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Functional traits explain seasonal variation effects of plant communities on soil erosion in semiarid grasslands in the Loess Plateau of China

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A R T I C L E I N F O

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A B S T R A C T

Improved understanding of the impact of vegetation on soil erosion is critical for identifying effective strategies to use in soil and water conservation. Recently, although the concept of functional identity and diversity has been applied extensively in ecology, few studies have attempted to explore the effects of functional identity and diversity on soil erosion. In this study, the plant functional traits in different periods of a season were measured, and soil erosion was monitored in runoff plots of different types of plant community in the field under actual rain events. The measured plant functional traits were extrapolated to functional identity and diversity on the plant community scale. The impacts of functional identity and diversity on soil erosion in different periods of a season and with different rainfall intensity conditions were analyzed. The results showed that in the early and middle season, functional richness and functional evenness of the plant community play an important role in reducing soil erosion during low rainfall intensity. Plant tensile strength has a great effect on soil erosion at intermediate and high rainfall intensity in the early season. However, at the intermediate and high rainfall intensity in the middle season, plant aboveground parts has the greatest effect on soil erosion. At the end of the growing season, functional divergence is the largest determinant of soil erosion form low to high rainfall intensity. This work can provide insight into the mechanism of soil erosion and provide a valuable reference for plants used in soil and water conservation.

1. Introduction

Water and soil conservation is related to ecological security and human wellbeing. Vegetation restoration is an important component of water and soil conservation efforts. As it is easier to research the effects of plant functional traits on soil erosion at the individual plant scale than at other scales, lots of research on the effects of vegetation on soil erosion have been carried out at the individual scale. Of these, most studies have focused on the functional traits of plant root systems (Erktan et al., 2015; Erktan et al., 2018; Ilunga wa Ilunga et al., 2015; Kervroëdan et al., 2018; Wang et al., 2015; Zhang et al., 2012). For example, at Leuven University Campus of Belgium, De Baets et al. (2007) analyzed the effects of different root traits on soil erosion, and found that roots can significantly reduce concentrated flow erosion. At Shaanxi Province of China, Zhou and Shangguan (2007) carried out a research on the effects of ryegrass roots on soil erosion under simulated rainfall in a crop field, and found that there is a negative linear relationship between the soil erosion ratio and the root surface area. Compared with plant roots, some research has been carried out that focuses on the effects of plant leaf traits on soil erosion. For example, Xu et al. (2008) studied the effects of leaf areas on soil erosion, and found that relatively small leaf area but low height and dense canopy can have an positive effect on controlling soil erosion. Zhang et al. (2012) studied the differences between leaves and roots in effecting soil erosion, and the results revealed that plant roots can have stronger effect on sediment reduction than leaves. From the results of these studies, it can be found that because plant roots and leaves can intercept runoff, fix soil, and limit splash effects, much research on the effects of plant traits on soil erosion have been carried out at the individual scale. But few related studies have been implemented on the slope scale. However, due

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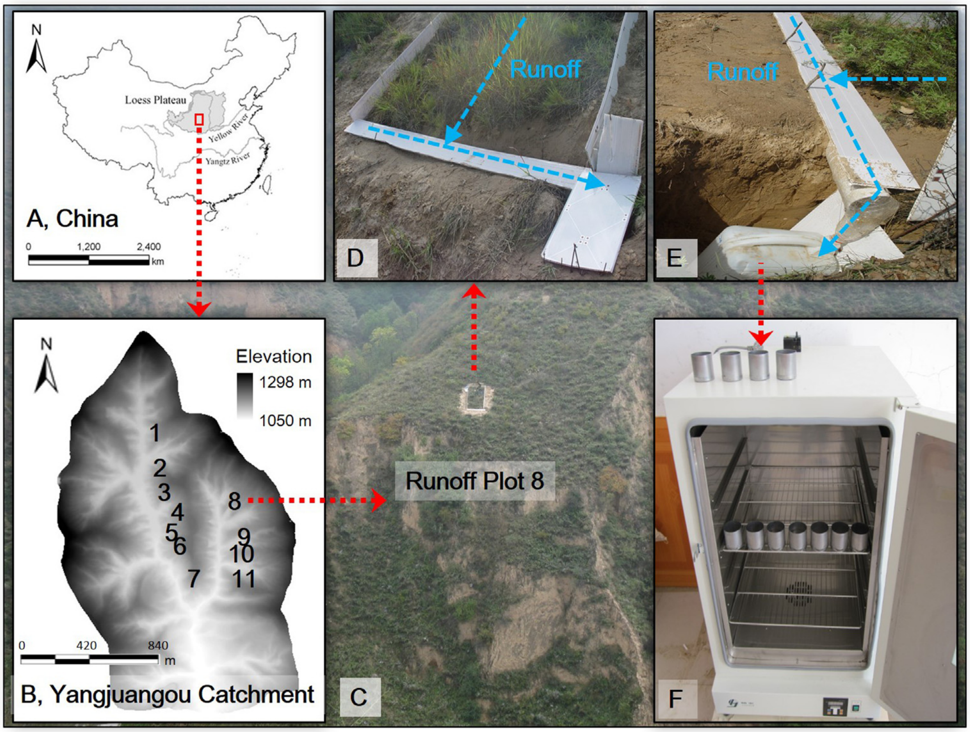

Fig. 1. Research site and experimental approach of this study. A, Location of Yangjuangou Catchment in China. B, Locations of runoff plot 1–11 in Yangjuangou Catchment. C, A photo for runoff plot 8. D, Graphic expression for erosion monitoring. The process of runoff mixed with the sediment in runoff plot can be showed by the blue dotted line. E, Runoff discharged from each plot was tubed at the plot bottom and collected into a plastic bucket. F, The sediment was separated from the water, dried in an oven for 8 h, and weighed to obtain the erosion amount.

to soil erosion process often generates on the slope scale, it is better to carry out the related research on slope scale than individual plant scale. So, more work about the role of plant functional traits on soil erosion on the slope scale is needed, in order to conserve water and soil.

