

Article

The Impact of Land Use Types on the Soil Erosion Resistance in the Arid Valley Region of Southwest China

Jinhuan Li ^{1,2,3}, Shoujiang Liu ^{1,2,3}, Dan Yang ^{1,2,3,*}, Fei Suo ⁴, Yushou Yu ^{1,2,3}, Zihao Wang ^{1,2,3} and Qihua Liao ^{1,2,3}¹ School of Geographical Sciences, China West Normal University, Nanchong 637009, China² Sichuan Provincial Engineering Laboratory of Monitoring and Control for Soil Erosion on Dry Valleys, China West Normal University, Nanchong 637009, China³ Institute of Jialing River Basin, China West Normal University, Nanchong 637009, China⁴ Big Data Center of Geospatial and Natural Resources of Qinghai Province, Xining 810008, China

* Correspondence: yangdan1963@126.com; Tel.: +86-18583389850

Abstract: Changes in land use can alter the physicochemical properties of soil, thereby leading to variations in soil erosion resistance. In the past few decades, land use has changed very rapidly in the arid valley region in the Anning River Basin of Southwest China, but the impact of these changes on soil erosion resistance is still not yet clear. Thus, five typical land use types in this region, namely woodland, cropland, orchard land, abandoned land, and grassland, have been selected to explore the impact of land use types on soil erosion resistance, including factors such as the mean weight diameter (MWD), dispersion rate (DR), clay ratio (CR), soil organic carbon cementing agent index (SCAI), soil structure stability index (SSSI), K-factor, and comprehensive soil erosion resistance (CSER). The results showed that the land use type had a significant effect on soil erosion resistance, but the intensity of its influence varied across each soil erosion resistance index. Generally, woodland, abandoned land, and grassland demonstrated higher erosion resistance compared to cropland and orchard land. Additionally, surface soil exhibited stronger erosion resistance compared to subsoil, with the impact of land use types primarily concentrated in the surface soil layers. Moreover, soil organic matter content (SOM) emerged as the primary factor influencing soil erosion resistance. The research results can provide valuable guidance for regional land-use planning, aiming to reduce soil erosion and enhance the ecosystem's service capacity, and can provide a theoretical basis for trade-offs between ecosystem services and food security.



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Keywords: soil erosion resistance; K-factor; land use types; soil properties; arid valley

1. Introduction

Soil erosion is a primary threat to global food security, as it significantly diminishes regional food production, leading to landscape degradation and a decrease in soil microbial biodiversity [1], which has garnered significant attention from countries around the world [2,3]. Soil erosion and soil erosion resistance are closely related, both being influenced by a variety of factors, such as climate, topography, vegetation, soil texture, and land use type. Soil erosion resistance can be quantified by a series of indicators. Among them, the most commonly used is the K-factor, which was proposed by Wischmeier and Smith [4]. In addition to the K-factor, several other indicators can be used to depict the soil erosion resistance, such as the mean weight diameter (MWD), the dispersion rate (DR), the soil structure stability index (SSSI), the clay ratio (CR), the soil organic cementation agent index (SCAI), and the comprehensive soil erosion resistance (CSER) [5,6]. Among them,

the MWD and DR of soil macro-aggregates and micro-aggregates can be used to quantify the soil aggregate stability, which is commonly used to characterize soil erosion resistance and tillage quality [7–10]. Both Zhou et al. [11] and Tian et al. [12] found that reducing soil disturbance enhances the stability of soil aggregates and reduces soil erodibility. The SSSI is typically used to indicate the risk level of soil structure degradation. Some previous studies have demonstrated that the risk of soil structure degradation is lower in forestland, while cultivated land and roads face a higher risk of degradation [6,13–15]. The CR, representing the proportion of clay content in the soil, has been reported in some studies to be similar to the K-factor in predicting soil erosion [16–18], which is popularly used for soil erodibility evaluation [19–22]. Furthermore, the SCAI indicates the influence of the quality of the soil organic content cementing for the stability of soil aggregates. Dong et al. [23] found that the SCAI of cropland is higher than that of grassland, followed by woodland. Although all these indicators can be used to quantify soil erosion resistance, soil erosion resistance is influenced by numerous factors and cannot be comprehensively described by a single indicator. Therefore, to quantify the overall soil erodibility level, some research has proposed the CSER, which integrates multiple soil erosion resistance indexes such as the MWD, DR, SSSI, CR, and SCAI. This holistic approach aims to provide a more accurate and comprehensive assessment of soil's susceptibility to erosion [5,6,23]. In fact, soil erosion resistance is influenced by some inherent soil parameters, such as soil particle size composition, moisture content, bulk density, pore structure, and organic matter concentration [24]. On the other hand, surface vegetation characteristics can also influence soil erosion resistance because the root systems of vegetation contribute additional shear strength, root exudates increase adhesion between soil particles, and plant litter can transform into soil organic matter [25–27].

Land use is an important factor that changes the surface vegetation conditions and influences soil physicochemical properties, plant root systems, and the decomposition of plant litter, resulting in long-term effects on soil properties [28–30]. This is because different land uses usually mean different cultivation practices, which can indeed alter soil properties, such as soil bulk density, permeability, soil organic matter, and soil water retention characteristics [31,32]. The physicochemical properties of soil will affect the stability of soil aggregates and the strength of soil erosion resistance [33–35]. Zheng et al. [36] found that soil water stability aggregates, organic matter, and soil texture are the reasons for the higher soil erosion resistance in forestland compared with other land uses. Another study conducted by Yang et al. [37] found that the high organic carbon content in woodlands can regulate key groups of soil bacteria and fungi. Soil microorganisms can increase the content of soil macro-aggregates, enhancing the soil's ability to resist runoff erosion [38–40]. In addition, Wang et al. [41] found that abandoned lands on the Loess Plateau exhibit a decrease in soil erodibility with increasing abandoned time, indicating that natural restoration is an effective measure in reducing erodibility on the Loess Plateau. All these studies have proved that land use can not only alter soil physiochemical properties but also affect the corresponding soil erosion resistance. It is worth noting that the impact of land use on soil erosion resistance is primarily concentrated in the Loess Plateau, the southern red soil hilly regions, and the central Sichuan hilly areas, whereas the southwest arid valleys have been less studied [42–44].

The arid valley region of Southwest China is mainly located in the Anning River Basin, which is the second-largest grain production area in Sichuan Province. Due to the complex terrain, variable climate, large population, and high demand for food, the land use in this area is diverse. Previous studies have shown that different land use types typically indicate variations in soil physical and chemical properties, as well as in soil erosion resistance [42]. However, because the existing studies primarily concentrate on the connection between

land use types and ecosystem services as well as soil anti-scourability [45,46], there is a lack of emphasis on the impact of land use types on soil erosion resistance. Therefore, a series of field investigations and detailed experimental analyses have been conducted to (1) examine the influence of land use type on soil erosion resistance and (2) identify the key soil physiochemical properties that affect soil erosion resistance. The results will provide a theoretical basis for implementing reasonable land use policies and benefit soil erosion prevention in the arid valley regions in Southwest China.

