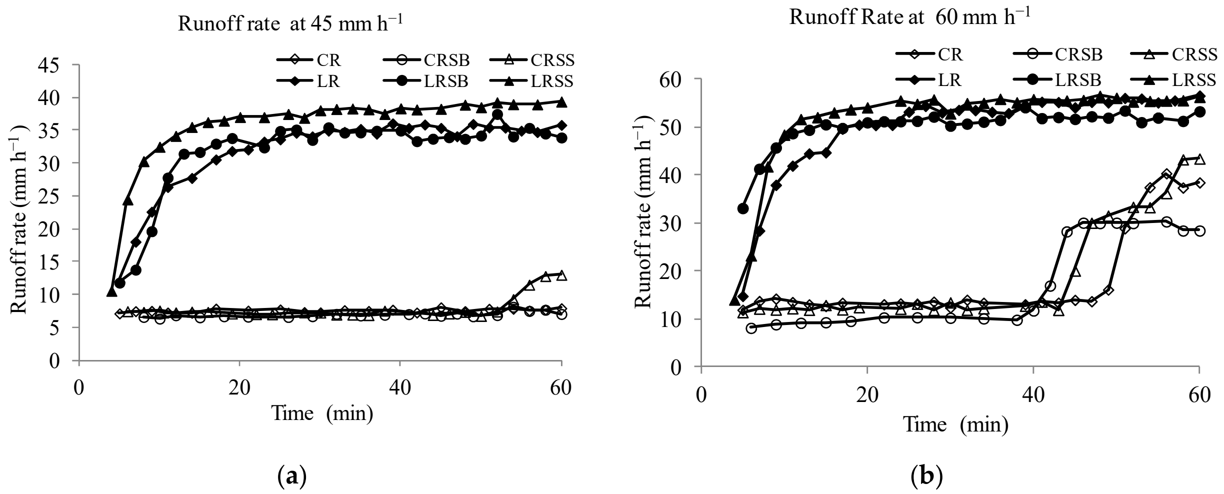


Figure 3. Runoff rates versus time for different ridge and straw returning practices. CR, contour ridge; CRSB, contour ridge with straw below the furrow; CRSS, contour ridge with straw on the furrow surface; LR, longitudinal ridge; LRSB, longitudinal ridge with straw below the furrow; and LRSS, longitudinal ridge with straw on the furrow surface. (**a**) Runoff Rate at 45 mm h^{-1}; (**b**) Runoff Rate at 60 mm h^{-1}.

The treatments with longitudinal ridge showed a steady growth stage and a relative stationary stage. The magnitudes of runoff rates were greatly higher than treatments with contour ridge for the convergent flow [14] and slope gradient. The average runoff rate for treatments with contour ridge before ridge failure were only 22.5% and 24.1% than those of treatments with longitudinal ridge separate at 45 and 60 mm h^{-1}. There were significant differences (Table 2) in total runoff among treatments with longitudinal ridge and contour ridge separated at 45 and 60 mm h^{-1}. The values for treatments with longitudinal ridge were 4.6 and 2.7 times more than treatments with contour ridge separate at 45 and 60 mm h^{-1}. Rainfall intensity was an important agent for erosion, at 60 mm h^{-1} the total runoff of treatments with longitudinal and contour ridge being separated 2.6 and 1.5 times more than at 45 mm h^{-1}. Ridge tillage practice had the greatest impact on the runoff rate, followed by the impact of rainfall intensity, and the interaction between ridge tillage and rainfall intensity followed (Table 3).

Contour ridge had good effect on decreasing total runoff than longitudinal ridge, which had been showed in previous studies with decrement rates of 67.0–96.8% [13,28]. The average total runoff for the treatments with contour ridge decreased 78.3% and 63.0% more than treatments with longitudinal ridge separate at 45 and 60 mm h^{-1} (Table 2). There was 76.8–86.2% of rainfall infiltrated or stored in the furrows for the treatments with contour ridge before the ridge failure, but the value was only 8.3–22.2% for the treatments with longitudinal ridge in the stable stage. Even after ridge failure, the average runoff rate of treatments with contour ridge was 67.3% of treatments with longitudinal ridge at

