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Effects of Crop Rotation and Topography on Soil Erosion and Nutrient Loss under Natural Rainfall Conditions on the Chinese Loess Plateau

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Abstract: Erosive rainfall results in the loss of both soil and nutrients, which indirectly triggers soil deterioration and a reduction in land productivity. However, how rainfall affects runoff, soil erosion, and nutrient loss under different crop rotation patterns and topographic factors remains unclear. This experiment observed nine runoff-erosion plots on the Chinese Loess Plateau (CLP) from 2019 to 2020 to determine the effects of crop type, rotation pattern, and slope gradient and length on runoff, soil erosion, and nutrient loss. Runoff, soil erosion, and nutrient loss were highest for the fallow plots; values for these variables for spring corn and winter wheat plots were not significantly different. Crop rotation generated greater runoff, soil erosion, and nutrient loss compared to non-rotation. Soil erosion and associated nutrient loss increased, but not significantly, with slope for gradients of 0.5°, 1°, and 3°, while runoff and associated nutrient loss did not increase. In addition, soil erosion and associated nutrient loss were significantly greater for slope lengths of 20 m vs. 50 m. A structural equation model showed rainfall characteristics significantly impacted runoff and soil erosion and subsequently affected nutrient loss. This study increases the understanding of runoff, soil erosion, and nutrient loss from cropland with gentle slopes on the CLP.

Keywords: crop rotation; runoff and sediment; nitrogen and phosphorus losses; Chinese Loess Plateau

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1. Introduction

Soil erosion driven by runoff and sediment generally takes nutrients away from soil, reduces soil fertility, and then causes soil degradation [1,2]. Therefore, soil erosion has attracted widespread attention as a worldwide problem [3–5], especially in severe soil erosion areas, such as the Chinese Loess Plateau (CLP). The CLP is the most erosive area in the world, generating approximately 90% of the sediment and nutrients that enter the Yellow River [6], as well as a large amount of soil nitrogen and phosphorus that cause water pollution and eutrophication [7]. Soil nutrients are critical to the productivity of terrestrial ecosystems and have received a large amount of attention [8,9]. Some research shows inappropriate land use and tillage practices can increase soil nutrient loss [10], which usually occurs via two mechanisms—sediment-bound nutrients lost as particles and soluble nutrients lost with runoff [11]. Runoff and soil erosion from farmland are considered the main sources of soil nutrients entering water bodies [12,13]. Therefore, investigating the soil erosion and nutrient loss from farmland is important for better management of agricultural production and the ecological environment.

Soil nutrient loss processes are complex and controlled by various factors, such as rainfall, soil tillage system, and topography [14–16]. The main driver of soil erosion in semi-arid systems is rainfall, with characteristics such as duration, amount, and intensity controlling hydrological processes [17,18]. Rainfall characteristics are also the main factors that affect soil nutrient loss and have been extensively studied [19,20]. The sediment yield rate decreases with increasing rainfall duration [21], and even the form of nutrient loss varies with rainfall duration [22]. Sediment concentration and soil loss increase as rainfall amount increases [23]. In general, heavy rainfalls of short duration and high intensity cause the most erosion [24] and also drive the redistribution of nutrients [25]. Rainfall reaching an intensity of 15 mm/h can cause severe soil erosion [26]. However, previous studies have mainly focused on simulated rainfall [27–29] and long-term natural rainfall experiments are relatively rare [30,31]. Therefore, soil nutrient migration in farmland ecosystems needs to be characterized under natural precipitation conditions.

Crop type and rotation are other major factors that affect soil erosion and nutrient loss from farmland [32,33]. The direct impact of cultivating different crops on soil loss and water erosion has been widely studied. Carroll et al. (1997) show that, in central Queensland, the average annual runoff from wheat is lower and the soil loss higher than that from sorghum and sunflower [34]. Prasuhn (2012) demonstrates that, among 203 crop fields in the Swiss Midlands, the greatest total soil erosion occurs in winter wheat fields, followed by potato and fallow fields [35]. Based on 198 rainfall-runoff events, Fiene and Auerswald (2007) show the obvious difference in soil loss based on the previous season crop [36]. However, inadequate information is available about the effect of winter wheat and spring corn (common crops on the CLP) on soil and nutrient loss in surface runoff. Moreover, research on crop rotation has mainly focused on crop yield and soil moisture [37,38], while relatively little has been carried out to study soil erosion and nutrient loss in the CLP region [33,39]. Therefore, conditions of soil erosion and nutrient loss under common crop types and rotation need to be clarified to inform the development of more effective cropping systems to replace those in current use.

Topographic factors such as slope gradient and length also affect soil erosion and nutrient loss. In some soil erosion models (such as USLE, CSLE, and EUROSEM), slope gradient and length are important parameters [40–42]. Many studies show the amount of soil erosion and associated nutrient loss are positively related to the gradient of cultivated land [43,44]. The occurrence of soil erosion will especially increase when crops are cultivated on farmland with steep slopes [45]. However, some reports indicate total nitrogen and total phosphorus in surface runoff decrease with increasing slope gradient [46]. Slope length also plays a key role in soil erosion and nutrient loss. Lal (1997) shows total runoff nutrient losses decrease with increasing slope length under conventional tillage practices, whereas the opposite result is obtained under no-till practices [47]. Xing et al. (2016) indicate that sediment-associated total nitrogen loss increases with slope length under simulated rainfall conditions [48]. Overall, studies to date show slope gradient and length can have either positive or negative impacts on runoff, erosion, and nutrient loss and have mainly focused on soil erosion and nutrient loss for steep slopes. The influence of slope gradient and length on soil erosion from gently sloping agricultural land has not received sufficient attention, and studies are needed to facilitate the development of new technologies for erosion control on gently sloping agricultural fields.

Overall, the influence of rainfall, crop type and rotation, and topography on soil erosion and nutrient loss under gently sloping agricultural land in the CLP is not well understood. Therefore, the objectives of this study were to: (1) identify the runoff, soil erosion, and nutrient loss for different crops and crop rotation systems; (2) explain the effects of slope gradient and length on runoff, soil erosion, and nutrient loss for gently sloping agricultural land; (3) investigate how rainfall factors affect runoff, soil erosion, and nutrient loss. The results of this study can clarify the nutrient loss pathways of runoff and sediment from cropland and may also provide a theoretical basis for solving problems caused by nutrient loss.

