



OPEN Spatiotemporal evolution and attribution analysis of ecological quality in the alpine meadow region of Shangri-La based on natural-social dimensions

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In response to the impacts of climate change and the intensity of human activities in the alpine meadow region, there is an urgent need to determine the ecological quality and its drivers in alpine meadow areas. In this paper, Shangri-La was adopted as an example, the spatial and temporal evolution patterns of the ecological quality in Shangri-La were determined in both natural and social dimensions, and the contributions of various driving factors were analyzed. The conclusions are as follows: (1) the natural status index of Shangri-La from 2000 to 2020 generally showed a spatial distribution pattern that decreased from the central townships toward the north and south, and the social pressure index was irregularly distributed in high-value areas and continuously distributed in low-value areas. (2) From 2000 to 2020, the areas with high values of the ecological quality index were mainly distributed in central Shangri-La, with a maximum value of 0.91, while the low values were largely distributed in some townships in the north and south, with a minimum value of 0.26. (3) In the driving factors, the influences of the normalized difference vegetation index (NDVI) and net primary productivity (NPP) were greater than those of the other factors, among which the NDVI attained the largest mean value of 0.452, while the relative humidity (RHU) attained the lowest value of 0.036. (4) In terms of relative contributions, evapotranspiration (EVP) and precipitation (TEM) shifted from a positive drive to a negative drive from south to north. The contribution of the temperature to the ecological quality was the highest, at 64%. The spatial heterogeneity in the contributions of human disturbance activity factors to the ecological quality varied significantly, with the largest negative driving contribution of the NPP, at – 42.36%. The results could provide a basis for regional ecological quality protection and restoration.

Keywords Ecological quality, Attribution, Influence, Relative contribution

Ecological quality is a key indicator of ecosystem health and sustainability at specific spatial and temporal scales and characterizes the ability of ecosystems to continuously support the survival and development of individuals and populations^{1,2}. As human demands on ecosystems increase, a series of problems, such as resource depletion, ecological damage, and environmental pollution, have emerged, posing notable challenges to sustainable development^{3,4}. In addition, global climate change has led to the frequent occurrence of extreme events such as floods, extreme low temperatures, and droughts, which has increased the scope of their impacts, intensified their severity, and enhanced their frequency, further highlighting the contradictory relationships between humans and the environment⁵. Especially in ecologically fragile areas, the problems of biodiversity reduction

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and ecosystem degradation have become key constraints to regional development^{6–8}. Within the context of the current theory of ecological civilization construction and the policy concept of “green mountains are golden mountains”, the coordination of economic and green relationships and promotion of the coordination and sustainability of the two systems are urgent problems and trends that are important for maintaining ecological security, facilitating the harmonious coexistence of humans and nature, and achieving high-quality economic and social development in the future^{3,6,7,9}. This is important for maintaining ecological security, promoting the harmonious coexistence of humans and nature, and realizing high-quality economic and social development in the future.

As an important indicator of the regional ecological environment, the habitat quality plays an important role in maintaining biodiversity, water conservation and other ecological functions^{1,10,11}. Changes in the ecological quality directly affect the energy flow and material cycle in global or regional ecosystems. Therefore, fully recognizing and systematically assessing the regional ecological quality can help to analyze and study the ecological quality in a given region and formulate regional development planning^{12–15}. Existing research on the habitat quality is mainly based on two methods: the use of a landscape pattern index system and model simulation. Common evaluation models include the habitat suitability (HIS) model, Social Valuation of Ecosystem Services (SoIVES) model, and Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) model^{16,17}. Among these options, the InVEST model, which provides the advantages of convenient data acquisition, accurate analytical capability and visualization of results, has been widely adopted by scholars in habitat quality assessment^{17–19}. With further research, remote sensing indices based on the fusion of multiple types of remote sensing data have been used to measure changes in ecological quality conditions^{6,20}, such as the normalized difference vegetation index (NDVI), leaf area index (LAI), and scaled drought condition index (SDCI), but most indices are limited to a specific topic and cannot be employed to comprehensively evaluate the actual changes in the regional ecological environment quality. With the national emphasis and enhancement in ecological environmental protection, the Ministry of Ecology and Environment constructed an ecological index for regional ecological environment quality assessment based on indicators such as the biological abundance index, vegetation cover index, water network density index, land degradation index, and environmental quality index^{21,22}. For example, Li et al. studied changes in ecological quality in relation to land cover and the Normalized Difference Vegetation Index (NDVI) in the Maowusu Sandy Land in China. De Keersmaecker et al.²³ used a remote sensing (RS) method and assessed a framework for the stability of major ecosystems globally using an RS database. Xu²⁴ and Hu and Xu²² assessed the spatial heterogeneity in the ecological quality in urban areas of China using the remote sensing ecological index (RSEI). In summary, the current general aspects of ecological quality assessment can be summarized as follows: (1) the impact of urbanization on the ecological quality can be determined based on the urban expansion process, mainly focusing on the study of the reduction in the ecological quality due to construction land expansion during urbanization. (2) The spatial and temporal evolution characteristics of the ecological quality have been obtained on specific regional scales, mainly exploring the evolution of the ecological quality on large scales, such as watersheds, urban agglomerations, and provinces and cities. Currently, insufficient attention has been given to the spatial and temporal evolution patterns of the ecological quality and trends in ecologically fragile areas.

Scholars in the America and Europe have also achieved remarkable results in ecological quality assessment, and the research content is similar to the research framework system of Chinese scholars. They usually focus on ecosystem service assessment, biodiversity research, environmental impact assessment and the impact of climate change on ecology^{25,26}, and the methods mainly include model simulation, remote sensing technology, field monitoring and big data analysis²⁷. The European region focuses on ecosystem health assessment, land use and ecological quality relationship, ecological restoration and reconstruction and ecological risk assessment, which are generally analyzed by spatial analysis methods, ecological monitoring networks and experimental studies^{28,29}. In terms of problems, it also faces challenges such as difficulty in data integration and sharing, adaptability of indicator systems, model uncertainty, and insufficient interdisciplinary research.

Based on the natural and human impact dimensions, factors affecting the ecological quality can be categorized into natural and anthropogenic factors. In addition to natural factors driving the observed response, various economic and social activities dominated by humans could explain the decline in the ecological quality^{10,30,31}. Methodologically, attribution analysis is mainly conducted using multiple regression residual analysis, change trend analysis, geodetector-based evaluation, assessment of the impact of priority weights, and color map sharpening^{10,17,18,32}. For example, Li et al.³³ and Yu et al.³⁴ used normalized difference vegetation index (NDVI) data to explore the interrelationships between the interannual changes in different vegetation types and precipitation and air temperature, while Zhou et al.³⁵ used sensitivity analysis to explore the sensitivity of vegetation cover to the air temperature and precipitation. Li et al.³ employed correlation analysis to analyze the driving role of climate factors in vegetation cover changes. Liu et al.³⁶ performed multiple regression analysis to quantify the contribution of vegetation change to climate change in the Qiangui Karst Mountains from 2002 to 2015. Ma and Sun³⁷ noted that vegetation change and climate in the Gahai wetland were weakly positively correlated and that vegetation change exerted a greater impact on precipitation than on temperature. The above studies focused on the ecological quality response relationship under the influence of a single factor, ignoring the interaction between different influencing factors and the spatial heterogeneity in the ecological quality.

The Shangri-La River is located in the eastern part of the Three Rivers longitudinal valley area of the Hengduan Mountains at the southeastern edge of the Tibetan Plateau, which is an important part of the Three Rivers area and an important ecological zone in the Sichuan-Yunnan ecological barrier area, fulfilling a crucial role in maintaining regional biodiversity, water conservation, and other ecological functions³. The unique geographic location results in a regional alpine climate. In recent years, global climate change intensification and the increase in the intensity of human activities have amplified the sensitivity of the alpine meadow area to the impacts of climate change and human activities, which has caused the emergence of various ecological environmental

problems, such as the degradation in forests and grasslands, the recession of snow and ice lines, and the decline in ecological functions. Additionally, the regional ecological quality is facing a serious problem, and there is an urgent need to explore the pattern of ecological quality evolution in alpine meadows and the driving forces. Therefore, in this paper, the alpine meadow area of Shangri-La, Yunnan Province, was chosen as the study area, and the following research questions were addressed: What are the spatial and temporal evolution patterns of the ecological quality in the alpine meadow area? What are the driving attributes of the ecological quality in alpine meadows? To address these questions, the spatiotemporal evolution pattern of the ecological quality in Shangri-La was obtained from the perspectives of natural conditions and social pressures, the relevant drivers were analyzed, and feasible suggestions were proposed to improve the ecological quality of alpine meadows for providing a basis for their ecological restoration and protection.

