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Threshold effects of vegetation coverage on runoff and soil loss in the Loess Plateau of China: A *meta*-analysis

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ABSTRACT

In the loess plateau, due to the vegetation recovery has achieved preliminary results, while it is controversial whether the vegetation cover can be increased unrestrictedly for a long time, thus defining the vegetation coverage threshold is gaining urgency. The purpose of this study was to define the vegetation coverage thresholds of runoff and soil erosion in the Loess Plateau, and quantify the effect of vegetation coverage changes on soil and water loss, and evaluate the effective vegetation coverage in different climatic regions. A total of 59 watersheds were involved in the *meta*-analysis, including 38 counties belonging to 6 provinces in the Loess Plateau. The vegetation coverage increased from 2.51% to 86.80%, the runoff modulus ranged from 155.7 to 780431.8 $m^3 \cdot km^{-2} \cdot a^{-1}$, and the soil erosion modulus ranged from 400 to 58285 $t \cdot km^{-2} \cdot a^{-1}$. Three specific vegetation coverage thresholds were identified for soil erosion: the lower threshold (0%–35%), the transition (35%–65%), and the upper threshold (65%–100%); four specific vegetation coverage thresholds were identified for runoff: the low threshold (0%–20%), the transition (20%–50%), the high threshold (50%–75%), and the upper threshold (75%–100%). In the Loess Plateau, the effective vegetation coverage in the cold and arid regions is 25.12%, in the semi-humid region is 51.02%, in the semi-arid region is 45.92%, and in the arid region is 26.53%, to which corresponding ecological management strategies should be adopted. Clarifying the impact of vegetation coverage on water and soil loss at the regional scale can provide insight into suitable management programs for the new pattern of runoff and soil erosion formed by the vegetation restoration in the Loess Plateau.

1. Introduction

Soil and water loss are important causes of soil degradation, reduction in agricultural productivity, and disruption to regional ecological balance, affecting global ecosystem security (Guerra et al., 2020; Liu et al., 2019; Nikolic et al., 2019). Among the factors affecting runoff and soil erosion, vegetation is the key factor in controlling the occurrence and development of water and soil loss (Fu, 2011; Nunes et al., 2009). The occurrence of soil erosion can be reduced by the functions of vegetation cover (effectively weakening raindrop kinetic energy, reducing splash erosion, and increasing surface roughness to intercept sediment) and plant roots (consolidating soil, improving soil resistance, and enhancing soil infiltration) (Liu et al., 2018; Martin et al., 2010; Zhang et al., 2018). Therefore, a reasonable increase in vegetation coverage is the key to controlling soil erosion and regulating runoff.

Vegetation restoration is deemed effective means to increase the vegetation coverage, an important indicator of the ecological condition of the terrestrial ecosystem (Sun et al., 2015; You et al., 2005). The distribution of vegetation is affected by many factors, such as topography, meteorology, socio-economic development, and national resource protection policies (Dwarakish et al., 2015; Xin et al., 2012). A reasonable increase in vegetation cover can effectively control the soil erosion rate, increase soil carbon sequestration, and conserve environmental resources (Wu et al., 2019; Zhang et al., 2020). However, unsuitable vegetation coverage changes can spell pernicious environmental issues such as water shortages and increased erosion,

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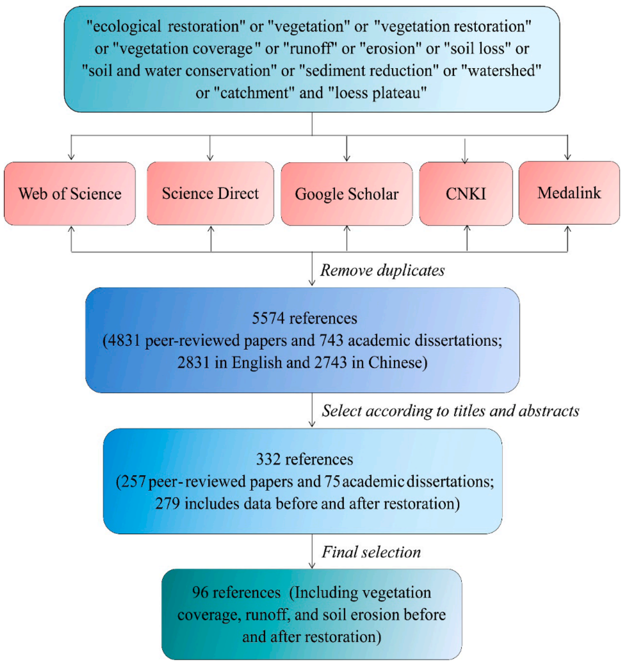


Fig. 1. Schematic representation for the literature search process of *meta*-analysis.

especially in regions prone to soil erosion (Mao and Cherkauer, 2009; Tong et al., 2018; Zhang et al., 2011). Consequently, assessing the impact of human-induced vegetation coverage changes on water and soil loss is important for the sustainable management of watersheds.

As an important ecological process, the impact of vegetation coverage on runoff and soil loss under different restoration modes exhibits threshold behaviors (Chen et al., 2019; Liu et al., 2018). Determine the threshold values of vegetation coverage can effectively improve the accuracy of soil loss prediction, especially in the regions with severe soil erosion (Xia et al., 2018). While ignoring the threshold effect between soil loss and vegetation coverage will lead to a series of problems in the process of vegetation restoration, such as unreasonable woodland structure and poor ecosystem function (Zhang et al., 2019). Some scholars have examined the threshold effect of vegetation coverage on water and soil loss in the process of vegetation restoration. For instance, in northeastern Iran, the vegetation cover has a greater impact on soil loss than on runoff, with 50% of coverage being the strongest control effect on soil erosion (Eshghizadeh et al., 2018). Such a finding was confirmed in central-eastern Spain, where the control of soil erosion achieves a satisfactory level when the vegetation coverage reaches at least 50% (Moreno-de Las Heras et al., 2009). In the tropical mountainous areas of Central America, the vegetation coverage reaches 60% or even 65% for effective soil erosion control (Chartier and Rostagno, 2006). In southeastern China, when vegetation coverage reaches over 80%, the soil loss was slight and stable (Chen et al., 2019). In Nigeria, soil loss can be minimized or even eliminated during the rainy seasons when the vegetation cover reaches about 95% (Jimoh, 2011). It can be seen that the vegetation coverage thresholds vary greatly in different climatic environments, hence define the effective vegetation coverage threshold needs to be adaptation to local conditions.

Meta-analysis is deemed a suitable means to explore the effect of vegetation coverage on water and soil loss on a regional scale (Chen et al., 2019; Hu et al., 2017). This method can comprehensively analyze multi-source data and eliminate multi-party differences, thereby enabling the assessment of the effective thresholds of vegetation coverage. The *meta*-analysis approach has been applied to investigate the effect of vegetation cover on soil loss in the northeast of Iran (Eshghizadeh et al., 2018), and on annual soil loss and runoff in Brazil (Anache et al., 2017). In the southeast of China, reasonable upper thresholds of vegetation coverage were determined through *meta*-analysis during regional ecological restoration (Chen et al., 2019). In addition, the *meta*-analysis has been involved in exploring the effects of land use on water and soil loss in the Euro-Mediterranean region (Maetens et al., 2012).

Currently, studies on the thresholds of vegetation cover on soil and water conservation were mainly conducted at the runoff plot and small watershed scales (Chen et al., 2019; Eshghizadeh et al., 2018). The results of these small-scale studies are inconsistent owing to different climatic factors, topographic conditions, erosion types, and study scales. With a lack of analysis at a regional scale, it is difficult to meet the needs of large-scale ecological management (Chen et al., 2018; Eshghizadeh et al., 2016; Mohammad and Adam, 2010). On the Loess Plateau, without considering runoff previous studies have paid attention to the effect of vegetation coverage on soil loss (Sun et al., 2013; Zhao et al., 2020b). In contrast, our research analyzed the comprehensive effect of vegetation coverage on runoff and soil erosion, which can better explore the scientific management of regional ecological restoration and the optimal allocation of vegetation.

