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Phosphorus losses under heavy rain from the sloping farmlands in the purple hilly region of Southwestern China

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Abstract

Purpose Phosphorus (P) and sediment loss through runoffs to surface and ground water represent a risk to human and environmental health. The objective of this work was to understand the mechanisms of P loss under heavy rain from the purple soil of sloping farmlands.

Materials and methods The work was carried out with simulated rainfall experiment at different maize growth stages. The combination of three factors was studied: tillage methods (flat planting, longitudinal ridge, and cross-ridge), slope gradients (10°, 15°, and 20°), and maize growth stages (seedling stage, elongation stage, tasseling stage, and maturity stage). Surface runoff, subsurface runoff, sediment, P content in runoff, and sediment were determined.

Results and discussion The rate of sediment yield was positively and non-linearly correlated with the runoff shear force and increased quickly when using the longitudinal ridge tillage method. Longitudinal ridge and 20° slope croplands showed greater erodibility, which resulted in higher runoff, sediment yield, and associated P loss. Total phosphorus (TP) and available phosphorus (AP) losses during the entire growth period were 17.58 mg m^{-2} and 32.86 mg m^{-2}, in the longitudinal ride on 20° slope. Cross-ridge treatment can effectively prevent the loss of P. The P loss occurred violently on 20° slope, and there was little difference in the P loss between 10° and 15° slopes. Dissolved total phosphorus (DTP) loss dominated the TP loss in runoff, accounting for more than 55.58% of the DTP losses in all the treatments.

Conclusions These results indicate the application of flat planting and cross-ridge tillage in croplands with less than 20° slope, as these will minimize the pollution of soil and water resources by reducing P loss in runoff and sediment.

Keywords Growth stages of maize · Heavy rain · Phosphorus loss · Purple soil · Slope gradients · Tillage methods

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1 Introduction

Phosphorus (P) is one of the essential nutrients for plant growth. The application of P fertilizers can accelerate the crop growth. Excess use of P fertilizers in agricultural activities to maintain crop productivity has been observed for several decades (Bouraima et al. 2016). However, only a part of the P fertilizer is absorbed and utilized by the crop, and most of it accumulates in the soil (Cao et al. 2014; Tang et al. 2017). When rainfall occurs, excessive P losses from agriculture due to soil erosion can cause eutrophication of surface water. Because P is one of the key limiting factors influencing eutrophication of water bodies (Ma et al. 2008; Wu et al. 2012; Dari et al. 2017), it can be a restricting supplement determining algal efficiency in freshwater, and eutrophication then occurs at concentrations of 0.01 mg dissolved total phosphorus

(DTP) L^{-1} and 0.02 mg total phosphorus (TP) L^{-1} (Tabbara 2003). Agricultural land is the major source of P pollution. The water quality in the Three Gorges Reservoir remains poor, largely due to diffuse pollution from agricultural land entering surface systems (Cao et al. 2014; Zhang et al. 2017). This has already influenced the life and production activities of human beings (Kleinman et al. 2015; Toor and Sims 2016). P loads to waters must be reduced to control eutrophication.

The extent of P loss depends on many related factors to water-induced soil erosion that includes natural factors (soil type, slope gradient, and rainfall) or anthropogenic factors (tillage methods, management, and plant, etc.) (Liu et al. 2014a, 2014b; Li et al. 2015; Chowaniak et al. 2016). Slope gradient not only is one of the major factors affecting soil particle detachment and transport but also related to several critical factors affecting the infiltration rate; these factors include surface sealing, water surface storage, effective rainfall intensity, and overland flow depth (Fu et al. 2011; Liu et al. 2015). Meyer and Harmon (1987) observed that soil erosion slightly increased, and soil cohesiveness decreased as the slope increased from 5 to 30%. Many studies have assessed the effects of tillage methods on the decrease of soil erosion, on the increase of soil nutrient sequestration, and on the improve of the cropping systems' sustainability (Kurothe et al. 2014; Ruisi et al. 2014; Preiti et al. 2017). Ridge cultivation is an effective tillage method for the decrease of soil erosion and the increase of crop yield. By increasing the roughness of the soil surface, contour ridging results in rainwater ponding in the furrow area, which reduces the runoff velocity, increases infiltration, and reduces soil erosion and P loss (Liu and Huang 2013; Liu et al. 2014a, 2014b; Schoumans et al. 2014). However, impracticable tillage methods can cause serious soil erosion. Liu et al. (2014a, 2014b) found a negative effect on soil erosion control when the contouring was broken in the ridge tillage system.

The purple hilly region is an important agricultural production area in Southwestern China. Most agricultural lands here are sloping farmlands, which account for about 28,521 km^2. Around 46.2% of the soil loss in this area occurs in the sloping farmlands. Slopes in this region range between 7 and 25°, covering 52.1% of the area (Bouraima et al. 2016). In the purple hilly region in Southwestern China, an important agricultural production area with abundant rainfall, the average annual precipitation is about 966 mm, of which heavy rain (162.03 mm) accounts for 18%. Rainstorms usually occur from April to October, which coincides with the period of crop growth (Lin et al. 2009). Therefore, soil erosion and P loss caused by rainstorms, which become the main source of nonpoint source pollution in the Three Gorges Reservoir area, have created the increasingly serious social and environmental problems of declining crop yields (Zhang et al. 2009; Li et al. 2015; Sun et al. 2016). Management of the sloping land is a key factor in determining ecological sustainability. However,

few references tackle the question of what impact slopes and tillage methods have on P loss of plants in different periods of growth during heavy rain.

In this study, we explored the spatial and temporal variabilities of P transport in the typical slope gradients and tillage methods with high utilization rates with simulated rainfall experiment. The objectives of our study were the following: (1) to quantify the independent effects of slope gradients and tillage methods on soil erosion and P loss during the whole growth stages of maize under heavy rain, (2) to discuss the influence of different forms of P concentrations on the erosion processes, and (3) to determine the best slope gradients and tillage methods to minimize P loss in agricultural runoff in the purple hilly region of Southwestern China.

2 Materials and methods

2.1 Study site

The experimental soil was collected from 0 to 80 cm of a soil profile on sloping farmland in Songtao of Sichuan Province in the upper reaches of the Tuo River system of the Yangtze River (104° 34′ 12″–104° 35′ 19″ E and 30° 05′ 12″–30° 06′ 44″ N) (Fig. 1), at an elevation of 395 m. The annual average temperature here is 16.8 °C. The average annual rainfall is normally 966 mm (ranging from 725.2 to 1290.7 mm), and rainstorms often occur from April to October. The area is dominated by purple soil (clay loam soil) formed in the Purple sandy shale, classified as Entisol according to the soil taxonomy of the U.S.D.A. (Soil Survey Staff 1999), which is usually 50–80 cm in depth with relatively light texture and poor soil fertility (Lin et al. 2009; Luo et al. 2018). In the top 20 cm, it consisted of 49% sand, 29% silt, and 22% clay. The soil pH is 8.1, and its bulk density is approximately 1.3 ± 0.1 g cm^{-3}. Soil organic matter and the concentrations of total nitrogen (TN), TP, and total potassium (TK) were 7.34, 0.91, 0.80, and 18.80 g·kg^{-1}, respectively. The concentrations of available nitrogen (AN), available phosphorus (AP), and available potassium (AK) were 100.36, 6.26, and 134.00 mg kg^{-1}, respectively.

2.2 Rainfall simulator

The rainfall simulator was programmed and equipped with two spray nozzles (SR). The SRs were of the V-80100 series and installed by the Institute of Soil and Water Conservation, Chinese Academy of Sciences. The operating pressure ranged from 0 to 5.0 bar. The rainfall simulator height was 7 m, and the effective rainfall area was approximately 5 m × 6 m (Liu et al. 2016). For height, the point of reference was the lowest soil surface, and within the rainfall area, the simulator had an approximate rainfall uniformity of 90%. In this study, rainfall
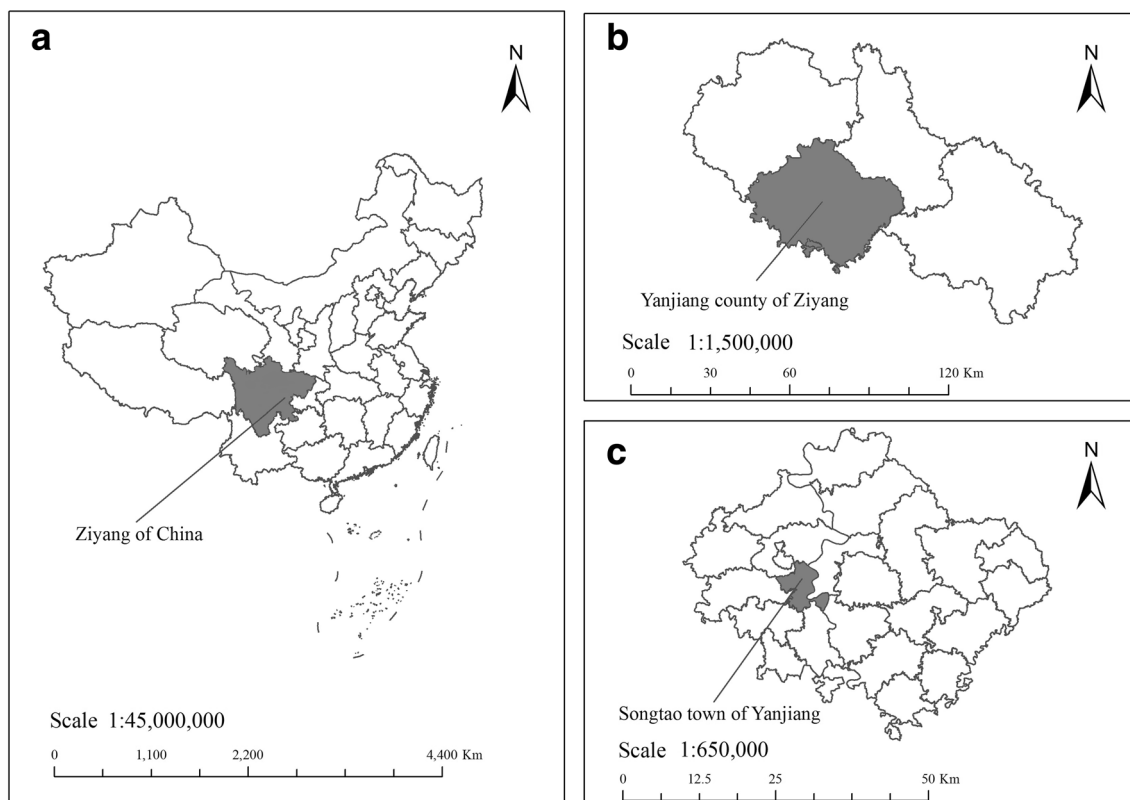
Fig. 1 Study plot location in Songtao town(C) of Yanjiang county (B) in Sichuan province (A)

