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Original Article

Development of a landscape index to link landscape pattern to runoff and sediment

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Abstract: Linking landscape indexes to ecological processes is the key topic of landscape ecology. However, traditional landscape metrics based on the Patch-Mosaic Model have no ecological significance. In this study, the runoff-sediment landscape index coupling land use, topography, soil, and vegetation factors was constructed to link landscape patterns to runoff and sediment. In the study area, the runoff-sediment landscape index at the class scale showed an increasing trend from 0.10 in 1995 to 0.26 in 2015. Cropland had a higher runoff-sediment landscape index compared to grassland or forestland. At the landscape scale, the runoff-sediment landscape index showed a decreasing trend since 1995; furthermore, it decreased by 36.24% in 2015 compared with the index in 1990. The runoff-sediment landscape index had higher correlations with runoff and sediment compared with traditional landscape metrics. Redundancy analysis showed that the runoff-sediment landscape index had a higher contribution to runoff and sediment compared to traditional landscape metrics, explaining 90.1% of the variability. The soil erosion risk assessed by the runoff-sediment landscape index showed an increasing trend upstream of the Dali River watershed. More attention should be paid to this area in future vegetation restoration attempts, as exploring the impact of landscape pattern changes on ecological processes, especially hydrological processes, plays an important role in comprehensive watershed management.

Keywords: Runoff; Sediment; Landscape index; Process-oriented; Soil erosion risk; Landscape planning

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1 Introduction

Worldwide, the Loess Plateau has been and is still subject to the most severe soil erosion conditions (Fu et al. 2017; Shi et al. 2020). Indeed, more than 60% of the land in the Loess Plateau shows the impact of soil erosion, such that contributes more than 90% of the sediment reaching the Yellow River (Hu 2020). The process of soil and water loss in the Loess Plateau is affected by many factors, including natural factors, such as regional climate, topography, and soil properties, as well as human activities, such as vegetation destruction, heedless land reclamation, and irrational land use (Li et al. 2019; Yu et al. 2022). Runoff and sediment transportation are two of the most important ecological processes on the surface of the earth, determined by landscape type, composition, and distribution pattern (Li and Zhou 2015).

Research on the relationship between landscape patterns and hydrological processes has always been the key topic in landscape ecology (Bin et al. 2018; Wei et al. 2022; Zhang et al. 2021). In the 1970s, traditional landscape metrics were developed with the help of GIS tools, based on the Patch-Mosaic Model (Wu and Hobbs 2002). Thus, for example, Wei et al. (2022) found that runoff and sediment yields were negatively correlated with landscape metrics of Largest Patch Index (LPI), Contagion Index (CONTAG), Patch Cohesion Index (COHESION) and Edge Density (ED). Similarly, Zhang et al. (2019) reported that Number of Patch (NP), Patch Density (PD), COHESION, Landscape Division Index (DIVISION) and Shannon's Diversity Index (SHDI) were negatively correlated with runoff and sediment, whereas CONTAG and runoff sediment were positively related. However, these metrics only focused on a simple description of the spatial distribution of the landscape, but with no ecological significance.

Land use data obtained by remote sensing interpretation is the main data source in traditional landscape pattern analysis. Further, the traditional landscape pattern index does not consider specific topographical or environmental characteristics such as soil, slope, and vegetation coverage. Moreover, the traditional landscape pattern index only focuses on the analysis and description of the geometric characteristics of the landscape pattern. With the increasing complexity of ecological processes, the ecological significance of the traditional landscape pattern index becomes less clear, and some landscape indexes even present contradictory phenomena (Kupfer 2012; Peng et al. 2009). Linking ecological processes with landscape patterns has been and will continue to be among the frontier research issues. Thus, recently, Bin et al. (2018) developed a runoff landscape index to evaluate the effect of landscape patterns on surface runoff. Similarly, Li and Zhou (2015) constructed a comprehensive landscape index and coupled this with an analysis of landscape patterns and hydrological processes. In turn, Liu et al. (2013) modified the Directional Leakiness Index (DLI) and Flow length to reflect the vegetation cover pattern and linked it with runoff and soil erosion. Further, Zanandrea et al. (2021) modified the hydrosedimentological connectivity index based on topographic and land use information, and the modified index showed a high correlation with runoff and sediment. By designating landscape units as "source", "sink", or "pathway", Chen et al. (2019b) proposed a source-pathway-sink index in landscape pattern analysis; an index that is process-oriented, dynamic, and scale-dependent. These new indices effectively integrate ecological processes with landscape patterns. However, research is seldom focused on soil erosion processes-oriented landscape indices and this is reflected in the relationship between landscape patterns and runoff and sediment.

In 1999, China implemented the Grain for Green Project on the Loess Plateau (Shi et al. 2021). Since then, the project has converted more than 16,000 km^2 of sloping cropland to vegetation (Yu et al. 2020), resulting in an increase in vegetation cover from 23% to 45% after 20 years of restoration (Feng et al. 2016). In the meantime, recent satellite data (2000-2017) showed that China alone accounted for 25% of the global net increase in leaf area (Chen et al. 2019a). Vegetation restoration changes land use and land cover and affects the distribution of the landscape pattern. Exploring the impact of landscape pattern changes on ecological processes, especially hydrological processes, plays an important role in comprehensive watershed management.

In this study, we developed a runoff-sediment landscape metric by coupling land use, topography, soil, and vegetation factors. The new landscape metric reflected the dynamics of landscape composition, spatial structure, and spatial configuration, and was related to the spatial pattern of ecological processes. The landscape indices can be used in runoff and sediment prediction and land use planning. The goals of this study were: (1) to compare the relationships between the traditional landscape index and the new landscape index with hydrological processes; (2) to apply the new landscape metric to soil erosion risk assessment and provide suggestions for land use development and landscape planning.

2 Materials and Methods

2.1 Study area

The Dali River watershed is in the middle of the Loess Plateau (37°30′-37°56′ N, 109°14′-110°13′ E). The Dali River is the largest tributary of the Wuding River, with a total length of 170.0 km and an area of 3,906 km², with a typical temperate continental monsoon climate. The annual average temperature is 8.5℃ and the annual average precipitation is 416.4 mm. The main soil type is loess soil (Calcaric Regosols according to the WRB soil classification), which has a loose structure and poor resistance to erosion. The main vegetation types in this area include *Leguminosae*, *Pinaceae*, *Salicaceae*, and *Gramineae*. There are four hydrological stations in the Dali River watershed (Fig. 1). The Suide Station is the outlet control station of the watershed. Qinyangcha, Lijiahe, and Caoping stations are located upstream, midstream, and downstream, respectively.

2.2 Spatial data

Runoff and sediment data from 1960 to 2015 in the four stations (Suide, Qiangyangcha, Lijiahe and Caoping) were obtained from the Yellow River Conservancy Commission of the Ministry of Water Resources. Precipitation in the years 1960-2015 was measured at three rainfall stations, namely, Suide, Qingyangcha and Lijiahe. Land use, vegetation coverage, and soil data were downloaded from the Resource and Environment Science and Data Center (http://www.resdc.cn), with a spatial resolution of 30, 500, and 1,000 m, respectively. The digital elevation model (DEM) was obtained from the Geospatial Data Cloud (http://www.gscloud.cn), with a spatial resolution of 30 m. The periods of land use and vegetation coverage analysis were from 1990 to 2015. The period of soil data was 2010. These spatial data were resampled to a spatial resolution of 30 m by ArcGIS 10.7 to calculate the runoff-sediment landscape index.

