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Evaluation of the driving effects of socio-economic development on soil erosion from the perspective of prefecture-level

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Soil erosion is affected by nature and human activities. Compared with biophysical factors, the effects of socio-economic factors on soil erosion have not been well investigated. Here, taking two prefectures (Yan'an and Qingyang) with different socio-economic conditions and ecological restoration intensity on the Chinese Loess Plateau (CLP) as a case, we combined the Revised Universal Soil Loss Equation (RUSLE), partial least squares structural equation modeling (PLS-SEM), and gray relation analysis to explore the response of soil erosion to socio-economic development. Our results showed that Grain for Green Program (GGP) has effectively controlled soil erosion and increased the vegetation coverage of the study area. For Yan'an, the vegetation coverage was increased by 6.2% and erosion modulus was decreased by 33.9% in 2015 compared with that in 1995. The differences in industrial structure and agricultural input led to different responses of soil erosion to socio-economic development. Economic development and agricultural input accelerated soil erosion in Qingyang but inhibited soil erosion in Yan'an due to different development strategies. Moreover, the increase of the gray relation grade between socio-economic factors and soil erosion in Yan'an indicates that soil erosion is easier to be controlled by the development of the socio-economy. The results indicate that the triple-win situation of economic development, vegetation restoration, and soil conservation can be realized by adjusting the economic structure, strengthening ecological restoration, and agricultural investment. This research emphasizes the important effect of socio-economic development on soil erosion and provides a reference for soil erosion control and ecological restoration for regions suffering from severe soil erosion.

KEYWORDS

soil erosion, Grain for Green Program, socio-economic factor, RUSLE, PLS-SEM

1 Introduction

Soil erosion remains one of the most important environmental problems in the world, which accelerates land degradation, promotes water pollution, and threatens food security, thereby impeding the achievement of sustainable development goals 2.4 and 15.3 of the United Nations (Pradhan et al., 2017; Fu et al., 2019; Wuepper et al., 2020). Compare with socio-economic factors, current researches focus more on the effects of biophysical factors on soil erosion (Luetzenburg et al., 2020; Liang and Fang, 2021). However, with the acceleration of urbanization, the effect of socio-economic factors such as economic development, population, and land use structure on erosion has gradually increased (Panagos et al., 2018). Borrelli et al. (2017) found that human activities and relevant land use changes are the main factors that accelerate global soil erosion. Wuepper et al. (2020) compared the soil erosion rate of different countries and found that agricultural activities are the main driving force of soil erosion acceleration. Therefore, the relationship between socio-economic development and soil erosion deserves further exploration.

In the initial period of social development, urbanization and economic development always rely on secondary industries including mining and construction, which bring enormous destruction on the ecological environment and further accelerate soil erosion (Wang et al., 2018; Jeong and Dorn, 2019). At the same time, the increase in urban population put more pressure on food security, and the expansion of cropland leading to improved agricultural activities change the land use structure and accelerate land degradation (Shi et al., 2020). With the development of urbanization, the government paid more attention to soil conservation and a series of ecological programs have been implemented to control soil erosion (Cao et al., 2021). However, differences in socio-economic conditions led to different effects of soil conservation among regions, and the key socio-economic factors that affect soil erosion have not been well assessed (Zhou et al., 2021).

The Chinese Loess Plateau (CLP) is one of the most severely eroded areas of the world (Xu and Zhang, 2021b). Rapid urbanization and unbalanced socio-economic development have led to deforestation and accelerated soil erosion (Wei et al., 2006). To mitigate the degradation of the environment, the world's largest ecological restoration program named the Grain for Green Program (GGP) has been implemented on the CLP from 1998 (Bryan et al., 2018). The implication of GGP significantly improved the ecosystem in multiple aspects, and soil erosion has been controlled through the optimization of land use structure (Jin et al., 2021; Zhang et al., 2021). However, the soil conservation effect of GGP was different in each administrative region of CLP, which has gained much attention in recent years (Li et al., 2021; Yang and Zhang, 2021). Sun et al. (2013) found there are significant differences in erosion rates among different prefectures on the CLP. Ning et al. (2021) hold the view that GGP implementation intensity influences soil conservation effects in different counties. These previous studies have focused more on the impact of vegetation restoration project on soil erosion, ignoring the role of potential socio-economic factors, which greatly limited the sustainability of vegetation restoration and soil conservation. Therefore, it is urgent to identify the socio-economic driving forces of soil erosion under the background of GGP and analyze how to coordinate the relationship between socio-economic development and ecological restoration.

To address the problems mentioned above, this work selected Yan'an and Qingyang on the CLP, with different socio-economic development and ecological restoration, as our study area. The effectiveness of GGP and the effects of socio-economic development on soil erosion in different prefectures were evaluated. Specifically, this study aimed to 1) analyze the dynamic changes in land use and soil erosion in different prefectures, 2) quantify the driving effects of socio-economic factors on soil erosion, and 3) clarify the interaction between socio-economic development and ecological restoration.

2 Materials and methods

2.1 Study area

Yan'an and Qingyang prefectures are located in the center of CLP and belong to typical hilly and gully regions (35°15′–37°31′N, 106°20′–110°31′E). Our study area covers an area of 64,119 km^2, with 37,000 km^2 of Yan'an and 27,119 km^2 of Qingyang. Yan'an is situated in the north of Shaanxi Province and has 13 counties; Qingyang is located in the east of Gansu Province and has 8 counties (Figure 1). The terrain of the study area is high in the north and low in the south, with an average elevation of about 1,300 m. The study area has a semi-arid climate with an annual average temperature of about 9.5°C. The annual average precipitation is about 500 mm, and the rainfall is mainly concentrated from July to September, which accounts for 60%–80% of the total amount.