2. Materials and Methods

2.1. Study Area

The study area is located in arid valley region in the Anning River Basin, Sichuan Province, China, which extends between $26^{\circ}35'$ N and $28^{\circ}54'$ N latitude and between $101^{\circ}49'$ E and $102^{\circ}42'$ E longitude, accounting for about 11,064 km² (Figure 1). It is located in the axial part of the Kang-Dian Anticline, which belongs to a faulted basin serving as a transitional zone among the Sichuan Basin, the Qinghai–Tibet Plateau, and the Yunnan–Guizhou Plateau. The exposed strata are composed of semi-consolidated rocks from the Quaternary and Tertiary periods, with lithology consisting of sandstone and claystone [47]. This region belongs to a subtropical monsoon climate with distinct dry and wet seasons. The elevation ranges from 1200 m to 3700 m, with average annual temperatures varying between 6 °C and 16 °C. The annual average precipitation ranges from 308 mm to 720 mm, and the rainy season usually accounts for over 90% of the annual precipitation. The rainfall in the rainy season is characterized by high intensity and short duration, which often leads to flash floods and causes severe geological hazards and soil erosion. Due to the huge height difference (approximately 2500 m), the vertical zonality of climate is particularly obvious [48]. The zonal soil types are purple soil, with paddy soil, tidal soil, red soil, yellow soil, yellow-red soil, brown soil, and dark soil also being widespread [49]. In addition, the woodland is dominated by *Pinus yunnanensis*, which was planted in the 1960s, and the primary economic crops cultivated in the cropland are corn, potatoes, and tobacco.

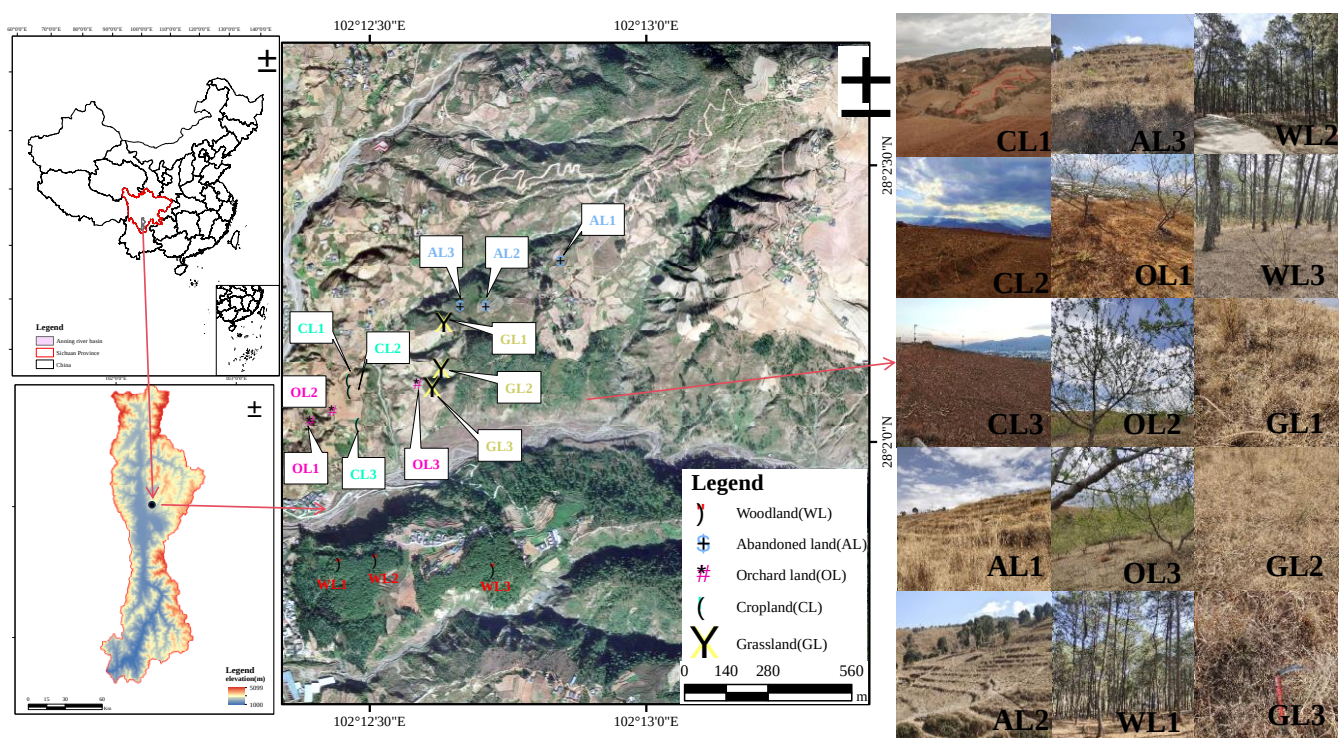


Figure 1. Location of the study area and sample sites.

2.2. Sites Selection

To explore the influence of land use types on soil erosion resistance, a series of detailed field investigations have been conducted in the arid valley region in Aning River Basin from March to May 2023, and five typical land use types with the same soil type (yellow soil), including woodland, cropland, orchard land, abandoned land, and grassland, have been selected. Among these, the woodland mainly consists of *Pinus yunnanensis* which was planted approximately 60 years ago. The cropland is mainly used to plant corn and potatoes. The orchard land is used to plant the economic crop dominated by *Zanthoxylum bungeanum*. The age of the abandoned land is more than 20 years, and it was originally cropland. The dominant species on the abandoned land are *Leptochloa panicea* and *Rumex hastatus*. In addition, the dominant plants on the grassland are *Saccharum arundinaceum* and *Heteropogon contortus*. To eliminate errors and increase the comparability between various treatments, three independent replicate sites with similar elevations (measured by GPS), aspects (measured by geological compass), slope gradients (measured by inclinometer), and vegetation coverage (measured by quadrat method) have been selected for each of the mentioned five land use types, totaling 15 study sites (Figure 1, Table 1). The specification of each study site is set as 10 m × 10 m.

Table 1. Basic information for each sample site.

