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Analysis of factors controlling soil phosphorus loss with surface runoff in Huihe National Nature Reserve by principal component and path analysis methods

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Abstract Phosphorus (P) loss with surface runoff accounts for the P input to and acceleration of eutrophication of the freshwater. Many studies have focused on factors affecting P loss with surface runoff from soils, but rarely on the relationship among these factors. In the present study, rainfall simulation on P loss with surface runoff was conducted in Huihe National Nature Reserve, in Hulunbeier grassland, China, and the relationships between P loss with surface runoff, soil properties, and rainfall conditions were examined. Principal component analysis and path analysis were used to analyze the direct and indirect effects on P loss with surface runoff. The results showed that P loss with surface runoff was closely correlated with soil electrical conductivity, soil pH, soil Olsen P, soil total nitrogen (TN), soil total phosphorus (TP), and soil organic carbon (SOC). The main driving factors which influenced P loss with surface runoff were soil TN, soil pH, soil Olsen P, and soil water content. Path analysis and determination coefficient analysis indicated that the standard multiple regression equation for P loss with surface runoff and each main factor was

$Y = 7.429 − 0.439$ soil TN $− 6.834$ soil pH $+ 1.721$ soil Olsen-P $+ 0.183$ soil water content ($r = 0.487$, $p < 0.01$, $n = 180$). Soil TN, soil pH, soil Olsen P, and soil water content and the interactions between them were the main factors affecting P loss with surface runoff. The effect of physical and chemical properties of undisturbed soils on P loss with surface runoff was discussed, and the soil water content and soil Olsen P were strongly positive influences on the P loss with surface runoff.

Keywords Phosphorus loss · Surface runoff · Principal component analysis · Path analysis · Determination coefficient · Huihe National Nature Reserve

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Introduction

Soil erosion is a serious problem in the agricultural field, especially in arid and semi-arid ecosystems (Abrol et al., 2013; Abdullah et al., 2017) and is recognized as a severe threat to socio-ecological security and stability (Marzen et al., 2017). Nutrient losses caused by soil erosion not only reduced land productivity and biodiversity, but also resulted in eutrophication and agricultural nonpoint source pollution on water bodies (Kumar and Saha 2011; Yang et al., 2014). Nitrogen (N), carbon (C), and phosphorus (P) are the major nutrients causing freshwater eutrophication because the supply rates of these nutrients most often restrict or limit primary production of aquatic plants. However, most attention has focused on controlling P inputs, because of the free air–water exchange of N and C and fixation of atmospheric N by some blue-green algae (Hart et al., 2004). P is widely believed to be the main limiting nutrient in freshwater eutrophication (Søndergaard and Jeppesen 2007), and its control is of prime importance in reducing the accelerated eutrophication of fresh

waters (Bertol et al., 2007). P in water bodies mainly originates from runoff, marine organisms' excretions and diffusion across the sediment–water interface (Hessen et al., 2010; Han et al., 2015), and the P loss with runoff is influenced by soil depth through which rain and soil solution mixes during runoff generation and contact time between infiltrating rain and soil particles (Nash et al., 2002). Hence, a clearer understanding of the key mechanisms of P transport with surface runoff will contribute to efficient management of manure application and environmental risk assessment.

Agricultural runoff (surface and subsurface) and erosion from high P soils may be major contributing factors to surface water eutrophication (Kleinman et al., 2002; Shigaki et al., 2006). There are two pathways of P transfer from agricultural soil into receiving waters. The surface runoff is accepted by most researchers as being the most important, and the other is P leaching by vertical downloading, which is usually insignificant as P is widely considered so firmly fixed on the soil particle surface (Regan et al., 2010; Brennan et al., 2011).

Factors affecting P loss with surface runoff from soils have been widely studied and applied in models. For example, Torbert (Torbert 2003) indicated factors affecting nonpoint loss of nutrients from agricultural soils are numerous and complex. Many of the factors that affect nutrient losses can be greatly impacted by agricultural management practices. He also pointed out that manure rate, manure incorporation, and slope were three important factors on runoff losses of P (Torbert et al., 2005). Both soil physical properties and land use can influence the P content of surface runoff and deposited sediment (Ballantine et al., 2009). The effect of rainfall intensity and vegetation cover on soil loss, sediment-associated N and P losses, and particle size distribution (PSD) of the eroded sediment was studied (Zhang et al., 2011). Manure application increased dissolved reactive P losses but did not ignore the effect of soil P status, and reducing soil P is therefore crucial to reduce runoff P (Hahn et al., 2012a). Poor surface soil structure elevates the risk of soil erosion by water, and eroded clay-sized particles can carry adsorbed P to the surface water, thus inducing eutrophication of receiving water (Song et al., 2012). Management practices, e.g., reduced tillage, used to reduce erosion can lead to enrichment of P in the surface soil layers, which leads to increased risk for dissolved P loss in the surface runoff (Tiessen et al., 2011). The relatively high P loading rate was associated with harvest flooding of organic-rich soils and periods of winter flooding, and the discharge of harvest floodwater from mineral soils resulted in relatively low P loss (Kennedy et al., 2015). Surface runoff, which primarily occurred during winter thaws, exported disproportionately more P relative to its contribution to flow (Esbroeck et al., 2016). On some soil types, legacy P poses

a significant long-term threat to water quality, even at agronomically optimum soil P levels (Cassidy et al., 2017). P transport and loss in farmlands are affected by factors such as land cover, fertilization, soil type, rainfall, and management practices (Wang et al., 2016).