intensity was designated to be 2.0 mm min^{-1} with 30 min of rainfall, according to the hydrological data of the research area (National Meteorological Information Center, China) in recent years.

2.3 Experimental design

According to the local conditions, the staple crop was maize (*Chuandan 13*). Forty thousand plants were cultivated in 1-hm^2 area, and the plant spacing and row spacing were 80 and 25 cm, respectively. The entire growth period of corn was divided into the seedling stage, elongation stage, tasseling stage, and maturity stage. Nitrogen (N), phosphate (P_2O_5), and potash (K_2O) fertilizers were applied at rates of 250, 125, and 150 kg hm^{-2}, respectively, which is similar to the local fertilization practice. N fertilizer was urea (46.3% N), P fertilizer was calcium superphosphate (12% P_2O_5), and K fertilizer was potassium chloride (60% K_2O). The fertilizer was applied in one dose before sowing. The N fertilizer was applied in solution form. The P fertilizer and K fertilizer were applied in solid form. Other management methods were all based on the local farming practices.

The simulation rainfall experiments were conducted on three tillage methods, to which the following were applied: (1) flat planting: flat slope without furrow; (2) longitudinal ridge: ridges of about 15 cm height and 40 cm wide, all ridges perpendicular to the contour line; and (3) cross-ridge: ridges of about 15 cm height and 40 cm wide, all ridges parallel to the contour line (Fig. 2). Every tillage method was tested on three slope gradients (10°, 15°, 20°). A total of nine treatment combinations were conducted. Each treatment had three replications. Twenty-seven runoff plots were built to collect surface runoff, subsurface runoff, and sediment in the simulated precipitation events.

The size of the plot was 2 m × 1 m × 0.8 m (length × width × height). The plot area was mainly aimed at stimulating small and scattered sloping farmland in study area. The bottom of each plot was reinforced by concrete to facilitate the formation of a relatively impermeable layer, which had to coincide with the slope gradient of the soil surface (Fig. 3). The surface runoff, moving down the inclined surface soil towards every plot, was drained through an outlet into a concrete pond. The subsurface runoff reached the impermeable layer through small holes of 2 cm of diameter on the flapper, and a PVC pipe was used to connect the tank and the runoff collection barrel. The simulation rainfall experiments were conducted during the maize seedling stage (May 1–6, 2015), the elongation stage (June 5–11, 2015), the tasseling stage (July 2–9, 2015), and the maturity stage (August 1–7, 2015). A canvas sheet was used to keep the wind out, and the rainwater was originally tap water, which was sampled to assay P before application to the soil.
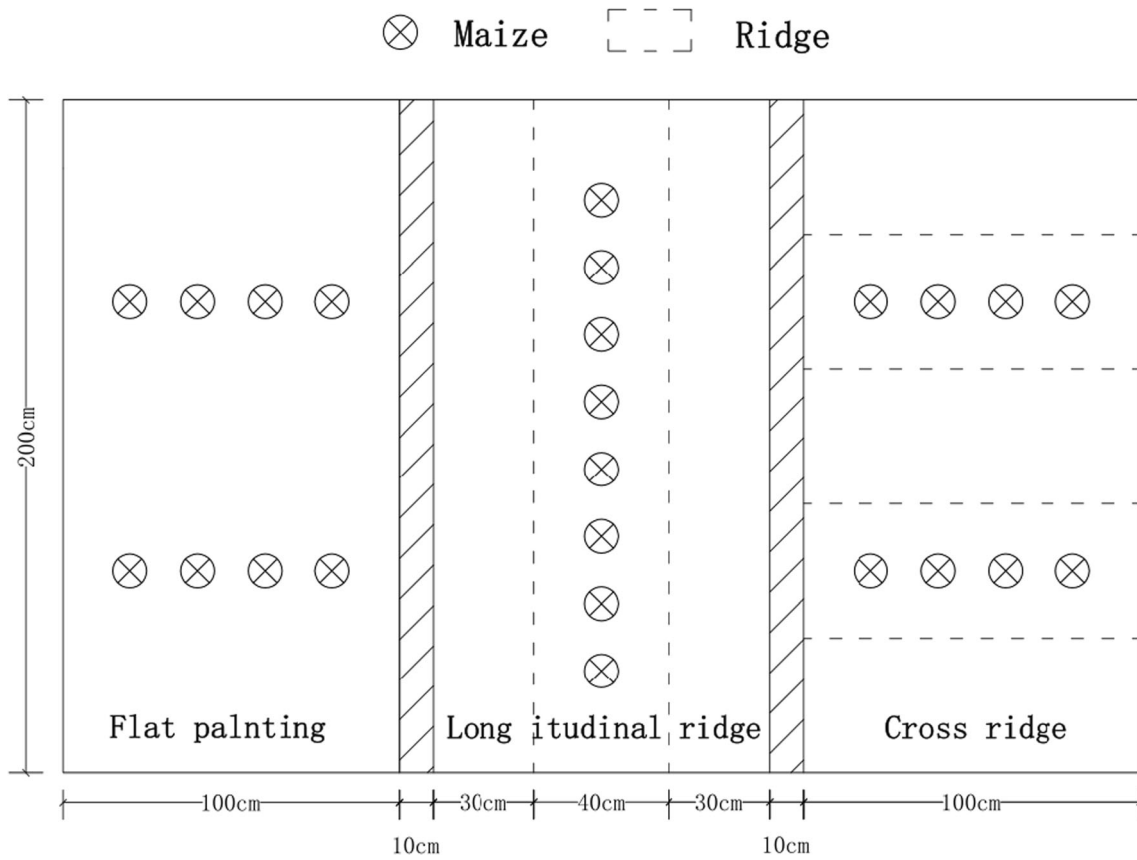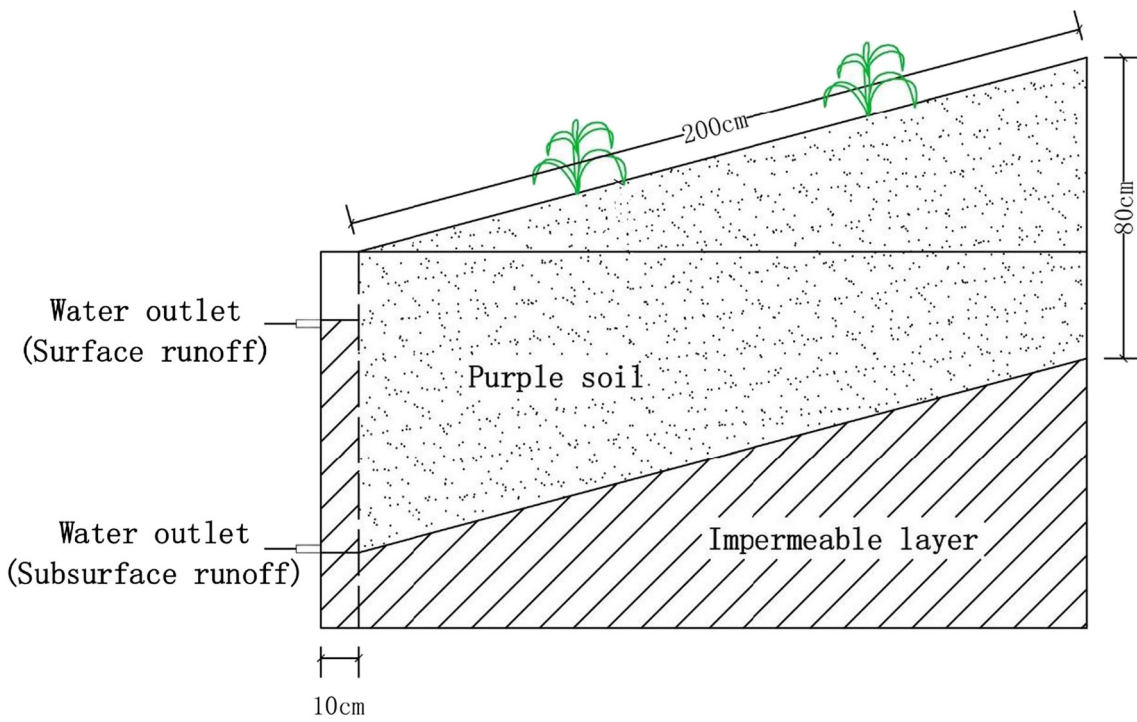
Fig. 2 The layout of experimental plots

Fig. 3 The section of experimental plots

2.4 Experimental analysis

Surface runoff samples were collected in plastic buckets every 3 min after their generation. The entire subsurface runoff samples were collected in plastic buckets. The runoff samples were kept for 4–5 h at the laboratory for sedimentation and for measuring the runoff volume. After sedimentation, each runoff sample was filtered. The runoff samples were collected in 500-mL plastic bottles, to which 0.5 mL of 98% H_2SO_4 was added to restrict any microbial movement. The sediment samples were oven-dried (105 °C, 8 h) after having been weighed. Runoff and sediment samples were transported to the laboratory and the P were measured.

