RESEARCH ARTICLE

Transport of colloidal phosphorus in runoff and sediment on sloping farmland in the purple soil area of south-western China

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Abstract
Colloidal particles in runoff could play an important role in phosphorus (P) transfer from sloped farmland to waterbodies. We investigated the distribution of P in different-size particles from a purple soil and colloidal phosphorus (CP) loss in runoff and sediment from sloped farmland in south-western China. The profile distribution of P showed obvious surface accumulation. The risk of P loss in topsoil was greater than those of the other soil layers on sloping farmland of purple soil. The concentration of soil particles of < 0.002 mm in purple soil profiles was low, but the total phosphorus (TP) and available phosphorus (AP) concentrations of soil particles of < 0.002 mm were high. During a rainfall event, CP loss is significantly power function related to the runoff yield rate, and is linearly related to the sediment yield rate. The majority of P in runoff was CP. The total loss of CP in runoff was 139.52 g ha^{-1}, in which surface runoff accounted for 64.3%. CP loss can be controlled by controlling runoff from sloping farmland, especially surface runoff. Our results suggest that CP loss should be valued in the process of nutrient loss, as well as CP transfer should be given greater consideration in the mechanistic studies of the P transfer process.

Keywords Colloidal phosphorus · Surface runoff · Subsurface runoff · Sediment · Sloping farmland · Purple soil

Introduction

The migration and variation of phosphorus (P) significantly impact eutrophication control in an agricultural system (Kragh et al. 2017; Kleinman et al. 2017; Zhang et al. 2017a, b). In general, migration and transformation of P occur in a stable solid phase and a removable aqueous phase; however, the colloid phase can remarkably improve the ability of contaminant adsorption owing to its mobility (Turner et al. 2014; Zang et al. 2011; Liu et al. 2010). Presently, most researchers consider 0.45 μm to be a cut-off point and divide P in sediment and water into particulate phosphorus (PP) and dissolved phosphorus (DP) (He et al. 2018; Zhang et al. 2017a, b; Qian et al. 2014; Barbosa et al. 2009). Colloidal phosphorus (CP) refers to P that is absorbed on colloids (Gottselig et al. 2017a; Liang et al. 2016; Kretzschmar et al. 1999). In particular, colloids have a large specific surface area and strong adsorption capacity, are mobile in soil, and remain in solution for a long time. Retention of CP occurs through sorption, flocculation, and deposition. Colloids play an important role in biogeochemical cycles of P (Yan et al. 2017; Turner et al. 2014; Baalousha et al. 2011). In surface runoff, rivers, and lakes, CP has been observed to reach up to 50% of total phosphorus (TP) (Missong et al. 2017), because CP can be easily released from the soil in contact with water, and waterways enriched with P can develop blue-green algal blooms, which can produce harmful toxins, reduce aesthetic appearance, and worsen eutrophication. In areas with soil erosion, CP loss is frequently a long-term environmental problem (Gottselig et al. 2017b; Montalvo et al. 2015; Zang et al. 2011; Heathwaite and Dils 2000). Therefore, understanding the distribution characteristics and loss regularities of CP in soil, the impact of P speciation, and environmental behaviour and loss potential of P is important.

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Purple soils on the hilly area of the upper Yangtze River are thin Entisols with high erosivity and strong dispersibility and are the potential contribution source of colloidal particles (Wang .2017; Ding et al. 2017; Wang et al. 2013), which are known to have a remarkable capacity to carry and transport P (Liu et al. 2014a, b; Siemens et al. 2004). This area is characterized by scattered small plots of steep slopes. Rainfall is uneven, mainly concentrated in summer, and mostly in the form of heavy rainstorms (Xian and Tang 2017; Sun et al. 2016; Lin et al. 2009). This causes frequent wet-dry cycles, thus complicating and changing the surface and subsurface runoffs of sloped lands. Thus, the migration of CP severely affected the water environment of the upper reaches of the Yangtze River already being affected adversely (Ding et al. 2017; Khan et al. 2016; Wang et al. 2015a, b). Several studies have produced estimates of P loss (Zhang et al. 2017a, b; Ding et al. 2017; Bouraima et al. 2016; Zeng et al. 2008), but there is still insufficient data for CP loss in the area.

In this study, the plots on sloped purple soils were used to simulate rainfall in order to compare losses characteristic of different P forms. This study aimed to (1) investigate P concentration of different-size particles in purple soil profiles; (2) quantify the relationships between CP loss and soil erosion; and (3) identify the pathway of CP transport from sloping farmland.

Materials and methods

Study site

The experimental field is located 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), at an elevation of 395 m. Mean annual temperature is 16.8 °C, and mean annual precipitation is normally 966 mm. The greater part of annual precipitation is mainly distributed from April to October. The area is dominated by purple soils formed in purple sandy shale, classified as Entisol according to the soil taxonomy of the U.S.D.A. (Soil Survey Staff 1999). Soil physical-chemical properties are listed in Table 1.

Experimental setup and sample collection

The study area was cultivated with maize (*Zhenghong 6*). There was a total of 40,000 plants ha^{-1}, with plant spacings and row spacings of 80 and 25 cm, respectively. Nitrogen (N), phosphate (P_2O_5), and potash (K_2O) fertilizers were applied at rates of 250, 125, and 150 kg ha^{-1}, respectively, before sowing. The N fertilizer was urea (46.3% N); P fertilizer, calcium superphosphate (12% P_2O_5); and K fertilizer, potassium chloride (60% K_2O). The tillage method was cross ridge, and the slope gradient was 15°.

