The HANTS-fitted data in the vegetation growing season can improve RSEI accuracy in revealing the spatiotemporal patterns of ecological quality in Yuxi of China

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Article

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The HANTS-fitted data in the vegetation growing season can improve RSEI accuracy in revealing the spatiotemporal patterns of ecological quality in Yuxi of China

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Abstract: Yuxi, a region of active economic development in China's central Yunnan Plateau, is subject to the ecological pressures brought about by rapid urbanization. In order to provide a scientific rationale for making decisions about environmental management, a long-term and accurate methodology for appraising and evaluating the ecological condition is required. Firstly, this study used 30 m-resolution Landsat data to reconstruct four indices, including greenness, wetness, dryness, and heat, during the vegetation growth period in Yuxi from 2000 to 2020 by using the HANTS filtering method. Secondly, we computed the annual RSEI using reconstructed indices to assess ecological quality in Yuxi. Thirdly, through Sen +MK trend analysis, spatial autocorrelation analysis, and geographical detectors on year-by-year RSEI, the spatiotemporal pattern and determinants of Yuxi’s ecological quality were revealed. The results showed that: (1) vegetation seasons obviously affect the accuracy of the RSEI, and the data of the vegetation growing season is suggested to construct the RSEI model; (2) HANTS can effectively optimize the ecological indices of constructing the RSEI model, making the missing data filling smoother and more continuous. The reconstructed RSEI and the original RSEI have an absolute difference ranging between -0.15 and 0.15; (3) the comprehensive ecological quality of Yuxi is moderate according to the RSEI mean value (0.5413), and the ecological quality of mountainous areas is better than that of valleys and plains. Yuxi's ecological quality manifests a clear center-edge pattern. (4) Between 2000 and 2020, the ecological quality of Yuxi exhibited a fluctuation and slightly rising trend as a whole, and the alteration in land utilization patterns was the primary determinant of Yuxi’s ecological quality shift, especially forestry land and impervious surface. Based on Yuxi, a city on the Central Yunnan Plateau, this study can serve as a reference for scientific decision-making regarding sustainable development and ecological protection.

Keywords: Ecological quality; RSEI; Spatiotemporal analysis; Vegetation seasons; HANTS
1 Introduction

Ecological environment surrounds the natural environment, human activities, and economic variables, all of which are crucial in promoting human well-being and facilitating social progress. The increasing population and the extension of human activity have been identified as factors that lead to disruptions in ecosystems on a variety of scales. The Earth's biosphere, hydrosphere, atmosphere, and pedosphere are subject to a range of ecological disturbances that have significant impacts on human well-being, including living quality, health, social stability, and economic development. Moreover, numerous ecological issues, like pollution in the environment, ecological degradation, and biodiversity loss, have presented obstacles to the ecological environment and social development.

Ecological quality assessment, a fundamental component of ecological environmental research, distinguishes itself from conventional ground survey methodologies. The monitoring of ecological quality through the utilization of remote sensing observations has emerged as a prominent subject of interest in contemporary times. This is primarily attributed to its several benefits, including a vast repository of long-term data, the ability to capture multi-temporal and spatial information, and the capacity to cover broad geographical areas. Remote sensing indices have the ability to effectively assess and quantify the condition and dynamics of ecological quality. Various remote sensing indices based on spectral inversion have been developed and utilized in ecological studies. These indices include the normalized difference vegetation index (NDVI), leaf area index (LAI), soil adjusted vegetation index (SAVI), among others. These indices serve as important environmental driving factors, predictive factors, or fundamental biodiversity variables for assessing ecological quality. However, in reality, the ecological environment is an intricate system. The components of the environment in the system are inseparable, and their interaction may affect the whole ecological environment. Therefore, one remote sensing indicator alone cannot precisely reflect regional ecological quality. A more effective method is to utilize various indicators for a thorough ecological quality evaluation.

However, the Remote Sensing Ecological Index (RSEI) integrates four ecological indicators—greenness, wetness, dryness, and heat—via principal component analysis, forming a comprehensive ecological index. All characteristics in this indicator are tightly linked to ecological quality and may be obtained through remote sensing technology alone. Therefore, it can monitor the ecological quality objectively, low-costly, and quantitatively, and perform spatiotemporal visualization analysis. Several studies utilized the RSEI model to monitor ecological quality alterations in interior cities, coastal island cities, and plateau basins. These studies were carried out based on medium- and low-resolution satellite data. The MODIS satellite data products can control the quality availability to some extent through approaches including quality assurance and perspective limitations. Nevertheless, the
spatiotemporal consistency of satellite data products such as Landsat, SPOT, and Sentinel is inevitably still affected by unstable negative factors such as clouds, rain, climate, and problems with sensors. Therefore, noise and other negative effects should be eliminated before applying the RSEI index. Local filtering and function fitting approaches have advantages in maintaining image details (Yang et al., 2015). These five-time series reconstruction techniques are employed by many people, including harmonic analysis (HA), asymmetric gaussian (AG), double logistic (DL), savitzky-Golay filter (SG), and whittaker smoothing (WS), due to their simplicity in implementation or ability to derive phenological markers from the time series. Harmonic analysis of time series (HANTS) is a way to rebuild based on harmonic analysis. Relevant research shows that HANTS filtering can effectively filter residual cloud cover while retaining the differences between years in the original data. The amplitude and phase of the harmonic components serve as quantitative measurement indicators of vegetation phenology, in addition to cloud eradication, which makes HANTS also have a good application effect in phenology research.

Ecological quality and vegetation are strongly associated. The selection of vegetation seasons is a key factor in the RSEI construction, because the vegetation information in different vegetation seasons is different, which will affect the expression and changes of ecological index components. with vegetation greenness serving as a primary indicator in the RSEI score. It is necessary to ensure the precision of greenness information in the study region. However, existing RSEI research often ignores the condition of limiting image data in the vegetation growing season and introduces a large amount of data in non-vegetation growing seasons, causing uncertainty in the results of RSEI inversion.

Yuxi is situated at the heart of the plateau of Yunnan Province, China. It is a famous plateau water town in China. The plateau area has unique and fragile ecological characteristics due to its special geographical location and climatic conditions. Once damaged, it is extremely difficult to recover, and may even cause irreversible ecological disasters. Since the beginning of the 21st century, the ecological quality of Yuxi has faced a series of problems under the impact of natural, population, economic, and policy factors, such as eutrophication, debris flow disasters, serious landslides, and drought climate, which endanger the ecological environment of Yuxi. Thus, it is necessary to study the spatiotemporal pattern of ecological quality in Yuxi to lay a solid foundation for formulating ecological protection strategies. This study aims to accomplish the following goals: (1) Explore the performance of RSEI in the vegetation growing season and non-growing season. (2) Verify the effectiveness of HANTS in constructing RSEI based on Landsat data. (3) Reveal the spatiotemporal spread as well as changing trends of Yuxi’s ecological quality. (4) Analyze the main factors affecting changes in Yuxi’s ecological quality.

