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Effects of land use on slope runoff and soil loss in the Loess Plateau of China: A meta-analysis

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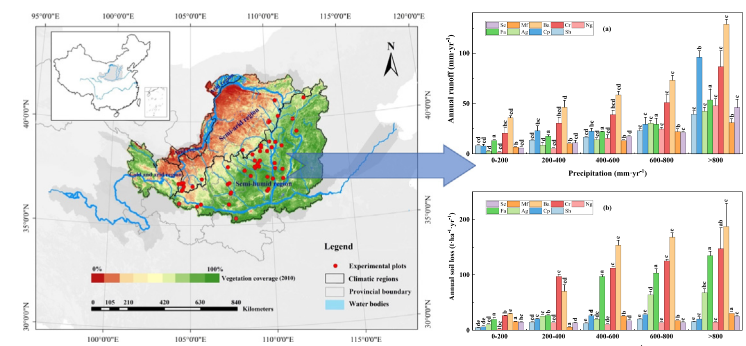
HIGHLIGHTS

- The data sets of all available runoff plots in the Loess Plateau were compiled.
- The optimization of the land use in the Loess Plateau was evaluated.
- Evaluated the ability of different land-use types to intercept and store rainfall.
- Shrubland could be preferred in the ecological management in Loess Plateau.

GRAPHICAL ABSTRACT



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ABSTRACT

In the Loess Plateau, due to the inappropriate vegetation restoration mode, large areas of artificially restored vegetation began to degrade, thus the optimization of vegetation allocation has become an urgent necessity. The main purpose of this study was to identify and evaluate slope runoff and soil loss rates, and to review all of the plot-scale studies in the Chinese Loess Plateau, by meta-analysis. Based on data collected from the runoff plot, the effect of land use on annual runoff and annual soil loss under natural rainfall conditions was analyzed. The optimization of land use in different climatic regions of the Loess Plateau was evaluated. The plot database contained 55 plot measuring sites in the Loess Plateau, which included 461 runoff plots and 535 soil loss plots. Bare soil was found to have the highest average annual runoff (58.57 $mm\cdot yr^{-1}$) and annual soil loss (122.06 $t\cdot ha^{-1}\cdot yr^{-1}$). Natural grassland and mixed forest had the lowest annual runoff (<15 $mm\cdot yr^{-1}$) and annual soil loss (<20 $t\cdot ha^{-1}\cdot yr^{-1}$), exhibiting a better effect of soil and water conservation when the precipitation was <200 mm and >600 mm, respectively. When the precipitation was 400–600 mm, shrubland showed the lowest mean annual runoff (21.36 $mm\cdot yr^{-1}$) and annual soil loss (13.36 $t\cdot ha^{-1}\cdot yr^{-1}$), which conducive to reducing water and sediment. Therefore, shrubland could be selected as the recovery vegetation type in the semi-humid climatic region. Land-use types determined the relationship between annual soil loss and annual runoff with plot length and slope gradient. These results enabled the assessment of the impact of land-use change on water erosion, providing a basis for formulating soil and water conservation management programs.

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1. Introduction

As important processes leading to soil erosion, soil loss and runoff changes, induced by inappropriate land use, are among the most severe global environmental issues (Fu et al. 2011; Nyssen et al. 2015; Robinson et al. 2013). A comprehensive approach to these problems at a regional scale needs to involve the representative environmental conditions for the assessment of soil loss and runoff. Furthermore, through the rational allocation of land use modes, the soil structure can be improved, so do the erosion resistance and the scour resistance of the soil (Fu et al. 2011; Maetens et al. 2012; Xin et al. 2008). For instance, the Grain for Green project was launched in 1999 on the Loess Plateau, with the aims of controlling soil erosion and mitigating land degradation (Wang et al. 2007). These ecological restoration measures promoted the transformation of land type in the region, reducing the sediment discharge in the Loess Plateau by 90% (Deng et al. 2012; Vina et al. 2016; Wang et al. 2008). However, in order to gain insight into these processes and to develop strategies to mitigate their impacts, it is necessary to determine the sediment yield of the different landforms and land-use types. More detailed field measurements are needed to better quantify the soil loss.

Various methods have been employed to obtain field-measured soil loss data. The field runoff experimental plot is regarded as the most common and widely used method (Bagarello and Ferro 2010; Wei 2002). Most studies were based on the continuous observation of multiple runoff plots to analyze the relationship between runoff and sediment yield and obtain the estimation and characterization of soil erosion. A good example was the development of the universal soil loss equation (Laflen and Flanagan 2013; Renard et al. 1997; Wischmeier and Smith 1978). The studies of runoff plots in the Loess Plateau have mostly involved single runoff plots, focusing on the relationship among rainfall and different ecological measures, runoff, and soil loss (Chen et al. 2010; Kang et al. 2001; Liu et al. 2019). These case studies provide a good understanding of the impact of local erosion control factors on soil loss and runoff. However, because of the diversity and variable nature of plot-scale studies, the findings of these independent plot-scale studies are difficult to be extended to regional scales (Bagarello et al. 2012; Labriere et al. 2015; Maetens et al. 2012).

To extrapolate the plot-scale runoff and soil loss data to larger areas, all available data on soil loss and runoff at the regional scale need to be compiled. Such compilation of relevant datasets for the runoff plots has been carried out in the Mediterranean and in European regions for further analysis (Maetens et al. 2012). The compilation of field measurements in Brazil revealed that the relationship between rainfall with soil loss and runoff at the plot-scale was affected by the land-use types and the spatio-temporal patterns of land use coverage (Anache et al. 2017). In China, an extensive dataset was compiled from erosion plot measurements after applying soil and water conservation measures, which, subsequently, was used to assess the efficacy of the measures on reducing soil and water loss (Zhao et al. 2019b). These compilation shed light on the key factors that determine the rate and variation of annual soil loss and runoff on subcontinent and regional scales.

Although there are many descriptive comments and viewpoints on the relationship between land use with soil loss and runoff in the Loess Plateau, the impact assessment of slope erosion was mainly carried out at the plot-scale, which cannot be directly applied up to larger scales due to the limitation of scale effects (e.g. different measurement methods employ, experiments performed over different time periods or insufficient treatment repetitions) (Chen et al. 2018; Eshghizadeh et al. 2016; Nunes et al. 2011). Most studies have only evaluated the overall impact of governance measures on soil erosion or watershed runoff, and lack information on other important control factors on soil loss and runoff by only assessing the effect of a single control factor (e.g. soil and water conservation technique) (Zhang et al. 2010a; Zhao et al. 2013). Although quantitative analysis of the ecological rehabilitation has been carried out in the Loess Plateau (Hu et al. 2017), the impacts of the slope gradient and the plot length of the runoff plot have not been assessed. While Zhao et al. (2019a) recognized the importance of rainfall, the direct relationship between rainfall and land use was not analyzed. Furthermore, no comprehensive compilation of soil loss and runoff data at runoff plot scales exists in the Loess Plateau, hindering the intuitive analysis of the factors of erosion processes and the optimal vegetation type in the Loess Plateau.

Therefore, we integrated runoff plot-scale data to quantify the effect of land-use types on runoff and soil loss via a meta-analysis. The main objectives of this study were: (1) to compile data on the soil loss and runoff rate at the plot-scale in the Loess Plateau; (2) to analyze the relationship between runoff and soil loss rate with different land-use types and their relationships with annual precipitation; and (3) to evaluate the optimal land-use types in different climatic regions in the Loess Plateau.

2. Materials and methods

2.1. Literature search and runoff plot selection criteria

The data for the meta-analysis were collected from peer-reviewed journals. English literature was obtained from academic databases such as Web of Science, Science Direct, and Google Scholar, while papers published in Chinese journals were retrieved from the China National Knowledge Infrastructure (CNKI) and Medalink. Keywords were employed during the search processes included "land use", "runoff", "erosion", "soil loss", "soil and water conservation", "sediment reduction", "plot*", "plot data", "plot length", "plot gradient", and "loess plateau" (Fig. 1). The studies that met the following criteria were selected: (1) studies reported at least one variable including runoff and sediment generation before and after land use change; (2) means and sample sizes were directly reported or could be found from the articles; (3) number of replications was considered; (4) experiments were carried out on bounded runoff plots with a measurement period of at least one year. The data rendered in a graphical form only were extracted using GetData Graph Digitizer and Origin. A total of 59 articles were identified in this process (Table S1 Supplementary).