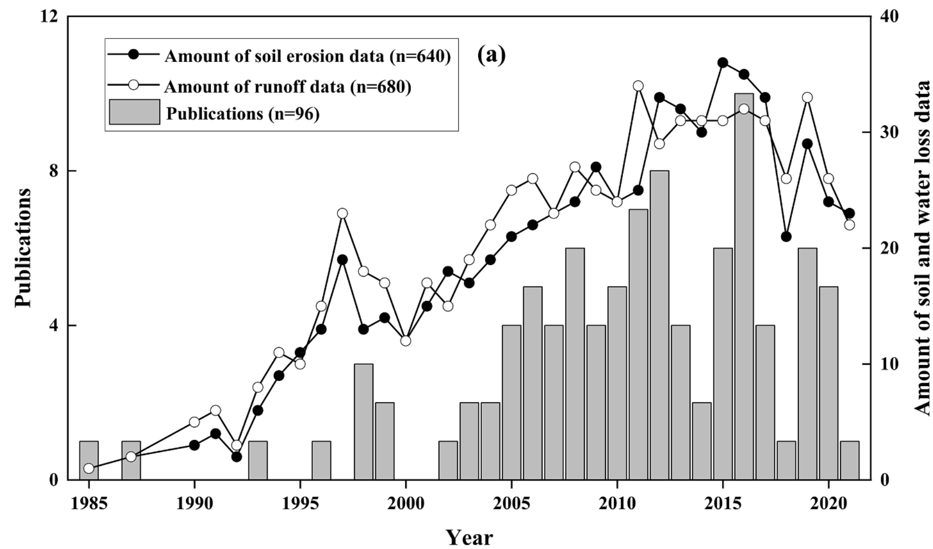
Since the implementation of large-scale vegetation restoration on the Loess Plateau in 1999, although the severe erosion situation has been effectively controlled, it has also been accompanied by controversial problems such as soil desiccation, deterioration of indigenous ecosystems, and unreasonable regional vegetation restoration (Han et al., 2020; Otsuki et al., 2014). In this paper, we hypothesized that: (1) vegetation coverage has a threshold influence on soil and water loss provided vegetation is sufficiently developed or good management; and (2) the threshold range can be divided by *meta*-analysis. This study integrated watershed-scale data from the Loess Plateau and used *meta*-analysis to quantify the comprehensive threshold effect of vegetation coverage on runoff and soil erosion. Therefore, the specific research purposes of this paper were: (1) identify the influence of vegetation coverage on soil and water loss in the Loess Plateau; (2) determine the threshold effect of vegetation coverage with runoff and soil erosion; and (3) assess the effective vegetation coverage of the Loess Plateau.

2. Materials and methods

2.1. Literature search and watershed selection criteria

The data used in the *meta*-analysis were obtained through a collection of peer-reviewed papers in journals. We searched Chinese (via Medalink and China National Knowledge Infrastructure) and English (via Google Scholar, Web of Science, and Science Direct) dissertations or journal articles published from 1985 to 2021. Keywords involved were “ecological restoration”, “vegetation”, “vegetation restoration”, “vegetation coverage”, “land cover”, “runoff”, “sediment reduction”, “soil loss”, “soil and water conservation”, “erosion”, “watershed”, “catchment”, and “loess plateau” (Fig. 1). EndNote X7 and E-study software were used to filter and manage documents and remove duplicate content. The data in the literature presented only in the form of pictures were extracted using Origin and GetData Graph Digitizer.

The collected literature need to meet the following criteria: (1) the watersheds involved were located in the Loess Plateau, and the sample data, treatments, and research method could be found directly in the articles; (2) the study recorded variables, at least partly, including soil erosion, runoff, and vegetation coverage before and after restoration; (3) number of replications was considered, and the same watershed data of different articles are only included once; (4) clear information about the study area has been presented, such as geographic coordinates, watershed description, vegetation coverage, and monitoring period. A *meta*-analysis of the soil properties, such as texture, soil organic matter content, and soil erodibility, was not conducted, because quantitative data on these properties were not systematically reported in the extracted literature. In this *meta*-analysis, a final data set of 96 articles and 59



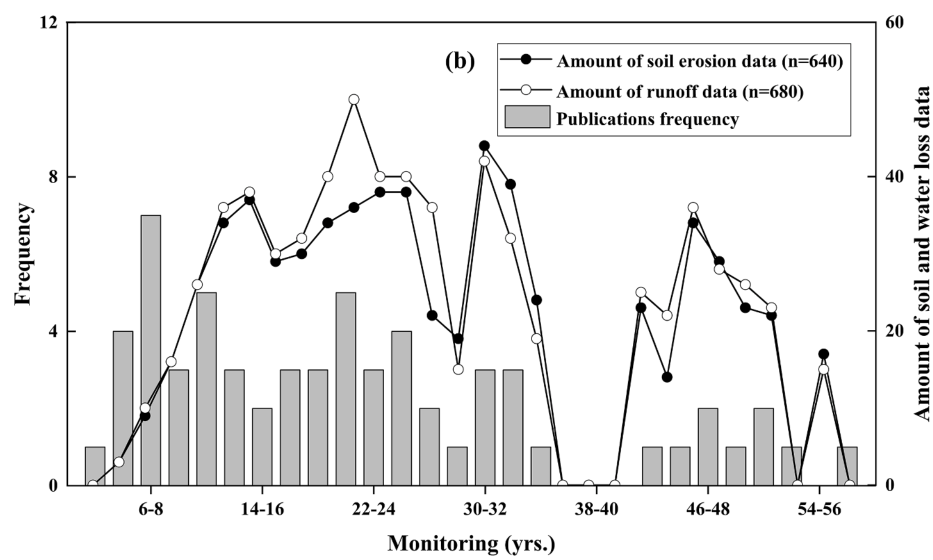


Fig. 2. (a) The total number of watershed data recorded for annual runoff and/or soil erosion in the Loess Plateau, and the distribution of the contributing references (n = 96). (b) The frequency distribution of the number of watershed data with continuous measured annual runoff or annual soil loss as a function of the monitoring years (yrs) in the Loess Plateau.

watersheds were involved (Supplementary Table S1).

2.2. Data compilation and preprocessing

The data characteristics and the data sources were first identified in the analysis. The number of research papers has increased since 2006 according to the year of publication (Fig. 2a). The average measurement period is 20 years, with most of the monitoring period being at least 2 years (Fig. 2b). This study included 59 watersheds, distributed across 38 counties in 6 provinces (Gansu, Shaanxi, Qinghai, Shanxi, Inner Mongolia, and Ningxia) in the Loess Plateau (Table 1). The geographical location of each watershed can be found directly in the publications. Considering the comprehensive effects of vegetation communities in the watershed (Cammeraat, 2004; De Vente and Poesen, 2005; Jiao et al., 2000), only the effects of vegetation coverage on runoff and soil erosion reduction were analyzed in this study. The data of runoff modulus, erosion modulus, and vegetation coverage before and after the restoration of the watershed were compiled (Table 2). The annual NDVI data was available from the National Earth System Science Data Center (http://loess.geodata.cn/index.html) and the Resource and Environment Science and Data Center (https://www.resdc.cn/Default.aspx). Hydrological station reports were available from the China National Data Sharing Infrastructure for Earth System Science (http://www2.geodata.cn/), and meteorological data sources were from the China Meteorological Data Service Centre (http://data.cma.cn/).

According to the "Standards for Classification and Gradation of Soil Erosion (SCGSE) (SL190–2007)" (Bai and Yan, 2013; Rao et al., 2015), the soil erosion of watersheds in the Loess Plateau is divided into six grades: slight (<1000 $t{\cdot}km^{-2}{\cdot}a^{-1}$), mild (1000–2500 $t{\cdot}km^{-2}{\cdot}a^{-1}$), moderate (2500–5000 $t{\cdot}km^{-2}{\cdot}a^{-1}$), strong (5000–8000 $t{\cdot}km^{-2}{\cdot}a^{-1}$), extremely strong (8000–15,000 $t{\cdot}km^{-2}{\cdot}a^{-1}$), and intense (>15,000 $t{\cdot}km^{-2}{\cdot}a^{-1}$). With the regulations of "Specification for Division and Coding of Small Watershed (SL 653-2013)" (Zhang et al., 2016b), the small watersheds of the Loess Plateau include three scales: large-scale (1000–500 km^2), medium-scale (500–50 km^2); and small-scale (<50 km^2). The comprehensive quantitative index of plant community coverage is defined as the vegetation coverage, and then comprehensively analysis the effect of vegetation coverage on soil and water loss (Guo, 2000; Jin et al., 2014). Due to the complex topography of the Loess Plateau, four climatic regions were divided based on climatic and

Table 1
Overview of the number of the selected watersheds (NW) in the Loess Plateau by county and source.