Because the vegetation community can make a larger contribution to slope soil conservation than individual plants, it is essential to study the effect of vegetation on soil erosion at the scale of the vegetation community. In the works carried out at the community scale, some vegetation parameters such as plant coverage, plant diversity, and species composition have been studied (El Kateb et al., 2013; Liu et al., 2012; Phan Ha et al., 2012). These studies tried to determine the mechanism of the effects of vegetation on soil erosion by studying the relationships among different parameters (plant coverage, diversity, species composition, *etc.*) or the relationships of these parameters and soil erosion on community scale (Hou and Fu, 2014). Though the results of these studies have revealed some relationships between vegetation parameters and soil erosion, such as a negative correlation between plant coverage and erosion, the mechanism of effects of vegetation on soil erosion was not fully revealed. Currently, trait-based approaches are increasingly used to understand the relationship between vegetation and ecological processes (Faucon et al., 2017). These approaches may have greater explanatory power than species-based approaches (Cadotte et al., 2011). However, the mechanisms of the relationships between plant functional traits and ecological processes are not very clear (Cadotte, 2017).

At the community scale, plant functional traits can be expressed in many ways. For example, the mean value of plant functional traits as expressed by the community-weighted mean (CWM), and the distribution of a plant functional trait in a plant community as expressed by functional diversity, such as functional richness indices (FRic), functional divergence indices (FDiv) or functional evenness indices (FEve) (Mouchet et al., 2010). In recent studies, the CWM has often been used to scale plant functional trait data from the individual plant scale to the community scale based on the biomass ratio hypothesis (Bu et al., 2019; Sena et al., 2018). At the community scale, plant functional traits can be defined as functional identity and diversity. Currently, functional identity and diversity have been used in many fields, such as soil nutrient cycling (Markowicz et al., 2015; Schnoor et al., 2015), plant adaptation strategy (Jiang et al., 2015; Kraft et al., 2015), and climate change (Moor et al., 2015). Even fewer studies have attempted to explore the effects of functional identity and diversity on soil erosion (Zhu et al., 2015). Therefore, it is rare to use functional identity and diversity to reveal the mechanisms of the effects of vegetation on soil erosion. For example, a study of the Loess Plateau, China, Zhu et al. (2015) found that a soil erosion model constructed using functional identity and diversity showed better explanatory power than the model constructed by traditional plant parameters such as plant coverage and plant diversity. Studies of the effects of functional identity and diversity on soil erosion are needed to better determine the mechanisms of soil erosion and to optimize soil and water conservation efforts.

In addition, seasonal variations are a very important factor affecting relationship between functional identity or functional diversity and soil erosion. Plant traits with significant effects on soil erosion, such as plant height and leaf area, can grow and develop during the growing season (Kervroëdan et al., 2018). At the plant community scale, plant diversity shows obvious variations during a growing season due to the variations in community composition resulting from the growth and development of the annual plants in the community. According to Liu et al. (2010) in the Loess Plateau, China, erosive rainfall is mainly distributed from May to September (approximately 85.67% of the year) in our study area. Therefore, in different periods of a season or even in different months, the effects of the functional identity and diversity on soil erosion should be different. Thus, although seasonal variation is a significant determinant of the effects of vegetation on soil erosion, this factor has been considered in few studies. The goal of this work was to study the impacts of functional identity and diversity on soil erosion to determine if the effects of vegetation on soil erosion differ for different periods of a season and for different rainfall intensities. The results of this work should provide insight into the mechanisms of soil erosion and provide a valuable reference for vegetation restoration.

Table 1
The environmental parameters of runoff plots.

Plot	Topography				Vegetation		
	Elevation (m)	Slope gradient (°)	Slope aspect	Slope position	Abandoned time (yrs.)	Species richness	Vegetation community[a]
1	1208	25	West- South	Downslope	35	13	*Artemisia dalailamae* + *Artemisia sacrorum*
2	1210	24	West-South	Downslope	35	12	*Artemisia sacrorum* + *Lespedeza bicolor*
3	1199	23	West-South	Downslope	30	12	*Artemisia dalailamae* + *Lespedeza bicolor*
4	1200	23	West-South	Downslope	30	11	*Artemisia sacrorum* + *Artemisia dalailamae*
5	1199	24	West- South	Downslope	30	12	*Artemisia dalailamae* + *Glycyrrhiza uralensis*
6	1207	24	West-South	Mid-slope	30	14	*Lespedeza bicolor* + *Artemisia sacrorum*
7	1206	24	West-South	Mid-slope	35	8	*Lespedeza bicolor* + *Salsola collina*
8	1207	24	West-South	Downslope	35	12	*Artemisia sacrorum* + *Cirsium setosum*
9	1201	23	West-South	Downslope	35	11	*Artemisia sacrorum* + *Carex korshinskyi*
10	1199	25	West-South	Downslope	35	10	*Artemisia sacrorum* + *Setaria viridis*
11	1195	24	West-South	Downslope	30	14	*Salsola collina* + *Artemisia sacrorum*

[a] The nomenclature of vegetation community is dominant-species nomenclature, followed by *Chinese Flora*. The vegetation community can be defined by two plants which own the biggest importance value in the vegetation community.

2. Materials and methods

2.1. Study area

This research was performed in the Yangjuangou catchment (36°42′N, 109°31′E) in the Loess Plateau, Shaanxi Province, China (Fig. 1). This catchment has a semiarid continental climate, a mean annual precipitation of 535 mm, a mean air temperature of 10.6 °C (from 1988 to 2017), and an elevation that ranges from 1050 to 1298 m (Liu et al., 2012). The erosive rainfall in this catchment is concentrated between May and September. The composition of the soil is generally more than 50% silt (0.002–0.05 mm) and less than 20% clay (< 0.002 mm), and its porosity is nearly 50% (Liu et al., 2012). Soil properties among individual areas of the research region vary little (Hou and Fu, 2014; Zhu et al., 2015). The main form of vegetation is restored grassland, dominated by several *Artemisia* species, in the study plots (Table 1).