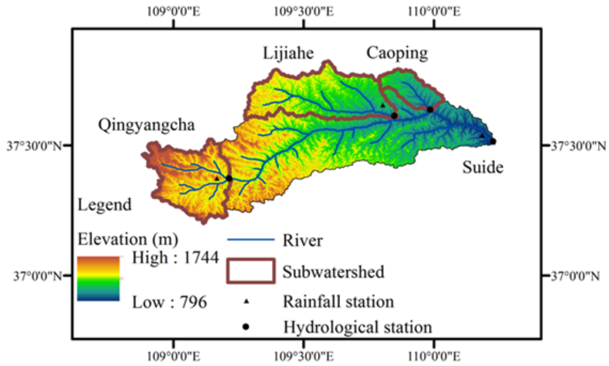

Fig. 1 Location of the Dali River watershed.

2.3 Calculation of the runoff-sediment landscape index

2.3.1 Landscape factors

(1) Land use factor

The contribution of land uses (λ_c) to runoff and sediment was evaluated according to land use types (Fig. 2a). Each land cover was assigned a λ_c value by referring to existing research results (Bin et al. 2018; Li and Pan 2018). Cropland, forestland, grassland, and building land had λ_c values of 0.69, 0.35, 0.48, and 0.85, respectively.

(2) Soil factor

Soil erodibility (λ_k) represents the sensitivity of the soil to erosion (Fig. 2b). Soil erodibility was calculated using the following equation (Wischmeier and Smith 1965):

$$\lambda_k = \frac{2.1\times10^{-4}\mathrm{ST}^{1.14}(12-\mathrm{SOM})+3.25(s-2)+K_p}{100}\times0.1317 \quad (1)$$

$$\mathrm{ST} = (\mathrm{STsilt}+\mathrm{STsand})\times(100-\mathrm{STclay}) \quad (2)$$

$$K_p = 2.5\times(p-3) \quad (3)$$

where SOM is the soil organic matter content (%), s is the soil structure grade, ST is the soil texture, STsilt is the silt content (%), STsand is the sand content (%), STclay is the clay content (%), p is the soil infiltration index and K_p is the effect of soil infiltration index on soil erodibility. The λ_k value calculated in the study area was similar to that reported by Wang et al. (2018).

(3) Topography factor

Slope was used to assess the effect of topography on runoff and sediment (Fig. 2c) using the following equation:

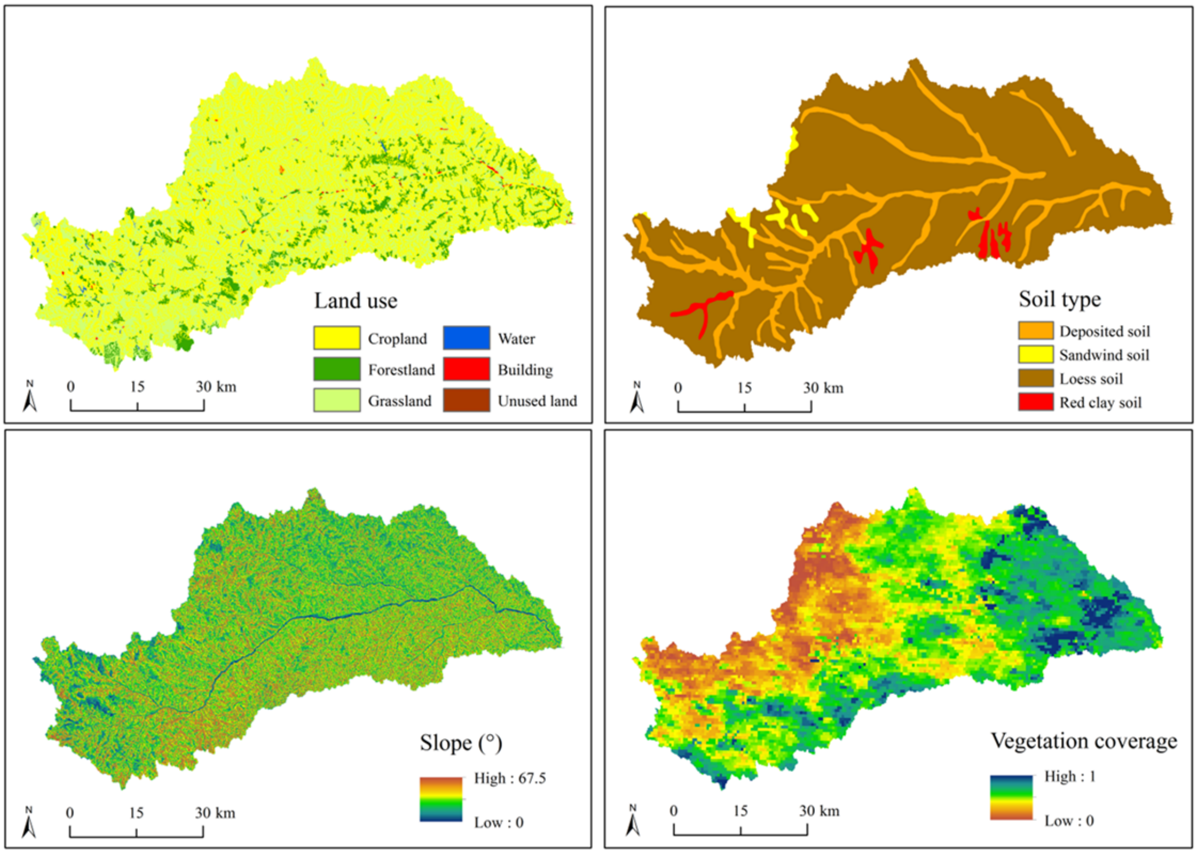

Fig. 2 Landscape factors calculated for the Dali River watershed: land use, soil type, slope, and vegetation coverage.

$$\lambda_s = \frac{1}{\cos\alpha} \tag{4}$$

where λ_s is the topography factor and α is the slope. The slope was calculated by the tool of 3D Analyst of ArcGIS 10.7 with degree as the output data.

(4) Vegetation factor

Vegetation coverage (λ_d) was used as the vegetation factor (Fig. 2d). Higher vegetation coverage results in a higher runoff interception effect. Thus, λ_d was represented by the normalized difference vegetation index (NDVI):

$$\lambda_d = \frac{\text{NDVI} - \text{NDVI}_{\min}}{\text{NDVI}_{\max} - \text{NDVI}_{\min}} \tag{5}$$

where $\text{NDVI}_{\max}$ and $\text{NDVI}_{\min}$ are the maximum and minimum of NDVI in the study area, respectively. The NDVI data were obtained from Moderate-resolution Imaging Spectroradiometer (MODIS) vegetation index dataset produced by the National Aeronautics and Space Administration (NASA) with a 16-day interval. The maximum-value-composite-method (MVC) was used to obtain the annual NDVI data.