Site Code	Land Use Type	Elevation (m)	Aspect	Slope Position	Slope Gradient (°)	Vegetation Coverage (%)
1	Woodland	1723 ± 2	Southwest	Downstream	8 ± 1	87 ± 2
2		1736 ± 3	Southwest	Middle	5 ± 1	74 ± 4
3		1780 ± 4	Southwest	Upstream	7 ± 1	81 ± 6
4	Cropland	1703 ± 2	Southwest	Downstream	4 ± 1	4 ± 3
5		1711 ± 4	Southwest	Middle	5 ± 1	7 ± 1
6		1717 ± 2	West	Upstream	8 ± 1	2 ± 2
7	Orchard land	1706 ± 4	West	Downstream	3 ± 0	26 ± 2
8		1718 ± 3	West	Middle	2 ± 1	22 ± 3
9		1727 ± 3	West	Upstream	3 ± 1	31 ± 2
10	Abandoned land	1773 ± 3	West	Downstream	6 ± 1	73 ± 4
11		1796 ± 1	West	Middle	7 ± 1	77 ± 3
12		1851 ± 1	West	Upstream	6 ± 1	76 ± 7
13	Grassland	1737 ± 3	West	Downstream	8 ± 1	83 ± 8
14		1753 ± 2	Southwest	Middle	6 ± 1	87 ± 3
15		1761 ± 1	West	Upstream	7 ± 1	81 ± 6

2.3. Soil Samples and Analysis

According to previous investigations, the average soil depth in the study area was less than 50 cm, and the soil layer in the upper 30 cm was predominantly influenced by land use type. Consequently, the soil samples were collected from depths of 0–10 cm, 10–20 cm, and 20–30 cm after removing the above-ground portion of vegetation and litter from each sample plot. To ensure that the soil samples were more representative, three sub-plots measuring 1 m × 1 m were randomly selected within each study plot. Subsequently, a series of undisturbed soil samples were collected at each sampling depth and sub-plot using a ring knife to determine soil bulk density (BD) and capillary porosity (CP). Meanwhile, additional soil samples (1 kg) were directly collected across each sampling depth and sub-plot. These directly collected soil samples from the same sampling depth across the three sub-plots within a single study plot were mixed to represent the samples from a specific soil layer at that plot. Consequently, each of the mixed soil samples was divided into several parts. Some of these parts were used to determine the aggregate-related indicators using the Yoder method, while others were used to determine soil texture and micro-aggregates using the pipette method [41,49,50]. In addition, soil organic carbon (SOC) was measured

using the Vario MAX cube elemental analyzer manufactured by the German company Elementar (Langensfeld, Germany) [51,52]. Finally, all these measured data were used to determine soil erosion resistance indexes including the K-factor.

2.4. Calculation of Soil Erosion Resistance Index

Previous studies showed that the mean weight diameter (MWD) [53,54], dispersion rate (DR) [55], soil structure stability index (SSSI) [56], clay ratio (CR) [19], soil organic content cementation agent index (SCAI) [57], and K-factor [58] are the most widely used indicators to quantify soil erosion resistance [59].

(1) The soil MWD is usually used to characterize the permeability, water retention, and fertility preservation ability of soil. In addition, it is commonly used to indicate the stability of soil macro-aggregates. The calculation formula is shown by Equation (1) [54].

$$\text{MWD} = \sum_{i=1}^n x_i w_i \quad (1)$$

where MWD is the mean weight diameter (mm), x_i is the mean diameter between two adjacent sieves (mm), and w_i is the weight fraction of the aggregates remaining on the i th sieve (%).

(2) The soil DR represents the ability of soil micro-aggregates to resist water erosion. A higher DR value usually indicates more severe destruction of micro-aggregates, and the calculation formula is shown by Equation (2) [55].

$$\text{DR} = \frac{< 0.05 \text{ mm micro-aggregate content}}{< 0.05 \text{ mm mechanical composition content}} \quad (2)$$

(3) The SSSI is typically used to indicate the risk level of soil structure degradation. The SSSI can be calculated according to Equation (3) [56].

$$\text{SSSI} = \frac{\text{SOM}}{\text{Clay} + \text{Silt}} \times 100\% \quad (3)$$

where SOM represents the soil organic matter content (%). $\text{SSSI} \geq 7\%$ indicates a low risk of soil structure degradation, $5\% < \text{SSSI} < 7\%$ implies a high risk of soil structure degradation, and $\text{SSSI} \leq 5\%$ usually represents severe loss of organic matter leading to soil structure degradation.

(4) The calculation formulas for CR and SCAI are shown as Equations (4) and (5), respectively [19,57].

$$\text{CR} = \frac{\text{Sand} + \text{Silt}}{\text{Clay}} \quad (4)$$

$$\text{SCAI} = \frac{\text{MWD}}{C} \quad (5)$$

where Sand, Silt, and Clay respectively represent the content of sand, silt, and clay (%) in the soil; the parameter C indicates the content of soil organic carbon (%).

(5) The K-factor reflects the ease or difficulty with which soil particles can be separated and transported by hydraulic forces, serving as an important indicator for evaluating soil erosion sensitivity. The calculation method for the K-factor is as follows [59].

$$K = \left\{ 0.2 + 0.3 \exp \left[-0.256 \text{SAN} \left(1 - \frac{\text{SIL}}{100} \right) \right] \right\} \times \left(\frac{\text{SIL}}{\text{CLA} + \text{SIL}} \right)^{0.3} \times \left[1.0 - \frac{0.25C}{C + \exp(3.72 - 2.95C)} \right] \left[1.0 - \frac{0.7\text{SN}_1}{\text{SN}_1 + \exp(-5.51 + 22.9\text{SN}_1)} \right] \quad (6)$$

where SAN, SIL, and CLA represent the content of sand silt and clay in the soil, respectively; C represents the soil organic carbon content, and $\text{SN}_1 = 1 - \text{SAN}/100$.

(6) In addition to above-mentioned indicators, the comprehensive soil erosion resistance (CSER) is commonly used to express the overall resistance of soil to erosion. It can be calculated using Equation (7) [41].

$$CSER = \sum_{i=1}^n W_i S_i \quad (7)$$

where n is the number of soil resistance indexes (in this study, it was 6), W_i is the weight of a given soil erosion resistance index, and S_i is the score of the i th soil erosion resistance index. W_i was calculated using principal component analysis, and S_i was estimated by membership functions. More detailed calculation processes can be found in reference [41].

2.5. Statistical Analysis

The differences in soil erosion resistance indexes among various land use types and soil layers were analyzed using one-way analysis of variance (ANOVA). Multiple comparisons are conducted with the method of the least significant difference (LSD) at 0.05 level. Pearson correlation analysis was used to determine the relationships between soil erosion resistance indexes and soil properties. The structural equation modeling was performed based on the piecewiseSEM package in R (Version 4.4.1). The ANOVA was conducted in SPSS 26, and the graphs were generated in Origin 2021 and Graphpad Pism 9.5.