Three runoff plots (2 m × 1 m × 0.4 m) were built for collecting surface runoff, subsurface runoff, and sediment samples under the simulated precipitation events (Fig. 1). This plot area was mainly used in order to simulate sloping farmland of scattered and small areas in the study area. The bottom of each plot was reinforced with concrete to create a relatively impermeable layer. Each concrete layer was covered by a 40-cm-thick soil layer to simulate the natural bulk density of approximately 1.41 g cm^{-3}(0– 10 cm), 1.44 g cm^{-3}(10–20 cm), and 1.6 g cm^{-3}(20– 40 cm). The surface runoff in each plot was drained through an outlet into a concrete trough (Fig. 1). The subsurface runoff reached the impermeable layer through small holes of 2 cm diameter, and a PVC pipe was used to connect the tank and the runoff collection barrel. The experiment was conducted during the maize seedling stage in spring 2016 (3–5 May).

Surface and subsurface runoffs were collected in plastic buckets every 3 min. The first collection was made at the start of rainfall (time zero). Each runoff sample was filtered. Runoff samples were collected in 500-mL plastic bottles, to which 0.5 mL of 98% H_2SO_4 was added to reduce microbial activity. The runoff samples were taken back to the laboratory frozen (− 4 °C) for immediate analysis. The sediment samples were oven-dried (105 °C) and passed through 2-mm sieves for measurements.

Bulk soil samples were collected by shovel from alongside the plots up to 0–10, 10–20, and 20–40 cm depths. To minimize the disturbance caused by other factors, the soil samples were collected on the day the rainfall began. All soil samples were collected on the same day with three replications. The soil samples were air-dried and then sieved < 2 mm.

Table 1 Basic physical characteristics of the purple surface soil in the study area

Soil layer (cm)	Bulk density (g cm^{-3})	pH	TP (mg kg^{-1})	AP (mg kg^{-1})	Soil particle size classification (%)			
					0.2–2 mm	0.02–0.2 mm	0.002–0.02 mm	< 0.002 mm
0–10	1.41 ± 0.05	8.1	1457.88 ± 149.9	255.28 ± 5.78	38.51 ± 3.6	17.99 ± 2.5	24.05 ± 2.8	19.45 ± 4.4
10–20	1.44 ± 0.02	8.1	1026.00 ± 118.43	171.01 ± 0.75	38.20 ± 2.1	23.74 ± 2.0	22.00 ± 0.9	16.06 ± 3.3
20–40	1.55 ± 0.08	8.2	977.57 ± 149.9	112.73 ± 3.46	43.29 ± 1.7	23.84 ± 1.2	18.63 ± 1.0	14.25 ± 2.1
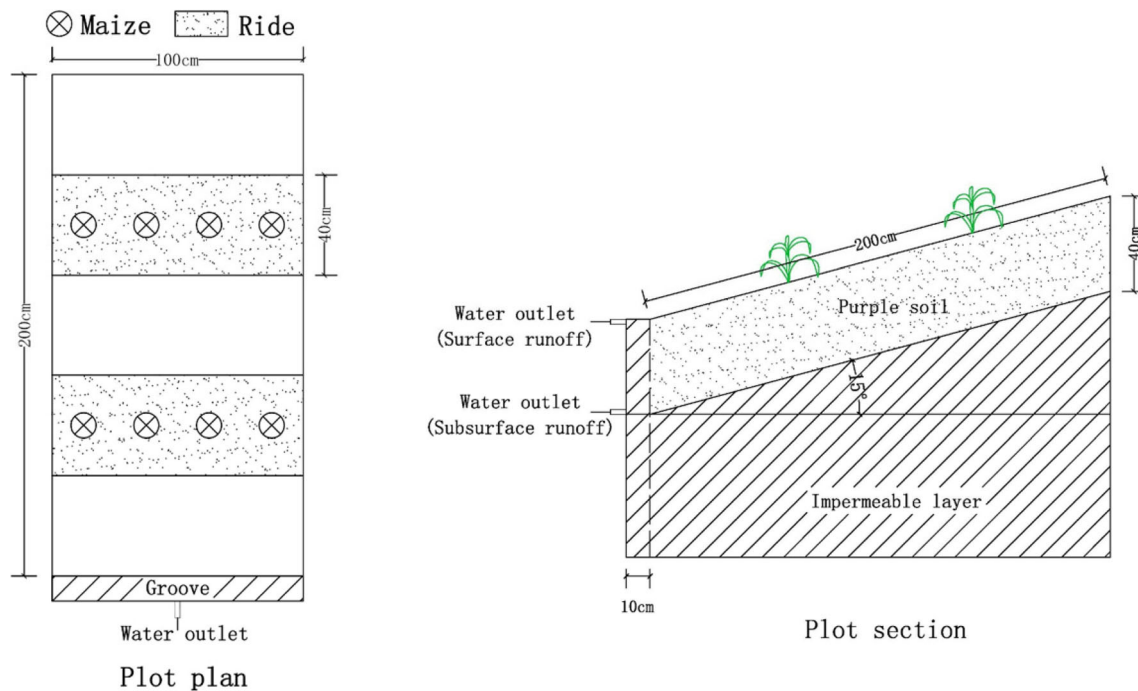
Fig. 1 The layout of experimental plots

Rainfall simulator

The rainfall simulator was programmed and equipped with two V-80100 series spray nozzles (SRs) manufactured by the institute of Soil and Water Conservation, Chinese Academy of Sciences (Liu et al. 2014a). The operating pressure ranged from 0 to 5.0 bar. The height of the rainfall simulator was 6.5 m, and the effective rainfall area was approximately 48 m². The rainfall uniformity of the simulator was approximately 85%. The simulated rainfall intensity was 1.5 mm min⁻¹ according to the hydrological data of the research area (National Meteorological Information Center) in recent years. The rainfall duration was 72 min for each simulated rainfall event.