2.3.2 Runoff-sediment landscape index calculation

(1) Runoff-sediment landscape index at the patch scale (P_i)

The four landscape factors of each grid cell were multiplied. The runoff-sediment landscape index at patch i was the arithmetic mean of the landscape factors multiplied, as shown in the equation below:

$$P_i = \frac{\sum_{i=1}^{n} \lambda_{ci} \times \lambda_{ki} \times \lambda_{si} \times \lambda_{di}}{n} \times 100 \tag{6}$$

where P_i is the runoff-sediment landscape index at the patch scale, λ_{ci} is the land use factor, λ_{ki} is the soil factor, λ_{si} is the topography factor, λ_{di} is the vegetation factor, and n is the number of grids in the patch.

(2) Runoff-sediment landscape index at the class scale (C_i)

The runoff-sediment landscape index at the class scale was calculated using the following equation:

$$C_i = \sum_{i=1}^{k} p_i \frac{a_i}{A} \tag{7}$$

Table 1 Descriptions of landscape pattern metrics

Landscape metrics	Abbreviation	Description
Patch Density	PD	Patch Density is the number of corresponding patches divided by total landscape area.
Largest Patch Index	LPI	The area of the largest patch of the corresponding patch type divided by total landscape area.
Landscape Shape Index	LSI	The area of the largest patch of the corresponding patch type divided by total landscape area.
Contagion Index	CONTAG	Extent to which patch types are aggregated or clumped as a percentage of the maximum possible.
Patch Cohesion Index	CONHESION	The physical connectedness of the corresponding patch type, it is an area-weighted mean perimeter-area ratio.
Landscape Division Index	DIVSION	Reflect the degree of fragmentation of the landscape.
Shannon's Diversity Index	SHDI	The number of different patch types and the proportional area distribution among patch types.
Edge Density	ED	Ratio of total length and total area of patch boundary in landscape.
Shape Index	SHAPE_MN	Patch perimeter divided by the patch area.
Mean Patch Fractal Dimension	FRAC_MN	The weighted average value of the fractal dimension of a single patch in the landscape component based on the area.
Aggregation Index	AI	Agglomeration degree or extension trend of different patch types in the landscape.

where a_i is the area of patch i (km^2) and A is the area of the corresponding land uses of cropland, grassland, forestland or building (km^2).

(3) Runoff-sediment landscape index at the landscape scale (RLSI)

The runoff-sediment landscape index at the landscape scale was calculated using the following equation:

$$\mathrm{RLSI} = \sum_{i=1}^{k}\sum_{j=1}^{m} p_{ij}\frac{a_{ij}}{\mathrm{A}} \tag{8}$$

where P_{ij} is patch ij, a_{ij} is the area of patch ij (km^2), and A is the total area of the landscape (km^2). The runoff-sediment landscape index ranged from 0 to 1, and the value of the index indicated the contribution of landscape factors to surface runoff and sediment. The higher the value, the more surface runoff and sediment will be generated, and the greater the risk of soil erosion.

2.4 Traditional landscape metrics

Traditional landscape metrics can indicate the spatial distribution of the landscape patterns. Fragstats 4.2 software was used to calculate 11 landscape metrics based on landscape level, including PD, LPI, Landscape Shape Index (LSI), CONTAG, Patch Cohesion Index (CONHESION), Landscape Division Index (DIVSION), SHDI, ED, Shape Index (SHAPE_MN), Mean Patch Fractal Dimension (FRAC_MN), and Aggregation Index (AI) (Table 1). These landscape metrics reflect the landscape features of area-edge, shape, contrast, aggregation and diversity. Principal component analysis was used to select independent and representative metrics; seven metrics were selected (PD, LSI, CONTAG, DIVISION, ED, SHAPE_MN, and AI) and these metrics were used for the further analysis of the relationship between runoff or sediment with landscape metrics.

2.5 Soil erosion risk

The sub-watershed of the Dali River watershed was extracted by the tool of Hydrology of ArcGIS 10.7, and the watershed was divided into 91 sub-watersheds. The soil erosion risk of each sub-watershed was calculated by the normalization of the runoff-sediment landscape index:

$$\mathrm{SER}_i = \frac{\mathrm{RSLI}_i - \mathrm{RSLI}_{\min}}{\mathrm{RSLI}_{\max} - \mathrm{RSLI}_{\min}} \tag{9}$$

where SER_i was soil erosion risk in the i sub-watershed, RSLI_i was the runoff-sediment landscape index in the i sub-watershed, $\mathrm{RSLI}_{\min}$ was the minimum of the runoff-sediment landscape index in the i sub-watershed, $\mathrm{RSLI}_{\max}$ was the maximum of the runoff-sediment landscape index in the i sub-watershed.

2.6 Analytical method

Changes in precipitation, runoff, and sediment trends were calculated using the M-K test (Yue et al. 2002). Pearson's correlation coefficient was used to analyze the relationship between landscape metrics and runoff and sediment. Redundancy analysis (RDA) was used to calculate the contributions of landscape metrics to runoff and sediment. RDA is a ranking method of regression analysis combined with principal component analysis. In RDA analysis, the data-set was divided into two groups of sample variables (runoff and sediment) and environmental variables (PD, LSI, CONTAG, DIVISION, ED, SHAPE_MN, AI and the runoff-sediment landscape index). The relationship between sample variables and environmental variables was quantized by the length of the arrow and the angle between the two arrows (Shi et al. 2021).

3 Results

3.1 Changes in precipitation, runoff, and sediment

The average precipitation of the Dali River from 1960 to 2015 was 416.4 mm per year (Fig. 3a). The annual variation of precipitation in the watershed was high, showing a fluctuating and increasing trend ($Z > 0$). Conversely, the runoff of the Dali River showed a decreasing trend (Fig. 3b), as the annual runoff of the river significantly ($Z < 0$ and $P < 0.01$) decreased from 114.5 million m^3 in 1960 to 74.6 million m^3 in 2015, for an overall decrease of 34.85%. Similarly, the sediment yield of Dali River showed a decreasing trend (Fig. 3c), with the annual sediment yield decreasing from 22.3 million ton in 1960 to 2.4 million ton in 2015, i.e., a marked overall decrease of 19.9 million t (89.14%). The annual sediment yield showed a significantly decreasing trend ($Z < 0$ and $P < 0.01$).

3.2 Land use and vegetation cover changes

Cropland and grassland were the main land use types in the watershed, followed by forestland. From 1990 to 2015, the cropland area decreased by 139.45 km^2 (Fig. 4). Concomitantly, forestland showed an increasing trend, with an increase rate of 38.45%. The area of grassland and building increased by 48.03 km^2 and 2.97 km^2, respectively.

The vegetation coverage in the Dali River watershed showed an increasing trend from 1990 to 2015 (Fig. 5). However, in 1990, the annual average

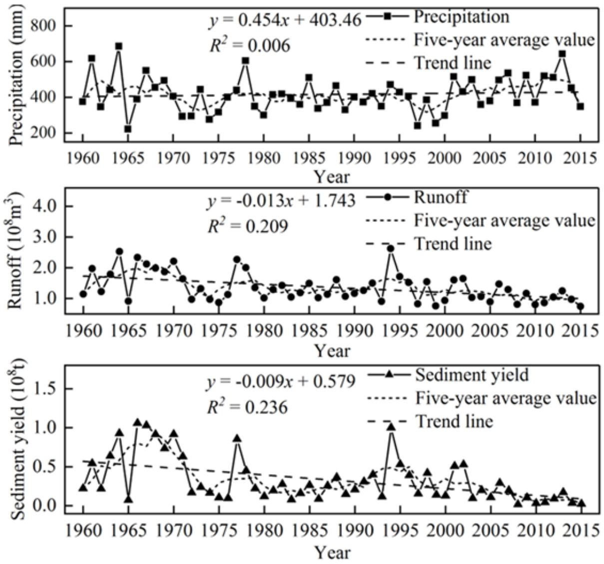

Fig. 3 Precipitation, runoff, and sediment yield in the Dali River watershed from 1960 to 2015.

vegetation coverage was 21.0%. In 2000, the average-annual vegetation coverage was 79.4% higher than that in 1990. The highest annual-average vegetation coverage was recorder for 2010 when its value was 41.0%. However, in 2015, vegetation coverage in the watershed was 31.0%, which was lower than the five-year average value for the 2000-2015 periods, presumably due to the low precipitation in 2015, which negatively influenced vegetation growth. The vegetation coverage showed a higher spatial distribution pattern in the eastern region of the watershed than that in the western region.

