agronomy

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Dynamic Change Patterns of Soil Surface Roughness and Influencing Factors under Different Tillage Conditions in Typical Mollisol Areas of Northeast China

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Abstract: Soil surface roughness is an important factor affecting hydrology and soil erosion processes, and its development is influenced by precipitation, topography, and tillage practices. In this study, the typical mollisol area in northeast China was taken as the research object. Then, the variation in soil surface roughness with time was analyzed under different terrains, as well as different tillage methods, and the effect of the precipitation condition on roughness was also discussed in detail. Through the design of field experiments, the height information of the soil surface was measured using a probe-type roughness plate. Two parameters, the root-mean-square height (RMSH) and the correlation length (CL), were selected to quantitatively characterize the soil surface roughness. In addition, the dynamic change patterns of surface roughness resulting from five tillage methods, including rotary tillage, combined tillage, no tillage, conventional tillage, and reduced tillage, under both sloping and flat land, were compared and analyzed throughout the soybean growing season, under the influence of rainfall. The results show that with the increase in rainfall, the RMSH of the soil surface, under different tillage methods, showed a trend of first decreasing, and then increasing. The results also showed that the RMSHs under rotary tillage, combined tillage, conventional tillage, and reduced tillage in flat land were greater than those in sloping land, and that the CLs of the soil surface under different tillage methods in flat land were smaller than those in sloping land. In addition, the degree of variation in the soil surface roughness was greater in flat land than that in sloping land under all tillage practices, indicating that this study is of great practical importance in the rational selection of tillage methods, and in the scientific quantification of soil erosion, which also show obvious significance for soil and water conservation.

Keywords: soil roughness; root-mean-square height; correlation length; tillage practice; mollisol

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Citation: Zhou, S.; Ren, J.; Chen, Q.; Zhang, Z. Dynamic Change Patterns of Soil Surface Roughness and Influencing Factors under Different Tillage Conditions in Typical Mollisol Areas of Northeast China. *Agronomy* **2023**, *13*, 1817. https://doi.org/10.3390/agronomy13071817

Academic Editor: Koffi Djaman

Received: 1 June 2023
Revised: 5 July 2023
Accepted: 7 July 2023
Published: 8 July 2023

1. Introduction

The environmental damage caused by soil erosion has attracted widespread attention, and the problem of soil erosion in the mollisol region of China has greatly increased, seriously affecting crop growth, as well as crop yield. As an important factor affecting wind and water erosion, the soil surface roughness is capable of describing soil microscale heaving on the centimeter-to-decimeter scale, caused by tillage practices and soil erosion [1,2]. It has been shown that the soil roughness can influence the surface runoff, infiltration, flow production, sand production and erosion processes [3–5]. The soil surface roughness can be used as an important indicator factor in soil erosion monitoring [6,7]. In addition, the soil surface roughness can also change the distribution of precipitation, and affect the direction of flow production and sink flow, which in turn affects the erosion process of the soil [8]. Therefore, quantitative research on the development of soil roughness and its influencing factors is of great significance for quantifying the degree of soil erosion, controlling the scope of arable land erosion, and measuring soil degradation [9]. In addition, the accurate measurement and evaluation of soil surface roughness can also effectively improve the accuracy of large-scale synchronous inversion of the surface parameters, using remote sensing technology [10,11].

Up to now, the results of numerous studies have shown that the soil surface roughness is mainly influenced by tillage practices [12,13], precipitation [14,15], and topography [16,17]. Regarding the effect of tillage methods on the soil surface roughness, Zheng et al. [12] conducted simulations of different soil surface roughness types, using four tillage methods: raking cropland, artificial hoeing, artificial digging, and contour tillage, on smooth slopes under simulated precipitation conditions. Their findings indicated that the degree of sheet erosion was influenced by the soil surface roughness resulting from each tillage method, and that this effect varied under different rainfall intensities. For fine furrow erosion, the soil surface roughness increased for the monopoly and manual tillage treatments, while it decreased for the artificial hoeing and contour tillage treatments, under both rainfall intensities. Martinez-Agirre et al. [13] graded the soil surface roughness produced under three tillage methods, mouldboard, harrow, and seedbed; they also assessed that the most distinguishing roughness parameters were selected as the limiting height difference and the mean upslope depression index, while the most sensitive parameters to the effect of rainfall were the limiting slope, and the cross length measured by the semi-variance function method.

To assess the effect of precipitation on the soil surface roughness, Vermang et al. [14] screened four different soil surface roughness classes under simulated precipitation conditions. They then represented them using several existing soil surface roughness parameters, and found that random roughness proved to be the best estimate for distinguishing soil surface roughness classes. They also found that, in addition to the variogram function range and correlation length according to a Gauss–Markov model, most of the soil surface roughness parameters were higher before the rainfall event than after the event; this was because the agglomerates were disrupted, and the depressions were filled with sediments during the rainfall event, thus making the soil surface smooth. After studying the effect of continuous precipitation on the surface roughness and physical crusting of very fine soils with low organic matter content in a typical semi-arid environment, Bullard et al. [15] quantified the changes in the soil surface roughness using semi-variance functions deriving from the high-resolution laser scanning of high soil surfaces. They also found that the effect of rainfall on the surface roughness characteristics of very fine soils was significantly dependent on the amount of rainfall.

In the studies of the influence of the terrain on the soil surface roughness, Zhang et al. [16] measured the soil surface roughness, using a handheld 3D scanner, at six plots with different slopes. They also measured the soil surface roughness at three different slope locations along a 60 m plot, with the results showing that the soil surface roughness was significantly affected by slope and location, and that the soil random roughness increased exponentially with the increasing slope. Li et al. [17] conducted a series of rainfall simulations on stony soils, and measured the soil surface roughness under three slope treatments (5%, 12%, and 20%). Their findings highlighted that the degree of soil surface roughness and hydraulic roughness increased with steeper slopes, and that the impact of slope on soil erosion was modulated by the dynamic interplay among soil erosion, surface morphology, and water flow. They also described that the effect of slope on soil erosion decreased due to the dynamic interaction of soil erosion, surface morphology, and water flow.