60 mm h^{-1}. At 60 mm h^{-1}, the runoff rate order from large to small was CR, CRSS, and CRSB no matter before or after ridge failure (Figure 3b). For the straw below the furrow, the soil absorbed rainfall in the initial period of the experiment and rainfall penetrated to the straw barrier as the experiment continued. However, the gaps between the straw made the rainfall store quickly; hence, the average runoff rate of CRSB was 77.1% of CR before ridge failure. However, the penetration of straw was smaller than soil, and the straw formatted an interlayer, which partly prevented rainfall from infiltrating into the soil below and reduced the advanced depth of the wetting front [37]. The rainfall accumulated on the top of the less-permeable boundary, and the topsoil was saturated gradually, and then the preferential runoff surge point produced with the increase of the rainfall intensity. Thus, CRSB emerged ridge failure first (Table 4) at 60 mm h^{-1}, and the total runoff of LRSB was 106.8% of LR at 60 mm h^{-1}. However, CRSB released the water slowly to a certain extent for the straw layer, and the ridges made up a container. Therefore, the average runoff rate of CRSB was 80.6% of CR after ridge failure at 60 mm h^{-1} (Figure 3b). However, the total runoff of CRSB was 1.0 mm higher than CR due to its longer ridge failure time at 60 mm h^{-1}, and CRSS was a similar phenomenon at 45 mm h^{-1} (Table 2).

Table 2. Total soil loss and runoff for different ridge and straw returning practices. CR, contour ridge; CRSB, contour ridge with straw below the furrow; CRSS, contour ridge with straw on the furrow surface; LR, longitudinal ridge; LRSB, longitudinal ridge with straw below the furrow; and LRSS, longitudinal ridge with straw on the furrow surface.

Rainfall Intensity (mm h^{-1})	Tillage Practices	Total Runoff (mm)	Total Soil Loss (g)
45	CR	7.3 ± 0.4b	31.1 ± 4.8b
	CRSB	6.4 ± 0.3b	12.8 ± 4.6b
	CRSS	7.5 ± 0.2b	19.0 ± 2.7b
	LR	30.7 ± 0.7a	211.9 ± 2.9a
	LRSB	32.8 ± 0.8a	222.3 ± 18.4a
	LRSS	34.5 ± 0.5a	70.3 ± 10.7b
60	CR	17.7 ± 0.3b	344.7 ± 30.3b
	CRSB	19.1 ± 0.6b	241.9 ± 32.9b
	CRSS	18.1 ± 0.6b	245.6 ± 30.8b
	LR	47.8 ± 0.5a	1213.1 ± 180.2a
	LRSB	49.3 ± 0.5a	1505.9 ± 214.3a
	LRSS	51.4 ± 1.0a	323.5 ± 82.7b

Notes: Different letters (i.e., a, b) indicate significant difference among the six tillage practices at $p < 0.05$ according to the Games-Howell test. $n = 2$.

Table 3. MANOVA of runoff rate and soil loss rate.

Effect	Runoff Rate				Soil Loss Rate			
	Type III Sum of Squares	Mean Square	F	Sig.	Type III Sum of Squares	Mean Square	F	Sig.
RI	1181.7	1181.7	1781.3	0.000	1,823,038.9	1,823,038.9	123.3	0.000
RT	4839.4	4839.4	7295.5	0.000	1,172,095.6	1,172,095.6	79.3	0.000
SR	16.0	8.0	12.1	0.001	515,423.1	257,711.5	17.4	0.000
RI*RT	47.1	47.1	70.9	0.000	521,383.3	521,383.3	35.3	0.000
RI*SR	1.0	0.5	0.7	0.504	300,545.3	150,272.7	10.2	0.003
RT*SR	11.6	5.8	8.7	0.005	472,262.2	236,131.1	16.0	0.000
RI*RT*SR	2.5	1.2	1.9	0.198	271,352.5	135,676.3	9.2	0.004

RI, rainfall intensity; RT, ridge tillage; SR, straw returning. * mean interactions, e.g., RI*RT denotes the interaction of RI and RT.

The straw on the furrow abated the kinetic energy of raindrops [21], and gaps between the straw was larger than the soil made the rainfall store quickly, which allowed more time for rainfall permeation. The average runoff rate of CRSS before the ridge failure was 95.5% of CR and after ridge failure was 98.3%. However, the runoff rates of LRSS were the highest most of the time (Figure 3). That was for two main reasons: one was the ridges in longitudinal ridge treatments were not obstacles, but a favorable condition for forming a drainage ditch; the other was straw gaps could store rainfall and reduced rainfall infiltrated into the soil under the straw. The average runoff rate of LRSS was 106.4% of LR. Regardless of straw on the furrow or under the furrow, they all reduced runoff rate in contour ridge but increased runoff rate in longitudinal ridge. Both straw returning and its interaction with ridge tillage had significant impacts on the runoff rates, but its impact was less than those of ridge tillage and rainfall intensity (Table 3). The interaction between rainfall intensity and straw returning and the interaction of rainfall intensity, ridge tillage, and straw returning had no significant effect on the runoff rates.