2 Materials and methods

2.1 Overview of the study region
The study region is located in Yuxi, central Yunnan, spanning 23°30'-25°N latitude and 101°33'-103°E longitude. Yuxi covers a total area of 15,000 km² and is located on the western edge of the Central Yunnan Plateau, in the transitional zone between the Ailao Mountains and the Hengduan Mountains, as shown in Fig. 1. The topography of Yuxi is marked by a diverse and complex terrain, with elevations ranging from 1500 meters to 3144 meters. Three plateau lakes—Fuxian Lake, Xingyun Lake, and Qilu Lake—are found within its borders. The climate is characterized by humid and mild conditions, exhibiting a yearly mean temperature variation of 15.4°C to 24.2°C and a yearly precipitation range of 787.8mm to 1000mm. The region has a unique seasonal climate pattern, encompassing both the arid season (November to April) and the annual wet season (May to October). Additionally, the area boasts rich forest resources, with a forest coverage rate of approximately 64.06%. The growth season of vegetation in Yuxi's forest typically commences and concludes during the rainy season, coinciding with increased precipitation and higher temperatures.

![Fig. 1. Geographical location and elevation map of the study region.](image)

### 2.2 Data and processing

#### 2.2.1 Landsat Series Imagery

This study reconstructed ecological indicator time series and calculated RSEI using Landsat series data (30m resolution) collected by the Google Earth Engine (GEE). Satellite path/row 129-043 in the study region, Table. 1 provides detailed data information. The CFMASK algorithm is used to reduce interfering elements such as shadows and clouds in satellite imagery to ensure data quality and accuracy.
Table. 1


<table>
<thead>
<tr>
<th>Sensor</th>
<th>Time</th>
<th>Quantity</th>
<th>GEE datasets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Landsat 5 TM</td>
<td>2000-2011</td>
<td>640</td>
<td>LANDSAT/LT05/C02/T1_L2</td>
</tr>
<tr>
<td>Landsat 7 ETM+</td>
<td>2012</td>
<td>110</td>
<td>LANDSAT/LE07/C02/T1_L2</td>
</tr>
<tr>
<td>Landsat 8 OLI</td>
<td>2013-2020</td>
<td>657</td>
<td>LANDSAT/LC08/C02/T1_L2</td>
</tr>
</tbody>
</table>

2.2.2 Ancillary data

This study used various ancillary data sets, including digital elevation models (DEM), temperature records, precipitation data, and land use type datasets (Table 2). DEM data are employed in creating an overview of the study region and determining terrain parameters such as slope, aspect, and elevation. Land use type data were used to calculate the proportion of forest area, crops and impervious land in Yuxi from 2000 to 2020, and the factors affecting the ecological quality of Yuxi were jointly analyzed using temperature and precipitation data. All spatial data in this study were projected using the WGS_1984_UTM_Zone_48N coordinate system and resampled to a consistent resolution of 30 m.

Table. 2

Summary of Auxiliary Datasets Used in the Study.

<table>
<thead>
<tr>
<th>Data</th>
<th>Products and source</th>
<th>Resolution</th>
<th>Pre-processing</th>
</tr>
</thead>
<tbody>
<tr>
<td>DEM</td>
<td>ALOS DSM: Global 30m v3.2</td>
<td>30m</td>
<td>Calculate elevation, slope, and aspect</td>
</tr>
<tr>
<td></td>
<td>(<a href="https://www.eorc.jaxa.jp">https://www.eorc.jaxa.jp</a>) China 1km resolution</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temperature data</td>
<td>monthly average temperature dataset $^{40}$</td>
<td>1000m</td>
<td>Resample to 30m and filter for the specified year</td>
</tr>
<tr>
<td>Precipitation data</td>
<td>monthly average precipitation dataset $^{41}$</td>
<td>1000m</td>
<td>Resample to 30m and filter for the specified year</td>
</tr>
<tr>
<td>Land use type data</td>
<td>CLCD dataset $^{41}$</td>
<td>30m</td>
<td>Calculate the proportion of land classes</td>
</tr>
</tbody>
</table>

2.3 Method

This study structured its workflow (Fig. 2) to meet the research aims, which essentially consist of three key parts: (1) Construction of the RSEI model and reconstruction of ecological indicator reconstruction: We utilized HANTS fitting to reconstruct the time series of four ecological indices, then built the RSEI model using the fitting indices. (2) Ecological quality assessment in the study region: This study assessed the ecological quality of Yuxi using the reconstructed RSEI model. (3) Analysis of the spatiotemporal evolution of the Yuxi’s ecological quality and discussion of the elements that influence it: This study used the reconstructed RSEI model to look at how ecological quality changes over time and space in the study area and find out what factors are most important in causing these changes.
RSEI is a comprehensive evaluation model that combines four ecological parameters: greenness, wetness, dryness, and heat, and is intimately associated with ecological quality. There are four ecological parameters that can represent RSEI:

\[
RSEI = f(\text{Greenness}, \text{Wetness}, \text{Dryness}, \text{Heat})
\]  

where \text{Greenness}, \text{Wetness}, \text{Dryness}, and \text{Heat} include the normalized difference vegetation index (NDVI), tasseled cap transform wetness index (TCW), surface reflected temperature (LST), and normalized difference bare soil index (NDBSI).

Calculated from Eq. (2)-Eq. (5):

\[
NDVI = \frac{\rho_{\text{nir}} - \rho_{\text{red}}}{\rho_{\text{nir}} + \rho_{\text{red}}}
\]  
\[
TCW = c_1 \rho_{\text{blue}} + c_2 \rho_{\text{green}} + c_3 \rho_{\text{red}} + c_4 \rho_{\text{nir}} + c_5 \rho_{\text{swir1}} + c_6 \rho_{\text{swir2}}
\]  
\[
NDBSI = \frac{SI + IBI}{2}
\]  
\[
LST = \gamma \left[ e^{-1}(\psi_1 L_{\text{sensor}} + \psi_2) + \psi_3 \right] + \delta
\]

where \(\rho_{\text{blue}}, \rho_{\text{green}}, \rho_{\text{red}}, \rho_{\text{nir}}, \rho_{\text{swir1}}, \rho_{\text{swir2}}\) represent the B1, B2, B3, B4, B5,
and B7 bands of the TM and ETM+ sensors, as well as the B2, B3, B4, B5, B6, and B7 bands of the OLI sensor. In Eq. (3), $c_i$ represents the tassel cap variation coefficient of TCW indices. The coefficients of Landsat TM, ETM+ and OLI are different. Eq. (4) calculated from soil index (SI) and building index (BI). Eq. (5) represents a surface temperature inversion algorithm based on the single-channel method. In this algorithm, $\gamma$ and $\delta$ are two parameters determined by the Planck function, $L_{sensor}$ representing radiance values. $\varepsilon$ represents surface emissivity, while $\psi_1$, $\psi_2$, and $\psi_3$ are three correction coefficients related to atmospheric water vapor content ($w$).