As a mathematical expression of the undulating condition of the ground surface, the soil surface roughness is often difficult to describe using a single parameter, due to its complexity. Although many different types of quantitative metric are available, the root-mean square-height (RMSH) and correlation length (CL) are most often used to describe the variation in soil surface roughness. The RMSH can be considered as a metric in the vertical direction that reflects the degree of deviation of the surface height from the mean height, which describes the characteristics of the stochastic process at each isolated location. The CL is a measure of the soil surface roughness in the horizontal direction, describing the variation in heights in the horizontal direction, and reflecting the connection between observations at different locations. In general, the rougher the surface, the greater the RMSH, and the smaller the CL [18,19]. Specifically, Lv et al. [20] used the RMSH and CL to study the spatial and temporal variation in the soil erosion process, as well as the surface roughness in gangue hills; their results showed that both the RMSH and CL changed drastically when the rainfall was highly variable. Liu et al. [21] designed four groups of trenching depths, and two surface conditions, under indoor trenching test conditions. After comparing the RMSH and CL data calculated before and after wavelet treatment, they found that the random roughness parameters could accurately characterize the surface under each group of tests, and that the RMSHs greatly increased after trenching treatment, while the CLs showed an obvious opposite trend in all five sections under each group of trenching depth treatments, proving that the directional roughness component of monopoly formation has a significant effect on the calculation of soil surface roughness. Zheng et al. [22] used four soil surfaces with the RMSH and CL, showing that the RMSH and CL were exponentially related to the relative change in cumulative rainfall, and that there was a significant difference in the change in soil surface roughness with cumulative rainfall for ridged and unridged soils.

Although the effects of tillage practices, precipitation, topography, and other factors on surface roughness were common studied, most of the previous research was carried out through controlled simulation experiments in the short term, rather than over all-time dynamic change under natural conditions, and only considered the influence of one or two factors on soil surface roughness, rather than their simultaneous influence due to the increasing complexity. In addition, the studies on soil surface roughness, such as the RMSH and CL, are mostly carried out considering the effect of rainfall on soil surface roughness under the same topographic conditions, yet a comparative analysis of roughness parameters under different topographic conditions is also lacking. This paper intends to use the RMSH and CL to parameterize the soil surface roughness of the mollisol of northeast China, and to study the dynamic changes in soil roughness with time, under different tillage practices and natural rainfall conditions, during the whole soybean-planting season. This study also aims to compare and analyze the changes in soil roughness between different tillage methods in two topographic conditions, including flat and sloping land, in order to investigate the optimum tillage method for soil conservation in mollisol, as well as quantifying the soil degradation, and determining the scope of arable land erosion, in northeast China.

2. Materials and Methods

2.1. Experimental Design

The mollisol area in China is commonly located in the Songliao Plain, which is mainly located in Heilongjiang Province, Jilin Province, Liaoning Province, and Inner Mongolia Province, with an area of about 1.09×10^6 km^2, and is considered an important commercial grain production area. In this study, two typical mollisol regions with different terrains were selected as study areas in Hailun City. Specifically, the National Field Scientific Observation and Research Station of Hailun Farmland Ecosystem of Chinese Academy of Sciences (47°26′ N, 126°38′ E) was selected as the flat land study area (test site 1), and the Hailun Black Soil Water and Soil Conservation Monitoring Research Station of Chinese Academy of Sciences (47°23′ N, 126°51′ E) was selected as the sloping land study area (test site 2) with a topographic slope of 5°, which is 10 km away from test site 1 (Figure 1).

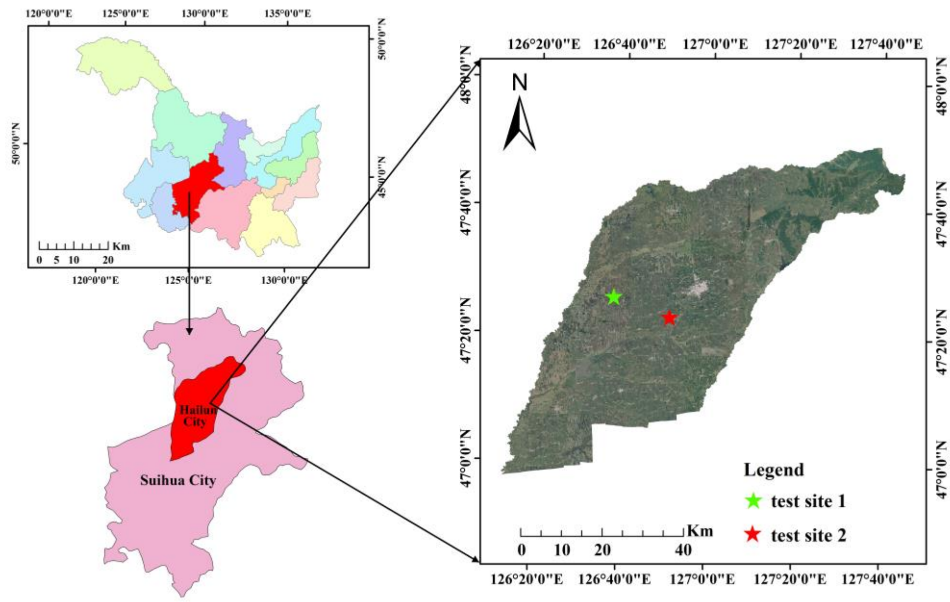

Figure 1. The study area and test sites.

Hailun City has a temperate continental monsoon climate, with cold and dry winters and hot and rainy summers. The two experimental stations are close to each other, indicating that their climates and soil types do not differ significantly. In addition, the same soybean crops were planted at both experimental stations. The timeframe selected for this experiment was from 17 June to 17 September 2018, which covers almost the whole period of soybean growth, from emergence to maturity. In this study, the dynamic change in soil roughness was qualitatively studied under five typical tillage practices of northeast China: rotary tillage (spinning and ridging after harvest in autumn); combined tillage (deep furrow loosening in summer, together with rotational loosening and ridging after harvest in autumn for corn, then ridging over winter, and cultivating directly in spring for soybean); no tillage (no tillage except for sowing in spring, and covering the surface with crushed straw rods after harvest in autumn); conventional tillage (plowing and ridging after harvest in autumn); and reduced tillage (deep furrow loosening in summer, and retaining stubble for winter after harvest), which are shown in Figure 2. Specifically, the same sample area for each tillage method was selected as 336 m^2 (8.4 m $\times$ 40 m) in test site 1, and the same sample area for all tillage practices was selected as 100 m^2 (5 m $\times$ 20 m) in test site 2; all sample regions covered an adjacent and parallel distribution. For both test sites, four replicates were set under every tillage practice, for the measurement of the soil surface height, and the extractions of the surface roughness.

Figure 2. Photographs of each tillage practice in the field: (**a**) rotary tillage; (**b**) combined tillage; (**c**) no tillage; (**d**) conventional tillage; (**e**) reduced tillage.

2.2. Extraction of Soil Surface Height

The pin-profiler method was adopted in this study, to acquire the soil surface roughness [23], by measuring the height data of the soil surface undulation, based on photography. The method has a low acquisition cost, low time consumption, convenient acquisition process, and high measurement efficiency. In addition, as the bottom of the measuring needle within the roughness plate is equipped with a protective round cap, the measuring needle cannot penetrate the surface and insert itself into the soil's interior, avoiding damage to the soil surface [24]. The soil surface roughness plate used in this study is 140 cm long, with probes installed sequentially at 1 cm intervals from the bottom to the top. Specifically, the surface roughness plate was firstly inserted into the ground with its upper edge kept horizontally; after that, the digital camera was fixed onto the metal bracket to adjust the camera angle, so that its lens was kept perpendicular to the roughness plate; thirdly, the soil roughness plate was photographed, with a unified distance of 3 m. Importantly, the points of the four corners of the roughness plate must be kept from any occlusion [25].