2.2. Measurements of soil and water loss

Runoff plots are widely used to investigate soil and water loss, and this field method has many advantages to measure soil erosion (Boix-Fayos et al., 2006). Thus, this method was selected in this research. The measurement process is as follows: First, eleven closed runoff plots were established and distributed on different abandoned farmland (abandoned time: 30–35 years) locations with different plant communities (Fig. 1AB; Table 1). The plots were parallel to the slope, and the gradient of each slope was nearly 24° (Fig. 1C; Table 1). The width of each runoff plot was 2 m and the length was 5 m. Each plot was surrounded by polyvinyl chloride (PVC) boards, which were embedded in the soil at a depth of 50 cm to impede the lateral movement of sediment and water (Fig. 1D). The runoff mixed with the sediment discharged from each plot was tubed and gauged into a plastic bucket after each erosive rainfall (Fig. 1E). Second, the sediment was separated from the water, dried in an oven for 8 h, and weighed to obtain the erosion amount for each runoff plot (the mass of the displaced soil) (Fig. 1F). This procedure was performed after each erosive rainfall from May 2014 to September 2016, and the amount and duration of rainfall were also measured by a tipping bucket rain collector (Davis Instruments, Diablo, Hayward, CA, USA) for each erosive rainfall event. During the study period, there were several runoff events that exceeded the storage capacity of the plastic buckets or resulted in other significant losses from the buckets in some runoff plots. To avoid errors from these inaccurate monitoring results, nine erosive rainfall events with different rainfall intensities in different growing seasons were selected for further analysis (Fig. 2; Table 2).

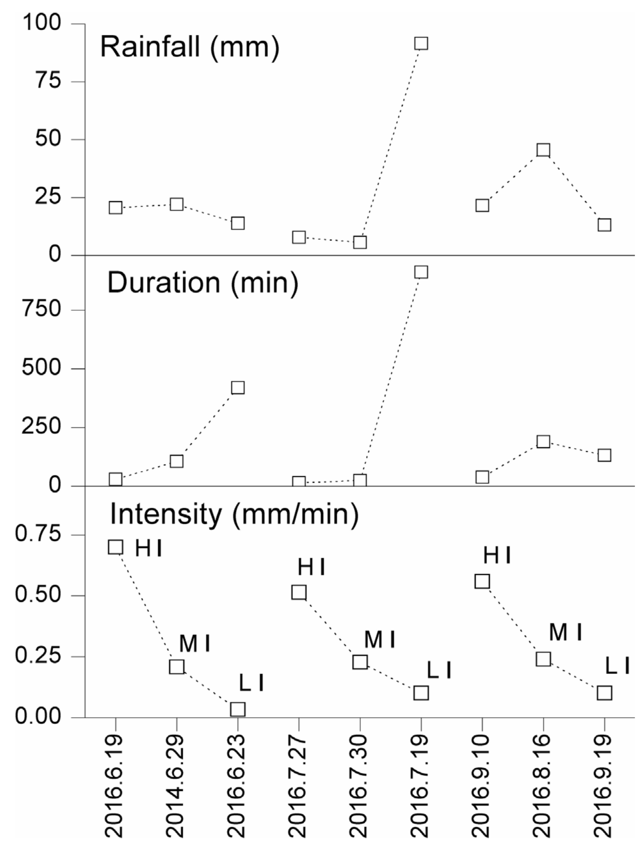

Fig. 2. The nine selected erosive rainfall events in this study. HI, high intensity rainfall; MI, intermediate intensity rainfall; LI, low intensity rainfall.

2.3. Vegetation surveys

Different runoff plots, with different abandoned time and slope position, had different plant species composition (Table 1). To minimize the effects of vegetation surveys and plant sampling on the plots, nondestructive sampling was conducted. Adjacent to each plot, five quadrats (1 × 1 m) were randomly established. The plant species composition of the runoff plot was obtained from the mean value of the plant species composition of the five quadrants. All plant species in the quadrats were identified and the number of each plant species was recorded. This work was carried out in three different seasonal periods (mid-June, late July, and early September).

Table 2
The acronyms used in this study.

Acronyms	Meaning
HI	High intensity rainfall (from 0.5 to 0.75 mm min^{-1})
MI	Intermediate intensity rainfall (close to 0.2 mm min^{-1})
LI	Low intensity rainfall (approximately 0.05 mm min^{-1})
PC 1–2	Axis 1–2 of principal component analysis for all of the functional traits of the community weighted mean
FDiv	Functional divergence, characterizes the degree of niche differentiation
FEve	Functional evenness, quantifies the degree of trait regularity across the functional space
FRic	Functional richness, measures the amount of trait space occupied by a community

2.4. Measurements of plant functional traits

Based on previous literature, ten traits related to soil erosion were selected for measurement (Kervroëdan et al., 2018; Qiao et al., 2018; Zhu et al., 2015). Measurements were performed in three different seasonal periods (mid-June, late July, and early September). For each period, at least ten plants of each species were randomly selected near the quadrants, and ten traits were measured. The measurements were performed at the same time of plant community survey. The plant height and leaf length were measured using a ruler. The leaf area was measured using a universal scanner (HPG3110; Hewlett-Packard Company, Palo Alto, CA, USA) and software developed for leaf area measurements (Leaf Area Measurement, version 1.3; University of Sheffield, Sheffield, UK). Specific leaf area was calculated based on the leaf area and leaf dry weight. Root volume, root surface area, root length, and root average diameter were determined using WinRHIZO Pro (version 2004a; Regent Instrument, Quebec, Canada). Leaf force-to-tear and root tensile strength were measured with a universal tensile and compression test machine (Instron 5942, Canton, MA, USA). All measurements were performed according to the “New handbook for standardized measurement of plant functional traits worldwide” (Pérez-Harguindeguy et al., 2013).

2.5. Calculations of functional traits of CWM

All measured plant functional traits were then scaled from the individual plant scale to the community scale. The functional traits of CWM were calculated according to the method of Garnier et al. (2004). The 10 CWM traits used in this research can be found in Table 3. The analyses were performed using R 3.4.3, using “FD” packages.