2. Materials and Methods

2.1. Study Site

The study was conducted in the Wangdonggou watershed (latitude: 107°40′30″–107°42′30″ E; longitude: 35°12′16″–35°16′00″ N; altitude: 946–1226 m) at the Changwu Agro-ecological Experiment Station, Chinese Academy of Sciences (CAS) and Ministry of Water Resources (MWR), in Shaanxi Province, China. The watershed is a typical loess tableland-gully region with an area of 8.3 km^2 and a gully density of 2.78 km/km^2 (Figure 1). The gradient of tableland varies from 0–3°. The study area has a warm-temperate semi-humid continental monsoon climate with an average annual temperature of 9.2 °C (1957–2014) [49]. The average annual precipitation is 579 mm (1960–2016), with more than 70% falling from April to September [50]. The soil in this watershed is dominated by Heilu soil [51], and the parent material is medium loamy Malan loess. The thickness of the loess layer is more than 100 m, and the soil in the whole profile is uniform and loose with good air permeability.

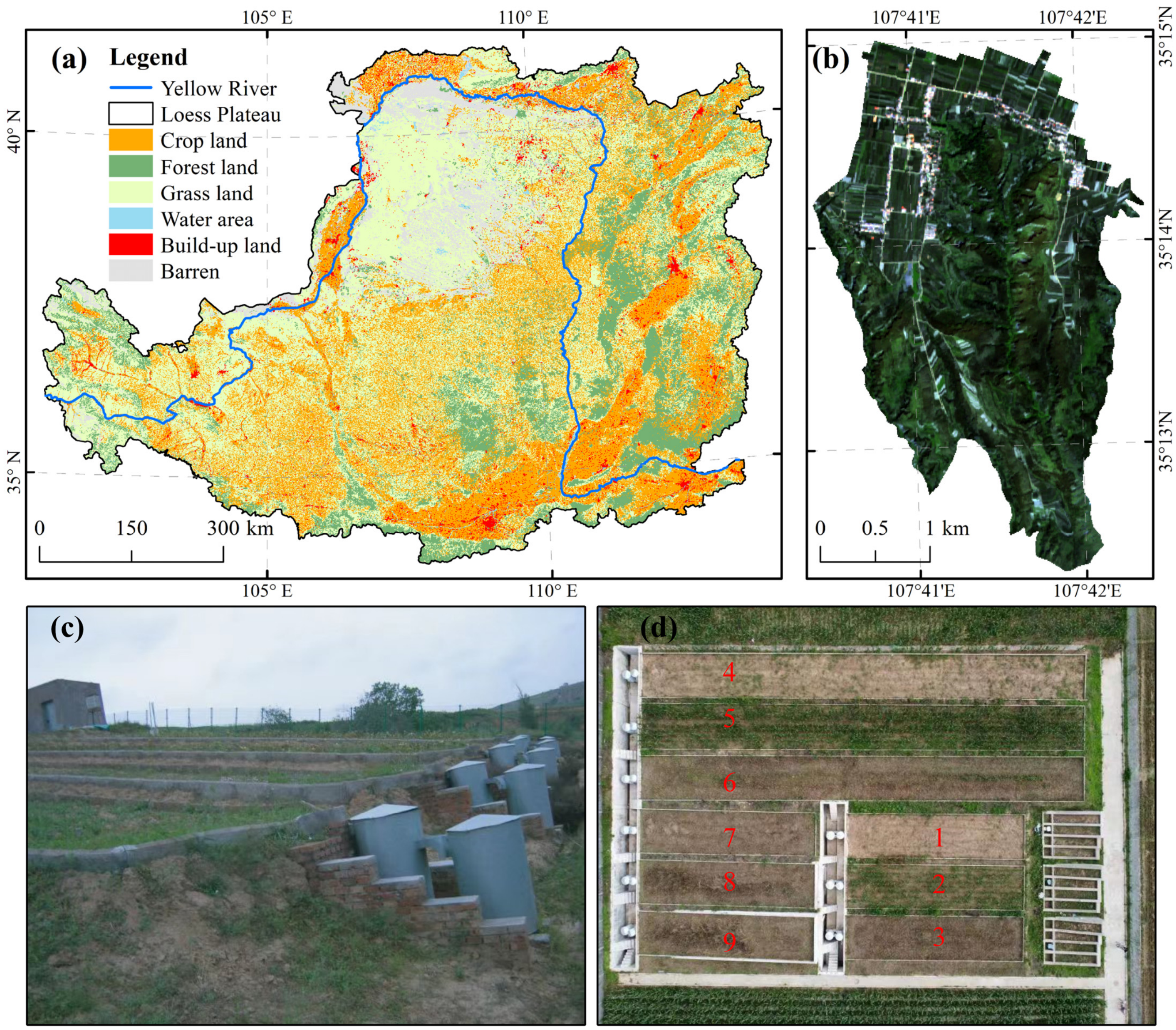

Figure 1. Location of the study site and experimental design. (**a**) the Loess Plateau of China, (**b**) Wangdonggou watershed on the Loess Plateau of China, (**c**) runoff and sediment collecting equipment, and (**d**) nine runoff plots. Numbers of 1–9 show the locations of all nine runoff plots.

2.2. Experimental Design

Nine loess experimental plots were arranged at Changwu station with three crop/land use types: winter wheat (*Triticum aestivum* L.), spring corn (*Zea mays* L.) and fallow (Table 1). Winter wheat was sown in September and harvested in early June; spring corn was sown in April and harvested in September. The boundaries of each plot were constructed by reinforced concrete baffles with 35 cm buried and 15 cm above ground to separate runoff from inside and outside the plots. A self-recording rainfall gauge was placed around the experimental plots to record rainfall. Each plot had a set of equipment for collecting runoff and sediment, including a water collection tank, water conveyance tank, water-retaining dike, and runoff barrel.

Table 1. Basic information about the study plots.

Plot		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Slope length (m)		20	20	20	50	50	50	20	20	20
Slope gradient (°)		0.5	0.5	0.5	0.5	0.5	0.5	0.5	1	3
Crop rotation		Yes	Yes	Yes	Yes	Yes	Yes	No	No	No
Crop/land type	2019	SC	WW	FA	SC	WW	FA	WW	WW	WW
	2020	FA	SC	WW	FA	SC	WW	WW	WW	WW
Coverage (%)	2019	78.0	80.0	47.3	74.7	78.0	48.0	79.3	76.7	78.0
	2020	67.3	75.0	45.0	69.7	73.3	45.7	76.7	75.0	76.7

Note: FA: Fallow; SC: Spring corn; WW: Winter wheat. Coverage was measured in October of 2019 and 2020, respectively. The coverage of winter wheat fields took into account the presence of weeds and stubble at that time.