Figure 3a shows the process of measuring the soil surface height using a surface roughness plate. After the field measurements were finished, the obtained photos were subjected to standardized pre-processing operations [26,27]. Firstly, geometric correction was carried out using polynomial models; after that, the corrected images were uniformly cropped, with the results shown in Figure 3b; thirdly, the red, green, and blue components of the color-cropped images were arithmetically averaged, in order to be converted into grayscale images (shown in Figure 3c); fourthly, the highest point above each probe was marked and plotted; and finally, the grayscale images with marked plots were binarized (Figure 3d). After pre-processing the standardized image of the probe, the vertical scale factor was calculated based on the actual width of the roughness plate of 1.4 m, and the actual height of the roughness plate of 0.4 m. The actual height of each probe was then calculated based on this scale factor, and the recorded values of the vertical coordinates of the image elements at the top of the probe, which were considered as the actual height of the probe, corresponding to the soil surface.

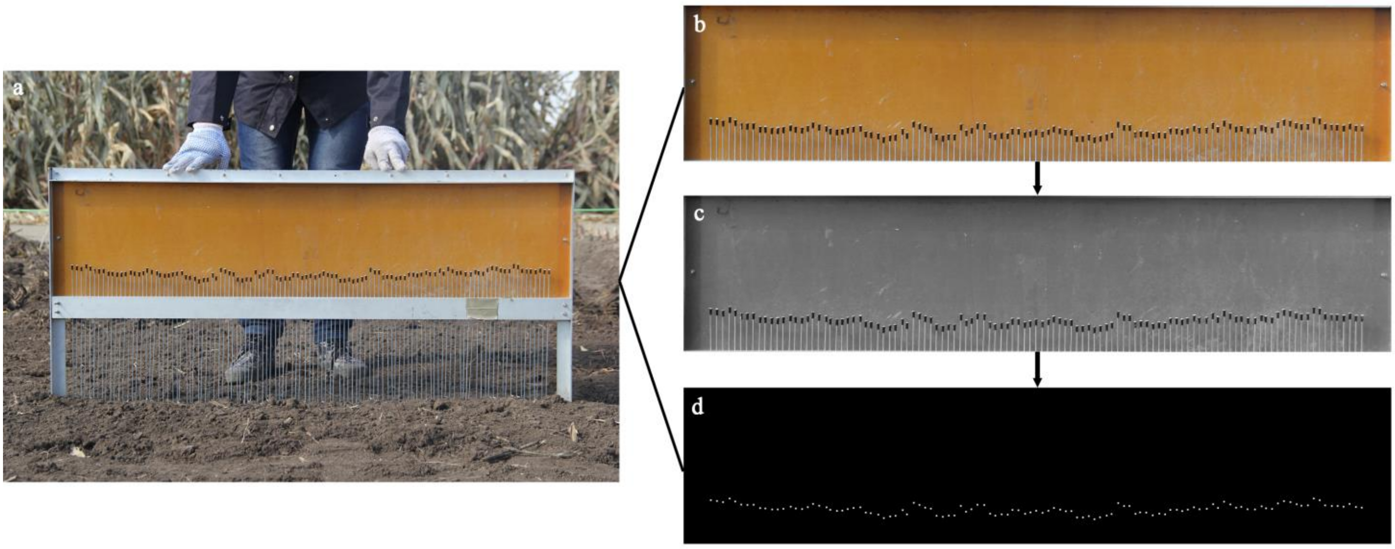

Figure 3. The processing of the soil surface roughness: (**a**) the measurement of the height of the soil surface using a roughness plate; (**b**) the geometric correction and cropping result of the roughness plate; (**c**) the grayscale processing result of cropping the result image; and (**d**) the binarization result of the probe height marker.

2.3. Calculations of Soil Surface Roughness

Although there are various parameters for describing the soil surface roughness, the two most commonly used roughness parameters, the root-mean-square height (RMSH) and the correlation length (CL), were adopted in this experiment to parametrically express the soil surface condition. The arithmetic mean of the roughness parameters of four replicate samples, under the same tillage practice at each measurement, was calculated as the final roughness parameter. The RMSH was proposed by Allmaras et al. [28] to describe the variation in soil surface roughness in the vertical direction, using the following equation:

$$\mathrm{RMSH} = \sqrt{\frac{1}{n-1}\sum_{\mathrm{i}=1}^{\mathrm{n}} (\mathrm{z_i} - \overline{\mathrm{z}})^2}, \tag{1}$$

$$\overline{\mathrm{z}} = \frac{1}{\mathrm{n}}\sum_{\mathrm{i}=1}^{n} \mathrm{z_i}, \tag{2}$$

where n is the number of measurement points on the profile, z_i represents the elevation value at the measurement point with unit of cm; $\overline{z}$ refers to the average height value of all measurement points.

The CL is determined by solving the autocorrelation function for a set of data, which describes the correlation of the surface height in the horizontal direction, and is an important indicator for characterizing temporal or spatial correlation. The CL is calculated as follows:

$$\mathrm{CL(h)} = \frac{\sum\limits_{\mathrm{i}=1}^{\mathrm{N(h)}} \mathrm{z_i z_{i+h}}}{\sum\limits_{\mathrm{i}=1}^{\mathrm{N}} \mathrm{z_i}}, \tag{3}$$

where CL(h) is an autocorrelation function that represents the correlation existing between the height of point i (z_i) and the height of point i + h (z_{i+h}) located at a lag distance of h cm from point i. The units of z_i and z_{i+h} are both cm. N(h) is the number of height pairs considered in each lag h. The CL is defined as the critical length at which the heights of the two points are considered independent, while the actual length corresponding to h when CL(h) equals 1/e [20,29].

3. Results

3.1. Soil Surface Roughness Measurements

3.1.1. Statistical Results of Soil Surface Roughness under Sloping Land

From Table 1, it can be seen that the average values of both roughness parameters under different tillage methods differed significantly in size, in the descending order of no tillage > reduced tillage > conventional tillage > combined tillage > rotary tillage for the RMSH, and the descending order of no tillage > rotary tillage > conventional tillage > combined tillage > reduced tillage for the CL, respectively. Table 1 also indicates that the RMSHs were more evenly distributed than the CLs, and the coefficients of variation of the CLs under sloping land were significantly lower than those of the RMSHs under the same tillage method, indicating that the dispersion of the RMSHs was significantly higher than that of the CLs. In addition, the kurtosis of the RMSHs (−1.14 to 1.54) and the CLs (−0.95 to 3.08) was quite limited under sloping land, demonstrating that the distribution of RMSHs and CLs was concentrated for all tillage practices; the skewness of the RMSHs (0.20 to 0.55) and CLs (1.26 to 7.87) for all tillage practices suggested that the RMSHs and CLs for all tillage practices had a tendency to be distributed in favor of higher values.