Yan'an and Qingyang prefectures are geographically adjacent to each other and have similar climate and terrain conditions. Since 1999, GGP has been adopted in Yan'an and Qingyang; as a result, soil erosion has been controlled and the vegetation coverage has improved significantly. However, we found that the effects of GGP have significant differences by analyzing the annual maximum NDVI variations of the two prefectures. Moreover, the socio-economic development of these prefectures has obvious differences. The GDP of Yan'an reached 119.58 billion yuan in 2015, which is nearly twice as high as that of Qingyang (Figure 2).

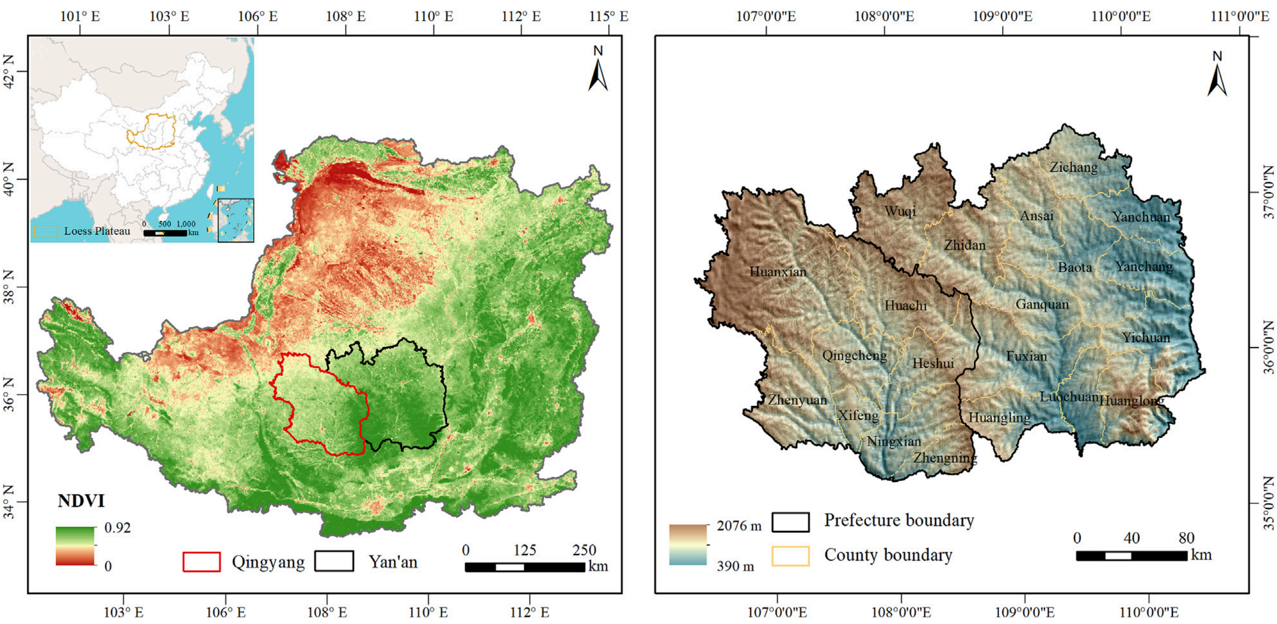

FIGURE 1
Location and digital elevation model (DEM) of the study area.

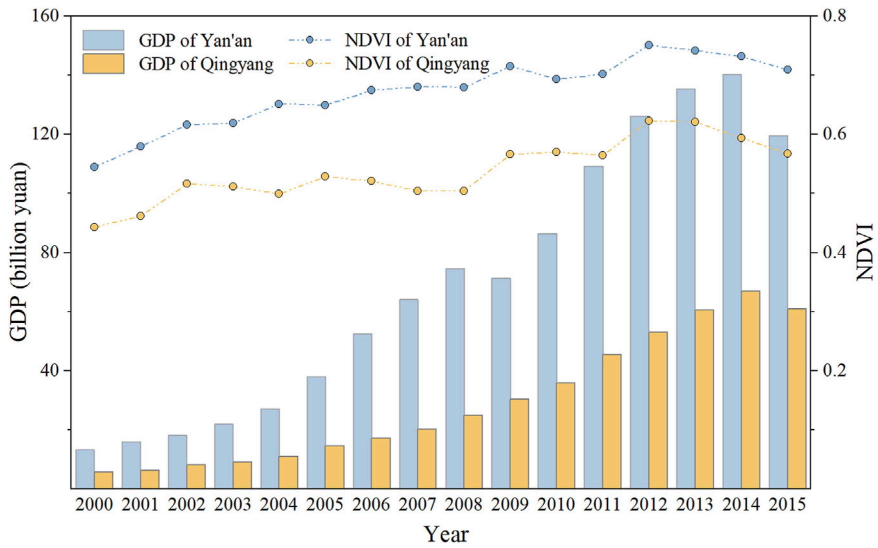

FIGURE 2
Changes in the annual maximum NDVI and GDP of the study area between 2000 and 2015.

2.2 Soil erosion model

The Revised Universal Soil Loss Equation (RUSLE) is one of the most widely adopted models that can represent the effects of climate, soil, topographic, and land use on soil erosion (Ghosal and Das Bhattacharya, 2020; Borrelli et al., 2021). It has been proven to be suitable for CLP and can provide reliable simulation results (Sun et al., 2014; Li et al., 2017). Therefore, the RUSLE was utilized to estimate the annual average erosion modulus of the study area in ArcGIS 10.3. All raster data were resampled to 30 m resolution for calculation. The RUSLE is defined as follows:

$$A = R \cdot K \cdot LS \cdot C \cdot P \tag{1}$$

where A is the average soil loss (t hm^{-2} yr^{-1}), R is the rainfall erosivity factor (MJ mm hm^{-2} h^{-1} yr^{-1}), K is the soil erodibility factor (t hm^{2} h hm^{-2} MJ^{-1} mm^{-1}), LS is the topographic factor (dimensionless), C is the vegetation coverage and management factor (dimensionless), and P is the support practice factor (dimensionless).