Analytical methods

Soil particle size classification of different soil layers The soil particles of 0.2–2, 0.02–0.2, 0.002–0.02, and < 0.002 mm were separated using a nylon sieve, the sedimentation siphonic method, and the centrifugation method. The samples were freeze-dried before measurements of P were made.

Analysis of soil physical and chemical properties Soil pH was measured with distilled water in a 1:2 soil and water suspension by a glass electrode. Soil bulk density was measured with the ring cutting method. The TP and available phosphorus (AP) of soil samples were determined according to Hooda et al. (2001) and Olsen and Sommers (1982).

Analysis of P in runoff TP was determined after digestion (121 °C, 30 min) with acidic potassium persulphate. The runoff samples were filtered through 2-μm microporous membranes and digestion at 121 °C for 30 min with acidic potassium persulphate; the P was composed of CP and TDP. The first 5 mL of filtrates was discarded. An aliquot of the filtrate was ultracentrifuged at 300,000g for 2 h to remove colloids, and TDP was determined after digestion at 121 °C for 30 min with acidic potassium persulphate. The concentration of CP was calculated as the difference between the concentration of total P in the ultracentrifuged and non-ultracentrifuged samples (Ilg et al. 2005). The concentration of PP was calculated as the difference between the concentrations of total P in filtered and non-filtered samples.

Analysis of P in sediment The TP and AP of sediment samples were determined according to Hooda et al. (2001) and Olsen and Sommers (1982). Sediment CP was extracted by gently shaking 10 g of air-dried sediment samples with 80 mL deionized water at 25 °C for 24 h. The extracts were centrifuged at 3000g for 10 min to remove coarse particles. Thereafter, the extracts were filtered through 2-μm microporous membranes to separate out particles < 2 μm, which are defined as colloids (Kretzschmar et al. 1999). The extracts total phosphorus (ETP), TDP, and PP in extracts were determined with the same method as that in runoff.

Statistical analysis

Statistical analysis of the data was carried out 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. Graphs and tables were generated using Origin Pro 8.0 and Excel (2016).

Results

P level of different particle sizes in purple soil profiles

The soil particle percentage was reduced with decreasing particle size in the 20–40-cm layer; the percentage of 0.2–2-mm particles was significantly higher than that of the other particle sizes (Table 1). The percentage of the same size class particles in different soil layers was not significantly different. The concentrations of TP and AP of < 0.002-mm particles were higher than those of other particle sizes in every soil layer, and those of the 0–10-cm soil layer were higher than those of the other soil layers (Table 2).

Despite the difference in concentration, about 38% to 50% of TP and AP were adsorbed on 0.2–2-mm particles in every soil layer (Table 3). In the 0–10-cm soil layer, the contribution rate of 0.2–2-mm particles to TP and AP was the highest and that of 0.02–0.2-mm particles was the lowest. However, the particle size contribution rate to TP and AP decreased with the reduction in particle size in the 10–20-cm and 20–40-cm soil layers. Thus, the larger the soil particle size, the higher was the P loss, thereby increasing the risk of P loss via surface runoff.

Surface pathways of CP transport

Surface pathways of CP transport are divided here into key pathways of CP loss: surface runoff and sediments. The distinction between surface runoff and sediment pathways is made because the controls on P loss differ.

CP transport in surface runoff

The distribution of CP, PP, and true dissolved phosphorus (TDP) in surface runoff is shown in Fig. 2. The P loss caused by rainfall in surface runoff was dominated by CP and PP; PP accounted for 16.0–82.8% of TP. CP accounted for 17.2–83.9% of TP (Fig. 2). TDP was the least and accounted for 0.01–0.05% of TP. The TP concentration showed a bimodal pattern with an increase in the rainfall time. Peaks appeared after 27 and 54 min, with PP and CP concentrations at 0.64 mg L^{-1}, 0.92 mg L^{-1} and 0.20 mg L^{-1}, 0.35 mg L^{-1}, respectively, which were all above the threshold P for eutrophication of a water body (0.2 mg L^{-1}). During the rainfall event, the concentration of CP remained stable at the early period, but increased subsequently. The concentration of TDP was extremely low, and no obvious changes occurred; the mean concentration was only 0.09 μg L^{-1}, which was below the threshold for eutrophication.

Surface runoff volume showed a wave form, increasing with rainfall time and remaining stable after about 50 min (Fig. 3). During a rainfall event, the surface runoff rate ranged from 0.22 to 1.17 mm min^{-1}, and the total runoff depth was 51.81 mm. The mean values of PP, CP, and TDP were 1.63, 1.30, and 0.001 g ha^{-1} min^{-1}, respectively. During rainfall, the account of PP loss load showed two peaks, and the CP loss load remained stable at the early period, but varied widely at the later period. TDP loss load was the lowest and constantly changed during the simulated rainfall event. During a single rainfall event, the total loss load of PP, CP, and TDP in surface runoff was 112.72, 89.70, and 0.10 g ha^{-1}, respectively. The CP and PP loss represented a significant division of TP losses in the surface runoff.

CP transport in sediments

The characteristics of TP and AP loss can be used to evaluate the sediments delivering CP. The TP loss load showed a wave-like pattern, rising with increasing rainfall time (Fig. 4). It varied widely with two peaks at 9 and 48 min, and then showed a stable rate of loss till the end of a rainfall event. The rate of TP loss ranged from 1.67 to 36.43 g ha^{-1} min^{-1}, with an average of 18.49 g ha^{-1} min^{-1}. The rainfall event eventually caused a TP loss load of 1275.99 g ha^{-1}. The AP loss tended to increase first and then remained stable at the end of the rainfall. The rate of AP loss ranged from 0.52 to 6.82 g ha^{-1} min^{-1}, with an average of 3.24 g ha^{-1} min^{-1}. The rainfall event caused an AP loss load of 223.54 g ha^{-1}.