While the driving factors of P loss with surface runoff from agricultural soils and grassland soils have been extensively studied (Rer et al., 2007; Hahn et al., 2012b), the interaction among these factors on the P loss with surface runoff is not well-understood. Path analysis, a statistical technique that differentiates between correlation and causation, has been increasingly utilized to define the best criteria for selection in biological and agronomic studies. Path analysis is a standardized partial regression analysis which appears to be helpful in partitioning the correlation coefficients into direct and indirect effects. However, no published research exists to describe the interaction of driving factors of P loss with surface runoff by path analysis.

Rainfall simulation has been used extensively as a cost-effective method to evaluate the effects of management on erosion and nutrient mobilization processes and quantities under a wide range of conditions (Kleinman et al., 2002; Wang et al., 2011). The advantages of rainfall simulation are the relatively low cost, the ability to collect data quickly, and the ability to investigate many processes and treatments efficiently. The purpose of this study was to investigate the major factors controlling P loss with surface runoff and their relationship using correlation analysis, principal component analysis, and path analysis and on the basis of rainfall simulation.

Materials and methods

Study area

Surface soil samples (depth from 0 to 20 cm) were collected from grassland soils in the Huihe National Nature Reserve, Hulunbeier, China (Fig. 1). Three sampling points were set for each type of soil, and each sampling point takes 11 samples of original soil, one of which was used for the determination of soil physical and chemical properties. The climate of Hulunbeier is classified as continental monsoon climate: Winters are cold and snowy, and summers are warm and humid. The landscape of the Huihe National Nature Reserve includes forest ecosystem, grassland ecosystem, and wetland ecosystem. The soils sampled from grassland ecosystem were classified as Aeolian sandy soil (S1), chestnut soil (S2), meadow soil (S3), bog soil (S4), alkaline saline soil (S5), and chernozem soil (S6) according to the legend of the national standard of classification and codes for Chinese soil (General Administration of Quality Supervision 2009).
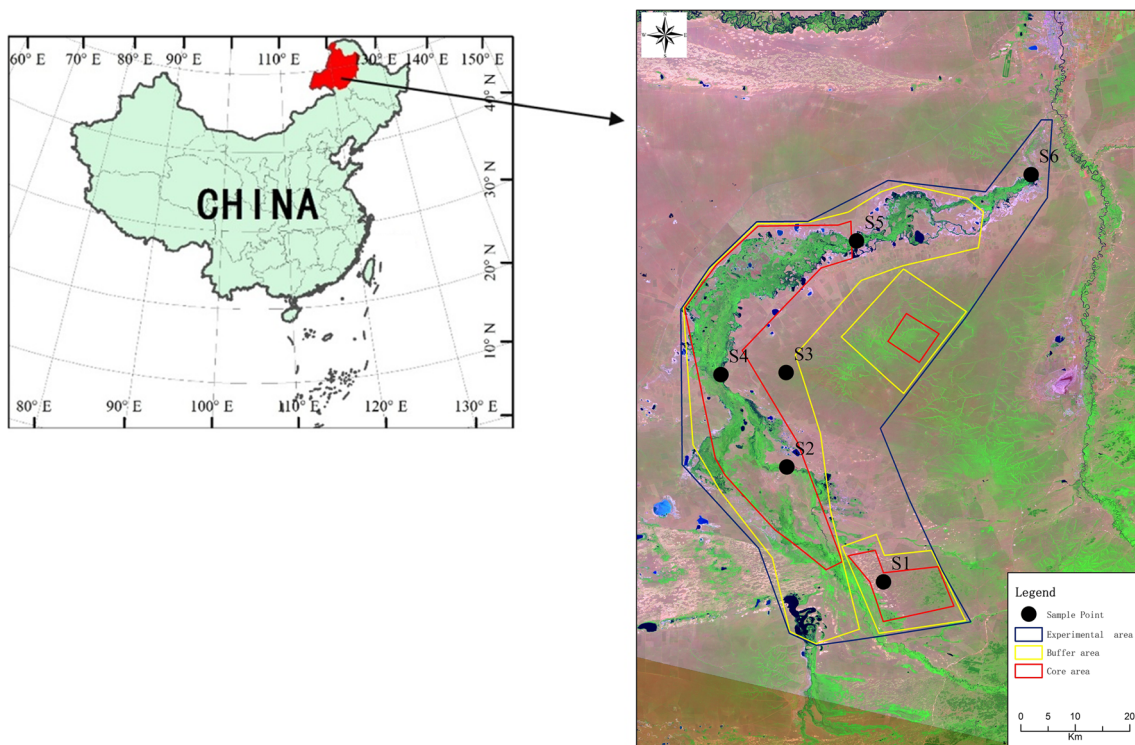
Fig. 1 Location of the Huihe National Nature Reserve and distribution of sampling points