The plot database included natural rainfall, which was measured on runoff plots in the Loess Plateau (Fig. 2). The criteria of the plot data had to fulfill the following conditions: the experimental site was located in the Loess Plateau; the experimental plot data was recorded under natural rainfall; the monitoring of the data was continuous; clear basic information was provided for the experimental plot, including the latitude and longitude, the land-use type, the runoff plot description, and the measuring period. All selected papers in this study are listed in Table 1.

2.2. Data compilation and preprocessing

The year of publication indicated that the number of research articles increased after 2004 (Fig. 3a). Most of the runoff plots had been measured for at least one year, with an average measurement period of 5 years (Fig. 3b). The research sites were distributed across 17 counties (Shanyin, Ji, Jingle, Lishi, Ansai, Shenmu, Suide, Mizhi, Zizhou, Changwu, Qingyang, Jingchuan, Xifeng, Tianshui, Dingxi, Guyuan, and Jungar Banner) over five provinces (Shanxi, Shaanxi, Gansu, Ningxia, and Inner Mongolia) in the Loess Plateau (Table 1). The land-use types (shrubland, Chinese pine, artificial grassland, cropland, bare soil, mixed forest, fallow, sea-buckthorn, and natural grassland) in the study are described in Table 2.

A total of 55 runoff plot measurement sites were counted in the plot database, compiled from 59 individual publications (Fig. 2). The location of each measurement sites was determined according to the coordinates given in the publications. All studies included two time scales: the annual scale and the rainfall event scale. Based on the altitude and climate differences, the Loess Plateau was divided into four climatic

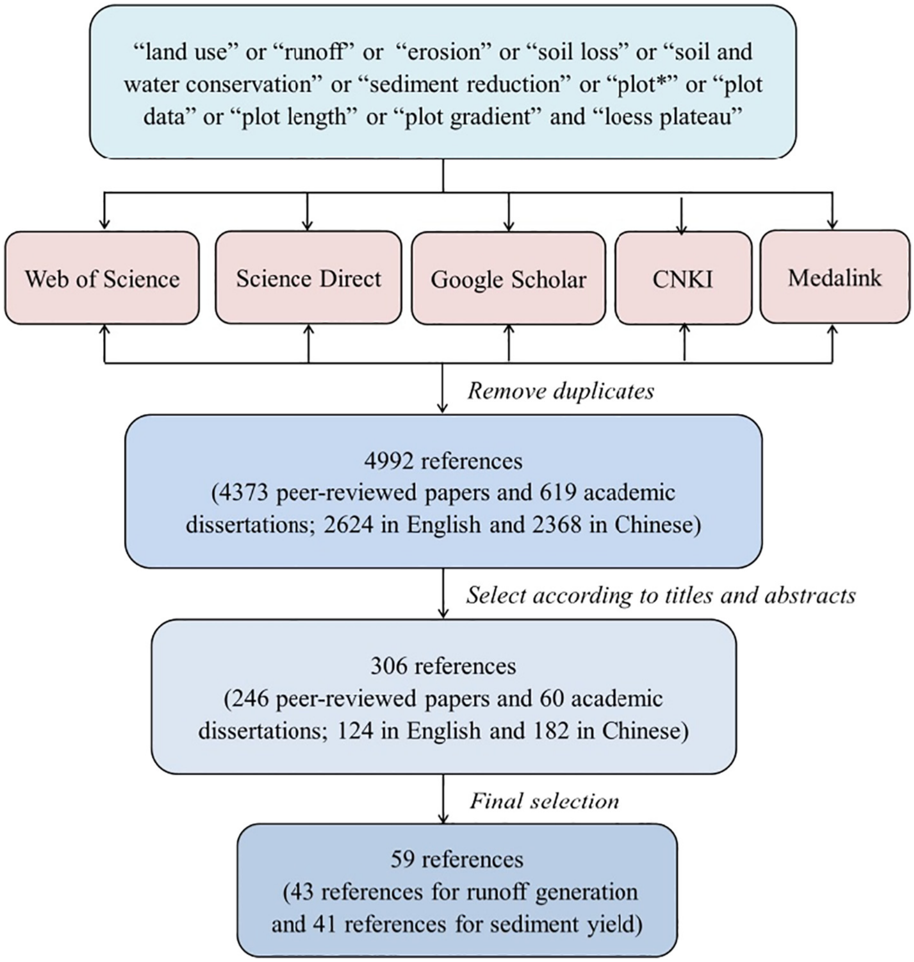

Fig. 1. The meta-analysis literature search process.

regions: the arid region, the semi-humid region, the semi-arid region, and the cold and arid regions (Fig. 2) (Xiao et al. 2017). Erosion type in the arid region was mainly wind erosion with no runoff plot counted. The distribution points with other runoff plots are as follows: 40 in the semi-humid region, 13 in the semi-arid region, and 2 in the cold and arid regions.

2.3. Data analysis

The units of all data were standardized prior analysis to enable cross-study comparison. The units of runoff and soil loss were converted into $mm \cdot yr^{-1}$ and $t \cdot ha^{-1} \cdot yr^{-1}$, respectively. Normality and homoscedasticity of data were verified with the Kolmogorov-Smirnov test. The content data, which does not meet the normal distribution, was normalized by the logarithmic transformation. One-way analysis of variance (ANOVA) and Tukey's HSD (honest significant difference) were used to test for differences (significance level at $p < 0.05$) in runoff and soil loss with land-use types. The same procedure was applied to test for significant differences between climatic regions for each land-use type. The Spearman rank correlation index was used to assess the effect of slope gradient and plot length on the annual runoff, the soil loss, and the annual runoff coefficient. Finally, regression analysis was used to ascertain the relative effects of annual precipitation on runoff and soil loss. All statistical analyses were performed using IBM SPSS Statistics 21.0 (IBM Corporation, NY, USA).

The standard error of the sample mean was inversely proportional to the square root of the number of observations according to the central limit theorem (Tijms 2004). Therefore, the square root of the number of plot-years was used as a weighting factor for the means and standard deviations calculated according to Eq. (1) (Anache et al. 2017; Guo et al. 2015):

$$A_l = \sum_{i=1}^{m} A_{li}\sqrt{n_{li}} / \sum_{i=1}^{m} \sqrt{n_{li}} \tag{1}$$

where A_l is the runoff or the soil loss rate with land use l. A_{li} is the average runoff or the soil loss rate for plot i; and n_{li} is the number of plot-years for the plot i.

3. Results

3.1. The effects of plot length and slope gradient on annual runoff and soil loss

The result of correlation coefficient tests for slope gradient and plot length with runoff, annual runoff coefficients, and soil loss were summarized in Table 3. The annual runoff was positively related to the plot length for plots with Chinese pine, artificial grassland, cropland, bare soil, and fallow. A significant negative relationship between annual runoff and plot length was found for plots with natural grassland, sea-buckthorn, mixed forest, and shrubland. Concerning the relationship between slope gradient and annual runoff, a significant positive correlation was found for cropland and bare soil ($p < 0.05$). Regarding the relationship between plot length and soil loss a significant positive correlation was found for cropland, bare soil, and fallow ($p < 0.05$). The slope gradient of cropland and bare soil was positively correlated with soil loss. For natural