Plots 1 to 3 had a slope length of 20 m and gradient of 0.5° with a wheat-corn-fallow rotation treatment; plots 4 to 6 had a slope length of 50 m and gradient of 0.5° with a wheat-corn-fallow rotation treatment; plots 7 to 9 had a slope length of 20 m and gradients of 0.5°, 1°, and 3°, respectively, with a winter wheat monoculture (Figure 1). Table 1 shows crop types planted during the study period (2019 and 2020). Data from plots 2 and 7 in 2019 and plots 3 and 7 in 2020 for winter wheat were used to compare the effects of rotation and no-rotation on runoff, soil erosion, and nutrient loss. Data from plots 1 and 4 in 2019 and plots 2 and 5 in 2020 for spring corn, data from plots 2 and 5 in 2019 and plots 3 and 6 in 2020 for winter wheat, and data from plots 3 and 6 in 2019 and plots 1 and 4 in 2020 for fallow were used to analyze the effects of different crop/land uses on runoff, soil erosion, and nutrient loss. Data from plots 7, 8, and 9 were used to compare the effect of slope gradient on runoff, soil erosion, and nutrient loss with precipitation as a random variable. Data from plots 1 to 6 were used to contrast the effects of slope length and crop type on runoff, soil erosion, and nutrient loss.

2.3. Data Collection

Data were collected from May to October of 2019 and 2020 because most of the rainfall and runoff on the CLP occurs during these months. The total rainfall, rainfall duration, average rainfall intensity (ARI), and the maximum rainfall intensity (MRI) for each rainfall event were obtained from the self-recording rainfall gauge and are given in Table 2. The runoff volume of each plot was obtained by measuring the height of the inside of the runoff barrel according to the known barrel bottom area after the occurrence of erosive rainfall. The suspension (runoff + sediment) in the runoff barrel was thoroughly stirred and samples were collected using 5000-mL plastic bottles. Some samples were filtered through medium-speed phosphorus-free filter paper, and approximately 300-mL samples were immediately refrigerated (4 °C) and brought back to the laboratory for determination of total nitrogen and total phosphorus in 24 h. The total nitrogen of water samples was measured by alkaline potassium persulfate ablation UV spectrophotometry and the total phosphorus of water samples was measured by ammonium molybdate spectrophotometry. The remaining samples were separated by filtering through filter paper after settling for

24 h. Total sediment was calculated by air drying sediment samples and weighing them to obtain the sediment sample mass. Subsequently, the sediment samples were brought back to the laboratory for determination of total nitrogen and total phosphorus. Soil total nitrogen was measured by the semi-micro Kjeltec method, and soil total phosphorus was measured by the $HClO_4$–H_2SO_4 elimination method. The vegetation cover, plant spacing, and height of the plots were measured, and soil samples were collected in September and October 2019 for determination of their physical and chemical properties. The basic physical and chemical indicators are shown in Table 3.

Table 2. Erosive rainfall characteristics during the study period.

Date (d/m/y)	Rainfall (mm)	Rainfall Duration (h)	ARI (mm/h)	MRI (mm/h)
05/06/2019	56.5	18.5	3.1	6.8
28/06/2019	49.3	28.2	1.8	3.0
23/07/2019	28.6	4.0	6.3	7.2
29/07/2019	34.2	4.7	7.3	9.8
04/08/2019	20.5	13.3	1.5	3.7
26/08/2019	71.6	12.5	5.7	25.2
15/09/2019	70.0	8.0	3.6	8.8
19/06/2020	58.5	53.0	1.1	3.6
26/06/2020	66.0	17.3	3.8	14.8
11/07/2020	41.4	24.0	1.7	5.0
26/07/2020	47.0	32.5	1.4	4.6
07/08/2020	31.0	6.0	5.2	7.8
13/08/2020	20.8	9.5	2.2	4.6
19/08/2020	88.3	40.0	2.2	6.0

Note: MRI: maximum rainfall intensity; ARI: average rainfall intensity.

Table 3. Soil properties of experimental plots.

Plot	SOC (g/kg)	TN (g/kg)	TP (g/kg)	AP (mg/kg)	AK (mg/kg)	pH –	BD (g/cm^3)	Clay (%)	Silt (%)	Sand (%)	Soil Texture –
1	9.33	0.98	0.99	14.51	139.82	7.93	1.21	27.92	37.1	34.98	Loamy clay
2	8.67	1.02	0.87	10.01	125.66	7.95	1.28	27.31	37.28	35.41	Loamy clay
3	8.07	0.97	0.81	7.87	117.56	7.96	1.27	27.78	37.42	34.8	Loamy clay
4	7.78	0.91	0.99	10.85	112.84	8.08	1.25	28.08	39.04	32.88	Loamy clay
5	8.28	0.96	0.97	13.19	136.62	7.96	1.24	27.75	37.35	34.9	Loamy clay
6	8.15	0.98	0.94	7.91	134.93	7.79	1.48	26.63	36.77	36.6	Loamy clay
7	9.03	1.11	0.86	7.57	117.73	7.77	1.29	26.3	37.76	35.94	Loamy clay
8	8.85	1.07	0.84	11.46	107.95	7.72	1.38	26.9	39.42	33.68	Loamy clay
9	8.1	0.97	0.84	9.38	113.35	7.74	1.3	25.29	36.29	38.42	Loamy clay

Note: SOC: soil organic carbon; TN: total nitrogen; TP: total phosphorus; AP: available phosphorus; AK: available potassium; BD: bulk density.

2.4. Data Analysis

All statistical analyses were performed using R version 4.0.2. The mixed linear model and multiple comparisons based on Tukey's test were used to identify the differences in the effects of tillage practices (rotation and no-rotation), crop type (spring corn, winter wheat, and fallow), and topography (slope gradient and length) on runoff, soil erosion, and nutrient loss; significance differences were judged based on the R package *lmerTest* [52]. The main factors influencing nutrient loss were decided using a random forest model [53], and the significance of each predictor was assessed using the R package *rfPermute* [54]. A structural equation model was constructed in combination with professional knowledge using R package *piecewiseSEM* [55], which was used to quantify the direct and indirect effects of explanatory variables on response variables.