Table 3
The loadings of axis 1–2 of principal component analysis (PC1–2) for functional identities in different periods of a season.

	Mid June		Late July		Early September	
	PC 1	PC 2	PC 1	PC 2	PC 1	PC 2
Proportion of variation (%)	36.14	27.67	44.56	18.28	39.32	22.12
CWM.AD	0.33	0.33	0.36*	0.16	0.39*	0.06
CWM.Ft	−0.21	0.30	−0.36*	0.18	−0.11	−0.56*
CWM.H	0.42*	−0.11	0.35	−0.23	0.38	0.02
CWM.LA	−0.12	0.50	−0.26	0.39	−0.34	−0.11
CWM.LL	−0.31	0.37	−0.34	−0.01	−0.32	−0.41
CWM.RL	0.38	0.00	−0.22	0.55	−0.06	−0.41
CWM.RTS	0.06	0.54*	−0.30	0.02	0.22	−0.52
CWM.RV	0.35	0.30	0.34	0.33	0.38	−0.13
CWM.SA	0.42*	0.13	−0.32	−0.10	0.37	−0.20
CWM.SLA	−0.35	0.06	−0.28	−0.57*	−0.39*	0.11

Note: value with *, maximum absolute value of the loading in an axis. CWM.AD, community weighted mean values for root average diameter; Ft, leaf force to tear; H, plant height; LA, leaf area; LL, leaf length; RL, root length; RTS, root tensile strength; RV, root volume; SA, root surface area; SLA, specific leaf area.

2.6. Calculations of functional identity and diversity

In each period of a season, five independent indices were selected to characterize the functional identity and diversity. The first two indices were obtained by principal component analysis (PCA) for all of the functional traits of CWM within each season. In each growing season, ten functional traits of CWM were aggregated in PCA axes, and the first 2 axes (PC 1 and PC 2) that explained the greatest part of the variation were selected (Table 3). The last three indices, independent of each other (Mason et al., 2005; Villeger et al., 2008), are related to the calculated functional diversity in each growing season. These three indices, which were proposed by Villeger et al. (2008), were calculated on the 10 measured trait values together. FDiv characterizes the degree of niche differentiation; FEve quantifies the degree of trait regularity across the functional space; FRic measures the amount of trait space occupied by a community (Laliberte and Legendre, 2010). Together, these five indices (two indices related to functional identity: PC 1, and PC 2; three indices related to functional diversity: FDiv, FEve, and FRic) provide a comprehensive description of community functional composition (Table 2). The analyses were performed using R 3.4.3, using “FD” and “stats” packages.

2.7. Data analysis

Prior to data analysis, the Shapiro–Wilk normality test was used to check the normal distribution of the data. The data was transformed to a normalized pattern by the Box–Cox transformation if necessary. In addition, predictors were standardized for the performed models prior to analysis. The analyses were performed using R 3.4.3, using the “MASS” and “stats” packages.

The effects of five indices on soil erosion were examined by multi-model inference (MMI). This approach can provide more reliable inference results than the traditional method (Burnham et al., 2011). We built separate models for each rainfall event using this method. In each case, the response is the amount of erosion from a plot and the predictors are five indices. We built all possible global models, in which all five indices were included, for each case (Table 4). Possible candidate models were selected from the global models by a model selection approach and ranked according to the second-order Akaike's Information Criterion (Table 4). The effect size of each index was indicated as the averaged model parameter or the relative importance of the indices. The averaged model parameter was calculated by averaging the parameters of the candidate models whose accumulated model probability exceeded 95%. The relative importance of the indices was calculated by summing the Akaike's weights of each candidate model, which included the indices. The analyses were performed using R 3.4.3 with “MuMIn” packages.

3. Results

Nine selected erosive rainfall events were grouped into three periods of a season in this research based on the time of rainfall. The first period was from 19 June to 29 June, the second period was from 19 July to 30 July, and the third period was from 16 August to 19

Table 4
Summary of the multiple regression models for soil erosion in 9 rainfall events. Of all 32 models, the top 3 models are displayed and ranked according to their AICc values.

	PC1	PC2	FDiv	FEve	FRic	R^2	logLik	AICc	weight
Mid-June					−0.54	0.29	−13.21	35.85	0.20
LI				0.49		0.24	−13.58	36.58	0.14
				0.41	−0.47	0.45	−11.75	38.17	0.06
Mid-June		−0.45				0.20	−13.85	37.14	0.21
MI		−0.46	0.16			0.23	−13.67	42.00	0.02
		−0.46			0.10	0.21	−13.79	42.25	0.02
Mid-June		−0.53				0.28	−13.26	35.95	0.24
HI					−0.41	0.17	−14.05	37.53	0.11
		−0.48			−0.35	0.40	−12.26	39.19	0.05
Late July				−0.48		0.23	−13.66	36.76	0.22
LI			0.30	−0.55		0.31	−13.02	40.71	0.03
		0.29		−0.50		0.31	−13.05	40.77	0.03
Late July		0.41				0.17	−14.08	37.59	0.16
MI		1.30	−0.97			0.30	−13.09	40.85	0.03
		0.58			0.36	0.26	−13.39	41.45	0.02
Late July		0.46				0.22	−13.75	36.92	0.17
HI	0.34					0.11	−14.41	38.26	0.09
		1.54	−1.17			0.42	−12.12	38.90	0.06
Early September			−0.59			0.34	−12.76	34.96	0.27
LI			−0.87		−0.54	0.55	−10.63	35.93	0.16
			−1.04	0.61		0.51	−11.20	37.07	0.09
Early September			−0.43			0.19	−13.93	37.30	0.17
MI			−0.89	0.61		0.35	−12.68	40.03	0.04
	−0.32		−0.57			0.27	−13.34	41.35	0.02
Early September			−0.42			0.18	−14.02	37.48	0.18
HI			−0.74	0.42		0.26	−13.46	41.60	0.02
			−0.51		−0.18	0.20	−13.87	42.40	0.02

Note: LI, MI, and HI: the low, intermediate, and high intensity rainfall; R^2, R-squared values; logLik, Log Likelihood for the model; AICc, Second-order Akaike Information Criterion; weight, Akaike's weights. The other acronyms can be found in Table 2.