2.3.2 **Fitting indices based on HANTS**

Harmonic Analysis of Time Series (HANTS) is a time series analysis method that combines both smoothing and filtering techniques. This method effectively leverages the spatiotemporal characteristics of remote sensing images, bridging the spatial distribution patterns with temporal variations. The core of this algorithm lies in Fourier transformation and linear regression using the method of least squares, where it decomposes time spectral data into multiple sine and cosine curves, including various frequencies. Afterwards, a subset of these curves that accurately represents the features of the time series is overlaid to accomplish the reconstruction of time series data. The fundamental equations for HANTS data reconstruction are presented in Eq. (6) and Eq. (7):

$$\hat{y}(t_j) = a_0 + \sum_{i=1}^{nf} [a_i \cos(2\pi f_i) + b_i \sin(2\pi f_i t)]$$

$$y(t_j) = \hat{y}(t_j) + \varepsilon(t_j)$$

where $y$ denotes the original $NDVI$, $TCW$, $NDBSI$, or $LST$ data; $\hat{y}$ denotes the rebuilt data; and $\varepsilon$ denotes the error sequence. $t_j$ denotes the time at which the observation $y$ is made, where $j$ ranges from 1 to $N$, and $N$ represents the maximum length of the observation sequence. Where $nf$ signifies the count of periodic components in the time series, while $n$ stands for the quantity of harmonics. The coefficient $a_0$ corresponds to the zero-frequency coefficient, which represents the average of the entire time series. $a_i$ and $b_i$ are the trigonometric components of frequency $f_i$. In this study, the HANTS is implemented through GEE.

2.3.3 **RSEI model construction**

As RSEI measures the health of land ecosystems, the information about bodies of water within the designated research region needs to be hidden. The modified normalized water index (MNDWI) (Xu, 2005) of Eq. (8) is utilized to find and mask the water body information in the study region. Also, because the scale difference between the four ecological indicator components must be removed before principal component analysis can be done, this study normalized and standardized several indices. The masked water and standardized indicators were then subjected to principal
component analysis (PCA). If the contribution rate of the first principal component (PC1) is much greater than that of the other principal components, it means that PC1 contains most of the information, and then PC1 is selected as the initial $RSEI_0$. $RSEI_0$ can be expressed in Eq. (9). If the eigenvectors of the NDVI and TCW indices have negative signs, restoration must be performed by subtracting PC1 from 1.

$$MNDWI = \frac{(\rho_{Green} - \rho_{swir1})}{(\rho_{Green} + \rho_{swir1})}$$  \hspace{1cm} (8)

$$RSEI_0 = \begin{cases} PC1[[NDVI,TCW,NDBSI,LST]], & NDVI > 0 \text{ and } TCW > 0 \\ 1 - PC1[[NDVI,TCW,NDBSI,LST]], & NDVI < 0 \text{ and } TCW < 0 \end{cases}$$  \hspace{1cm} (9)

Where $\rho_{Green}$ and $\rho_{swir1}$ represent the B2 and B7 bands of the TM and ETM+ sensors, as well as the B3 and B7 bands of the OLI sensor. In Eq (9), $RSEI_0$ represents initial RSEI, and $NDVI$, $TCW$, $NDBSI$, and $LST$ represent eigenvectors of PC1.

To ensure the comparability and measurability of RSEI, Eq. (11) was adopted to normalize $RSEI_0$ to be in the range of 0 to 1 in this study. The closer the RSEI value is to 1, the better the ecological quality is. Drawing on previous research, the RSEI results were divided into five levels: poor (0–0.2), fair (0.2–0.4), moderate (0.4–0.6), good (0.6–0.8), and excellent (0.8–1) (Geng et al., 2022; Xu et al., 2019).

$$RSEI_{normalized} = \frac{RSEI_0 - RSEI_{omin}}{RSEI_{omax} - RSEI_{omin}}$$  \hspace{1cm} (10)

Where $RSEI_{normalized}$ represents normalized RSEI, $RSEI_0$ represents initial RSEI, $RSEI_{omin}$ represents the minimum value of initial RSEI, and $RSEI_{omax}$ represents the maximum value of initial RSEI.

2.3.4 Accuracy evaluation

Ecological indices evaluation: To assess the accuracy of the HANTS algorithm in reconstructing ecological indicator time series, we adjusted the parameter frequencies, $f_i$, within the HANTS algorithm. We then compared the year-by-year correlation coefficients (R), root mean square error (RMSE) and standard deviation (STD) among the reconstructed indicators and the original indicators under different parameter settings. The calculation formulas are presented in Eq. (12)-(14). Based on these evaluation indices, a Taylor diagram was constructed to determine the optimal parameters and validate the accuracy of the reconstructed indicators.

$$R = \frac{\sum_{i=1}^{N}[y^o_i - \bar{y}^o][y^o_i - \bar{y}^o]}{\sqrt{\sum_{i=1}^{N}[y^o_i - \bar{y}^o][y^o_i - \bar{y}^o]}}$$  \hspace{1cm} (11)

$$STD = \sqrt{\frac{1}{N} \sum_{i=1}^{N}(y^o_i - \bar{y}^o)^2}$$  \hspace{1cm} (12)
\[ RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (y_i^o - \bar{y}_i^D)^2} \]  

(13)

where \( y_i^o \) represents the original indicators, \( y_i^D \) represents the reconstructed indicators, and \( i = 1,2,3\ldots N \), with \( N \) as the time series length.

RSEI evaluation: To ensure the comprehensiveness of information in the reconstructed RSEI model and the precision of measurable assessment, 10,500 sample points were randomly selected during the period from 2,000 to 2020, including 500 points. The variables were projected into a three-dimensional space to examine spatial dependence and determine if there is a spatial correlation and its degree between the independent variable RSEI and the four ecological indices, which are dependent variables. Additionally, to compare the differences between the RSEI models constructed based on the reconstructed indicators and those constructed based on the original indicators, the disparities were calculated between the reconstructed RSEI models and the RSEI models constructed from the original indicators for the years 2000, 2012, and 2020.

2.3.5 Ecological quality trend analysis

First, the Theil-Sen evaluation trend value (Sen) of the RSEI sequence is found. Next, the Mann-Kendall test (M-K) is used to see how important the trend is, looking at the change in ecological quality.

Sen is a non-parametric statistical method for viewing trends. The calculation is shown in Eq. (14). This method works very well for analyzing trends and doesn't care about measurement mistakes or outliers. Because of this, it is often used to look for trends in long-time-series information. 53.

\[ \beta = \text{mean}\left(\frac{x_j - x_i}{j - i}\right), \quad \forall j > i \]  

(14)

where \( \beta \) represents the value of Sen, \( x_j \) and \( x_i \) represent time series data points, where a value of \( \beta \) exceeding 0 suggests an increasing trend in the time series, while \( \beta \) below 0 signifies a declining trend.