Table 1. Statistical results of soil surface roughness under sloping land.

		Rotary Tillage	Combined Tillage	No Tillage	Conventional Tillage	Reduced Tillage
RMSH	Minimum value (cm)	0.55	0.85	2.50	1.72	2.19
	Maximum value (cm)	1.66	1.46	3.46	2.53	3.84
	Average value (cm)	0.94	1.19	3.08	2.15	2.76
	Standard deviation (cm)	0.32	0.19	0.30	0.24	0.53
	Coefficient of variation (%)	34	16	10	11	19
	Kurtosis	1.54	−1.14	−0.86	−0.74	0.06
	Skewness	0.33	0.20	0.31	0.25	0.55
CL	Minimum value (cm)	58.00	58.33	78.33	68.00	43.67
	Maximum value (cm)	89.50	78.50	82.00	78.67	83.00
	Average value (cm)	78.24	69.10	80.88	72.56	62.83
	Standard deviation (cm)	7.56	6.39	1.21	3.38	12.87
	Coefficient of variation (%)	10	9	2	5	20
	Kurtosis	3.08	−0.95	−0.40	−1.05	−0.79
	Skewness	7.87	6.65	1.26	3.52	13.40

3.1.2. Statistical Results of Soil Surface Roughness under Flat Land

From Table 2, it can be seen that the soil surface roughness parameters varied differently for various tillage methods under the flat-land condition. The average value of both roughness parameters under different tillage methods were quite different, with an obvious trend of reduced tillage > combined tillage > conventional tillage > rotary tillage > no tillage for the RMSH, and the corresponding order regarding to reduced tillage > conventional tillage > combined tillage > rotary tillage > no tillage for the CL. It can also be seen from Table 2 that the RMSHs were still more evenly distributed than the CLs under flat land; however, the coefficients of variation of the CLs were significantly higher than the coefficients of variation extracted from the RMSHs under different tillage methods, indicating a large degree of dispersion, which was contrary to the measurement results under sloping land. Table 2 also indicates that the kurtosis of the RMSHs was less than 0 for all five tillage methods under flat land, with a range from −1.78 to −0.41, and that the kurtosis of the CLs covered a larger range, from −1.28 to 0.64. In addition, the skewness of the CLs (10.87 to 19.19) was significantly greater than that of the RMSHs (0.66 to 0.98).

Table 2. Statistical results of soil surface roughness under flat land.

		Rotary Tillage	Combined Tillage	No Tillage	Conventional Tillage	Reduced Tillage
RMSH	Minimum value (cm)	2.87	2.92	1.07	2.89	3.34
	Maximum value (cm)	5.12	5.64	3.11	5.44	5.61
	Average value (cm)	4.22	4.31	2.03	4.27	4.50
	Standard deviation	0.74	0.94	0.63	0.75	0.71
	Coefficient of variation (%)	17	22	31	18	16
	Kurtosis	−0.92	−1.78	−1.07	−0.41	−0.91
	Skewness	0.77	0.98	0.66	0.78	0.74
CL	Minimum value (cm)	19.50	25.50	16.00	29.33	41.00
	Maximum value (cm)	78.33	76.50	52.67	81.00	73.50
	Average value (cm)	48.13	49.49	31.40	54.37	59.30
	Standard deviation	18.44	12.63	11.22	15.39	10.44
	Coefficient of variation (%)	2.87	2.92	1.07	2.89	3.34
	Kurtosis	−1.28	0.64	−0.62	−0.80	−1.13
	Skewness	19.19	13.14	11.68	16.02	10.87

3.2. Soil Surface Roughness Variation Law on the Same Land

3.2.1. Variation Law of Soil Surface Roughness under Sloping Land

Figure 4 indicates that the RMSHs and CLs of all tillage methods showed a similar trend, and that both roughness parameters were higher and more stable for the no-tillage method than they were for other tillage methods, under sloping land. Specifically, from Figure 4a, it can be seen that as the weekly cumulative precipitation increased from 17 June to 17 July, the RMSH under all tillage methods increased, except for reduced tillage, and that the RMSH under all tillage methods except for reduced tillage showed a trend of first increasing and then decreasing from 7 July to 29 July, as the weekly cumulative precipitation increased to 81.93 mm. Although the weekly cumulative precipitation decreased rapidly from the highest value to 0 mm, from 29 July to 12 August, the changes in the RMSH were not significant. In addition, the RMSHs of different tillage practices remained basically the same from 12 August to 17 September. Figure 4b represents the CLs of no tillage, which described a very stable trend; however, the CLs from the other four tillage methods showed an obvious fluctuation, with two troughs on 30 June and 12 August, and a clear peak on 29 July.

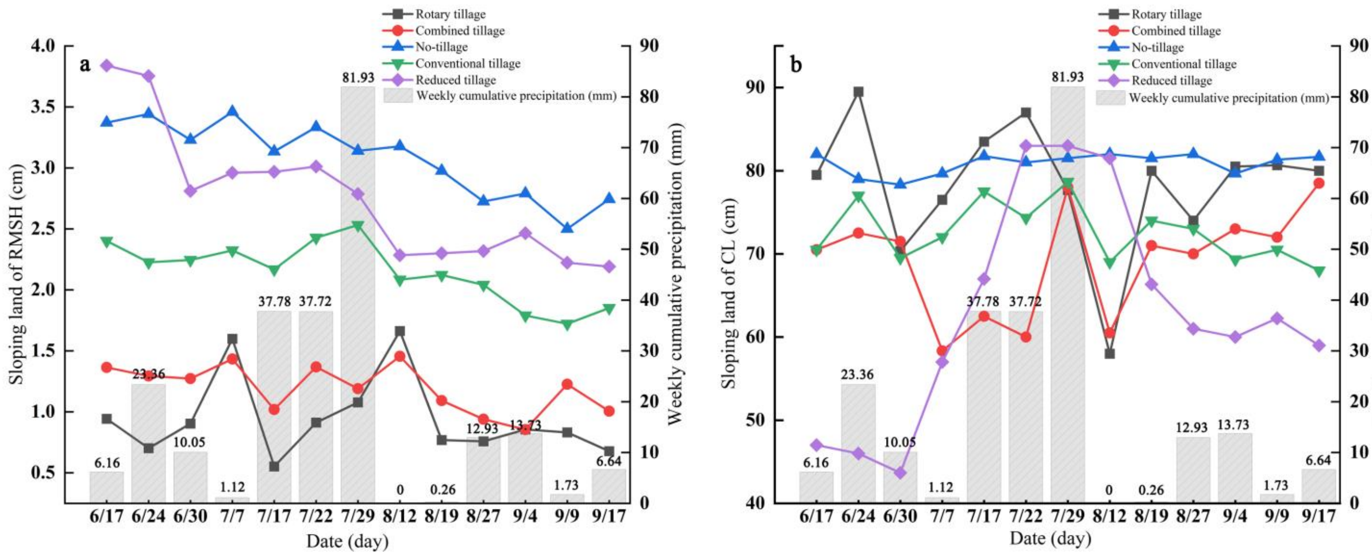

Figure 4. Plot of variation of soil surface roughness parameters on sloping land from 17 June to 17 September, 2018: (**a**) the RMSH variation; (**b**) the CL variation.