Table 2 Phosphorus characteristics in different particle size distributions of soil layers

Soil layer (cm)	TP (mg kg^{-1})				AP (mg kg^{-1})			
	0.2–2 mm	0.02–0.2 mm	0.002–0.02 mm	< 0.002 mm	0.2–2 mm	0.02–0.2 mm	0.002–0.02 mm	< 0.002 mm
0–10	1537.32 ± 149.9	1239.882 ± 149.9	1320.09 ± 149.9	1734.24 ± 149.9	247.64 ± 8.04	232.33 ± 9.63	253.00 ± 3.70	288.15 ± 6.20
10–20	1035.61 ± 82.4	982.37 ± 91.5	935.76 ± 149.9	1150.24 ± 149.9	174.44 ± 5.97	167.03 ± 7.25	164.19 ± 3.61	178.37 ± 5.70
20–40	1163.02 ± 149.9	761.98 ± 149.9	919.05 ± 149.9	1066.24 ± 149.9	103.08 ± 6.97	91.64 ± 2.20	120.41 ± 2.45	135.78 ± 11.57

Table 3 The contribution rate of TP and AP in different particle size distributions of soil layers

Soil layer (cm)	The contribution rate of TP (%)				The contribution rate of AP (%)			
	0.2–2 mm	0.02–0.2 mm	0.002–0.02 mm	< 0.002 mm	0.2–2 mm	0.02–0.2 mm	0.002–0.02 mm	< 0.002 mm
0–10	40.28 ± 3.9	15.18 ± 1.8	21.60 ± 2.5	22.95 ± 2.0	37.54 ± 1.2	16.45 ± 0.7	23.95 ± 0.4	22.06 ± 0.5
10–20	38.81 ± 3.1	22.88 ± 2.1	20.19 ± 3.3	18.12 ± 2.4	38.96 ± 1.3	23.18 ± 1.0	21.12 ± 0.5	16.74 ± 0.5
20–40	49.93 ± 6.4	18.02 ± 1.8	16.98 ± 0.9	15.07 ± 0.5	41.22 ± 2.8	20.18 ± 0.5	20.72 ± 0.4	17.87 ± 1.5

P losses were mainly in the form of CP loss, which accounted for 36.67% to 96.19% of the total water-dispersive P in sediment (Fig. 5). CP concentrations ranged from 2.40 to 3.51 mg kg^{-1} with an average of 2.92 mg kg^{-1}. PP loss accounted for 3.78% to 63.31% of the total water-dispersive P in sediment. PP concentrations ranged from 0.11 to 5.10 mg kg^{-1}, with an average of 0.82 mg kg^{-1}. Losses of TDP were the lowest and accounted for 0.01% to 0.05% of the total water-dispersive P in sediment. During rainfall events, PP concentrations peaked at 33 min, with 5.10 mg kg^{-1}. CP concentrations remained stable, and TDP concentrations were extremely low without any obvious changes.

The sediment yield rate first increased gradually from 0 to 24 min, and then sharply from 24 to 60 min (Fig. 6). It reached a peak at 60 min and then remained stable. Sediment yields ranged from 5.22 to 67.56 kg ha^{-1} min^{-1}, with total sediment yields of 2217.23 kg ha^{-1}. During the rainfall period, the CP loss rate trends were similar to that of the sediment yield rate: a

gradual upward trend with increasing rainfall duration and fluctuation at the end of the rainfall event. PP loss rates were stable early in rainfall events, peaked at 33 min, and then varied widely. The TDP loss rate was less and stable than PP and CP. Mean losses of PP and CP were 0.023 and 0.096 g ha^{-1} min^{-1}, respectively. TDP loss rates were extremely low with a mean value of 0.048 mg ha^{-1} min^{-1}. The total loss loads in sediment caused by rainfall were 1.61 g ha^{-1} of PP, 6.60 g ha^{-1} of CP, and 0.003 g ha^{-1} of TDP. Therefore, the water-dispersible P loss in sediment was mainly CP loss.

## Subsurface pathways of CP transport

The P concentration in subsurface runoff was dominated by CP loss, which accounted for 16.7–89.9% of TP in subsurface runoff with a mean concentration of 0.157 mg L^{-1} (Fig. 7). PP accounted for 10.0–83.3% of