M-K test is a method for analyzing time series with unstable central tendencies and is ideal for examining time series data that exhibit consistent and persistent upward or downward trends. Since it is a non-parametric test, data do not need to adhere to the normal distribution assumption, but should exhibit serial correlation 54,55. The calculations are provided in Eq. (16)-(19):
where $S$ represents the statistic, which is obtained by summing $sgn(x)$, $VAR(S)$ represents the variance, $n$ denotes the quantity of data entries, $Z_{MK}$ is the statistic for the Mann-Kendall test, and $q_k$ represents the count of identical data groups. The Sen slope estimation and the Mann-Kendall test in this study were conducted using ArcGIS Pro software.

2.3.6 Spatial correlation analysis

Spatial autocorrelation analysis is a statistical technique employed to assess the distribution properties and interdependencies of spatial data. Analyzing spatial autocorrelation in ecological quality helps unveil its distribution patterns and interconnections across the study area. This study uses global Moran index and local Moran index to explore the spatial correlation of RSEI ratings. This study investigates the spatial correlation of RSEI ratings by utilizing both global and local spatial autocorrelation analyses. The Global Moran’s $I$ in Eq. (19) represents global spatial autocorrelation, which quantifies the degree of correlation between values of neighboring spatial units. A Moran’s $I$ close to 1 indicates a strong presence of spatial autocorrelation. The Local Moran’s $I$ in Eq. (20) stands for local indicators of spatial association (LISA), depicting connections between ecological quality across various grid units within the study region. LISA cluster map defines five forms of local spatial clustering, including high-high (H-H), low-low (L-L), low-high (L-H), high-low (H-L), and non-significance.

$$
Global Moran’s I = \frac{m \times \sum_{i=1}^{m} \sum_{j=1}^{m} W_{ij} (D_i - \bar{D})(D_j - \bar{D})}{\sum_{i=1}^{m} \sum_{j=1}^{m} W_{ij} (D_i - \bar{D})^2}
$$

(19)

$$
Local Moran’s I = \frac{(D_i - \bar{D}) \times \sum_{j=1}^{m} W_{ij} (D_j - \bar{D})}{\sum_{i=1}^{m} (D_i - \bar{D})^2}
$$

(20)

In Eq (19) and (20), $m$ denotes the total of elements; $D_i$ signifies the ecological quality value located on $I$; $\bar{D}$ stands for the mean ecological quality value across all elements in the study region, and $W_{ij}$ for the spatial weight.
2.3.7 Analysis of driving factors of ecological quality

Geographic detectors are a group of statistical approaches that identify geographical differentiation and reveal the mechanisms that drive it. They include four detectors: factor detectors, interaction detectors, danger area detectors, and ecological detectors. This study chose eight factors related to ecological quality as independent variables: average annual temperature (X1), average annual precipitation (X2), slope (X3), slope aspect (X4), altitude (X5), forest area proportion (X6), construction land area proportion (X7), and cultivated land area proportion (X8), and used the geographical detector's factor detector and interaction detector to detect the impact of natural and economic factors on ecological quality.

Factor detector: Detect factor X's contribution to explaining spatial variation in variable Y. Use q-values to measure:

\[ q = 1 - \frac{\sum_{h=1}^{L} N_h \sigma_h^2}{N \sigma^2} = 1 - \frac{SSW}{SST} \]  

(21)

where \( h = 1 \ldots n \), \( L \) is the strata of variable Y or factor variance. \( SSW \) and \( SST \) represent variances within a layer and the total variance of the entire area, respectively. The value of q is from 0 to 1.

Interaction test: Determine if factors X1 and X2 enhance or diminish the ability to explain the dependent variable Y when they interact. The method of evaluation is to first compute the q-values of components X1 and X2 for Y, then compute their interaction for comparison. The association between two factors can be categorized as shown in Table. 3.
Table 3
Geographic detector interaction factor level judgment.

<table>
<thead>
<tr>
<th>Judgments based</th>
<th>Interaction type</th>
</tr>
</thead>
<tbody>
<tr>
<td>(q(X_1 \cap X_2) &lt; \min(q(X_1), q(X_2)))</td>
<td>nonlinear weakening</td>
</tr>
<tr>
<td>(\min(q(X_1), q(X_2)) &lt; q(X_1 \cap X_2) &lt; \max(q(X_1), q(X_2)))</td>
<td>Single factor nonlinear weakening</td>
</tr>
<tr>
<td>(q(X_1 \cap X_2) &gt; \max(q(X_1), q(X_2)))</td>
<td>two-factor enhancement</td>
</tr>
<tr>
<td>(q(X_1 \cap X_2) = q(X_1) + q(X_2))</td>
<td>independent</td>
</tr>
<tr>
<td>(q(X_1 \cap X_2) &gt; q(X_1) + q(X_2))</td>
<td>nonlinear enhancement</td>
</tr>
</tbody>
</table>

*\(\min(q(X_1), q(X_2))\): Take the minimum value among \(q(X_1)\), \(q(X_2)\), \(\max(q(X_1), q(X_2))\): Take the minimum value among \(q(X_1)\), \(q(X_2)\), \(q(X_1)+q(X_2)\): the sum of the two, \(q(X_1 \cap X_2)\): the interaction of the two.

3 Results

3.1 RSEI of the different vegetation seasons

In order to analyze the RSEI difference between the plant growth period and the non-plant growth period, Yuxi’s vegetation growth period data (May-October 2020) and data outside the vegetation growth period (November 2020-April 2011) were selected to establish RSEI for each period. The RSEI results of three types of land objects, namely forest, cropland and impervious land, were compared (Fig. 3). There are changes in the forest greenness information in the satellite photos between the growth period and the non-growth period. The greenness in the growing period is significantly greater than that during the non-growth phase; however, compared with the growing season, the RSEI rating of the non-growing season forest is higher. There is large-volume crop information in the farmland images in both periods, but the greenness in the growing season is significantly higher than that in the non-growing season. However, the RSEI rating of non-growing season farmland is concentrated as good, and the RSEI rating of non-growing season is moderate. From the perspective of impervious images, the urban information in the two periods remains consistent, but from the RSEI results, the score during the non-growth phase is notably higher than that in the growth phase.
Fig. 3 Comparison of RSEI of various species in the vegetation growing season and non-growing season.

3.2 Ecological indices fitted by HANTS

The HANTS frequency parameter $f_i$ is adjusted between 1 and 10, and ten models for each ecological indices are constructed to form a Taylor diagram (Fig. 4). The HANTS performs best when the parameter $f_i$ is set to 1, as the reconstructed values of the four ecological indicators are closest to the observed values (Ref). TCW and NDBSI rebuilt models performed best, with correlation coefficients R above 0.9 and RMSE and STD less than 0.01. Furthermore, the reconstructed NDVI demonstrated a high correlation, with R larger than 0.7 and both RMSE and STD less than 0.05. LST has an R of 0.4, and the RMSE and STD are around 1.5.
Fig. 4. Reconstruction - Accuracy comparison of original ecological indices (a-d respectively correspond to the accuracy of the reconstructed NDVI, TCW, NDBSI, LST indices and each original indicator under different HANTS parameter (f1-f10) settings).