Province	County	NW	Source
GS	DX; QY; TS; PL; XF	14	Bian et al., 2015; Chen, 2006; Chen, 2015; Gao, 2005a; Gao, 2005b; Han, 2011; Hu, 2007; Li, 2011; Wang et al., 2004; Wang and Wang, 2016; Wang, 2007; Wang, 2015c; Xia et al., 2016; Yang, 2009; Yang, 2016; Yang, 2019; Yuan et al., 2021; Zhang, 2008; Zhang et al., 2011; Zhou, 2005; Zhou, 2013
NX	XJ; PY; GY	4	Li et al., 1997; Shi, 2016; You and Li, 2005; Zhou et al., 2016
SN	AS; CW; DH; FG; HS; JB; LT; QJ; SD; SM; WQ; YA; YC; YL; ZD; ZC; ZZ	26	Bai, 2011.; Chang, 2006; Chen, 2015; Cheng, 2011; Cheng, 2010; Cheng, 2016; Feng and Zheng, 1998; Fu and Chen, 1999.; Fu, 2017; Fu et al., 2017; Fu, 2011; Hao, 1985; Hu, 2020; Lan and Kang, 2010; Li et al., 2008; Li, 2019; Li, 2013; Lu, 2009; Lu, 2014; Luan, 2008; Luo, 2007; Ma, 2012; Pei, 2019; Qi et al., 2010; Qi, 2010; Shi, 2019; Shi et al., 1999; Song et al., 2018; Su, 2016; Wang et al., 2020; Wang, 2020a; Wang, 2015a; Wang, 2006; Wang, 2016; Wang, 2003; Wen et al., 1998; Wu, 2003; Wu et al., 1996; Wu et al., 2020; Xu et al., 2012; Xu et al., 2008; Yan et al., 2019; Yan, 2017; Yang, 2012; Yao et al., 2015; Yao, 2012; Yu, 2011; Zhang et al., 2002; Zhao et al., 2012; Zhao et al., 2013; Zhao et al., 2016
IM	DB; DS; JBr	3	Li, 2016; Ran, 2006; Wang, 2015b; Xu, 2019
SX	DN; X; HQ; JX; LX; LI; SL; LS;	9	Dou, 2010; Du, 2012; Guo, 2013; Huo, 2006; Jin et al., 2004; Jin et al., 2017; Li, 2004; Liu, 2004; Liu, 1987; Tang, 2009; Wang et al., 2014; Wu, 2007; Yuan, 2009; Zhang, 2011; Zhao and Zhang, 2012
QH	DT; PA	3	Gu, 2012; Jiang, 2008; Wang and Gao, 1993; Wang, 2020b; Yao, 2012; Zhao et al., 2008

Gansu, GS (Pingliang, PL; Dingxi, DX; Qingyang, QY; Tianshui, TS; Xifeng, XF); Ningxia, NX (Guyuan, GY; Pengyang, PY; Xiji, XJ); Shaanxi, SN (Ansai, AS; Changwu, CW; Dunhua, DH; Fugu, FG; Hengshan, HS; Jingbian, JB; Lantian, LT; Qingjian, QJ; Suide, SD; Shenmu, SM; Wuqi, WQ; Yanan, YA; Yanchuan, YC; Yulin, YL; Zhidan, ZD; Zichang, ZC Zizhou, ZZ); Inner Mongolia, IM (Dalad Banner, DB; Dongsheng, DS; Jungar Banner, JBr); Shanxi, SX (Daning, DN; Hequ, HQ; Jixian, JX; Lanxian, LX; Lin, LI; Lishi, LS; Shilou, SL; Xing, X); Qinghai, QH (Datong, DT; Pingan, PA).

altitudinal differences: the semi-arid region, the cold and arid regions, the arid region, and the semi-humid region (Xiao et al., 2017; Zhang et al., 2021a). Erosion type in the arid region was mainly wind erosion with no watershed data counted. The distribution of the selected watersheds is, 6 in the cold and arid regions, 17 in the semi-arid region, and 42 in the semi-humid region (Fig. 3).

2.3. Data analysis

All data were transformed into uniform units before analysis to enable the comparison of soil erosion and runoff data across all studies. The units of soil erosion modulus and runoff modulus were converted into $t \cdot km^{-2} \cdot a^{-1}$ and $m^3 \cdot km^{-2} \cdot a^{-1}$, respectively. 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 restoration years was used as a weighting factor for the means and standard deviations to calculate the average runoff and soil erosion modulus. The Kolmogorov-Smirnov test revealed that the data in this study were normally distributed. One-way analysis of variance (ANOVA) and Tukey's HSD (honest significant difference) was used to test for differences (significance level at $p < 0.05$) in runoff and soil loss with vegetation coverages. The same procedure was applied to test for significant differences between climatic regions for different vegetation restoration times. The Spearman rank correlation coefficient was used to assess the correlations of runoff, soil erosion, and precipitation of the different vegetation coverages.

Table 2
Statistical of runoff modulus, soil erosion modulus, and vegetation coverage before and after restoration.

Stage		Minimum	Maximum	Average
Before restoration	Vegetation coverage rate (%)	2.51	57.10	25.08
	Soil erosion modulus ($t \cdot km^{-2} \cdot a^{-1}$)	1600	58,285	18531.92
	Runoff modulus ($m^3 \cdot km^{-2} \cdot a^{-1}$)	1327.7	780431.8	68827.24
After restoration	Vegetation coverage rate (%)	30.56	86.80	58.68
	Soil erosion modulus ($t \cdot km^{-2} \cdot a^{-1}$)	400	13624.51	3137.99
	Runoff modulus ($m^3 \cdot km^{-2} \cdot a^{-1}$)	155.7	489325.8	31042.21

The Posterior distribution is used to determine the vegetation coverage threshold of soil and water loss (Qian, 2014; Zhang et al., 2019). The determination result shows that Wilks' lambda is 0.379 and the discrimination accuracy was 90.7% (Fig. 4a), which proved that there was a threshold for vegetation coverage controlling soil and water loss. The vegetation coverage thresholds for soil and water loss were delineated by constructing a schema chart (Fig. 4b), and piecewise linear regression was applied to detect the threshold effects of vegetation coverage with runoff and soil erosion (Chen et al., 2019; Toms and Lesperance, 2003). An important prerequisite for linear regression analysis is that the coefficient of determination of the regression equation is greater than or equal to 0.95 ($R^2 \geq 0.95$), where the regression starts from 0% and in steps of 5%. Data processing and mapping were performed using OriginPro 2021, ENVI 5.3, and ArcGIS 10.2, and IBM SPSS Statistics 21.0 (IBM Corporation, NY, and the USA) was used for regression analysis.

The annual variation trends for Normalized Difference Vegetation Index (NDVI) during the years from 1979 to 2019 were calculated by the slope Eq. (1):

$$Slope = \frac{n \times \sum_{i=1}^{n}(i \times V_i) - \sum_{i=1}^{n} i \sum_{i=1}^{n} V_i}{n \times \sum_{i=1}^{n} i^2 - \left(\sum_{i=1}^{n} i\right)} \quad (1)$$

where i is the year from 1 to n; n is the number of years; V_i is the NDVI of the year i. A $p < 0.05$ was considered significant. A positive value of *Slope* indicates an increase in NDVI.

Vegetation coverage was calculated using the NDVI as follows:

$$VC = \frac{NDVI - NDVI_{soil}}{NDVI_{veg} - NDVI_{soil}} \quad (2)$$

where VC is the vegetation coverage, $NDVI_{soil}$ represents the $NDVI$ value of the bare soil pixels ($VC = 0\%$), $NDVI_{veg}$ represents the $NDVI$ value of pure vegetation pixels ($VC = 100\%$). In the actual calculation process, $NDVI_{veg}$ and $NDVI_{soil}$ are the raster values for a cumulative rate of 95% and 5% from small to large in the area, respectively.