Experimental design

PP plastic soil boxes were used in the simulated rainfall experiment (Fig. 2). The boxes were 120 cm long, 20 cm wide, and 15 cm deep with a box baffle 4 cm higher than the soil surface to prevent the water in the boxes from spilling out of the box during the rainfall simulation test. Meanwhile, a V-shaped runoff funnel was installed at the lower end of each box to collect runoff samples. Plastic sheet was used to cover the runoff funnel at the lower end to prevent direct
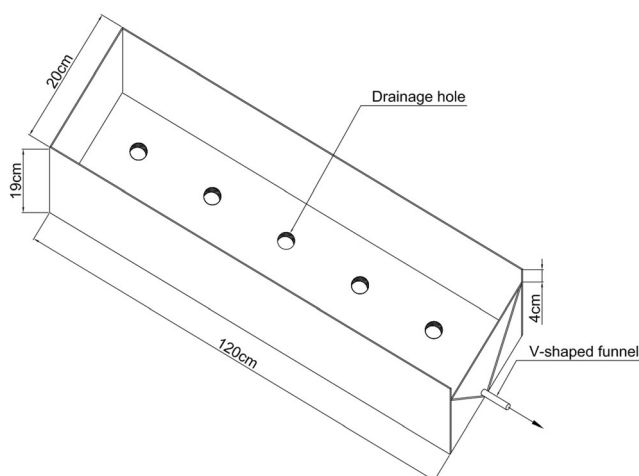

Fig. 2 Schematic representation of PP plastic box used in this experiment

rainfall from falling into the collection system. There were five 8-mm drainage holes on the bottom of each box to ensure soil water infiltrating freely.

The original soil samples were collected by the undisturbed soil-sampling device (Lv et al. 2011). The device comprises a soil drill and a plate spade, wherein the soil drill is used to realize the depth of the soil to be taken and the plate spade can help the soil sample to be completely enclosed in the bore of the drill pipe. Undisturbed soil was used in this simulation experiment. A total of 198 soils were sampled, 18 of which were used for the measurement of physical and chemical properties. In this study, ground vegetation of soil samples was excluded to ensure that each soil sample has no vegetation coverage. Each sample was used for one treatment.

The artificial rainfall was simulated by a sprinkler device with the simulated rainfall machines placed 2.5 m above the soil surfaces. The rainfall height could satisfy the demand of experiment design, and the speed of rainfall drops was close to that of natural rainfall. A total of two rainfall intensities were designed in the rainfall experiment to study their influences on P loss within the surface runoff. Under the same rainfall intensity condition, a total of three soil boxes with varied slope gradients were designed in this study (Table 1). Each experimental treatment was conducted with three replicates.

The rainfall uniformity coefficient reached over 0.85. The distilled water was used in the rainfall experiment, and the experiment began after the rainfall intensity and uniformity coefficient had been marked. The runoff samples were

Table 1 Experimental design scheme of soil P loss with surface runoff under different rainfall intensities and slope gradients

Rainfall intensities (mm/h)	Slope gradients (°)		
	0	10	15
23.36	T_1	T_2	T_3
47.61	T_4	T_5	T_6

T treatment

collected every 2 min after runoff generation started, and the collection was stopped till the runoff generation was constant (the average collection time for this study is 10 min). The runoff samples were immediately filtered (0.45 μm) and divided into water samples and soil particle samples. Rainfall intensity was strong during the experiment, and the duration was short. Therefore, the effect of evaporation during the rainfall experiment was not considered.

Laboratory and statistical analysis

The basic properties of the soil before the rainfall experiment were determined using the methods of Bao (2000) and are presented in Table 2. Soil pH was measured using Thermo Russell RL060P at room temperature, and soil electrical conductivity was measured by Thermo Russell RL060C.The soil compaction was measured by TYD-1 (Techlab Precision Instrument Co., Ltd., Shenzhen) instrument.