The rainfall erosivity factor (R) is relevant to rainfall amount, duration, and intensity, and it is usually estimated based on precipitation data (Nearing et al., 2017). Given that our study mainly considers the driving effects of socio-economic factors on soil erosion, the grid data of annual average rainfall erosivity in China developed by Xie et al. (2018) were adopted.

$$R = \frac{1}{N}\sum_{i=1}^{N}\sum_{k=1}^{m}\alpha \cdot P_{i,k}^{1.7394} \tag{2}$$

where N is the total number of years, m is the total number of days with erosivity rainfall, $P_{i,k}$ is the daily rainfall for day k in the i-th year (mm), α is a coefficient which is 0.3946 in the warm season (May to September) and 0.3156 in the cold season (September to April).

The soil erodibility factor (K) represents the susceptibility of soil to erosion by rain water and runoff and can be measured on standard plot (Parysow et al., 2003). The K factor is related to the texture, structure, and organic matter content of soil erosion (Sharpley and Williams, 1990). In the present study, we calculated K by using the EPIC equation developed by Williams and Jones. (1984):

$$K = \left\{0.2 + 0.3*\exp\left[-0.0256*SAN\left(1-\frac{SIL}{100}\right)\right]\right\}*\left(\frac{SIL}{CLA+SIL}\right)^{0.3} *\left(1-\frac{0.25*C}{C+\exp(3.722.95*C)}\right)*\left(1-\frac{0.7*SN1}{SN1+\exp(-5.51+22.9*SN1)}\right) \tag{3}$$

$$SN1 = 1 - \frac{SAN}{100} \tag{4}$$

where SAN, SIL, and CLA are the sand, silt, and clay fractions (%), respectively; and C is the soil organic carbon content (%).

The effect of slope length and slope gradient on soil erosion is represented by the topographic factor (LS), which can be estimated based on the digital elevation model (DEM) (Hickey et al., 1994). In this study, we calculated LS by the algorithms developed by Liu et al. (1994). All the results were based on DEM (ASTER GDEM) with 30 m resolution (http://www.gscloud.cn):

$$L = \left(\frac{\gamma}{22.13}\right)^{m} \quad m = \begin{cases} 0.5 & \theta \geq 9^{\circ} \\ 0.4 & 9^{\circ} > \theta \geq 3^{\circ} \\ 0.3 & 3^{\circ} > \theta \geq 1^{\circ} \\ 0.2 & \theta < 1^{\circ} \end{cases} \tag{5}$$

$$S = \begin{cases} 21.9\sin\theta - 0.96 & \theta > 18^{\circ} \\ 16.8\sin\theta - 0.05 & 18^{\circ} > \theta \geq 9^{\circ} \\ 10.8\sin\theta + 0.03 & \theta < 9^{\circ} \end{cases} \tag{6}$$

where γ is the slope length (m), θ is the slope angle (%), and m is a dimensionless constant depending on the slope.

The C factor reflects the effects of vegetation coverage and cropping management measures on soil erosion. It is always related to the fractional vegetation cover (f), which can be calculated by NDVI. In the present study, the NDVI dataset with 30 m resolution was composited by Landsat5 TM and Landsat8 OLI images in the Google Earth Engine system, and the method developed by Cai and Ding. (2000) was adopted to calculate the C factor. The formula is expressed as follows:

$$C = \begin{cases} 1 & f = 0 \\ 0.6508 - 0.3436lg\ f & 0 < f \leq 78.3\% \\ 0 & f > 78.3\% \end{cases} \tag{7}$$

$$f = \frac{(NDVI - NDVI_{soil})}{(NDVI_{max} - NDVI_{soil})} \tag{8}$$

where $NDVI_{soil}$ is the NDVI value for pure bare soil pixel, and $NDVI_{max}$ refers to the NDVI value for regional pure vegetation pixel.

The P factor reflects the ratio of soil loss in specific measures and is the most difficult factor to determine in the RUSLE (Lane et al., 1992). According to previous studies, P is closely related to land use and slope. Thus, we determined this factor based on land use classification map and slope gradient by referencing the method of Sun et al. (2014). Among them, the p-value of water and construction land is 0, the p-value of forest is 0.7, the p-value of grassland is 0.9, the p-value of unused land is 1, and the p values of cropland with slope of 0–15°, 15–25°, and >25° are 0.2, 0.35, and 0.8, respectively.

2.3 Data analysis

2.3.1 Partial least squares structural equation modeling (PLS-SEM)

PLS-SEM is typically used for casual network estimation among latent variables (Grace et al., 2012). The manifest variables can be measured directly, and the latent variables can be expressed by a series of manifest variables. Compared with SEM, PLS-SEM is suitable for small sample sizes and can be used to evaluate the interaction between variables effectively (Shen et al., 2016). It relaxes the assumption of normal distribution and has the ability to solve the model with numerous indicators, which is more appropriate in social science studies (Hair et al., 2019; Wang et al., 2022).

In this work, the driving effects of socio-economic factors on soil erosion during the whole period (1995–2015) were analyzed based on PLS-SEM. The

TABLE 1 The details of socio-economic factors system.