3.3 Landscape metric changes

3.3.1 Traditional landscape metrics

The PD and AI landscape metrics showed increasing tends (Fig. 6). PD increased from 0.6693 in 1990 to 0.7275 in 2015, while AI increased by 0.2073 in the same 15-year period. In turn, ED and LSI increased from 1990 to 2005, and then both decreased. The change of CONTAG showed an opposite trend, compared to ED and LSI, as this metric decreased in the beginning, but then has been increasing since 2005. DIVISION and SHAPE_MN decreased in the study years. The changes observed in the traditional landscape metrics indicated that landscape patterns in the watershed tend to be regularization, connectivity, and aggregation.

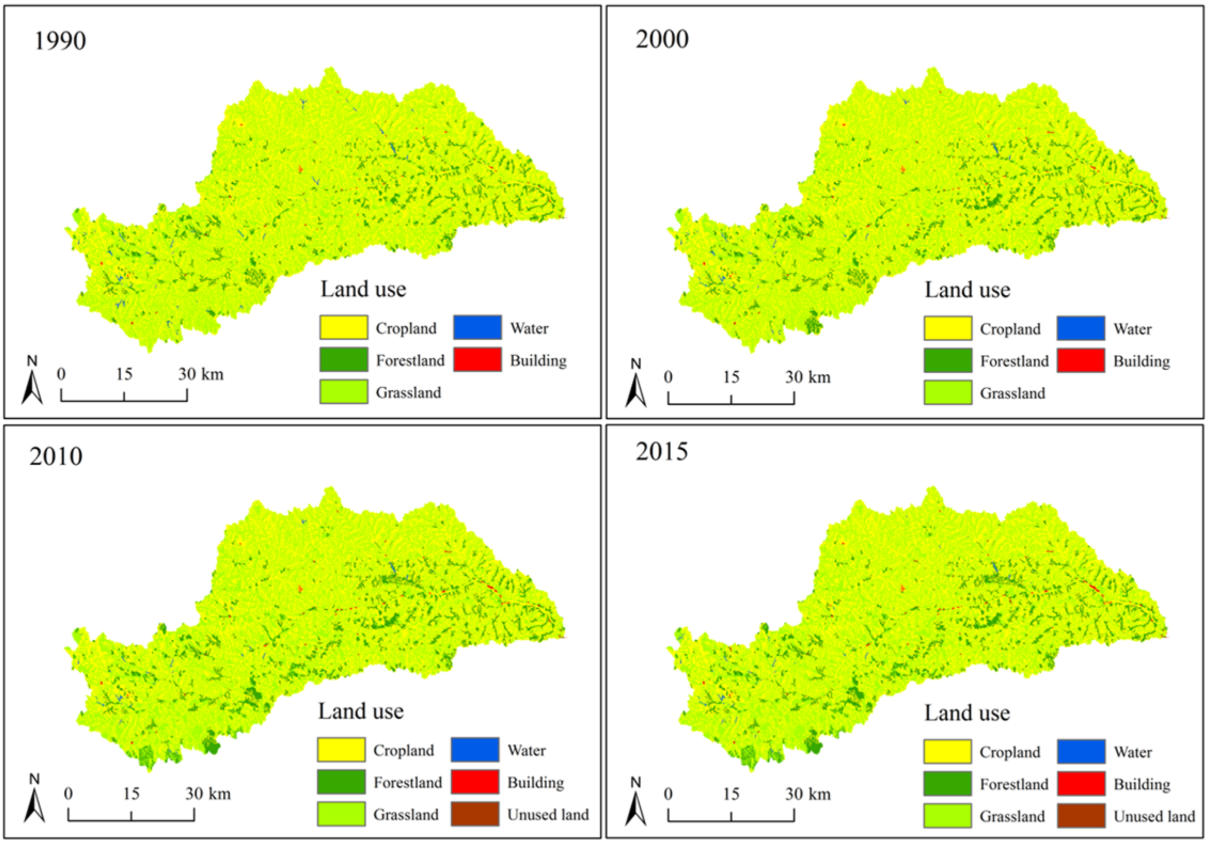

Fig. 4 Land use changes in the Dali River watershed from 1990 to 2015.

3.3.2 Runoff-sediment landscape index at the class scale

The runoff-sediment landscape index of four land use types ranged from 0.10 to 0.26 and showed a decreasing trend between 1995 and 2015 (Fig. 7). Cropland had the highest value of the runoff-sediment landscape index among all land use types studied, followed by grassland and forestland. The results indicated that cropland showed a higher soil erosion risk and contributed more to runoff and sediment yields. In the spatial distribution analysis, the runoff-sediment landscape index was higher in the southeast and lower in the southwest region (Fig. 8).

3.3.3 Runoff-sediment landscape index at the landscape scale

At the landscape scale, the runoff-sediment landscape index increased from 0.63 to 0.70 from 1990 to 1995 (Fig. 9). Furthermore, the runoff-sediment landscape index has been decreasing since 2000. Particularly, in 2015, the runoff-sediment landscape index decreased by 36.24%, compared with the value in 1990.

3.4 Relationship of landscape metrics with runoff and sediment

PD, ED, LSI, SHAPE_MN, and CONTAG all correlated negatively with runoff and sediment yields at the landscape scale (Suide Station, Table 2). Specifically, ED had the highest correlation

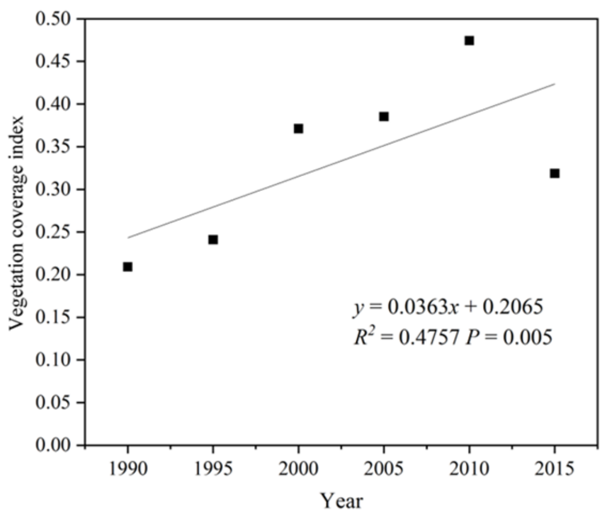

Fig. 5 Vegetation coverage change in the Dali River watershed from 1990 to 2015.