Water samples collected from the rainfall experiment were stored at 4 °C until tested. Total P in water samples was measured by $K_2S_2O_8$ digestion–antimony molybdenum spectrophotometry method. Eleven factors were considered for this study: rainfall time (RT), slope (S), rainfall intensity (RI), soil compaction (SH), soil water content (SW), soil electrical conductivity (SC), soil pH (pH), soil Olsen P (SO), soil total nitrogen (TN) (SN), soil organic carbon (SOC) (SS), and soil total phosphorus(TP) (SP). These physical and chemical properties are the state of undisturbed soil before the rainfall simulation experiment. There is a certain function relationship between the surface runoff and rainfall intensity (Yang 2007). P loss with surface runoff is closely related to the physical structure of soil, slope, and rainfall (Anbumozhi et al., 2005;

Yuan et al., 2016). Therefore, all these factors which affected the P loss with surface runoff (PL) were selected.

This study used the correlation analysis to analyze the relationship between the P loss with surface runoff and the other driving factors. Then, the principal component analysis method was used to choose the main driving factors on P loss with surface runoff from the factors selected above. Principal component analysis is a method of multivariate statistical analysis of important variables by linear transformation (Garg et al., 2006). Finally, path analysis was used to reveal the relationship between the P loss with surface runoff and the main driving factors and the interrelations between the main driving factors. Path analysis can be used for the statistical analysis of multiple variables and the linear relationship between variables. It was the development of regression analysis (Berger et al., 2002).

Results and discussion

P loss with surface runoff from 6 types of soil

In this experiment, the sediment collected from the surface runoff was quite small, so P loss with surface runoff refers to the total P loss with water only. P loss with surface runoff from S1, S2, S3, S4, S5, and S6 is shown in Fig. 3. The P loss with surface runoff under different rainfall intensities was different, and its trend changed with the time of runoff generation (Fig. 3a). When the rainfall intensity was 23.36 mm/h, the P loss with surface runoff was different, among which S5 is significantly higher than others while S1 and S6 which have no significant difference between each other were significantly lower than the others (Fig. 3b). However, the P loss with surface runoff of S1, S2, S3, and S6 was not significantly different when rainfall intensity is 47.61 mm/h, and all of them were significantly higher than S4 and S5 (Fig. 3c).

Correlation analysis

P loss with surface runoff was significantly and positively correlated with soil electrical conductivity, soil Olsen P, and soil TP ($r = 0.310$, 0.292, 0.206, respectively; $p < 0.01$;

Table 2 Physical and chemical properties of the six types of soil sampled in the Huihe National Nature Reserve