Materials and methods

Study area

Shangri-La, which is the alpine meadow area in northwest Yunnan, is located in the eastern part of the Sanjiang longitudinal valley area of the Hengduan Mountain Range at the southeastern edge of the Tibetan Plateau and is a part of the Sanjiang parallel flow area ($26^{\circ} 52' - 28^{\circ} 52' \text{ N}$, $99^{\circ} 22' - 100^{\circ} 19' \text{ E}$), with an east-west width of 88 km and a north-south length of 218 km, forming a willow-leaf-shaped, narrow and long zone. With a land area of 11,613 km² and 11 townships (Township is the lowest level of administration in China, and is the centre of politics, economy, culture and information in a certain area with villages having direct socio-economic exchanges), the county exhibits the largest total land area in Yunnan Province. From a regional perspective, northwest Yunnan occurs on the Tibetan Plateau, and the East Asian monsoon, South Asian monsoon and central and southern peninsula tropical monsoon zones are three natural geographic regions at the intersection of the unique natural resources and ecological environments within the Shangri-La territory (Fig. 1). The region exhibits a north-south vertical distribution and east-west juxtaposition of geomorphic landscapes and diverse geomorphic types. The typical landscape encompassing high mountains and canyons facilitates moisture, light and heat redistribution, resulting in the three-dimensional climatic conditions of “four seasons on one mountain and different days within ten miles”. Moreover, the region is located in one of the ecologically fragile areas in the Three Rivers region of China. In recent years, global climate anomalies have intensified, and long periods of high temperatures, droughts and other extreme climate conditions have frequently occurred, as have an increased intensity of human activity interference and expansion of the scope of influence, causing severe ecological problems such as fragmentation of ecosystem patterns and sharp reduction in the ecosystem service supply capacity in the alpine meadow area. This has created notable challenges for developing and maintaining ecosystem stability in alpine meadow areas. There is an urgent need for practical measures and actions to achieve ecological quality management and protection in alpine meadow areas.

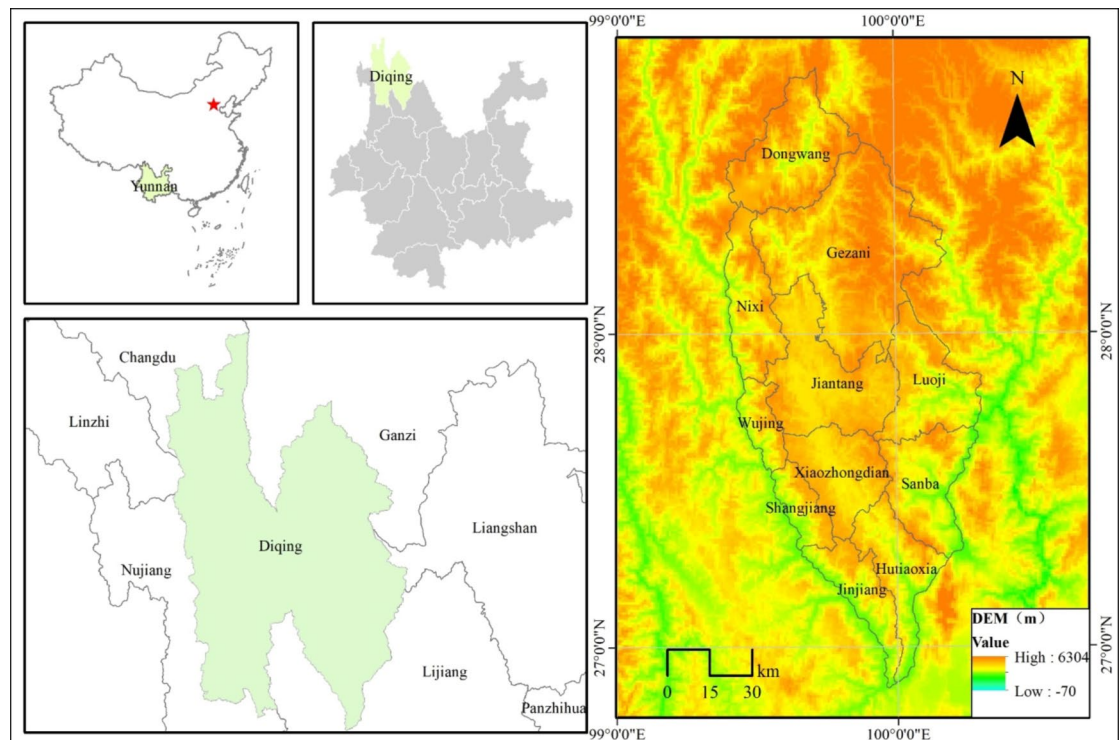


Fig. 1. Map of the study area (Generated by ArcGIS 10.8, <https://desktop.arcgis.com>).

Data

The data used in this study include land use data, administrative boundary data, net primary productivity (NPP) data, normalized difference vegetation index (NDVI) data and meteorological spatial interpolation data. The land use data, administrative boundary data, NDVI data and meteorological spatial interpolation data were obtained from the Resource and Environmental Science and Data Center of the Chinese Academy of Sciences (resdc.cn), with a spatial resolution of 1000 m. The meteorological data are based on the observed values of meteorological elements from more than 2,400 stations in China, and are interpolated using the Anusplin software, which introduces a covariate (elevation) in the interpolation, resulting in a higher interpolation accuracy and smoother interpolation results. NPP data were retrieved from the net primary productivity (NPP) raster dataset of vegetation in the Yangtze River Economic Zone (2000–2021), which was acquired from the National Science and Technology Resources Sharing Service Platform and the Lake-Basin Subcenter of the National Earth System Science Data Center (<http://lake.geodata.cn>), with a spatial resolution of 500 m. All the data were uniformly cropped and coordinate transformed in ArcGIS 10.7, and the NPP data were resampled to a spatial resolution of 1000 m. The NPP data were obtained from the National Science and Technology Resources Sharing Service Platform (NSTRSSP).

Methods

Ecological quality assessment method

Research framework and indicators Ecological quality represents the health of ecosystems and the degree of ecological service functionality, including ecosystem stability, diversity, productivity, ecological service functions and other indicators, and the ecological quality directly affects the survival and development of humans^{3,38}. The ecological quality is driven by both natural and anthropogenic influences, and the coupling of natural and anthropogenic factors for comprehensively evaluating the ecological quality is the top priority of existing ecological quality evaluation efforts¹⁴. Therefore, in this study, the ecological quality was evaluated from multiple perspectives, including ecological patterns, ecological functions, natural habitats, anthropogenic impacts, surface pollution loads, and land use dynamics, by integrating ecosystem characteristics from the dimensions of natural conditions and social pressures (Fig. 2).

