Spatial–temporal evolution patterns of soil erosion in the Yellow River Basin from 1990 to 2015: impacts of natural factors and land use change

Xiao, Yang, Bing Guo, Yuefeng Lu, Rui Zhang, Dafu Zhang, Xiaoyan Zhen, Shuting Chen, Hongwei Wu, Cuixia Wei, Luoan Yang, Yi Zhang, Wenqian Zang, Xiangzhi Huang, Guangqiang Sun and Zhen Wang

Key Laboratory for Digital Land and Resources of Jiangxi Province, East China University of Technology, Nanchang, China; School of Civil Architectural Engineering, Shandong University of Technology, Zibo, Shandong, China; Key Laboratory of National Geographic Census and Monitoring, Ministry of Natural Resources, Wuhan, China; MOE Key Laboratory of Western China’s Environmental System, Lanzhou University, Lanzhou, Gansu, China; Key Laboratory of Geomatics and Digital Technology of Shandong Province, Qingdao, China; Aerospace Information Research Institute, Chinese Academy of Sciences, Beijing, China; Key Laboratory of Meteorology and Ecological Environment of Hebei Province, Shijiazhuang, Hebei, China; State Key Laboratory of Resources and Environmental Information System, Institute of Geographic Sciences and Natural Resources Research of Chinese Academy of Sciences, Beijing, China; Land Satellite Remote Sensing Application Center, Ministry of Natural Resources, Beijing, China

ABSTRACT

This study optimized the slope and slope length factor (LS) and crop management factor (P) of the RUSLE model and then introduced the gravity centre model to analyze the spatial–temporal variation patterns of soil erosion in Yellow River Basin from a new perspective. Results showed that: (1) The improved model of RUSLE with optimized factors of LS and P had better applicability in Yellow River Basin; (2) The average erosion intensity was 2777.5 t/a, which belonged to moderate erosion. The soil erosion intensity of the Yellow River Basin showed an overall trend of increasing firstly (1990–2005) and then decreasing (2005–2015). (3) During 1990–2015, the gravity centre of soil erosion moved to the southwest, indicating that the increment and increasing rate of soil erosion in the southwest parts of the Yellow River Basin were greater than that in the northeast parts. (4) The intensity of soil erosion aggravated with the increasing slope. The sandy soil, chestnut soil, light-grey calcium soil and fluvo aquic soil had severe erosion intensity due to the regional climate and their own physical–chemical structure. The woodland and shrubbery land were more susceptible to soil erosion.
1. Introduction

With the increasing impacts of global warming and human disturbance, soil erosion has become one of the dominant environmental threats affecting the sustainable development of regional and national social economies (Peng 2000; Liu et al. 2016; Zhao et al. 2017; Guo et al. 2020a, 2020e). Under the influences of water, gravity, wind and other external forces, soil and water resources and land productivity are greatly damaged (Kwanele and Njoya 2019; Rajbanshi and Bhattacharya 2020). Therefore, how to evaluate and analyze the spatial–temporal variation patterns of soil erosion quantitatively in different regions and scales has become a hot topic among scholars home and abroad (Peng 2000; Chen et al. 2017; Guo et al. 2018, 2019; Luo et al. 2020).