| No.	SH (kg/cm²)	SW (%)	SC (μS)	pH	Olsen P (mg/kg)	TN (g/kg)	TP (mg/kg)	SOC (g/kg)
S1	0.70 ± 0.02	1.04 ± 0.08	29.3 ± 8.21	7.35 ± 0.02	21.04 ± 3.12	33.58 ± 9.99	497.07 ± 211.03	5.49 ± 2.19
S2	8.16 ± 2.21	27.13 ± 5.14	156.9 ± 18.7	8.25 ± 0.04	33.19 ± 13.55	120.38 ± 41.22	522.98 ± 88.84	6.17 ± 1.19
S3	3.93 ± 0.84	30.03 ± 2.00	60.8 ± 10.77	7.24 ± 0.04	27.46 ± 13.37	288.28 ± 105.36	619.46 ± 111.31	4.00 ± 0.98
S4	4.42 ± 1.02	30.08 ± 4.01	57.1 ± 19.81	7.19 ± 0.08	24.02 ± 8.54	304.98 ± 88.24	642.86 ± 211.03	4.61 ± 1.03
S5	11.03 ± 3.33	4.82 ± 1.11	1422 ± 355.8	8.40 ± 0.03	48.08 ± 12.11	79.72 ± 10.22	785.15 ± 201.25	3.66 ± 0.77
S6	8.45 ± 2.17	25.63 ± 3.94	231 ± 88.57	8.21 ± 0.08	34.10 ± 15.33	79.62 ± 12.35	819.39 ± 299.89	1.99 ± 0.86
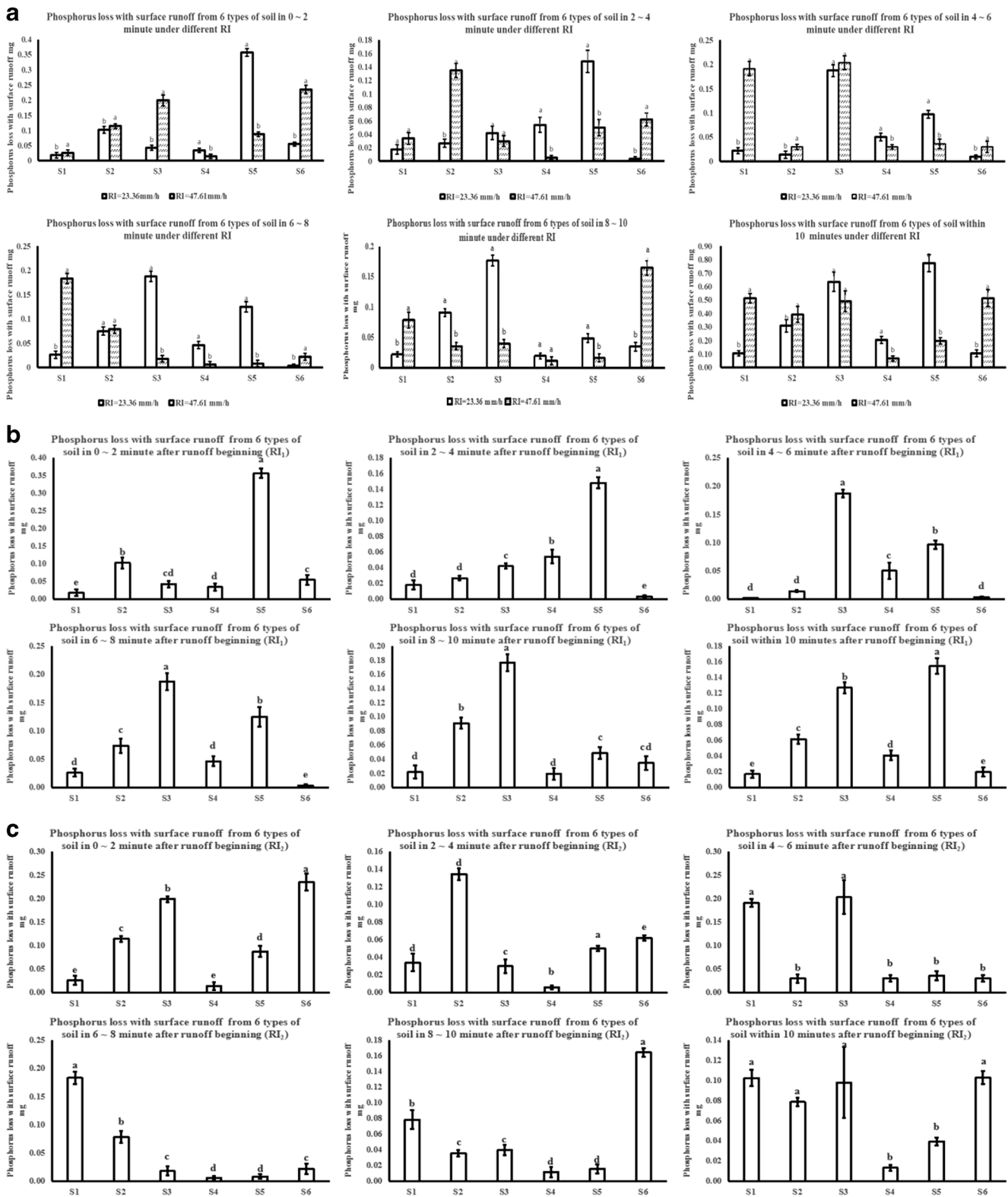
Fig. 3 P loss with surface runoff from Aeolian sandy soil (S1), chestnut soil (S2), meadow soil (S3), bog soil (S4), alkaline saline soil (S5), and chernozem soil (S6). **a** P loss with surface runoff from six types of soil under two rainfall intensities of 23.36 and 47.61 mm/h. **b** P loss with surface runoff from six types of soil under rainfall intensity of 23.36 mm/h. **c** P loss with surface runoff from six types of soil under rainfall intensity of 47.61 mm/h. Different lowercase letters mean differences at the 0.05 level.

Table 3 The correlation coefficient of P loss with surface runoff and other factors

	RT	S	RI	SH	SW	SC	pH	SO	SN	SP	SS	PL
RT	1.000	0.000	0.000	− 0.001	0.003	− 0.001	− 0.056	− 0.002	0.000	− 0.006	0.028	− 0.053
S		1.000	0.000	− 0.009	0.004	− 0.003	− 0.103	− 0.013	0.000	− 0.012	0.090	0.092
RI			1.000	− 0.007	0.009	0.048	0.323**	0.324**	− 0.039	0.417**	− 0.609**	0.013
SH				1.000	0.578**	0.773**	0.606**	0.776**	0.295**	0.583**	− 0.265**	0.143
SW					1.000	− 0.040	0.005	0.100	0.795**	0.234**	− 0.165*	− 0.140
SC						1.000	0.735**	0.921**	− 0.190*	0.631**	− 0.261**	0.310**
pH							1.000	0.841**	− 0.375**	0.574**	− 0.418**	0.160*
SO								1.000	− 0.118	0.726**	− 0.473**	0.292**
SN									1.000	0.049	0.089	− 0.223**
SP										1.000.	− 0.796**	0.206**
SS											1.000	− 0.180*
PL												1.000

***Correlation is significant at the 0.05 level (two-tailed); Correlation is significant at the 0.01 level (two-tailed)

Table 3). P loss with surface runoff was decreased when soil TN was increased. The P concentrations in runoff are often higher when soil total P is increased (Hart and Cornish 2012). Soil Olsen P content involves all water-soluble P, which dissolved in the solution and was lost with the flow of water. Soil electronic conductivity is a comprehensive reflection of the physical properties of soil and can reflect changes in salinity, moisture, porosity, and other parameters of soil (Du et al., 2014).