TP of runoff samples were determined after digestion (121 °C, 30 min) with acidic potassium persulphate. The runoff samples were passed through a 0.45-μm filter, and the subsamples were analyzed colorimetrically after digestion (121 °C, 30 min) with acidic potassium persulphate for DTP. Particulate phosphorus (PP) was calculated by subtracting DTP from TP (Uusitalo et al. 2000).

The TN and AN of the experiment soil were measured with Kjeldahl method. The TK and AK of the experiment soil were analyzed by flame photometry. The pH of the experiment soil was measured at a soil: water ratio of 1:2.5 (weight/weight). The TP and AP of the experiment soil and the sediments were analyzed by the colorimetric method (Lu 2000).

The runoff shear force can destroy soil structure and transport soil particles down the slope and has a great influence on the characteristics of sediment yield and the movement of soil particles. The magnitude of the runoff shear force can indicate the erosion capacity of runoff and predict the amount of erosion (Sun et al. 2016). The runoff shear force, τ, by the principle of hydraulics, is calculated as follows (Xiao et al. 2011):

$$\tau = \gamma \cdot R \cdot J = \rho \cdot g \cdot h \cdot \sin\alpha \tag{1}$$

$$h = q/U = Q/(U \cdot B \cdot t) \tag{2}$$

where ρ is the runoff density (1000 kg m^{-3}), g is the gravitational acceleration (N kg^{-1}), α is the slope gradient (°), h is the runoff depth (m), q is the discharge per unit width (m^3·(min m)$^{-1}$), Q is the runoff volume in time t (m^3), t is the runoff sampling interval (min), U is the runoff velocity (m min^{-1}), and B is the cross-sectional width of the runoff (m).

To evaluate the controllability of soluble P losses in surface runoffs under different agricultural practice treatments, we computed the losses of the various types of P in the runoff and sediment from each plot. The total nutrient losses were estimated as the sum of the values of these precipitation events. The TP, DTP, PP, and AP losses (Q) under a rainstorm event were calculated in the same manner as in the study by Zhou et al. (2012)

$$Q = \sum_{i=1}^{n} C_i \times qi \tag{3}$$

where C_i is the TP, DTP, or PP concentration in runoff (mg L^{-1}) and AP concentration in sediment (mg kg^{-1}) and q_i is the runoff discharge (L m^{-2}) or sediment discharge (g m^{-2}) ($i = 1$ to n, the number of runoff and sediment samples collected throughout the period of the simulated rainfall event).

2.5 Statistical analysis

Statistical analysis of the data was carried on SPSS 22.0. Multiple comparisons were made by the Fisher's least significant difference test. Differences were considered significant at the P value of 0.05. Graphical works were performed by Origin 8.3.

3 Results

3.1 The characteristics of surface runoff and subsurface runoff

Four stages (seedling stage, elongation stage, tasseling stage, and maturity stage) were chosen to study the varieties in the loss of TP, DTP, and PP in surface runoff and subsurface runoff. The characteristics of surface runoff and subsurface runoff under different treatments during the period of experiment are presented in Fig. 4. Surface runoff volumes were higher in the seedling and maturity stages than those of the elongation and tasseling stages. The total surface runoff volume during the entire growth period on the 20° slope was significantly higher than those of the other slope gradients, and it was significantly higher in longitudinal ridge than those of the other tillage methods. The surface runoff on the 20° slope of longitudinal ridge during the entire growth period was largest in the nine treatments with an average of 148.04 L m^{-2}. The surface runoff during the entire growth period on the 10° slope of cross-ridge was least with an average of 42.67 L m^{-2}. On the contrary, subsurface runoffs were higher in the elongation and tasseling stages than those of the seedling and maturity stages. The total subsurface runoff volume during the entire growth period on the 20° slope was significantly higher than those of the other slope gradients, and it was significantly higher in cross-ridge than those of the other tillage methods.
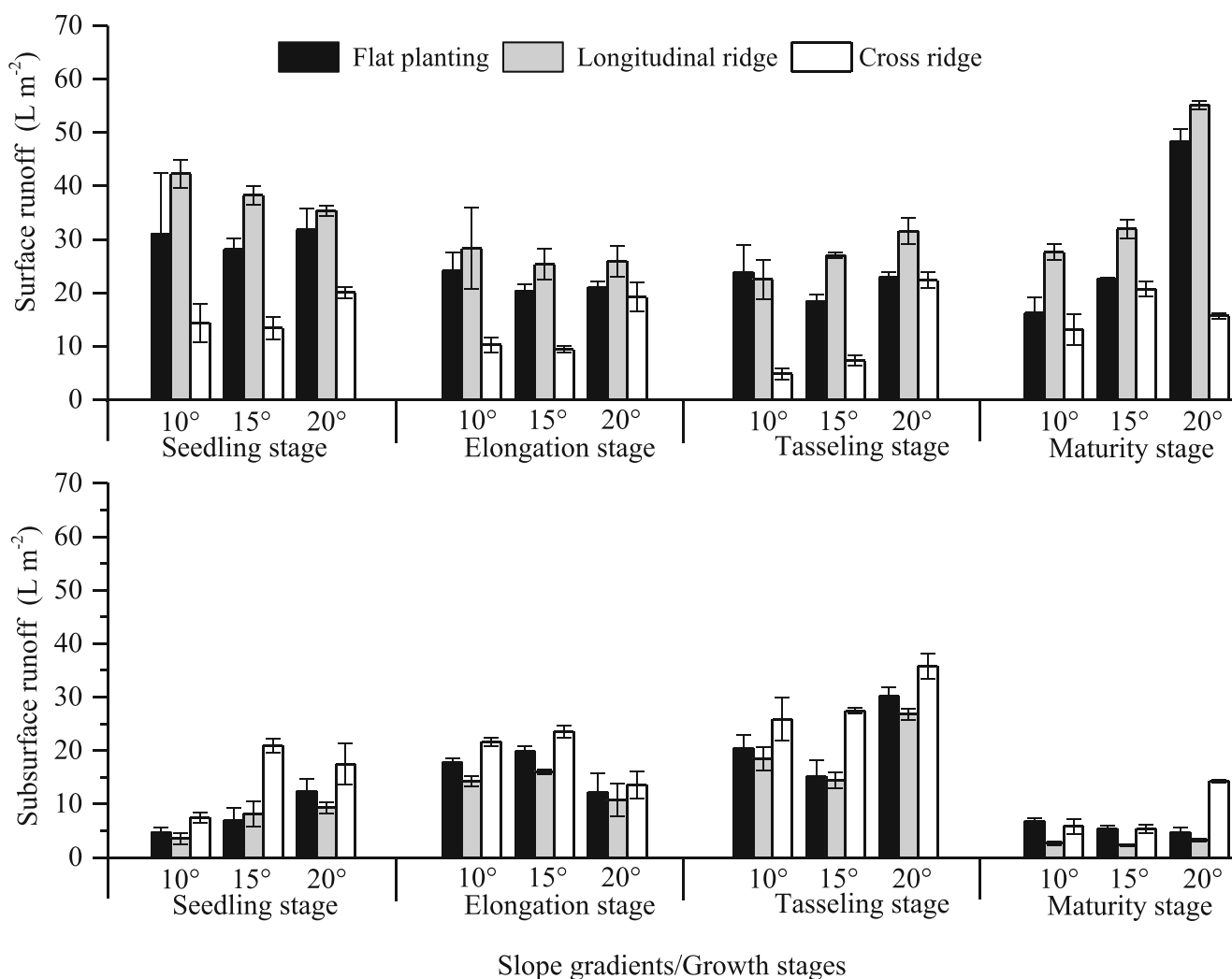
Fig. 4 The characteristics of surface runoff and subsurface runoff

3.2 The characteristics of sediment yields

The sediment yields in the seedling stage were higher compared with those of the other stages under most treatments (Table 1). The sediment yields in longitudinal ridge were significantly higher than those of the other tillage methods, and it increased with the increasing slope gradients. Total sediment yield was the highest (2080.70 g m^{-2}) in longitudinal ridge on

Table 1 Characteristics of the sediment yields under different treatments (g·m^{-2})

Tillage method	Slope gradient (°)	Seedling stage	Elongation stage	Tasseling stage	Maturity stage	Total stage
Flat planting	10	266.43b[a]	83.1ab[a]	56.53a[a]	72.91ba[b]	478.97b[a]
	15	226.34a[a]	55.16b[b]	60.01a[a]	75.47b[b]	416.98b[b]
	20	860.24a[a]	154.68a[c]	59.18a[b]	212.96a[b]	1287.06a[b]
Longitudinal ridge	10	264.89b[a]	84.18c[a]	70.81a[a]	128.67c[ab]	548.55c[a]
	15	470.74b[a]	214.09b[a]	79.36a[a]	230.86b[a]	995.05b[a]
	20	1017.66a[a]	327.72a[a]	334.66a[a]	400.66a[a]	2080.7a[a]
Cross-ridge	10	60.73a[b]	11.86b[b]	14.97b[b]	42.75b[b]	130.31b[b]
	15	15.71a[b]	19.95b[b]	16.88a[b]	68.67a[b]	121.21b[c]
	20	126.1a[b]	243.73a[b]	76.96a[b]	41.18a[c]	487.97a[c]

Different letters indicate significant differences at $p \leq 0.05$ among the different slope gradients. Different superscript letters indicate significant differences at $p \leq 0.05$ among the different tillage methods

the 20° slope, which was 3.8 and 2.1 times as much as those in the corresponding treatments on the 10° and 15° slopes, respectively. Sediment yield in cross-ridge was less than those of the flat planting and longitudinal ridge in each of the growth stages, but there was no significant difference for the slope gradients. Total sediment was the least (121.21 g m^{-2}) in cross-ridge on the 15° slope, which accounted for 24.8% of that of the corresponding treatment on the 20° slope.

