



# Research on remote sensing ecological environmental assessment method optimized by regional scale

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## Abstract

As the global ecosystem has been severely disturbed by an increasing number of human activities at different scales, remote sensing technology, as an effective quantitative measure of environmental quality, has been widely used. The remote sensing ecological index (RSEI) is one of the most popular and comprehensive ecological quality assessment indices based on the remote sensing data. However, the RSEI model exhibits that the ecological environment under natural conditions is not limited by the spatial scales. In addition, the model has major shortcomings in index selection and eigenvector, which greatly limit the application of RSEI. In this paper, the RSEI model is improved and a remote sensing ecological index optimized by the regional scale (RO-RSEI) is proposed. The result of the study, conducted in Shuangyang District, Changchun City, Jilin Province, shows that the RO-RSEI model has regional ecological significance after the introduction of the scale theory of landscape ecology; the index is preferred to solve problems like the RSEI model applied mechanization and baseless index selection. Meanwhile, due to the optimization of the eigenvector contribution of the optimal index, it solves the problems like non-unique model calculation result caused by principal component analysis or even antipodal calculation result. Compared with the RSEI model, the monitoring result of RO-RSEI model can better reflect the regional ecological changes. The improved model offers the possibility of monitoring ecological environment quality with remote sensing big data and provides a scientific basis for future scholars' batch computing.

**Keywords** Regional scale · Remote sensing ecological index · Eco-environment · Eigenvector · Principal

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## 1. Introduction

Due to the impact of human activities on the global carbon cycle, the floor space on the natural landscape has increased significantly and ecosystems at various scales have been disturbed. As a result, the world's ecosystem is facing unprecedented challenges (McDonnell and MacGregor-Fors 2016). Human-induced ecological disturbances vary in range, duration, and intensity of disturbance. Therefore, it is necessary to seek a fast, effective, and accurate ecological monitoring method. Remote sensing techniques can be used to simulate the real situation on the surface and obtain electromagnetic signals of surface features without touching the object. Because of its efficient, real-time, and dynamic monitoring features, remote sensing technology is widely applied in the ecological environmental assessment (Xu et al. 2019).

Since 2000, remote sensing technology has been used for ecosystem assessment in China (Ouyang et al. 2014). Similar studies have been conducted in Europe, America, and other parts of the world (De Araujo Barbosa et al. 2015; Willis

2015). Remote sensing was used combined with landscape ecological index (Maleky and Razavi 2013), land adaptability parameters (Marull et al. 2006), land cover type (Jaafari et al. 2016), land parcel environmental composition (Dizdaroglu and Yigitcanlar 2012), water quality health status (Michael 2000), and other parameters to construct an ecological assessment model. These methods of monitoring the ecological environment have gradually become popular in the Americas, Europe, Australia, and other regions. It has been widely used on a large scale such as in the world or throughout countries.

The use of remote sensing technology in combination with other data to assess the ecological environment is difficult in terms of data fusion and data collection. How to quickly assess the ecological environment based entirely on remote sensing images has become a hot topic. With the development of remote sensing technology, the spatial and temporal resolutions of remote sensing images have improved, so some scholars have tried to estimate the ecological environment quality based entirely on remote sensing images (e.g., normalized differential vegetation index (NDVI)) (Schell 1973; Ivits et al. 2011; Alcaraz-Segura et al. 2017). However, most models tend to be used for ecological topics, and such models can hardly reflect adequately the strengths and weaknesses of the ecological environment. To solve this problem, Xu (2013a, b) has analyzed the principal components with physical quantities, such as greenness (NDVI) (Samuel et al. 2002), humidity (WET) (Crist 1985), heatness (land surface temperature (LST)) (Chander et al. 2009), dryness (normalized difference built-up and soil index (NDBSI)) (Zha et al. 2003), and the urban remote sensing ecological index model (RSEI), built from the first principal component to be widely applied (Qiao et al. 2020; Liu et al. 2020a, b; Wang et al. 2019a, b; Zhu 2017). The proposal of RSEI has greatly shortened the time of ecological environment quality monitoring. The model has the advantages of fast calculation speed, fewer auxiliary parameters required, and better result reliability, and has been widely used. The RSEI provides a new method for ecological environment quality assessment based entirely on remote sensing data.