The ecological quality provides the basis for the normal functioning of regional ecosystems and is an ecological geographical aspect reflected by a range of vegetation conditions and human impacts³⁹. In addition, as an important feature of ecosystems, the pattern and functions of ecosystems are mainly reflected at the landscape scale, such as a series of landscape pattern indicators and ecosystem service indicators^{14,40,41}. Based on the research framework shown in Fig. 2 and 12 secondary indicators, such as the ecological land area ratio index and the regional condition quality index, were constructed, and the meanings and calculation methods for the indicators are listed in Table 1. To eliminate the different orders of magnitude and scales of the considered indicators, the data for all indicators were standardized using the method of standardization of extreme deviations:

The positive indicators can be standardized as follows:

$$x' = \frac{x - x_{\min}}{x_{\max} - x_{\min}} \tag{1}$$

The negative indicators can be normalized as follows:

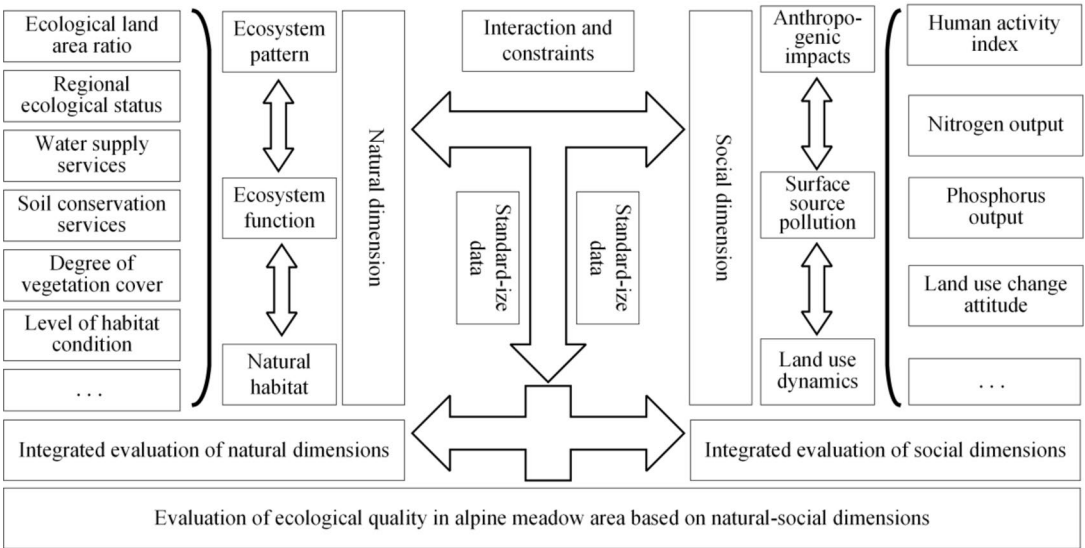


Fig. 2. Ecological quality evaluation framework for alpine meadow areas.

Dimension	Indicator level 1	Indicator level 2	Calculation method	Attributes	code
Natural conditions	Ecosystem pattern: $EPI = 0.32 \times EL + 0.68 \times (0.8 \times HQI + 0.2 \times PC)$ where EPI is the ecological pattern quality index, EL is the ecological land area ratio index, HQI is the habitat quality index, and PC is the critical ecological spatial connectivity index.	Ecological land area ratio index	The calculation is based on the area of land with ecological attributes such as woodlands, grasslands, wetlands, and agricultural land.	+	A1
		Regional condition quality index	Calculated from the quality indices for woodlands, grasslands, wetlands, etc.	+	A2
		Index of the connectivity of important ecological spaces	The calculation is based on the plate area, distance, etc.	+	A3
	Ecosystem function: $EFI = \frac{SCI+WYI+CSI}{3}$ where EFI is the ecosystem function composite index, SCI is the soil and water conservation index, WYI is the water supply index, and CSI is the carbon sequestration service index.	Water supply	The calculation is based on the water balance principle.	+	A4
		Soil conservation	The calculation is based on the modified generalized soil loss equation.	+	A5
		Carbon sequestration services	The calculation is based on the principle of ecosystem carbon sequestration.	+	A6
	Natural habitat index: $NHI = \frac{HLI+VCI}{2}$ where NHI is the natural habitat index, HLI is the habitat level index, and VCI is the vegetation cover index.	Habitat level index	The habitat level index is calculated by semisaturation equations based on the habitat suitability index and habitat degradation degree.	+	A7
		Vegetation cover index	Vegetation cover is calculated using a dichotomous model based on the NDVI.	+	A8
Social pressure	Impact of human activities	Human activity index	The calculation is based on nighttime light data.	–	B1
	Surface source pollution load: $SPI = \frac{NOI+POI}{2}$ where SPI is the surface pollution index, NOI is the nitrogen output index, and POI is the phosphorus output index.	Nitrogen output	The calculation is based on the hydrologic module of the InVEST model	–	B2
		Phosphorus output	The calculation is based on the hydrologic module of the InVEST model	–	B3
	Land use dynamics	Land use dynamics	The calculation is based on land use data.	–	B4

Table 1. Construction of an ecological quality evaluation indicator system.

$$x' = \frac{x_{\max} - x}{x_{\max} - x_{\min}} \quad (2)$$

where x' is the standardized indicator value and $x_{\max}$ and $x_{\min}$ are the maximum and minimum values, respectively, of indicator x .

Ecological quality assessment methodology (a) Evaluation of the natural state index.

The natural state index (NSI) was comprehensively evaluated based on ecosystem patterns, ecosystem functions, and natural habitats in the natural state dimension as follows:

$$NSI = \frac{(EPI + EFI + NHI)}{3} \quad (3)$$

where NSI is the natural state index, EPI is the ecological pattern index, EFI is the ecological function index, and NHI is the natural habitat index.

(b) Evaluation of the social stress index.

The social stress index (SSI) was comprehensively evaluated based on anthropogenic impacts, surface source pollution loads and land use dynamics in the social pressure dimension, and these indices can be calculated as follows:

$$SSI = \frac{(HII + SPI + LDI)}{3} \quad (4)$$

where SSI is the social stress index, HII is the human impact index, SPI is the surface pollution index, and LDI is the land dynamics index.

(c) Evaluation of the ecological quality index.

The ecological quality index was comprehensively evaluated based on the natural state and social pressure dimensions as follows:

$$EQI = \frac{(NSI + SSI)}{2} \quad (5)$$

where EQI is the ecological quality index, NSI is the natural state index, and SSI is the social stress index.

Ecological quality transfer matrix

The overall characteristics of regional spatial changes in the ecological quality can be visualized based on the number of direct transformations of different levels of the ecological quality. Moreover, by analyzing the

characteristics of the number of transfers and direction of the ecological quality, the distributional characteristics of the spatial changes in the ecological quality can be obtained as follows:

$$S_{ij} = \begin{bmatrix} S_{11} & S_{12} & \cdots & S_{1n} \\ S_{21} & S_{22} & \cdots & S_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ S_{n1} & S_{n2} & \cdots & S_{nn} \end{bmatrix} \quad (i, j = 1, 2, \dots, n) \quad (6)$$

where S denotes the area share; n denotes the number of ecological quality class types before and after transfer; i denotes the ecological quality class type; and j denotes the ecological quality class type after transfer.

Attribution analysis methods

The ecological quality of alpine meadow areas is greatly influenced by climatic conditions and human disturbance factors, so an indicator system was constructed from both climate and human disturbance perspectives. The climate factors mainly include temperature (TEM), precipitation (PRE), evapotranspiration (EVP), sunshine duration (SSD), and relative humidity (RHU). The anthropogenic disturbance factors include four main indicators: gross domestic product (GDP), population density (POP), vegetation cover index (NDVI), and net primary productivity (NPP).

Geodetector method The geodetector technique is a statistical method for detecting the spatial and temporal variabilities of variables and explaining the drivers underlying these variations. This method can be employed to measure the extent to which different factors affect the habitat quality. Interactions between different factors can be detected to determine whether there are variations in the influence of different combinations of factors on the spatial distribution of the habitat quality:

$$q = 1 - \frac{\sum_{h=1}^L N_h \sigma_h^2}{N \sigma^2} \quad (7)$$

where q is the influence of an influencing factor on the spatial and temporal variations in the habitat quality, L is the number of samples of the influencing factor, and N_h and N are the numbers of samples in stratum h and the whole area, respectively. The value of q ranges from 0 to 1, and the larger the value of q is, the higher the explanatory power of the impact factor for the habitat quality.

Regression model A linear regression model between the ecological quality and its driving variables was developed using partial least squares regression (PLSR) analysis, and the contribution of each driving variable to ecological quality changes was estimated based on the PLSR regression model. The PLSR method integrates the advantages of multiple linear regression and principal component analysis, but the main difference from ordinary least squares regression analysis is the use of data dimensionality reduction, information synthesis and screening techniques in the regression modeling process, and new composite components that best explain the system can be extracted. Compared to multiple linear regression analysis, the PLSR method can better address the multicollinearity among variables and improve the robustness of the model. The distinction of driving factor contributions based on the PLSR method is described below. A partial least squares regression (PLSR) model between the ecological quality and its driving variables was first developed on a pixel-by-pixel basis, and it was assumed that the ecological quality responds similarly to trend and year-to-year changes in each of the driving variables. Then, the following equation was used to calculate the actual and relative contributions of the different driving variables to ecological quality changes:

$$Q_i = \beta_i x_{i-trend} \quad (8)$$

$$RC_i = \frac{Q_i}{|y_{trend}|} \times 100\% \quad (9)$$

where Q_i and RC_i are the actual and relative contributions, respectively, of driving variable x_i to ecological quality changes; β_i and $x_{i-trend}$ denote the regression coefficient and actual trend, respectively, in driving variable x_i ; and y_{trend} is the actual trend in the response variable y (i.e., the ecological quality). The signs of Q_i and RC_i indicate the direction of the contribution to the observed change, with a positive sign indicating an increase in the ecological quality as a result of a change in x and a negative sign indicating a decrease in the ecological quality as a result of a change in x .