3.3 The characteristics of P loss in surface runoff

With regard to the characteristics of the P forms losses in surface runoff (Fig. 5), the minimum was in cross-ridge and the maximum in longitudinal ridge. TP, DTP, and PP losses on the 20° slope were higher than those on the 10° and 15° slopes in the elongation, tasseling, and maturity stages. However, TP, DTP, and PP losses on the 20° slope were less than those on the 10° and 15° slopes in the seedling stage. The TP loss during the entire growth period was 15.24 mg m^{-2},

17.58 mg m^{-2}, and 9.54 mg m^{-2} in flat planting, longitudinal ridge, and cross-ridge on the 20° slope. The TP, DTP, and PP losses increased with the increasing slope gradient during the entire growth period in flat planting and cross-ridge; while these parameters first increased, they then decreased with the increase in the slope gradient in longitudinal ridge. In addition, among the proportions of TP existing in various forms, the proportion of DTP in the seedling stage was the highest, and DTP loss constituted 68.00–92.14% of TP loss, because a large amount of phosphate fertilizer had not been absorbed by the plants. The proportions of DTP in longitudinal ridge or 20° slope were less than those of the other treatments. In other words, PP loss in longitudinal ridge or 20° slope was higher than those of the other treatments. DTP loss in flat planting, longitudinal ridge, and cross-ridge constituted 55.59–90.97%, 49.97–82.63%, and 55.85–92.14% of TP loss, respectively. DTP loss on 10°, 15°, and 20° slopes constituted 57.20–90.97%, 55.85–80.52%, and 49.97–75.74% of TP loss, respectively. This shows that P loss in surface runoff consisted
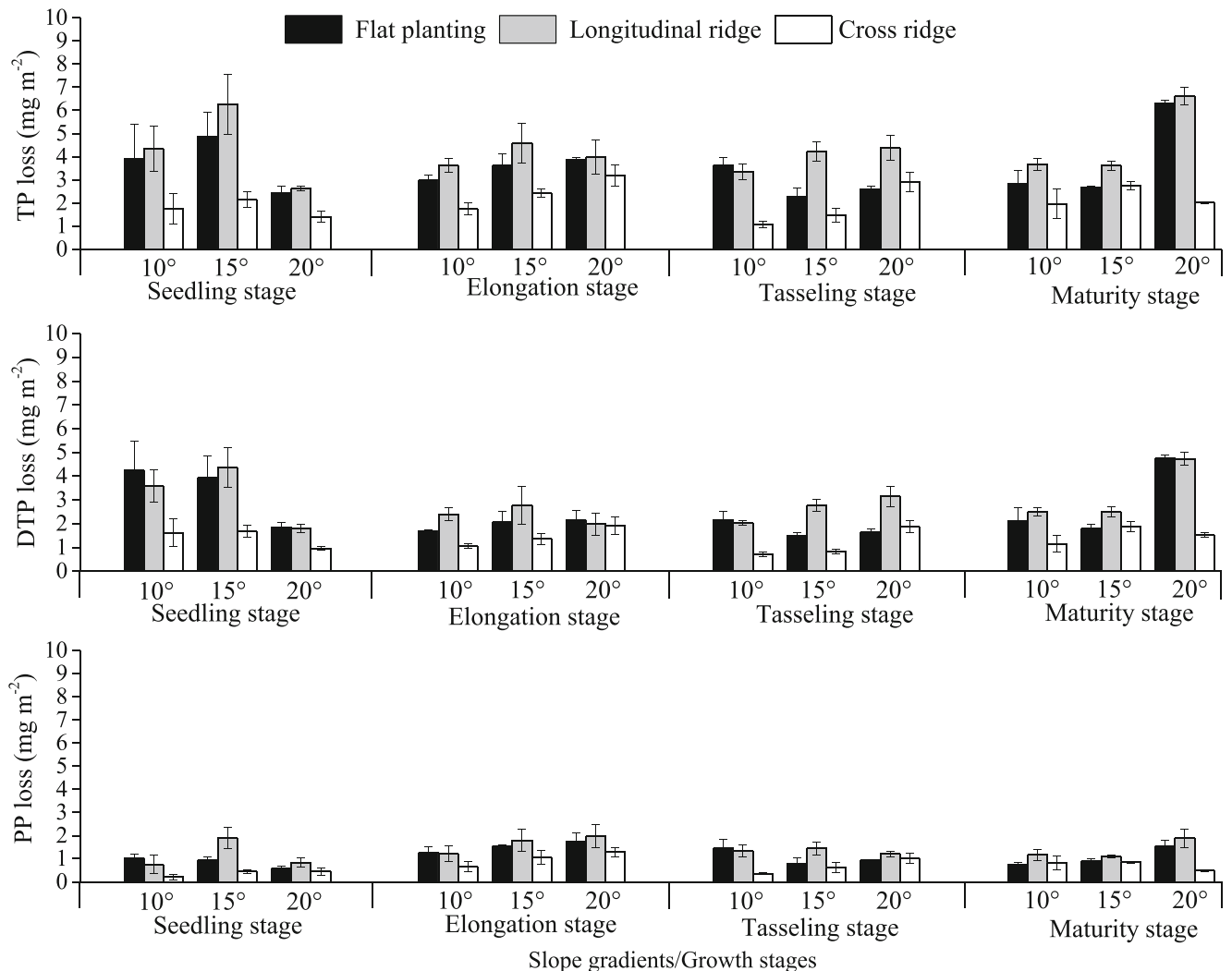

Fig. 5 The characteristics of P loss in surface runoff under different treatments

primarily of DTP, but the greater the erosion intensity, the greater the loss of PP.

3.4 The characteristics of P loss in subsurface runoff

P loss in subsurface runoff cannot be ignored (Fig. 6). TP, DTP, and PP losses were the highest in cross-ridge. This result may have been due to the larger flow of subsurface runoff. Moreover, the rainwater gathered in the cross-slope furrows after slow infiltration had enabled interactions of the infiltrated water with the phosphorus in the soil during the infiltration process, which had caused a large quantity of phosphorus to be extracted. TP, DTP, and PP losses in subsurface runoff in the tasseling stage were higher than those in the other stages. The reason was due to the growth of the maize root system soil porosity was higher, thereby increasing both subsurface runoff and concentration of P. The proportion of DTP was slightly lower than the proportion of PP in subsurface runoff on the 15° and 20° slopes in the elongation stage. Apart from that, the proportion of

DTP loss constituted more than 50% of TP loss in the other treatments. Thus, P loss in subsurface runoff consisted primarily of DTP.