The vegetation soil and water conservation efficiency (VSWCE) was employed to evaluate the effect of vegetation coverage on runoff and soil

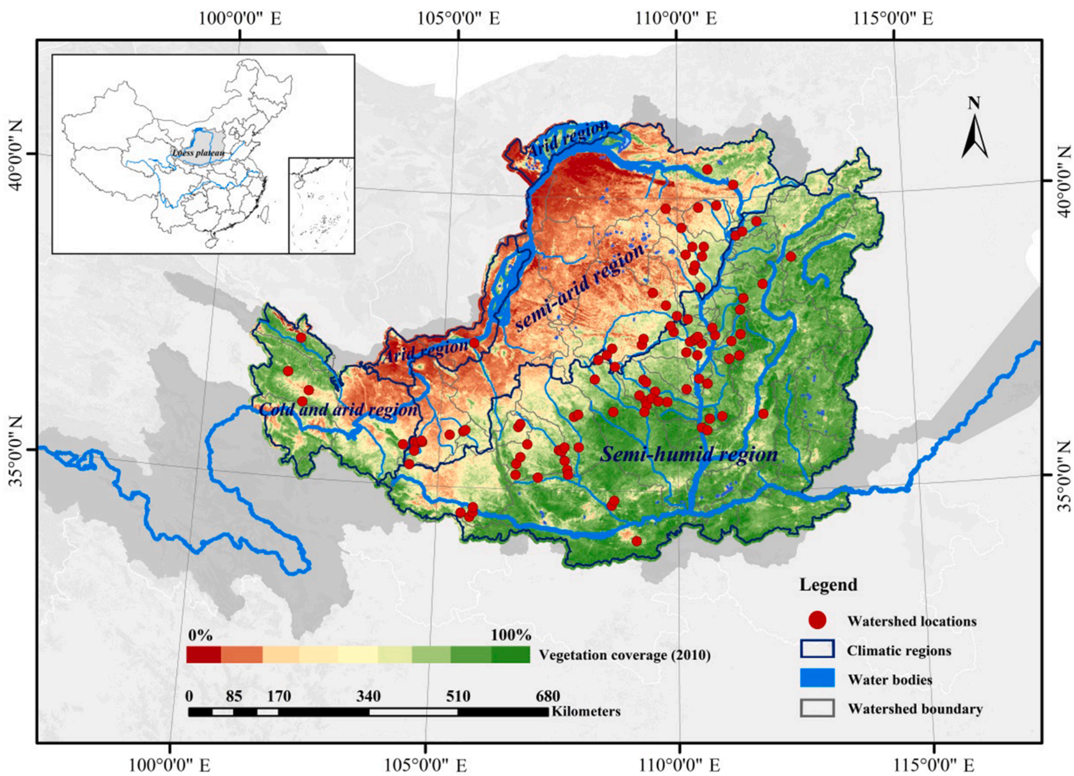


Fig. 3. The spatial distribution of the watersheds measuring sites in the Loess Plateau (n = 103). Vegetation coverage was calculated from the satellite datasets, as proposed in the materials and methods. The Loess Plateau is divided into four climatic regions: I. Arid region; II. Cold and arid regions; III. Semi-arid region; IV. Semi-humid region (Xiao et al, 2017; Zhang et al., 2021a).

erosion. VSWCE represents the ratio of the reduction in soil erosion and runoff modulus to the increase in vegetation coverage, i.e. the decrease in soil erosion and runoff modulus for each 1% increase in vegetation coverage (Chen et al., 2019). The calculation formula is:

$$VCE_{sl} = \frac{SEM_i - SEM_j}{VCR_i - VCR_j} \tag{3}$$

$$VCE_r = \frac{RM_i - RM_j}{VCR_i - VCR_j} \tag{4}$$

Where, VCE_{sl} represents the soil conservation efficiency of vegetation, and VCE_r is the runoff conservation efficiency of vegetation. SEM_i and SEM_j indicate the soil erosion modulus after and before restoration, respectively; RM_i and RM_j denote the runoff modulus after and before restoration, respectively; VCR_i and VCR_j represent the vegetation coverage after and before restoration, respectively.

3. Results

3.1. Spatial and temporal characteristics of vegetation cover, runoff, and soil erosion

The spatial pattern of the average NDVI trend from 1979 to 2019 is shown in Fig. 5. The vegetation change trend was heterogeneous across the Loess Plateau, in which most of the areas showed an increasing trend in NDVI (83% of the whole study area, Fig. 5a), and more than 75% of the regions were statistically significant ($p < 0.05$), mainly concentrated in the semi-humid and cold and arid regions (Fig. 5b). The NDVI decreased significantly mainly in parts of the arid region, the cold and arid regions, and the semi-humid region (6% of the whole study area, Fig. 5a). While on temporal scales, NDVI was homogeneous, increasing on a regional scale for more than 40 years. The average annual growth rate of NDVI in the Loess Plateau was 0.0012 yr^{-1} from 1979 to 1999 ($r = 0.516$, $n = 21$, $p < 0.05$), and it increased significantly at a rate of 0.0049 yr^{-1} from 1999 to 2019 ($r = 0.937$, $n = 21$, $p < 0.05$).

From 1979 to 2019, the average soil erosion modulus was reduced from a strong level before restoration (1979–1999, 5619 $t{\cdot}km^{-2}{\cdot}a^{-1}$) to a mild level after restoration (2000–2019, 1978 $t{\cdot}km^{-2}{\cdot}a^{-1}$). The runoff modulus and soil erosion modulus before restoration were significantly higher than those after restoration ($p < 0.05$; Fig. 6). Overall, the average soil erosion modulus of the Loess Plateau exhibited a decreasing trend, with a rate of −158 $t{\cdot}km^{-2}{\cdot}a^{-1}$ ($p < 0.05$). The average runoff modulus also showed a decreasing trend with a rate of −481 $m^3{\cdot}km^{-2}{\cdot}a^{-1}$ ($p < 0.05$). However, the decreasing trend of soil erosion and runoff has gradually slowed down (Fig. 6). The watershed data of different restoration times were grouped to analyze the relationship between restoration time and soil and water loss in different climatic regions (Table 3). The runoff modulus and soil erosion modulus for all restoration time in cold and arid regions were smaller than those in the other two climatic regions (Table 3). In the different climatic regions, the runoff modulus and soil erosion modulus of restoration time <5 years were significantly higher than those of the other restoration time ($p < 0.05$; Table 3). The soil erosion modulus of restoration time between 15 and 20 years was significantly lower than those of the other restoration time ($p < 0.05$; Table 3).

3.2. The effects of precipitation on runoff and soil erosion in different vegetation coverage

The result of correlation coefficient tests for precipitation with runoff and soil erosion and runoff with soil erosion was summarized in Table 4. The precipitation had a significant correlation with the runoff and soil erosion when the vegetation coverage was <20% ($p < 0.01$; Table 4). When vegetation coverage ranged between 30% and 40%, a significant positive correlation was identified between precipitation and runoff, but there was no correlation with soil erosion ($p < 0.05$). The precipitation

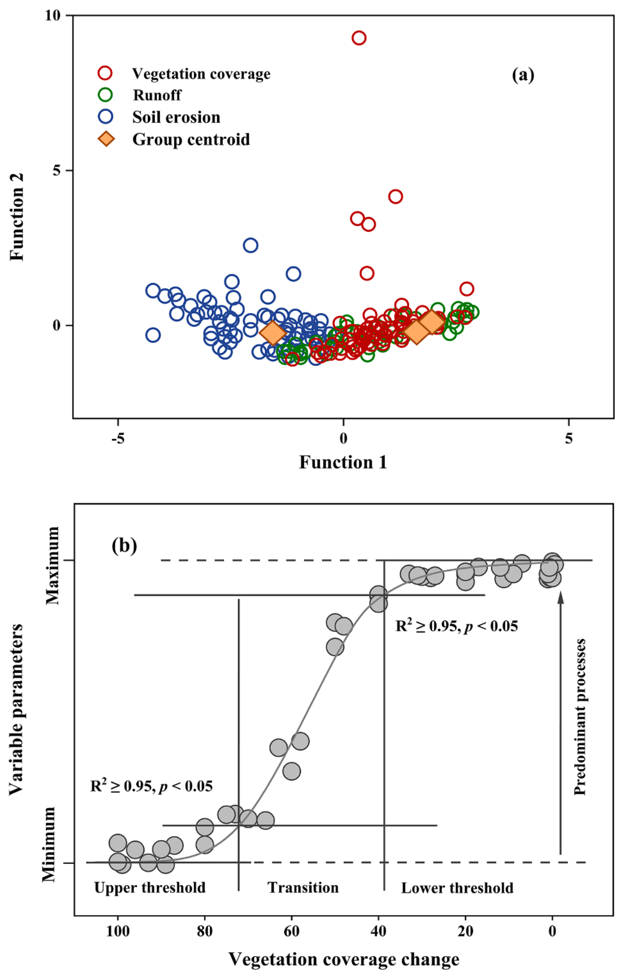


Fig. 4. (a) The determination of vegetation coverage threshold. (b) The schema chart of vegetation coverage threshold.