September. In each period of a season, rainfall events were defined as high, moderate, and low intensity rainfall (Fig. 2). High intensity rainfalls were from 0.5 to 0.75 mm min^{-1}, moderate intensity rainfalls were close to 0.2 mm min^{-1}, and the low intensity rainfalls were approximately 0.05 mm min^{-1}. The duration of high intensity rainfalls were from 15 to 29 min, the duration of moderate intensity rainfall were from 20 to 190 min, and the duration of low rainfalls were from 177 to nearly 900 min (Fig. 2).

Nineteen plant species with different life forms were observed in this study (Table 5). Measurement of the ten functional traits for each plant species in each seasonal period revealed that the value of each trait changed during one year but that different traits peaked at different times of the year. Generally, values of leaf traits, such as specific leaf area and leaf force to tear, were highest in the first period of the season (mid-June), but traits associated with root traits, such as root average diameter and root volume, were highest in the third period of

Table 5
The maximum values of species functional traits during a season.

	H (cm)	LL (mm)	LA (mm^2)	SLA (cm^2/g)	Ft (N/mm)	RTS (N/mm)	RL (cm)	SA (cm^2)	AD (mm)	RV (cm^3)
Artemisia giraldii	57.5	47.5	214.3	197.8	0.3	33.2	389.5	281.7	2.3	16.2
Artemisia sacrorum	57.0	41.2	368.7	137.3	0.4	12.1	494.0	178.6	1.9	13.5
Carex korshinskii	24.3	164.0	452.1	211.8	11.6	51.9	873.0	331.2	2.5	17.1
Cleistogenes hancei	42.0	100.6	145.6	203.2	1.8	20.5	855.0	359.0	5.0	38.2
Cynanchum thesioides	8.0	39.0	217.1	415.0	0.2	39.1	416.6	175.5	1.3	5.9
Gueldenstaedtia verna	35.0	11.0	367.1	110.8	0.2	18.4	35.7	16.1	2.4	1.0
Heteropappus altaicus	52.5	40.6	69.9	236.5	0.6	19.9	820.6	230.6	0.9	5.2
Leontopodium leontopodioides	12.0	5.0	109.8	203.4	0.3	21.6	26.1	8.2	0.5	0.1
Patrinia scabiosaefolia	52.3	76.0	571.4	170.9	0.2	10.8	123.2	50.3	0.6	0.8
Phragmites australis	90.0	286.6	2743.7	118.4	5.9	160.7	283.2	139.8	3.6	14.6
Potentilla bifurca	15.0	14.0	938.5	224.6	0.3	19.5	200.6	50.0	1.4	0.8
Potentilla tanacetifolia	53.3	50.2	4033.4	262.2	0.4	33.6	268.0	160.0	1.9	7.6
Setaria viridis	56.0	342.3	661.4	488.4	17.8	19.4	586.3	190.3	0.9	3.1
Stipa grandis	88.0	872.3	1601.0	312.3	27.1	30.4	1423.3	535.8	1.4	17.5
Taraxacum mongolicum	32.3	123.2	947.9	340.9	2.4	11.8	239.1	99.5	2.4	1.8
Vicia cracca	60.0	11.9	612.5	464.6	0.5	22.9	55.6	19.0	2.4	1.0
Viola verecunda	12.2	134.3	1078.1	292.5	0.2	9.6	310.0	67.9	0.7	1.2
Viola dissecta	15.9	80.6	1202.7	220.1	0.1	9.5	228.3	53.9	0.6	0.5

Note: Light grey background, the maximum value have been got from mid-June; white background, the maximum value have been got from late July; dark grey background, the maximum value have been got from early September. Abbreviations of the trait can be found in Table 3.

the season (early September; Table 5).

CWM of those 10 functional traits was aggregated in PCA axes in each period of a season. The loadings of PC1–2 for functional identities were different in different periods of a season (Table 3). For example, in mid June, PC2 mainly reflected the variation in the root tensile strength, leaf force to tear, leaf area, and root volume (Table 3). The combination of these functional identities could be suggested as plant tensile strength. In late July, PC2 mainly reflected the variation in the specific leaf area, plant height, root length, and root volume (Table 3). Among these functional identities, aboveground vegetation part (specific leaf area and plant height) was negative related to PC2, while the root system (root length and root volume) was positive related to PC2 (Table 3). This suggested that, in late July, PC2 had a positive relationship with a developed root system and a negative relationship with a developed plant aboveground parts.

Calculation of the effects of the functional identity and diversity on soil erosion by MMI showed that the main functional identity and diversity affecting soil erosion were different in different periods and under different conditions of rainfall intensity. During mid-June, there was a negative relationship between PC2 and soil erosion in moderate and high intensity rainfall (Table 6). It was suggested that PC2 was the main factor reducing soil erosion under this condition (Tables 6 and 7). Thus, plant tensile strength is the main factor reducing soil erosion in mid-June under moderate and high intensity rainfall. For low intensity rainfall, the averaged model parameter of FRic was −0.181, a larger absolute value than for the other indices, after calculations using all 32 possible models for soil erosion for each rainfall event (Table 6). Thus, FRic was the main factor affecting soil erosion in mid-June under low intensity rainfall (Tables 6 and 7). During late July, there was a positive relationship between PC2 and soil erosion for both moderate and high intensity rainfall (Tables 6 and 7). During late July, PC2 had a negative relationship with a developed plant aboveground part. This indicated that a developed plant aboveground part could effectively reduce soil erosion during this time period. For low intensity rainfall, FEve was of relatively higher importance than other indices, after summing the Akaike's weights of all the models calculated for soil erosion (Table 7). The averaged model parameters of FEve calculated from all 32 possible models for soil erosion was −0.158, indicating that FEve was the main index related to soil erosion in late July under low intensity rainfall. During early September, FDiv was negatively correlated with soil erosion for all intensities of rainfall (Table 5), suggesting it was the main determinant of soil erosion for this time period regardless of the intensity of rainfall (Tables 6 and 7). This result suggested that niche differentiation of plants is a more important limitation to soil erosion than other indices during early September.