3.5 The characteristics of AP loss in sediment yield

The considerable amounts AP of sediment may be algal available under the appropriate environmental conditions. The AP of sediment is the major source of P pollution of water. There was a great similarity between AP loss (Table 2) and sediment yield (Table 1). The AP loss in sediment in the longitudinal ridge was significantly higher than those of the other tillage methods, and it increased with the increasing slope gradients. AP loss in flat planting and cross-ridge was a little different on the 10° and 15° slopes. In all treatments, the total loss of AP in sediment was lower in cross-ridge on the 10 and 15° slope. The total loss of AP in longitudinal ridge was the most notable in all treatments at 32.86 mg m^{-2} on the 20° slope. The loss of AP in the seedling stage was the greatest, especially on the
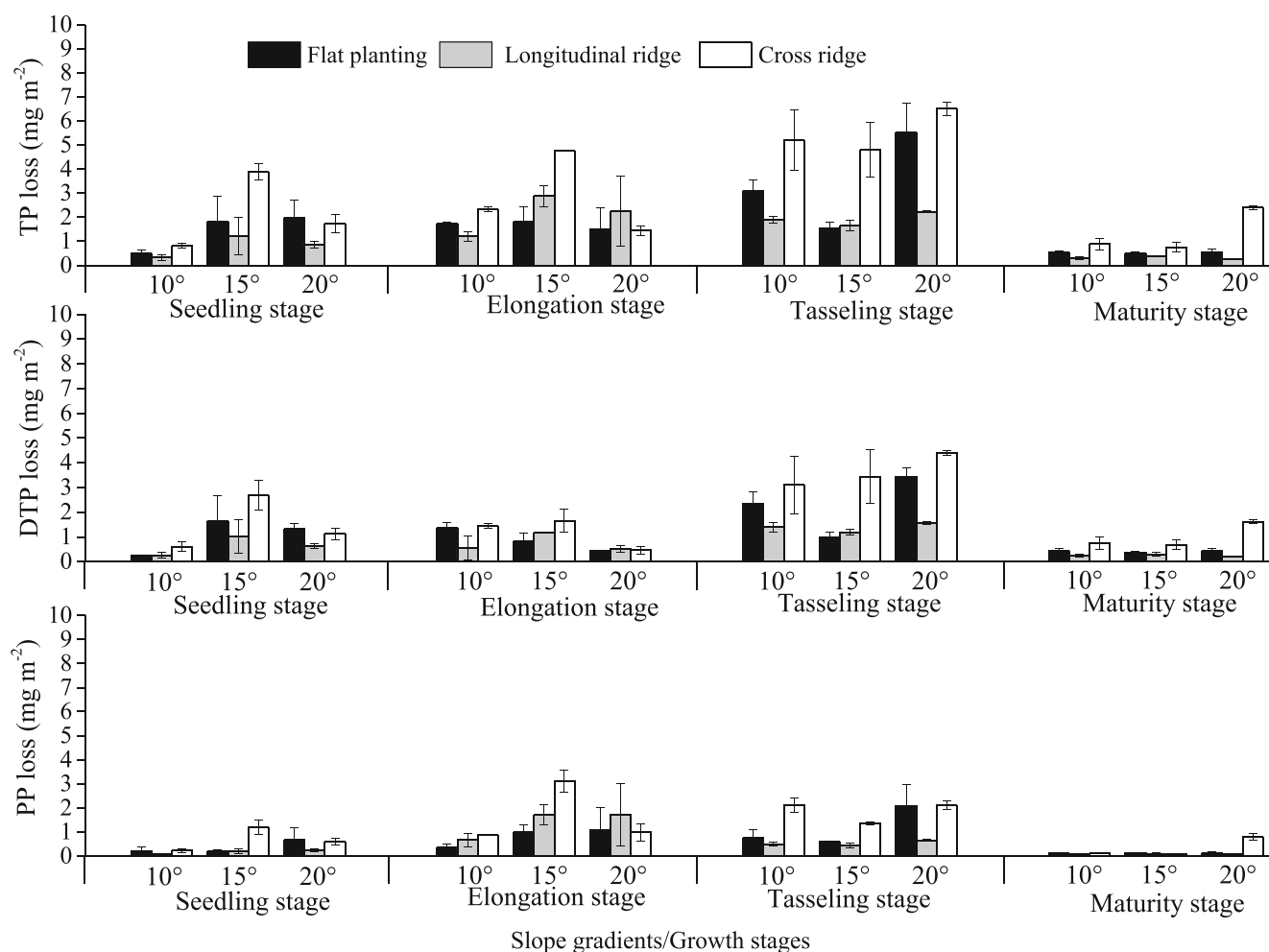

Fig. 6 The characteristics of P loss in subsurface runoff under different treatments

Table 2 Characteristics of the quantity of AP loss in sediment under different treatments (mg m^{-2})

Tillage method	Slope gradient (°)	Seedling stage	Elongation stage	Tasseling stage	Maturity stage	Total
Flat planting	10	2.50b[a]	1.32b[a]	1.55a[a]	1.48b[a]	6.85b[a]
	15	4.45b[a]	0.67b[b]	1.37a[a]	1.04b[b]	7.53b[b]
	20	18.91a[a]	2.74a[a]	1.68a[b]	4.36a[a]	27.69a[a]
Longitudinal ridge	10	0.83b[a]	1.63c[a]	1.70b[a]	1.92b[a]	6.08c[a]
	15	7.83ab[a]	3.04b[a]	1.83a[a]	1.72a[a]	14.42b[a]
	20	18.47a[a]	3.99a[a]	5.47a[a]	4.93a[a]	32.86a[a]
Cross-ridge	10	0.81a[a]	0.21b[b]	0.34a[a]	0.86b[a]	2.22b[b]
	15	0.41a[a]	0.38b[b]	0.34a[a]	0.88b[a]	2.01c[c]
	20	2.40a[b]	2.93a[a]	1.51a[b]	0.62a[b]	7.46b[b]

Different letters indicate significant differences at $p \leq 0.05$ among the different slope gradients. Different superscript letters indicate significant differences at $p \leq 0.05$ among the different tillage methods

20° slope. A large amount of P loss with sediment was also an important reason for the reduced loss of P in the runoff on the 20° slope, as mentioned earlier.

4 Discussion

4.1 The relationship between P loss and soil erosion

P loss is mainly caused by runoff and sediment, so there is a certain relationship between the three (Sun et al. 2016). Significant positive relations between the TP loss rate and the surface runoff rate were observed ($p < 0.01$) (Fig. 7). The TP loss rate was influenced by the differences in surface runoff and demonstrated a direct increase with the runoff rate. This phenomenon could be attributed to the effects of fluctuating P concentration and precipitation forces (Zhang et al. 2017). There was also a very significant linear relationship between the sediment yield rate and the AP loss rate (Fig. 8). The sediment yield rate had a crippling effect on the AP loss rate in each growth stage of maize. This occurred because the P fertilizer was applied to the superficial soil, and the level of P in sediment was correlated to the level of P in the superficial soil layer (Barbosa et al. 2009). The results of regression analysis of the different treatments suggest that the relations between runoff and sediment yield and P loss were binomial (Table 3). This finding showed that runoff and sediment discharge controlled the P loss in our experiment. In addition, the runoff shear force is an important impetus for the runoff to destroy soil structure and transport soil particles down the slope, and it has a huge impact on the movement characteristics of sediment yield. The relationship between the runoff shear force and the rate of sediment yield was found to be polynomial, that is, the rate of sediment yield increased as the runoff shear force increasing (Fig. 9). Expanding runoff and sediment caused P to be delivered

to surface runoff in every treatment during heavy rain. Therefore, controlling water and soil losses is indispensable for alleviating P losses from slope farmlands. These findings are similar to the findings of the study conducted by Barbosa et al. (2009).

4.2 The effect of tillage methods on P loss

Tillage methods resulted in soil degradation and oftentimes increased soil erosion (Schoumans et al. 2014). P can be transported from the soil to surface water by runoff and sediment loss (Hu et al. 2013). Vincent and Yves (2003) confirms the sharp relation between tillage methods and runoff pathways. Cross-ridge is one of the traditional methods adopted for preventing soil erosion of slope farmlands, as it can retain the rainwater landing on the ridge and the furrow. In this study, surface runoff and sediment loss in cross-ridge were clearly lesser at every growth stage of maize than those in longitudinal ridge and flat planting. However, subsurface runoff in cross-ridge was clearly greater in every growth stage of maize than those in the other tillage methods. Cross-ridge created a barrier effect to overland flow, increased surface detention storage and increased time of the opportunities for infiltration, and in turn decreased water and soil erosion (Kurothe et al. 2014; Liu et al. 2014a, 2014b). This finding indicated that cross-ridge can block runoff, decrease flow, and cause sedimentation along the upside of contour supports on the crop sloping land. The levels of P in runoff and sediments were affected by the amount of runoff and sediments (Table 3). Therefore, P loss in surface runoff and sediment in cross-ridge was the least, and P loss in subsurface runoff was the greatest. The cross-ridge treatment can effectively prevent the loss of P to improve the utilization rate of P in the soil. Stevens et al. (2009) reported there were benefits to be gained from using cross-ridge to reduce runoff sediment and P losses. However, if the water volume following a
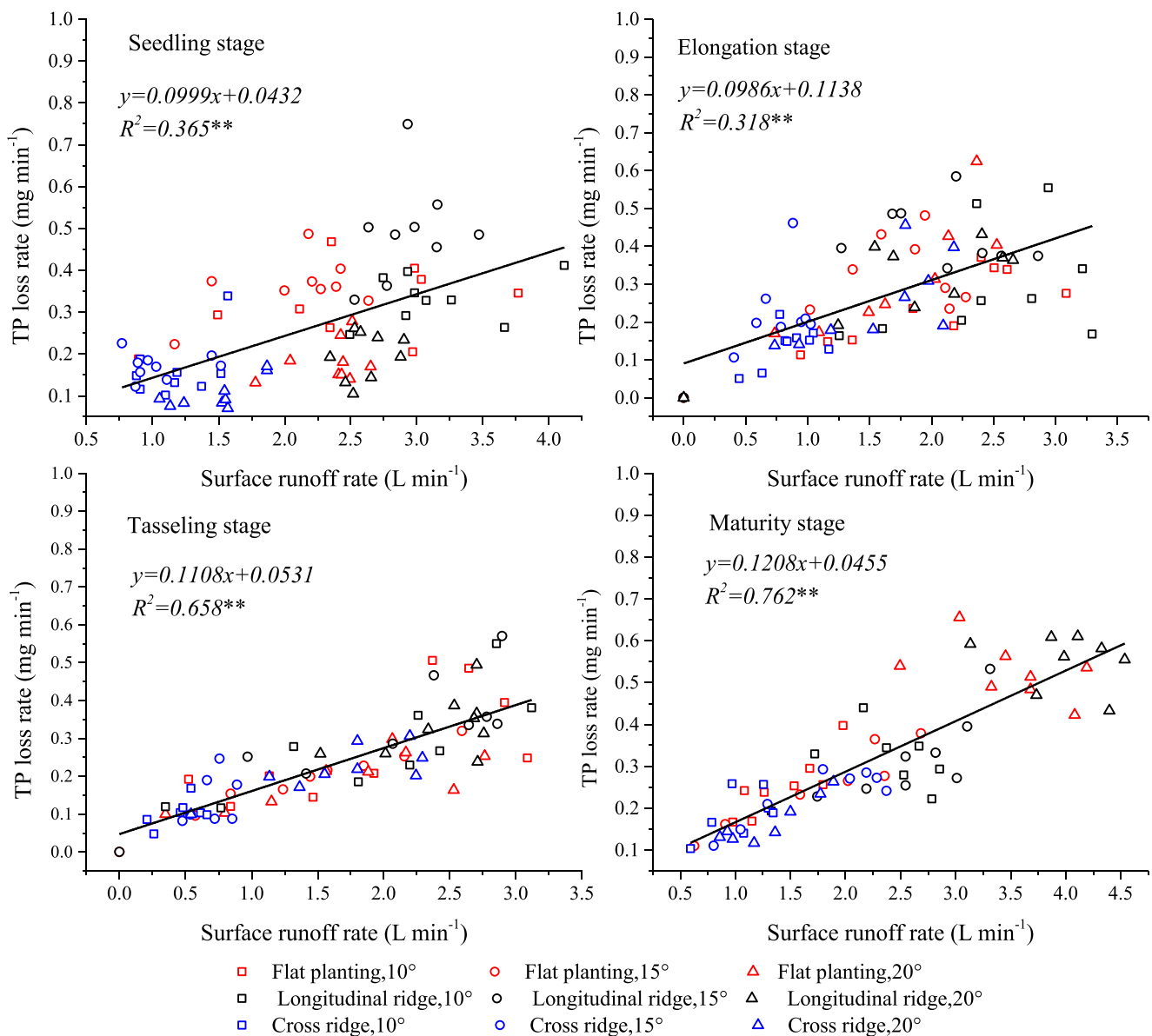
Fig. 7 The TP loss rate as a function of the surface runoff rate under different treatments during various growth stages of maize