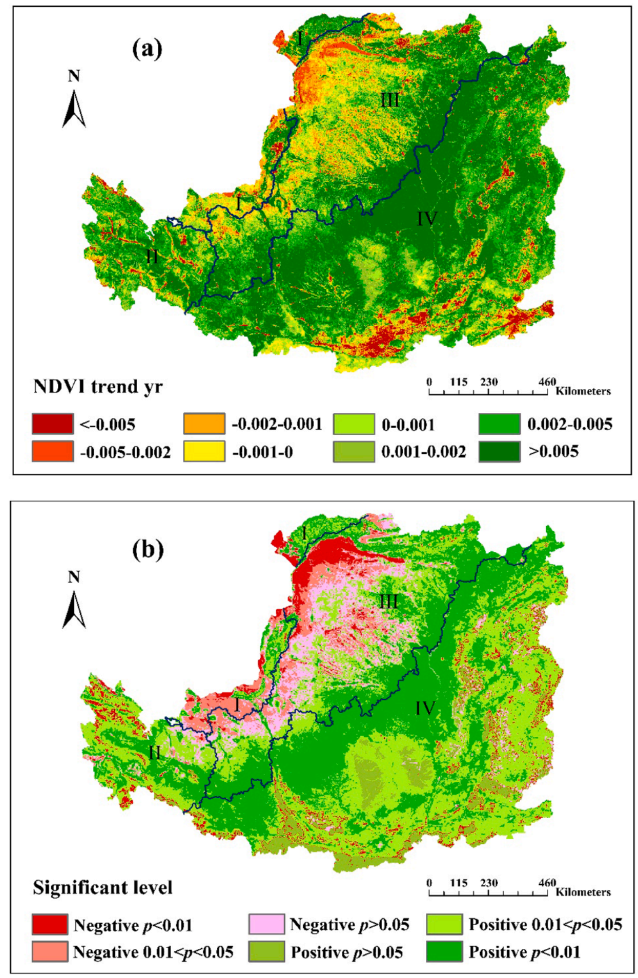


Fig. 5. Spatial distribution of NDVI trends in the Loess Plateau in 1979–2019: (a) the annual NDVI trend, (b) significance of the NDVI trend. The green color indicates an increasing NDVI, and the red color indicates a decreasing NDVI. The blue lines are the boundaries of the climatic regions (the position of the climate regions is shown in Fig. 3). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

had no significant effect on runoff and soil erosion when the vegetation coverage exceeded 40%. In addition, the correlation between runoff and soil erosion was significant only when the vegetation coverage was <30%. Although the annual rainfall erosivity is increasing in the Loess Plateau, the precipitation has been fluctuating at a steady range (Fig. S3). The average annual precipitation only increased about 17 mm after vegetation restoration.

3.3. The effects of vegetation coverage on runoff and soil erosion

The analysis of 59 watersheds revealed that the vegetation coverage had a significant effect on soil erosion and runoff ($p < 0.05$). Both the annual runoff modulus and the soil erosion modulus are negatively correlated with vegetation coverage (Fig. 7). When the vegetation coverage was <65%, the soil erosion and runoff were both significantly different. While the runoff was not significant when the vegetation coverage was greater than 70% (Fig. 7b). Although there is no significant difference between the runoff in vegetation coverage of 50%-70% and the runoff in vegetation coverage is greater than 70%, while increasing the vegetation coverage still has a sustained effect on reducing runoff (Fig. 7b).

Fig. 8 shows the relationship between vegetation coverage and soil erosion and runoff. When the vegetation coverage is <35%, it has the greatest impact on the soil erosion modulus (Fig. 8a). While when the vegetation coverage is greater than 35%, its impact on the erosion modulus drops sharply, and then the effect on soil erosion gradually stabilizes until the vegetation coverage reached 65% (Fig. 8a). When the vegetation coverage is <20%, it has the greatest influence on runoff (Fig. 8b). While when the vegetation coverage is greater than 20%, its influence on runoff decreases rapidly. When the vegetation coverage is 50%-70%, increasing vegetation coverage still has a significant impact on runoff. When the vegetation coverage exceeds 70%, its influence on runoff tends to be stable (Fig. 8b). With the increase of vegetation coverage, the runoff modulus and soil erosion modulus declined, the overall trend being initial drastic decreases, which leveled off till eventually remaining stable (Fig. 8a and b). Such a trend indicates a threshold phenomenon between the runoff and the vegetation coverage, as well as between the soil erosion and the vegetation coverage.

3.4. Threshold analysis of vegetation cover with runoff and soil erosion

The regression analysis of soil erosion modulus, runoff modulus, and vegetation coverage was used to further divide the relevant vegetation coverage threshold (Fig. S5) According to the functional relationship between the soil erosion and runoff with vegetation coverage ($y = 39204\exp^{-0.046x}$, $y = 153597\exp^{-0.048x}$; $n = 118$, $p < 0.01$, Fig. S5), the first derivative of the runoff equation ($y' = -7372.66\exp^{-0.048x}$) and the first derivative of the soil erosion equation ($y' = -1803.38\exp^{-0.046x}$) were obtained. Then the threshold effect of vegetation coverage for VSWCE was determined ($R^2 \geq 0.95$, Fig. 9). The threshold analysis

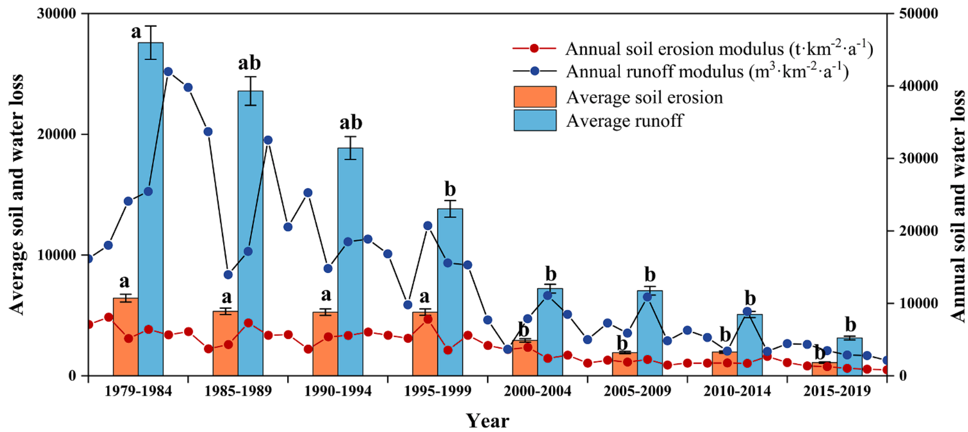


Fig. 6. The inter-annual variation of the runoff modulus and the soil erosion modulus of the Loess Plateau.

Table 3
The weighted mean and standard deviation (SD) of annual runoff and annual soil loss for each vegetation restoration time for all data, grouped by climatic regions in the Loess Plateau. Data were weighted based on the square root of restoration years. Different capital letters in the same row indicate significant differences among different climatic regions ($p < 0.05$). Different lowercase letters in the same column indicate significant differences between different vegetation restoration times in the same climatic region ($p < 0.05$).

Vegetation restoration time	Semi-arid region		Semi-humid region		Cold and arid regions	
	Runoff modulus ($\times10^4$)	Soil erosion modulus ($\times10^4$)	Runoff modulus ($\times10^4$)	Soil erosion modulus ($\times10^4$)	Runoff modulus ($\times10^4$)	Soil erosion modulus ($\times10^4$)
	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)
<5 (VC* < 20%)	2.35 (0.73)^{aA}	1.39 (0.36)^{aA}	2.27 (0.38)^{aA}	1.42 (0.35)^{aA}	1.93 (0.57)^{aA}	1.17 (0.31)^{aA}
5–10 (VC* = 20%–40%)	1.70 (0.39)^{abA}	0.89 (0.16)^{bA}	1.73 (0.16)^{bA}	1.09 (0.24)^{abA}	1.17 (0.63)^{abA}	0.49 (0.16)^{bB}
10–15 (VC* = 40%–60%)	1.13 (0.32)^{bA}	0.56 (0.13)^{bcA}	1.18 (0.25)^{cA}	0.68 (0.2)^{bA}	0.73 (0.15)^{bB}	0.18 (0.06)^{bcB}
15–20 (VC* >60%)	0.47 (0.13)^{bB}	0.28 (0.08)^{cB}	0.7 (0.12)^{dA}	0.24 (0.08)^{cB}	0.37 (0.11)^{bB}	0.12 (0.04)^{cA}

* VC is the vegetation coverage.

Table 4
Spearman rank correlation coefficient (r_s) and p-values for the correlations of runoff, soil loss, and precipitation of the different vegetation coverages in the Loess Plateau. Values in bold indicate significance at a < 0.05.