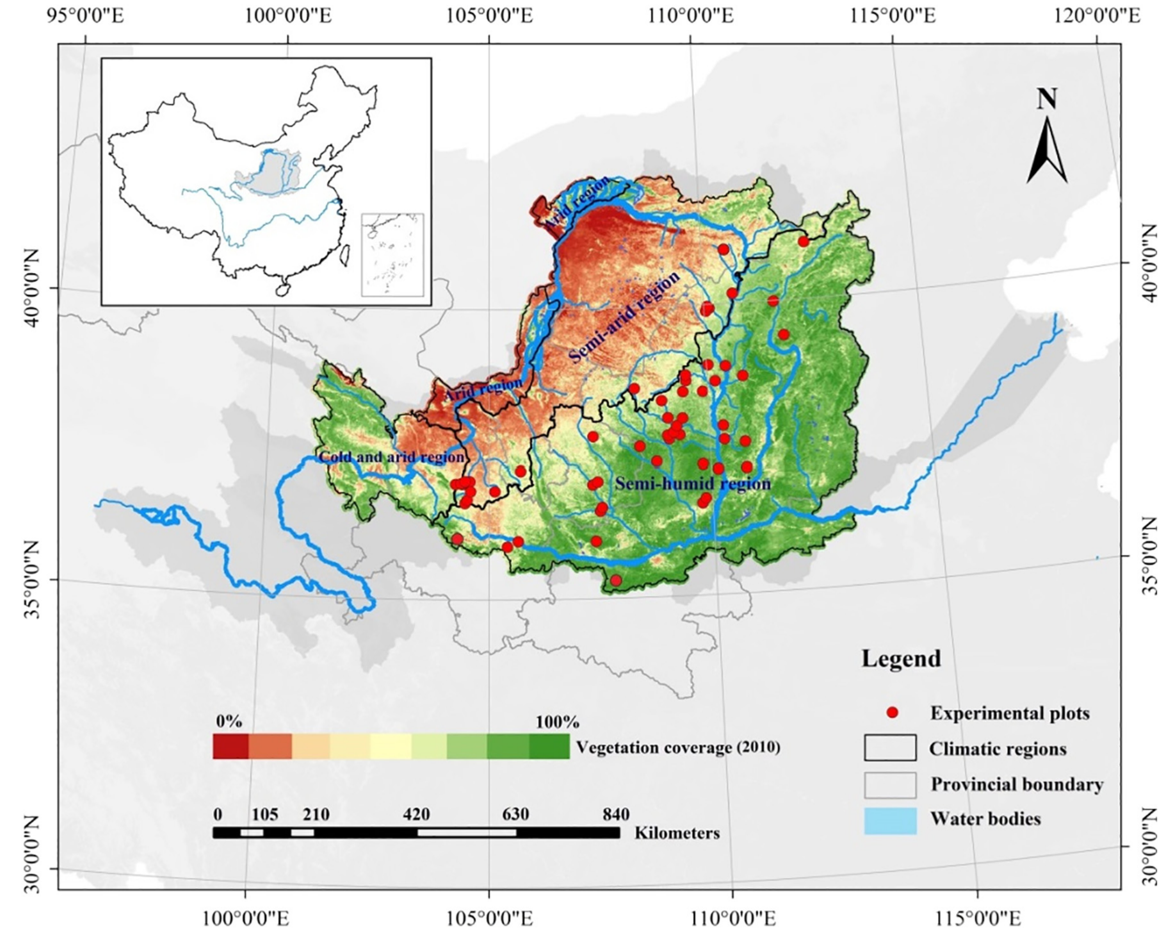

Fig. 2. The spatial distribution of the runoff plots and soil erosion measuring sites in the Loess Plateau (n = 55). Vegetation coverage was calculated from the satellite dataset, as proposed in the materials and methods. The Loess Plateau is divided into four climatic regions: I. Arid region; II. Cold and arid regions; III. Semi-arid region; IV. Semi-humid region (Xiao et al. 2017).

grasslands, the slope length was negatively correlated with soil loss ($p < 0.05$). Except for shrubland, the relationship between the slope gradient and the slope length of the other land-use types had no significant relationship with the annual runoff coefficient.

3.2. Differences in annual runoff and soil loss for various land-use types

The calculations of annual soil loss and annual runoff between the nine land-use types were based on annual scale and event scale

Table 1
Overview by county in the Loess Plateau of the number of plots (*PN*), plot-years (*PY*), and the source included in the plot database.

Province	County	PN	PY	Source
GS	DX	129	421	Chen, 2010; Chen et al. 2010; Gao, 2005; Ren et al., 2018; Wei et al. 2007; Wei et al., 2009; Zhang and Wang, 2008; Zhang et al., 2015; Zhao et al., 2004; Zhou et al., 2014
	JC	18	36	Wang, 1986
	TS	48	80	Lv et al. 2015; Wu et al. 1993
	QY	4	24	Li, 2006; Zheng 2006; Zhou et al., 2011
	XF	3	9	Shi et al., 2018
IM	JB	5	9	Kang et al. 2001; Xiao et al., 2016
NX	GY	9	22	Ma et al., 2007
SN	AS	189	794	Ai et al., 2017; Ai et al., 2013; Cheng et al., 2018; Fang et al. 2008; Feng et al., 2015; Feng et al., 2016; Li et al., 2004; Liu et al., 2000; Liu et al., 2011b; Luo et al., 2004; Shen et al., 2006; Wang et al., 2011; Yao et al., 2012; Zhao et al., 2006; Zhao, 2015; Zheng and Chen, 2015; Zheng et al., 2012; Zhou et al. 2016; Zhou et al., 2017; Zhu et al. 2015
	CW	28	107	Kang et al. 2001; Shi et al., 2018; Song et al., 2000
	HY	9	27	Liu et al., 2011a
	MZ	2	12	Yang et al., 1990
	SM	2	9	She et al., 2011
	SD	22	112	Huang et al. 2007; Jiang and Shao, 2011; Jiang et al., 2013; Liu et al., 2000; Yi and Fan, 2016
	ZZ	34	125	Chen et al. 2018; Cheng et al., 2018; Fang et al. 2008; Fang et al., 2011a; Fang et al., 2011b; Liu et al., 2000; Liu et al., 2012; Zheng et al., 2012
SX	J	21	38	Liu, 2004; Yan et al., 2015; Zhang et al., 2006
	JL	9	26	Wang, 2017
	LS	18	52	She et al., 2011; Zhu and Zhu, 2014
	SY	26	63	Zhang et al., 2015; Qu, 2017; Zhang, 2017

County by province: Gansu, GS (Dingxi, DX; Jingchuan, JC; Tianshui, TS; Qingyang, QY; Xifeng, XF); Inner Mongolia (Jungar Banner, JB); Ningxia, NX (Guyuan, GY); Shanxi, SX (Ji, J; Jingle, JL; Lishi, LS; Shanyin, SY); Shaanxi, SN (Ansai, AS; Changwu, CW; Heyang, HY; Mizhi, MZ; Shenmu, SM; Suide, SD; Zizhou, ZZ).

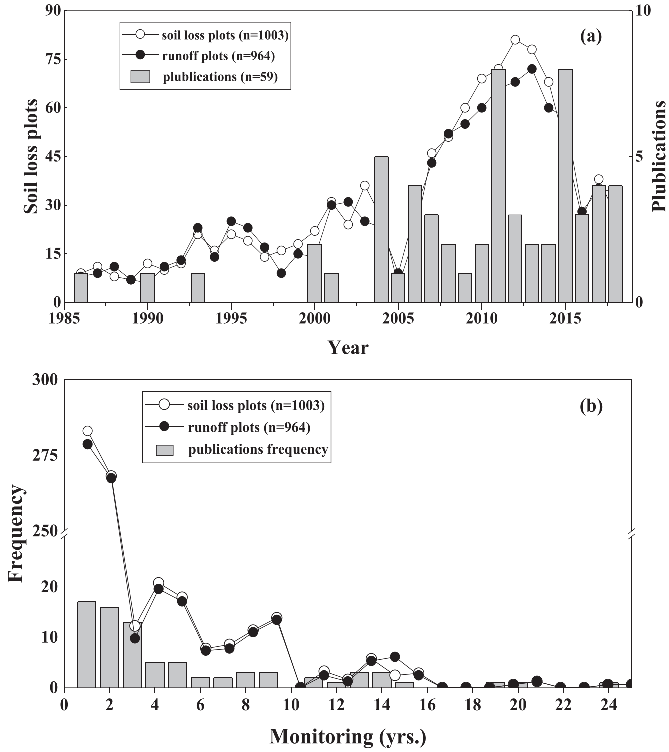

Fig. 3. (a) The total number of plots recorded for annual runoff and/or soil loss in the Loess Plateau, and the distribution of the contributing references (n = 59). (b) The frequency distribution of the number of plots with continuous measured annual runoff or annual soil loss as a function of the monitoring years (yrs) in the Loess Plateau.

(Fig. 4). The annual runoff and annual soil loss of bare soil and cropland were significantly higher than those of the other land-use types ($p < 0.05$). Natural grassland had the lowest annual runoff and annual soil loss, whereas the annual runoff and annual soil loss of the other land-use types had no significant difference (Fig. 4a and c). On the rainfall event scale, bare soil and cropland had the highest runoff and soil loss than those of other land-use types (Fig. 4b and d), whereas the event runoff of mixed forest, shrubland, artificial grassland, natural grassland, and sea-buckthorn were significantly lower than those of fallow and Chinese pine ($p < 0.05$). Except for bare soil, the event soil loss of the other land-use types had no significant difference (Fig. 4b and d).