rain capacity exceeds the storage capacity within a contour row, the surface runoff will spill from the ridge, and that can instantly increase the runoff shear force. When the runoff shear force exceeds the critical value, rills will form on the ridge-side slope, and these rills gradually widened and deepened with increasing erosive power, which ultimately will lead to ridge collapse. If such collapse occurs, the cross-ridge will have lost its anti-erosion capacity, with the result of the soil erosion becoming even worse (Liu et al. 2011; Liu et al. 2014a, 2014b). Our results showed that the critical runoff shear forces were determined as being 39.51 N m^{-2} in flat planting, 47.90 N m^{-2} in longitudinal ridge, and 25.68 N m^{-2} in cross-ridge (Fig. 9); the critical runoff shear forces of cross-ridge were much less than those of flat planting and longitudinal ridge.

The surface runoff, the sediment, and P loss were the largest in longitudinal ridge, because the direction of furrow was the same as the direction of surface runoff, in addition to the role of the ridge, which forced the surface runoff to collect in a ditch. Therefore, surface runoff in the ditch increased, leading to increased soil erosion. Compared with flat planting, total surface runoff and sediment in longitudinal ridge increased by 17.4–31.5% and 14.5–138.6%, respectively. The average runoff shear force in longitudinal ridge was 1.26 times as much as that in flat planting. So, the runoff erosivity of longitudinal ridge was the strongest. Several other studies have reported that the tillage with ridge in the slope is the least desirable tillage method (Quinton and Catt 2004; Stevens et al. 2009; Kateb et al. 2013; Kurothe et al. 2014). There was a very
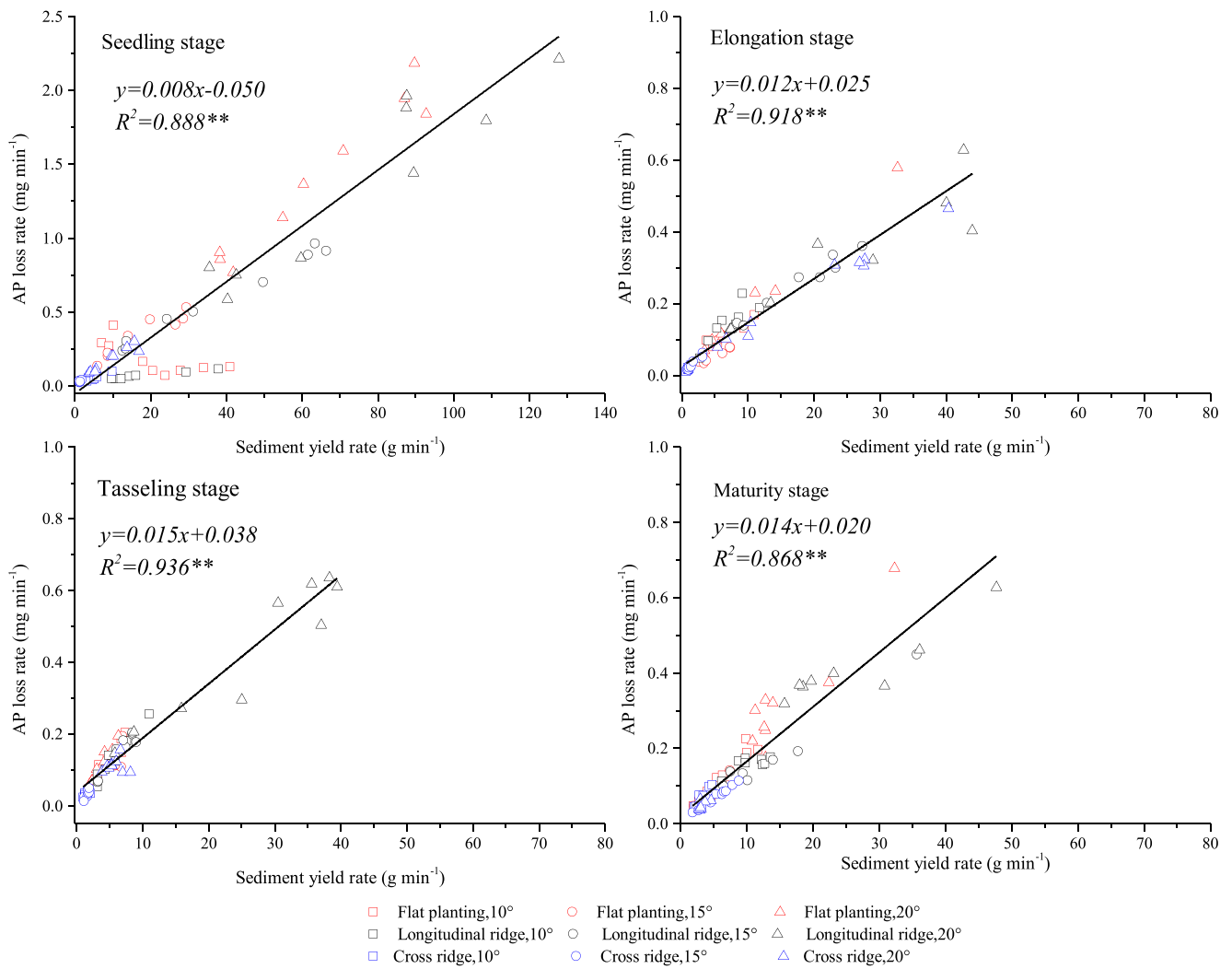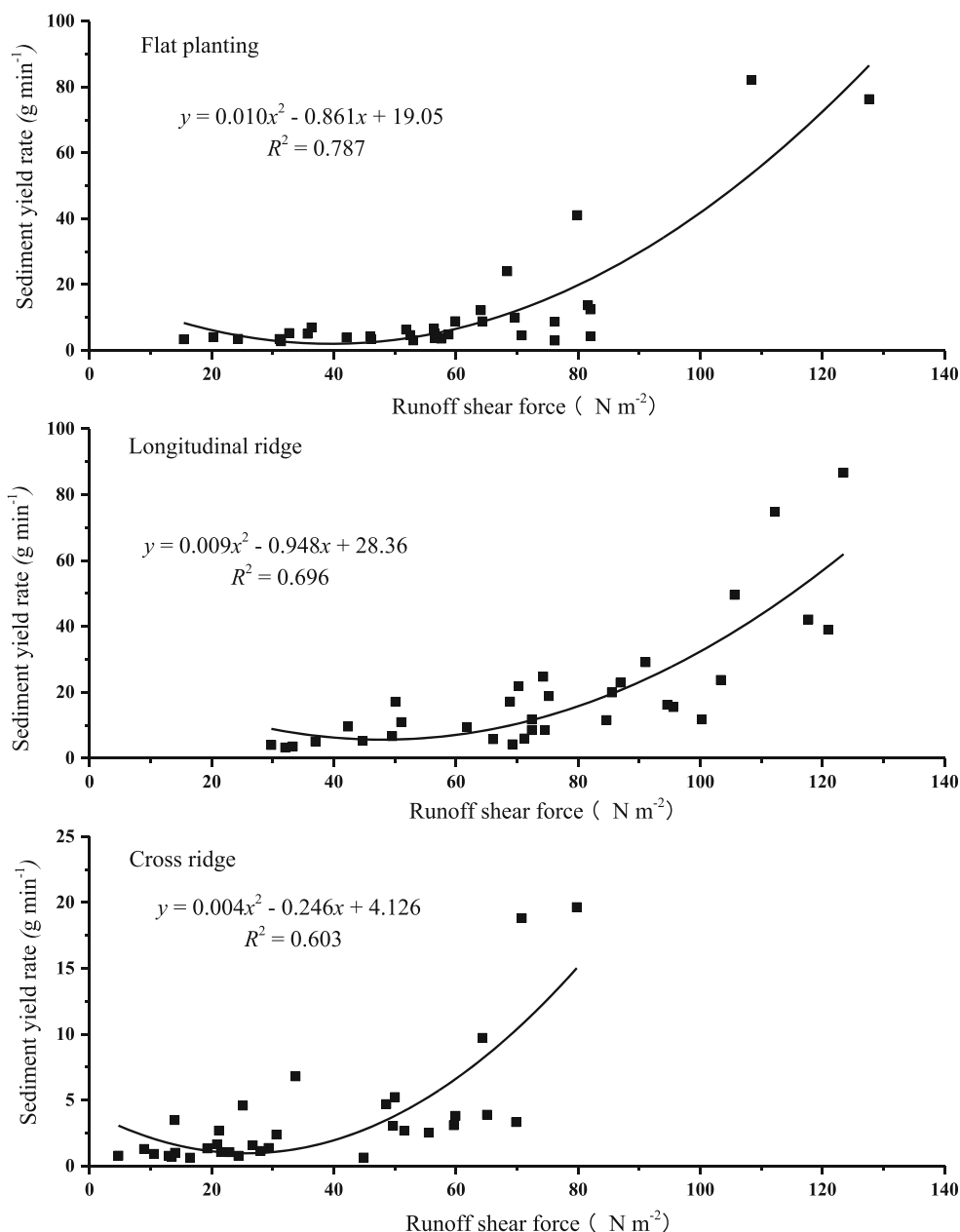
Fig. 8 The sediment-associated AP loss rate as a function of the sediment yield rate under different treatments during various growth stages of maize