To carry out a more comprehensive analysis on the usability of reconstructed indices, we proceeded to produce both reconstructed and raw time series data for a total of 519 ecological indices images spanning the period from May to October, covering the years 2000 to 2020 (Fig. 5). The results of HANTS effectively eliminate noise, identify and resolve outliers in the data set, and provide reasonable filling of missing data. The indices sequence that has been reconstructed has a higher level of smoothness compared to the original sequence, thereby enabling a more distinct representation of the dynamic patterns exhibited by each of the four ecological indices. Among them, the reconstructed LST sequence eliminates the influence of extreme temperatures in the original sequence, making the sequence more average. This is also the reason why the reconstructed LST sequence is less accurate than the original LST sequence. The observed pattern of change in the reconstructed ecological indices sequence aligns with that of the original ecological index sequence, suggesting that the reconstructed sequence holds potential as a viable foundation for the development of the RSEI model.
Fig. 5. Original-reconstructed ecological indices time series comparison chart. (a)-(d) represent NDVI, WET, NDBSI, and LST indices time series respectively.

3.3 RSEI model based on reconstruction indices

The annual $RSEI_0$ was obtained by principal component analysis of the median composite images from May to October in the reconstructed index series (Table.4). The contribution rates showed that the lowest value was in 2010 (66.32%), while the highest was in 2002 (87.24%). The average contribution rate was 78.52%, indicating that each first principal component contained the most ecological index information. However, the feature vectors of each index showed that the vector directions of NDVI and TCW, which had positive effects on the ecological quality, were negative, which was inconsistent with the objective facts. Therefore, they needed to be restored by 1-PC1. In addition, the feature vector values showed that NDBSI had the most significant proportion among the four indices, while LST had the most minor proportion. WET remained relatively stable, and NDVI fluctuated. This indicated that dryness was the dominant factor affecting the ecological quality of Yuxi. The annual mean values of RSEI showed that the ecological quality of Yuxi was moderate from 2000 to 2020, with a mean value of 0.5413. By combining the feature vector values, it could be observed that RSEI values were low in years with small NDVI values. RSEI increased in years with large NDVI values, indicating that greenness was also one of the critical factors affecting ecological quality.
The 10,500 sample points that were chosen were assigned the four ecological indices and the RSEI values for each year. These points were then projected onto a 3D space (Fig. 6) in order to analyze the link between each of the four ecological indices and RSEI. The ecological quality level is represented by the height of the scatter points in the picture, where good ecological quality is shown at the top and bad ecological quality is shown at the bottom. The objective laws are in line with the findings that greenness and wetness have a positive impact on ecological quality, while dryness and temperature have a negative effect. Fig. 6 (a) shows a positive correlation between NDVI and TCW and RSEI, while Fig. 6 (b) shows a negative correlation between NDBSI and LST and RSEI. The scatter points also exhibit good aggregation, suggesting that the ecological indicator components can be taken into account by the reconstructed RSEI model, which can then be utilized as a foundation for assessing ecological quality.

### Table 4

<table>
<thead>
<tr>
<th>Year</th>
<th>NDVI</th>
<th>TCW</th>
<th>NDBSI</th>
<th>LST</th>
<th>Contribution rate%</th>
<th>RSEI mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
<td>-0.4277</td>
<td>-0.5913</td>
<td>0.6711</td>
<td>0.1298</td>
<td>84.72%</td>
<td>0.5257</td>
</tr>
<tr>
<td>2001</td>
<td>-0.4414</td>
<td>-0.5270</td>
<td>0.6161</td>
<td>0.3843</td>
<td>70.03%</td>
<td>0.5411</td>
</tr>
<tr>
<td>2002</td>
<td>-0.4532</td>
<td>-0.5772</td>
<td>0.6577</td>
<td>0.1695</td>
<td>87.24%</td>
<td>0.5637</td>
</tr>
<tr>
<td>2003</td>
<td>-0.4157</td>
<td>-0.5719</td>
<td>0.6565</td>
<td>0.2627</td>
<td>86.22%</td>
<td>0.5529</td>
</tr>
<tr>
<td>2004</td>
<td>-0.4320</td>
<td>-0.5117</td>
<td>0.5853</td>
<td>0.4569</td>
<td>75.37%</td>
<td>0.5500</td>
</tr>
<tr>
<td>2005</td>
<td>-0.3678</td>
<td>-0.5431</td>
<td>0.6195</td>
<td>0.4310</td>
<td>70.11%</td>
<td>0.5434</td>
</tr>
<tr>
<td>2006</td>
<td>-0.3050</td>
<td>-0.5426</td>
<td>0.6175</td>
<td>0.4808</td>
<td>75.65%</td>
<td>0.5239</td>
</tr>
<tr>
<td>2007</td>
<td>-0.3415</td>
<td>-0.5381</td>
<td>0.6038</td>
<td>0.4786</td>
<td>74.99%</td>
<td>0.5410</td>
</tr>
<tr>
<td>2008</td>
<td>-0.3186</td>
<td>-0.5482</td>
<td>0.6025</td>
<td>0.4846</td>
<td>75.11%</td>
<td>0.5144</td>
</tr>
<tr>
<td>2009</td>
<td>-0.2966</td>
<td>-0.5525</td>
<td>0.6164</td>
<td>0.4761</td>
<td>75.35%</td>
<td>0.5221</td>
</tr>
<tr>
<td>2010</td>
<td>-0.2435</td>
<td>-0.6097</td>
<td>0.6664</td>
<td>0.3531</td>
<td>66.32%</td>
<td>0.5136</td>
</tr>
<tr>
<td>2011</td>
<td>-0.2355</td>
<td>-0.5768</td>
<td>0.6330</td>
<td>0.4592</td>
<td>73.46%</td>
<td>0.5081</td>
</tr>
<tr>
<td>2012</td>
<td>-0.5017</td>
<td>-0.5634</td>
<td>0.6128</td>
<td>0.2349</td>
<td>86.4%</td>
<td>0.5505</td>
</tr>
<tr>
<td>2013</td>
<td>-0.4633</td>
<td>-0.5285</td>
<td>0.5712</td>
<td>0.4237</td>
<td>79.47%</td>
<td>0.5263</td>
</tr>
<tr>
<td>2014</td>
<td>-0.4611</td>
<td>-0.5193</td>
<td>0.5621</td>
<td>0.4489</td>
<td>82.79%</td>
<td>0.5424</td>
</tr>
<tr>
<td>2015</td>
<td>-0.4674</td>
<td>-0.5394</td>
<td>0.5723</td>
<td>0.4036</td>
<td>78.91%</td>
<td>0.5582</td>
</tr>
<tr>
<td>2016</td>
<td>-0.4510</td>
<td>-0.5456</td>
<td>0.5778</td>
<td>0.4060</td>
<td>78.08%</td>
<td>0.5826</td>
</tr>
<tr>
<td>2017</td>
<td>-0.4636</td>
<td>-0.5278</td>
<td>0.5644</td>
<td>0.4332</td>
<td>82.9%</td>
<td>0.5555</td>
</tr>
<tr>
<td>2018</td>
<td>-0.4447</td>
<td>-0.5352</td>
<td>0.5669</td>
<td>0.4408</td>
<td>81.12%</td>
<td>0.5397</td>
</tr>
<tr>
<td>2019</td>
<td>-0.4496</td>
<td>-0.5351</td>
<td>0.5691</td>
<td>0.4329</td>
<td>81.2%</td>
<td>0.5468</td>
</tr>
<tr>
<td>2020</td>
<td>-0.4660</td>
<td>-0.5275</td>
<td>0.5626</td>
<td>0.4334</td>
<td>83.52%</td>
<td>0.5671</td>
</tr>
<tr>
<td>Mean</td>
<td>-0.4022</td>
<td>-0.5481</td>
<td>0.6050</td>
<td>0.3916</td>
<td>78.52%</td>
<td>0.5413</td>
</tr>
</tbody>
</table>
indicates the relationship between NDVI, WET indices and RSEI. (b) indicates the relationship between NDBSI, LST indices and RSEI.