Since the 1950s, the researches and applications of soil erosion models have been conducted by scholars worldwide (Wen and Deng 2020). The development process of soil erosion models can be roughly divided into three stages: empirical statistical model, physical process model and distributed model (Shi et al. 2012; Kwanele and Njoya 2019; Guo and Wen 2020; Guo et al. 2020b). Chen et al. (2017) found that the RUSLE model was sensitive to the slope steepness, slope length, vegetation factors and digital elevation model (DEM) resolution in Karst Basin of Southwest China. Vahid et al. (2021) investigated the use of erosion pins and artificial neural networks (ANNs) to assess the spatial distributions of annual soil erosion rates in the mountainous areas of the north of Iran. Numerous researchers have conducted studies based on the universal soil loss equation (USLE) and the modified USLE (RUSLE) established by the US Department of Agriculture and achieved remarkable results (Zhang et al. 2018; Li et al., 2019; Guo et al. 2020c). Plambeck (2020) assessed the potential risk of soil erosion by water on arable land in accordance with ABAG and imposed appropriate management restrictions on farmers. Kirill and Oleg (2020) quantitatively assessed the soil lost by erosion in the arable lands of the macro-region using an USLE empirical mathematical model modified to suit the harsh climatic conditions of Russia. Bircher et al. (2019) found that the calculation of LS-factors of RUSLE based on field blocks offered a number of advantages in determining the channel network and maximum flow length. Shrestha et al. (2020) analyzed the relationships between climate, discharge, and sediment yield using the Soil and Water Assessment Tool (SWAT). Fayas et al. (2019) found that the severity information developed with RUSLE along with its individual parameters could help to design land use management practices. Ciampalini et al. (2020) tested the potential impacts of climate and vegetation on soil loss by surface-runoff with a sensitivity analysis of the Pan-European Soil Erosion Risk Assessment (PESERA) soil erosion model. Luetzenburg et al. (2020) applied the Geospatial Interface for the Water Erosion Prediction Project (GeoWEPP) to model these two agricultural catchments at a fine spatial resolution. Compared with the USLE model, the RUSLE model can be used in non-agricultural areas and the factors affecting soil erosion are considered in RUSLE. Chuenchum et al. (2020) quantitatively evaluated the annual soil erosion in terms of spatial distributions and the trends of sediment yield with the climate and land changes in future scenarios in 2030 and 2040 based on modified RUSLE model. However, the applicability of each influence factor in RUSLE must be clearly...
understood and some factors should be revised in accordance with the actual situations. On the basis of Geographic Information System (GIS) and the RUSLE model, Chen (2019) conducted a quantitative study on soil erosion in the hilly and mountainous areas of southern China (including Hunan, Jiangxi, Zhejiang and Fujian) and analyzed the relationships between the spatial distribution characteristics of soil erosion and slope and altitude. Ni et al. (2008) proposed a soil erosion index (EI) based on standardized environmental information stored in minimum polygons to assess the soil erosion condition of Yellow River Basin. Wang et al. (2014) applied the Cesium (Cs)-137 concentrations in soils to quantify erosion rates and identify the main factors involved in the erosion in the source region of the Yellow River. Du et al. (2016) utilized the Integrated Wind Erosion Modeling System (IWEMS), the Revised Wind Erosion Equation (RWEQ) and the RUSLE to perform an assessment of soil erosion risk by wind and water. Hu et al. (2020) applied the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) model to quantitatively evaluate the water yield and soil erosion modulus in 2030 for the Shaanxi–Gansu Loess Plateau under different land use and climate change scenarios. Lin et al. (2020) combined the RUSLE model and a geographically weighted regression model to evaluate the contributions of influencing factors to the net water-erosion rate and the soil and water conservation benefits of the “Grain to Green Program” (GTGP).

The Yellow River Basin is one of the most serious soil erosion zones in the world with a total erosion area of $21 \times 10^8$ t (Ni et al. 2008; Ouyang et al. 2010; Du et al. 2016). During the past 20 years, the spatial–temporal distributions and change patterns of soil erosion in the Yellow River Basin have undergone profound changes under the stress of global warming and human activities (excessive reclamation and constructions of large-scale ecological engineering). Therefore, the quantitative evaluation of soil erosion and the driving mechanism analysis of its spatial–temporal evolutions in the Yellow River Basin are crucial. However, 30% of the total study area has a slope greater than 25°, and the farmlands with steep slope are widely distributed in this study region. However, in the traditional USLE and RUSLE models, zones with slope $>25^\circ$ are not fully considered in the calculation of slope and slope length factor, and the differences of crop management factors in different types of steep slope farmland are also ignored.

In this study, combined with the geographical conditions of the Yellow River Basin, the calculation parameters of slope and slope length factor (LS) and crop management factor (P) were optimized based on the basic form of the RUSLE monthly model. Then, the gravity centre model was introduced to analyze and discuss the spatial and temporal change patterns of soil erosion and the driving mechanisms in recent 25 years.