With the widespread application of RSEI, some scholars have questioned the possibility of monitoring the ecosystem with different regular indices under the influence of compound environment, such as climate, location, precipitation, and human activities. After considering the applicability of the RSEI model in the research area, Wang et al. (2020) monitored the ecosystem in the arid desert area with salinity and land degradation rather than dryness index. Wang (2020) monitored the ecosystem in the alpine region with total primary productivity, leaf area index, and vegetation coverage rather than normalized differential vegetation index and dryness. However, there is no quantitative basis for the forced substitution of indices. As a result, the application of the RSEI model is more arbitrary and difficult to apply uniformly.

In addition to model applicability and exponential suitability, Song et al. (2019) and Pan (2020) believed that a lot of details may be missed if the first principal component is regarded only as the ecological assessment index in the RSEI model. They obtained the contribution values of the indices after principal component analysis as the weighted value to conduct the linear combination and to obtain the better results. However, for the direction of contribution of different principal components, not all parameters output with the principal component analysis method are unique, which means that the feasibility of using the second, third, and fourth principal components to characterize ecological quality needs further study.

Shi et al. (2018) believed that some unknown information obtained with the principal component analysis method could affect accuracy of the ecological monitoring results. Thus, they proposed a remote sensing ecological distance index (RSEDI). However, a certain prior knowledge is needed in this model, and the ecological significance of the developed model is not obvious and scientific.

The above changes are only the preliminary revisions of the RSEI model and some of the model's mechanistic flaws have not really been eliminated. Li et al. (2020a, b) tried to solve a major problem in the application of the RSEI model through the theoretical derivation and practice: the model calculation results are subject to stochastic effects due to changes in the direction of the eigenvectors. This attempt is of great significance in that it makes automate dynamic monitoring of RSEI possible. The model is established based on the assumption that the correct results can only be obtained when the eigenvector contributions of NDVI, WET, NDBSI, and LST are in the same direction. Unfortunately, this assumption is not statistically significant.

Zhu et al. (2020a, b) found no ecological effect in the ecological quality calculated by the RSEI model with the whole study area as a window, so they optimized the RSEI model again with a sliding window. The introduction of regional-scale ideas in the field of landscape ecology provides complete ecological significance for the RSEI model. This work has important implication in the field of ecological remote sensing quality monitoring. Unfortunately, they obtained the mean value of the contribution rate of four indices calculated in all windows as the weighted value to conduct the linear combination and to monitor the ecological quality. The result is that the ecological implication is ignored if the results calculated in the sliding window with ecological effects are obtained by the entire image and linear combination.

Based on the previous studies and taking into account the specificity of the research field, this paper presents the basis for index selection in a quantitative form by selecting the best index from a number of indices. We found that there is a high degree of consistency in the preferred indices within the same research area and over the same period of time. Thus, we only need to preferentially select indices in any given year to obtain

the best index for the research area rather than putting forward multiple indices year by year. The selected indices are completely consistent in the eigenvector direction. The eigenvectors calculated by four fixed indices are largely different with different research areas and image acquisition time. Thus, it is necessary to optimize the indices. In this paper, the preferred indices are calculated as the principal component in the sliding window at the regional scale in ecology to solve the problem that the eigenvector direction of all indices in the ecological monitoring model is not unique. As a result, regardless of the order of the input bands, the results always conform to previous knowledge, overcoming the shortcomings of the RSEI model which lacks ecological significance, providing a more stable, scientific, and accurate model for regional ecological evaluation, and providing technical support for scientific design-making and sustainable development.

## Study area and data sources

In this paper, Shuangyang District of Changchun City is chosen as the test site. Changchun is located in northeastern China, in the hinterland of the Northeast Plain in the mid-latitude North Temperate Zone of the Northern Hemisphere. It is located at latitude 43°05′~45°15′ N and longitude 124°18′~127°05′ E and is also a famous old industrial base in China. It covers an area of 625.5 km<sup>2</sup> and its urbanization rate reaches 59%. The data used in the experiment were obtained from Landsat8 OLI/TIRS and Landsat5 TM of the United States Geological Survey (USGS). The images were separately acquired in September 2000, on September 22, 2010, and October 3, 2020, respectively, with no cloud cover over the research area. The spatial resolution of the remote sensing image is 30 m, the geographic coordinate system is GCS\_WGS\_1984, and the spatial projection coordinate system is WGS\_1984\_UTM\_Zone\_51N. The coverage of an image is 185×185km<sup>2</sup>. The location map of Shuangyang district is shown in Fig. 1.