Latent variables	Manifest variables	Units
Economic variables (ECO)	GDP	yuan
	GDP per capita (GDP_CAP)	yuan/person
Population variables (POP)	Total population (TATAL_POP)	person
	Population density (POP_DEN)	person/km^2
	Rural population (RU_POP)	person
Land use variables (LU)	Area of cropland (Area_CROP)	km^2
	Area of forest (Area_FOR)	km^2
	Area of construction land (Area_CON)	km^2
Agricultural input variables (AGI)	The intensity of fertilization (FER)	t
	Total power of agricultural machinery (TAMP)	Myriad watt
Agricultural output variables (AGO)	Total grain production (TOTGRA_PRO)	t
	Gross agricultural output value (GDP_AGR)	yuan

construction and analysis of PLS-SEM were based on Smart-PLS 3.0. Considering the influence factors of soil erosion are various, we selected socio-economic factors based on relevant literature (Du et al., 2011; Wang et al., 2020; Yu et al., 2021a). A total of 12 manifest variables were selected to construct a socio-economic factor system, which includes two economic factors (GDP and GDP per capita), three population factors (total population, rural population, and population density), three land use factors (area of cropland, area of forest and area of construction land), two agricultural input factors (the intensity of fertilization and total power of agricultural machinery), and two agricultural output factors (total grain production and gross agricultural output value) (Table 1). All socio-economic panel data at the county level were collected from Yan'an and Qingyang statistical yearbooks.

The reliability and validity of PLS-SEM were evaluated by the goodness of fit (GOF) in this study. GOF refers to a statistical test that determines how well sample data fits a distribution from a population with a normal distribution, which is required to be better than 0.5. It was calculated as follows (Tenenhaus et al., 2005):

$$\overline{communality} = \frac{1}{P}\sum_{p=1}^{P} communality_p \tag{9}$$

$$GOF = \sqrt{\overline{communality} \times \overline{R^2}} \tag{10}$$

where P is the number of latent variables, $\overline{R^2}$ is the average R^2 of all latent variables. More details about GOF can be found in (Tenenhaus et al., 2005).

2.3.2 Gray relation analysis

Gray relation analysis, which was developed by Ju-Long. (1982), is a multi-factor statistical method for determining the correlation grade between factors by judging the geometric proximity of different factor sequences. This method has less requirements on sample size and typical probability distribution and is very easy to calculate. The relationship between socio-economic factors and soil erosion is complicated and it contains incomplete information, which actually can be seen as a gray system. In this study, gray relation analysis was used to evaluate gray relation grade (GRG) between socio-economic factors and soil erosion in different periods. The method developed by Winarni and Indratno. (2018) was used to calculate GRG in SPSS 26.0. The steps are as follows: 1) normalize the socio-economic data, 2) reference sequence definition, 3) gray relation coefficient calculation, and 4) gray relation grade calculation.

3 Results

3.1 Spatiotemporal variation in land use and soil erosion of different prefectures

Land use changes in these two prefectures have differences in the past 20 years. As shown in Figure 3A, the cropland area of Yan'an decreased from 11,762 km^2 to 9,350 km^2 of which 95.8% was converted into forest and grassland. The forest area gained about 1,271 km^2 from 1995 to 2015, and the vegetation coverage reached 73.5% in 2015. Compared with Yan'an, the increase of

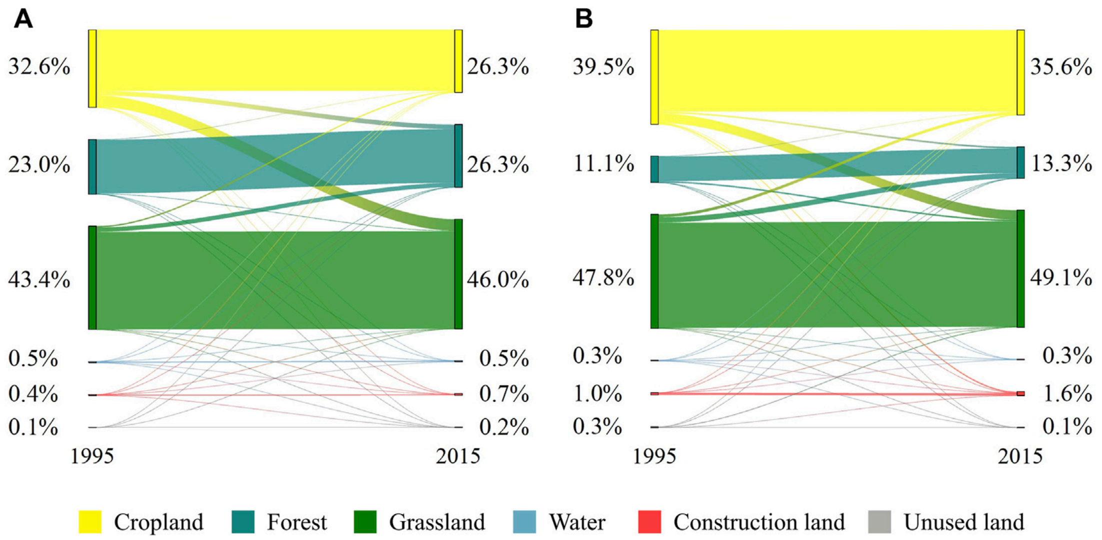

FIGURE 3
Land use change in Yan'an **(A)** and Qingyang **(B)** from 1995 to 2015.

vegetation coverage in Qingyang was not notable (Figure 3B). A total of 1,053 km^2 of cropland was estimated to be lost from 1995 to 2015. The forest area only increased by 579 km^2, and the vegetation coverage increased to 62.5% in 2015.