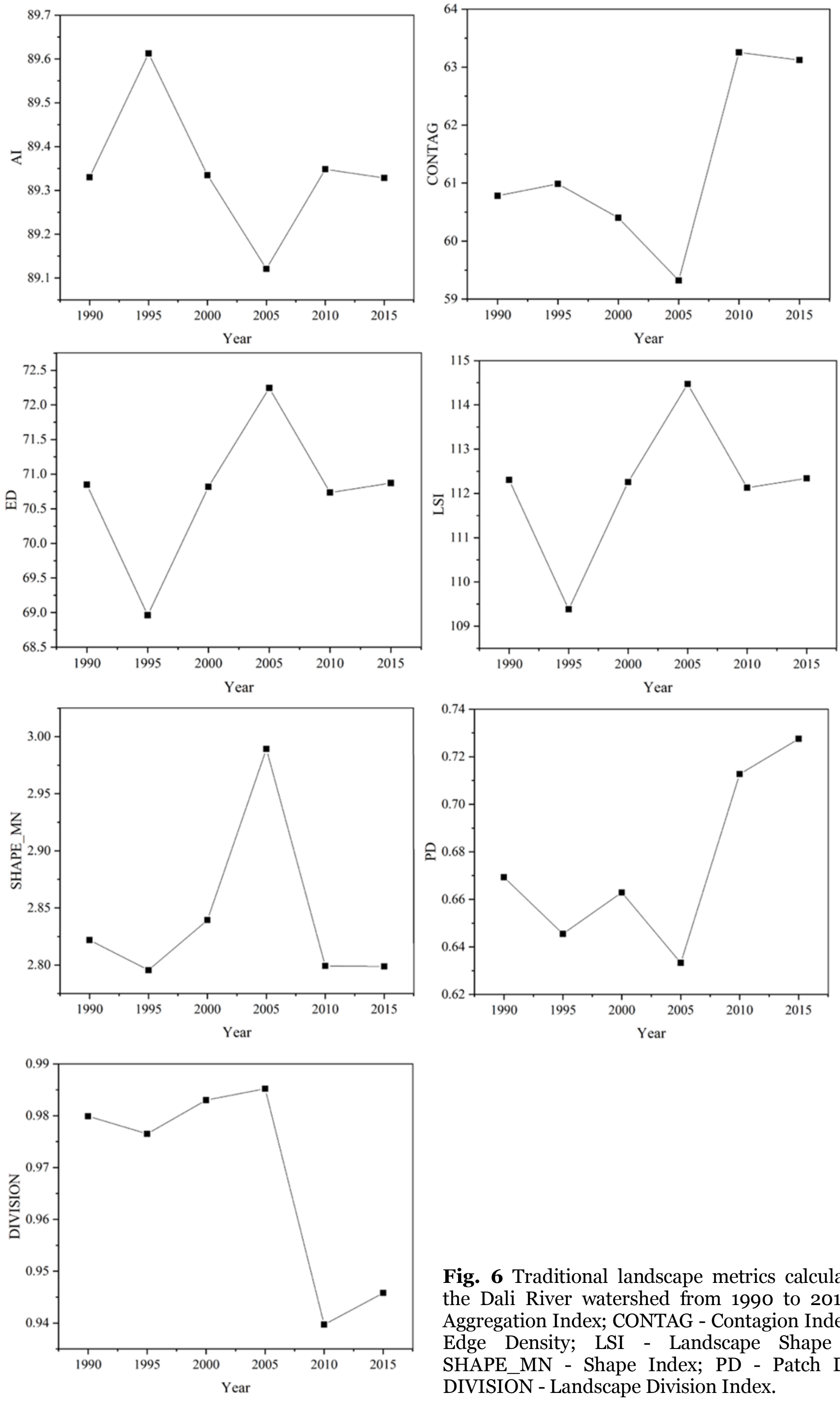

Fig. 6 Traditional landscape metrics calculated for the Dali River watershed from 1990 to 2015. AI - Aggregation Index; CONTAG - Contagion Index; ED - Edge Density; LSI - Landscape Shape Index; SHAPE_MN - Shape Index; PD - Patch Density; DIVISION - Landscape Division Index.

coefficient for runoff (-0.774) and sediment (-0.766). Conversely, AI and DIVISION showed a positive correlation with runoff and sediment (correlation coefficients between AI and runoff and sediment were 0.772 and 0.763, respectively). On the other hand, the correlations between seven traditional landscape metrics and runoff and sediment were not significant. Similar results were found by regression analysis, which showed that PD, ED, LSI, SHAPE_MN, and CONTAG were negatively related to runoff and sediment yields; particularly, ED and LSI showed higher regression coefficients than other landscape metrics (Table 3). Runoff and sediment showed higher regression coefficients (R^2 = 1.000, P < 0.001) with the combined seven landscape metrics than with any single metric. At the class scale, forestland showed higher regression coefficients between hydrological parameters and landscape metrics than either cropland, grassland, water, or building (Table 4). Furthermore, PD and ED were significantly related to runoff and sediment in forestland (P < 0.05).
The runoff-sediment landscape index showed positive correlations with runoff and sediment (Table 5). The relationship of the runoff-sediment landscape index with runoff in the Suide Station was significant at the 0.01 level of probability, with a coefficient of 0.992. Meanwhile, in the Lijiahe Station, the relationship of the runoff-sediment landscape index with runoff was significant at the 0.05 probability level. As for Qingyangcha and Caoping stations, the correlations between the runoff-sediment landscape index and runoff were lower and the relationships were not significant. The runoff-sediment landscape index was significantly correlated with sediment, with P < 0.01 in Lijiahe station and P < 0.05 in the other stations. The correlation coefficients between the runoff-sediment landscape index and sediment yields in the Suide, Qingyangcha, Lijiahe, and Caoping stations were 0.909, 0.862, 0.922, and 0.873, respectively.

The Redundancy analysis was used to examine the correlation between landscape metrics and runoff and sediment (Fig. 10). The first two axes explained

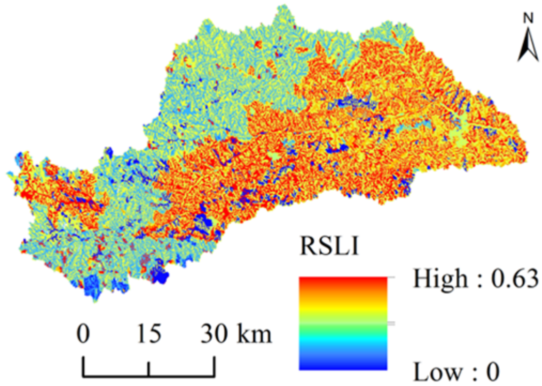

Fig. 8 Spatial distribution of the runoff-sediment landscape index for the the Dali River watershed at the class scale in 2015.

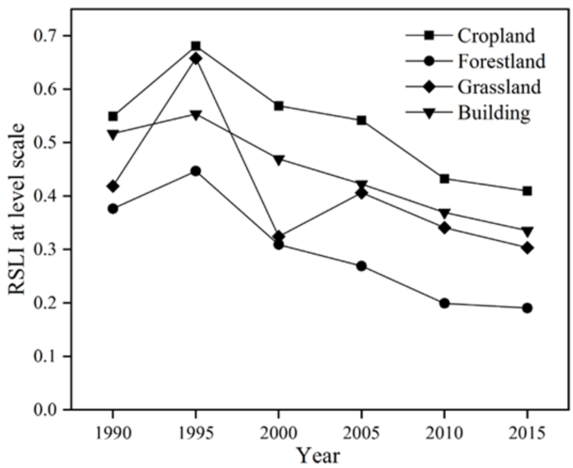

Fig. 7 Runoff-sediment landscape index change in the Dali River watershed at the class scale from 1990 to 2015.