Vegetation coverage	Precipitation–runoff		Precipitation–soil erosion		Runoff–soil erosion	
	r_s	p	r_s	p	r_s	p
<10	0.933	$<0.001^{**}$	0.667	$<0.001^{**}$	0.615	**0.033***
10–20	0.950	$<0.001^{**}$	0.833	$<0.001^{**}$	0.867	**0.02***
20–30	0.783	**0.013***	0.329	0.297	0.699	**0.011***
30–40	0.767	**0.016***	0.476	0.118	0.552	0.063
40–50	0.343	0.077	0.2	0.606	0.483	0.187
50–60	0.017	0.966	0.567	0.112	0.033	0.932
60–70	0.117	0.765	0.167	0.668	0.617	0.077
70–80	0.3	0.433	0.267	0.488	0.533	0.139
>80	0.383	0.308	0.483	0.187	0.05	0.898

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

identified three threshold zones for the vegetation coverage threshold of soil erosion in the watersheds of the Loess Plateau: the lower threshold is 0%–35%, the transition zone is 35%–65%, and the upper threshold is 65%–100% (Fig. 9a). While, four threshold zones can be divided for the vegetation coverage threshold of runoff: the low threshold is 0%–20%, the transition zone is 20%–50%, the high threshold is 50%–75%, and the upper threshold is 75%–100% (Fig. 9b).

With the increase in vegetation coverage, the runoff and soil erosion both decreased sharply in the lower threshold. The average VCE*r* and the average VCE*sl* were 5911.42 m^{3}·km^{-2}·a^{-1} and 630.45 t·km^{-2}·a^{-1}, respectively. When the vegetation coverage threshold was in the transition, the reduction rate of runoff and soil erosion controlled by vegetation coverage gradually slows down, with the average VCE*r* and the average VCE*sl* being 2113.94 m^{3}·km^{-2}·a^{-1} and 304.21 t·km^{-2}·a^{-1}, respectively. Compared with the upper threshold of vegetation coverage for erosion (VCE*sl* = 167.66 t·km^{-2}·a^{-1}), the upper threshold for runoff can be further divided into a high threshold zone (VCE*r* = 1027.88 m^{3}·km^{-2}·a^{-1}) and an upper threshold (VCE*r* = 391.69 m^{3}·km^{-2}·a^{-1}).

4. Discussion

4.1. The effect of vegetation coverage on runoff and erosion

Hydraulic erosion is the main erosion type in most areas of the Loess Plateau, while vegetation coverage is the main factor regulating water and soil loss (Liu et al., 2018; Wen and Deng, 2020; Zhang et al., 2021a). Our results show that as the average vegetation coverage of the Loess Plateau increased by 33.60% from 1984 to 2018 (Table 2), soil erosion decreased by 83.07% and runoff decreased by 84.05% (Fig. 6). The above results indicate that large vegetation coverage can effectively reduce the occurrence of water and soil loss, which is confirmed by previous research (Eshghizadeh et al., 2018; Yu et al., 2006). However, the temporal effects of vegetation coverage on runoff and soil erosion are different. Generally, short-term vegetation restoration can quickly control the generation of runoff, because the increased area and density of vegetation cover could improve rainfall interception and soil infiltration (Liu et al., 2018; Wen and Deng, 2020; Zhang et al., 2021b). Before reaching the upper threshold, sustained vegetation restoration is more conducive to soil erosion control, owing to the enhanced ability of its roots to consolidate soil and the increased soil anti-erodibility, which could be greater than the runoff interception (Deng et al., 2018; Feng

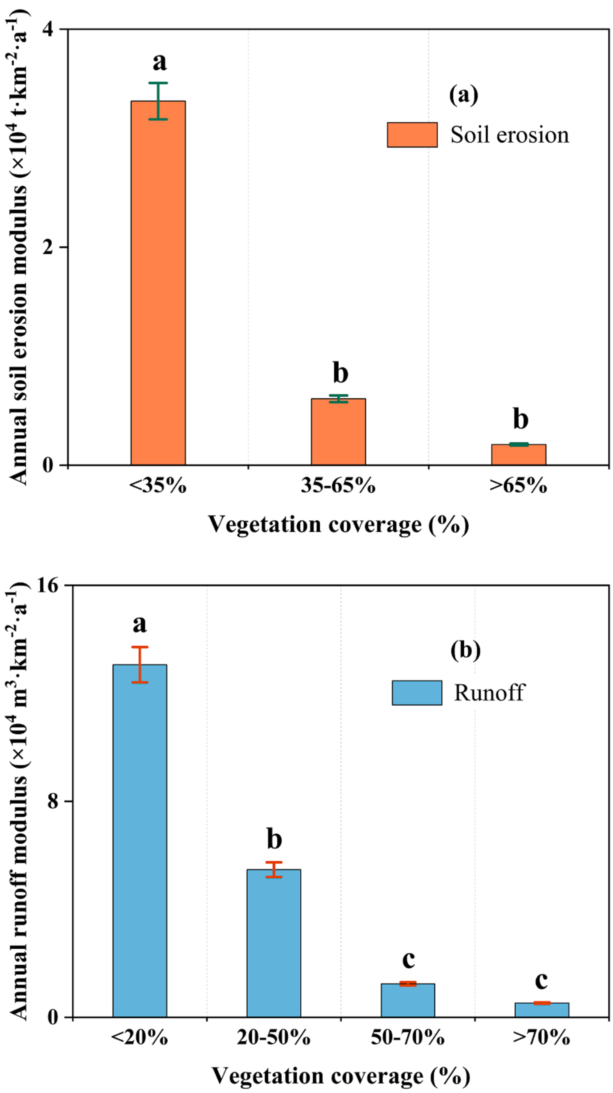


Fig. 7. The effect of vegetation coverage on annual runoff modulus and soil erosion modulus. Different letters indicate significant differences among different vegetation coverage, and vice versa ($p < 0.05$).

et al., 2012; Li et al., 2014; Zhang et al., 2021a). Therefore, for the Loess Plateau, where soil loss is intense, long-term vegetation restoration within the transition threshold range should be the main restoration mode.

In the Loess Plateau, the vegetation coverage exhibited significant spatial heterogeneity (Fig. 4), and the effect of vegetation coverage on soil erosion and runoff varies considerably among the different climatic regions. The analysis of 59 watersheds in the Loess Plateau found that in the semi-humid region the effect of vegetation coverage on soil erosion was greater than that on runoff, which is consistent with the study by Zhang et al. (2021a). That may be the vegetation coverage in this region are between 35% and 45% and the soil is loose, hence increasing the vegetation coverage can significantly affect the amount of soil erosion (Huang et al., 2021). However, the water storage capacity is weak due to the single vegetation structure, so compared to soil erosion the impact on runoff is relatively small. In the cold and arid regions and the semi-arid region, increasing vegetation coverage has a greater impact on runoff. Owing to the low soil erosion and seasonal rainfall in the two climatic regions, increasing vegetation coverage can effectively intercept rainfall and increase soil infiltration (Sadeghi et al., 2015). In the arid region, the relationship between vegetation coverage with water and soil loss was first promoted and later inhibited. At the initial stage of vegetation restoration, the runoff converges in areas with low vegetation coverage and sparse vegetation distribution, which increases the susceptibility to gully erosion, and the occurrence of water and soil loss (Zhu, 2012). With the vegetation coverage increases, the effect of vegetation reduction on water and sediment is enhanced, which in return reduces soil erosion (Teng and Liu, 2018).

All current results of water and soil conservation benefits are obtained based on long time scales (including inter-annual or inter-decadal scales) (Fig. 2), while the research on shorter intervals (including seasons, months, and events) is relatively scarce. The vegetation growth and coverage are closely related to seasonal variation, and the effects of vegetation canopy interception and plant litter retention also exhibit seasonality (Gabarrón-Galeote et al., 2013). Therefore, the existing studies could not well reflect the seasonal effects of vegetation on water and soil loss control. However, our research is based on a comprehensive analysis of long-term vegetation restoration to soil and water loss on a regional scale, which can provide a basis for vegetation regional planning. In addition, frequent extreme rainfall events should also be considered, since they exert disproportionate impacts on water and soil conservation (Ran et al., 2013). Especially for the Loess Plateau, the water and soil loss produced by extreme rainfall accounts for more than 60% of the annual runoff and sediment transportation (Zhai et al., 2021).

4.2. *Cause analysis for vegetation coverage threshold phenomenon of runoff and soil erosion*

In the process of vegetation restoration, the control of soil and water loss by increasing vegetation coverage will inevitably reach a critical state. Identifying the vegetation coverage threshold prior to the critical state is the key to controlling soil and water loss (Chen et al., 2019; Eshghizadeh et al., 2018; Liu et al., 2018). Threshold behaviors existed between the vegetation coverage and soil erosion, as well as the vegetation coverage and runoff in the Loess Plateau (Fig. 8). Compared with the three threshold zones for soil erosion, and runoff is more complex with four threshold bands (Fig. 9). The vegetation coverage change plays a major role in controlling soil and water loss before reaching the vegetation coverage threshold. While the effect on soil and water loss will become weaker when the vegetation coverage threshold is reached. However, changes in soil hydrology (i.e., raised soil water storage capacity, enhanced soil infiltration, increased soil porosity) caused by vegetation restoration still exert an effect on runoff once reaching the threshold (Deng et al., 2020; Neave and Abrahams, 2002; Zhang et al., 2014). While after reaching the threshold, its effect on soil erosion will be weak. Thus, sustained vegetation restoration has a stronger long-term effect on runoff.