3. Results

3.1. Runoff, Soil Erosion, and Nutrient Loss for Different Crops/Land Uses

Runoff, soil erosion, and nutrient loss for the spring corn, winter wheat, and fallow plots are compared in Figure 2. The fallow plots had more runoff, soil erosion, and nutrient loss than the spring corn or winter wheat plots. Specifically, the fallow plots were significantly different from the spring corn and winter wheat plots in terms of runoff depth, soil erosion, total phosphorus in runoff (RTP), total nitrogen in soil loss (STN), and total phosphorus in soil loss (STP). For total nitrogen in runoff (RTN), the fallow plots were only significantly different from the spring corn plots and not from winter wheat plots (Figure 2c). Spring corn plots had a lower runoff depth and associated RTP and RTN but higher soil loss and associated STP and STN compared to winter wheat plots; however, the differences were not significant. Overall, runoff, soil erosion, and nutrient loss from the fallow plots were significantly higher than for spring corn and winter wheat plots, but the differences between the latter two crops were not significant.

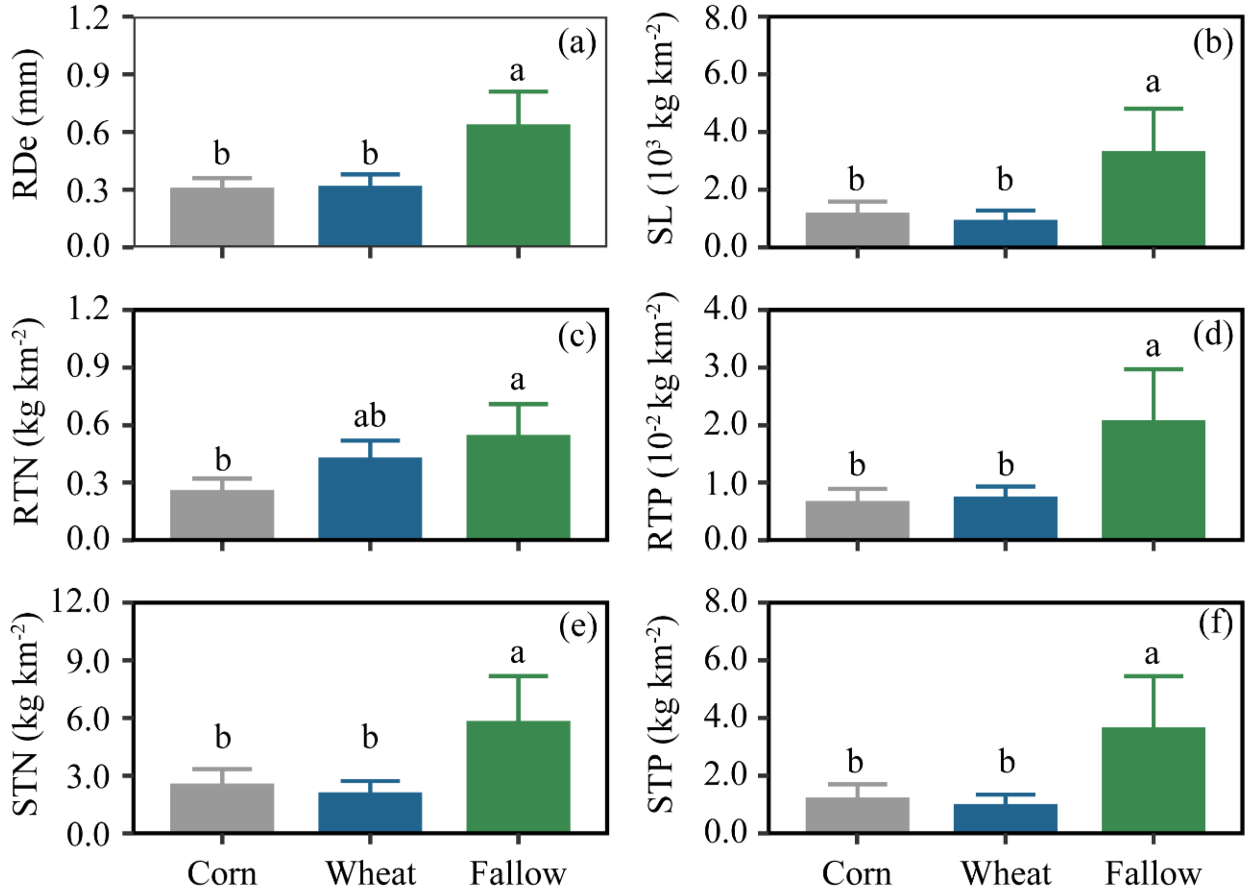

Figure 2. The (**a**) runoff depth (RDe), (**b**) soil loss (SL), (**c**) total nitrogen in runoff (RTN), (**d**) total phosphorus in runoff (RTP), (**e**) total nitrogen in soil loss (STN), and (**f**) total phosphorus in soil loss (STP) for spring corn, winter wheat, and fallow plots. Values followed by different letters above a column are significantly different at $p \leq 0.05$. Different letters indicate significant differences between treatments.

3.2. Runoff, Soil Erosion, and Nutrient Loss for Different Rotation Systems

The runoff, soil erosion, and nutrient loss for winter wheat cropped under rotation and no-rotation systems are compared in Figure 3. Runoff depth, soil erosion, RTN, and STP were significantly higher under the rotation system than under the no-rotation system in 2019; only RTP was significantly higher in 2020. Combining data from the two years, the rotation system resulted in significantly greater runoff depth, RTN, and

STN than the no-rotation system by 72.74, 99.41, and 182.06%, respectively. For soil erosion, RTP, and STP, the rotation system yielded higher values than the no-rotation system, but the differences were not significant. Overall, the use of a rotation system for winter wheat resulted in more runoff, soil erosion, and nutrient loss compared to a no-rotation system.