Table 4. Water storage volume of contour ridge practices under 45 and 60 mm h^{-1} rainfall intensities. CR, contour ridge; CRSB, contour ridge with straw below the furrow; CRSS, contour ridge with straw on the furrow surface; LR, longitudinal ridge; LRSB, longitudinal ridge with straw below the furrow; and LRSS, longitudinal ridge with straw on the furrow surface.

Rainfall Intensity (mm h^{-1})	Tillage Practices	Time of Ridge Failure (min)	Water Storage (mm)
45	CR	—	37.5 ± 0.2a
	CRSB	—	37.1 ± 0b
	CRSS	54.0 ± 0.7	34.5 ± 0.4c
60	CR	49.0 ± 0.8	38.0 ± 0a
	CRSB	42.5 ± 0.5	37.0 ± 0b
	CRSS	43.0 ± 0.7	34.4 ± 0.6c

Notes: Different letters (i.e., a–c) indicate significant difference among the three tillage practices at $p < 0.05$ according to the LSD test. $n = 4$.

There were significant differences for the water storage capacity between CR, CRSS, and CRSB. However, the capacities of CR, CRSS, and CRSB remained constant between different rainfall intensity (Table 4). The capacities were defined by the soil infiltration and the furrow specification. Treatments with contour ridge had the same specification and soil type. The disparity of water storage capacity depended on the straw returning style. The straw below the furrow prevented rainfall from further infiltrating into deep soil to a certain extent, which made the storage capacity was 1.0 mm lower than that of CR. The straw in CRSS diminished water storage capacity, and the value was 3.0 mm lower than that of CR, which was why only CRSS emerge ridge failure at 45 mm h^{-1}. The storage capacity of CR was 38.0 mm, which was nearly the same as that observed by Xu et al [14], which was for the same specification of ridge and soil type in two trials, but the breach time was later than that for different rainfall intensities.

Contour ridge stores rainfall in the furrows, then increases infiltration, and decreases the soil losses [12,15]. When rainfall intensity is small, all rainfall is stored in the furrows. The ability of conserving water and soil depends on the size of ridge for the same soil type. CR, together with CRSB, CRSS, and conservation tillage practices, such as furrow dikes, basin tillage, and furrow blocking, has good effect on soil and water conservation for their structure increase storage capacity to a certain extent. However, the ridge failure still emerges for large total rainfall, and even the gully emerged [14]. Contour ridge and other conservation tillage practices are suitable for application in arid and semiarid regions. However, contour ridge and its transformation emerge ridge failure if enough rainfall occurs. Thus, the arrangement of drainage facilities is necessary to reduce the possibility of ridge damage for rainstorm is the main rain form in Northeast China.

3.2. Soil Loss Responses

The soil loss trends of treatments with contour ridge were similar to those of the runoff. Only the eroded soil on the first ridge close to the outlet was moved outside, and the eroded soil up to the first ridge was trapped in the furrow before ridge failure in treatments with contour ridge. The soil loss rates of LR and LRSB increased rapidly and stayed higher than those of other treatments for the whole experiment process (Figure 4), which was for the rapid convergent flow from ridge tops and ridge side-slopes [14]. However, there was a small drop after the peak value for the seal formed [38] to prevent further soil erosion to a certain extent. The same phenomenon occurred in the treatments with contour ridge in the initial stage. However, the state of LRSS was stable in the whole experiment duration. The average soil loss rate of treatments with contour ridge before ridge failure was 11.9% of the average of LR and LRSB at 45 and 60 mm h^{-1}. Contour ridge treatments have a good effect on reducing soil loss rates before ridge failure.