2. Methods and data source

2.1. Study area

The Yellow River Basin covers four geomorphic units from west to east, namely, the Qinghai–Tibet Plateau, the Inner Mongolia Plateau, the Loess Plateau and the Huang–Huaihai Plain ($32^\circ–42^\circ$N, $96^\circ–119^\circ$E; Figure 1). The altitude of the Yellow
River Basin decreases from the west to the east, with a topographic difference of 3000 m (Ouyang et al. 2010; Du et al. 2016). The central region, with an average altitude of 1000–2000 m, has a loess landform with serious soil erosion. The eastern part is mainly composed of the Yellow River alluvial plain. The study region is located in the mid-latitude zone, which is mainly affected by monsoon circulation. The climates in different sub-regions of the basin differ significantly with great annual and seasonal variations. The precipitation in most areas of the basin ranges from 200 to 650 mm, whereas that in the middle and upper reaches is more than 650 mm (Wang et al. 2014). The annual temperature difference in the Yellow River Basin is also relatively large. The temperature of the northern part is between 31 and 37 °C, while that of the southern part ranges from 21 to 31 °C. The Vegetation types are diverse, including deciduous broadleaf forest, grassland, and desert.

2.2. Data source

The daily precipitation data was obtained from China’s daily surface climatic dataset, which could be downloaded free from the China Meteorological Data Sharing Services Network (http://data.cma.cn/). The dataset of 90 national meteorological stations in the Yellow River Basin and its surrounding areas was used for calculating rainfall erosion force factors. In this study, 1:100,000 soil data and 1 km grid data of soil nitrogen (N), phosphorus (P), potassium (K) and organic matter content (C) were obtained from the Nanjing Institute of Soil Research, Chinese Academy of Sciences. In addition, the dataset of 1:100,000 land use was obtained from The...
Institute of Geography, Chinese Academy of Sciences. This dataset contained six primary land use types, including cultivated land, woodland, grassland, water area, residential land and unused land. Digital Elevation Model (DEM) data was obtained from the International Scientific Data Mirror website of the Computer Network Information Centre, Chinese Academy of Sciences, with a spatial resolution of 90 m. All the above datasets were resampled to 1 km with Co-krigering method.

2.3. Methods
2.3.1. Improved model of RUSLE
Since the 1980s, scholars in China have further improved the soil loss equation in accordance with field observation parameters. With the development of GIS and remote sensing technologies, it has been developed into a tool applicable to the quantitative evaluation of regional soil and water loss. However, due to the larger topographic relief and complex cultivation types, the RUSLE model is not applicable, which ignores the effects of steep slope. Therefore, with the basic form of RUSLE (Equation (1)), the slope length factor (LS) and crop management factor (P) are optimized (You and Li 1999; Cui et al. 2006; Yang and Gao 2012; Shi et al. 2012; Liu et al. 2016; Zhang et al. 2018)

\[ A = R \times K \times LS \times C \times P, \]  

where \( A \) is the soil erosion modulus \((t \times (km^2 \times a)^{-1})\), \( R \) is the rainfall erosion factor, \( K \) is the soil erodibility factor, \( LS \) is the slope and slope length factor, \( C \) is the vegetation cover factor and \( P \) is the crop management factor.

(1) Rainfall erosion force \((R)\)
Rainfall erosion force \((R)\), reflecting the potential for rainfall-induced soil loss, is defined as the product of rainfall kinetic energy and maximum rainfall intensity in 30 min in the RUSLE model. The daily model of rainfall erosive force (Equation (2)) has been adopted in this study, which can better reflect the semi-monthly and monthly variation. In addition, it has been widely used in the calculation of rainfall erosion force and then even used in the first national water conservancy survey (2020–2012) that aimed to investigate the conditions of development, control and protection of rivers and lakes in China (Du et al. 2016; Liu et al. 2016; Guo et al. 2020f).

\[ \partial = 21.239 \beta^{-7.3967}, \]  

\[ \beta = 0.6243 + \frac{27.346}{P_{d_0}}, \]  

\[ P_{d_0} = \frac{1}{N} \sum_{i=1}^{N} \sum_{k=1}^{12} \sum_{j=1}^{M} P_{dijk}, \]
\[
R_k = \frac{1}{N} \sum_{i=1}^{N} \left( \partial \sum_{j=1}^{M} P_{dij}^\theta \right), \tag{5}
\]

\[
\bar{R} = \sum_{k=1}^{12} R_k, \tag{6}
\]

In this formula, \( R_k \) is the rainfall erodibility in month \( K \); \( N \) is the time series of the calculated data; \( M \) is the number of the erosive rainfall in month \( K \) of year \( i \); daily precipitation greater than 12 mm is taken as erosive rainfall; \( \bar{P}_{d0} \) is the average value of erosive rainfall; \( \bar{R} \) is the annual average rainfall erodibility; and \( \alpha, \beta \) are the model parameters.