3. Results

3.1. Simple Soil Erosion Resistance Index

3.1.1. MWD and DR

Figure 2 illustrates the variation in the soil mean weight diameter (MWD) and the dispersion rate (DR) across different land use types and soil layers. Overall, the soil MWD levels of woodland, abandoned land, and grassland are significantly higher than that of orchard land ($p < 0.05$), and the soil MWD of orchard land is significantly higher than that of cropland ($p < 0.05$). However, there is no significant difference in soil MWD among woodland, abandoned land, and grassland (Figure 2a). Further analysis shows that the influence of land use type on soil MWD differs across different soil layers. In detail, in soil layers of 0–10 cm and 10–20 cm, the soil MWD levels of woodland, abandoned land, and grassland are significantly higher than those of cropland and orchard land ($p < 0.05$). However, no significant differences in soil MWD are observed among woodland, abandoned land, and grassland, or between cropland and orchard land in the mentioned two soil layers. In the soil layer of 20–30 cm, a significant difference in soil MWD is observed, with woodland and grassland having higher values than orchard land, which in turn has higher values than cropland. No significant difference is detected between woodland, grassland, and abandoned land, or between abandoned land and orchard land, or between orchard land and cropland. Moreover, there is a general decreasing trend for soil MWD along with the soil depth throughout the soil profile. Specifically, the soil MWD of woodland and abandoned land shows significant differences between the 0–10 cm and 20–30 cm soil layers (Figure 2a).

In terms of the soil DR, cropland shows significantly higher levels compared to woodland and grassland, while woodland and grassland exhibit significantly higher soil DR than orchard land and abandoned land ($p < 0.05$). No significant differences in soil DR are observed between woodland and grassland, or between orchard land and abandoned land ($p > 0.05$). Moreover, the influence of land use types on soil DR varies across different soil layers. Specifically, there are no significant differences in soil DR in the soil layers of 0–10 cm and 10–20 cm, while a significant difference in soil DR is observed in the soil layer of 20–30 cm across the five studied land use types. In detail, in the soil layer of

20–30 cm, the soil DR of grassland is significantly lower than that of woodland, cropland, and orchard land ($p < 0.05$), whereas the soil DR of abandoned land does not show a significant difference compared to the other four land use types ($p > 0.05$). In addition, no significant differences in soil DR are observed among different soil layers within the same land use types (Figure 2b). All these findings indicate that both macro-aggregates and micro-aggregates exhibit the lowest stability in cropland, while the stability of woodland and grassland is significantly higher than that in cropland.

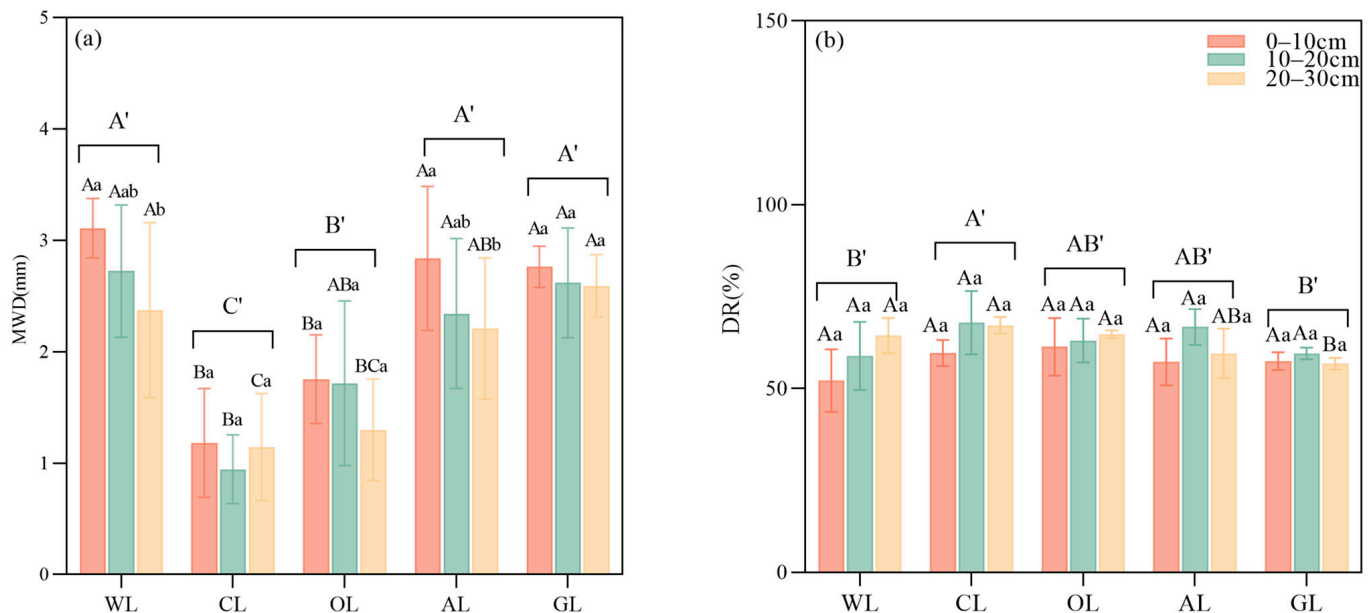


Figure 2. Variation in soil MWD (a) and DR (b) under different land use types and soil layers. Notes: WL, CL, OL, AL, and GL represent woodland, cropland, orchard land, abandoned land, and grassland, respectively. Capital letters signify differences among different land use types within the same soil layer. Lowercase letters indicate differences among different soil layers within the same land use type. Labeled capital letters indicate differences across different land use types throughout the entire soil profile.

3.1.2. CR and SCAI

Figure 3 shows the variation in the soil clay ratio (CR) and the organic content cementation agent index (SCAI) under different land use types and soil layers. Overall, the soil CR of the orchard land is significantly lower than that of woodland and abandoned land ($p < 0.05$), while no significant difference is found for soil CR between cropland, grassland, and the other three soil land use types ($p > 0.05$). Further analysis shows that land use types will alter the variation trend of soil CR along the soil profile. In detail, the soil CR values of woodland, abandoned land, and grassland have a decreasing trend with increases in soil depth, while the soil CR of cropland and orchard land has an increasing trend (Figure 3a).

Regarding the SCAI, those of woodland, abandoned land, and grassland are significantly higher than that of cropland ($p < 0.05$), while no significant difference is found between orchard land and the other four land use types (Figure 3b). In the soil layers of 0–10 cm and 10–20 cm, there is no significant difference in SCAI among different land use types ($p > 0.05$). However, in the soil layer of 20–30 cm, the SCAI of orchard land is significantly lower than those of woodland, abandoned land, and grassland ($p < 0.05$). In addition, it can be found that there is no significant difference in SCAI across different soil layers in cropland, orchard land, and abandoned land ($p > 0.05$). In contrast, a significant difference in SCAI across soil layers is observed in woodland and grassland. Specifically, the SCAI in the soil layer of 0–10 cm is significantly lower than those in the soil layers of

10–20 cm and 20–30 cm ($p < 0.05$) in woodland and grassland, indicating that land use type has an influence on the variation trend of SCAI along the soil profile (Figure 3b). Overall, these results imply that land use type has an obvious impact on the overall average soil CR and SCAI but has very limited influence on the variation trend of SCAI along the soil profile.