The central area of Yuxi was chosen as the observation area, and three time periods (representing TM, ETM+, and OLI sensors, respectively) were compared. Fig. 7 shows the gap between the original RSEI and the rebuilt RSEI. The results reveal that the initial model was influenced by the noise and cloud removal technique, resulting in missing and muddled RSEI information. The RSEI created by the reconstructed indicator based on HANTS filtering, on the other hand, filled the missing data area and removed the noise impact in the ecological indicator, thus increasing the quality of the RSEI image and more accurately portraying the ecological quality. According to the absolute difference analysis, the difference between the recreated and original models is primarily dispersed between -0.15 and 0.15. This suggests that the RSEI model, which is generated using ecological indicators reconstructed by the HANTS algorithm, is capable of effectively representing the information contained in the original RSEI model when applied to Landsat data.

![Fig. 7. Calculate the absolute difference between the reconstructed RSEI model and the original RSEI model, where (a), (d), and (g) represent the original RSEI for the years 2000, 2012, and 2020, respectively, (b), (e), (h) represent the reconstructed RSEI index.](image)

3.4 The spatiotemporal pattern of ecological quality in Yuxi

3.4.1 The temporal variations in ecological quality in Yuxi

The RSEI change of Yuxi in the past 20 years is shown in Fig. 8. The RSEI fluctuates up and down, with a slight upward trend overall. In order to more objectively
and comprehensively evaluate the spatiotemporal pattern of ecological quality in Yuxi over the last two decades (2000-2020), the turning point year of ecological quality change, i.e., the inflection point of RSEI, was first determined. The segmented linear regression model was used to construct two regression results (Fig. 9) by the cost function, respectively. The $R^2$ of the four segmented regression functions of the two regression models were similar, but the cost function $J$ result of Fig. 9 (a) was smaller than that of Fig. 9 (b). Therefore, we chose the result of Fig. 9 (a) as the basis for the trend of ecological quality change in Yuxi. The turning point years of ecological quality change in Yuxi were 2003, 2010 and 2016 respectively. The ecological quality of Yuxi increased from 2000 to 2003, decreased from 2003 to 2010 and reached the lowest point, reached the highest point in 2016, and then began to decline. From the annual average RSEI value, the ecological quality of Yuxi from 2000 to 2020 was at a moderate level, with a mean RSEI value of 0.5413.

![Fig. 8. Changes in the average RSEI value of Yuxi each year from 2000 to 2020.](image)
3.4.2 The spatial variations in ecological quality in Yuxi

The RSEI series of Yuxi is classified into four phases based on the inflection points of RSEI changes, and the RSEI's geographical distribution in Yuxi at the inflection years is depicted in Fig. 10. Geographically, in each transition year, the western portion of Yuxi has much greater overall ecological quality than the eastern region, and the mountainous regions in the west and central regions primarily have good and excellent grades. Lower ecological quality exists in the western valley, the middle and eastern plains, and the lands surrounding the lake, with rating levels ranging from moderate to poor.
Sen trend analysis and the M-K test were performed on Yuxi’s RSEI in four stages to better understand the ecological change characteristics (Fig. 11). The findings showed that the RSEI of Yuxi exhibited a clear increase trend from 2000 to 2003 (a decrease trend was only detected around lakes in the northeastern region). From 2003 to 2010, the RSEI in the lakes' surrounding areas remained steady, with only a few locations continuing to fall. However, the RSEI fell dramatically in the central region, particularly in the plains west of the "Three Lakes" and in the districts surrounding the southern valley. The RSEI in Yuxi climbed dramatically between 2010 and 2016, but the RSEI in the central plains decreased significantly. The ecological condition of the entire region began to drop dramatically between 2016 and 2020, however some places around the "Three Lakes" showed major improvements. The four-stage trend chart reveals that RSEI variations in Yuxi have a cyclical rising and downward tendency, which is consistent with the piecewise linear regression model results (Fig. 8).
In order to confirm the spatial correlation of RSEI in Yuxi, spatial autocorrelation analysis was conducted on RSEI in the transition years using 1 Km×1 Km fishnet point sampling. The vast majority of points are spread in the first and third quadrants, as seen in Fig. 12, and the mean value of Moran’s I at five time points is 0.44, indicating that the RSEI in research area has a robust positive spatial connection, and these values exhibit a clustered pattern rather than a random one. This implies that the regions with higher ecological quality have similar high ecological quality as their neighboring regions, or the regions with lower ecological quality have similar low ecological quality as their neighboring regions, and there is a certain association among them.

The findings of a local spatial autocorrelation study on RSEI (Fig. 13) using LISA indicate that the majority of the unimportant areas at five time periods are located in
the central and western valleys, as well as in hilly regions. The L-L cluster area is primarily dispersed throughout the plains and valleys, whereas the H-H cluster area is primarily found in the western and central mountains. This suggests that Yuxi's ecological quality varies significantly across space, with high-quality ecological areas geographically isolated from low-quality ecological areas.

Fig. 13. LISA analysis results, (a)-(e) represent 2000, 2003, 2010, 2016, 2020 respectively.

3.4.3 The spatiotemporal trends in ecological environment quality in Yuxi

Yuxi's overall ecological quality has been gradually improving over the last 20 years, remaining at a moderate level. In particular, there has been an increasing trend and a declining trend in the change of ecological quality. The areas with ecological quality ratings of poor, fair, and moderate are primarily concentrated in the relatively flat plains and areas near water sources, according to the results in the spatial arrangement of ecological quality, whereas the areas with ecological quality ratings of good and excellent are concentrated in the steep mountains. Fig. 14 displays the general RSEI trend changes. The areas with sharp drops in RSEI are concentrated in Xinping County, Yuanjiang County valley area, southeast of Yimen County, central Eshan County area, and near the "Three Lakes." These areas are also relatively gentle positions or plains in large and medium undulating mountains, surrounded by mountains with large undulations. Furthermore, RSEI indicates a very strong increasing tendency in regions with substantial topographical undulations and a considerable distance from bodies of water. This suggests that both human activity and natural geographical factors have an impact on Yuxi's ecological quality. While the plains and valleys' ecological quality is more under pressure, the mountains and water sources contribute significantly
Fig. 14. Sen + M-K analysis of RSEI in Yuxi from 2000 to 2020.