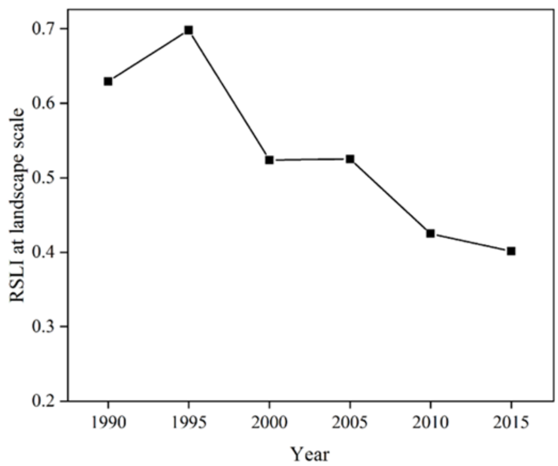

Fig. 9 Runoff-sediment landscape index (RSLI) change in the Dali River watershed at the landscape scale from 1990 to 2015.

Table 2 Relationships between runoff and sediment with landscape metrics.

Factor	PD	ED	LSI	SHAPE_MN	CONTAG	DIVISION	AI
Runoff	-0.559	-0.774	-0.774	-0.243	-0.315	0.451	0.772
Sediment	-0.587	-0.766	-0.765	-0.205	-0.344	0.472	0.763

99.7% of the variance; furthermore, Axis 1 and Axis 2 accounted for 62.3% and 37.4% of the variance, respectively. The runoff-sediment landscape index and AI pointed approximately in the same direction with runoff and sediment, indicating highly positive correlations. Additionally, the runoff-sediment landscape index had longer arrows compared with traditional landscape metrics, indicating that the developed landscape metric showed higher correlations with runoff and sediment. In fact, the

Table 3 Regression analysis of runoff and sediment with landscape metrics at landscape scale

Landscape metrics		Regression	R^2	P
Runoff	PD	y=-13.805x+12.00	0.313	0.248
	ED	y=-0.683x+50.984	0.599	0.071
	LSI	y=-0.440x+52.053	0.599	0.071
	SHAPE_MN	y=-2.992x+11.177	0.059	0.643
	CONTAG	y=-0.186x+14.068	0.099	0.543
	DIVISION	y=20.640x-17.309	0.204	0.369
	AI	y=4.544x-403.273	0.596	0.072
	y=-90.941PD+0.001ED+0.001LSI+25.782SHAPE_MN +7.151CONTAG +349.952DIVISION-1.360AI		1.000	< 0.001
Sediment	PD	y=-7.597x+5.572	0.344	0.221
	ED	y=-0.354x+25.505	0.586	0.076
	LSI	y=-0.228x+26.060	0.586	0.076
	SHAPE_MN	y=-1.324x+4.204	0.042	0.697
	CONTAG	y=-0.106x+6.962	0.118	0.504
	DIVISION	y=11.336x-10.534	0.223	0.344
	AI	y=2.357x-210.190	0.582	0.078
	y=-34.485PD+0.001ED+0.001LSI+13.034SHAPE_MN +2.935CONTAG +147.607DIVISION+0.856AI		1.000	< 0.001

Table 4 Regression analysis of runoff and sediment with landscape metrics at class scale

Land use type	Landscape metrics		Regression	R^2	P
Cropland	Runoff	PD	y=-12.560x+5.928	0.222	0.345
		ED	y=-0.140x+12.198	0.024	0.768
		LSI	y=-0.167x+3.207	0.250	0.978
		SHAPE_MN	y=-4.715x+17.595	0.167	0.420
		DIVISION	y=-256.542x+257.544	0.342	0.223
		AI	y=3.205x-285.942	0.724	0.032
	y=-23.876PD-0.587ED-0.216LSI-1.182SHAPE_MN -17.452DIVISION+75.259AI			0.957	0.306
	Sediment	PD	y=-6.857x+2.217	0.241	0.323
		ED	y=-0.072x+5.303	0.023	0.774
		LSI	y=-0.257x+38.651	0.857	0.005
		SHAPE_MN	y=-2.245x+7.546	0.138	0.468
		DIVISION	y=-135.489x+135.047	0.183	0.347
		AI	y=1.686x-151.408	0.728	0.031
	y=1.441PD+0.061ED-0.351LSI+2.561SHAPE_MN -11.355DIVISION+48.967AI			0.982	0.201
Forestland	Runoff	PD	y=-45.446x+9.427	0.669	0.047
		ED	y=-0.514x+7.777	0.724	0.032
		LSI	y=-0.178x+12.893	0.728	0.019
		SHAPE_MN	y=-10.647x+26.226	0.469	0.134
		DIVISION	y=11755.928x-11752.662	0.361	0.122
		AI	y=2.370x-210.319	0.209	0.362
	y=-41.173PD+141.031ED-0.416LSI-3.952SHAPE_MN -24913.864DIVISION+0.332AI			0.997	0.081
	Sediment	PD	y=-23.871x+3.988	0.671	0.046
		ED	y=-0.264x+3.058	0.692	0.040
		LSI	y=-0.092x+5.732	0.703	0.023
		SHAPE_MN	y=-5.312x+12.191	0.424	0.161
		DIVISION	y=6019.085x-6018.341	0.466	0.135
		AI	y=1.447x-129.592	0.283	0.277
	y=-14.996PD+51.367ED-0.208LSI-1.677SHAPE_MN -12156.503DIVISION+0.421AI			1.000	0.029

(-To be continued-)

(-Continued-)

Table 4 Regression analysis of runoff and sediment with landscape metrics at class scale