According to the Technological Standard of Soil and Water Conservation SL190-2007, soil erosion can be classified into six levels: Slight, mild, moderate, intense, extreme, and severe (Ministry of Water Resources of PR China, 2008). Figures 4A–C illustrates that the annual average erosion modulus of Yan'an decreased by 30.54 t hm^{-2} yr^{-1} and reached the minimum of 59.58 t hm^{-2} yr^{-1} in 2015. Specifically, the proportion of areas with slight erosion (<10 t hm^{-2} yr^{-1}) increased by 17.13% and accounted for 38.04% of the total area. At the county level, the annual average erosion modulus decreased most in Yanchang county, which decreased by 63.76 t hm^{-2} yr^{-1} in the past 20 years and the erosion modulus decreased by more than 30 t hm^{-2} yr^{-1} in 9 counties of Yan'an (Table 2). These results depict that the implementation of GGP has alleviated soil erosion significantly in Yan'an. For Qingyang, the annual average erosion modulus decreased from 75.18 t hm^{-2} yr^{-1} to 62.68 t hm^{-2} yr^{-1} from 1995 to 2015 (Figures 4D–F). About 28.7% and 33.6% of areas with severe erosion (>150 t hm^{-2} yr^{-1}) were transformed into areas with moderate and intense erosion. However, the area of slight erosion increased a little. More specifically, only the annual average erosion modulus of Zhengning county decreased by more than 30 t hm^{-2} yr^{-1} and the erosion modulus decline in other counties was not obvious (<20 t hm^{-2} yr^{-1}). In general, the ecological environment of the study area continuously improved during GGP, but Yan'an has gained more remarkable achievements compared with Qingyang.

3.2 Driving effects of socio-economic factors on soil erosion during the whole period

Based on the socio-economic panel data and erosion modulus of Yan'an (n = 65) and Qingyang (n = 40), the PLS-SEM was constructed to analyze the overall driving effect of socio-economic factors on soil erosion from 1995 to 2015. The GOFs of Yan'an and Qingyang are 0.58 and 0.52 (>0.5), respectively. It indicates that all the models are effective and reliable.

As shown in the model of Yan'an in Figure 5A, population variables promoted soil erosion with a path coefficient of 0.376. By contrast, the effects of agricultural input and agricultural output variables were negative with direct effects of −0.063 and −0.071. Economic and Land use variables had significant controlling effects of −0.100 and −0.737 on soil erosion. The path coefficient of Qingyang is presented in Figure 5B and had notable differences compared with Yan'an. Economic variables were important promoting factors with a path coefficient of 0.326, and the promoting effects of agricultural input and population variables were 0.025 and 0.450, respectively. Land use and agricultural output had the highest controlling effect, with path coefficients of −0.760 and −0.562, respectively.