Fig. 2 Size distribution of P in surface runoff, presented as **a** absolute concentrations and **b** percentage fractionation patterns
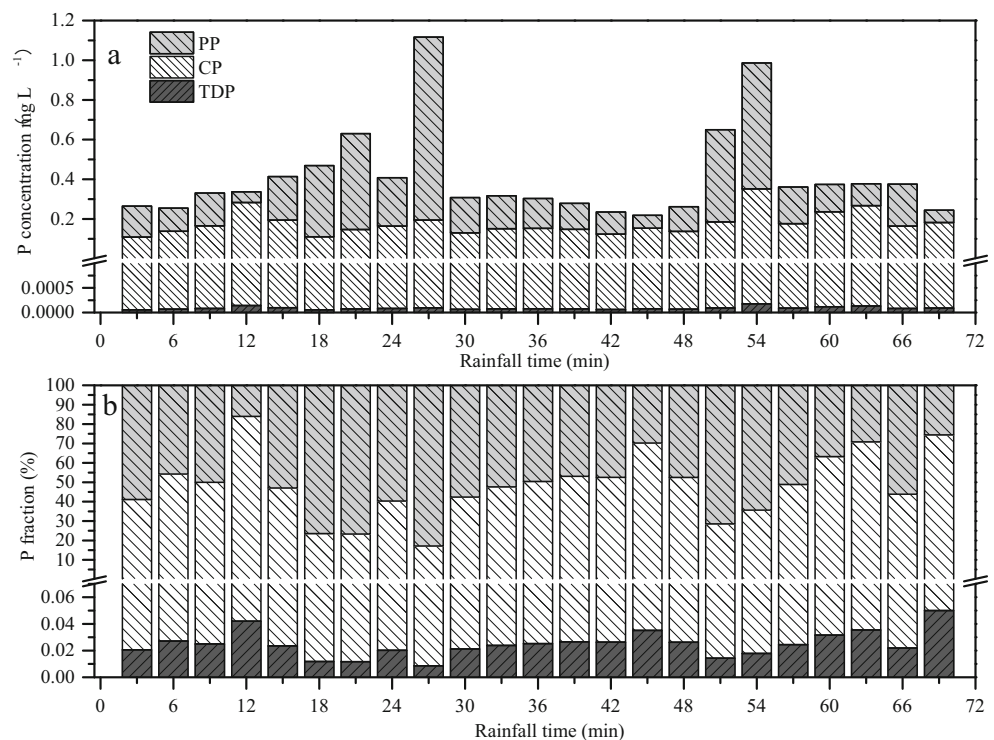
Fig. 3 Characteristic of CP loss in surface runoff
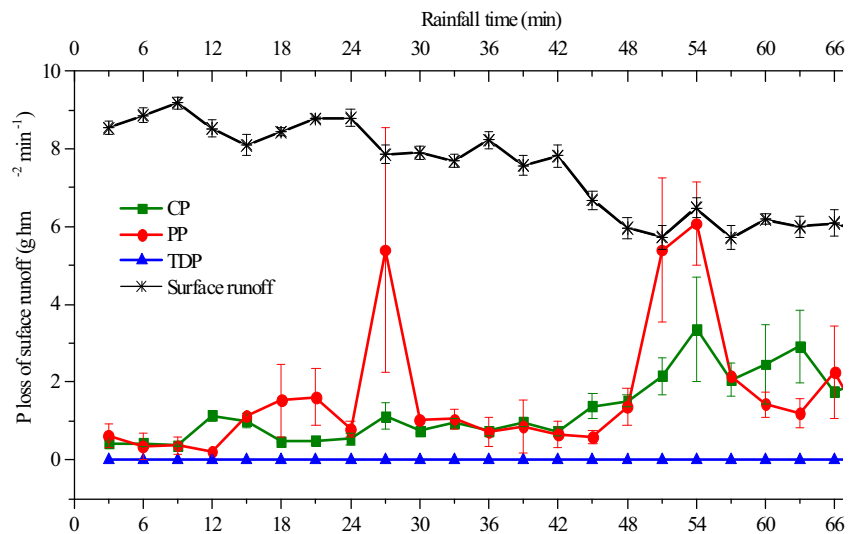
TP in the subsurface runoff with a mean concentration of 0.104 mg L^{-1}. Losses of TDP were the lowest and accounted for 0.03–0.07% of TP in the subsurface runoff with a mean concentration of 0.131 μg L^{-1}. During the rainfall events, the PP concentration peaked at 33 min with 0.753 mg L^{-1}, whereas the CP concentration was stable; the TDP concentration was extremely low without any obvious changes.

The subsurface runoff peaked at 65 min and then decreased at the end of rainfall (Fig. 8). The subsurface runoff was produced at 21–24 min and ranged from 0.33 to 0.90 mm min^{-1} during the rainfall events. The mean rates of PP, CP, and TDP losses were 0.65, 1.04, and 0.0008 g ha^{-1} min^{-1}, respectively. During the rainfall events, the PP loss rate showed one peak, and the CP loss rate had a steady increase. The TDP loss rate was the least and changed stably. The total loss loads of CP, PP, and TDP in the subsurface runoff were 49.82, 31.39, and 0.04 g ha^{-1}, respectively. Therefore, the P loss in subsurface runoff caused by rainfall was mainly CP and PP losses.

Discussion

Fertilizers have long been used in farmland soil; they are responsible for the remarkable accumulation of P in topsoil (Wang et al. 2015a, b; Zeng et al. 2008). In our study, the TP and AP concentrations were 1457.88 and 255.28 mg kg^{-1} in the 0–10-cm soil layer, respectively, which were considerably greater than those of the other soil layers (Table 1). The profile distribution of TP and AP showed obvious surface assembly, because excessive fertilizer was applied to retard the supply and requirement contradiction of population and land resources. During rainfall events, the higher the concentrations of P in the topsoil, the greater the potential loss of P in the topsoil (Moges et al. 2017; Barbosa et al. 2009). The concentrations of TP and AP of < 0.002-mm particles were higher than those of other particle sizes in all soil layers (Table 2). Because P concentrations of different particle sizes were not the same, the environmental behaviour of P varied widely in soil (Dari et al. 2017). In this study, the