Results

Dimensional analysis of the ecological quality

Dimensional analysis of the state of nature

Based on the ecosystem pattern, functions and habitat conditions, a dimensional analysis of the natural status of Shangri-La from 2000 to 2020 was conducted, and the results are shown in Fig. 3 (a–c). From 2000 to 2020, the areas with the highest natural status index (NSI) values were mainly located in two townships, namely, Luogi township and Wujing township, with the highest NSI value of 0.85 (0.84 in 2020). The main reason is that the Jinsha River flows through the territory of Wujing township, the area exhibits a significant dry and hot valley

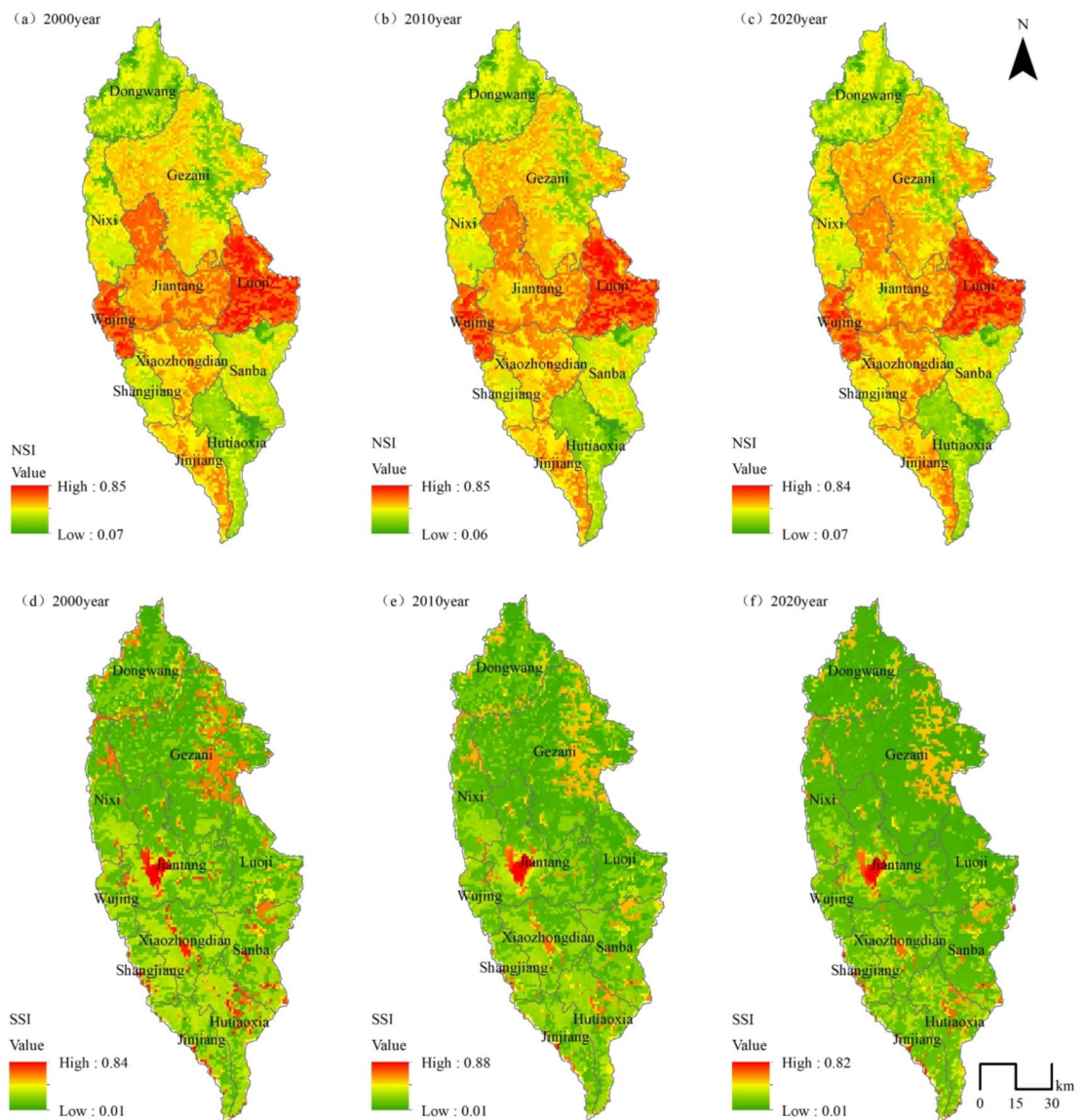


Fig. 3. Analysis of the ecological quality evaluation dimensions (Generated by ArcGIS 10.8, <https://desktop.arcgis.com>).

climate that provides abundant water vapor, and the vegetation cover is dominated by continuous trees and shrubs. The Pudacuo National Forest Park is located in the area of Luogi township, and the terrain exhibits a slight difference in undulation, resulting in a superior ecological environment. As a result, these two townships exhibited the highest levels of the natural state index within the region. The areas with the lowest NSI values were scattered, with distributions in Tiger Leaping Gorge township, Gezhan township, Dongwang township and Nixi township, with the lowest NSI value of 0.07 (0.06 in 2010). Spatially, the areas with the lowest ecological status index values were concentrated in the northern part of Shangri-La, mainly due to the proximity of the northern part to the Hengduan Mountains, where the large differences in topographic relief result in fragmented landscapes and a sparse, discontinuous vegetation cover, leading to a low index of natural ecological conditions in the region. Most townships in the central Shangri-La region exhibited a relatively moderate Natural status index. In terms of change, there was a significant difference in natural status index change in the region from 2000 to 2020 (the color varies), indicating that the natural status index of the region exhibited a significant downward trend. The topography of the region is relatively moderate in terms of relief, and the vegetation cover is dominated by trees and shrubs. However, the cause of surface landscape destruction due to anthropogenic development activities constrains the decline in the natural status index of the area. Overall, from 2000 to 2020, the natural status index of Shangri-La generally showed a spatial distribution pattern that decreased from the central townships to the north and south. In terms of temporal changes, the natural status of the central townships of Shangri-La significantly changed and showed a downward trend, while the remainder of the area indicated nonsignificant changes.

Dimensional analysis of social stress

The social pressure dimension in Shangri-La from 2000 to 2020 was analyzed based on the impacts of human activities, surface source pollution and land use, and the results are shown in Fig. 3 (d-f). From 2000 to 2020, the areas with the highest social status index (SSI) values were sporadically distributed in the towns of Jiantang, Xiaozhongdian, and Tiger Leaping Gorge, as well as in parts of certain townships along the Jinsha River, where the SSI reached a maximum of 0.88 (0.84 in 2000 and 0.82 in 2020). In regard to population concentration in these areas, terrain undulations slightly increased the amount of arable land available, resulting in greater land use pressure and higher land use dynamics, coupled with the use of pesticides, so that the surface pollution pressure in the region increased, resulting in a high SSI value. The areas with the lowest SSI values exhibited the widest distribution area and were distributed within townships. These areas are sparsely populated, the land use is mostly pristine ecological land, such as trees, shrubs and grass, and there is little pressure from surface pollution. Thus, these areas attained the lowest SSI value (0.01). In terms of spatial and temporal changes, the SSI of Shangri-La showed a decreasing trend, especially in some areas of the northern townships of Shangri-La (e.g., Gerzan township). This is mainly due to a series of ecological protection measures implemented in Shangri-La since the early stages of the twenty-one year study period. For example, returning farmland to forestland and grassland resulted in a lower regional land use pressure, less surface source pollution, and a lower SSI. Overall, high values of the social stress index were scattered in Shangri-La, while low values were distributed in patches. In terms of temporal trends, the SSI generally showed a downward trend.