P loss with surface runoff was not correlated with rain time ($r = − 0.053$) and rain intensity ($r = 0.092$). Soil compaction was significantly and positively correlated with soil electrical conductivity, soil pH, soil Olsen P, soil TN, and soil TP ($r = 0.773, 0.606, 0.776, 0.295$, and 0.583 respectively, $p < 0.01$). Soil compaction was not correlated with P loss with surface runoff ($r = 0.143$). Both P loss with surface runoff and soil Olsen P were not correlated with soil water content ($r = 0.100$ and $− 0.140$, respectively; $p > 0.05$). Soil water content was significantly and positively correlated with soil TN and soil TP ($r = 0.795$ and 0.234, respectively; $p < 0.01$). This may be because soil compaction and soil water content affect P loss with surface runoff through the chemical composition of soil.

Principal component analysis

To convert observations of possibly correlated variables into values of linearly uncorrelated variables, principal component analysis method was used to determine the major driving factors of P loss with surface runoff (Tables 4 and 5).

The combined score of the former five principal components is larger than 1 (Table 4). The cumulative variance contribution rate of the former five principal components was 81.468% (Table 4). Therefore, to determine the major factors influencing P loss with surface runoff, only the former five

components were further examined. The first principal component was analyzed as the main object and the other four components as supplements to determine the factors influencing P loss with surface runoff in the present study.

The component score coefficient matrix was used to determine the main factors in each principal component (Table 5). Soil electrical conductivity, soil compaction, soil Olsen P, and soil pH largely accounted for the first principal component, with characteristic vectors of 0.316, 0.267, 0.252, and 0.226, respectively. This implies that soil electrical conductivity, soil compaction, soil Olsen P, and soil pH were the main factors to drive P loss with surface runoff.

Soil TN (with a characteristic vector of 0.454) contributed less to P loss with surface runoff than soil water content (with a characteristic vector of 0.450) in the second component. The rain intensity is the highest in the third component (with a characteristic vector of 0.506). The soil compaction and soil pH did in the first component, and they were high in the second component (with characteristic vectors of 0.260 and − 0.125). Therefore, the soil compaction and soil pH might have played a vital function in the P loss with surface runoff. The soil compaction represented the physical properties of soil while the soil pH reflected the soil chemical properties. Slope is an important contributing factor that impacts P loss with surface runoff (Chen et al., 2013), and it is the highest in the fourth component, but it contributed little in the former three components. Rain time contributes highly in the fifth component, but it contributed little in the former four components.

Overall, principal component analysis showed that soil compaction, soil water content, soil electrical conductivity, soil pH, soil Olsen P, and soil TN were more important factors affecting P loss with surface runoff and should be considered when designing a model for more robust simulation of P loss with surface runoff.

Table 4 Total variance of factors which affected P loss with surface runoff was explained by principal component analysis

Component	Initial eigenvalues			Extraction sums of squared loadings		
	Total	Variance (%)	Cumulative (%)	Total	Variance (%)	Cumulative (%)
1	4.375	39.770	39.770	3.742	34.016	34.016
2	2.085	18.954	58.725	2.104	19.124	53.140
3	1.491	13.556	72.281	2.099	19.077	72.217
4	1.011	9.187	81.468	1.014	9.221	81.439
5	1.000	9.092	90.560			
6	0.496	4.507	95.067			
7	0.346	3.143	98.210			
8	0.114	1.035	99.245			
9	0.060	0.544	99.789			
10	0.020	0.181	99.970			
11	0.003	0.030	100.000			

Path analysis

According to correlation analysis and principal component analysis, soil compaction, soil water content, soil electrical conductivity, soil pH, soil Olsen P, and soil TN were the main controlling factors of P loss with surface runoff. Path analysis was used to analyze the relationship among these six factors and establish a model to determine the relative importance of direct and indirect effects on P loss with surface runoff. The results of stepwise multiple-regression analysis are shown in Table 5. The standard multiple regression equation for P loss with surface runoff and each main factor was $Y = 7.429 - 0.439$ soil TN $- 6.834$ soil pH $+ 1.721$ soil Olsen-P $+ 0.183$ soil water content ($r = 0.487$, $p < 0.01$, $n = 180$). The direct-path coefficient of each factor was

Table 5 Component score coefficient matrix of factors which affected P loss with surface runoff