Land use type	Landscape metrics		Regression	R^2	P
Grassland	Runoff	PD	y=24.038x-3.154	0.065	0.310
		ED	y=-0.351x+24.788	0.067	0.620
		LSI	y=-0.029x+7.177	0.237	0.845
		SHAPE_MN	y=-0.802x+5.073	0.011	0.845
		DIVISION	y=19.292x-16.129	0.020	0.353
		AI	y=0.122x-8.103	0.003	0.923
	y=-41.460PD+2.165ED-0.998LSI-22.233SHAPE_MN +128.747DIVISION+1027.290AI			0.960	0.296
	Sediment	PD	y=12.245x-2.528	0.238	0.326
		ED	y=-0.196x+12.823	0.077	0.596
		LSI	y=-0.014x+2.547	0.239	0.861
		SHAPE_MN	y=-0.264x+1.230	0.004	0.902
		DIVISION	y=10.540x-9.833	0.234	0.331
		AI	y=0.039x-2.974	0.001	0.953
	y=-22.789PD+0.982ED-0.487LSI-17.297SHAPE_MN +67.277DIVISION+799.247AI			0.976	0.232
Water	Runoff	PD	y=10.009x+2.585	0.249	0.970
		ED	y=5.392x+0.752	0.189	0.389
		LSI	y=0.205x-0.059	0.125	0.542
		SHAPE_MN	y=4.912x-8.095	0.269	0.292
		DIVISION	-	-	-
		AI	y=0.481x-38.327	0.145	0.457
	y=4755.783PD-298.459ED+13.649LSI-0.293SHAPE_MN+15.472AI			1.000	< 0.001
	Sediment	PD	y=-4.175x+0.482	0.250	0.976
		ED	y=2.448x-0.431	0.142	0.462
		LSI	y=0.090x-0.751	0.164	0.615
		SHAPE_MN	y=2.367x-4.748	0.227	0.339
		DIVISION	-	-	-
		AI	y=0.255x-21.314	0.148	0.451
	y=2880.957PD-188.969ED+8.526LSI+2.380SHAPE_MN+9.159AI			1.000	< 0.001
Building	Runoff	PD	y=-119.417x+4.527	0.041	0.701
		ED	y=-3.724x+3.818	0.030	0.743
		LSI	y=0.006x+2.604	0.250	0.993
		SHAPE_MN	y=7.401x-8.506	0.032	0.735
		DIVISION	-	-	-
		AI	y=-1.128x+100.823	0.425	0.161
	y=-1990.269PD+48.806ED+2.162LSI-8.430SHAPE_MN-1.962AI			1.000	< 0.001
	Sediment	PD	y=-62.311x+1.408	0.041	0.702
		ED	y=-1.700x+0.963	0.023	0.776
		LSI	y=0.012x+0.297	0.250	0.974
		SHAPE_MN	y=5.046x-7.182	0.054	0.659
		DIVISION	-	-	-
		AI	y=-0.543x+47.655	0.357	0.210
	y=-958.538PD+2.708ED+2.152LSI-1.003SHAPE_MN-0.563AI			1.000	< 0.001

runoff-sediment landscape index contributed to runoff and sediment to greater extent compared to traditional landscape metrics (explaining 90.1% of the variability; P < 0.01; Table 6), followed by AI, PD, CONTAG, and SHAPE_MN. Conversely, the contributions of DIVISION, LSI, and ED were < 0.01.

3.5 Soil erosion risk assessment

The runoff-sediment landscape index is based on specific ecological processes and could be used to assess soil erosion risk. In 1990, the soil erosion risk index in the midstream and downstream of the Dali River was higher than in other areas (Fig. 11a). The highest risk index appeared in the sub-watersheds of Lijiahe and Caoping. In contrast, the soil erosion risk decreased in most areas of the watershed in 2015 (Fig. 11b). Specifically, the risk index in Lijiahe and Caoping decreased by more than 10%. With the implementation of large-scale

Table 5 Correlation between the runoff-sediment landscape index and runoff and sediment for the four hydrological stations in the Dali River watershed

Factor	Suide	Qingyangcha	Lijiahe	Caoping
Runoff	0.922**	0.306	0.812*	0.267
Sediment	0.909*	0.862*	0.922**	0.873*

*Significant at 0.05 level, **Significant at 0.01 level.

Table 6 Explanation of runoff and sediment by landscape metrics.

Landscape metric	Explanation (%)	*P*
Runoff-sediment landscape index	90.1	0.004
AI	51.9	0.148
PD	39.6	0.182
CONTAG	16.5	0.452
SHAPE_MN	3.2	0.662

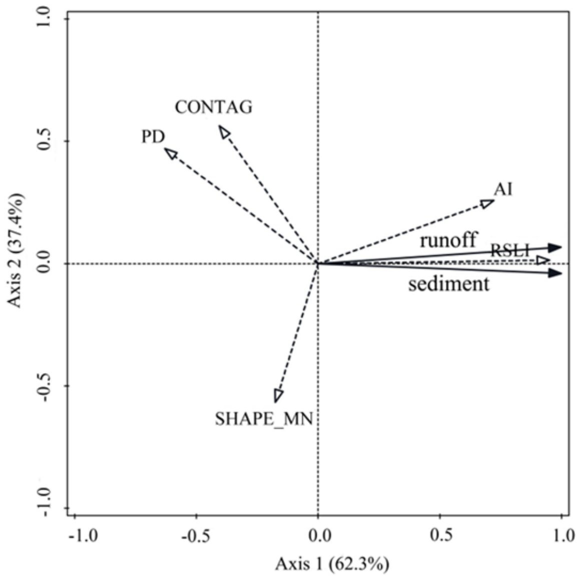

Fig. 10 Redundancy analysis of landscape metrics with runoff and sediment for the the Dali River watershed.

vegetation restoration in China since 1999 in the Loess Plateau, soil erosion risk has been gradually decreasing, and soil and water conservation is continuously enhanced. However, the soil erosion risk in parts of the upstream area has increased. Therefore, closer attention should be paid to this area in future vegetation restoration efforts.

4 Discussion

4.1 Comparison between traditional landscape metrics and the runoff-sediment landscape index

In this study, traditional landscape metrics showed lower correlations with runoff and sediment. Traditional landscape metrics comprise a description of the landscape pattern. Most of these metrics come from mathematical statistics and the mathematical expression of geometric characteristics and spatial relationships. However, the index itself has no ecological significance. Consequently, the traditional landscape pattern index can only describe the current situation and overall characteristics of the landscape, but cannot reflect the relationship between any specific ecological process and the landscape pattern. Further, these results might be attributed to many other environmental factors, such as topography, vegetation, soil type, and rainfall, which were not considered. Landscape pattern generally reflects the spatial structure characteristics of the landscape and can be used to evaluate the impact of land cover changes on ecological processes. Currently, many studies use landscape metrics to explore the relationship between landscape patterns and soil and water losses. Thus, for example, Kim and Park (2016) evaluated the impact of landscape patterns on peak runoff and indicated that size, fragmentation, and connectivity of landscape were negatively associated with peak runoff. Additionally, Zhang et al. (2015) suggested that the LPI and AI landscape metrics were important in green space to reduce flooding risk, and in turn, Yohannes et al. (2021) revealed that water yield and sediment export were strongly influenced by landscape composition and metrics such as percentage of landscape, mean patch size, and large patch index. Lastly, Zhang et al. (2021) found that six typical landscape pattern metrics namely, FRAC_MN, PAFRAC, IJI, AREA_MN, PD, and SHEI, affected runoff and sediment yield. However, the traditional landscape metrics are usually based on land use/land cover calculation and the ecological significance of landscape metrics was not clear. Considering the different descriptions of landscape patterns by traditional landscape metrics (e.g., LPI and ED indicate area-edge, FRAC_MN and SHAPE_MN indicate shape, AI, CONTAGE, CONHESION, DIVISION, PD, and LSI indicate aggregation, SHDI indicates diversity), it is more meaningful to relate each index with the runoff-sediment landscape index separately. Compared to each traditional landscape metric, the runoff-sediment landscape index had stronger relationships and significant correlations with runoff and sediment. The results of the comparisons made, indicated that the new landscape metric was