The nine land-use types were divided into two groups. The first group included a runoff plot covered by bare soil and unnatural vegetation (i.e., artificial grassland, cropland, and fallow), with an average annual runoff ranging from 20 $mm \cdot yr^{-1}$ to 150 $mm \cdot yr^{-1}$ (Fig. 4a), and an annual soil loss of 20 $t \cdot ha^{-1} \cdot yr^{-1}$ and 270 $t \cdot ha^{-1} \cdot yr^{-1}$ for bare soil and unnatural vegetation, respectively (Fig. 4c). On the event scale, the runoff ranged from 10 $mm \cdot yr^{-1}$ to 30 $mm \cdot yr^{-1}$ (Fig. 4b) and soil loss from 30 $t \cdot ha^{-1} \cdot yr^{-1}$ to 150 $t \cdot ha^{-1} \cdot yr^{-1}$ (Fig. 4d). The second group of land-use types included runoff plots covered by natural vegetation (i.e. natural grassland, shrubland, mixed forest, Chinese pine, and sea-buckthorn). The annual runoff and soil loss were less than 15 $mm \cdot yr^{-1}$ and 20 $t \cdot ha^{-1} \cdot yr^{-1}$, respectively (Fig. 4a and c). On the event scale, the runoff was between 5 $mm \cdot yr^{-1}$ and 15 $mm \cdot yr^{-1}$ (Fig. 4b), and the soil loss was between 5 $t \cdot ha^{-1} \cdot yr^{-1}$ and 30 $t \cdot ha^{-1} \cdot yr^{-1}$ (Fig. 4d). The one-way ANOVA test found significant differences between the land-use type with crops and those with natural vegetation.

3.3. The effects of precipitation on annual runoff and soil loss in different land-use types

Fig. 5 shows the relationship between precipitation and runoff for different land-use types. Regressions between annual precipitation and runoff were found significant for all land-use types, with small differences among r^2 values. The annual runoff of all land-use types generally increased with rainfall, in which Chinese pine, bare soil, mixed forest, and fallow were positively correlated with annual precipitation (Fig. 5). Under the same rainfall conditions, the runoff of bare soil, cropland, and Chinese pine were significantly higher than those of the other land-use types (Fig. 6). Application of the one-way ANOVA test found that the runoff of bare soil and unnatural vegetation were significantly higher than those of natural vegetation.

The soil loss of all land-use types has an obvious linear relationship with precipitation (Fig. 7). Among them, the annual soil loss of cropland, bare soil, fallow, and artificial grassland were positively related with rainfall (Fig. 7). When the precipitation was within the range of 200–400 mm and 600–800 mm, the annual soil loss of shrubland, Chinese pine, artificial grassland, natural grassland, fallow, cropland, and bare soil was increasing (Fig. 6). When the rainfall ranged between 400 mm and 600 mm, the annual soil loss of the natural grassland and shrubland decreased, with the annual soil loss of the other vegetation types increasing (Fig. 6). An analysis of the characteristic values of runoff and soil loss based on different land-use types revealed a linear relationship between annual soil loss and annual runoff. The annual runoff of Chinese pine, bare soil, mingled forest, fallow, and natural grassland had a significant correlation with the annual soil loss ($p < 0.01$; Table 4).

Table 2
Description of land-use types in the plot database for the Loess Plateau.

Land-use type	Abbreviation	Description
Shrubland	Sh	Natural vegetation or plantation with predominance of shrub species.
Chinese pine	Cp	Plantation with a canopy closure >30%.
Artificial grassland	Ag	Grassland for grazing and managed through agricultural practices. Main plant species are *Medicago sativa* and *Wheatgrass*.
Cropland	Cr	The land for planting crops, including mature cultivated land and newly-opened wasteland, is cultivated for more than three years of agricultural land.
Bare soil	Ba	Continuously bare soil without crops or natural vegetation.
Mixed forest	Mf	Natural vegetation or plantation with predominance of tree species.
Fallow	Fa	Plowed and harrowed but left unsown for a period in order to restore its fertility as part of a crop rotation or to avoid surplus production.
Sea-buckthorn	Se	Dwarf woodland with a canopy density > 40% and a height below 2 m.
Natural grassland	Ng	All kinds of grassland with a growing herbaceous plant and coverage of 5% or more.

3.4. The impact of land use on runoff and soil loss in different climatic regions

The runoff plot data were grouped according to the climatic region to analyze the relationship between annual land-use types and soil loss in different climatic regions. After preliminary data compilation, all runoff plot data were divided into four climatic regions: arid, cold and arid, semi-arid, and semi-humid regions. The arid region was not considered due to insufficient plot data. Weighted average and median values of annual soil loss and annual runoff for different land-use types and climate regions are shown in Table 5, and the number of plots and plot-years for each land-use type can be found in Table S2 Supplementary. The basic conditions of the main climatic regions in the Loess Plateau can be found in Table 6.

The annual runoff, annual Runoff coefficient, and annual soil loss for all land-use types in cold and arid regions were smaller than those in the

Table 3
Spearman rank correlation coefficient (r_s) and p-values for the correlations between annual runoff, annual runoff coefficients, soil loss, plot length, and the slope gradient for the different land-use types in the Loess Plateau. Values in bold indicate significance at a < 0.05.

Land-use types	Runoff				Runoff coefficient				Soil loss			
	Plot length		Slope gradient		Plot length		Slope gradient		Plot length		Slope gradient	
	r_s	p	r_s	p	r_s	p	r_s	p	r_s	p	r_s	p
Shrubland	−0.69	$<0.01^{**}$	−0.39	0.21	−0.59	0.02^{*}	0.26	0.05^{*}	0.36	0.02^{*}	0.11	0.03^{*}
Chinese pine	0.73	0.02^{*}	0.45	0.15	0.38	0.17	−0.33	0.23	0.61	0.02	0.46	0.02^{*}
Artificial grassland	0.72	$<0.01^{**}$	0.47	0.01^{*}	0.17	0.54	−0.20	0.47	0.56	0.03	0.64	0.11
Cropland	0.54	0.037^{*}	0.68	$<0.01^{**}$	0.21	0.45	0.15	0.59	0.66	$<0.01^{**}$	0.75	$<0.01^{**}$
Bare soil	0.57	0.024^{*}	0.63	$<0.01^{**}$	0.37	0.18	0.19	0.51	0.78	$<0.01^{**}$	0.69	$<0.01^{**}$
Mixed forest	−0.65	$<0.01^{**}$	−0.37	$<0.01^{**}$	0.71	0.28	0.33	0.23	0.56	0.12	0.62	0.25
Fallow	0.62	0.01^{*}	0.41	0.03	−0.14	0.62	−0.37	0.17	0.57	0.03^{*}	0.71	0.21
Sea-buckthorn	−0.78	$<0.01^{**}$	−0.62	0.01^{*}	−0.23	0.42	−0.16	0.68	0.74	0.02	0.68	0.13
Natural grassland	−0.68	$<0.01^{**}$	−0.46	0.02	−0.38	0.16	−0.10	0.72	−0.61	0.01^{*}	0.47	$<0.01^{**}$

Significant correlations at a $p < 0.05^{*}$ and $p < 0.01^{**}$.

other two climatic regions (Table 5). In the different climatic regions, the annual runoff, annual soil loss, and annual runoff coefficient of bare soil and cropland were significantly higher than those of the other land-use types ($p < 0.05$; Table 5). The annual soil loss of shrubland, mixed forest, and natural grassland were significantly lower in the cold and arid regions than those in the other climatic regions ($p < 0.05$), except the differences between Chinese pine and artificial grassland in the cold and arid regions (Table 5). The average annual runoff coefficient was highest in the semi-humid region, and the median annual runoff coefficient of the cropland and bare soil in the semi-humid region were significantly higher than those in other climate regions ($p < 0.05$). In the different climatic regions, the annual runoff and annual runoff coefficient of natural grassland, shrubland, and sea-buckthorn had no significant difference.