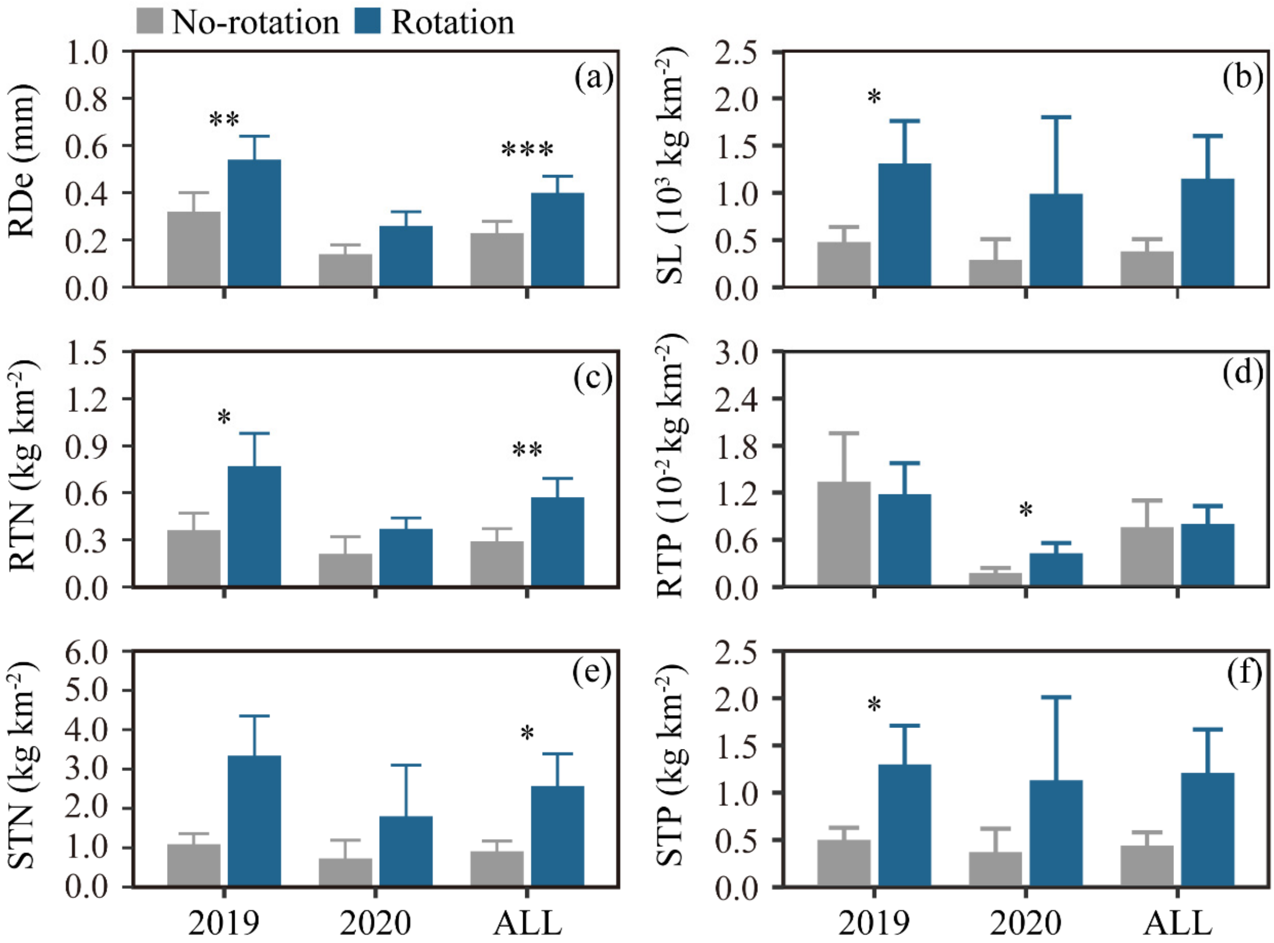

Figure 3. The (**a**) runoff depth (RDe), (**b**) soil loss (SL), (**c**) total nitrogen in runoff (RTN), (**d**) total phosphorus in runoff (RTP), (**e**) total nitrogen in soil loss (STN), and (**f**) total phosphorus in soil loss (STP) in rotation and no-rotation systems for 2019 and 2020. ALL: both years (2019 and 2020); *, $p < 0.05$; **, $p < 0.01$; *** $p < 0.001$.

3.3. Impact of Slope Gradient and Length on Runoff, Soil Erosion, and Nutrient Loss

A comparison of runoff, soil erosion, and nutrient loss for gradients of 0.5°, 1°, and 3° is illustrated in Figure 4. Soil loss and associated STP and STN losses increased with the gradient but differences between the various slopes were not significant. Runoff depth and associated RTP and RTN losses did not increase with slope gradient. In general, slope had no significant effect on soil erosion and nutrient loss for the gentle slope range considered (0.5–3°).