(2) Soil erodibility factor (\( K \))

Soil erodibility factor (\( K \)) is a measure of soil corrosion resistance and it is used to reflect the sensitivity of soil to erosion. This study adopted the Environmental Policy-Integrated Climate (EPIC) model (Zhang et al. 2009; Shi et al. 2012). The formula of the model is as follows:

\[
K_{EPIC} = \left\{ 0.2 + 0.3 \exp \left[ -0.0256 SAN \left( 1 - \frac{SIL}{100} \right) \right] \right\} \left( \frac{SIL}{CLA+SIL} \right)^{0.3} \times \left[ 1 - \frac{0.25C}{C + \exp(3.72 - 2.95C)} \right] \times \left[ 1 - \frac{0.7SN_1}{SN_1 + \exp(-5.51 + 22.9SN_1)} \right], \tag{7}
\]

\[
SN_1 = 1 - SAN, \tag{8}
\]

where SAN is the percentage of sand grain (particle size: 0.05–2 mm); SIL is the percentage of silt sand (particle size: 0.002–0.05 mm); CLA is the percentage of clay (particle size: <0.002 mm); \( C \) is the percentage (%) of organic carbon. However, the actual \( K \) value in all regions of China and the \( K \) value calculated by the EPIC model are different from each other. Therefore, the \( K \) value correction equation that proposed by Liu et al. (2016) has been adopted (Liu et al. 2016):

\[
K = -0.01383 + 0.51575 K_{EPIC}, \tag{9}
\]

(3) Slope and slope length factor (\( LS \))

Slope and slope length factor (\( LS \)) represent the ratio of soil loss on the slope surface of a given slope length and slope to soil loss on the slope surface of a standard runoff plot with other conditions unchanged. However, zones with slope > 25° are widely distributed in this study region and the original calculation algorithms of \( LS \) ignore this above problem (Liu et al. 2016). In this study, the slope factor (\( S \)) algorithm was optimized to calculate the slope factor of the Yellow River Basin, and the formula is as follows:
S = \begin{cases} 
10.8 \sin \theta + 0.03 & \theta \leq 5^\circ \\
16.8 \sin \theta - 0.50 & 5^\circ < \theta \leq 10^\circ \\
20.204 \sin \theta - 1.2404 & 10^\circ < \theta \leq 25^\circ \\
29.585 \sin \theta - 5.6079 & \theta > 25^\circ 
\end{cases} 
\quad (10)

The formula of slope length factor (L) is as follows (Guo et al. 2018):

\[ L = \left( \frac{\lambda}{22.13} \right)^m, \quad (11) \]

\[ m = \begin{cases} 
0.2 & \theta \leq 1^\circ \\
0.3 & 1^\circ < \theta \leq 3^\circ \\
0.4 & 3^\circ < \theta \leq 5^\circ \\
0.5 & \theta > 5^\circ 
\end{cases} \quad (12) \]

where \( L \) is the slope length factor, \( S \) is the slope factor, \( \lambda \) is the slope length (m), and \( \theta \) is the slope (°).

(4) Vegetation coverage factor (C)
Vegetation cover factor (C) refers to the ratio of soil loss under a particular crop or vegetation cover to the loss of continuous fallow after cultivation (You and Li 1999; Yu et al. 2009; Guo et al. 2018, 2020e). According to study of Cai et al. (2000), the calculation formula of \( C \) is as follows:

\[ C = \begin{cases} 
1 & f_c = 0 \\
0.6508 - 0.3436 \lg f_c & 0 < f_c \leq 0.783, \\
0 & f_c > 0.783 
\end{cases} \quad (13) \]

In the formula, \( f_c \) is the vegetation coverage, and its formula is Guo et al. (2018), (2020a):

\[ f_c = \frac{\text{NDVI}_{\text{veg}} - \text{NDVI}_{\text{soil}}}{\text{NDVI}_{\text{veg}} - \text{NDVI}_{\text{soil}}}, \quad (14) \]

where \( \text{NDVI}_{\text{veg}} \) is the maximum value of pure vegetation at a confidential level of 0.95, and \( \text{NDVI}_{\text{soil}} \) refers to the minimum value of pure bare soil at a confidential level of 0.05.