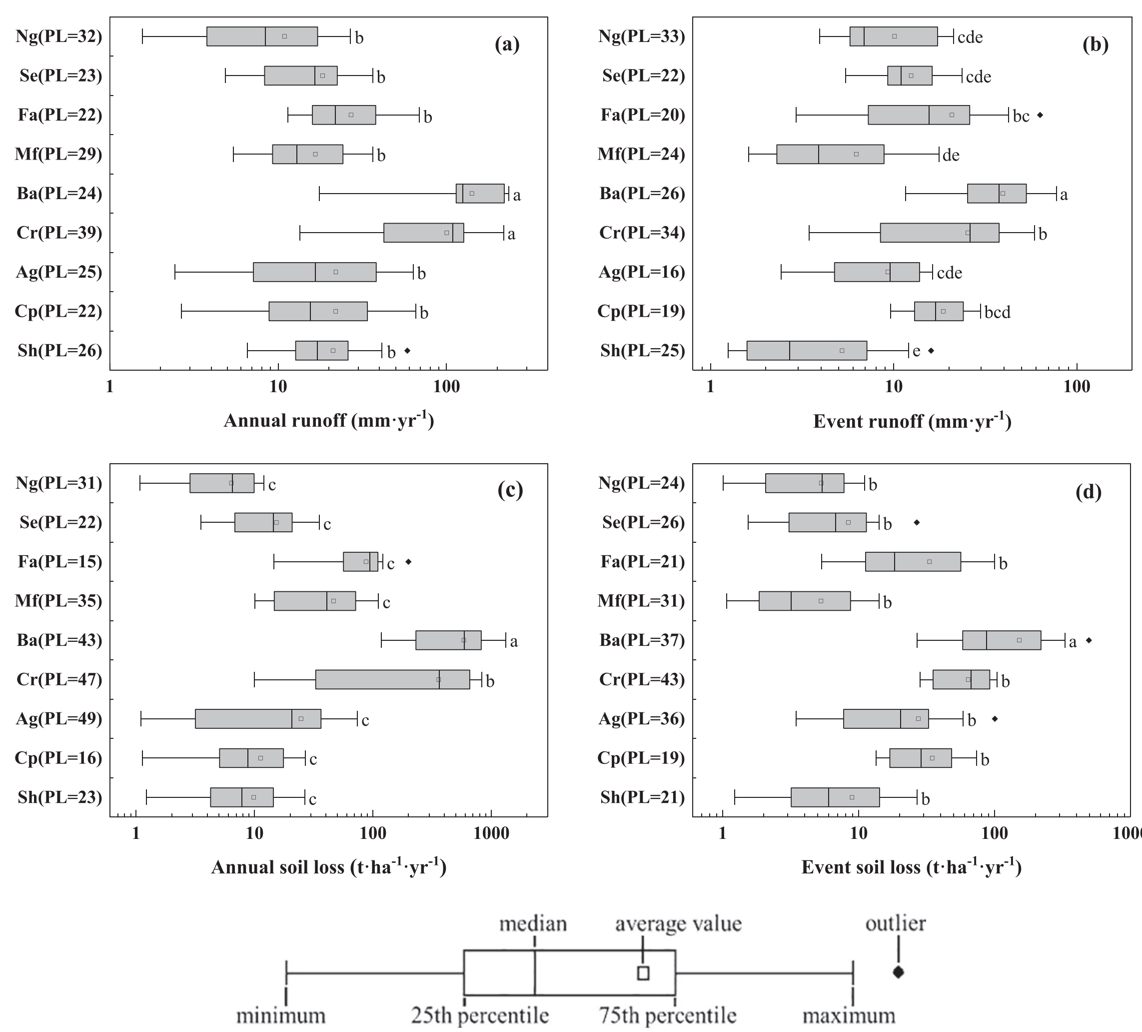

Fig. 4. A comparison of runoff and soil loss rates under different land uses. Different letters represent different statistical groups by Tukey-HSD comparisons at $p < 0.05$. Abbreviation of land use types can be found in Table 2.

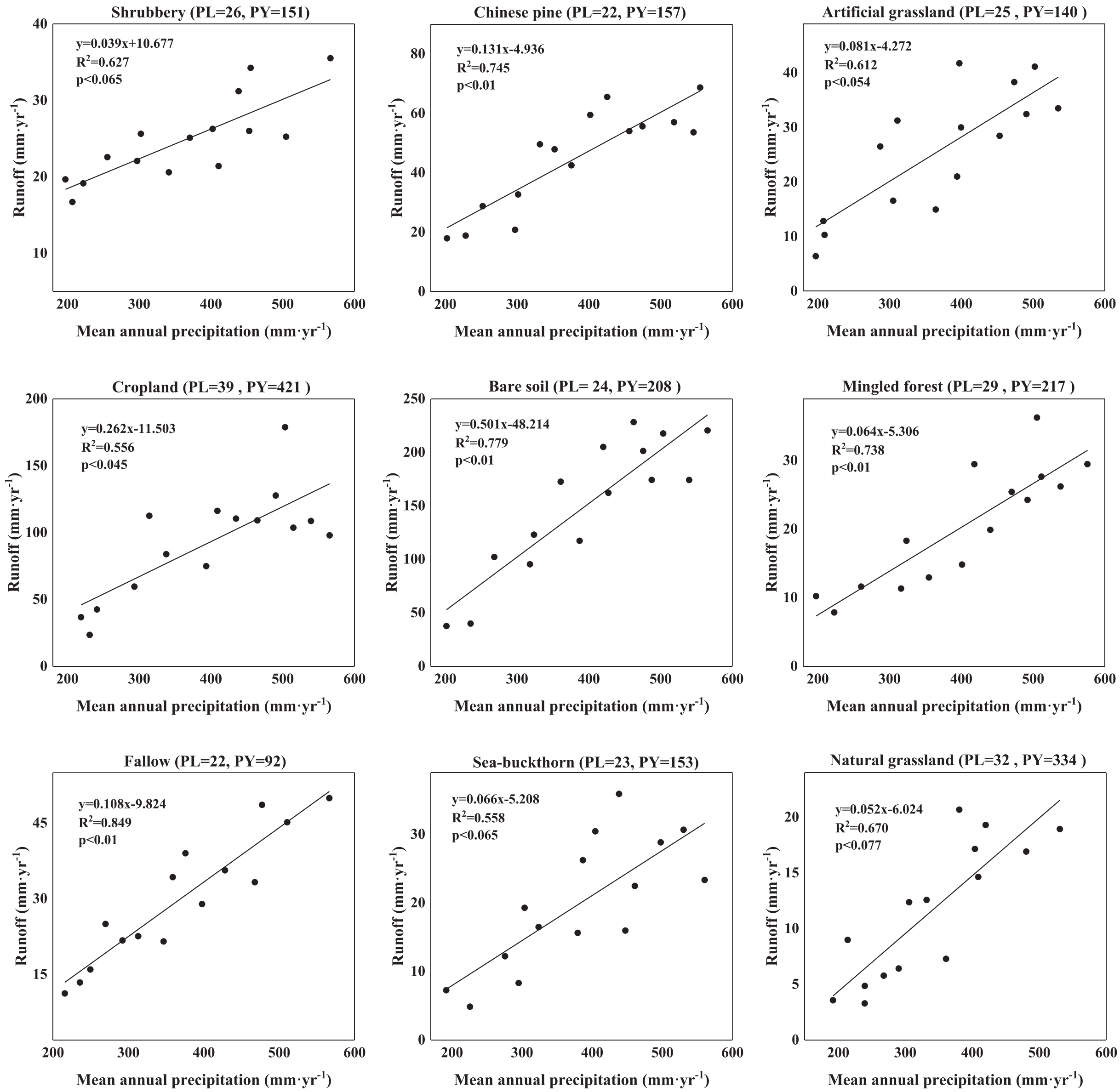

Fig. 5. Relation between mean annual precipitation and runoff for different land-use types in the Loess Plateau. R^2 = coefficient of determination.

4. Discussion

4.1. Implications of the analyses of the database from the plot area for the Loess Plateau

In the runoff plot database, most of the research was conducted on cropland, which was related to the land use type of the Loess Plateau. The area of the Loess Plateau is approximately 620,000 km^2, up to 32.6% of which is cultivated land (Zhou et al. 2016). Meanwhile, more than 73% of the literature considered grassland and bare soil as control groups. The runoff plot data can account for the severity of erosion in the Loess Plateau (Wu et al. 1993). However, of all the runoff plots in the database, the number of erosion measurements (plots = 1003) was greater than the runoff measurement data (plots = 964) (Fig. 3a). The complex relationship between soil erosion and environmental variables was one of the contributing factors to this difference. Generally, runoff data are easy to obtain, but it is necessary to combine these with soil loss data to explain the problem. As one of the regions that are most severely affected by soil erosion, the study of soil loss in the Loess Plateau is important. Therefore, most studies paid more attention to soil loss compared to runoff (Jiao et al. 2009; Wei et al. 2007; Zhao et al. 2013).