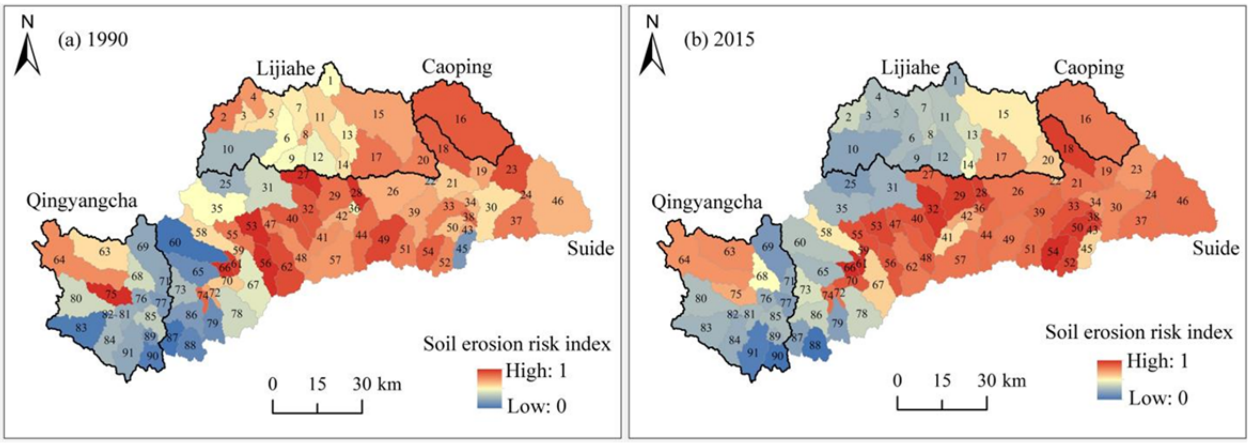

Fig. 11 Soil risk assessment by the runoff-sediment landscape index for the the Dali River watershed for the year 1990 and 2015. The number from 1 to 91 was the label of sub-watershed.

more effective and sensitive for hydrological prediction.

4.2 Hydrological process indicated by the runoff-sediment landscape index

The runoff process refers to the entire physical process from the beginning of rainfall to the flow out of the watershed outlet. The runoff process includes the following aspects: (1) precipitation falls to the ground, infiltrates into the soil, replenishes groundwater, and the rest part forms soil flow; (2) water evaporates from the soil and returns to the atmosphere; (3) surface runoff forms and enters the river. The sediment process is accompanied by the runoff process, including splash erosion caused by raindrop impact, surface erosion caused by surface runoff, and gully erosion caused by rill development (Shi et al. 2022). The runoff and sediment processes are affected by the surface cover, soil, and topography. The regulation function of vegetation on runoff and sediment yield is mainly reflected in the following aspects: shielding from raindrops and reducing splash erosion; increasing canopy interception, litter absorption, and soil infiltration of precipitation; improving surface roughness and reducing flow velocity; helping plant roots increase soil erosion-resistance (Hou et al. 2020). Soil erosion resistance is the ability of the soil to resist the dispersion and suspension due to runoff. Soil erosion resistance is closely related to soil type, structure, and texture, as well as the organic matter content and other indicators. The slope factor has a direct impact on the process of soil and water loss. Generally, steep slope plots produce more runoff than gentle slope plots and the intensification of surface fragmentation creates stronger soil erosion. Within a certain range, the amount of soil and water loss in the basin is positively correlated with the slope gradient. The greater the slope, the more severe soil and water loss.

Landscape pattern refers to the spatial arrangement of landscape elements with different sizes, shapes, compositions, and configurations. The purpose of landscape pattern analysis is to describe the interaction between landscape patterns and ecological processes. The broken terrain and spatial variation of vegetation and soil in the Loess Plateau lead to the spatial and temporal variations of the runoff and sediment processes in this region. The landscape pattern analysis of soil and water loss needs a landscape pattern index that can reflect land use type, topographic features, soil, and vegetation. The runoff-sediment landscape index effectively and comprehensively reflects landform, soil properties, and vegetation of the underlying patches in the watershed. There were four landscape factors including land use type, soil, vegetation coverage, and slope factor, which were multiplied in the index at patch, class, and landscape scales. The developed landscape metric integrated ecological processes and effectively characterized the runoff and sediment changes by considering soil erosion processes-oriented landscape elements.

The landscape pattern metric of the runoff-sediment landscape index related to the hydrological process. This index was used in flood forecast, runoff and sediment prediction, soil erosion-risk assessment, and land use planning. In recent years, linking landscape patterns to ecological processes has been the central topic in landscape ecology.

Thus, Miller et al. (2016) established a multi-scale landscape metric for vegetation, soil, algae, and water to assess the status of freshwater wetlands in the Northeastern United States. Similarly, Bin et al. (2018) developed a Runoff Landscape Index by considering land-cover, soil, and topography to evaluate the effect of landscape factors on surface runoff in the Haihe River Basin. In turn, Li and Zhou (2015) built a slope-HRU landscape index to reflect the relationship between landscape pattern and soil erosion processes in the Yanhe watershed, while Chen et al. (2019b) considered topography, distance, and land use, and proposed the application of a source-pathway-sink model to research soil and water loss, Borselli et al. (2008) established the connectivity index to model the transport process of runoff and sediment in the Bilancino watershed.

The interaction between landscape patterns and ecological processes is strongly spatial-scale dependent. The runoff-sediment landscape index is mainly used at the watershed scale. In future studies, a multi-scale landscape pattern index should be developed that reflects the process of soil and water loss at multi-scales of slope-catchment-watershed. Although the underlying surface was considered in the runoff-sediment landscape index, other factors affecting soil erosion processes, such as ecological measures, were ignored. The runoff-sediment landscape index might be improved by considering terrace, check dam, and agricultural measures.

5 Conclusions

The annual precipitation in Dali Watershed showed an increasing trend. However, runoff and sediment yields in the watershed showed significantly decreasing trends. Concomitantly, the area of cropland decreased by 139.45 km^2, and the areas of forestland, grassland, and building increased between 1990 and 2015. Meanwhile, the vegetation coverage showed an increasing trend over the same period. Thus, traditional landscape metrics PD and AI while DIVISION and SHAPE_MN decreased over the 25 years. In contrast, ED and LSI increased during the first 15 years and then both decreased, whereas, CONTAG decreased first and then increased since 2005.

The traditional landscape metrics were calculated based on land use/land cover, which focused on a simple description of the spatial distribution of the landscape and lacked any ecological significance. The hydrological processes are affected by the surface cover, land use, soil, and topography. The runoff-sediment landscape index, a runoff-sediment landscape metric, was developed by coupling land use, topography, soil, and vegetation factors, to link ecological processes with landscape patterns. At the class scale, the runoff-sediment landscape index of four land use types showed a decreasing trend. Cropland had the highest value of the runoff-sediment landscape index among land use types. At the landscape scale, the runoff-sediment landscape index increased from 1990 to 1995, and then decreased since 2000. The runoff-sediment landscape index showed higher and more significant correlations with runoff and sediment compared with traditional landscape metrics including, PD, LPI, LSI, CONTAG, CONHESION, DIVSION, SHDI, ED, SHAPE_MN, FRAC_MN, and AI. Further, the runoff-sediment landscape index explained 90.1% of the runoff and sediment registered, which was higher than the percentage explained by traditional landscape metrics.

The runoff-sediment landscape index was considered for the assessment of hydrological processes and may be used to assess soil erosion risk. In future studies, the runoff-sediment landscape index might be improved by considering ecological measures, such as terrace, check dam, and agricultural measures. This newly developed landscape index linking landscape patterns to runoff and sediment will facilitate land use development and landscape planning.

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