3.2.2. Variation Law of Soil Surface Roughness under Flat Land

As can be seen from Figure 5, both roughness parameters showed basically the same trend under different tillage methods under the flat land. Specifically, Figure 5a indicates that the curves of the RMSHs under different tillage methods remained basically stable until 30 June; after that, the curves were found to increase rapidly from 30 June to 17 July. The RMSH curves all showed obvious valleys on 22 July and 12 August, then, in the period after 19 August, the RMSHs of all tillage methods showed an obvious decreasing trend. For the CL (Figure 5b), the entire measurement period can be divided into three phases: from 17 June and 7 July, the CLs of different tillage methods showed a tendency to decrease and then increase, with a minimum on 24 June; from 7 July to 19 August, the CLs of different tillage methods also showed a trend of first decreasing and then increasing, with the lowest point on 29 July; and then from 19 August to 17 September, the CLs of different tillage methods still showed a trend of decreasing and then increasing. In addition, the variation in the CLs with time was basically the same for the five tillage practices.

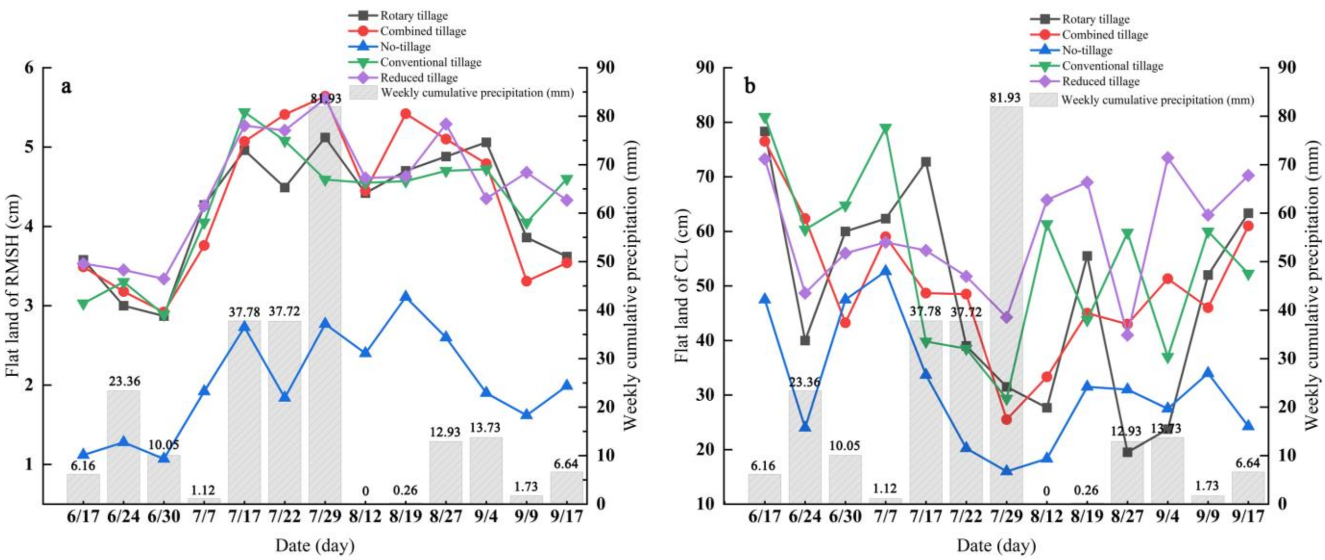

Figure 5. Plot of variation in the soil surface roughness parameters in flat land from 17 June to 17 September, 2018: (**a**) the RMSH variation; (**b**) the CL variation.

3.3. Comparison of the Variation in Soil Surface Roughness Parameters under Different Lands

3.3.1. Comparison of the Variation in the RMSH under Different Lands

From Figure 6, it can be seen that the RMSHs of rotary tillage, combination tillage, traditional tillage, and reduced tillage under flat land were greater than under sloping land, and that combination tillage and rotary tillage were found to have the greatest difference under different terrains. In addition, the RMSHs of all the tillage methods under flat land showed an opposite trend to those under sloping land, with the greatest changes in RMSH found using the no-tillage and less-tillage methods. Figure 6 also shows that, in contrast to the above four tillage methods, the RMSH of no tillage measured under sloping land was significantly higher than that measured under flat land. Specifically, the RMSH of no tillage measured under flat land decreased by 1 cm during the entire cultivation period, while it increased by 0.8 cm when measured under sloping land. Moreover, for the reduced-tillage method, the RMSH obtained under flat land decreased by 1.7 cm under sloping land, and increased by 1.2 cm under flat land, respectively.

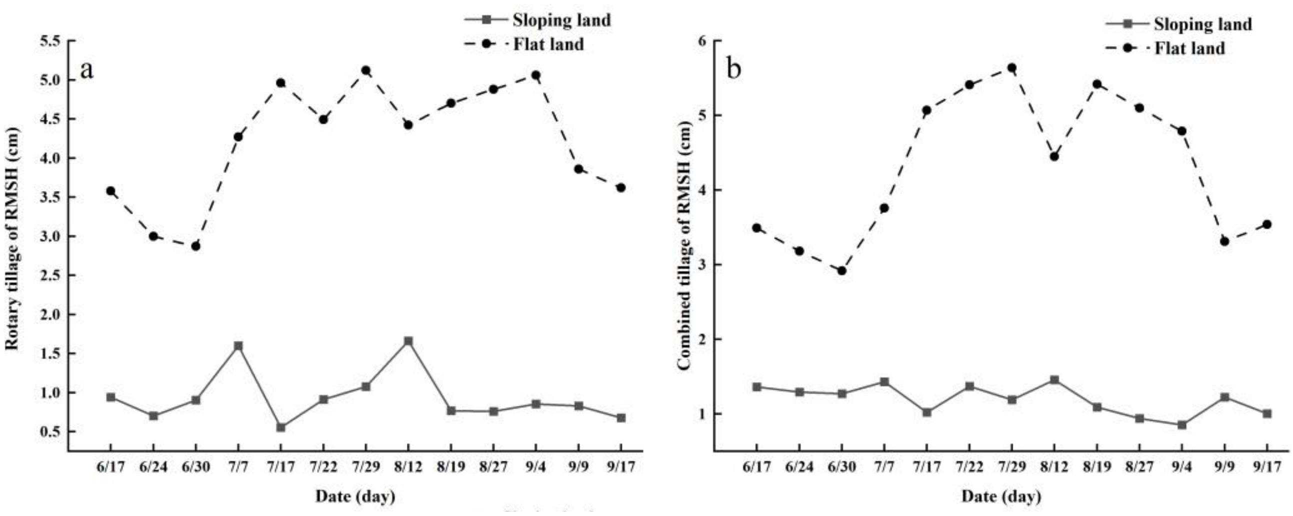

Figure 6. *Cont*.