In the database, runoff plots were mostly established in semi-humid regions, with only a small number in semi-arid regions and cold and arid regions (Fig. 2). The annual precipitation in the arid area was less than 200 mm (Huang et al. 2007), and the type of erosion was mainly wind erosion. Relevant runoff plot data were not counted in the database. Therefore, the soil loss and runoff data presented in this study may not represent the arid region of the Loess Plateau. Nevertheless, the relationships between the annual precipitation, annual soil loss, and annual runoff of the different land-use types available were still best reflected in the scope of the database compiled.

4.2. The effective mechanisms of land use and plot structure for annual runoff and soil loss

The soil loss was proportional to the slope gradient under a certain range and condition (Hu and Jin 1999; Liu et al. 1994). In this study,

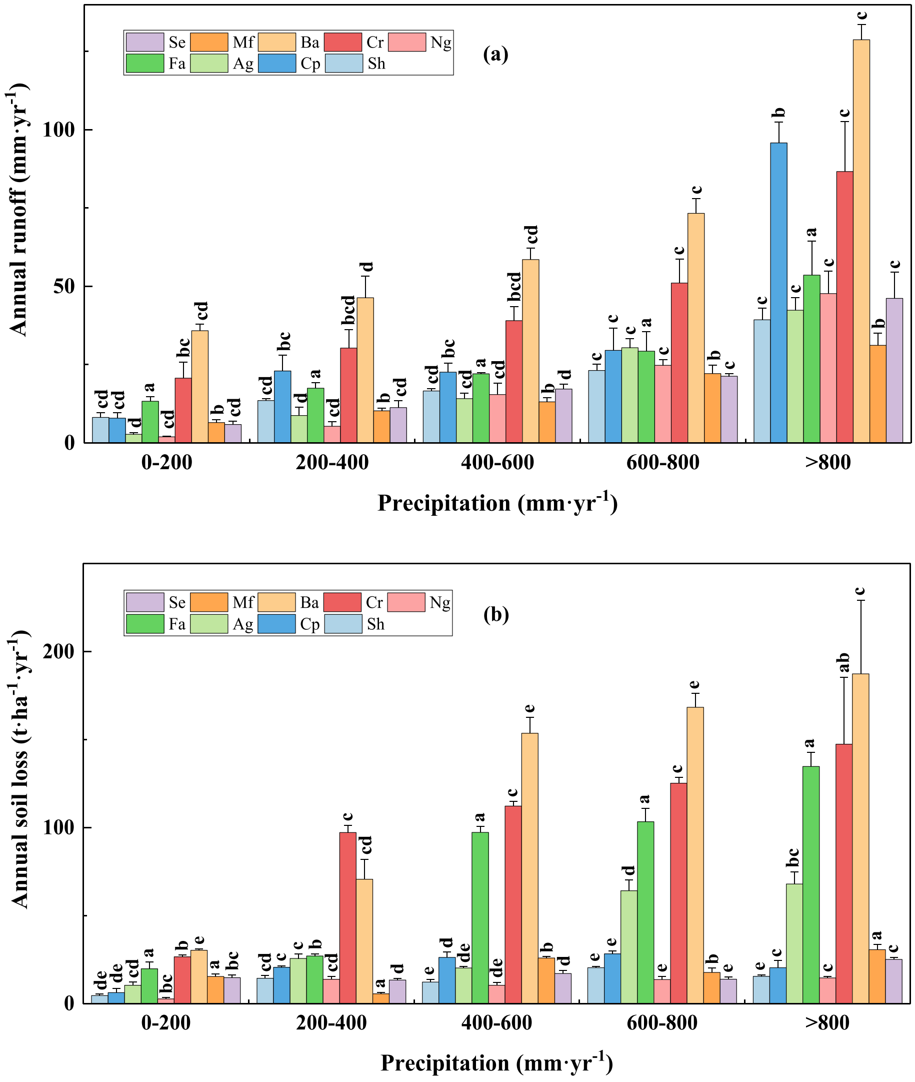

Fig. 6. The weighted average annual runoff and annual soil loss for each land-use type in the Loess Plateau with respect to the annual precipitation range. Different letters represent different statistical groups by Tukey-HSD comparisons at $p < 0.05$. Abbreviation of land use types can be found in Table 2.

we confirmed that the runoff and soil loss of bare soil and cropland increased with the slope gradient (Table 3). While Tang et al. (2015) considered that when the slope gradient reached a critical level, the amount of erosion began to decline. Due to the limitations of rainfall and soil infiltration, when the slope gradient reached to a certain degree, both runoff and soil erosion peaked or even decreased. Field and laboratory studies in most areas of China suggest that the critical slope gradient ranges from 25° to 29° (Huang et al. 2005; Liu et al. 2009). In this study, through the collected data and subsequent analysis, we found that the critical slope gradient of the runoff plot in the Loess Plateau was between 26° and 30° (Table 7). However, the influence of the critical slope gradient on runoff and soil loss was not considered due to small amount of data. The plot length was mostly 10 m and 20 m, and the projected area was a standard runoff plot (5×20 m^2). For natural grassland, the slope length was negatively correlated with runoff and soil loss, while no significant correlation with slope gradient was identified (Table 3). This was related to the high root density of natural grass, reducing soil erodibility to enable a better water storage capacity (Baets et al. 2006; Zhu et al. 2015). For shrubland and sea-buckthorn, a significant negative correlation between plot length and annual runoff was found (Table 3). This was probably related to the heterogeneity of soil cover and macropore distribution in these land-use types, while the soil infiltration capacity increased with longer slope length (Chen et al. 2013; Xiao et al. 2017). For mixed forest, a significant negative relation was noted between the slope gradient and annual runoff (Table 3). This is probably due to the wet clayey subsoil in the southern regions, which often need drainage (Chen et al. 2010; Fang et al. 2008; Lv et al. 2015). Overall, runoff and soil erosion increased with the slope gradient, while the slope length weakened the influence of the slope. In addition, the relationship between topographic factors and soil loss was not uniform among the land-use types.

Previous research has shown that vegetation is the key factor affecting soil erosion, while the effects of land-use types on soil loss differ (Fu et al. 2009; Wei et al. 2007; Zheng 2006). By analyzing precipitation at the annual scale and the event scale (Fig. 4), the runoff and sediment produced by unnatural vegetation were significantly larger than that of the natural vegetation on the event scale. It also proved that soil disturbance of natural vegetation was relatively small (Kinnell 2016; Phinzi and Ngetar 2019). High vegetation coverage and the formation of a protective layer after withering can effectively reduce the occurrence of erosion (Tadesse et al. 2017). However, the soil erosion process can occur more readily due to artificial disturbances, such as farming (Clay and Lewis 1990; Zhou and Wang 1992).