The image was preprocessed with ENVI5.5, including geometric correction, radiometric calibration, and atmospheric correction. In order to avoid influence of water in the research area on the principal component analysis method, the water is removed from the images with the modified normalized difference water index (MNDWI) (Xu 2005), and the threshold was set to 0.5.

## Research methods

### Introduction to RSEI model

The ecological environment is expressed in a comprehensive way using the hydrothermal index. Xu (2013a, 2013b)

calculates the urban remote sensing ecological index (RSEI) with the NDVI, humidity amount (WET) of tasseled cap transformation, NDBSI, LST, and the principal component analysis (PCA) method (Xu 2013a, b), that is:

$$RSEI_0 = PC_1(NDVI, Wet, LST, NDBSI) \quad (1)$$

where  $PC_1$  represents the first principal component calculated with the principal component analysis method.

As the eigenvector direction calculated with the principal component analysis method is unit unique, some of the calculated results are not what the experimenter expects, or even the opposite of what the experimenter expects. In order to meet the previous knowledge, if  $RSEI_0$  does not meet the prior conditions, it needs to be normalized and flipped so that the computed results match the expected results in the space, that is:

$$RSEI_1 = \frac{RSEI_0 - RSEI_{0\_min}}{RSEI_{0\_max} - RSEI_{0\_min}} \quad (2)$$

$$RSEI = 1 - RSEI_1 \quad (3)$$

where  $RSEI_{0\_min}$  and  $RSEI_{0\_max}$  respectively refer to the minimum value and maximum value in the first principal component, where  $RSEI_0$  is the first principal component.

## 3.2 Model analysis and improvement

### 3.2.1 Model analysis

In fact, the RSEI was originally applied to the urban area in Fuzhou City in the subtropical monsoon region, and the index was selected for the research area. With the widespread application of the RSEI, the problems of the model are increasingly emerged, and could be seen mainly as follows:

- (1) Mechanization of model application. The RSEI was first proposed to be applied to the main urban area, but it is still applied for monitoring ecosystem in the arid region (Gao et al. 2020; Rukeya et al. 2020), plateau (Sun et al. 2019), and drainage basin (Wang and Wang 2019) and other ecosystems by many scholars without any changes to the model and the monitoring of ecosystems does not take into account the specificity of ecosystems and the applicability of models;
- (2) No basis for index selection. Some researchers replace the model indices without quantitative validation and establish a new ecological quality index after considering the particularity in the research area. Thus, the application of the RSEI model was subjective and random. Although the ecological assessment is conducted in the same research area at the same time, the subjective indices of the experimenter are different, and the quality