Analysis of the spatial and temporal patterns of the ecological quality

Spatial and temporal patterns of the ecological quality

The ecological quality of Shangri-La from 2000 to 2020 was spatially evaluated based on the dual dimensions of natural conditions and social pressure, and the results are shown in Fig. 4 (a-c). From 2000 to 2020, the areas with the highest ecological quality index in Shangri-La were mainly located in Luokei township and Wujing township (the darkest color). They exhibited the best ecological quality status in the region due to the high natural status index and low social pressure. In terms of temporal change, the highest EQI in the region increased from 0.89 in 2000 to 0.91 in 2020, with an increase in the EQI of 0.02. This indicates that this area is the main ecological barrier area in Shangri-La, playing an important role in maintaining the stability of the regional ecosystem and biodiversity. The spatial distribution pattern of low EQI values was similar to that of natural conditions, which are mainly scattered in the central townships of Shangri-La and the northern and southern townships. The central counties and towns are most notable within Jiantang, which is the seat of Shangri-La County, with a low natural status index and a high social pressure index, which are the main reasons for the low ecological quality of this region. The townships in the north and south, such as Tiger Leaping Gorge, exhibited a lower natural state index due to their unique geographic location, and at the same time, human impacts caused a certain amount of social pressure, resulting in a low ecological quality under the dual overlapping influences of natural and human factors. The ecological quality index of most townships in central Shangri-La was relatively moderate, and these areas should strengthen the management of ecological quality protection and enhance the regional ecological quality. Overall, the areas with high values of the ecological quality in Shangri-La from 2000 to 2020 were mainly distributed in central Shangri-La, and the areas with low values were largely distributed in some townships in the north and south.

Changes in the spatial and temporal patterns of ecological quality in Shangri-La city under different time gradients from 2000 to 2020 are shown in Fig. 4 (d-f). From 2000 to 2010, the townships in the central region of Shangri-La city mainly showed a decreasing trend, with the highest decline (darkest color) occurring within Jiantang township, where the ecological quality index decreased by a maximum of 0.16. The ecological quality of most communities in the north and south mainly showed increasing trends, among which the ecological quality of the Shangjiang Community and Gezhan Community increased most significantly, with a maximum increase of 0.05. The upward and downward changes in the ecological quality of Shangri-La from 2010 to 2020 were relatively “haphazard and disorganized”. Of these, areas of a declining ecological quality were mainly located in townships in the central and southern regions. In contrast, areas of an increasing quality were mostly located in townships in the northern region. In terms of the change from 2000 to 2020, the area with the most significant decline in the ecological quality encompassed the central townships of Shangri-La, among which Jiantang township exhibited the most obvious decrease, with a maximum decrease of 0.26. The change in the ecological quality of the northern townships mainly showed an increasing trend, among which Gezhan township exhibited the most obvious increase, with a maximum increase of 0.15 in the ecological quality index. Overall, regarding the change in the ecological quality index of Shangri-La from 2000 to 2020, the central townships, especially Jiantang township, mainly showed decreasing trends, while the northern and southern townships largely showed increasing trends. There was a larger difference in the decreasing magnitude of the ecological quality than in the increasing magnitude. The main reason for the decline in the ecological quality is the occurrence of various human activities in the central townships, so there is a need to reduce the impact of human disturbance activities on the ecological quality and to enhance ecological protection of the region.

Spatial and temporal shifts in the ecological quality

Based on the natural breakpoint method in ArcGIS, the ecological quality of Shangri-La was categorized into four grades, namely, poor, moderate, good and excellent, and the area transfer of the various ecological quality grades at different time stages was analyzed by combining the principle of the land transfer (Fig. 5). Generally, over the past 20 years, the area transfer of the various ecological quality classes in Shangri-La has been active, with different degrees of transfer for the different ecological quality classes and different types of transfer out of the area. Between 2000 and 2020, the main area transfer of the excellent ecological quality class was to the good class, with a transfer percentage of 13.28%. There was a slight tendency to transfer from the excellent class to

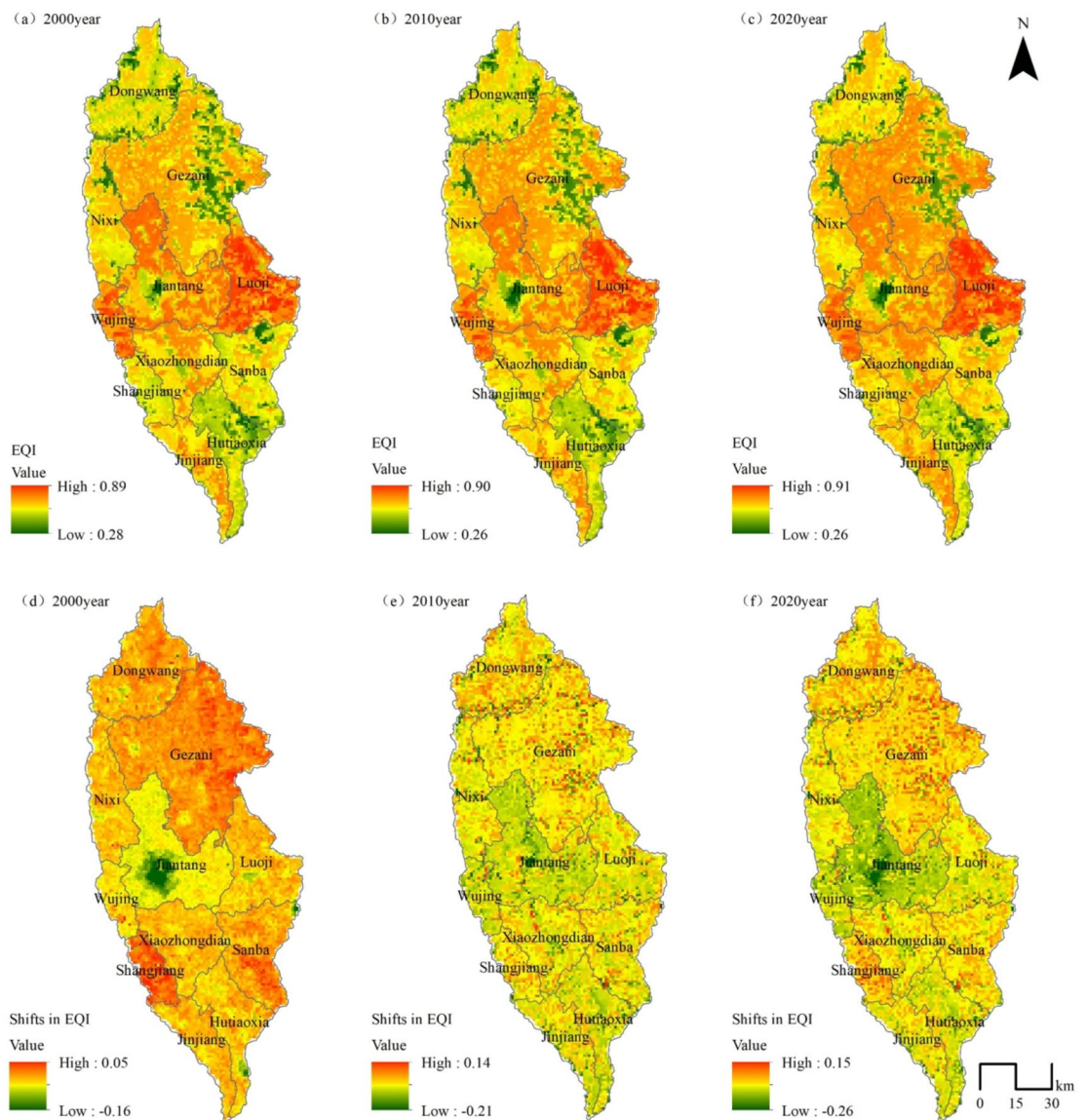


Fig. 4. Spatiotemporal pattern of the ecological quality index (Generated by ArcGIS 10.8, <https://desktop.arcgis.com>).

poorer classes (0.01%). The transfer from the good to excellent ecological quality classes was also notable, with a transfer percentage of 1.59, which was highest during the 2010–2020 period, at 3.02%. The poor ecological quality rating moved toward the good class, with a transfer percentage of 2.0% to the medium class from 2000 to 2020. This indicates that the ecological quality of areas with poorer ecological quality grades improved. Overall, the ecological quality grades of Shangri-La were primarily good and excellent, but there was a tendency for the higher ecological quality grades to shift to lower grades with increasing interference from human activities, requiring strengthening of efforts to manage and protect the ecological quality.