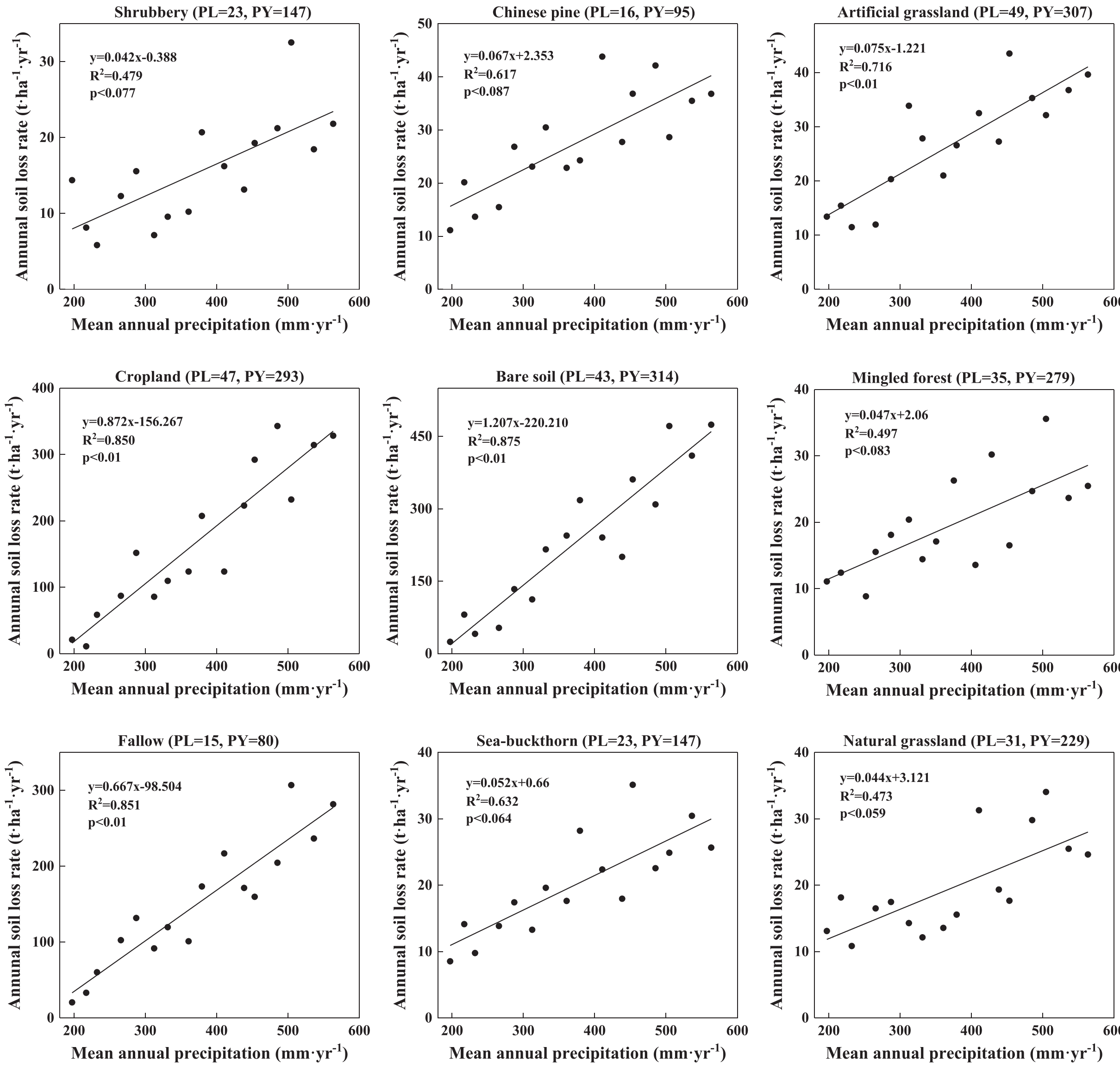

Fig. 7. Relation between mean annual precipitation and annual soil loss rate for the different land-use types in the Loess Plateau. R^2 = coefficient of determination.

4.3. Effects of precipitation on annual runoff and soil loss in different land uses

For all land uses, there was a consistent trend towards higher annual runoff with increasing annual precipitation, which was more pronounced for unnatural vegetation than for natural vegetation (Fig. 5). This indicated that the plot covered by the natural vegetation had a better ability to intercept and store rainfall than the unnatural vegetation. This may be related to the distribution of rainfall patterns. Regions with high annual precipitation exhibit more uniform

Table 4
Correlation analysis of runoff, soil loss and precipitation of the different land-use types in the Loess Plateau. Values in bold indicate significance at a < 0.05.

Land-use type	Precipitation-runoff		Precipitation-soil loss		Runoff-soil loss	
	Pearson correlation coefficient	Sig. (both sides)	Pearson correlation coefficient	Sig. (both sides)	Pearson correlation coefficient	Sig. (both sides)
Shrubland	0.823	<0.01**	0.611	0.016	0.313	0.257
Chinese pine	0.874	<0.01**	0.780	0.001**	0.823	<0.01**
Artificial grassland	0.800	<0.01**	0.739	0.002**	0.631	0.012
Cropland	0.767	0.001**	0.644	0.010	0.551	0.033*
Bare soil	0.892	<0.01**	0.743	0.001**	0.809	<0.01**
Mingled forest	0.870	<0.01**	0.766	0.001**	0.752	<0.01**
Fallow	0.927	<0.01**	0.687	0.005**	0.800	<0.01**
Sea-buckthorn	0.768	0.001**	0.717	0.003**	0.240	0.389
Natural grassland	0.844	<0.01**	0.502	0.056	0.831	<0.01**

Significant correlations at a $p < 0.05$* and $p < 0.01$**.

Table 5
The weighted mean and standard deviation (SD) of annual runoff, annual runoff coefficient, and annual soil loss for each land-use type for all data, grouped by climatic regions, in the Loess Plateau. Data was weighted based on the square root of plot-years. Different capital letters in same row indicate significant differences among different climatic region ($p < 0.05$). Different lowercase letters in same column indicate significant differences between different land-use types in the same climatic region ($p < 0.05$). *NA* = no data available.

Land-use types	Cold and arid regions			Semi-arid region			Semi-humid region		
	Annual runoff	Annual runoff coefficient	Annual soil loss	Annual runoff	Annual runoff coefficient	Annual soil loss	Annual runoff	Annual runoff coefficient	Annual soil loss
	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)
Shrubland	12.2 (0.15) ^{bA}	3.2 (0.41) ^{cA}	6.8 (0.28) ^{bA}	18.6 (0.37) ^{bA}	4 (0.21) ^{bA}	20.7 (0.67) ^{bB}	26.7 (0.42) ^{bA}	6.1 (0.42) ^{cA}	23.4 (0.74) ^{cB}
Chinese pine	13.87 (0.18) ^{bA}	3.7 (0.46) ^{cA}	NA	16.5 (0.9) ^{bA}	5.1 (0.25) ^{bA}	25.8 (0.46) ^{bB}	22.67 (0.52) ^{bB}	5.9 (0.37) ^{bcA}	44.3 (0.77) ^{bcB}
Artificial grassland	9.1 (0.15) ^{bA}	2.4 (0.17) ^{cA}	NA	12.6 (0.48) ^{bA}	3.6 (0.29) ^{bA}	20.9 (0.34) ^{bA}	20.6 (1.39) ^{bB}	3.9 (0.4) ^{cA}	27.1 (0.79) ^{cB}
Cropland	57.4 (1.26) ^{aA}	15.4 (0.57) ^{bA}	54.4 (2.89) ^{aA}	97.2 (3.37) ^{aB}	22.3 (0.34) ^{aB}	55.8 (3.01) ^{bA}	124.5 (7.41) ^{aC}	31.2 (1.69) ^{bB}	76.9 (2.66) ^{bB}
Bare soil	67.1 (2.25) ^{aA}	17.9 (0.45) ^{aA}	87.4 (1.08) ^{aA}	93.7 (1.21) ^{aB}	23.9 (0.37) ^{aB}	105.2 (1.39) ^{aB}	127.6 (2.08) ^{aC}	30.7 (0.69) ^{aB}	134.1 (1.77) ^{aB}
Mixed forest	17.4 (0.12) ^{aA}	4.9 (0.31) ^{cA}	11.2 (0.75) ^{bA}	29.3 (0.63) ^{aB}	5.6 (0.33) ^{bA}	26.7 (0.71) ^{bB}	34.9 (0.72) ^{aB}	10.3 (0.38) ^{cB}	35.6 (0.57) ^{bcB}
Fallow	16.7 (0.09) ^{bA}	4.5 (0.47) ^{cA}	20.7 (0.26) ^{bA}	23 (0.68) ^{bA}	6.4 (0.22) ^{bA}	32.6 (0.51) ^{bA}	29.1 (0.84) ^{bA}	7.8 (0.37) ^{bcA}	48.7 (0.51) ^{bcB}
Sea-buckthorn	12.6 (0.1) ^{bA}	3.4 (0.23) ^{cA}	23.5 (0.31) ^{bA}	17.2 (0.41) ^{bA}	4.2 (0.25) ^{bA}	22.5 (0.47) ^{bA}	20.1 (0.49) ^{bA}	5.3 (0.21) ^{cA}	39.6 (0.57) ^{bcA}
Natural grassland	8.3 (0.11) ^{bA}	2.3 (0.23) ^{cA}	19.3 (0.37) ^{bA}	10.4 (1.03) ^{bA}	2.4 (0.16) ^{bA}	19.6 (0.34) ^{bB}	12.8 (0.52) ^{bA}	3.6 (0.32) ^{cA}	24.1 (0.46) ^{cB}

precipitation distribution throughout the year (Beats et al., 2006; Chen et al. 2018). Comprehensive research has revealed similar spatial distribution characteristics for the average annual erosive rainfall and the rainfall erosivity in the Loess Plateau, while the annual rainfall was positively correlated with erosive rainfall. Precipitation generally increased from northwest to southeast, but the amplitude of variation was quite different (Xiao et al. 2017).