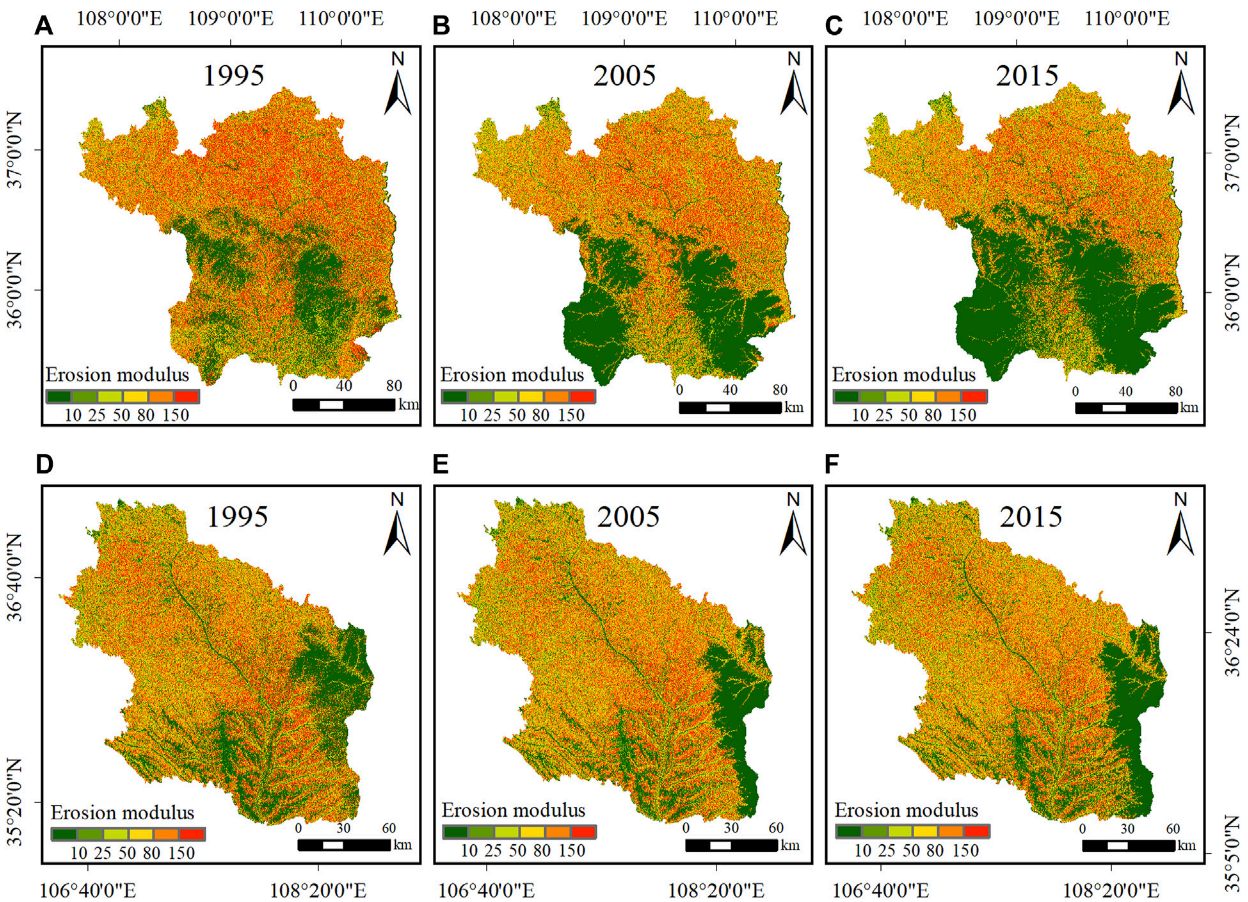

FIGURE 4
Spatial distribution of soil erosion (t·hm^{-2}·yr^{-1}) in Yan'an **(A–C)** and Qingyang **(D–F)** in 1995, 2005, and 2015.

3.3 Gray relation grade between socio-economic factors and soil erosion

The gray relation analysis was used to analyze the socio-economic driving effects of soil erosion at different stages based on socio-economic and soil erosion data. The correlations between socio-economic factors and soil erosion were represented by gray relation grade (GRG).

As shown in Figure 6A, soil erosion was significantly affected by socio-economic factors in Yan'an, and the GRG of each factor gradually increased over time. The GRG of agricultural output was higher than the other factors in 1995 and 2005. Population variable was the most important factor over time, indicating that urbanization and population growth are closely related to soil erosion. By contrast, GRG presented a downward trend at all times in Qingyang (Figure 6B). This phenomenon illustrates that socio-economic development has less impact on changes in soil erosion. The contradiction between socio-economic development and soil erosion should be further alleviated.

Then we calculated the GRG of manifest variables (Figure 7). For Yan'an, cropland area and rural population were the main factors that affected soil erosion. More specifically, the GRG of the cropland area increased from 0.85 to 0.89 after 20 years, and the GRG of rural population reached 0.82 in 2015. This finding indicates that GGP has a great impact on soil erosion by influencing cropland area and rural population. Conversely, for Qingyang, the GRG of most manifest variables decreased over time. The rural population had the highest GRG among these factors, indicating that it had a great impact on soil erosion, but the influence degree gradually decreased. The GRG of the total power of agricultural machinery slightly increased over 20 years, indicating that the development of agricultural technology could effectively influence soil erosion.

TABLE 2 Erosion modulus of each county from 1995 to 2015.

County	Area (km^2)	Erosion modulus ($t\ hm^{-2}\ yr^{-1}$)		
		1995	2005	2015
Baota	3556	93.64	69.52	49.14
Ansai	2950	134.08	92.86	74.6
Yanchang	2368.7	130.99	91.25	67.23
Yanchuan	1985	122.07	87.25	66.37
Zhidan	3781	100.45	79.77	60.16
Wuqi	3791.5	97.79	72.52	52.85
Ganquan	2300.7	51.55	46.52	36.87
Fuxian	4182	32.48	29.75	19.97
Luochuan	1804	62.47	42.31	29.37
Yichuan	2931	64.8	44.62	28.15
Huanglong	2752	12.78	6.84	4.61
Huangling	2292	25.22	15.51	8.55
Zichang	2405	121.67	83.92	65.43
Huanxian	9236	84.61	81.56	71.08
Huachi	3776	73.52	82.53	69.24
Heshui	2976	49.59	55.39	43.18
Ningxian	2633	68.8	64.91	48.54
Zhengning	1329	77.44	58.3	35.26
Zhenyuan	3500	71.17	71.95	60.82
Qingcheng	2673	89.73	93.58	79.1
Xifeng	996	57.97	65.68	54.02

4 Discussion

4.1 Driving effect of economic development on soil erosion

Based on the PLS-SEM results, the driving effect of each socio-economic factor on soil erosion varies between prefectures. Economic development is one of the key factors, and its impact on soil erosion has two sides (Vanwalleghem et al., 2017). On the one hand, economic development could increase the investment ability of soil conservation, but on the other, economic development is usually at the expense of resource consumption and ecological interference (Ekeocha, 2021). The final effect of economic development on soil erosion always depends on the trade-off between ecosystem damage and protection (Odongo et al., 2014; Vávra et al., 2019).

At the beginning of development, economic growth mainly relies on agricultural development, which comes at the cost of deforestation, land degradation, and soil erosion increase significantly (Ping et al., 2013; Eekhout and de Vente, 2022). After long-term development, the economic structure of Yan'an was dominated by secondary and tertiary industries, and the economic development could provide more financial support for ecological restoration and soil conservation (with a path coefficient of −0.100 in the whole period). However, the economic development of Qingyang still highly depended on agriculture and industry, the achievements of GGP were difficult to maintain under deeper land degradation, and socio-economic development accelerated soil erosion instead (with a path coefficient of 0.326 in the whole period) (Lu et al., 2019; Wang et al., 2019). Our results further confirm that scientific economic development strategy is the foundation for ecological restoration.

4.2 Gray relation grade evolution in different prefectures

From 1995 to 2015, GRG varied in different prefectures. Before the implementation of GGP, the influences of socio-economic factors on soil erosion in the two prefectures were similar and the GRG of each factor was close. Agricultural output had the highest GRG, which may be related to that agriculture was the leading industry in these two prefectures (Yu et al., 2021c). The development of agriculture came at the expense of the ecological environment, and agricultural output was the most important socio-economic factor contributing to the acceleration of soil erosion (Wang et al., 2016).