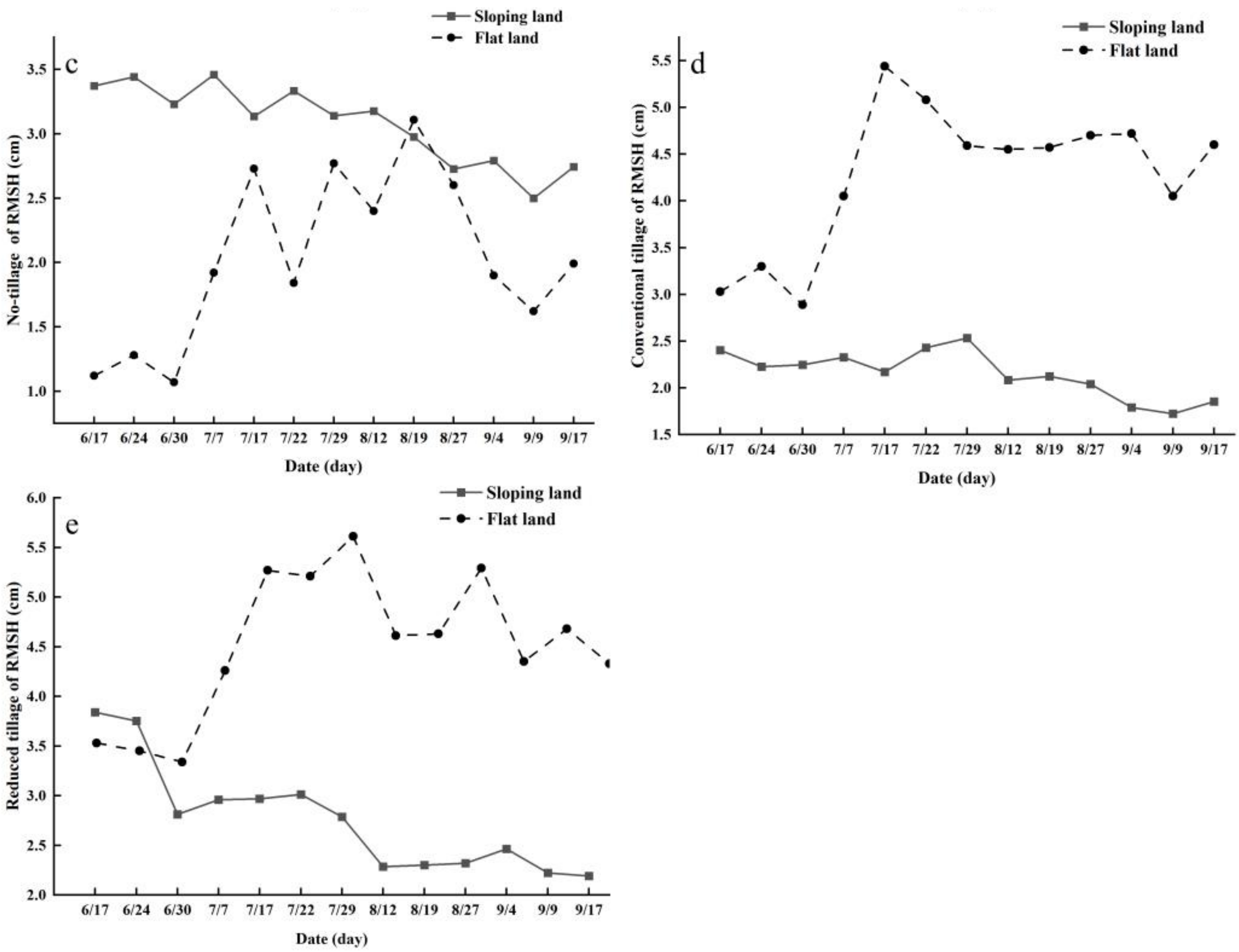

Figure 6. Comparison of the variation in the RMSHs under sloping land and flat land: (**a**) the variation in RMSHs with time under rotary tillage; (**b**) the variation in RMSHs with time under combined tillage; (**c**) the variation in RMSHs with time under no tillage; (**d**) the variation in RMSHs with time under conventional tillage; and (**e**) the variation in RMSHs with time under reduced tillage.

3.3.2. Comparison of the Variation in CLs under Different Land Types

Figure 7 indicates that during most of the cultivation period, the CLs of different tillage methods under sloping land were greater than those measured under flat land. In particularly, the CL of the no-tillage method suffered the least impact from the land, especially under sloping land, where the CL remained basically unchanged. Before 12 August, the changing tendency of the CLs remained the same under both flat and sloping land; with the decrease in precipitation, the trend of the CLs for rotary tillage, combined tillage, traditional tillage, and reduced tillage was basically the same after 12 August, and the trend of CL change was seriously affected by the terrain. Specifically, over the entire cultivation period, the CL of reduced tillage increased by 12 cm under sloping land, and decreased by 3 cm under flat land, respectively. Notably, the CLs of the no-tillage method suffered the least impact from the land, especially under sloping land, where the CL remained basically unchanged.