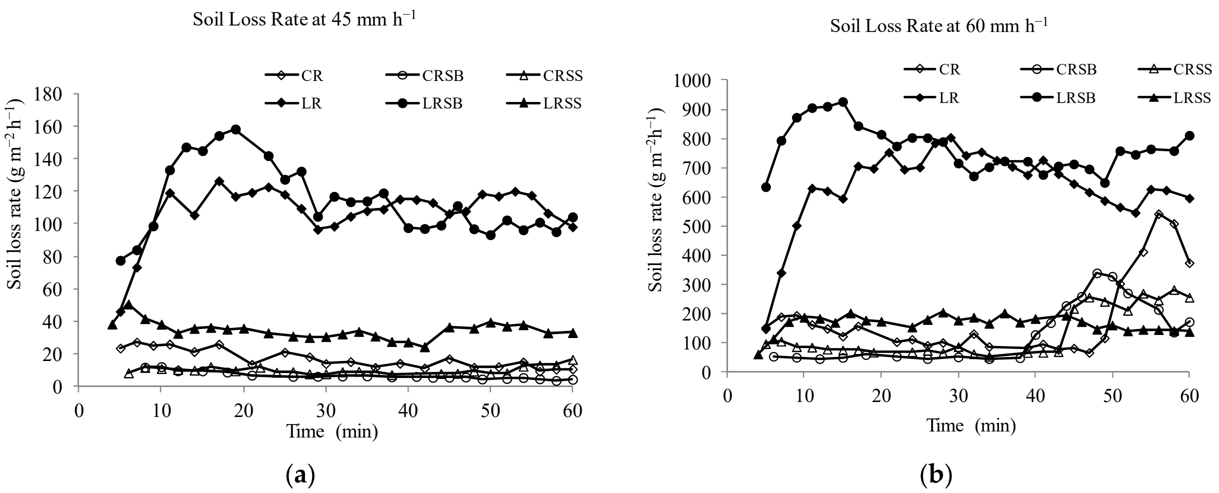


Figure 4. Soil loss rates versus time for different ridge and straw returning practices. CR, contour ridge; CRSB, contour ridge with straw below the furrow; CRSS, contour ridge with straw on the furrow surface; LR, longitudinal ridge; LRSB, longitudinal ridge with straw below the furrow; and LRSS, longitudinal ridge with straw on the furrow surface. (**a**) Soil Loss Rate at 45 mm h^{-1}; (**b**) Soil Loss Rate at 60 mm h^{-1}.

The rainfall accumulated in the furrows and different water levels occurred in the upper and lower furrows. Non-equilibrium hydraulic condition is a requirement for seepage [39]. Seepage occurred in treatments with contour ridge, and flow eroded the fine particles through the voids between coarse grains, reduced the matric suction, which dramatically increased the hydraulic conductivity [40], reduced the stress of surface soil particles [41], and exacerbated soil erosion [27]. After ridge failure, pooled runoff and seepage made the average soil loss rate of treatments with contour ridge to be 3.7 times more than before ridge failure while also being 43.3% of the average of LR and LRSB. Seepage produced cave-like features and leaded to cantilever failures [27], which negatively affected ridge stability. Thus, rills and gullies emerged in contour ridge, which were common phenomena in Northern of China [14,15].

The straw below the furrow had the rapid storage performance make the times of soil loss generation in CRSB and LRSB be later than the corresponding contour ridge treatments and longitudinal ridge treatments, respectively (Figure 4). In addition, the average soil loss rate of CRSB before and after ridge failure were separated were 56.5% and 56.8% of those of CR. In LRSB, the soils in the furrows absorbed more rainfall than that of LR for rapid water storage capacity of straw under the furrow. The increased soil moisture led to the decrease in soil shear strength [42]. Hence, the soil loss rates of LRSB in the initial stage were greater than those of LR (Figure 4). As the experiment ran, the differences of soil water content between LR and LRSB became smaller. Thus, the soil loss rates of LRSB were nearly the same as those of LR separate after 25 and 20 min at 45 and 60 mm h^{-1}. The soil loss rates of LRSB were significantly higher than those of LR at the last 10 min of the experiment at 60 mm h^{-1}. The average soil loss rate of LRSB under two rainfall intensities was 113.0%

of LR. The confluence runoff continuously scours the bottom of the longitudinal ridge, and rills appear in treatments with longitudinal ridge bottom [14]. The total soil loss of LRSB was the largest and was separated 1.2, 4.7, and 5.4 times as big as LR, LRSS, and the average value of treatments with contour ridge at 60 mm h^{-1} (Table 2). No matter the contour or longitudinal ridge, the straw layer prevents rainfall from further penetrating into the deep soil to a certain extent, and the plow pan also has the same effect, which increased the soil moisture and accelerates the destruction of the contour ridge and the longitudinal ridge soil loss. Thus, the water-resisting layer or the plow pan could increase the soil loss. However, breaking the plow pan could partially increase infiltration, and it was also proved that it can increase N use efficiency and crop yield [8].