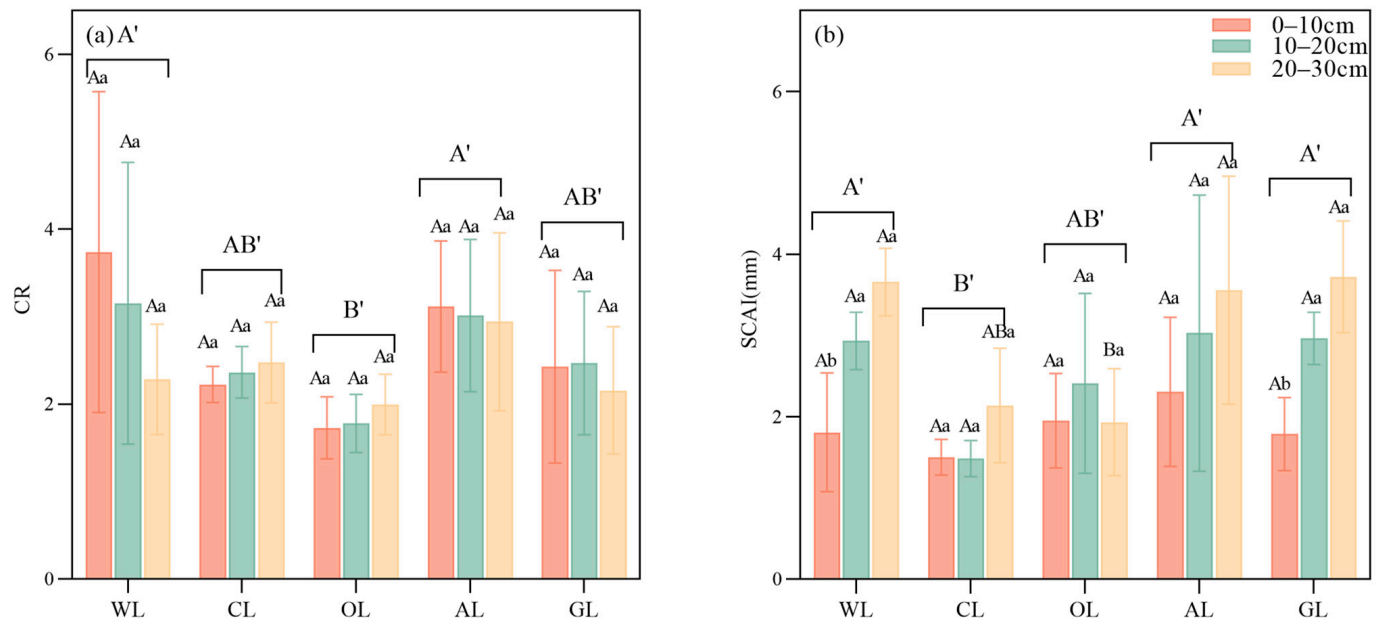


Figure 3. Variation in CR (a) and SCAI (b) under different land use types and soil layers. The letters and labels in the figure have the same meanings as those in Figure 2.

3.1.3. K-Factor and SSSI

Figure 4 shows the variation in the K-factor and the soil structure stability index (SSSI) under different land use types and soil layers. Overall, the K-factor does not show any significant differences among the five land use types ($p > 0.05$). The K-factor ranges from 0.0431 to 0.0529 ($\text{t} \cdot \text{hm}^2 \cdot \text{h} / (\text{hm}^2 \cdot \text{MJ} \cdot \text{mm})$), exhibiting no significant discrepancies within the five land use types across the soil layers of 0–10 cm, 10–20 cm, and 20–30 cm ($p > 0.05$). However, the K-factor of the surface soil layer (0–10 cm) of abandoned land and grassland is notably different from that of the soil layer of 20–30 cm ($p < 0.05$) (Figure 4a).

Regarding the SSSI depicted in Figure 4b, woodland exhibits significantly larger SSSI values compared to cropland and orchard land ($p < 0.05$). However, the SSSI values for abandoned land and grassland do not show significant differences when compared to the other three land use types ($p > 0.05$). In addition, the influence of land use types on SSSI varies across different soil layers. Specifically, in the surface soil (soil layer of 0–10 cm), woodland has the highest SSSI at 5.33%, which is significantly higher than those of cropland, orchard land, and abandoned land ($p < 0.05$). In contrast, within the soil layers of 10–20 cm and 20–30 cm, there are no significant differences in SSSI among the various land use types ($p > 0.05$). Furthermore, significant differences exist across soil layers within the same land use type. In detail, the SSSI values of woodland, orchard land, and grassland in the 0–10 cm soil layer are significantly higher than those in the 20–30 cm soil layer ($p < 0.05$). In contrast, there are no significant differences in SSSI among the 0–10 cm, 10–20 cm, and 20–30 cm soil layers in cropland and abandoned land ($p > 0.05$). Further analysis reveals that the SSSI values for all the five land use types range between 1 and 6, indicating that all these land use types are experiencing severe organic matter loss and soil structure degradation in the study area. Hence, it can be concluded that although the K-factor is not significantly

influenced by land use types, the SSSI demonstrates a high sensitivity to the impacts of land use.

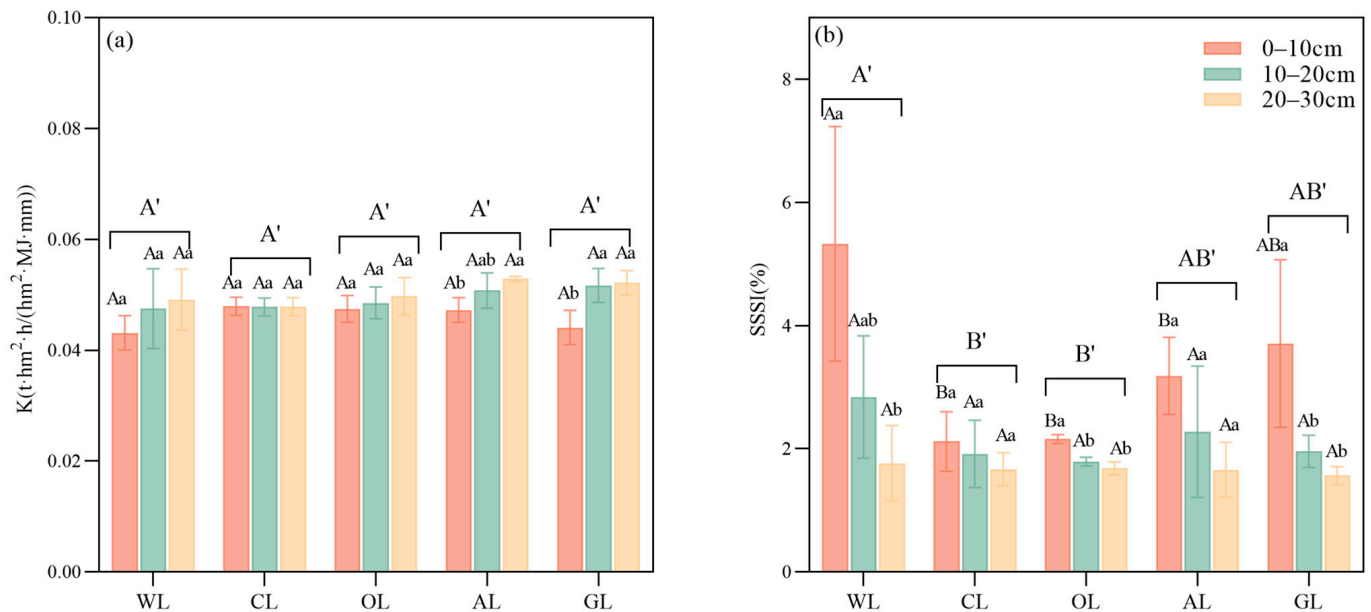


Figure 4. Variation in the soil K-factor (a) and SSSI (b) under different land use types and soil layers. The letters and labels in the figure have the same meanings as those in Figure 2.