Fig. 4 Characteristic of TP and AP loss in sediment
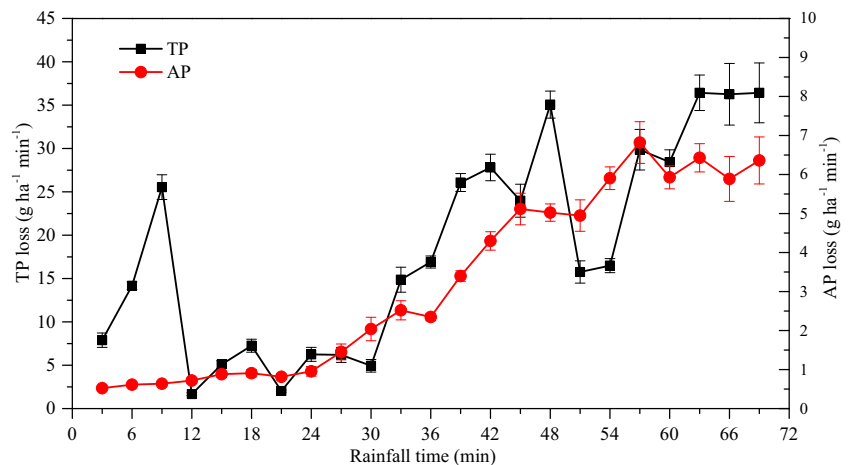
Fig. 5 Size distribution of P in sediment, presented as **a** absolute concentrations and **b** percentage fractionation patterns
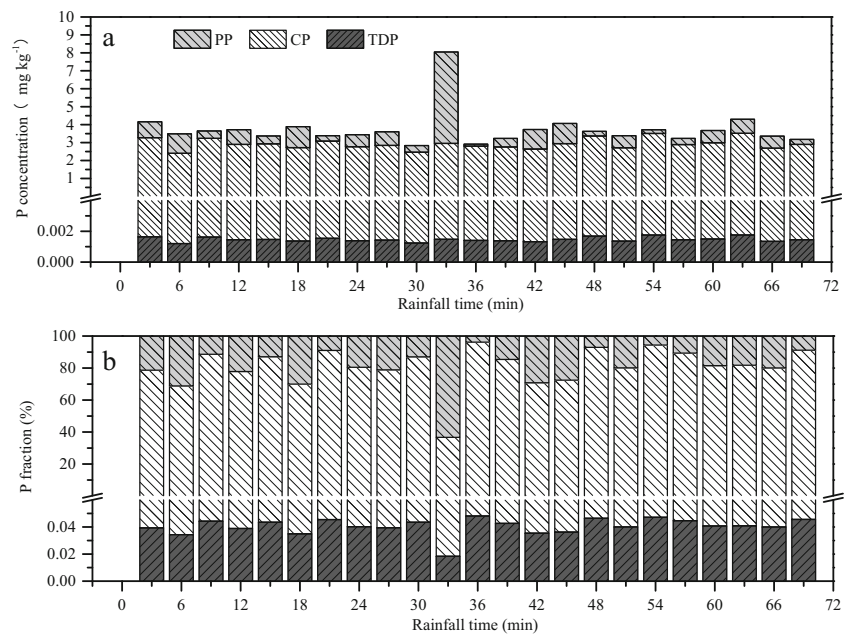

proportion of < 0.002-mm particles was the least (Table 1); however, previous studies indicated that the purple soil particles of < 0.002 mm in purple soil have colloidal properties (He and Lei 2003). Colloidal particles with a large specific surface area, strong surface charge, and superior mobility have an impact on the P concentration (River and Richardson 2018; Kotelnikova et al. 2017). This implied that greater CP loss during rainfall events was caused by the loss of < 0.002-mm soil particles.

Soil particles of > 0.002 mm accounted for 80.55% of total soil in the 0–10-cm soil layer, but PP (> 0.002 mm) was only 51.51% of TP in surface runoff, and water-dispersible PP in sediment was 19.00% of water-dispersible TP. This is probably because most P adsorbed on large-sized particles was

deposited during the runoff processes (Wang et al. 2017; Fink et al. 2016). In contrast, soil particles of < 0.002 mm accounted for 19.45% of the total soil in the 0–10-cm soil layer, and CP in the surface runoff reached 48.46% of TP. Loss of water-dispersible P in sediment was mainly CP loss, of which 80.98% was total water-dispersible P loss. The CP loss was caused by the soil colloid carrier (< 0.002 mm). That is, under the interaction of runoff and topsoil, soil particles of < 0.002 mm have a greater contribution to surface runoff and sediment P loss. Therefore, when the soil was dispersed and transported by water, the likelihood of P loss on soil colloids had increased (Yan et al. 2017; Turner et al. 2014; Baalousha et al. 2011). The annual downward migration rate of P in soil is very slow because the subsoil has a strong capacity for P