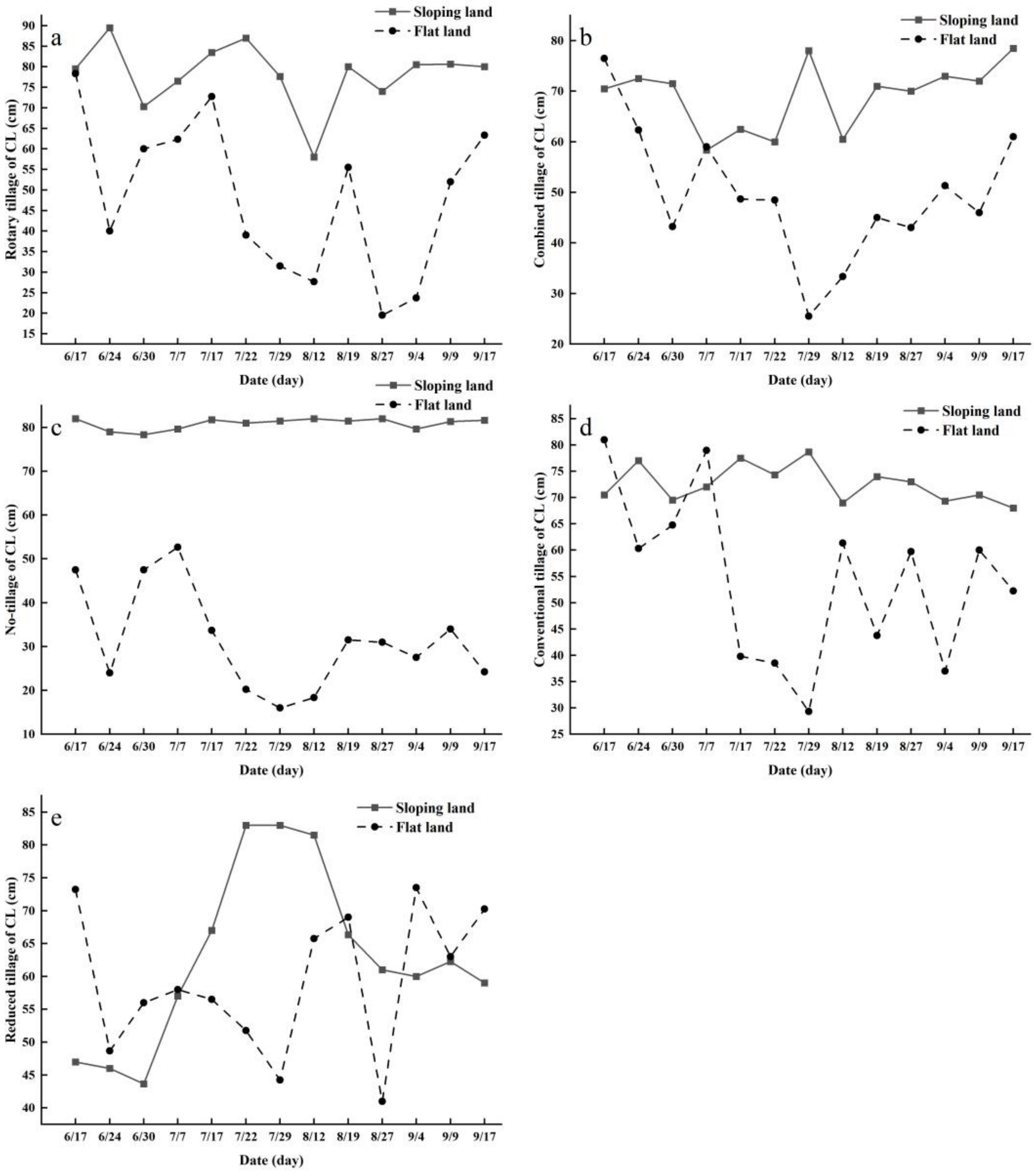

Figure 7. Comparison of the variation in the CLs under sloping land and flat land: (**a**) the variation in CLs with time under rotary tillage; (**b**) the variation in CLs with time under combined tillage; (**c**) the variation in CLs with time under no tillage; (**d**) the variation in CLs with time under conventional tillage; (**e**) the variation in CLs with time under reduced tillage.

4. Discussion

The experimental time of this study was from 17 June to 17 September 2018, which covered the entire soybean-planting season, and which also consisted of the period of concentrated precipitation in northeast China. During this period, the changes in the RMSH and CL were affected by factors including the cultivation methods, crop roots, slope conditions, and precipitation. Among these factors, the tillage practice was considered as the main cause of changes in the soil surface roughness. Specifically, tillage operations such as farming, seeding, hoeing, fertilizer application, and harvesting under different tillage practices disturbed the soil surface, and thus increased the soil surface roughness [28]. In this experiment, the mean size of the RMSH was most pronounced for the different tillage practices in the sloping land, in the order of no tillage > reduced tillage > conventional tillage > combination tillage > rotary tillage, which was caused by the differences in soil surface roughness produced by the different tillage methods.

Compared to other tillage methods, rotary tillage had the smallest soil surface roughness; this was because the rotary tillage was a type of operation that processed the soil surface and shallow layers with a cultivation depth of about 15 cm, which mainly involved crushing the straw on the surface of the field, and finely crushing the soil blocks, to facilitate sowing and other operations in the next season [30]. Combined tillage was mainly used for deep loosening and tillage, with the RMSH value ranging from 0.85 cm to 1.46 cm, and the tillage depth greater than that of rotary tillage, which could effectively loosen the subsoil and break the bottom layer of the plow, while maintaining the surface of the flat land [31]. Conventional tillage had a larger RMSH value, as the loose monopoly body in spring was more conducive to sowing. However, conventional tillage could destroy the continuous large pore space in the soil, with the soil seriously disturbed. In addition, the high RMSH values for reduced tillage and for no tillage were caused by the fact that the no-tillage method combined with straw mulching could effectively improve the soil surface roughness, increasing rainwater infiltration, and reducing rainfall spray erosion. No tillage and reduced tillage turned the soil less often during sowing, indicating that the soil structures of both the reduced tillage and no-tillage methods were stable, and there was a continuous larger-void soil that was not destroyed [32]. Moreover, the main crop planted in this experiment was soybean with a taprooted root system during its growing period, covering the whole rainfall season [33], which penetrated the soil, intertwined, and exerted its tensile strength to enhance the shear strength of the soil when the soil was stressed. The greater the shear strength of the soil, the stronger its ability to resist runoff shear damage, which could slow down the occurrence of soil erosion [34], increasing surface roughness, enhancing soil infiltration, and greatly reducing the level of soil loss.

Slope is also one of the factors affecting soil surface roughness that cannot be ignored [35]. According to the findings of this study, the RMSHs under flat land were greater than those under sloping land, except for with no tillage, and the CLs under flat land were all smaller than those under sloping land. These outcomes suggest that the soil surface roughness was comparatively higher in flat land than in sloping land. Moreover, from the findings in Section 3.3, it was observed that the soil roughness displayed a more considerable variance in flat land than in sloping land. In previous studies, the soil surface roughness was greater in sloping land than in flat land [36,37], due to the higher kinetic energy of rainfall under sloping land, the stronger ability of raindrops to strike the ground, and the greater impact on the surface than under flat land. In addition, the increase in slope also resulted in a lower soil infiltration rate, infiltration volume, and soil stability, which in turn accelerated the scouring of the soil surface, and resulted in changes in the soil roughness [38,39]. In previous studies, mostly in rock-covered or loess-covered areas, the effect of crops on the soil surface roughness may have been neglected. However, the magnitude of the soil surface roughness was closely related to the degree of ground cover, and soybeans grew better under flat land than under sloping land. Therefore, a higher ground cover of soybeans on flat land meant that the surface roughness of the soil in flat land was greater than the soil roughness in sloping land [40,41].