Table 3 Relationship between P loss (y) and surface runoff/sediment (x) for the entire growth stage of maize under different treatments

Tillage method	Slope gradient (°)	Surface runoff-associated TP loss (y)		Sediment-associated AP loss (y)	
		Equation	R^2	Equation	R^2
Flat planting	10	$y = -0.002x^2 + 0.214x - 0.117$	$R^2 = 0.675*$	$y = -2\text{E}{-}05x^2 + 0.017x + 0.384$	$R^2 = 0.730**$
	15	$y = 0.007x^2 - 0.186x + 3.337$	$R^2 = 0.567*$	$y = -4\text{E}{-}05x^2 + 0.038x - 1.172$	$R^2 = 0.849**$
	20	$y = 0.009x^2 - 0.565x + 10.93$	$R^2 = 0.806**$	$y = 5\text{E}{-}06x^2 + 0.015x + 0.585$	$R^2 = 0.999**$
	Total	$y = 8\text{E}{-}4x^2 + 0.042x + 1.687$	$R^2 = 0.533**$	$y = 2\text{E}{-}05x^2 + 0.000x + 1.640$	$R^2 = 0.941**$
Longitudinal ridge	10	$y = 0.001x^2 - 0.043x + 3.524$	$R^2 = 0.379$	$y = -5\text{E}{-}05x^2 + 0.017x + 0.540$	$R^2 = 0.539*$
	15	$y = -3\text{E}{-}05x^2 + 0.133x + 0.625$	$R^2 = 0.244$	$y = -1\text{E}{-}06x^2 + 0.010x + 0.592$	$R^2 = 0.709**$
	20	$y = 0.004x^2 - 0.216x + 6.481$	$R^2 = 0.638*$	$y = 3\text{E}{-}06x^2 + 0.015x - 0.843$	$R^2 = 0.983**$
	Total	$y = 0.001x^2 - 0.000x + 2.941$	$R^2 = 0.346**$	$y = 9\text{E}{-}06x^2 + 0.006x + 0.936$	$R^2 = 0.929**$
Cross-ridge	10	$y = 0.008x^2 - 0.078x + 1.325$	$R^2 = 0.672*$	$y = -0.000x^2 + 0.029x - 0.073$	$R^2 = 0.924**$
	15	$y = -0.001x^2 + 0.111x + 1.095$	$R^2 = 0.326$	$y = -4\text{E}{-}05x^2 + 0.013x + 0.130$	$R^2 = 0.983**$
	20	$y = 0.027x^2 - 0.997x + 10.93$	$R^2 = 0.222$	$y = -2\text{E}{-}05x^2 + 0.018x + 0.003$	$R^2 = 0.884**$
	Total	$y = 5\text{E}{-}4x^2 + 0.066x + 1.002$	$R^2 = 0.364**$	$y = 1\text{E}{-}06x^2 + 0.013x + 0.13$	$R^2 = 0.907**$

$*p < 0.05$; $**p < 0.01$

Fig. 9 The relationship between the runoff shear force and sediment yield rate under different tillage methods

Flat planting

$$y = 0.010x^2 - 0.861x + 19.05$$
$$R^2 = 0.787$$

Sediment yield rate (g min^{-1})

Runoff shear force (N m^{-2})

Longitudinal ridge

$$y = 0.009x^2 - 0.948x + 28.36$$
$$R^2 = 0.696$$

Sediment yield rate (g min^{-1})

Runoff shear force (N m^{-2})

Cross ridge

$$y = 0.004x^2 - 0.246x + 4.126$$
$$R^2 = 0.603$$

Sediment yield rate (g min^{-1})

Runoff shear force (N m^{-2})

significant linear relationship between surface runoff, sediment loss, and P loss, which was binomial (Table 3). P loss in surface runoff and sediment yield in longitudinal ridge was the largest, making longitudinal soil erosion and nutrient loss the most serious in this treatment, thereby suggesting that long-term use of longitudinal ridges may exacerbate soil degradation.

Longitudinal ridge and flat planting resulted in increases in surface runoff, sediment, and P losses and are not recommended as a mitigation option. Cross-ridge gave much more positive results: although subsurface runoff was higher, the surface runoff, sediment, and P losses were much lower. However, the additional time input required for cultivations and safety concerns means that this option may not be popular among

farmers (Quinton and Catt 2004; Stevens et al. 2009), but with the right incentive, this measure could be cost-effective.

Table 4 Regression equation values for the relationships between total AP loss in sediment and the slope gradient

Tillage method	Relationship type	a	b	R^2
Flat planting	Linear	2.084	− 17.237	0.774
	Exponential	0.14	1.386	0.801
Longitudinal ridge	Linear	2.678	− 22.383	0.955
	Exponential	0.169	1.132	0.999
Cross-ridge	Linear	0.523	− 3.942	0.720
	Exponential	0.121	0.527	0.689

Table 5 Regression equation values for the relationships between total TP loss in surface runoff and the slope gradient

Tillage method	Relationship type	a	b	R^2
Flat planting	Linear	0.191	11.142	0.797
	Exponential	0.013	11.436	0.800
Longitudinal ridge	Linear	0.259	13.192	0.471
	Exponential	0.016	13.389	0.495
Cross-ridge	Linear	0.299	3.795	0.931
	Exponential	0.038	4.652	0.911

4.3 The effect of slope gradients on P loss

Soil erosion is a selective process that removes fine-grained material from slope lands. As a result, lands become increasingly barren or to a great extent depleted (Kateb et al. 2013). Slope gradient is one of the major factors affecting soil particle detachment and transport, and it also affects runoff and sediment yield explicitly (Fu et al. 2011). The maximum runoff and sediment yields occurred in the 20° slopes, but the runoff and sediment yields remained similar between 10 and 15° slopes; we did not observed a significant difference between them. This is because the steeper a slope land, the more the component force of gravity on the slope direction increases and the more the component force along the vertical slope decreases, resulting in decreased total infiltration (Liu et al. 2015). The total quantity of surface runoff and its velocity increase, the impact of runoff on the soil increases, and the particles are washed out. That can be ascribed to the partition of raindrop impact force into normal and tangential components. So, the steeper a slope land, the higher the soil erosion rate. Our data corroborate the results obtained by Ribolzi et al. (2011).

There was a positive linear or exponential relationship between the slope gradient and AP loss in sediment or TP loss in surface runoff. The parameters of the equation are presented in Table 4 and Table 5; the correlation of the exponential relationship was better than that of the linear relationship in flat planting and longitudinal ridge, whereas the correlation of the linear relationship was better than that of the exponential relationship in cross-ridge. Increasing the slope gradient caused P loss to increase. Generally, an increase in slope gradient

caused soil and water erosion more easily to occur. The water flow overcame the resistance of the soil surface more readily when the slope was steeper, increasing flow velocity and runoff intensity (Huang et al. 2013; Shen et al. 2016). In addition, P losses are decided by the initial soil concentration of P and the erosion volume (Qian et al. 2014). Sun et al. (2016) reported that the relationship of slope gradient and sediment yield can be described as a linear relationship in the range from 10° slope to 20° slope. Many researchers have discussed the relationship between runoff, sediment, and slope gradient; relatively, few have focused on the relationship between P loss and slope gradient. But the P loss in the soil and in the runoff sediments was positively correlated (Barbosa et al. 2009). Hu et al. (2013) reported the P loss in runoff, and sediment was $17° > 9° > 4°$. However, our study found that P loss occurred violently on 20° slope and that there was little difference in the losses on 10° and 15° slopes. These discrepancies may have been due to the slope gradient-induced the differences of rill density and length. Jiang et al. (2018) reported that the effects of slope gradient were greater than those of other factors; especially, the steep slope directly influence to the rill erosion rates, which cause the soil loss rate sharply raised and irregularly fluctuated.