3.2. Comprehensive Soil Erosion Resistance Index

Comprehensive soil erosion resistance (CSER) is an indicator that comprehensively evaluates soil erosion resistance, where a higher value indicates lower soil erosion resistance. Figure 5 illustrates the variation in CSER under different land use types and soil layers. Overall, no significant difference in CSER can be found among the five land use types ($p > 0.05$). However, the influence of land use types on CSER varies across different soil layers. In soil layer of 0–10 cm, the CSER of woodland is significantly lower than that of cropland ($p < 0.05$), but no similar differences are observed among woodland, orchard land, abandoned land, and grassland, nor among cropland, orchard land, abandoned land and grassland ($p > 0.05$). In soil the layers of 10–20 cm and 20–30 cm, different land use types do not result in differences in CSER. On the other hand, the differences in CSER among different soil layers vary across land use types. Specifically, there is an increasing trend in CSER for abandoned land and grassland as the depth of the soil layer increases. For abandoned land and grassland, the CSER in the 0–10 cm soil layer is significantly lower than that in the 20–30 cm soil layer. Moreover, there is no significant difference in CSER for abandoned land between the 10–20 cm soil layer and the other two soil layers. In contrast, the CSER of grassland in the 10–20 cm soil layer is significantly greater than that in the 0–10 cm soil layer, although no significant difference is observed between the 10–20 cm and 20–30 cm soil layers. In terms of woodland, cropland, and orchard land, no significant difference in CSER among different soil layers within the same land use types has been found. All of the above findings suggest that while the overall CSER may not differ significantly among the land use types, the specific soil layer can play a crucial role in determining erosion resistance. Different land use practices might affect the physical and chemical properties of soil at various depths differently, leading to variations in CSER across soil layers. Understanding these layer-specific impacts is essential for developing targeted soil conservation strategies.

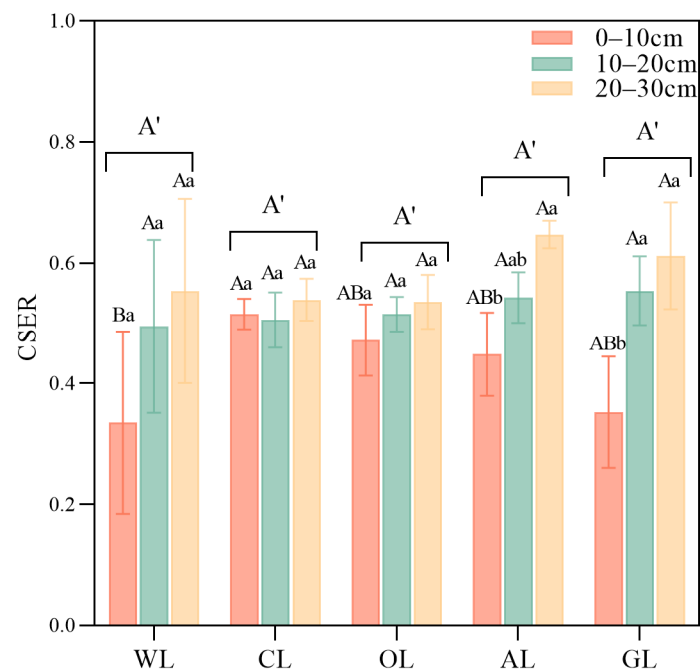


Figure 5. Variation in the comprehensive soil erosion resistance index (CSER). The letters and labels in the figure have the same meanings as those in Figure 2.

3.3. Influence of Soil Physiochemical Properties on Soil Erosion Resistance Index

Differences in land use types often result in variations in soil physicochemical properties, which could be a significant factor influencing soil erosion resistance. Figure 6 illustrates the relationship between the studied soil erosion resistance indexes (MWD, DR, CR, SCAI, K-factor, SSSI, and CSER) and soil physiochemical properties. It is evident that, except for CR, there is an extremely significant correlation between SOM and the other six soil erosion resistance indicators (MWD, DR, SCAI, K-factor, SSSI, and CSER) ($p < 0.01$). In contrast, soil sand content exhibits significant correlations only with MWD and CR, with correlation coefficients of -0.36 and 0.37 , respectively. Furthermore, the influence of soil silt content, clay content, BD, and CP on soil erodibility falls between the influences of SOM and sand content. Notably, significant positive relationships are observed between soil silt content and MWD and the K-factor, between BD and CR, SCAI, the K-factor, and CSER, as well as between CP and DR. Conversely, significant negative relationships can be detected between soil silt content and DR, between CP and MWD, and between CP and CR.

Further stepwise regression analysis reveals that the primary soil physicochemical properties influencing soil erosion resistance indicators vary depending on the specific erosion resistance indicator. This variation is evident not only in the number of influencing factors but also in the relative contribution of each factor (Table 2). Among these, CR is influenced solely by the soil clay content, while the remaining six soil erosion resistance indexes are influenced by two or three soil physicochemical properties. Specifically, DR and SSSI are influenced by SOM and either clay content or sand content. In particular, DR is almost equally influenced by SOM and clay content, whereas SSSI is more affected by SOM than by sand content. For MWD and SCAI, the three significant parameters are soil clay content, BD, and SOM. In detail, SOM has a stronger impact on MWD compared to soil clay content and BD, while BD exerts the greatest influence on SCAI among the three parameters mentioned. On the other hand, soil silt, clay, and SOM are the three significant parameters influencing the K-factor and CSER. Further analysis reveals that six soil erosion resistance indexes are influenced by SOM and clay content, two indexes are influenced by BD and silt content, and one index is influenced by soil sand content. These

findings suggest that SOM and clay content are the two most crucial factors influencing soil erosion resistance, followed by soil silt content and BD having a secondary impact, while the impact of soil sand content on soil erosion resistance is relatively weak. The underlying reason is that SOM and clay content greatly contribute to enhanced soil structure, water retention, viscosity, cation exchange capacity, and surface charge properties of clay particles. As a result, soil erosion resistance is primarily determined by SOM and clay content, and both the K-factor and CSER show negative correlations with SOM and clay content. It is worth noting that in this study, we initially constructed a series of functional models between soil erosion resistance index and soil physiochemical properties in the arid valley region. However, since the application of the model needs to comprehensively consider its universality, uncertainty, and the coupling effect of climate, soil, time, and other factors, the promotion and application of the above models in other soil types and other pedo-climatic zones still need further research and data support. In the future, we will also strengthen the multi-scale modeling of soil function-structure-process, etc., in order to build a functional model or a group of functional models that can accurately reflect the relationship between soil erosion resistance and soil physiochemical properties in a larger range.