(5) Crop management factor (P)
Crop management factor (P) refers to the ratio of soil loss after adopting soil and water conservation measures to the soil loss. It reflects the impacts of crop management measures on soil and water loss, and its value ranges from 0 to 1. The land use types in the Yellow River Basin mainly include paddy field, upland, woodland, and grassland and water area. However, cultivated lands with steep slope reclamation are widely distributed in this study region, which has been ignored by most previous studies (Guo et al. 2018; Hu et al. 2020). Therefore, in this paper, cultivated lands
(dryland) are divided into three categories: slope $< 15^\circ$, $15^\circ \leq$ slope $< 25^\circ$ and slope $\geq 25^\circ$, and the values are assigned to different regions, as shown in Table 1.

### 2.3.2. Gravity centre model

Gravity centre that derived from the field of physics refers to the point at which the gravity force is exerted equally on each part of an object. Moreover, in the field of soil erosion, the spatial variation characteristics of gravity centre can reflect the degrees of change trend of soil erosion. The erosion value of grid $i$ is $v_i$ and the spatial mean value of a region that composed of space units (grids) is defined as a $(\bar{x}, \bar{y})$ in the Cartesian coordinate, which can be expressed as follows:

$$\begin{align*}
\bar{x} &= \frac{\sum_{i=1}^{n} v_i x_i}{\sum_{i=1}^{n} v_i} \quad (15) \\
\bar{y} &= \frac{\sum_{i=1}^{n} v_i y_i}{\sum_{i=1}^{n} v_i} \quad (16)
\end{align*}$$

### 3. Spatial and temporal pattern of soil erosion in the Yellow River Basin in the recent 25 years

#### 3.1. Spatial distribution pattern of average soil erosion

Based on the RUSLE model, this study calculated the soil erosion intensities of the Yellow River Basin for 1990, 1995, 2000, 2005, 2010 and 2015 and then obtained the spatial distributions of soil erosion intensity with different levels by referring to the soil erosion intensity grading table (Table 2) of the Ministry of Water Resources (Guo et al. 2018).

| Erosion intensity | Mean modulus of erosion $\left( t/(km^2 \cdot a)^{-1} \right)$ | Average loss thickness $\left( mm/a \right)$ |
|-------------------|-------------------------------------------------------------|----------------------------------------|
| Slight erosion    | $< 1000$                                                    | $< 0.37$                               |
| Mild erosion      | $1000 - 2500$                                               | $0.37 - 1.9$                           |
| Moderate erosion  | $2500 - 5000$                                               | $1.9 - 3.7$                            |
| Intensive erosion | $5000 - 8000$                                               | $3.7 - 5.9$                            |
| Extreme intensive erosion | $8000 - 15000$ | $5.9 - 11.1$ |
| Severe erosion    | $> 15000$                                                   | $> 11.1$                               |

Table 1. $P$ values of different land use types.

| Land use type         | $P$ value |
|-----------------------|-----------|
| Paddy field           | 0.1       |
| $< 15^\circ$ dryland  | 0.45      |
| $15^\circ - 25^\circ$ dryland | 0.65  |
| $> 25^\circ$ dryland  | 0.85      |
| Forest                | 1         |
| High covered grassland| 1         |
| Middle covered grassland | 0.9    |
| Water area            | 0         |
| Residential land      | 0         |
| Marshland             | 0.01      |
| Un-utilized land      | 0         |

Note: $P$ is the soil and water conservation measure factor.

Table 2. Classification criteria for soil erosion intensity.
As shown in Table 3 and Figure 2, the average total erosion of the Yellow River Basin from 1990 to 2015 was $21.82 \times 10^8$ t/a, and the average soil erosion modulus was $2777.5$ t/(km$^2\cdot$a)$^{-1}$, which belonged to moderate erosion. Amongst them, the area of slight erosion was the largest with $44.96 \times 10^4$ km$^2$, accounting for 57.24% of the total area, whereas the proportion of total erosion amount was 2.27%. It was mainly distributed in the basins of Lanzhou to Hekou Town, the inner flow area, Hekou Town to Longmen Valley, the Longyang Gorge Basin above and the Huayuankou Basin below. Zone of moderate erosion covered an area of $9.24 \times 10^4$ km$^2$, accounting for 11.76% of the total area, and its total erosion amount accounted for 15.48%. It was mainly distributed in the northeast of the Longyangxia River Basin and the central and northern parts of the Longmenxia River Basin from the Longmen

Table 3. Classification of average soil erosion intensity in the Yellow River Basin from 1990 to 2015.