3.5 Geographic detector results

3.5.1 Analysis of RSEI Driver Factor Detection Results

Table.5 shows that the driving variables of different eras have varying influences on Yuxi’s RSEI. Forest proportion > impervious land proportion > slope ranked first among the driving factor q values from 2000 to 2003; similarly, forest proportion > impervious land proportion > altitude ranked first among the q values from 2010 to 2020; and forest proportion > impervious land proportion > precipitation ranked first among the driving factor q values from 2016 to 2020. In general, the primary factors influencing variations in RSEI are height, slope, precipitation, and the percentage of impervious land and forest.
Table 5
Geodetector single factor detection.

<table>
<thead>
<tr>
<th>Driving factors</th>
<th>Temperature</th>
<th>Precipitation</th>
<th>Slope</th>
<th>Aspect</th>
<th>Altitude</th>
<th>Forest ratio</th>
<th>Cropland ratio</th>
<th>Impervious ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
<td>0.03*</td>
<td>0.06*</td>
<td>0.07*</td>
<td>0.04*</td>
<td>0.03*</td>
<td>0.29*</td>
<td>0.01*</td>
<td>0.13*</td>
</tr>
<tr>
<td>2003</td>
<td>0.03*</td>
<td>0.07*</td>
<td>0.09*</td>
<td>0.03*</td>
<td>0.05*</td>
<td>0.35*</td>
<td>0.01*</td>
<td>0.19*</td>
</tr>
<tr>
<td>q 2010</td>
<td>0.05*</td>
<td>0.06*</td>
<td>0.06*</td>
<td>0.02*</td>
<td>0.09*</td>
<td>0.34*</td>
<td>0.01*</td>
<td>0.20*</td>
</tr>
<tr>
<td>2016</td>
<td>0.06*</td>
<td>0.11*</td>
<td>0.08*</td>
<td>0.01*</td>
<td>0.11*</td>
<td>0.38*</td>
<td>0.03*</td>
<td>0.21*</td>
</tr>
<tr>
<td>2020</td>
<td>0.08*</td>
<td>0.14*</td>
<td>0.08*</td>
<td>0.01*</td>
<td>0.13*</td>
<td>0.34*</td>
<td>0.02*</td>
<td>0.19*</td>
</tr>
</tbody>
</table>

(*) means $P<0.05$ for this item.

3.5.2 Analysis of RSEI Driver Factor Interaction Detection Results

The results of the interaction are all nonlinear enhancements or double-factor enhancements, based on the findings from the interactive detection results of the RSEI driving factors in Yuxi from 2000 to 2020 (Fig. 15). This suggests that the interaction of two factors is primarily responsible for the alterations in the ecological quality of Yuxi. The interaction of eight factors has a higher explanatory power than the individual effects when compared to a single factor. From 2000 to 2020, the interaction of forest cover with other seven factors had the highest $q$ value, which indicates that among the years when ecological quality showed a turning point, the interaction of forest cover with other factors had the greatest impact on the change of RSEI.

Fig. 15. Geographic driver factor interaction detection results, (a)-(e) represent 2000, 2003, 2010, 2016, and 2020 respectively.

3.5.3 Changes in land use types in Yuxi

The land use types in Yuxi City in 2000 and 2020 were mapped, and a transition matrix was used to examine the changes in each land use type in order to explore the impacts of changes in land use types on ecological quality (Fig. 16). Yuxi's land use types have changed dramatically during the previous 20 years. The total proportion of...
The proportion of forest has risen dramatically, whereas cropland and grassland have declined. These land use type changes are primarily influenced by economic development, population expansion, policy adjustments, natural disasters, and other variables, all of which affect Yuxi's ecology differently. Among them, the expansion of impervious has the greatest negative impact on the ecological quality, leading to the depletion of land assets, biodiversity decline, aggravation of soil and water loss, the deterioration of environmental pollution and other problems; while the increase of forest and shrub has a greater positive impact on the ecological quality, it is conducive to improving vegetation coverage, enhancing the stability of ecosystems, reducing greenhouse gas emissions, improving climate conditions and other aspects.

Fig. 16. (a), (b) are the land use maps of Yuxi in 2000 and 2020 respectively, and (c) is the land use transfer matrix of Yuxi from 2000 to 2020.

4 Discussion

4.1 The vegetation growing season is a optimization time window for evaluating ecological quality by using RSEI

Yuxi is located on the central plateau of Yunnan Province, China. The area has no obvious temperature difference in four seasons but has a significant distinction between the dry and wet seasons. The vegetation is divided into vegetation growing seasons and vegetation non-growing season in dry and wet season, respectively. We need to consider the seasonal variation of vegetation in the RSEI model results. The greenness information of the forest is different in the growing season and non-growing season. The growing season is significantly higher than the non-growing season. However, the RSEI performance is higher in the non-growing season than in the growing season. The stronger the inconsistent greenness information, the higher the
RSEI rating. The main crops in Yuxi are three crops a year, and most of the time in a year there are crops covered. The RSEI rating of farmland in the non-growing season is concentrated as good, but the crops will cause damage to the surface vegetation, affect the soil biocycle and ecological balance, and threaten the quality and stability of the atmospheric environment, leading to the decline of the ecological quality. Therefore, farmland should not have a higher ecological quality, and the moderate rating reflected by the non-vegetation growing season RSEI is in line with the objective law.

Urbanization has a complex and multi-dimensional impact on ecological quality. While there appears to be little difference between the two time periods in the impervious image, the RSEI data clearly favor the non-growing season grade. In summary, the RSEI rating of the non-vegetation growing season is generally higher than that of the growing season, but specifically, this higher situation is obviously not in line with the objective facts. The reason for this phenomenon may be that in the non-vegetation growing season, the greenness information intensity of the forest decreases, while the farmland is affected by the image of crops and urban evergreen plants, and the greenness information changes little, resulting in overestimating ecological quality. Therefore, in the process of constructing the RSEI model, we need to consider the impact of season on RSEI, avoid overestimating or underestimating the ecological quality, and ensure the accuracy of the RSEI inversion results.

4.2 **HANTS is capable of optimizing the filling results for Landsat missing data**

Noises such as clouds, fog, atmospheric scattering, and ground obstructions cause the loss of continuity and integrity of image data in some areas during a specific period, seriously affecting the credibility of the RSEI ecological quality evaluation. In previous studies, the construction of RSEI model was usually based on the best quality image data screened out in a year, or using interpolation method to optimize the data, but this would ignore phase changes in RSEI evaluation accuracy. HANTS is a technique for reconstructing time series data using Fourier analysis. It can remove noise and outliers based on the periodicity and frequency characteristics of the data, while maintaining the original characteristics and trends of the data, and accurately reconstruct the data at spatiotemporal frequencies. Reconstruction not only improves data quality but also preserves information about changes in indicators in the time series. HANTS filtering method is better than SG and WS in overall performance of constructing RSEI based on MODIS data. This study further verifies the adaptability of HANTS in constructing RSEI from Landsat images. It shows that HANTS also has good adaptability and reliability in smaller scale and higher resolution data. It shows that this method can not only fill in missing data, but also generate smoother time series curves in RSEI construction at different scales and resolutions, and can accurately convey the information of the original RSEI model, thereby effectively assessing ecological quality.