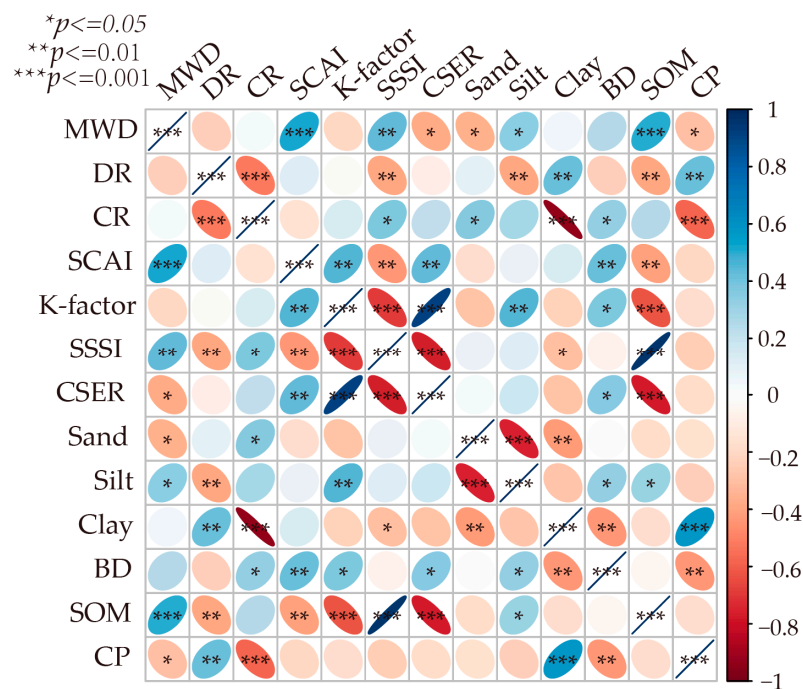


Figure 6. Correlation between soil erosion resistance indexes and soil physiochemical properties.

Table 2. The functional relationship between soil erosion resistance indexes and soil physiochemical properties.

Equation	N	R ²	p
MWD = $-2.117 + 0.581 \times \text{SOM} + 2.703 \times \text{BD} + 5.979 \times \text{Clay} - 5.671 \times \text{CP}$	45	0.494	0.000
DR = $0.550 + 0.345 \times \text{Clay} - 0.027 \times \text{SOM}$	45	0.277	0.001
CR = $6.348 - 12.756 \times \text{Clay}$	45	0.878	0.000
SCAI = $-1.831 + 4.259 \times \text{BD} - 0.476 \times \text{SOM} + 7.001 \times \text{Clay} - 7.389 \times \text{CP}$	45	0.470	0.000
K = $0.048 - 0.004 \times \text{SOM} + 0.028 \times \text{Silt} - 0.011 \times \text{Clay}$	45	0.912	0.000
SSSI = $-1.138 + 1.547 \times \text{SOM} + 3.221 \times \text{Sand}$	45	0.992	0.000
CSER = $0.735 - 0.146 \times \text{SOM} + 0.498 \times \text{Silt} - 0.606 \times \text{Clay}$	45	0.916	0.000

4. Discussion

4.1. Reasons of Land Use Types Affecting Soil Erosion Resistance

This study primarily focuses on exploring the impact of land use type on soil erosion resistance. The results show that land use types significantly impact soil MWD, DR, CR, SCAI, and SSSI while having a limited effect on the K-factor and CSER. The reason for this is that soil MWD, DR, CR, SCAI, and SSSI are highly responsive to changes in soil organic matter, vegetation cover, and management practices [53,55–57], which are significantly influenced by land use types [60–62]. However, the K-factor and CSER are more closely tied to intrinsic properties of the soil, such as texture, structure, and chemical composition [6,41,59], which are more stable and less affected by land use changes. Although the K-factor and CSER are also affected to some extent by soil organic matter, vegetation cover, and management practices, their primary determinants remain the inherent properties of the soil. This is why significant variations in the K-factor and CSER have been detected across soil layers rather than land use types.

Moreover, this study found that woodland, abandoned land, and grassland tend to have higher erosion resistance compared to cropland and orchard land. This finding is often attributed to the soil's physiochemical properties, particularly the higher soil organic matter and clay content. These results align with similar studies conducted in a wide area, such as the Loess Plateau [34,41], dry valleys in Southwest China [42], and karst hillslopes in Southwest China [63]. The underlying reason is that woodland, abandoned land, and grassland often have higher soil organic matter and clay contents compared to arable land due to a continuous input of organic material, the presence of stable root systems, and reduced soil disturbance [63,64]. In addition, the continuous input of organic material, the presence of stable root systems, and the reduction of soil disturbance highly contribute to the stability of soil clay particles, which are not easily damaged and eroded away. These factors create an environment conducive to the accumulation and preservation of organic matter and the formation of clay particles, which are essential for maintaining soil fertility and structure. In contrast, arable land often experiences higher rates of organic matter decomposition and erosion due to intensive management practices [65–67].

Finally, it has also been found that the impact of land use types is primarily concentrated on the surface soil layers. The underlying reason is that the combined effects of litterfall, plant root exudates and residues, microbial activity, oxygen availability, temperature, and moisture tend to cause soil organic matter to accumulate in the surface soil layer. The surface soil provides an excellent environment for the input, decomposition, and stabilization of organic matter, resulting in the variations in soil resistance indexes across different land use types being most pronounced in the surface soil layers [68,69]. Therefore, these findings demonstrate the mechanisms and reasons behind the impact of different land use types on soil erosion resistance. This knowledge is essential for developing sustainable land management practices, protecting the environment, and ensuring the long-term health and productivity of soils.

4.2. Limitations of the Study

This study primarily focuses on exploring the impact of land use type on soil erosion resistance. It is particularly crucial to eliminate the influence of other factors that may affect soil erosion resistance, such as climate, topography, vegetation, and soil type [70]. To achieve this objective, five experimental sites, comprising 15 sample plots, have been established within a linear distance of no more than 1 km to ensure consistent climatic conditions across all plots. In addition, aspects, slope gradients, elevations, and vegetation coverages have been meticulously taken into account to uphold uniformity throughout the experimental plots. Furthermore, the soil type across all experimental plots is yellow

soil. Despite attempts to minimize the impact of variables other than land use type on the findings, it is important to recognize that the presence of soil texture variances, as a reflection of soil heterogeneity, cannot be entirely eradicated (Figure 7). This is because the differences in soil texture are influenced by multiple factors, such as parent material, climate, biology, topography, and time [71–73], which contribute to the inherent complexity of soil characteristics.