| Erosion intensity   | Area (10$^4$ km$^2$) | Erosion modulus (t/(km$^2\cdot$a)$^{-1}$) | Total erosion (10$^4$ t/a) | Proportion of area/% | Proportion of erosion/% |
|--------------------|---------------------|----------------------------------------|---------------------------|---------------------|------------------------|
| Slight erosion     | 44.96               | 109.96                                 | 4944.25                   | 57.24               | 2.27                   |
| Mild erosion       | 8.83                | 1688.24                                | 14912.40                  | 11.24               | 6.83                   |
| Moderate erosion   | 9.24                | 3655.43                                | 33782.39                  | 11.76               | 15.48                  |
| Intensive erosion  | 6.74                | 6351.92                                | 42812.58                  | 8.58                | 19.62                  |
| Extreme intensive erosion | 6.28 | 10736.53                              | 67449.03                  | 8.00                | 30.91                  |
| Severe erosion     | 2.50                | 21728.17                               | 54300.87                  | 3.18                | 24.89                  |
| Total              | 785603              | –                                      | 218201.6                  | 100                 | 100                    |

Figure 2. Average soil erosion intensity in the Yellow River Basin from 1990 to 2015.
Xia to the Sanmenxia. The area of extreme intensive and severe erosion was smaller with $6.28 \times 10^4$ and $2.50 \times 10^4$ km$^2$, accounting for 8.00 and 3.18%, respectively, and its total erosion amount accounted for 55.8%. They were mainly distributed in the southeast of the Longyangxia River Basin, the south and northeast of the Longmenxia River Basin and the north of Sanmenxia River Basin–Huayuankou River Basin.

### 3.2. Changes of area and erosion amount for different levels of erosion intensity

In the recent 25 years, there was a decreased trend in soil erosion intensity on the whole, although some differences in the area and total erosion were observed in different levels of erosion intensity. As shown in Figures 3 and 4, the area of slight and mild erosion in the Yellow River Basin was the most widely distributed, accounting for approximately 65% of the total area, which was mainly distributed in the river basins of Lanzhou to Hekou Town, the inner flow zone, Hekou to Longmen, Longyangxia–Huayuankou. The intensive and above erosion levels accounted for approximately 20% of the total area, which were mainly distributed in the southeast of the Longyangxia River Basin, south and northeast of the Longmenxia River Basin and north of the Sanmenxia–Huayuankou River Basin.

From the perspective of the erosion area change for different levels during 1990–2015, the area proportion of the slight erosion showed a trend of firstly decreasing (1990–1995) and then increasing (1995–2015), whereas the moderate and its above erosion levels showed a trend of firstly increasing (1990–1995) and then decreasing (1995–2015). In terms of the total erosion amount, the proportion of total erosion amount in the slight, mild and moderate erosion firstly increased (1990–2005), then decreased (2005–2010) and finally increased (2010–2015), whereas the proportion of total erosion amount in the extreme intensive erosion firstly decreased (1990–2005), then increased (2005–2010) and finally decreased (2010–2015). These above analyses revealed that soil erosion intensity in the Yellow River Basin showed a decreased trend in the past 25 years.
3.3. Spatial distributions and migrations of soil erosion gravity centre

Distributions and migrations of gravity centre of soil erosion can effectively reflect the difference of increasing rate and increment for soil erosion inner the study area. In this study, the distributions and changes of gravity centre of soil erosion intensity in the recent 25 years were calculated and analyzed with tool ArcGIS 10.5 (Figures 5 and 6). The gravity centre of soil erosion in the Yellow River Basin in the recent 25 years was located at approximately 35°N and 108°E, indicating that soil erosion was mainly concentrated in the middle and upper reaches, including the central and western parts of Shaanxi Province, the southern part of Gansu Province and the northeastern part of Qinghai Province. To analyze the spatial change patterns of soil erosion in the recent 25 years, this study analyzed the migration direction and distance of the gravity centre. The results showed that the gravity centre of soil erosion...
generally moved to the southwest during 1990–2015, indicating that the increment and increasing rate of soil erosion in the southwest of the Yellow River Basin was greater than that in the northeast parts. In addition, the changes of the gravity centre in 1990–1995 and 2000–2015 were relatively smaller, indicating slighter change differences of soil erosion inner the Yellow River Basin occurred during these above periods. On the contrary, the migration distance of the gravity centre of soil erosion during 1995–2000 was relatively larger, indicating there were considerable change

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**Figure 5.** Spatial distribution of gravity centre for soil erosion from 1990 to 2015.