4.3 **Evaluation and analysis of ecological quality distribution in Yuxi**
Yuxi's ecological quality varies and is regionally correlated. High ecological quality can be found in the hilly and mountainous regions to the west and south (H-H clusters). These are national ecological functional areas with good natural conditions and a good cover of vegetation that are protected by the Ecological Protect Red Line (EPRL). Low ecological quality is found in the plain areas surrounding the central metropolitan areas (L-L clusters). Due to the accelerated urbanization process and high land use intensity, the green coverage rate is low. L-L clusters develop outward from major counties as a result of population growth and urbanization. The average RSEI of Yuxi has not changed much from 2000 to 2020, and regarding the ecological quality as a whole, it is stable. However, the ecological quality of county areas has declined, while mountainous areas' ecological quality has increased, showing an obvious center-edge pattern. The results of this study are somewhat consistent with the studies of Geng and Lin, that is the ecological quality of mountains and forests is better than that of plain basins and constructed areas. However, the difference in ecological quality may be related to geographical location and urban development stage. Yuxi is located in the central part of Yunnan Province and is a medium-sized interior plateau. In terms of urban size and geographical location, it is very different from Fuzhou and Haitan Island. Therefore, future research should conduct comparative studies on cities of different sizes and types to explore different influencing factors and mechanisms. In addition, future research should also consider the dynamic changes in ecological quality, analyze the changing trends and driving forces of ecological quality at different time scales, and examine the relationship between ecological quality and social and economic development. Finally, future research should also propose ecological protection and governance strategies for different regions and issues, providing scientific advice for Yuxi's sustainable development.

4.4 Land type changes dominate the ecological quality of Yuxi.

Land type is the main factor affecting ecological quality, and changes in land type are the dominant factor causing ecological quality (Table. 4). In the past two decades, there has been an obvious trend of urban expansion in Yuxi. There is a mutual conversion relationship between woodland, farmland, grassland, and shrubs. The percentage of forestland has substantially risen, while the percentage of cropland and grassland has decreased (Fig. 15). These changes in land use types have had different degrees of impact on the ecological quality of Yuxi. The expansion of impervious has the greatest negative impact on ecological quality, while the increase in forests and shrubs has a more favorable effect on the natural environment. The reason for this effect may be that the expansion of man-made surfaces leads to an increase in dryness information, while the increase in forest land increases greenness information. The dryness information represents the extent to which the land is in drought, and the greenness information indicates the level of vegetation coverage of the land. The changes in Yuxi's ecological quality during the course of the last twenty years are closely related to the urbanization process and ecological protection policies. Just
entering the 21st century, Yuxi's urbanization level was not high and its economic
development was slow, but it did not damage the natural environment too much. The
Chinese government has begun to attach importance to the construction of ecological
civilization and green development, and has implemented a series of ecological
projects, which has resulted in a significant upward trend in the overall ecological
quality of Yuxi. Since 2003, China's urbanization level has increased rapidly, including
Yuxi. The construction land area has increased by 50%, resulting in a rapid decline in
ecological quality. This is mainly because urban growth has taken over a sizable portion
of cropland and forest, causing land degradation and loss of biodiversity, while also
increasing pollutant emissions and resource consumption. Since 2010, the effects of the
policies and ecological projects implemented by the Chinese government such as
returning farmland to forests, watershed management, and the establishment of national
nature reserves have begun to show. The ecological quality of most of the mountains
and lakes in Yuxi has gradually improved, with significant improvements. However,
the shortcoming is that due to the rapid economic development, the ecological quality
of major towns and some river valleys has not been improved. Ecological strategic
planning and efficient management need to be further strengthened to achieve the
coordination and unity of promotion of economic and social progress alongside the
preservation of ecological and environmental well-being.

4.5 Uncertainty analysis

There remain certain areas for potential enhancement in our study. Although the
HANTS has proven to be effective in creating composite indices and is widely used for
time series reconstruction, our work did not conduct a comparative analysis of other
time series filtering techniques. Therefore, we are unable to quantify the optimal
filtering approach. Comparative analysis of filtering algorithms has the potential to
enhance the reliability of time series outcomes. Furthermore, the selection of the surface
temperature inversion algorithm may have an impact on the generation of the LST
series. In future research endeavors, it is advisable to explore various inversion
techniques in order to assess and contrast their respective performance disparities in the
estimation of LST. In this work, the data utilized for constructing the time series was
obtained from Landsat 5/7/8 sensors. However, it is important to acknowledge that the
presence of spectral disparities among these sensors can not be entirely eliminated. In
order to enhance data consistency, forthcoming research may opt to prioritize data
obtained from a singular sensor, hence mitigating potential uncertainties that may arise
due to spectrum disparities. This study presents significant findings on the assessment
of the ecological quality of Yuxi. However, future research should focus on enhancing
the time series construction method, improving data consistency, and enhancing the
accuracy and reliability of research outcomes. These proposed enhancements will
contribute to a more comprehensive comprehension of the dynamic patterns in
ecological quality.
5 Conclusions

Leveraging the GEE platform and HANTS filtering, this study optimizes the Landsat series data of Yuxi from 2000 to 2020; then based on four ecological indices in the vegetation growing season, this study constructed the RSEI long time series to assess the ecological quality and analyze the spatiotemporal pattern, and explored the influencing factors of its changes. This study draws the following main conclusions:

1. The data of the vegetation growing season is a priority of accurately evaluating the ecological quality by using RSEI. (2) HANTS filtering performs well in missing data filling of the Landsat series remote sensing images. It not only effectively conducts the missing data filling of the remote sensing imagery, but also significantly improves the data quality of the ecological index series. By comparing with the original data, the HANTS-filtering data has the advantages of smoother filling missing data with the time phase information in the RSEI long time series data. (3) According to the evaluation results of this study, the overall RSEI evaluation level of Yuxi is moderate. The ecological quality of Yuxi shows an obvious center-edge pattern. In the view of the spatial distribution, the ecological quality of the western region is significantly better than that of the eastern region, and the mountainous areas is also significantly better than that of the plains and valleys. (4) In the past 20 years, the RSEI of Yuxi has shown a fluctuation of rising and falling, with a slight overall upward trend. The ecological quality of the plains and valleys continued to decline, while the mountainous areas improved. The main factor affecting the changes of the ecological quality of Yuxi is the transformation of land use types, especially concerning about deforestation and urbanization.

Data availability

The data sets used in the current study are available from the corresponding author on reasonable request.

Reference


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Ethics declarations

Competing interests

The authors declare that they have no competing interests.