With the development of agricultural technology, inputs of fertilizer and agricultural machinery could help to improve soil fertility and grain yield production of cropland (Rasmussen et al., 2018). Meanwhile, the decrease in the cropland area reduces the risk of erosion occurrence (Yu et al., 2021b). The GRG of agricultural input increased from 0.696 to 0.769 in Yan'an and the proportion of the primary industry has declined, the economic structure has become more reasonable. However, the agricultural input has not alleviated soil erosion in Qingyang with GRG decreasing from 0.733 to 0.656. More frequent agricultural cultivation activities caused the disordered expansion of agriculture and difficulty in maintaining the achievement of soil conservation. The downward trend of GRG indicates that socio-economic development has less effect on soil erosion, and the contradiction between them will further deepen in the future.

4.3 Implications

Socio-economic development is the premise of soil conservation, and ecological restoration should be formulated and coordinated with local socio-economic conditions (Barbier, 2010). Although GGP has made great achievements, current policies at the prefecture-level need to be adjusted to realize the coordinated development of the economy and ecology (Zeng et al., 2022). The local government also should actively guide the adjustment of the industrial structure, and the pillar industries need to be adjusted from agriculture to secondary and service industries (Rao et al., 2016). A reasonable industrial structure is

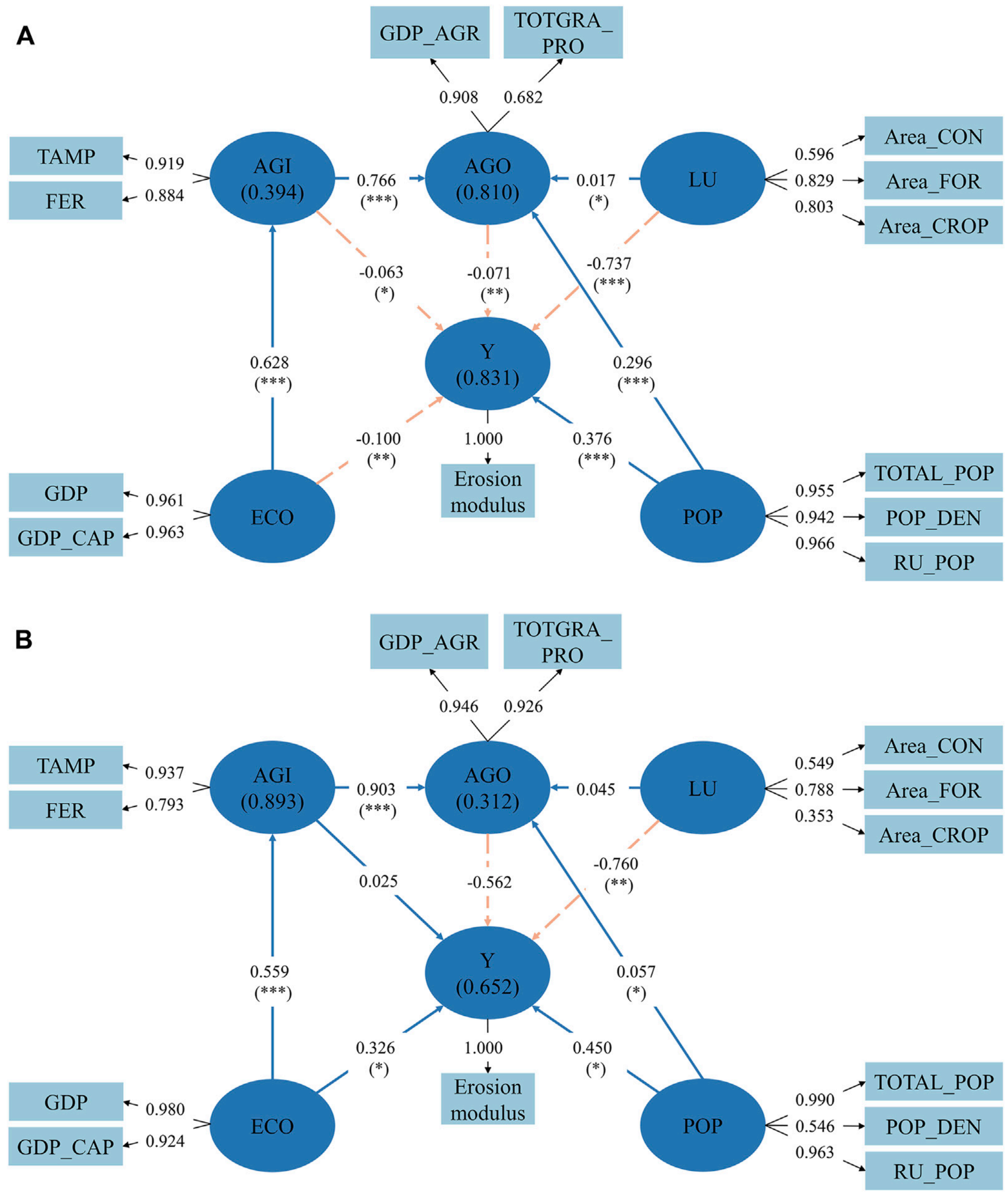

FIGURE 5
Partial least squares structural equation model showing the relationship between socio-economic factors and soil erosion of Yan'an **(A)** and Qingyang **(B)**. Abbreviations are defined in Table 1. The ellipses represent latent variables and the rectangles represent manifest variables. The lines between latent variables are paths, and the lines from latent variable to manifest variable are loadings. Orange lines indicate negative correlation and blue lines indicate positive correlation. *, ** and *** indicate significance levels of $p < 0.05$, 0.01, and 0.001, respectively.

a prerequisite for sustainable development (Olawumi and Chan, 2018).