Attribution analysis

Driving impact explained

There were differences in the influences of the various influencing factors on the habitat quality in Shangri-La, but the *p* values of the influencing factors in the different years passed the significance test at the 1% level. As indicated in Table 2, the influences of the NDVI and NPP were greater than those of the other factors, and they were the dominant factors influencing the spatial differentiation in the habitat quality because the distributions of the habitat quality and the NDVI and NPP were consistent, a high habitat quality was mainly distributed in the forestland and other protected areas within the study area, with a high ecological value, while a low habitat quality was mostly observed in construction land within the study area. Second, the influence values of the GDP, PRE, POP, SSD, and TEM on the ecological quality ranged from 0.1 to 0.2, indicating that anthropogenic influences and natural factors simultaneously operate to affect the spatial distribution of the habitat quality. These areas exhibited a relatively low habitat quality due to the constant disturbance of ecosystems by human

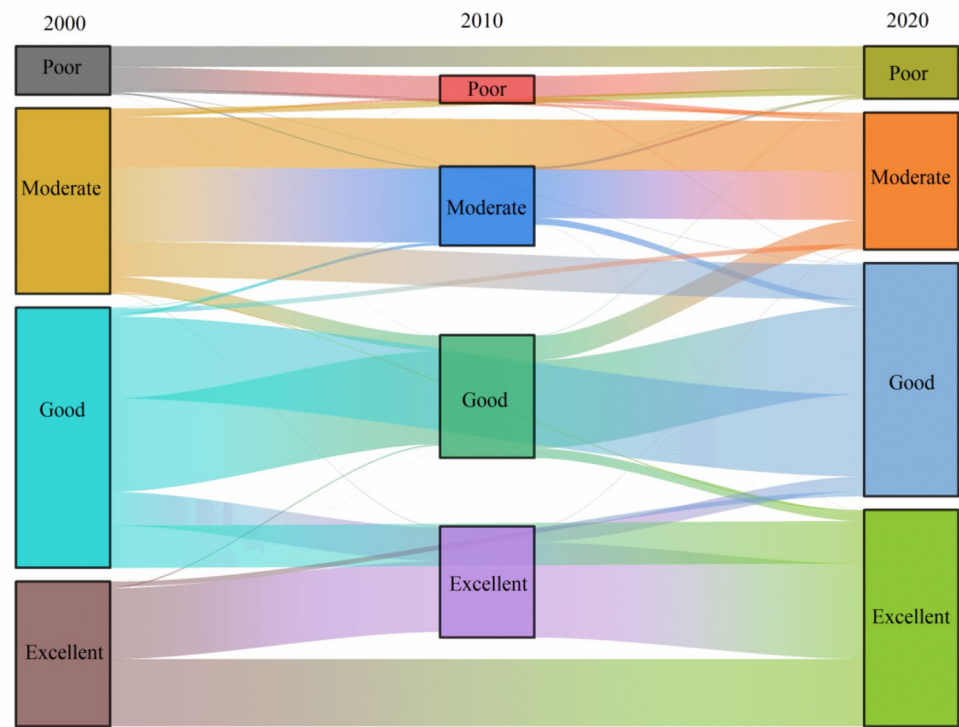


Fig. 5. Percentage area shift in the ecological quality rating from 2000 to 2020.

Particular year	Clout	EVP	GDP	NDVI	NPP	PER	POP	RHU	SSD	TEM
2000	<i>q</i>	0.011	0.135	0.529	0.325	0.011	0.138	0.070	0.271	0.140
2010		0.058	0.208	0.418	0.333	0.068	0.217	0.036	0.176	0.132
2020		0.086	0.206	0.410	0.278	0.256	0.213	0.002	0.042	0.114
Average values		0.052	0.183	0.452	0.312	0.112	0.189	0.036	0.163	0.129

Table 2. Results of the detection of ecological quality drivers in Shangri-La.

activities, which affects climatic conditions such as precipitation and temperature. However, human activities and ecological protection are not antagonistic, and the benefits of economic development could reduce the harm caused to the ecological environment, for example, through ecological restoration of vegetation and landscapes and enhancement in the environmental quality. Thus, climatic and economic factors generate cross-cutting influences on the habitat quality, and the habitat quality is influenced by multiple factors. It is also constrained by the spatially heterogeneous characteristics of different regions, and further information on the spatial contributions of drivers to the ecological quality is needed as a way to better understand driving factor spatial variability.

Analysis of the relative contributions

Based on the geodetector model and regression analysis, spatiotemporal attribution analysis of the ecological quality of Shangri-La was conducted, and the spatial attribution analysis results are shown in Fig. 6, exhibiting high spatial heterogeneity. Among the climate factors (Fig. 6 (a-e)), the driving contributions of EVP, PRE, RHU, SSD, and TEM to the ecological quality showed similar patterns of spatial changes from a negative to positive drive from south to north, but the driving contribution patterns of EVP and TEM where the opposite, namely, a shift from a positive to negative drive from south to north. In terms of the contribution rate, the contribution of EVP to the ecological quality in the southern-central region was mainly a positive driver, with a maximum contribution rate of 13.54%, while most of the areas of Dongwang and Gezhan townships in the north exhibited a negative correlation, with a maximum negative relative contribution rate of 24.23%. The driving contribution of the temperature to the ecological quality exhibited clear polarization, with a significant positive contribution, especially in the coastal areas of the Jinsha River, where the contribution was highest, reaching 64%. The prominent dry and hot valley climate along the Jinsha River, with high temperatures generating large amounts of EVP and periods of rain and heat coinciding, is important for the growth of a large amount of vegetation and the enhancement in the ecological quality. Thus, the EVP and TEM exhibited similar spatially driving contribution patterns. PRE, RHU and SSD attained similar driving contribution patterns (negative in the south and positive