Fig. 6 Characteristics of CP loss in sediment
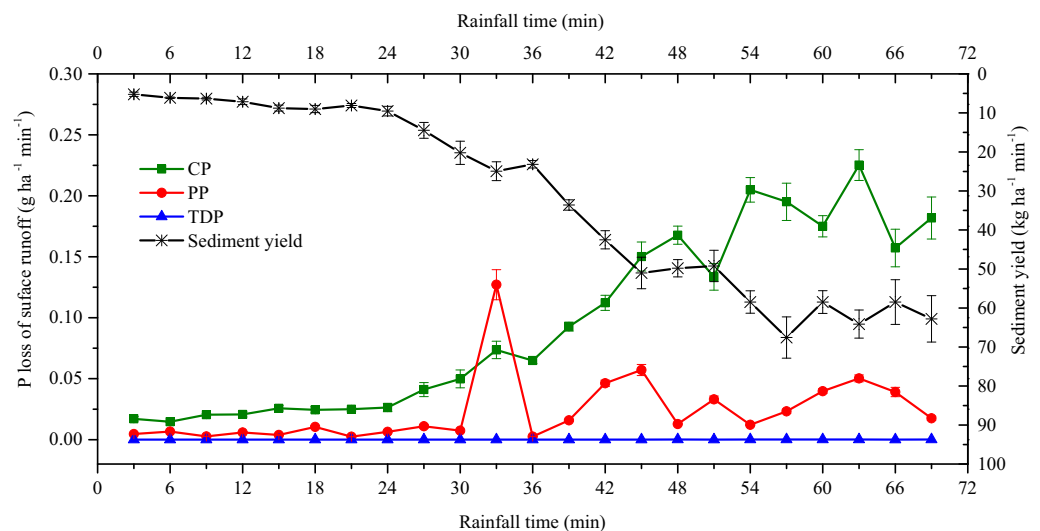
Fig. 7 Size distribution of P in subsurface runoff, presented as **a** absolute concentrations and **b** percentage fractionation patterns
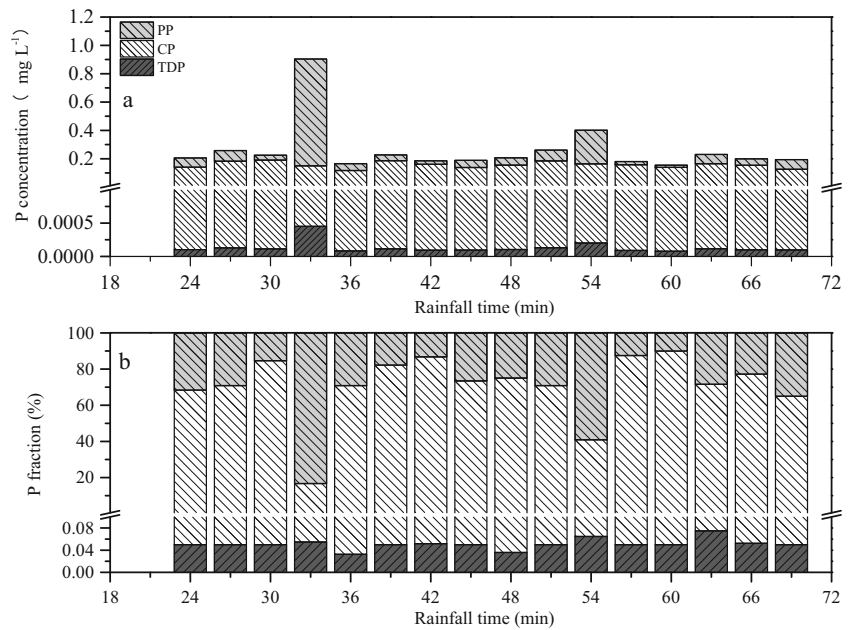

retention. However, with the constant input of P fertilizer, P was continuously bonded and accumulated in soil, and P loss occurred immediately when the soil reached the absorption limit (Ding et al. 2017; Cao et al. 2014; Barbosa et al. 2009).

The tillage method used in this study was the conventional cross ridge, which blocks surface runoff and stores it into ditches until the rainwater fills up the ditches (Barbosa et al. 2009; Liu et al. 2014a, b); the surface runoff then crosses the ridge and runs down the hillside, and surface runoff and sediment volume present a zigzag increasing trend (Figs. 3 and 6). We investigated the relationship between sediment and runoff and P loss (Table 4). Regression analysis showed that the CP loss is significantly power function related to the runoff yield and AP loss. P losses are linear related to sediment yield rate, in which AP and CP were remarkably influenced. This probably occurred because the top surface soil particles were

detached and dispersed under the kinetic energy of raindrops, and they then moved along with surface runoff during a rainfall event (Sun et al. 2016). With an increase in surface runoff volume (Fig. 3), the sediments yield were increased (Fig. 6). River and Richardson (2018) showed that the impact of dispersion, exfoliation, and migration on soil particles were reinforced, and rainwater flows turbulently, which increased the slope sediment yield and loss of P from small-sized particles carried by runoff and sediments. Therefore, the presence of CP in runoff has marked implications for understanding the P transfer process, because colloids facilitate the transport of P from the soil.

Rainfall began to generate subsurface runoff after 21 min, because the shear stress and frictional resistance acting on the flow in the internal layers are small and exfoliation on colloidal particles is weak (Wu et al. 2017; Turner et al. 2014), with

Fig. 8 Characteristic of CP loss in subsurface runoff
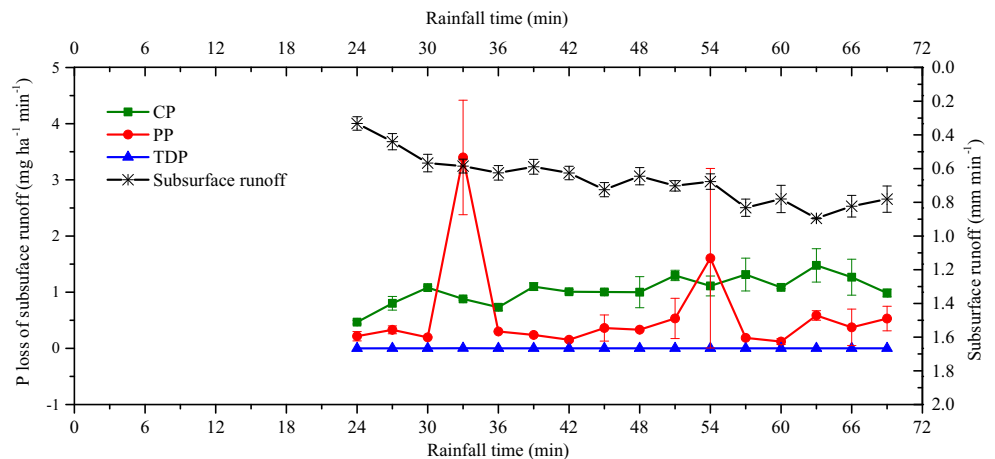
Table 4 Correlation analysis between P loss and runoff, sediment yield rate, and TP and AP in sediment