Raindrop energy breaks the bonds between soil particles [43] and enhances runoff disturbance, which accelerates soil particle separation [44]. The raindrop splash increases the soil erosion rate by up to 78.3–95.2% [34]. The loss of soil particles < 0.25 mm played a leading role in the sediment in the Chinese Mollisol region [23]. Straw reduces the kinetic energy of raindrops and the separation of soil particles. This effect prevented the appearance of crust to some extent, which allowed for more permeation for rainfall. The straw also blocked and infiltrated the soil particles to some extent. Hence, the average soil loss rate of CRSS before and after ridge failure was separates by 64.1% and 57.8% of those of CR at 60 mm h^{-1} (Figure 4b). The soil loss trend of LRSS always kept a relatively stable state under two rainfall intensities. The average soil loss rate of LRSS under two rainfall intensities was 29.0% of LR and 54.3% of the average value of treatments with contour ridge after ridge failure at 60 mm h^{-1}. Straw on the furrow surface could effectively reduce the soil loss rate.

Soil erosion rate of contour ridge decreased 99.2% [28], and the annual topsoil loss decreased 0.01–0.26 cm [13] compared with those of longitudinal ridge. The reduction extents of total soil loss were separated by 14.7% and 28.4% when comparing CR to LR at 45 and 60 mm h^{-1} (Table 2). At 60 mm h^{-1}, the total soil loss of CRSB was separate 70.2% and 98.5% of CR and CRSS. However, the total soil loss of LRSS was 93.8% of that of CR and was 1.3 times as big as the average of CRSS and CRSB (Table 2). Rainfall intensity had the greatest impact on soil loss rate, followed by ridge tillage, their interaction, and straw returning. Any control factors and the interaction between factors had significant impacts on soil loss rate (Table 3).

Longitudinal ridge is the dominant tillage practice in Mollisol region of Northeast China [14]. It is convenient for tillage, and it drains snowmelt in spring for providing a drier seedbed and increasing earth temperature. Longitudinal ridge furrows foster flow to concentrate, which causes severe soil erosion but has not obvious damage to the crop yield [14]. Straw mulching on longitudinal ridge furrow increases the runoff rate to a certain extent, but the soil loss rate decrease was significant, even much smaller than that of contour ridge after ridge failure. There were no significant differences in total soil loss between CR, CRSB, CRSS, and LRSS. Seepage is liable to occur in the ponding process in contour ridge treatments [30]. However, the longitudinal ridge treatments were easy to maintain stability for its drainage performance. Liu et al [45] also indicated that ridge tillage and the alternative use of straw on surface being incorporated into the soil was a suitable tillage practice for increasing maize yield in the Mollisol region. Therefore, LRSS with could be a suitable tillage practice, which reduced soil loss and increased yield. In a future study, the stability analysis under field positioning monitoring of LRSS should be added.

4. Conclusions

Rainfall simulation was conducted to demonstrate the effects of combinations of ridge tillage and straw-returning practices on runoff and soil loss with 5° slope under two rainfall intensities (45 and 60 mm h^{-1}) in Mollisol region of Northeast China. The results showed that (1) rainfall intensity had the greatest impact on soil loss rate, followed by ridge tillage and their interaction, but the order for the runoff rate was ridge tillage, rainfall intensity, and their interaction. (2) The straw below the furrow made the contour ridge treatment easily form contour ridge failure, meanwhile longitudinal with straw below the furrow treatment increased the total runoff and soil loss compared to those of longitudinal ridge treatment. The total runoff and soil loss of longitudinal ridge with straw below the furrow treatment were separate 106.8% and 124.1% of longitudinal ridge treatment at 60 mm h^{-1}. (3) The straw on or below the furrow with treatments of contour ridge had a positive effect on soil loss control. The soil loss rate and runoff rate of contour ridge with straw on and below the furrow treatments were smaller than those of contour ridge treatment nearly the whole procedure. (4) Contour ridge treatment and its modifications had good effects on reducing the runoff rate and soil loss rate for their water storage capacity, but when reaching the limit, drainage facilities should be considered in the area with heavy rainfall. (5) Longitudinal ridge with straw on the furrow surface treatment exhibited a stable state on controlling soil loss, which was even lower than treatments with contour ridge after ridge failure. The average soil loss rate of longitudinal ridge with straw on the furrow surface treatment under the two rainfall intensities was 29.0% of that of longitudinal ridge treatment and was 54.3% of the average value of treatments with contour ridge after ridge failure at 60 mm h^{-1}. This study recommends that the practice of longitudinal ridge with straw on the furrow surface treatment effectively control soil erosion in the Chinese Mollisol region.

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