As GGP is a top-down ecological policy, the annual task of GGP is transmitted stepwise from the provincial government and the final strategy always depends on the local government (Xu and Zhang, 2021a). The government should fully consider the local natural conditions and socio-economic development before planning scientific strategies. First, land use structures should be optimized to ensure food security, and farmers' livelihoods should be guaranteed by developing agricultural technology. Second, slope cropland should be converted to grassland or forest in time and soil conservation engineering, such as check dams and terraces, should be constructed to decrease erosion according to the situation of the regions (Shi et al., 2020). Finally, as the natural condition and resource endowment is similar in the watershed, the ecological restoration project should be

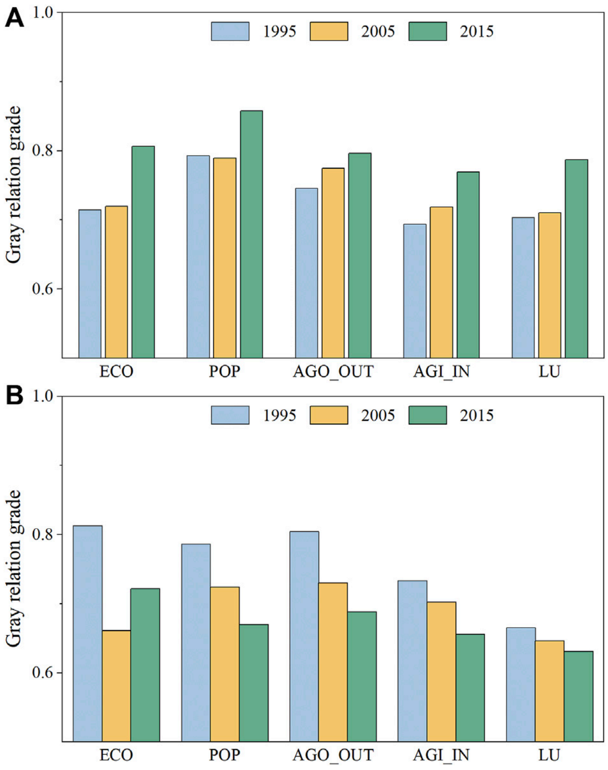

FIGURE 6
Gray relation grade of latent variables in Yan'an **(A)** and Qingyang **(B)**. ECO, economic development; POP, population; AGO, agricultural output; AGI, agricultural input; LU, land use.

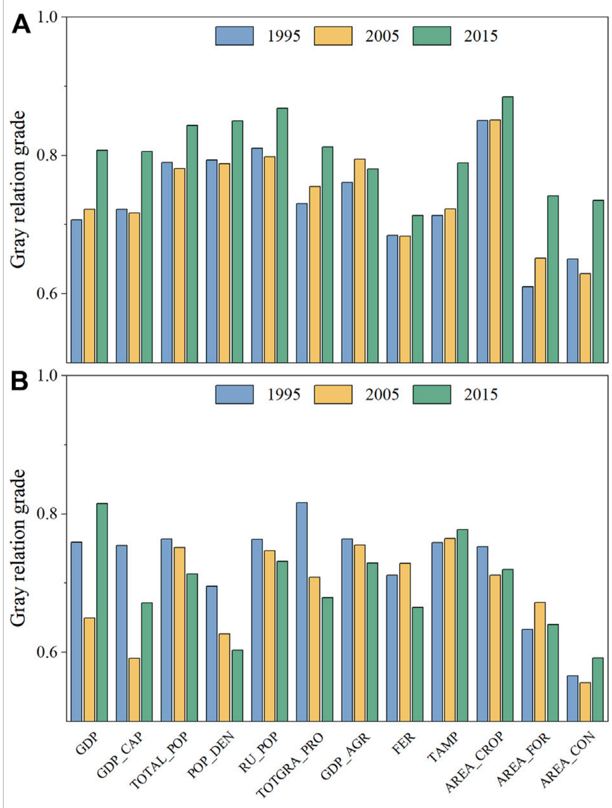

FIGURE 7
Gray relation grade of manifest variables in Yan'an **(A)** and Qingyang **(B)**. Abbreviations are defined in Table 1.

implemented based on the natural watershed unit to break the restriction of administrative division.

5 Conclusion

This study constructed a framework by using the RUSLE, PLS-SEM, and grey relation analysis to assess the effectiveness of GGP and evaluate the driving effects of socio-economic factors on soil erosion in Yan'an and Qingyang from 1995 to 2015. The valuable conclusions could be summarized as follows. First, GGP has made great contributions to vegetation restoration and soil erosion control. The annual average erosion modulus decreased by 30.54 t hm^{-2} yr^{-1} in Yan'an but 12.5 t hm^{-2} yr^{-1} only in Qingyang from 1995 to 2015, which indicates that GGP was more effective in Yan'an. Second, the driving effects of socio-economic factors on soil erosion varied between prefectures. Land use and population have the most positive and negative effects on soil erosion Economic development and agricultural input were promoting factors in Qingyang but controlling factors in Yan'an, and the difference in their effects could be related to the land use pattern and industrial structure of regions. Moreover, the GRG showed an upward trend in Yan'an but the opposite in Qingyang, indicating that the contradiction between socio-economic development and soil erosion will be further alleviated in Yan'an. To ensure coordinated social-economic and ecological construction, the dynamics of socio-economic context should always be considered during large-scale ecological program planning, monitoring, and implementation.

Data availability statement

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

Author contributions

Conceptualization, investigation, methodology, writing-original draft preparation, data collection, visualization, software: BW, HW, DC, and YZ; formal analysis, software: BW, YZ, ML, and YW; writing-review and editing: LN, NF, and YZ; funding acquisition, project administration: LN, NF.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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