**Figure 6.** Migration trajectory of gravity centre of soil erosion from 1990 to 2015.
differences in increment and increasing rate in the southwest and northeast of the Yellow River Basin during this period.

### 3.4. Changes of soil fertility loss and retention

Based on the total soil erosion amount and the contents of soil total N, total P, total K and organic matter in the Yellow River Basin from 1990 to 2015, the loss of N, P, K and organic matter in the recent 25 years was calculated (Figure 7). The results showed that the loss of N, P, K and organic matter decreased from 1990 to 2015, but an interval maximum was observed in 2005. The loss of N, P, K and organic matter was the largest in 1990 with $419.25 \times 10^4$ t, $228 \times 10^4$ t, $4941 \times 10^4$ t and $7935.75 \times 10^4$ t, respectively. From 1990 to 2000, the loss of N, P, K and organic matter firstly showed a decreasing trend and then increased sharply due to the increase of total soil erosion amount from 2000 to 2005, with increments of $70.5 \times 10^4$ t, $25.5 \times 10^4$ t, $543.75 \times 10^4$ t and $1417.5 \times 10^4$ t, respectively. From 2005 to 2015, the loss of N, P, K and organic matter decreased with the decrease in total soil erosion amount and reached the smallest value with $143.25 \times 10^4$ t, $89.25 \times 10^4$ t, $2064 \times 10^4$ t and $2563.5 \times 10^4$ t, respectively.

### 4. Discussion

To explore the driving mechanisms of spatial–temporal change patterns of soil erosion in the Yellow River Basin from 1990 to 2015, we analyzed the effects of slope, soil type and land use on soil erosion in the Yellow River Basin.

#### 4.1. Effect of slope on soil erosion

Slope is an important factor affecting soil erosion, in which slope steepness, slope length and slope shape all have great impacts on the erosion process. Therefore, slope...
is the dominant factor that determines runoff erosion capacity (Cai et al. 2000; Qian et al. 2018). As shown in Figure 8, the mean value and variance of soil erosion enlarged with the increase of slope. Amongst them, the mean value and variance of soil erosion were the smallest in zones with slope $< 3^\circ$. The reason was that the surface runoff velocity caused by precipitation was low so that the scouring capacity to the surface soil was weak in zones with small slope (Chen 2019). Meanwhile, the soil erosion intensities in these regions were smaller, belonging to slight and mild erosion, so the internal distribution patterns were relatively consistent. In zones with slope ranging from $3^\circ$ to $20^\circ$, the mean value and variance of soil erosion enlarged with the increase of slope. Meanwhile, such increase could lead to the increased velocity of surface runoff, which would wash away and transport more surface soil (Cui et al. 2006). In addition, the cultivated lands reclaimed in zones with steep slope, coupled with poor soil and water conservation measures, led to a large amount of soil washed away by precipitation and runoff (Cui et al. 2006). In zones with slope $< 20^\circ$, the increasing rate of soil erosion intensity decreased while the variance also showed a downward trend. The reason was that there were weaker human reclamation activities and increased vegetation coverage with the increase of slope (Feng et al. 2018). At the same time, the soil layer was thin in the steep slope zone, and the amount of soil that could be washed and transported became smaller, which led to the decrease in soil erosion (Wischmeier and Smith 1958; Yu et al. 2009; Liu et al. 2011; Guo et al. 2018).