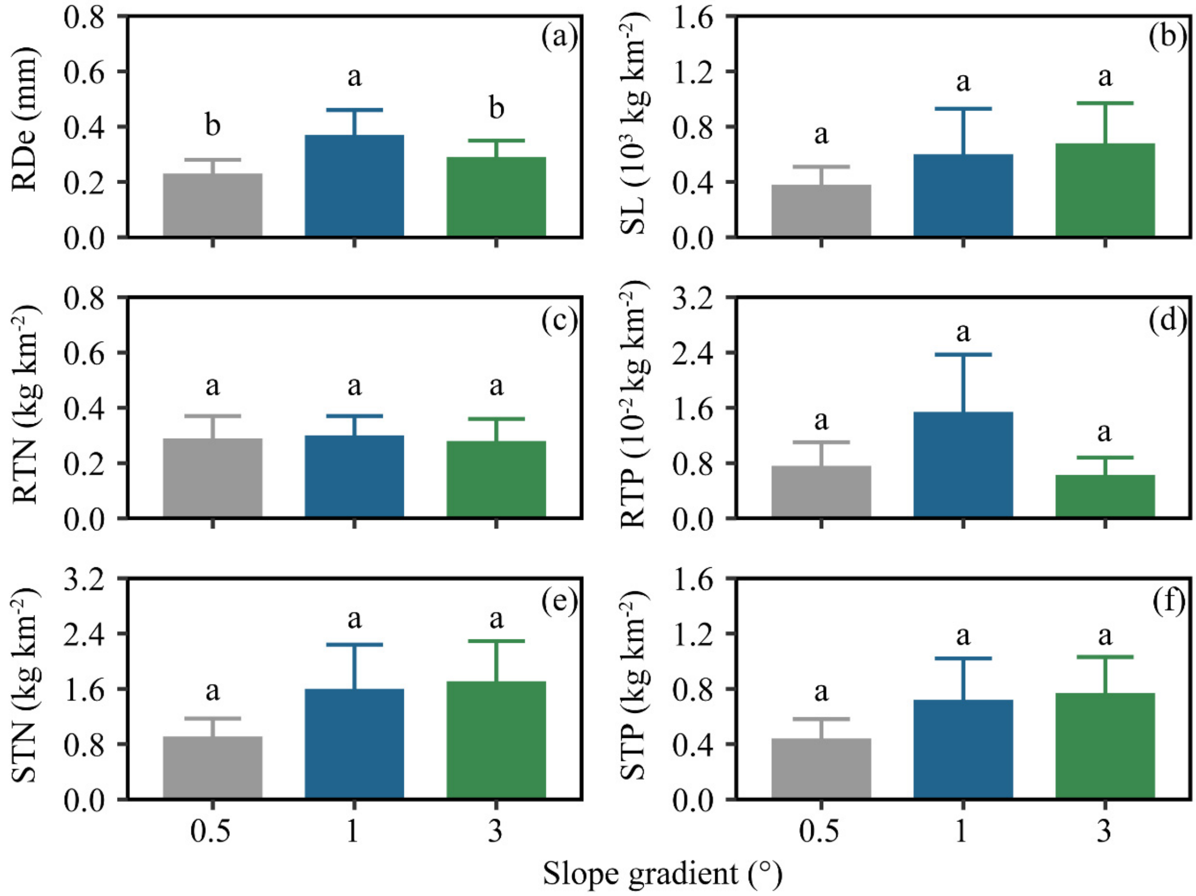

Figure 4. The (**a**) runoff depth (RDe), (**b**) soil loss (SL), (**c**) total nitrogen in runoff (RTN), (**d**) total phosphorus in runoff (RTP), (**e**) total nitrogen in soil loss (STN), and (**f**) total phosphorus in soil loss (STP) for slope gradients of 0.5°, 1°, and 3°. Values followed by different letters above a column are significantly different at $p \leq 0.05$.

Runoff, soil erosion, and nutrient loss for different slope lengths for the three land use types considered are shown in Figure 5. Plots with a slope length of 50 m had lower runoff depth, soil erosion, RTN, STN, RTP, and STP than plots with a slope length of 20 m for all crop/land use types, which implies runoff, soil erosion, and nutrient loss decrease with slope length. For spring corn and winter wheat, runoff depth, soil erosion, RTN, STN, and STP were significantly higher for the 20- vs. 50-m slope length; RTP was also higher for the 20-m slope, but the difference was not significant. For fallow plots, runoff depth and RTN were significantly lower for the 50-m slope; soil loss, RTP, STN, and STP were also lower, but the differences were not significant. When all crop/land use types were considered, increasing slope length resulted in significant decreases in runoff depth, RTN, and STN and insignificant decreases in soil loss, RTP, and STP. These results indicate that slope length significantly affected runoff and nitrogen loss.

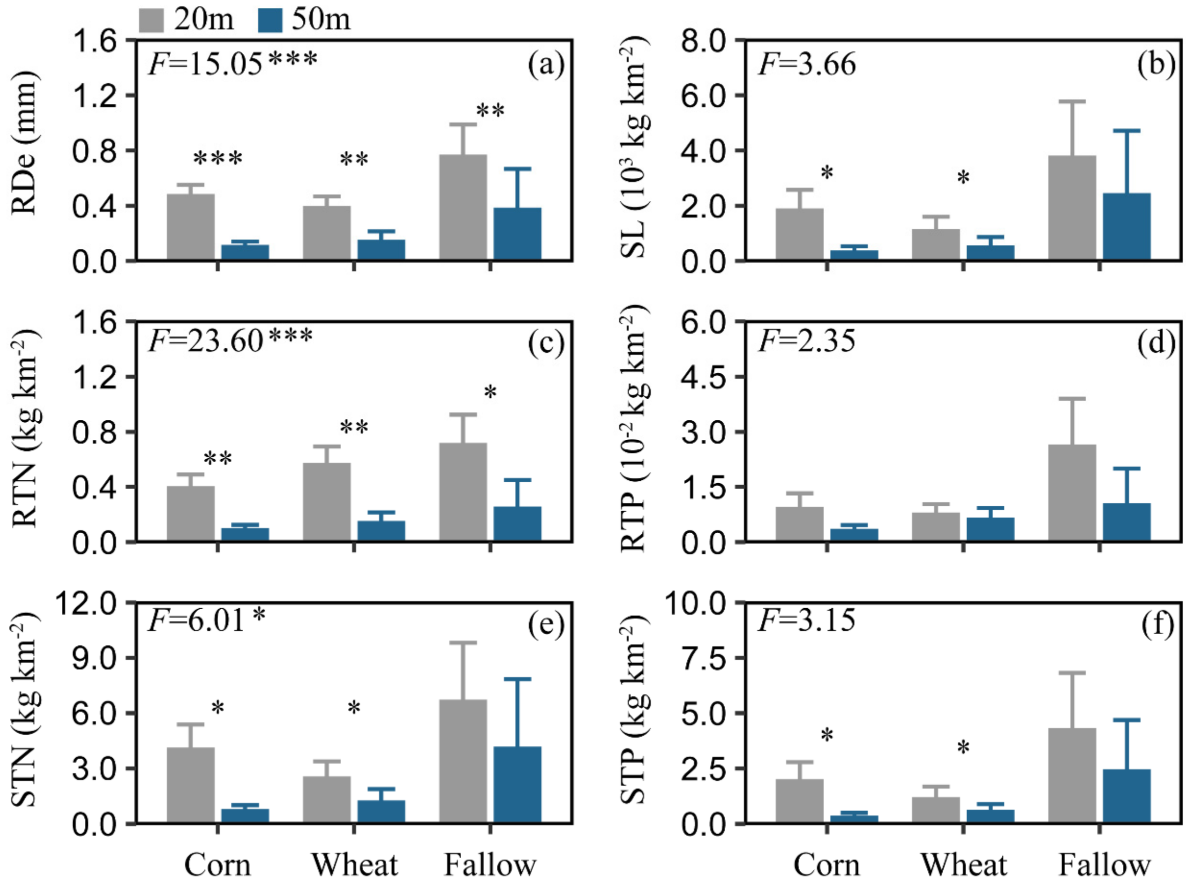

Figure 5. The (**a**) runoff depth (RDe), (**b**) soil loss (SL), (**c**) total nitrogen in runoff (RTN), (**d**) total phosphorus in runoff (RTP), (**e**) total nitrogen in soil loss (STN), and (**f**) total phosphorus in soil loss (STP) for slope lengths of 20 and 50 m. The significance value in the upper left corner represents the results of the analysis of all crops. *, $p < 0.05$; **, $p < 0.01$; *** $p < 0.001$.