	Component				
	1	2	3	4	5
RT	0.004	− 0.007	0.008	− 0.006	0.997
S	0.010	− 0.010	0.021	0.986	− 0.006
RI	− 0.151	− 0.029	0.506	0.060	0.017
SH	0.267	0.206	− 0.160	0.005	0.007
SW	− 0.003	0.450	0.024	− 0.014	− 0.008
SC	0.316	− 0.076	− 0.167	0.037	0.020
pH	0.226	− 0.125	0.006	− 0.080	− 0.049
SO	0.252	− 0.032	− 0.002	0.033	0.018
SN	− 0.069	0.454	0.003	− 0.004	− 0.005
SP	0.089	0.064	0.249	0.037	0.016
SS	0.068	− 0.019	− 0.452	0.049	0.011

Extraction method: principal component analysis

obtained from standardized coefficient β(Table 6). The indirect correlation coefficient between each factor was obtained by multiplying the direct-path coefficient and the correlation coefficient between each factor (Table 7).

Soil TN, soil pH, soil Olsen P, and soil water content showed a direct effect (the corresponding direct-path coefficients are $- 0.7190$, $- 0.8770$, 0.9100, and 0.3450, respectively) and an indirect effect (the total indirect-path coefficients are 0.4958, 1.0120, $- 0.6183$, and $- 0.4850$, respectively) on P loss with surface runoff (Table 7). This indicates that soil TN, soil pH, soil Olsen P, and soil water content could directly and indirectly affect the microbial activity and decomposition of P fractions in soil and control P loss with surface runoff.

The determination coefficients influencing P loss with surface runoff factors were in the order of $D_y X_3 X_4$ ($- 1.3426$) $> D_y X_2 X_3$ ($- 0.9899$) $> D_y X_4 X_4$ (0.8281) $> D_y X_3 X_3$ (0.7691) $> D_y X_2 X_2$ (0.5170) $> D_y X_2 X_5$ ($- 0.3944$) (Table 8). This confirms that soil TN, soil pH, soil Olsen P, and soil water content and the interactions between them were the main factors driving P loss with surface runoff.

Discussion

Adelaide et al. (Gaynor and Findlay 1995) pointed out the loss of soil P is mainly due to surface runoff by determining the P loss in Australian pastures and P loss with surface runoff exceeds twice the loss of the interlayer. This is mainly because1 P is susceptible to being fixed and adsorbed. The frequency of P leaching and infiltration was much lower than the P loss with surface runoff. Hence, this experiment only measured P loss with surface runoff.

Soil TN, soil pH, soil Olsen P, and soil water content showed a direct effect and an indirect effect on P loss with surface runoff. In the study of the various factors, the effect of soil pH and soil Olsen P on P loss with surface runoff was the

Table 6 The standard multiple-regression coefficient of factors which drive P loss with surface runoff

Model		Unstandardized coefficients		Standardized coefficients		
		β	Std. error	β	t	Sig.
1	Constant	0.490	0.046		10.651	0.000
	Soil compaction	0.106	0.024	0.310	4.356	0.000
2	Constant	0.699	0.099		7.059	0.000
	Soil compaction	0.095	0.024	0.278	3.881	0.000
	Soil TN	− 0.104	0.044	− 0.170	− 2.379	0.018
3	Constant	3.364	1.088		3.091	0.002
	Soil compaction	0.158	0.035	0.463	4.485	0.000
	Soil TN	− 0.144	0.046	− 0.236	− 3.127	0.002
	Soil pH	− 2.097	0.853	− 0.269	− 2.459	0.015
4	Constant	5.323	1.187		4.485	0.000
	Soil compaction	− 0.036	0.064	− 0.105	− 0.559	0.577
	Soil TN	− 0.237	0.052	− 0.388	− 4.592	0.000
	Soil pH	− 5.234	1.204	− 0.672	− 4.349	0.000
	Soil Olsen P	1.716	0.479	0.908	3.582	0.000
5	Constant	5.280	1.182		4.467	0.000
	Soil TN	− 0.226	0.048	− 0.371	− 4.717	0.000
	Soil pH	− 5.000	1.126	− 0.642	− 4.441	0.000
	Soil Olsen P	1.489	0.255	0.788	5.841	0.000
6	Constant	7.429	1.445		5.140	0.000
	Soil TN	− 0.439	0.097	− 0.719	− 4.528	0.000
	Soil pH	− 6.834	1.328	− 0.877	− 5.146	0.000
	Soil Olsen P	1.721	0.268	0.910	6.431	0.000
	Soil water content	0.183	0.073	0.345	2.511	0.013

most significant (Tables 7 and 8). Soil Olsen P has the largest direct-path coefficient for P loss with surface runoff, followed by soil pH. Soil pH has the largest sum of the indirect-path coefficients by other factors and is followed by Olsen P. It can be seen that soil pH and soil Olsen P have direct and indirect effects on soil P loss, and they are significantly related to soil P loss. This suggests that soil pH and soil Olsen P were the two most important factors affecting P loss with surface runoff.