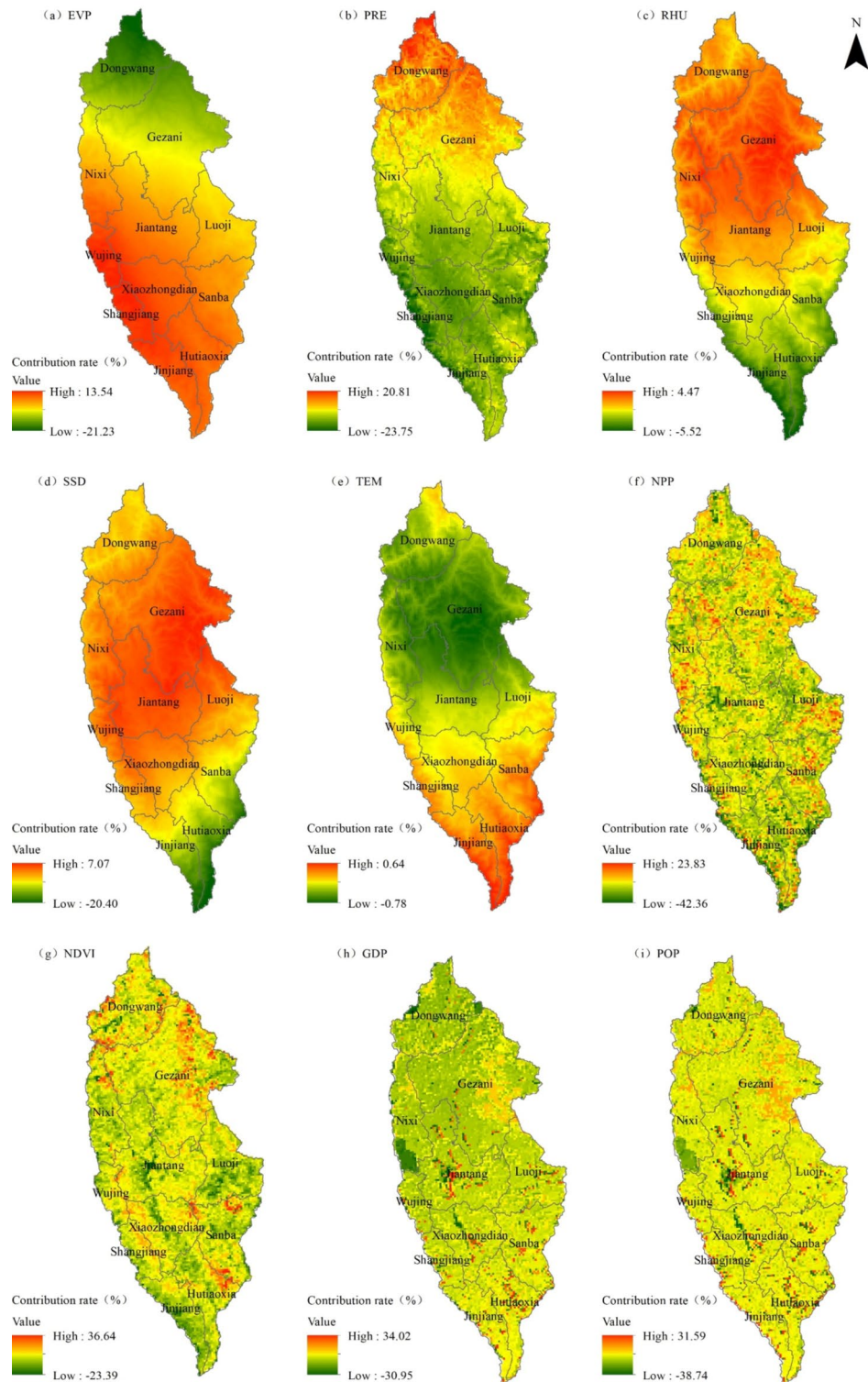


Fig. 6. Distribution of the relative spatial contributions of the drivers to the ecological quality (Generated by ArcGIS 10.8, <https://desktop.arcgis.com>).

in the north), and the negative driving contribution of precipitation reached a maximum (-23.75%) along the Jinsha River. Additionally, more precipitation occurs in mountainous terrain with high undulations in the surface, which is likely to lead to geologic hazards, such as erosion and mudslides, and damage to the surface landscape. In the northern region, as a positive contribution, northward moisture is usually blocked by high mountains and rarely reaches the northern region. As a result, the PRE level is usually much lower in the north than in the south, leading to large.

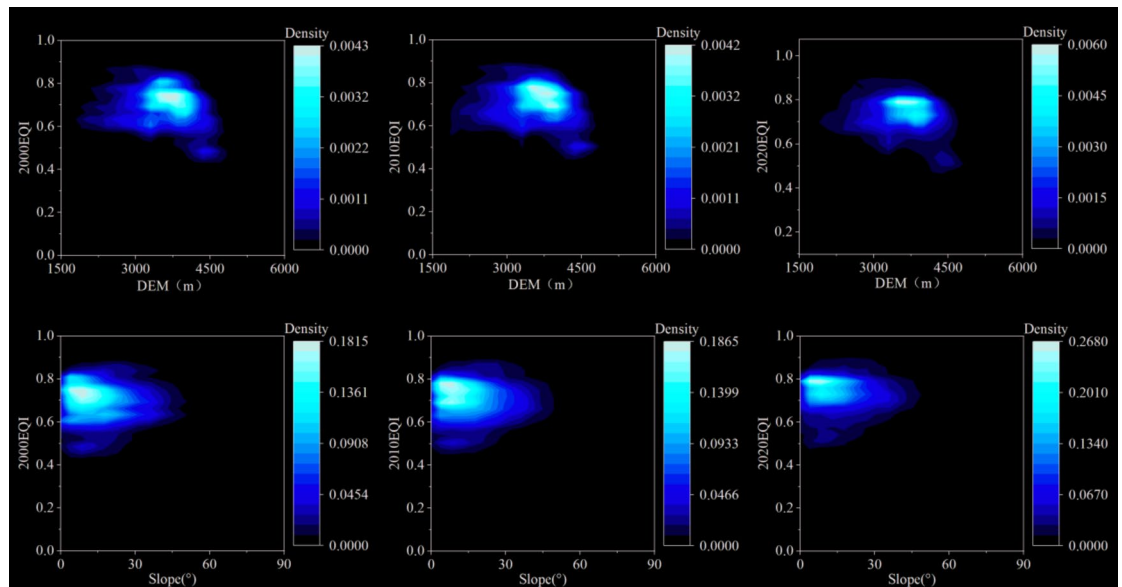


Fig. 7. Spatial aggregation distribution of the ecological quality index values under the influence of the DEM and SLOPE (Generated by Origin 2021, <https://www.originlab.com>).

differences in vegetation between the north and south. The driving contributions of RHU and SSD were low, but the negative driving contribution of the sunshine hours was significant in Jinjiang and Tiger Leaping Gorge towns, at -20.23% , which is closely related to the dry and hot valley climate. Overall, among the climate drivers, EVP, PRE, and TEM significantly contributed to driving the ecological quality.

The heterogeneity in the spatial driving contribution patterns was prominent among the human disturbance-dominated drivers such as NPP, NDVI, GDP, and POP, and the distribution of areas with high positive and negative spatial driving contributions was fragmented (Fig. 6 (f-i)). In terms of the distribution, areas with high negative spatial driving contributions were mainly concentrated in areas with a high population density and significant anthropogenic disturbances. For example, the areas with high NPP, NDVI, GDP, and POP negative driving contribution rates mostly occurred in regions with the highest levels of population concentration and economic development within the towns of Jiantang and Xiao-Zhongdian, where the negative driving contribution rates reached -42.36% , -23.39% , -30.95% , and -38.74% , respectively. Moreover, high positive driving contribution areas of the NDVI, GDP, and POP were found at the periphery, with driving contribution rates of 36.64% , 34.02% , and 31.59% , respectively. This suggests that anthropogenic disturbances are the main impediment to ecological quality improvement, but at the same time, they can be considered to improve the ecological quality of the region through ecological restoration and protection. Overall, the spatial heterogeneity in the driving contributions of human disturbance activity factors to the ecological quality significantly varied, and the impact of human disturbance activities on the ecological quality should be reduced.

Discussion

Effects of the elevation and slope on the spatial distribution of the ecological quality

Elevation and slope, as important indicators of the topography and geomorphology, impose extremely notable effects on the spatial distribution of the ecological quality^{6,42}. Elevation affects ecological factors such as temperature, precipitation and barometric pressure, thereby influencing the type and distribution of ecosystems²¹. Changes in altitude can lead to changes in ecological factors such as temperature, precipitation and light. At high altitudes, where the temperature and precipitation are low and solar radiation is high, ecosystem productivity is lower, but biodiversity may be greater⁴³. At lower elevations, where the temperature and precipitation are high and solar radiation is low, ecosystems are more productive, but biodiversity may be lower. Slope impacts the ecological quality mainly by affecting soil erosion, water loss and land use patterns^{3,10}. In areas with steep slopes, soil erosion and water loss are severe, and ecosystems are less stable. In gently sloping areas, there is less soil erosion and water loss, and the ecosystem remains more stable. The effects of elevation and slope on the ecological quality are complex and require comprehensive consideration of the interactions among multiple ecological factors. In ecological conservation and management, appropriate conservation and management measures must be implemented according to different altitude and slope conditions to maintain ecosystem health and stability. To investigate the influences of elevation and slope on the spatial distribution of the ecological quality in Shangri-La, the ecological quality at different elevations and slopes was determined and analyzed based on the principle of the geodetector model, and the spatial distribution of the ecological quality was obtained, as shown in Fig. 7.

Based on the results of spatial aggregation of the effects of elevation and slope on the ecological quality, the overall ecological quality index varied between 0.4 and 0.8, with a median of 0.6, which is generally a good level. The aggregated distribution interval of the altitude mainly varied between 2500 and 4000 m. The main reason for

this finding is that the average altitude of Shangri-La is above 3,000 m, and the region in general exhibits a high terrain elevation. At high altitudes, where the temperature, precipitation and air pressure are lower, ecosystems are usually dominated by alpine meadows, alpine shrublands, alpine forests, etc., which, together with the relatively low population density, exert a lesser impact on the ecological quality. In terms of the influence of slope, the ecological quality was mainly clustered in areas with gentler slopes ranging from 0–50°. According to the response of the ecological quality to the slope, the higher the slope, the more serious the soil erosion is, leading to soil impoverishment and ecosystem degradation, and the more easily precipitation is lost, leading to water shortages and affecting the ecosystem productivity. Moreover, the higher the slope, the more difficult it is for organisms to migrate and communicate, leading to a reduction in biodiversity. In addition, the slope affects the way land is utilized, and the higher the slope, the lower the availability of land in the area is, which in turn leads to overcultivation and overgrazing, affecting the stability of the ecosystem.