4. Discussion

4.1. Effects of functional identity and diversity on soil erosion in the first period of a season

When the rainfall intensity is low, FRic, the functional space occupied by a community, plays a more significant role for limiting soil erosion than the other indices (Tables 6 and 7) in mid-June. It can be speculated that in mid-June, early in the growth season in the research area, most plants are in the seedling stage. A community that occupies more functional space can counter the impact of low intensity rainfall more effectively in this stage. In addition, the functional space includes both the functional space occupied by the aboveground parts of a community and the functional space occupied by the root systems of a community. According to a related research carried out in China, Ghestem et al. (2014) suggested that root abundance in soil was an effective plant property to stabilize soil. Therefore, it can be found that a community with higher FRic can inhibit soil erosion more effectively when rainfall intensity is low in mid-June.

For intermediate and high rainfall intensity in mid-June, PC2 becomes more important in reducing soil erosion than the other indices (Tables 6 and 7) in this period. Combined with the analysis results of PCA, the data suggest that higher plant tensile strength reduces soil erosion (Table 3). In addition, plant tensile strength became increasingly important as rainfall intensity increased (Tables 6 and 7). It can be speculated that high rainfall leads to high runoff of surface soils, the main process responsible for erosion. This type of scouring can be greatly reduced by roots with high tensile strength (De Baets et al., 2008; Reubens et al., 2007). Therefore, plant tensile strength becomes increasingly important in reducing soil erosion with increasing rainfall intensity in mid-June.

In this research, FRic and plant tensile strength are found to limit soil erosion in mid-June. Because plant roots play an important role in preventing soil erosion in the early stage of a growing season when the plant coverage is low (Luo et al., 2019; Zhang et al., 2014), it can be speculated that the effects of FRic and plant tensile strength on erosion are likely attributed to plant root systems. Similarly, after carrying out a research study in Beijing of China, Zhang et al. (2014) also suggested that because the root system can increase soil resistance, enhance soil permeability, and improve physical properties of the soil, plant root systems can effectively reduce soil erosion in spring when the vegetation coverage is low.

Table 7
Relative importance of all indices, expressed by the sum of the Akaike's weights for all models calculated from all 32 possible models for soil erosion in each rainfall event.

	Mid June			Late July			Early September		
	HI	MI	LI	HI	MI	LI	HI	MI	LI
FDiv	0.10	0.10	0.12	0.18	0.14	0.12	**0.25**	**0.28**	**0.65**
FEve	0.14	0.09	0.24	0.14	0.11	**0.32**	0.11	0.12	0.18
FRic	0.23	0.09	**0.34**	0.12	0.11	0.10	0.10	0.10	0.26
PC 1	0.12	0.09	0.20	0.15	0.13	0.11	0.10	0.10	0.08
PC 2	**0.39**	**0.28**	0.08	**0.34**	**0.25**	0.13	0.11	0.19	0.11

Note: The top coefficients for each rainfall event are shown in bold. The acronyms can be found in Table 2.

Table 6
Averaged model parameters (standardized regression coefficients) calculated from all 32 possible models for soil erosion in each rainfall event.

	Mid June			Late July			Early September		
	HI	MI	LI	HI	MI	LI	HI	MI	LI
FDiv	−0.013	0.013	0.032	−0.055	−0.012	0.021	**−0.107**	**−0.148**	**−0.518**
FEve	−0.034	0.003	0.100	−0.036	−0.021	**−0.158**	0.001	0.025	0.078
FRic	−0.079	0.004	**−0.181**	0.023	0.014	0.007	0.003	−0.002	−0.119
PC 1	0.030	−0.002	−0.085	0.049	0.028	0.010	0.003	−0.012	−0.008
PC 2	**−0.210**	**−0.117**	−0.008	**0.244**	**0.138**	0.029	0.014	0.062	0.030

Note: The top coefficients for each rainfall event are shown in bold. The acronyms can be found in Table 2.

4.2. Effects of functional identity and diversity on soil erosion in mid-season

FEve plays a more significant role in reducing soil erosion when the rainfall intensity is low in late July (Tables 6 and 7). FEve is the evenness of trait representation and suggests that a community with more evenness of trait representation can counter low intensity rainfall more effectively in the second period of a season. Late July is mid-season in the study area. Compared with the situation in mid-June, most plants are mature individuals in late July, and a mature plant community with more evenness of trait can limit soil erosion more efficiently when rainfall intensity is low in this period.

PC2 shows a significant effect on soil erosion when rainfall intensity is intermediate and high (Tables 6 and 7). Combined with the results of previous PCA, the data suggest that developed plant aboveground parts is the most important factor for reducing soil erosion during intermediate and high intensity rainfalls. In late July, PC2 represented some characteristics, which included that the plant height tented to be short, leaf weight tended to be heavy, and the root system tended to be developed. It could be implied from the combination of these characteristics that PC2 mainly represented plant drought resistance. As it was shown that PC2 could promote soil erosion (Table 6), it could be further speculated that hygrophilous plants with a developed aboveground part can limit erosion in this period when rainfall intensity is intermediate and high.

Plant aboveground part is commonly suggested to be the key in reducing soil erosion (Rossi et al., 2018; Xu et al., 2008; Zhang et al., 2012). After carried out a mathematical model research in Ethiopia, Easton et al. (2010) found that in the early stage of the growing season when vegetation coverage was unestablished, erosion dominated sediment delivery to the river. Once vegetation coverage was established, erosion can be negligible (Easton et al., 2010). This conclusion is also supported by the measurements done by Yüksek and Yüksek (2015), who found that a higher erosion is expected in the spring season, when the plant height and coverage are lower. Our research found that FEve plays an important role in reducing erosion when the rainfall intensity is low in the late July. It is also found that most plant functional traits of aboveground part is well established in this stage (Table 5). Thus, it can be speculated that FEve of plant aboveground part is the main factor in reducing erosion under the low rainfall intensity in the late July.