Soil SN has a large direct-path coefficient and a small indirect-path coefficient which implies that it mainly affects P loss with surface runoff through a direct path. Contrarily, soil water content has a small direct-path coefficient and a large indirect-path coefficient which implies that it mainly affects P loss with surface runoff through an indirect path.

In the grassland ecosystem, the soil is a huge reservoir for nitrogen. The large-scale use of fossil fuels and nitrogen has accelerated the fixation and emissions of global active nitrogen (Zhang et al., 2009); the increase of atmospheric nitrogen deposition has become one of the important phenomena of global change (Zhou et al., 2012). A large amount of nitrogen input (natural nitrogen deposition and anthropogenic nitrogen application) not only affects the availability of nitrogen in terrestrial ecosystem, but also changes the nitrogen-related soil biochemical processes (Zhang et al., 2007). The changes of soil nutrients lead to the changes in microbial community activity, metabolic patterns, and functional diversity. The different community structures and functions of micro-organisms will affect the process of various nutrients cycling

Table 7 Path coefficient of each factor on P loss with surface runoff

Soil factor	Direct-path coefficient	Indirect-path coefficient				
		SN	pH	SO	SW	Total
SN	− 0.7190	–	0.3289	− 0.1074	0.2743	0.4958
pH	− 0.8770	0.2696	–	0.7407	0.0017	1.0120
SO	0.9100	0.2419	− 0.7376	–	0.0345	− 0.6183
SW	0.3450	− 0.5716	− 0.0044	0.0910	–	− 0.4850

Table 8 The determination coefficient of each factor which affected P loss with surface runoff

	X_2 (SN)	X_3 (pH)	X_4 (SO)	X_5 (SW)
X_2 (SN)	0.5170	− 0.9899	0.1544	− 0.3944
X_3 (pH)		0.7691	− 1.3423	− 0.0030
X_4 (SO)			0.8281	0.0628
X_5 (SW)				0.1190

in soil, which affects the quantity and morphology of soil nutrients (Wang et al., 2014). This may be the main reason for the effect of soil TN on P loss with surface runoff in this experiment.

Soil pH is an important attribute of soil, and it was produced by the combined effect of the biological, climate, geological, hydrological, and other factors in its formation process. The process of soil P transition from nonbioavailable (or difficult to use) to bioavailable (or readily available) is susceptible to influence by the external environment, particularly by the pH of soil (Hua et al., 2000). When the soil pH changes abruptly for various reasons, the bioavailability of soil P will also change. Adsorption, desorption, precipitation, and dissolution reactions of soil P were strongly influenced by soil pH (Han 2016). Soil pH might affect the P loss with surface runoff by changing the forms of P in soil. Soil water content is an important factor affecting slope erosion and hydrological processes (Fitzjohn et al., 1998; Castillo et al., 2003; Meyles et al., 2003; Seeger et al., 2004). Different soil water contents will lead to the formation of different splash erosion and water erosion rates (Truman and Bradford 1990) and are important factors affecting the initial runoff time (Mcdowell and Sharpley 2002). There was a positive direct-path coefficient between soil water content and P loss with surface runoff (Table 7). The P concentrations in runoff are often higher when soil total P is increased (Hart & Cornish 2012). The soil Olsen P strongly affected the P loss with surface runoff (Tables 7 and 8).

Many natural land anthropogenic factors are admitted to influence nutrient losses. The most important are climate, hydrology, soil, topography, land use, fertilization, and cultivation (Vinten et al., 1993; Ekholm et al., 2000). In this study, the effect of physical and chemical properties of undisturbed soils on P loss with surface runoff was discussed and the soil water content and soil Olsen P were strongly positive influences on the P loss with surface runoff.

Conclusions

This study used the correlation analysis, principal component analysis, and path analysis to analyze which were the main driving factors that affect P loss with surface runoff and the interrelation between them. The results showed that P loss with surface runoff was closely correlated with soil electrical conductivity, soil pH, soil Olsen P, soil TN, soil TP, and SOC. The main driving factors which influenced P loss with surface runoff were soil TN, soil pH, soil Olsen P, and soil water content. Path analysis and determination coefficient analysis indicated that the the standard multiple regression equation for P loss with surface runoff and each main factor was $Y = 7.429 − 0.439$ soil TN $− 6.834$ soil pH $+ 1.721$ soil Olsen-P $+ 0.183$ soil water content ($r = 0.487$, $p < 0.01$, $n = 180$). Soil TN, soil pH, soil Olsen P, and soil water content and the interaction between them were the main factors affecting P loss with surface runoff.

In this study, the effect of physical and chemical properties of undisturbed soils on P loss with surface runoff was discussed and the soil water content and soil Olsen P were strongly positive influences on the P loss with surface runoff. Furthermore, the analysis of other factors affecting P loss with surface should be carried out in the study area.

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