3.4. Impact of Natural Rainfall Characteristics on Runoff, Soil Erosion, and Nutrient Loss

The influence of total rainfall, rainfall duration, MRI, ARI, soil condition, runoff depth, and soil loss on RTN, RTP, STN, and STP losses were studied using a random forest model (Figure 6). The pathways and coefficients affecting runoff, soil erosion, and nutrient loss are presented in a structural equation model for each crop/land use type (Figure 7). The results show rainfall was the main driving force related to the occurrence of runoff and soil erosion, which indirectly leads to nutrient loss. For runoff, the structural equation model shows the total rainfall and rainfall duration significantly altered runoff depth in the spring corn plots (path coefficients of 0.714 and −0.335, respectively; Figure 7a), while the total rainfall only significantly influenced runoff depth in the winter wheat and fallow plots (path coefficients of 0.593 and 0.668, respectively; Figure 7b,c). Importantly, MRI did not significantly affect runoff depth for any of the three crop/land use types. Soil loss was significantly affected by runoff depth in spring corn and fallow plots (path coefficients of 0.403 and 0.845, respectively; Figure 7a,c), and significantly influenced by MRI in the winter wheat plots (path coefficient of 0.404; Figure 7b).

Figure 6. Random forest mean predictor importance (% increase in mean square error) of the factors influencing (**a**) total nitrogen in runoff (RTN), (**b**) total phosphorus in runoff (RTP), (**c**) total nitrogen in soil loss (STN), and (**d**) total phosphorus in soil loss (STP) for spring corn, (**e–h**) winter wheat, and (**i–l**) fallow plots, respectively. TR: total rainfall; SC: soil condition (including soil nutrients, bulk density, and saturated hydraulic conductivity); RDe: runoff depth; RDu: rainfall duration; MRI: maximum rainfall intensity; ARI: average rainfall intensity; SL: soil erosion. *, $p < 0.05$; **, $p < 0.01$.

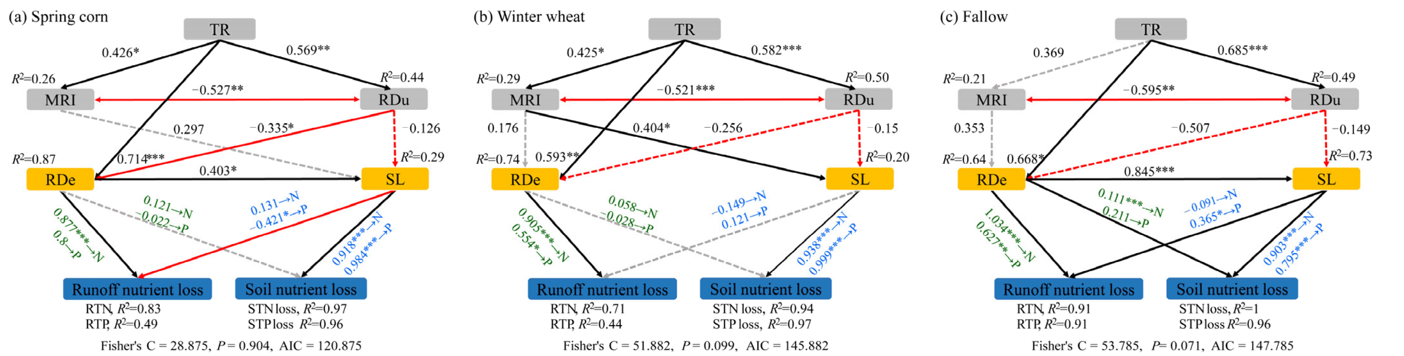

Figure 7. Structural equation models show the pathways and coefficients affecting runoff, soil erosion, and nutrient loss. Insignificant paths ($p \geq 0.05$) are semi-transparent dashed lines, while significant paths ($p < 0.05$) are shown with solid lines. Black and red arrows indicate positive and negative pathways, respectively. Conditional R^2 denotes the proportion of variance explained. The standardized path coefficient represents the extent of the effect of the independent variable on the dependent variable. Significant pathways are marked by: *, $p < 0.05$; **, $p < 0.01$; ***, $p < 0.001$.

For nutrient loss, the random forest model results indicate total rainfall, MRI, ARI, runoff depth, and soil erosion all had important effects (Figure 6). The results of structural equation modeling further demonstrate rainfall indirectly causes nutrient loss by affecting runoff depth and soil erosion (Figure 7). Runoff depth explains 83, 71, and 91% of the total variation in RTN loss and 49, 44, and 91% of the total variation in RTP loss for spring corn, winter wheat, and fallow plots, respectively. Soil erosion explains 97, 94, and 100% of the total variation in STN loss and 96, 97, and 96% of the total variation in STP loss for spring corn, winter wheat, and fallow plots, respectively (Figure 7).

However, some differences were evident among three plots. For the fallow plots (Figure 7c), runoff depth and soil loss significantly impacted RTN, RTP, STN, and STP losses. For the winter wheat plots, runoff depth only had a significantly positive effect on RTN and RTP losses (path coefficients of 0.905 and 0.554, respectively; Figure 7b), while soil erosion had a significantly positive effect on STN and STP losses (path coefficients of 0.938 and 0.999, respectively; Figure 7b). For spring corn plots, runoff depth only had a significantly positive effect on RTN loss (path coefficient of 0.877; Figure 7a), while soil loss had a significantly negative effect on RTP loss and a significantly positive effect on STN and STP losses (path coefficients of −0.421, 0.938, and 0.999, respectively; Figure 7a).