Defining the threshold range of vegetation coverage can ensure the efficient and rational utilization of land resources and reduce water resource consumption (Zhang et al., 2019; Zhang et al., 2020). When vegetation coverage does not reach the threshold value, ecosystem services (i.e., soil fertility, and soil and water conservation) are significantly weakened (Gao et al., 2011). Our results show that runoff and soil erosion can be effectively reduced only when the vegetation coverage reaches the transition zone (35%–65% for soil erosion; 20%–50% for runoff). Such effect is unstable if the vegetation coverage is <25%, with certain control on the soil erosion but little on the runoff. To control soil and water loss, the vegetation coverage only needs to reach 10% in semi-arid regions of southeastern Australia and northern Mexico (Liu et al., 2018; Puigdefábregas, 2005), while it increased to 30% in the Mediterranean region (Gimeno-García et al., 2007), and even 50% in central-east Spain (Moreno-de Las Heras et al., 2009). However, in the Loess Plateau, the vegetation coverage needs to reach 65% to effectively control soil erosion and runoff, owing to the serious water and soil loss (Hu and Zhang, 2020; Liu et al., 2020). When the vegetation cover is located in the upper threshold zones (soil erosion is 65%–100% and runoff is 75%–100%), no significant impact was identified on the

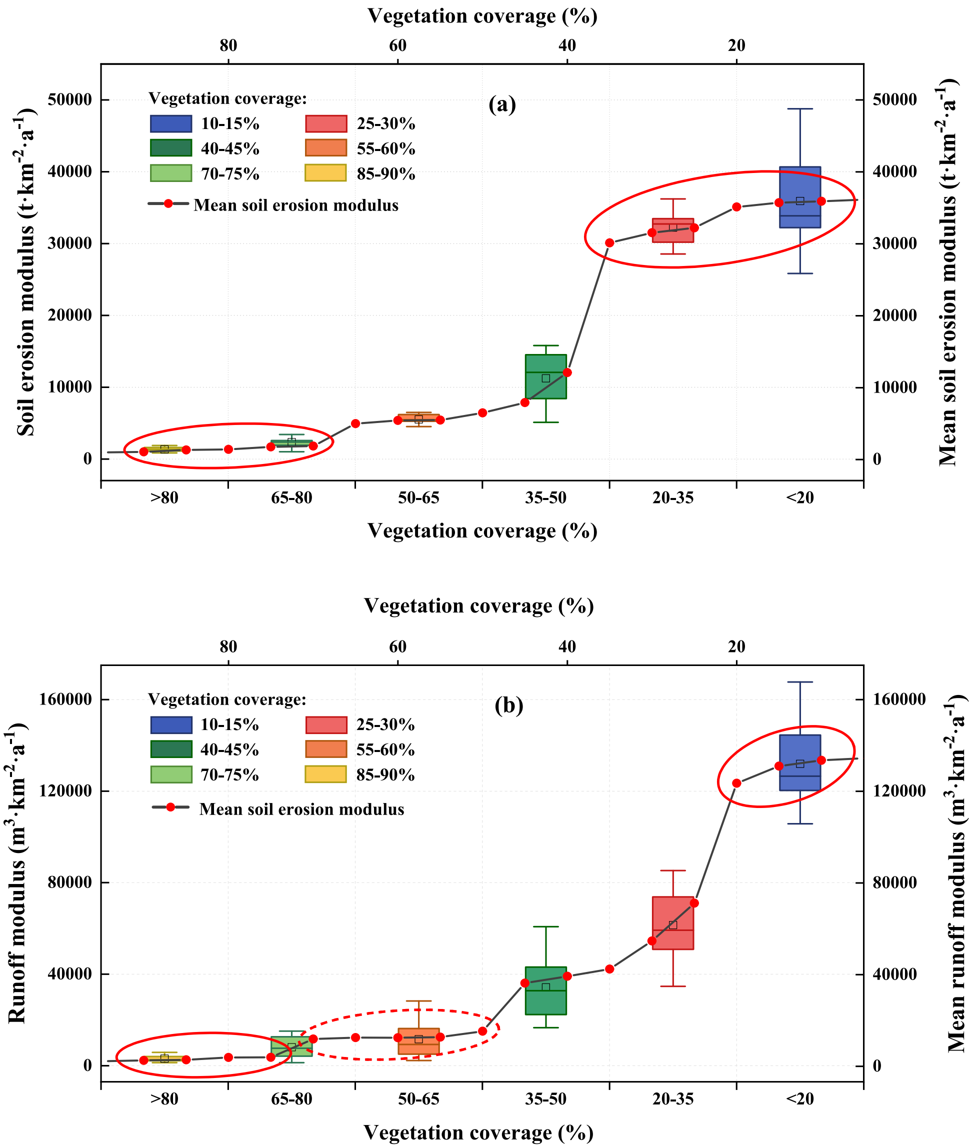


Fig. 8. The relationship between runoff and soil erosion modulus and vegetation coverage in the Loess Plateau.

efficiency of vegetation coverage in reducing water and soil loss. Such relationships have been confirmed in the region of southeastern China (Chen et al., 2019).

The vegetation coverage threshold can provide an important basis for the spatial distribution of vegetation restoration (Groffman et al., 2006; Moreno-de las Heras et al., 2011), which deserves further attention. This study provided detailed zoning of the vegetation coverage threshold for runoff and soil erosion. Note that, since many factors affect the threshold (i.e., soil characteristics, vegetation type, and topography) (Eshghizadeh et al., 2018; Sepúlveda and Carrillo, 2015), and have complex spatial and temporal scale effects, the thresholds behaviors differ across spatial (slope, watershed, and region) and temporal scales (Chen et al., 2019; Liu et al., 2018). Therefore, further research should take into account the combined effects of rainfall, vegetation characteristics, and topography, while factoring in the scale effects. In addition, the vegetation coverage threshold in this study is based on the existing observational data, while the number of factors affecting the threshold is increasing due to economic and climate changes. Therefore, it is necessary to further define the vegetation coverage thresholds under changing environments in future studies.

4.3. Application of the threshold effect of vegetation coverage

According to different stages of soil and water conservation objectives, the management patterns and measures of the Loess Plateau are also constantly changing (Table 5). In the Loess Plateau, after large-scale vegetation restoration, soil erosion has been effectively controlled (Chen et al., 2007; Fu, 2011). However, indiscriminate vegetation restoration has also led to a series of problems such as runoff decrease, dried soil layers, simplified vegetation structure, and increased forest diseases and insects (Chen et al., 2011; Li et al., 2016; Wang et al., 2011; Zhao et al., 2020a). In addition, due to the reduction of soil erosion and runoff, a new pattern of sediment and water has formed in the Yellow River, which calls for adjustment of the ecological restoration mode. The vegetation coverage, when reaching an effective level, plays an important role in preventing soil loss, and is conducive to the long-term stability of the plant community and stable performance of the soil and water conservation function (Guo, 2000; Liu et al., 2018). Referring to the effective vegetation coverage as the standard for vegetation restoration requires less input, such as human, material, and financial resources (Wu et al., 2019). Therefore, defining effective vegetation coverage in different climatic regions is of importance to the watershed ecological restoration, especially in the Loess Plateau with complex