4.3. Effects of functional identity and diversity on soil erosion in the latter growing season

In early September, FDiv plays a more significant role in limiting soil erosion than the other plant functional indices for all intensity rainfalls (Tables 6 and 7). This can be explained by the complementarity effect and by the sampling effect (Zhu et al., 2015). FDiv is the differentiation of niches and describes overlap in plant functional traits among different species. A higher value of FDiv in a plant community suggests a more complete use of both aboveground and underground space (Diaz et al., 2007). In this research, FDiv was calculated by erosion-relevant plant physical traits that are suggested to affect soil erosion (Reubens et al., 2007). A plant community with a higher value of FDiv has more abundant species with more extreme erosion-relevant functional traits. Thus, the community can reinforce the protective effect of plants to inhibit soil erosion (Gyssels et al., 2005; Reubens et al., 2007). Second, in early September, a latter growing season in the study area, many species have started to wither. Most erosion-relevant functions may have declined within communities. In this condition, the key species become more important than the other plant functional indices for determining soil erosion. In addition, a community with a higher value of FDiv has an increased probability of containing species with diverse root characteristics and is more likely to contain key species to effectively block soil erosion (Flombaum et al., 2014).

4.4. Effects of plants on soil erosion at the community scale

Many studies have reported that various ecosystem processes can be driven by plant functional diversity (Butterfield and Suding, 2013; Schumacher and Roscher, 2009). However, most work has focused on the relationship between functional diversity and biomass. For example, Cadotte (2017) explained why a multispecies ecosystem produces more biomass than monocultures by using a trait-based approach at the community scale. Here, the trait-based approach was used to explain the effect of plants on soil erosion at the plant community scale. These results build on our understanding of the relationship between vegetation and soil erosion processes based on trait-based approaches. This research could be helpful to determine the mechanisms and factors of soil erosion and to help guide soil and water conservation measurements. However, generalization of the conclusions of this study should be performed with caution when comparing different ecosystems because of different plant species compositions and rainfall characteristics. All the plant traits selected in this research can be related to soil erosion, but the selection of which are most important should be made on a site-specific basis, and other suitable plant traits related to soil erosion should be studied in further research.

5. Conclusions

Investigation of the mechanisms of vegetation impacts on soil erosion is critical to understand the soil and water conservation functions of plants and to understand the appropriate designs of plant measurement studies for soil and water conservation. In this study, the impacts of functional identity and diversity on soil erosion were determined in different periods of a season with different conditions of rainfall intensity. In the early and middle season, functional richness and functional evenness of the plant community play a great role in reducing soil erosion during low rainfall intensity. Plant tensile strength has a great effect on soil erosion under intermediate and high rainfall intensities in the early season. However, for the intermediate and high rainfall intensities in the middle season, the plant aboveground part has the greatest effect on soil erosion. At the end of the growing season, plant niche differentiation is the largest determinant of soil erosion from low to high rainfall intensity.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

Boix-Fayos, C., et al., 2006. Measuring soil erosion by field plots: Understanding the sources of variation. Earth Sci. Rev. 78, 267–285.
Bu, W.S., et al., 2019. Plant functional traits are the mediators in regulating effects of abiotic site conditions on aboveground carbon stock-evidence from a 30 ha tropical forest plot. Front. Plant Sci. 9.
Burnham, K.P., Anderson, D.R., Huyvaert, K.P., 2011. AIC model selection and multimodel inference in behavioral ecology: some background, observations, and comparisons. Behav. Ecol. Sociobiol. 65, 23–35.
Butterfield, B.J., Suding, K.N., 2013. Single-trait functional indices outperform multi-trait