Necessity of evaluating and attributing the ecological quality in alpine meadow areas based on the dimensions of nature and society

The ecological quality affects the survival and well-being of humans and sustainable development. As an important indicator for assessing the health and sustainable development of ecosystems, the ecological quality reflects the status of ecosystems in terms of productivity, resistance to disturbance, and ecological resilience^{2,16,43}. Therefore, ecological quality assessment must consider both natural and social factors of ecosystems. Scholars have conducted quantitative evaluation studies of the ecological quality of varying degrees according to specific objectives and contexts, focusing mainly on single-aspect evaluations in the natural dimension, such as evaluating changes in the ecological quality in terms of natural factors such as the NDVI, NPP, and FV^{36,42,44}. In recent years, with the intensification of human social activity interference, the constraints on the ecological quality have significantly increased, and the evaluation of the ecological quality from the perspective of a single natural factor cannot meet the needs of actual ecological quality evaluation research. Attribution analysis often focuses on the overall relationship between the ecological quality and driving factors, while quantitative research on the contributions of factors under spatial driving conditions is insufficient; therefore, it is impossible to accurately quantify the spatial driving differences among driving factors^{35,39}. It is difficult to provide effective decision-making information and suggestions for optimizing and improving the ecological quality. Therefore, existing research lacks the comprehensive evaluation of the ecological quality in the natural and social dimensions, and the results cannot meet the needs of ecological quality improvement.

Dynamic changes in ecological quality are mainly driven by natural ecosystems' ontogenetic interactions as well as by human economic and social development activities, and there is a strong need to analyse changes in ecological quality in the context of both natural ecological and societal drivers^{3,35}. In this study, we constructed an ecological quality evaluation index system based on the natural and social dimensions and performed an ecological quality evaluation and spatial-temporal dynamic analysis of the alpine meadow area under the comprehensive influence of the ecosystem pattern, ecosystem services, natural habitat index, human activities, surface source pollution load, and land use dynamics. A more comprehensive assessment of the ecological quality could reveal the health of ecosystems and change trends by integrating natural and social factors. By quantifying the contribution to the ecological quality through spatial driving heterogeneity, clarifying the spatial heterogeneity in the effect of driving factors on the ecological quality of alpine meadow areas, exploring the causes and influencing factors of ecological problems, and identifying the main driving factors and key links, decision-making departments can develop a clear understanding of the current status of the ecological quality of alpine meadow areas and trends and facilitate the formulation of relevant optimization policies and measures to enhance the ecological quality of the region and safeguard its ecological security.

Initiatives and recommendations to improve the regional ecological quality

The improvement in the ecological quality could safeguard the health and stability of ecosystems, reduce ecosystem degradation and destruction, and ensure ecological security^{45,46}. At the same time, it could promote sustainable economic development, encourage eco-agriculture, eco-tourism and other modes of sustainable development, improve the economic efficiency, reduce the impacts of ecological and environmental problems on social stability, and facilitate the harmonious development of the environment and humans^{47–50}. The specific recommendations are as follows.

(1) Park ecological protection zones: We should strengthen efforts to protect rare and endangered species and wildlife, prevent overcultivation and overgrazing, and reduce soil erosion. (2) Ecological functional zones: We should enhance the links between forests, grasslands, wetlands and other ecosystems, thereby repairing the ecological corridors connecting the different systems, promoting the circulation of materials and flow of energy between the different systems, and restoring the functions and stability of ecosystems. (3) Livestock farming areas: We should promote sustainable ecological agriculture in the study area, enhance sustainable development models such as eco-agriculture and eco-tourism, and strictly implement a system for controlling and limiting face-source pollution to reduce damage to the ecological environment. (4) Regional environmental monitoring: We should improve environmental monitoring in the study area, strictly control and limit the interference of human development activities with the ecological environment and ensure the safety of the ecological environment. (5) Publicity and popularization of science: Ecological education and publicity in the study area should be strengthened, public awareness of ecology and environmental protection should be increased, and public participation in ecological protection should be promoted. Improving the ecological quality of Shangri-La requires comprehensive measures, in addition to the actual conditions of the region, and corresponding protection and management measures are needed to maintain ecosystem health and stability. For example, in areas with steep slopes, measures such as afforestation and terracing should be implemented to reduce soil erosion, while in areas with gentle slopes, rational land use should be adopted to protect biodiversity.

Conclusions and prospects

Based on the framework of natural and social dimensions, we constructed an evaluation system and investigated the spatiotemporal evolution pattern and attributes of the ecological quality in alpine meadow areas from the aspects of ecosystem patterns, ecosystem services, current status of natural habitats, and impacts of human activities. The following conclusions can be obtained:

- (1) From 2000 to 2020, the natural status index of Shangri-La generally showed a spatial distribution pattern that decreased from the central townships to the north and south; in terms of temporal changes, the natural conditions of the central townships of Shangri-La changed significantly, showing a downward trend, while the changes in the rest of the area were not obvious. The social stress index of Shangri-La exhibited a fragmented distribution of high-value areas and a continuous patchy distribution of low-value areas; the temporal change trend of the social stress index showed an overall decreasing trend.
- (2) From 2000 to 2020, the high-ecological quality areas of Shangri-La were mainly distributed in central Shangri-La, with a maximum ecological quality index of 0.91, while the low-value areas were largely distributed in townships in the north and south, with the lowest ecological quality index of 0.26. In terms of trends, the central townships of Shangri-La, especially Jiantang township, mostly exhibited decreasing trends, while the northern and southern townships mainly showed increasing trends.
- (3) In terms of driving influences, the influences of the NDVI and NPP were greater than those of the other factors, with the NDVI exhibiting the highest mean value of influence, at 0.452, and the RHU exhibited the lowest value of influence, at 0.036. Among the climate factors, the driving contributions of precipitation (PRE), relative humidity (RHU), and sunshine hours (SSD) to the ecological quality demonstrated a similar pattern of spatial changes from a negative to positive drive from south to north, while evapotranspiration (EVP) and precipitation (TEM) showed a shift from a positive to negative drive from south to north. Among them, the driving contribution of the temperature to the ecological quality was the highest, with a maximum of 64%. The spatial heterogeneity in the driving contributions of the human disturbance activity factors to the ecological quality varied significantly, and the distribution of the high-value areas of positive and negative spatial driving contributions was scattered, of which the driving negative driving contribution of the NPP was the highest, at -42.36% .

Our study is based on a research framework of natural and social dimensions, coupling multisource remote sensing data and spatial analysis methods to explore the spatial and temporal evolution patterns and trends in the ecological quality in the alpine meadow area and to determine the relative contributions of factors. The spatial and temporal evolution patterns and development trends in the ecological quality in the alpine meadow area were clarified, the influences of various driving factors and the spatial heterogeneity were determined, the spatial influences of elevation and slope on the ecological quality were explored, and specific suggestions for protecting and managing the ecological quality in the alpine meadow area were proposed. However, the ecological quality is subject to the integrated response of various aspects and follows a complex driver-response mechanism. In subsequent studies, the relationship between drivers and ecological quality must be explored further, and the influence mechanism must be revealed in an integrated and multidisciplinary way.

Data availability

Data is provided within the supplementary information files.

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Author contributions

Author Contributions: Methodology, Z.L. and K.Z.; software, Y.B.; formal analysis, H.W.; investigation, L.S.; resources, Y.Z.(YanJun Zhang); data curation, C.H., Z.H., C. D. and Y.X.; writing-original draft, Z.L.; writing-review and editing, K.Z.; funding acquisition, Z.L., Y.B. and Y.Z.(YaZhang). All authors have read and agreed to the published version of the manuscript.

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Declarations

Competing interests

The authors declare no competing interests.

Additional information

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