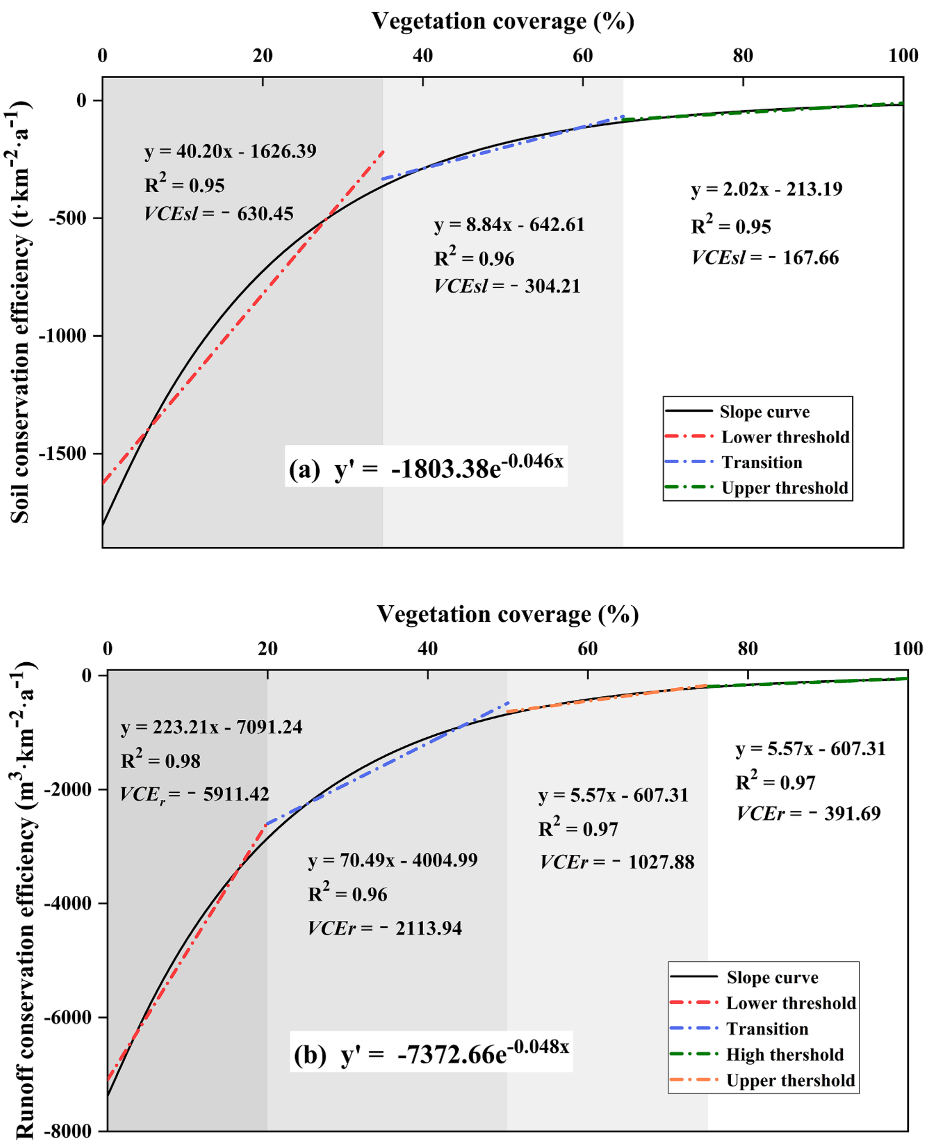


Fig. 9. Classification of vegetation coverage threshold for runoff and erosion in the Loess Plateau.

Table 5
Ecosystem management during the past 60 years in the Loess Plateau.

Control stage	Source	Control model	Control measures	Objectives
1950–mid 1960s	Wang et al., 2012	Slope improvement	Engineering measures (terrace and afforestation)	Control the slope erosion
The mid 1960s–Late 1970s	Li et al., 2015	Gully and slope improvement	Engineering measures (terrace, afforestation, and warping dams)	Control the gully and slope erosion, and intercept sediment
The late 1970s–Late 1990s	Wang et al., 2017	Small watershed management	The transition from engineering measures to ecological measures (terrace, afforestation, warping dams, and natural restoration)	Control the gully and slope erosion, intercept sediment, and improve the ecological environment
2000–2010	Gao et al., 2019	Grain for green *	Ecological measures (terrace, afforestation, backbone dam, and natural restoration)	Reduce soil erosion, and improve the ecological environment
2010–present	Li et al., 2019	Combining 'grain for green' with 'gully land consolidation'	Combining engineering measures and ecological measures (backbone dam, gully land consolidation, and natural restoration)	Reduce soil erosion, improve the ecological environment, increase food production, and increase farmers' income

* The "Grain for Green" program was implemented in 1999 in the Loess Plateau.

topography.

In the light of the SCGSE (SL190–2007), the soil loss tolerance of the Loess Plateau is 1523.44 t·km^{-2}·a^{-1} (Liu et al., 2020). We calculate the soil and water loss tolerance in different climatic regions (Table 6), then propose the effective vegetation coverage in different climatic regions. Therefore, the effective vegetation coverage in the arid region should be greater than 27%. Since the annual precipitation is <200 mm·a^{-1} (Zhang et al., 2016a), the vegetation restoration should pay attention to increasing drought-enduring plants and controlling wind erosion. The effective vegetation coverage in the semi-arid region should be more than 46%. With seasonal rainfall patterns and low and discontinuous vegetation cover (Kang et al., 2001; Zhang et al., 2021a), the restoration objects should be to restore the low vegetation cover areas, especially increasing the vegetation cover of bare land. For the semi-humid region, the effective vegetation coverage should exceed 51%. The vegetation cover can be increased rapidly owing to the great potential for ecological restoration (Su and Fu, 2013). In addition, because of the large area of agricultural lands in this region, the vegetation coverage is characterized by great seasonality (Xiao et al., 2017). At present, this region should focus on natural restoration. In the cold and arid regions, the effective vegetation coverage should be greater than 25%. Though the current vegetation coverage can meet such requirements, it should still be increased to resist the frequent heavy rains in summer (Zhang et al., 2021a). The specific restoration targets should be based on artificial forests and low vegetation cover lands.

As the effects of vegetation coverage on runoff and soil erosion are quite different in different climatic regions, and it can remain stable only when vegetation recovery is based on the vegetation coverage threshold of different climatic regions (Liu et al., 2018). In the semi-humid region and cold and arid regions, rainfall is the dominant factor in determining vegetation coverage threshold, while for the arid region and semi-arid region with high potential evapotranspiration, the soil moisture should be considered as a dominant limiting factor (Liu et al., 2020; Wen et al., 2018; Yang et al., 2011). A contradiction exists between the long-term goals of runoff control and soil loss control in the Loess Plateau. The long-term goals of soil loss control are to reduce the amount of soil erosion to 9.75×10^{8} t·a^{-1}, and the allowable soil loss to 1523.44 t·km^{2}·a^{-1} (Zhang et al., 2021a; Wang et al., 2012), which requires the vegetation coverage rate to reach 71.84%. To maintain an annual runoff of 250×10^{8} m^{3}·a^{-1} entering the Yellow River (Hu and Zhang, 2020), the vegetation cover should not exceed 20%. Such contradiction cannot be solved under the previous undifferentiated vegetation restoration patterns. Therefore, the different climatic regions need to be treated separately according to the characteristics of water and soil loss to control the amount of soil erosion while ensuring the stability of runoff, and also to solved the problem of the amount of runoff and sediment production are not uniform.

5. Conclusions

Ecological restoration in the Loess Plateau has effectively controlled soil erosion and increased vegetation coverage. However, the indiscriminate vegetation restoration has ignored the effect of the vegetation coverage threshold. Excessive attention was paid to sediment yield reduction and large-scale artificial forestation, which led to imbalances in regional ecological governance. Therefore, there is an urgent need to re-zone management of the new water and sediment yields formed by the vegetation restoration in the Loess Plateau. For this purpose, this study compiled all available watershed data in the Loess Plateau, including the soil erosion, runoff, and vegetation coverage data before and after vegetation restoration in 59 watersheds. The results indicate that the average coverage rate has increased by 33.6% after vegetation restoration. A negative exponential function was found between the vegetation coverage with runoff and soil erosion modulus, and the effect of vegetation restoration on soil erosion was found to be greater than that of runoff. Compared to the soil erosion with only three threshold zones (the lower threshold is 0%–35%, the transition is 35%–65%, and the upper threshold is 65%–100%), the runoff has more complex four threshold zones (the low threshold is 0%–20%, the transition is 20%–50%, the high threshold is 50%–75%, and the upper threshold is 75%–100%). The effective vegetation coverage in the cold and arid regions is 25.12%, in the semi-humid region is 51.02%, in the semi-arid region is 45.92%, in the arid region is 26.53%. However, a continuous increase in vegetation cover does not always have a significant impact on water and soil loss. Therefore, the future restoration measures of the Loess Plateau

Table 6
The main information about different climate regions in the Loess Plateau.

Climatic region	Effective vegetation coverage %	Area ratio %	Annual precipitation (mm·a^{-1})	Target erosion (10^{8}·t·a^{-1})	Target runoff (10^{8}·m^{3}·a^{-1})
Arid region	26.53	5.73	167.01	5.12	6.27
Cold and arid regions	25.12	10.61	396.63	9.64	12.94
Semi-arid region	45.92	29.65	334.83	10.33	9.63
Semi-humid region	51.02	54.01	528.57	14.24	12.58

should reduce the artificial forests and mainly with natural restoration. Focusing on soil erosion and runoff, the soil moisture situation should also be considered, so that transforms the management method of the Loess Plateau into a combination of engineering and biology.

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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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.geoderma.2022.115720.

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