4. Discussion

4.1. Impact of Crop Type on Runoff, Soil Erosion, and Nutrient Loss

Our results indicate natural rainfall causes greater runoff, soil erosion, and nutrient loss in fallow plots compared to spring corn and winter wheat plots (Figure 2). Many studies also report that the choice of crop can effectively reduce surface runoff and soil and nutrient losses [34,35]. In the study region, the growing season of spring corn is from April to September, which aligns with the rainy season [56,57]. The coverage of spring corn can reduce soil erosion by intercepting rainfall and decreasing raindrop kinetic energy [57]. In addition, the active root system can increase erosion resistance. However, the growing season of winter wheat is from September to May of the next year, which does not align with the rainy season. Therefore, runoff, soil erosion, and nutrient losses are higher but not significantly greater in spring corn vs. winter wheat fields [58]. In our study, the spring corn and winter wheat plots both had greater biomass and coverage than the fallow plot, which likely resulted in the reduced soil erosion and nutrient loss.

4.2. Impact of Crop Rotation on Runoff, Soil Erosion, and Nutrient Loss

Crop rotation is an important management practice [59]. Our results show rotation can result in greater runoff, soil erosion, and nutrient loss than no-rotation management in winter wheat plots (Figure 3). Crop rotation changes the coverage time and duration on the soil surface as well as the root distribution in the topsoil. In addition, farmers use different methods to harvest winter wheat and spring corn. Plots in the no-rotation system are left as wheat stubble after harvest, which provides better surface cover and roughness and reduces runoff and soil erosion [60,61]. Moreover, wheat residuals can increase soil organic matter content, improve soil physical characteristics, and subsequently reduce runoff, soil erosion, and nutrient loss [62,63]. For RTP, the major fraction of soil phosphorus is tightly adsorbed to mineral particles and bound within organic matter, so only a very small fraction leaches as dissolved soluble phosphate [64,65]. This might be the reason for the insignificant difference in phosphorus loss noted in our results for the different rotation systems.

In this study, the results show that crop rotation generates greater runoff, which is different from the conclusion of Jiao et al. (2011) [66]. Jiao et al. (2011) compares surface runoff for three double cropping systems of wheat/maize, wheat/cotton, and wheat/soybean with wheat/fallow and indicates that all double cropping systems increases the ground cover and significantly reduces runoff [66,67]. However, our result is drawn for the same crop type and coverage of winter wheat with rotation and no-rotation.

4.3. Impact of Slope Gradient and Length on Runoff, Soil Erosion, and Nutrient Loss

Sloping farmland is one of the main types of agricultural land on the CLP. The gradient affects runoff, soil erosion, and nutrient loss by altering runoff flow rates and infiltration rates [68,69]. Our results show soil erosion and associated STP and STN losses increased with slope gradient, but the differences among the three gentle slope gradients (0.5°, 1°, and 3°) were not significant (Figure 4b–f). Runoff depth and associated RTP and RTN losses did not increase with slope gradient, perhaps because the gentle gradients considered in this study were not sufficiently large to create stronger effects [68,70].

Slope length also impacts runoff, soil erosion, and nutrient loss [48,71]. Our study results show all indicators for the 20-m slope length were greater than those for the 50-m slope length. Among all indicators, runoff depth, RTN and STN were significantly larger for the 20-m slope length than for the 50-m slope length when all crop/land use types were considered (Figure 5a,c,e); these differences were not significant for soil erosion, RTP, and STP (Figure 5b,d,f). These findings confirm previous results reported by Xing et al. (2016) [48], where both runoff and associated total nitrogen loss rate decreased with increasing slope length. This is attributed to the longer slope increasing surface runoff infiltration and deposition of eroded soil along its length [72,73], which subsequently reduces runoff-associated RTN and RTP losses and sediment-associated STN and STP losses [74,75]. Furthermore, some studies suggest soil loss decreases with slope length according to a power-law trend [76,77], which might explain why the soil loss was less for the 50-m vs. 20-m slope. However, the two years of data from this study show significant nitrogen loss from runoff and soil but insignificant phosphorus loss for the different slope lengths. This might be due to RTN values being much higher than RTP values (Figure 5c,d). The latter were usually insignificant, likely due to phosphorus being predominantly and firmly associated with soil particle surfaces [78,79]; the amount of STP supports this suggestion.

4.4. Impact of Rainfall on Runoff, Soil Erosion, and Nutrient Loss

The results of our study show rainfall characteristics are the dominant driver of runoff, soil erosion, and associated nutrient loss (Figures 6 and 7). This result is consistent with those of many other studies [14,20,80]. Runoff depth was mainly positively associated with total rainfall and negatively associated with rainfall duration (Figure 7), which were in agreement with earlier studies [81,82]. These results suggest total rainfall and rainfall duration determine the runoff depth, which indirectly causes runoff-associated nutrient loss. Our results are also consistent with assertions that runoff and MRI are the main factors influencing soil loss [83]. This is because MRI can reflect rainfall impact on soil particle detachment, whereas surface runoff depth can be used to represent the transport of sediments [11]. Our study also found rainfall indirectly causes nutrient loss by affecting runoff depth and soil erosion, with nutrient loss due to both N and P dissolved in runoff as well as partially bonded to soil particles [11,84]. The forms of nutrient loss also differed for the three crops/land uses studied (Figure 7). This result aligns with those of previous studies that show the intensity of rainfall can impact the form of nutrient loss [85]. At higher intensity the nutrient loss is attributed more to soil nutrients being transported with sediments, while at lower intensity the nutrient loss is attributed more soluble elements carried with runoff. Overall, the responses of runoff, soil erosion, and nutrient loss to rainfall intensity in plots of different crops differed and, thus, resulted in different forms of nutrient loss.

5. Conclusions

This paper reports on an experiment featuring nine runoff-erosion plots on the CLP studied in 2019 to 2020 to determine the effect of crop type, rotation pattern, slope gradient, and slope length on runoff, soil erosion, and nutrient loss. Runoff, soil erosion, and nutrient loss were higher in fallow plots than in spring corn and winter wheat plots, with no significant differences noted between the latter two. Plots subject to crop rotation generated greater runoff, soil erosion, and nutrient loss compared to those managed with a no-rotation system. Soil loss and associated nutrient loss tended to increase with slope gradient, while runoff and associated nutrient loss did not show any trends. Runoff, soil erosion, and associated nutrient loss were significantly greater in plots with a slope length of 20- vs. 50-m under gentle gradient conditions. Total rainfall and rainfall duration were the primary factors determining runoff, soil erosion, and associated nutrient loss, and maximum rainfall intensity partially explained soil loss. Our results suggest that the effect of rainfall characteristics on soil nutrient loss varies with rotation system and crop type. These results are useful for developing targeted farmland nutrient conservation strategies.

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