Annual soil loss increased with annual precipitation for all land-use types (Fig. 7). Under the same rainfall amount, the sediment yields in bare soil and the unnatural vegetation covered plots were significantly higher than those in natural vegetation covered plots (Fig. 6). When the rainfall amount was within the range of 400–600 mm, shrubland had a better effect of reducing runoff and sediment, while when the rainfall amount was >600 mm, the natural grassland had the best effect on soil and water conservation. When the rainfall was <200 mm, the mixed forest affected soil and water conservation. A similar trend was noted by Wei et al. (2007), who attributed the reduction of erosion with the increase in vegetation coverage. This also agrees with the findings of Chen et al. (2018). However, as annual precipitation further increased, vegetation cover also increased, effectively reducing annual soil loss at higher annual precipitation.

4.4. Land use optimization of different climatic regions in the Loess Plateau

Owing to special natural factors and unreasonable land use patterns, the Loess Plateau is one of the areas with the most severe soil and water loss in the world (Dotterweich 2013; Zhang et al. 2010b). With the adoption of a series of ecological measures, such as Grain for Green, the construction of a shelter forest system and grazing bans, the land use pattern of the Loess Plateau has changed significantly, impacting soil erosion (Fu et al. 2011; Li et al. 2015). The long-term goals of controlling soil erosion in the Loess Plateau was to reduce the amount of sediment entering the Yellow River by 916 million tons per year (348 million $m^3 \times 26.33$ kg/m^3) and to ensure that soil loss was controlled at approximately 360 million tons, which required the vegetation coverage to reach over 40% (Wang et al. 2012; Zhao et al. 2013). Although large-scale soil erosion control in the Loess Plateau has been performed for more than 60 years, the vegetation coverage rate is only 25.9% (Table 6), of which the forest coverage is less than 16%. These factors are related to the environmental conditions in the different climatic areas of the Loess Plateau. Owing to the obvious difference in precipitation characteristics in each climatic region, the average precipitation gradually decreases from the southeast to the northwest. Therefore, ecological restoration measures need to be selected according to different climatic region.

When compared to the region with the same latitude in the Mediterranean, the semi-humid climate region of the Loess Plateau had higher soil erosion, which was related to rainfall and soil properties (Hu et al. 2017; Maetens et al. 2012). The semi-humid climate region has abundant rainfall, with an annual precipitation of more than 500 $mm \cdot yr^{-1}$ (Table 6). In addition, many agricultural lands exist in this region (Xiao et al. 2017). Vegetation restoration in this region has great potential, so ecosystem damage should be repaired quickly (Su and Fu 2013), such as barren mountains, barren slopes, sparse forest and shrubs, grassland, or sparse forests restored by turning farmland to forest. Compared to loess regions in Western and Central Europe, the higher annual runoff coefficient observed in the semi-arid region of the Loess Plateau may be attributed to the combination of soil properties and the discontinuous natural vegetation cover in the region (Kang et al. 2001; Zuo et al., 2016). In the semi-arid region, the annual precipitation is 334.83 $mm \cdot yr^{-1}$, which is beneficial to the restoration of vegetative growth (Yang et al. 2014), and ecological restoration should be focused on bare soil, gravel land, sparse grassland, shrubland, sparse forest land and returning farmland to forests. The annual precipitation in the arid region is less than 200 $mm \cdot yr^{-1}$ and the main soil erosion type is wind erosion; the ecological restoration of this region is difficult (Zhang et al. 2016). Therefore, the ecological restoration process should focus on the intensity of wind erosion. As the cold and arid regions are close to the Tibetan Plateau, the high altitude enhances the rainfall process (396.63 $mm \cdot yr^{-1}$, Table 6), and is higher than those of the semi-arid and arid regions (Li et al. 2012). Compared to the cold region in Europe, lower annual runoff and soil loss were observed in the cold and arid regions of the Loess Plateau, which may be related to the higher vegetation coverage in the region (Maetens et al. 2012; Xiao et al. 2017). Due to heavy rainfall in summer, the specific restoration objectives of this region should be based on farmland, the single forest species, grazing grassland, and hilly slopes.

Table 6
The basic conditions of the main climatic regions in the Loess Plateau.

Climatic region	Erosion area ($10^4 \cdot km^2$)	Area ratio %	Annual precipitation ($mm \cdot yr^{-1}$)	Erosion amount ($t \cdot a^{-1}$)	Erosion ratio %	Vegetation coverage %
Arid region	4.68	7.46	167.01	5123.82	3.62	10–25
Cold and arid regions	6.35	10.67	396.63	9637.84	6.98	19–26
Semi-arid region	22.09	26.83	334.83	42,364.91	32.06	15–25
Semi-humid region	28.68	45.71	528.57	73,262.55	51.83	25–35

Table 7
The compilation of research results on the critical slope of soil erosion.

Region	Source	Study year	Site (agrotype)	Research technique	Critical slope of soil erosion on slope
Loess Plateau	Chen et al. 2013	2013	Yangling District	Indoor simulated rainfall experiment	20°
	Fang et al. 2008	1961–1969	Zizhou county	Field simulated rainfall experiment	Total splash erosion is 21.4°; Slope splash erosion is 26.3°
	Huang et al. 2005	1986–1999	Dingxi county	Runoff observation on plots	Critical Slope of soil erosion is 21.4°–45°; loessal soil is 28°
	Hu and jin, 1999	1998	The topsoil of abandoned land	Artificial simulated rainfall erosion experiment	The rill erosion and surface erosion on loess slope is 22°–26°
	Liu et al. 2009	1990	Mizhi county	Runoff observation on plots	24°
	Wu et al. 1993	1945–1957	Ansai county	Indoor simulated rainfall experiment	Total splash erosion is 20°–25°, Splash erosion of lateral slope is 10°–15°
Other region	Bryan 1979	1979	Alberta soil	Simulated rainfall	15°–18°
	Liang et al. 2017	2016	Red soil	Indoor simulated rainfall experiment	The total amount of splash erosion is 19.6°; splash erosion is 24.8°
	Li et al. 2016	2015	Jiangsu Province	Indoor simulated rainfall experiment	26.5°
	Liu et al. 2001	2001	Beijing city	Theoretical derivation: slope flow shears stress.	41.5° ~ 50°
	Mccool et al. 1987	1939–1963	America	Manning formula calculation	57°

5. Conclusion

The ecological restoration of the Loess Plateau increases the vegetation coverage and effectively controls the soil erosion but leads to excessive land use. Because of the inappropriate vegetation restoration mode, large areas of artificially restored vegetation began to degrade, thus the optimization of vegetation allocation has become an urgent necessity. To evaluate the relationship between land use and runoff and erosion at the regional scale of the Loess Plateau, the data sets of all available runoff plots in the Loess Plateau were compiled, including the runoff and soil loss data from 461 runoff plots at 55 measuring points. Runoff plots covered by natural vegetation had a better ability to intercept and store rainfall than those with unnatural vegetation. A linear relationship was identified between runoff and soil loss. Natural grassland, mixed forest, and shrubland exhibited a positive effect on reducing runoff and soil erosion, of which shrubland was more effective in reducing soil erosion. Shrubland could be a preferred vegetation type for the ecological management in the Loess Plateau. Furthermore, the relationship between soil loss and runoff depended on the climate. The annual runoff coefficient was higher in the semi-humid regions and lower in the arid and semi-arid regions. In the future management of the Loess Plateau, natural recovery should be the main work, whose ecological benefits deserves attention. Meanwhile, the soil water condition should be taken into consideration, so that the treatment model of the Loess Plateau is changed from traditional large-scale afforestation to the treatment mode that involves a combination of biological and engineering measures.

CRediT authorship contribution statement

Xuexian Zhang: Investigation, Methodology, Writing- Original draft preparation.
Jinxi Song: Supervision, Conceptualization, Project administration, Funding acquisition.
Yirui Wang: Data curation, Software.
Wenjia Deng: Visualization.
Yifan Liu: Validation, Formal analysis.

Declaration of competing interest

We declare that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2020.142418.

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