4.2. Effect of soil type on soil erosion

The physical and chemical properties of surface soil, such as soil composition, structure and organic matter content, in different soil types can affect soil erosion intensity to a certain extent (Guo and Wen 2020; Guo et al. 2020a). In this study, eight typical
soil types were selected to analyze the effects of soil type changes on the soil erosion intensity. As shown in Figure 9, the loess had the largest soil erosion intensity of 4752.84 t/a\(^{-1}\), which belonged to moderate erosion. The main reason was that loess was loose and porous, with strong water storage capacity, good permeability, and better retention of water and fertilizer (Liu et al. 2016). Under high-intensity disordered cultivation, the physical structure of the soil surface was severely damaged, resulting in substantial soil erosion. At the same time, the loess with low content of organic matter and weak corrosion resistance was mostly distributed in zones with fragmented terrain, large slope, intensive precipitation, and sparse vegetation (Peng 2000). The saline–alkali soil type had smaller erosion intensity due to the fact that the saline–alkali soil had a salinized layer or alkali layer, which could protect the topsoil from precipitation and surface runoff (Yang and Gao 2012). The soil erosion intensity of cinnamon soil was the most heterogeneous in spatial distribution because this soil type was widely distributed throughout the study region, so that the inner difference in soil erosion intensity was significant (Zhang et al. 2018). Grassland sandy soil had the smallest soil erosion intensity with 117.76 t/a\(^{-1}\), which belonged to slight erosion. The main reason was that zones with grassland sandy soil type had a dryness of 1.50–3.50, with less erosive precipitation (Guo et al. 2018; Dang and Sun 2019). Meanwhile, the soil erosion intensity belonged to mild erosion, and the difference in its internal spatial distribution pattern was small (Ouyang et al. 2010). The soil erosion intensity of chestnut soil, sierozem and wet soil was smaller with 1359.17, 1010.18 and 348.31 t/a\(^{-1}\); respectively. The reason was that the contents of organic matter and CaCO\(_3\) in these above soil types were relatively high, so that the soil erosion resistance to surface runoff was strong (Dang and Sun 2019). In addition, the

![Figure 9. Comparisons of the average soil erosion amount of different soil types from 1990 to 2015 (1–6 represents the types of primary, semi-hydrated, hydrated, saline–alkali soil, artificial soil and alpine soil, respectively).](image-url)
vegetation coverage in these above zones was higher, which could also reduce the amount of soil erosion (Zhao et al. 2017).

4.3. Impact of land use types on soil erosion

The effects of land use type on the spatial distribution of soil erosion intensity considerably varied due to the differences of vegetation types and soil and water conservation measures (You and Li 1999; Guo et al. 2020b). In this study, nine typical land use types were selected to analyze and discuss the mean value and variance of soil erosion intensity under different land use types. As shown in Figure 10, the soil erosion intensity of shrub land and wooded land was relatively larger with 4712.16 and 4331.07 t/a$^{-1}$, respectively, which both belonged to moderate erosion. The main reason was that shrub land and woodland were mostly distributed in mountainous or hilly areas with steep slopes and poor water conservation measures (Shi et al. 2012). Meanwhile, significant differences in vegetation coverage were observed within the above land types, leading to a significant heterogeneity in the spatial distribution of soil erosion intensity (Zhang et al. 2018). Paddy fields and swamps with better soil and water conservation measures were covered by water in most of the year, whereas the swamps had higher vegetation coverage (Guo et al. 2018; Zhang et al. 2018). The urban and rural residential lands were covered by buildings and roads, whose soil erosion intensity was low.

5. Conclusion

In this study, the gravity centre model was introduced to quantitatively analyze the temporal and spatial evolution patterns of soil erosion in the Yellow River Basin from
1990 to 2015 based on the improved RUSLE model. The major conclusions were as follows:

(1) During 1990–2015, the annual average total soil erosion in the Yellow River Basin was $21.82 \times 10^8$ t/a, and the average erosion intensity was 2777.5 t/a, belonging to moderate erosion. Amongst them, the southeast part of the Longyangxia Basin, the south and northeast parts of the Longmen Sanmenxia Basin and the north part of Sanmenxia–Huayuankou Basin had larger soil erosion intensity, belonging to intensive and above erosion levels.

(2) During 1990–2015, the change trend of soil erosion intensity in the Yellow River Basin showed a “single-peak” pattern. The area and total amount in intensive and above erosion levels showed a decreasing trend, whereas that of the slight and mild erosion levels showed an increased trend.

(3) During the past 25 years, the gravity centre of soil erosion in the Yellow River Basin moved to the southwest, indicating that the increment and increased rate of soil erosion in the southwest part were larger than that in the northeast part.

(4) The intensity of soil erosion enlarged with the increase in slope. The soil erosion intensity of different soil types differed greatly due to the regional climate and their own physical and chemical structures, such as CaCO$_3$ and organic matter contents. Moreover, woodland and shrubbery land had severer erosion intensity than that of paddy field, marshland and residential area.

**Disclosure statement**

No potential conflict of interest was reported by the authors.

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**Data availability statement**

The data that support the findings of this study are available from the corresponding author, Guo B, upon reasonable request.
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