P loss y (g ha^{-1} min^{-1})	Surface runoff yield rate (mm min^{-1})	Subsurface runoff yield rate (mm min^{-1})	Sediment		
			Sediment yield rate (kg ha^{-1} min^{-1})	TP (g ha^{-1} min^{-1})	AP (g ha^{-1} min^{-1})
TP	$y = 3.065x^{0.8756}$ $R^2 = 0.7634$	$y = 1.8954x^{0.8356}$ $R^2 = 0.6997$	$y = 0.420x + 5.002$ $R^2 = 0.637$	–	–
CP	$y = 1.952x^{1.218}$ $R^2 = 0.707$	$y = 1.489x^{0.873}$ $R^2 = 0.673$	$y = 0.003x - 0.004$ $R^2 = 0.970$	$y = 0.0048x + 0.0071$ $R^2 = 0.6289$	$y = 0.0285x^{1.0148}$ $R^2 = 0.9892$
PP	$y = 1.334x^{0.574}$ $R^2 = 0.238$	$y = 0.974x^2 - 0.843x + 0.425$ $R^2 = 0.039$	$y = 0.001x + 0.001$ $R^2 = 0.502$	$y = 0.0022x^{0.6838}$ $R^2 = 0.3217$	$y = 0.0065x^{0.8646}$ $R^2 = 0.5271$
AP	–	–	$y = 0.1x - 0.002$ $R^2 = 0.9999$	–	–

the addition of lower P concentration in the subsoil (Table 2); therefore, the P level in subsurface runoff was lower than that in surface runoff, consistent with the results of Melland et al. (2008). The total runoff caused by rainfall was 85.94 mm, in which surface runoff accounted for 60.3%. The total loss load of CP in runoff was 139.52 g ha^{-1}, in which surface runoff accounted for 64.3%. The total loss load of PP in runoff was 144.12 g ha^{-1}, in which surface runoff accounted for 78.2%. The concentration and loss amount of TDP were extremely low and did not pose a risk to the environment. Therefore, the surface runoff was the main pathway of P loss for purple soil sloping farmland. However, Tan and Zhang (2011) reported a considerably higher contribution rate of subsurface runoff to the total P loss load on flat land. Because the slope gradient in our experiment was 15°, the P was detached and dispersed from the soil under the kinetic energy of raindrops, and then moved along with surface runoff. The sediment erosion from the slope was deposited into the downstream water body. The P in the sediment could be released into the water and become the potential pollution source of water eutrophication under certain conditions. Therefore, the concentration and loss of P in sediment are particularly important (River and Richardson 2018; Qian et al. 2014). The sediment yield caused by rainfall was 2217.23 kg ha^{-1}, and the TP, AP, and CP in the sediment were 1275.99, 223.54, and 6.60 g ha^{-1}, respectively. The small loss load of CP was found in the sediment, and only 0.5% of TP. However, the water-dispersible P loss in sediment was mainly CP loss. The CP was widely distributed in the sediment and soil profile because the hydrodynamic force of surface runoff has scouring and coercing effects on soil farmland, resulting in numerous colloidal particles being carried by the surface runoff. Thus, most of the CP in soil was released into the runoff under hydro-dynamism (River and Richardson 2018; Jiang et al. 2017; Zhang et al. 2017a, b). The AP load in the sediment is high. The CP is released from AP in sediment under certain conditions (temperature, illumination,

destabilization, etc.) when the sediment flows into the downstream water, and then subsides, which becomes the potential supply source of CP in water and becomes a real pollution risk (Qian et al. 2014).

The main pathway for CP loss was surface runoff. The concentration of CP in sediment was low but was the main part of water-dispersible P in sediment (Fig. 5). Because of its small size, the pedesis is stronger than the action of gravity; it exists stably in water. Furthermore, the mobility of CP is stronger than that of PP, and its migration distance is farther under the force of soil matrix space exclusion and electrostatic repulsion (Bol et al. 2016; Gottselig et al. 2014; Zang et al. 2011). Colloids act as a buffer and play an important role in the process of particle transformation through coagulation, collection, and flocculation. They effectively influence P distribution, and thus play an important role in water P distribution (Yasutaka et al. 2017).

Controlling P release into water is a focus issue in the prevention of soil erosion, and worldwide studies focus on water eutrophication. CP is a significant portion of P during the transportation from surface to subsurface water, which is mainly influenced by the P level of soil, surface runoff, subsurface runoff, and sediment. The CP loss on sloped farmland can be controlled by measures such as the utilization of soil P by crops, improvement of soil structure, and prevention of water and soil erosion.

Conclusions

The vertical distribution of P showed obvious surface accumulation. The risk of P loss in topsoil was greater than those of the other soil layers on sloping farmland of purple soil. The concentration of soil particles of < 0.002 mm in purple soil

profiles was low, but the TP and AP concentrations of soil particles of < 0.002 mm were high.

During a rainfall event, the concentration of CP was stable in runoff and sediment, but its loss load continued to increase with rainfall time. The CP loss is significantly power function related to the runoff yield rate, and is linear related to sediment yield rate.

The majority of P forms was CP in the runoff. The main pathway of CP loss load was surface runoff. Although the concentration of CP in sediment was low, it also dominated the water-dispersible P loss in the sediment. CP loss can be controlled by controlling runoff from sloping farmland, especially surface runoff.

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