4.4 The effect of maize growth stages on P loss

The effect of the growth stages on P loss was mainly caused by the differences in vegetation cover. On the other hand, the roots can change the structure of the soil, adhere soil particles, and increase soil porosity (Sun et al. 2016). The dense vegetation cover could significantly affect the changes in P concentrations in surface runoff by methods such as reducing the direct impact of the raindrops on the slope surface, reducing soil aggregate disintegration, accelerating the infiltration speed, and decreasing the surface runoff velocity (Qian et al. 2014). A number of studies have pointed out that there was a lower surface runoff from plots with larger vegetation coverage than that from wasteland or sparsely vegetation land (Mcconnell et al. 2013; Chau and Chu 2017. The vegetation cover in the different growth stages showed significant differences (Table 6). Under different tillage methods, the order of the vegetation cover was as follows: tasseling stage > maturity stage > elongation stage > seedling stage. Therefore, the

Table 6 Average vegetation cover (%) under different tillage methods during the growth stages of maize

Tillage method	Seedling stage	Elongation stage	Tasseling stage	Maturity stage
Flat planting	4.5a[d]	53.8a[c]	84.4a[a]	68.7a[b]
Longitudinal ridge	3.9b[d]	48.4b[c]	80.5b[a]	60.5b[b]
Cross-ridge	4.8a[b]	54.3a[c]	85.7a[a]	71.2a[b]

Different letters indicate significant differences at $p \le 0.05$ among the different tillage methods. Different superscript letters indicate significant differences at $p \le 0.05$ among the different growth stages

variation ranges of the mean runoff and sediment yield rates were wider in the seedling and maturity stages of maize than in the elongation and tasseling stages (Fig. 10). The average vegetation covers in elongation stage, tasseling stage, and maturity stage were 11.86, 18.98, and 15.18 times as much as that in seedling stage. In addition, we found that there was a very significant linear relation between surface runoff, sediment yield rate, and P loss rate in every stage (Figs. 7 and 8). Quinton et al. (2001) also found there were a significant positive correlation between the soil erosion and P loss.

Fig. 10 The mean rates of runoff and sediment yield during the growth stages of maize
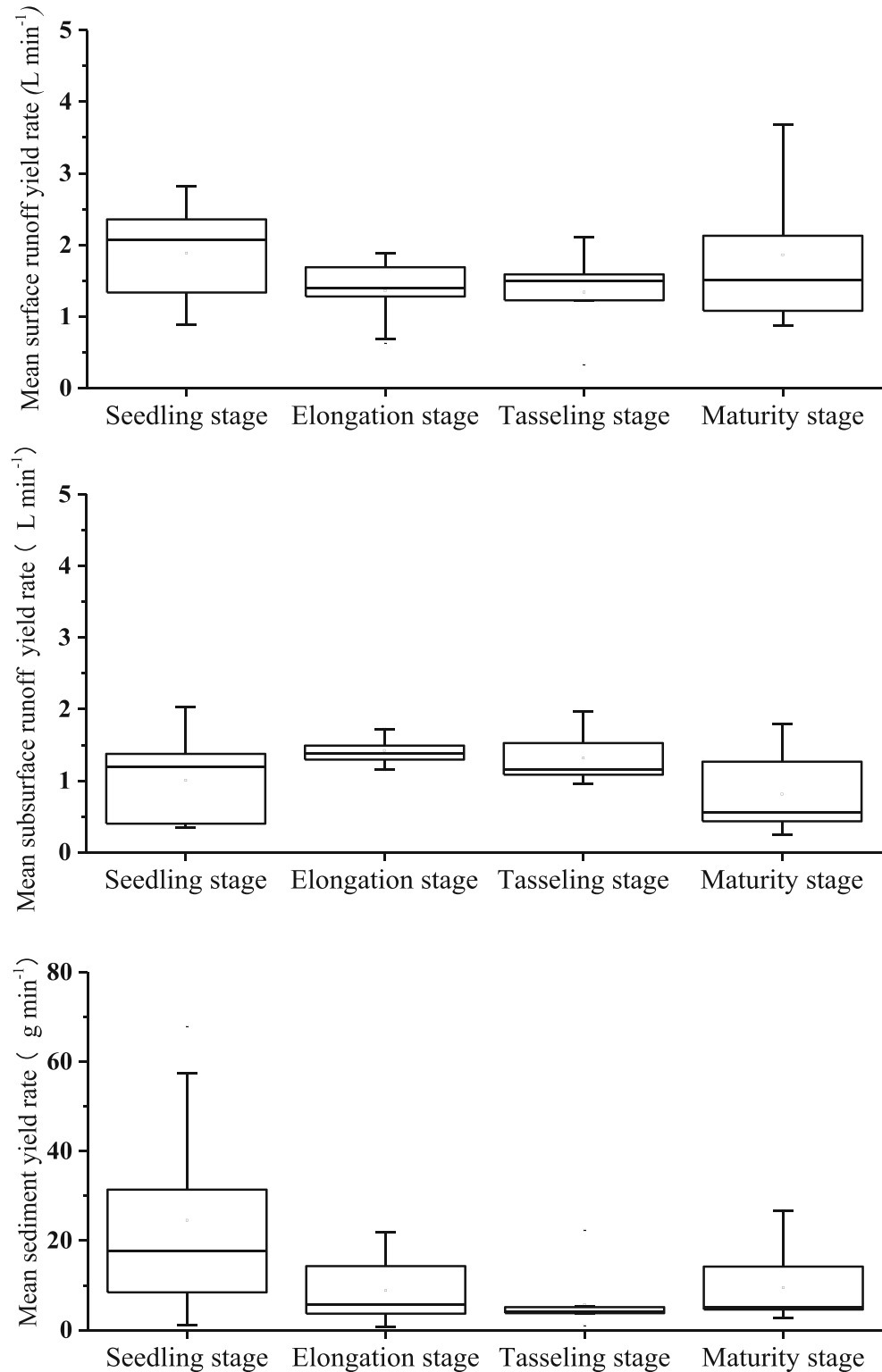
Therefore, the AP loss by the sediment in elongation stage, tasseling stage, and maturity stage decreased by 70.13%, 72.11%, and 68.54%, respectively, in comparison with the seedling stage. The TP loss by the runoff in elongation and tasseling stages increased by 16.36% and 36.10%, and in the maturity stage it decreased by 9.03%, respectively, in comparison with the seedling stage. The TP loss (1.09–4.49 mg m^{-2} in surface runoff and 1.55–6.51 mg m^{-2} in subsurface runoff) was found to have a greater risk in the tasseling stage. The multiple leaf layers of maize could further increase the surface area to intercept rainfall and reduce the impacts of the raindrops in the tasseling stage. Total runoff and sediment and P transport in the elongation and tasseling stages were lower than those in the seedling and maturity stages, which might have been due to the denser vegetation cover reducing the kinetic energy of the raindrops, thereby preventing surface soil sealing and reducing sediment yield (Yang et al. 2015; Lu et al. 2016). The vegetation cover in longitudinal ridge was significantly thinner than those in flat planting and cross-ridge. This is also one of the main causes leading to the largest surface runoff and sediment and P loss in longitudinal ridge. Leaves can decrease the energy of the raindrops and protect the soil surface (Zhang et al. 2011). The leaves covering the slope fields intercept raindrops, impede runoff, and increase the infiltration time, and the roots improve the soil infiltration capacity (Gao et al. 2009). So, subsurface runoff and P loss in the tasseling stage were much higher than those in the seedling stage (Figs. 4 and 5). Zhang et al. (2017) demonstrated vegetation cover can prevent raindrop splashing and mitigate runoff scouring, thus decreasing P losses caused by soil erosion. Therefore, to further reduce P loss, other methods, such as increasing the vegetation cover by crop selection or increasing planting density, can be considered.

5 Conclusions

In this paper, simulating rainfall was applied to evaluate, under heavy rain, the effect of the interactions between tillage methods, slope gradients, and maize growth stages on soil erosion and P losses. Results indicated there are positive and non-linear relations between the rate of sediment yield and the runoff shear force. The higher plant covers under different tillage methods can reduce the rate of sediment yield; therefore, high plant cover crops should be planted in areas that are prone to erosion by water. For the longitudinal ridge and 20° slope, runoff and sediment of croplands had higher P levels than that of the other treatments. The cross-ridge treatment can effectively prevent the loss of P. DTP loss dominated the total P loss in runoff, with more than 55.58% of the DTP losses in all the treatments. The runoff-associated and sediment-associated P loss increased linearly with the runoff and sediment yield rates during the whole growth stages of maize.

However, P loss was non-linearly related with the runoff and sediment yield rates under different treatments.

As above, controlling water and soil erosion is indispensable for alleviating P losses from slope farmlands, as well as using complementary practices for soil conservation, such as employing flat planting and cross-ridge, choosing the appropriate slope land with gradients of less than 20° slope, and increasing vegetation cover to avoid large amounts of bare land. We can minimize the agricultural pollution of soil and water resources by reducing P loss in runoff and sediment yield in the purple hilly region of Sichuan, China.

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