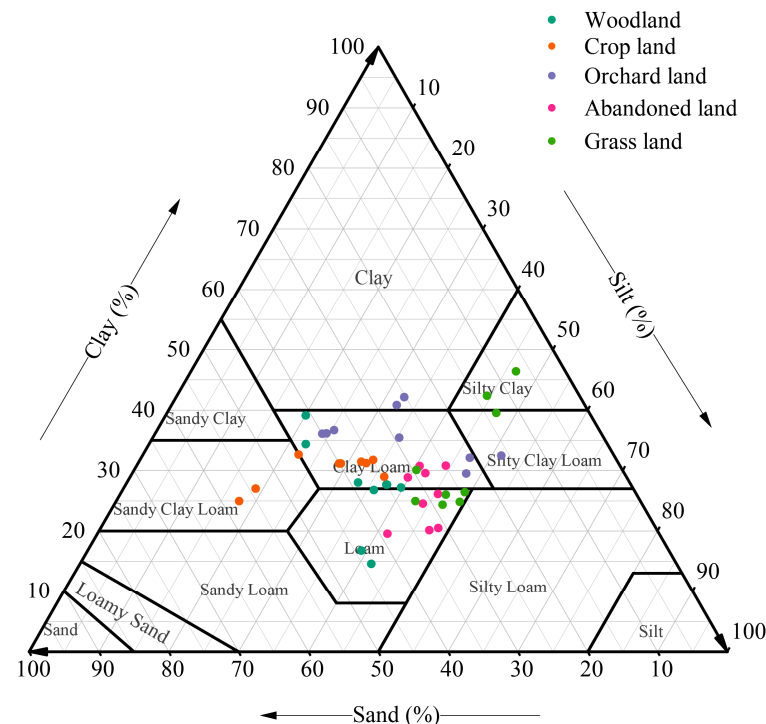


Figure 7. The soil texture of studied experimental plots.

To evaluate the impact of soil texture on soil erosion resistance, a structural equation model was employed to analyze the effects of soil texture (sand, silt, and clay content), bulk density (BD), capillary porosity (CP), and soil organic matter content (SOM) on CSER (Figure 8). It can be found that soil silt content, clay content, and SOM have direct or indirect effects on CSER, whereas BD and CP have no significant effect. Among these, the total effects of silt content, clay content, and SOM on CSER are -0.10 ($p < 0.05$), -0.286 ($p < 0.01$), and -0.963 ($p < 0.01$), respectively. This result means that SOM exerts a predominant impact on CSER, although soil silt and clay content also have some weak effects. From this perspective, variations in soil texture may have a limited influence on soil erosion resistance, which aligns with some previous studies [74,75]. Research has shown that the cohesion influenced by plant roots is the primary factor affecting differences in soil erosion resistance, rather than the mechanical composition of the soil [76]. Consequently, the findings of this study regarding the impact of land use type on soil erosion resistance are considered reasonable and acceptable.

Furthermore, it is worth noting that different land use types often imply variations in cultivation practices, irrigation methods, and fertilization intensities. This study only discusses the general aspects of the impact of different land use types on soil erosion resistance. Further research will continue to explore the specific aspects of cultivation practices, irrigation methods, and fertilization intensities associated with different land use types. Therefore, a comprehensive and systematic consideration of the potential factors affecting soil erosion resistance from all dimensions will broaden the field of soil science and environmental research. It will also help refine the models and methods used to assess soil health and erosion risk, leading to advancements in both theoretical and applied research.

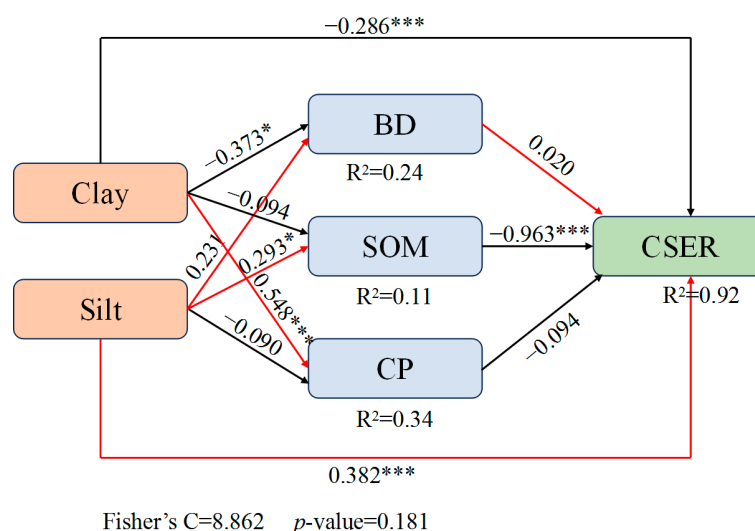


Figure 8. The structural equation model based on soil texture, bulk density (BD), capillary porosity (CP), soil organic matter content (SOM), and CSER. Notes: boxes represent measured variables. Arrows represent unidirectional relationships among variables. Red arrows denote positive relationships, and black arrows negative ones. The value on the arrow is the path coefficient. R^2 represents the proportion of variance explained for each dependent variable in the model, and asterisks indicate statistical significance ($^{***} p < 0.001$; $^* p < 0.05$). The direct effect is the path coefficient between the two variables, the indirect effect is the sum of the product of the relevant path coefficients, and the total effect is the sum of direct and indirect effects.

5. Conclusions

This study explored the effect of land use types on soil erosion resistance in the arid valley region of Southwest China. The findings suggest that different land use types have a significant impact on soil erosion resistance, with the manner and extent of this impact being correlated with erosion resistance indicators. It can be concluded that land use types significantly influence soil MWD, DR, CR, SCAI, and SSSI while having a limited effect on the K-factor and CSER. Overall, woodland, abandoned land, and grassland demonstrate higher erosion resistance compared to cropland and orchard land. Additionally, the effects of land use types on soil erosion resistance vary across different soil layers. Specifically, land use types significantly affect the MWD, SSSI, and CSER in the 0–10 cm, 10–20 cm, and 20–30 cm soil layers, while their impact on soil DR, CR, SCAI, and K-factor is minimal. Furthermore, surface soil exhibits stronger erosion resistance compared to subsoil, with the impact of land use types primarily concentrated in the surface soil layers. Moreover, SOM emerges as the primary factor influencing soil erosion resistance. All these findings will assist both the government and farmers in adopting efficient and appropriate land use practices to improve C sequestration, enhance soil resilience, and reduce soil erosion and will provide a theoretical basis for trade-offs between ecosystem services and food security.

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