In general, the CL and RMSH are used to describe different aspects of soil surface roughness. Specifically, the CL reflects the trend of soil surface undulations, while the RMSH describes the average height of soil surface undulations [18]. From 7 to 29 July was the period when precipitation increased intensively, and soil-roughness parameters were most obviously influenced by precipitation. The RMSHs showed a trend of decreasing and then increasing under the same topography, but the change pattern of the CL was not obvious. This was because precipitation is the main cause of changes in soil surface roughness when the topographic conditions and tillage practices remain unchanged. At the beginning of rainfall, raindrops fall and impact the soil surface, causing dislocation, reorientation, and accumulation of soil particles [14,42]. At the same time, depressions are formed in the soil surface, and the soil blocks decompose and fall off after precipitation. The previously generated depressions are filled with newly generated sediments, thus smoothing the soil surface and reducing the soil surface roughness [43,44]. Late in the rainfall, when raindrops come into contacting with the soil surface for a long time, the slope surface is initially covered by a very thin layer of water, and slope run off develops. The presence of a thin water layer on the slope surface changes the raindrop striking effect and enhances the raindrop splash effect, making it easier to form surface runoff. This continuous scouring of the ground by surface runoff produces fine furrows, which leads to an increase in the soil surface roughness [45]. Although many scholars have also used the RMSH and CL to characterize soil surface roughness, and have analyzed the trend of changes in the soil surface roughness after precipitation, the dynamic change in soil roughness showed quite a different tendency in this study [46,47]. This may be because the measurement time of the RMSH was not consistent with the time of the experiment carried out in this study. In addition, the measurement duration of the experiment, and the measurement interval for soil surface roughness, were relatively long in this study, which posed a certain impact on the characterization effect of the RMSH and CL. Moreover, the scanning method carried out in previous studies was different from the pin-profiler method in this research, which may also have led to different results.

Under the sloping land, the RMSHs under different tillage methods showed a trend of decreasing and then increasing from 7 July to 29 July, with the peak occurring on 7 July. Under the flat land, although the RMSHs also showed the same trend, a significant lag could be found, with the peak time delayed by about 10 days. This was due to the fact that during rainfall, the initial flow production time was earlier in sloping land than in flat land, and slopes can generate runoff faster [48], which thus increased the retention time of rainfall on the slope, and also enabled the earlier filling of depressions by rainfall. The pattern presented by the CLs with increasing precipitation was not obvious, probably because this experiment only focused on the effect of cumulative precipitation on soil surface roughness, and did not quantitatively study the effect of rainfall intensity on soil surface roughness. At the same time, the soybean growth was better under flat land, which also led to inconsistent changes in the soil surface relief under flat and sloping land and, in turn, affected the trend of the CLs.

During the no-tillage treatment, soil particles form larger agglomerates, due to the absence of the mechanical action of the plough. This helps to maintain the stability of the soil aggregates, and improves the physical structure of the soil, which in turn improves the permeability and aeration of the soil [49,50]. At the same time, the soil surface is less affected by the impact and splash of raindrops, which thus reduces the compaction and erosion of the soil. However, the RMSH only reflects the extent to which the soil height deviated from the mean height, and the surface roughness of the soil under no-tillage sloping land was greater than that under flat land. This was because of the absence of slope effects in flat land, which generated less runoff and splash erosion on the soil surface. In addition, the buffering effect of surface water accumulation on precipitation was stronger in flat land than sloping land, indicating that the soil surface roughness was lesser in flat land [51,52]. When the surface roughness was characterized using the CL, the soil surface roughness was smaller in sloping land than in flat land, with its value much higher than for the other tillage practices in that land, which is contrary to the performance of the RMSH values in both lands. This may be due to the better soybean growth in flat land, and more straw mulch under no tillage; the variability in soil surface undulations was greater in flat land than in sloping land, which had a significant effect on the variation in CL values. Therefore, compared to traditional tillage methods, the no-tillage method could maintain a high soil surface cover, indicating that the soil surface was effectively protected from erosion and damage by the natural environment. In addition, the no-tillage method also played a strong role in water storage and moisture retention, fertilization, the prevention of dust on farmland, the reduction of soil erosion, the promotion of sustainable agricultural development, and the protection of the ecological environment, indicating that the no-tillage practice could be preferable as a conservation tillage practice in arid and semi-arid areas of northern China.

In future studies, simulated precipitation experiments can be designed to quantitatively study the dynamic changes in the soil surface roughness under different rainfall intensities, and the impact of instantaneous precipitation on the soil surface roughness under different terrains and tillage practices, especially for conservation tillage practices, such as no tillage. Specifically, the 3D laser scanning method is also suggested to be combined with the pin-profiler method, to comprehensively measure the overall changes in soil surface roughness in different directions. In addition, water and soil conservation indicators such as runoff, sediment yield, and splash erosion can also be included, in order to scientifically quantify the degree of soil erosion, and comprehensively analyze the water and soil conservation status in the typical mollisol area of northeast China.

5. Conclusions

This study investigated the dynamic changes in soil surface roughness throughout the growing season of soybeans in a typical mollisol zone in northeast China, under different topographies and tillage practices. In conclusion, the significant changes in soil roughness are the result of a combination of rainfall, tillage practices, and topography. With the passage of time and the increase in precipitation, the root-mean-square height (RMSH) of all tillage methods under the same land showed a trend of first decreasing and then increasing with the implementation of different tillage methods, which showed a delayed phenomenon in flat land compared with in sloping land. In addition, the variation amplitude of both the RMSH and correlation length (CL) under the flat land were significantly larger than those under the sloping land. The RMSHs of the soil surface under the flat land under the four tillage methods of rotary tillage, conventional tillage, combined tillage, and reduced tillage were greater than those of the sloping land, and the CLs of the flat land under all tillage methods were less than that under the sloping land. In terms of the no-tillage treatment, the RMSHs and CLs extracted from the soil surface of the sloping land were greater than those of the flat land, indicating that as an effective conservation tillage method, no tillage plays an important role in reducing soil erosion, increasing soil productivity, improving tillage efficiency, and reducing input costs, and is therefore more suitable for the actual situation of agricultural production in arid and semi-arid areas in northern China.

Author Contributions: Conceptualization, J.R.; methodology, J.R. and Q.C.; software, J.R. and Z.Z.; validation, Q.C.; formal analysis, S.Z.; investigation, J.R. and Q.C.; resources, J.R.; data curation, S.Z. and Z.Z.; writing—original draft preparation, S.Z. and Z.Z.; writing—review and editing, J.R.; visualization, S.Z.; supervision, J.R.; project administration, J.R.; funding acquisition, J.R. All authors have read and agreed to the published version of the manuscript.

Funding: This study was supported by the Fundamental Research Funds for the Central Universities of China (No. 2022-KYYWF-0156), and the University Nursing Program for Young Scholars with Creative Talents in the Heilongjiang Province of China (No. UNPYSCT-2018180).

Institutional Review Board Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The authors would all like to thank Xingyi Zhang from the Northeast Institute of Geography and Agroecology, Chinese Academy of Sciences, for the assistance provided in the soil property measurements.

Conflicts of Interest: The authors declare no conflict of interest.

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