indices in linking environmental gradients and ecosystem services in a complex landscape. J. Ecol. 101, 9–17.
Cadotte, M.W., 2017. Functional traits explain ecosystem function through opposing mechanisms. Ecol. Lett. 20, 989–996.
Cadotte, M.W., Carscadden, K., Mirotchnick, N., 2011. Beyond species: functional diversity and the maintenance of ecological processes and services. J. Appl. Ecol. 48, 1079–1087.
De Baets, S., Poesen, J., Knapen, A., Galindo, P., 2007. Impact of root architecture on the erosion-reducing potential of roots during concentrated flow. Earth Surf. Proc. Land. 32, 1323–1345.
De Baets, S., Torri, D., Poesen, J., Salvador, M.P., Meersmans, J., 2008. Modelling increased soil cohesion due to roots with EUROSEM. Earth Surf. Proc. Land. 33, 1948–1963.
Diaz, S., et al., 2007. Incorporating plant functional diversity effects in ecosystem service assessments. PNAS 104, 20684–20689.
Easton, Z.M., et al., 2010. A multi basin SWAT model analysis of runoff and sedimentation in the Blue Nile, Ethiopia. Hydrol. Earth Syst. Sci. 14, 1827–1841.
El Kateb, H., Zhang, H., Zhang, P., Mosandl, R., 2013. Soil erosion and surface runoff on different vegetation covers and slope gradients: A field experiment in Southern Shaanxi Province, China. Catena 105, 1–10.
Erktan, A., et al., 2015. Increase in soil aggregate stability along a Mediterranean successional gradient in severely eroded gully bed ecosystems: combined effects of soil, root traits and plant community characteristics. Plant Soil 398, 121–137.
Erktan, A., McCormack, M.L., Roumet, C., 2018. Frontiers in root ecology: recent advances and future challenges. Plant Soil 424, 1–9.
Faucon, M.P., Houben, D., Lambers, H., 2017. Plant functional traits: soil and ecosystem services. Trends Plant Sci. 22, 385–394.
Flombaum, P., Sala, O.E., Rastetter, E.B., 2014. Interactions among resource partitioning, sampling effect, and facilitation on the biodiversity effect: a modeling approach. Oecologia 174, 559–566.
Garnier, E., et al., 2004. Plant functional markers capture ecosystem properties during secondary succession. Ecology 85, 2630–2637.
Ghestem, M., et al., 2014. A framework for identifying plant species to be used as 'ecological engineers' for fixing soil on unstable slopes. PLoS ONE 9, e95876.
Gyssels, G., Poesen, J., Bochet, E., Li, Y., 2005. Impact of plant roots on the resistance of soils to erosion by water: a review. Prog. Phys. Geogr. 29, 189–217.
Hou, J., Fu, B., 2014. Research on the relationship between vegetation and soil resource patterns on lands abandoned at different times. Catena 115, 1–10.
Ilunga wa Ilunga, E., et al., 2015. Plant functional traits as a promising tool for the ecological restoration of degraded tropical metal-rich habitats and revegetation of metal-rich bare soils: A case study in copper vegetation of Katanga, DRC. Ecol. Eng. 82, 214–221.
Jiang, Y., et al., 2015. Effects of soil and microclimatic conditions on the community-level plant functional traits across different tropical forest types. Plant Soil 390, 351–367.
Kervroëdan, L., Armand, R., Saunier, M., Ouvry, J.-F., Faucon, M.-P., 2018. Plant functional trait effects on runoff to design herbaceous hedges for soil erosion control. Ecol. Eng. 118, 143–151.
Kraft, N.J.B., Godoy, O., Levine, J.M., 2015. Plant functional traits and the multidimensional nature of species coexistence. PNAS 112, 797–802.
Laliberte, E., Legendre, P., 2010. A distance-based framework for measuring functional diversity from multiple traits. Ecology 91, 299–305.
Liu, C., Yang, Q., Xie, H., 2010. Spatial and temporal distributions of rainfall erosivity in the Yanhe River Basin. Environ. Sci. 31, 850–857.
Liu, Y., Fu, B.J., Lu, Y.H., Wang, Z., Gao, G.Y., 2012. Hydrological responses and soil erosion potential of abandoned cropland in the Loess Plateau, China. Geomorphology 138, 404–414.
Luo, J., Zheng, Z., Li, T., He, S., 2019. The changing dynamics of rill erosion on sloping farmland during the different growth stages of a maize crop. Hydrol. Process. 33, 76–85.
Markowicz, A., Wozniak, G., Borymski, S., Piotrowska-Seget, Z., Chmura, D., 2015. Links in the functional diversity between soil microorganisms and plant communities during natural succession in coal mine spoil heaps. Ecol. Res. 30, 1005–1014.
Mason, N.W.H., Mouillot, D., Lee, W.G., Wilson, J.B., 2005. Functional richness, functional evenness and functional divergence: the primary components of functional diversity. Oikos 111, 112–118.
Moor, H., Hylander, K., Norberg, J., 2015. Predicting climate change effects on wetland ecosystem services using species distribution modeling and plant functional traits. Ambio 44, S113–S126.
Mouchet, M.A., Villeger, S., Mason, N.W.H., Mouillot, D., 2010. Functional diversity measures: an overview of their redundancy and their ability to discriminate community assembly rules. Funct. Ecol. 24, 867–876.
Pérez-Harguindeguy, N., et al., 2013. New handbook for standardised measurement of plant functional traits worldwide. Aust. J. Bot. 61, 167–234.
Phan Ha, H.A., et al., 2012. Impact of fodder cover on runoff and soil erosion at plot scale in a cultivated catchment of North Vietnam. Geoderma 177–178, 8–17.
Qiao, W., et al., 2018. Relationship between the vegetation community and soil nutrient and enzyme activity during the restoration of abandoned land in the Loess Hilly region. Environ. Sci. 39, 5687–5698.
Reubens, B., Poesen, J., Danjon, F., Geudens, G., Muys, B., 2007. The role of fine and coarse roots in shallow slope stability and soil erosion control with a focus on root system architecture: a review. Trees-Struct. Funct. 21, 385–402.
Rossi, R., et al., 2018. Modelling the non-linear relationship between soil resistivity and alfalfa NDVI: A basis for management zone delineation. J. Appl. Geophys. 159, 146–156.
Schnoor, T., Bruun, H.H., Olsson, P.A., 2015. Soil disturbance as a grassland restoration measure-effects on plant species composition and plant functional traits. PLoS ONE 10.
Schumacher, J., Roscher, C., 2009. Differential effects of functional traits on aboveground biomass in semi-natural grasslands. Oikos 118, 1659–1668.
Sena, P.H.A., Lins, E.S.A.C.B., Goncalves-Souza, T., 2018. Integrating trait and evolutionary differences untangles how biodiversity affects ecosystem functioning. Oecologia 188, 1121–1132.
Villeger, S., Mason, N.W.H., Mouillot, D., 2008. New multidimensional functional diversity indices for a multifaceted framework in functional ecology. Ecology 89, 2290–2301.
Wang, B., Zhang, G.-H., Shi, Y.-Y., Li, Z.-W., Shan, Z.-J., 2015. Effects of near soil surface characteristics on the soil detachment process in a chronological series of vegetation restoration. Soil Sci. Soc. Am. J. 79, 1213.
Xu, X.L., Ma, K.M., Fu, B.J., Song, C.J., Liu, W., 2008. Influence of three plant species with different morphologies on water runoff and soil loss in a dry-warm river valley, SW China. For. Ecol. Manage. 256, 656–663.
Yüksek, F., Yüksek, T., 2015. Growth performance of Sainfoin and its effects on the runoff, soil loss and sediment concentration in a semi-arid region of Turkey. Catena 133, 309–317.
Zhang, G.-H., Tang, K.-M., Sun, Z.-L., Zhang, X.C., 2014. Temporal variability in rill erodibility for two types of grasslands. Soil Res. 52, 781.
Zhang, G.H., Liu, G.B., Wang, G.L., 2012. Effects of canopy and roots of patchy distributed artemisia capillaris on runoff, sediment, and the spatial variability of soil erosion at the plot scale. Soil Sci. 177, 409–415.
Zhou, Z.C., Shangguan, Z.P., 2007. The effects of ryegrass roots and shoots on loess erosion under simulated rainfall. Catena 70, 350–355.
Zhu, H., et al., 2015. Reducing soil erosion by improving community functional diversity in semi-arid grasslands. J. Appl. Ecol. 52, 1063–1072.