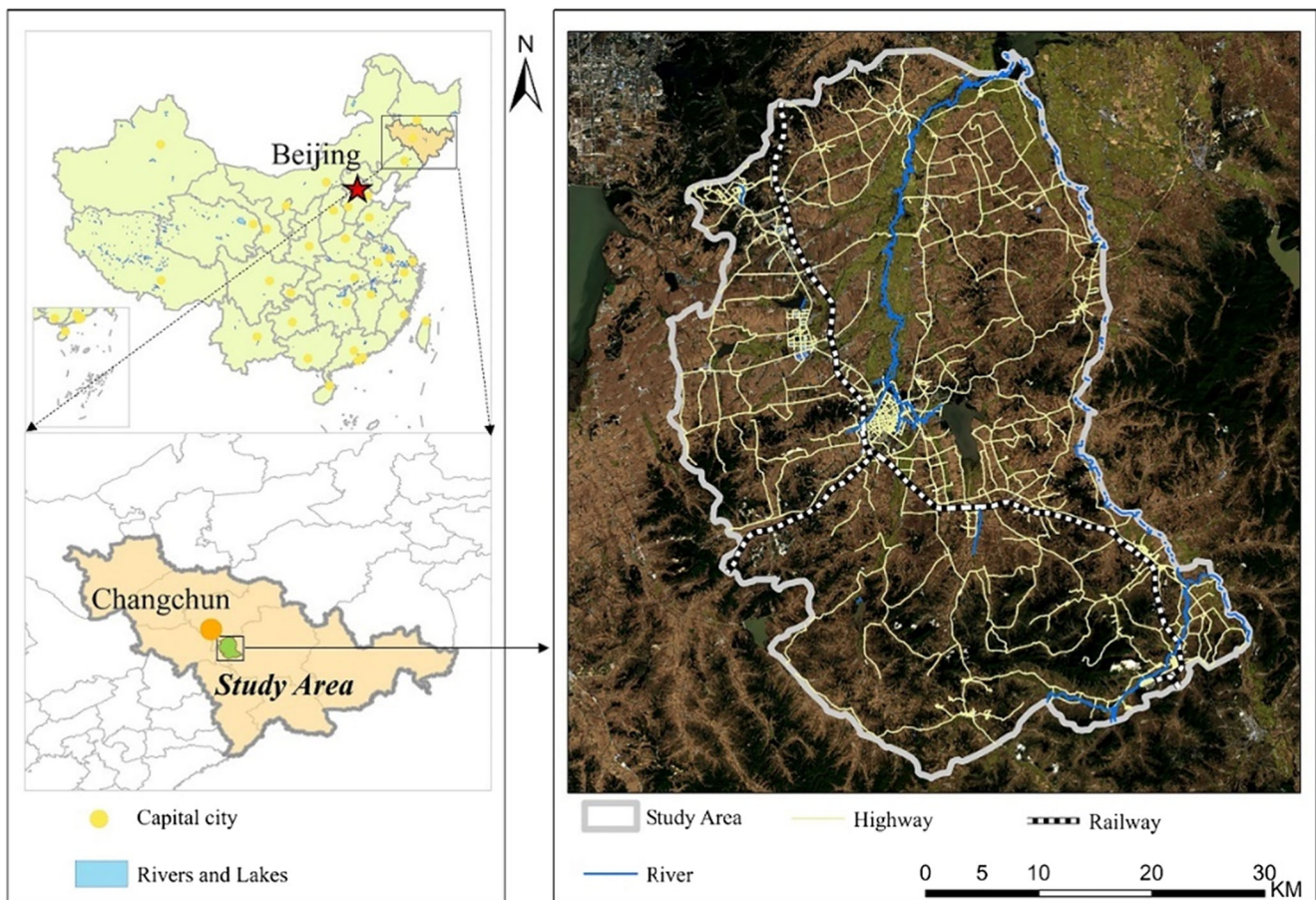


Fig. 1 Location map of Shuangyang district

monitoring results are largely different. Many of the indices are applied within a specific application, but not to a variety of study areas. For example, the NDVI is highly sensitive if the vegetation cover is 30–70%. If it is applied to the drier region or a region with higher coverage, it is poorly sensitive (Qi 2007), which hinders the application of the RSEI model;

- (3) Non-uniqueness of eigenvector direction. If RSEI is used to conduct the principal component analysis, the order of the band inputted is different and the eigenvector direction is not unique. Scholars always obtain an expected result based on the previous knowledge, and then reverse PC1 or do not make any modification if PC1 conforms to previous knowledge. However, there is no theoretical basis or scientific explanation for this;
- (4) Connections between ecosystems at regional scales are not considered. According to Wang (2010), ecological effects caused by complex ecosystem interactions will certainly change the function and structure of ecosystems at regional scales. Thus, it is necessary to monitor the ecological quality at the regional scale. According to the landscape ecology, the connections between the units and surrounding ground should be fully considered in the

ecological assessment process to avoid the influence of areas far away from the center pixel on the target area, which echoes the “diffusion theory” of physics (Wu et al. 2016). In the RSEI model, ecological quality is assessed with the entire image in the research area, ignoring the ecological effect at the regional scale. Thus, the ecological quality reflected by the RSEI is not ecologically significant and the model is mechanistically flawed.

### 3.2.2 Model improvement method

Zhang et al. (2020) found that fixed indices such as NDVI, WET, NDBSI, and LST are not effective in ecological applications under complex ecological influences, and multiple indices are preferred. Thus, the indices should be selected according to the local conditions. In the research, RSEI is used as the dependent variable and the initial value to conduct correlation analysis for nearly 20 indices, including greenness, dryness, humidity, and surface temperature. The optimal index is selected based on the  $R^2$  absolute value. The indices are selected as shown in Table 1. In Table 1,  $\rho_{blue}$ ,  $\rho_{green}$ ,  $\rho_{red}$ ,  $\rho_{nir}$ ,  $\rho_{swir1}$ , and  $\rho_{swir2}$  respectively represent the blue band, green

band, red band, near-infrared band, short-wave 1 infrared band, and short-wave 2 infrared band in remote sensing images.  $C_v$ ,  $C_s$ ,  $C_w$ , and  $C_4$  respectively represent the amount of calculations obtained by different samples of different sensors.  $T$  represents the temperature value at the sensor;  $\varepsilon$  is the surface emissivity;  $\lambda$  is the thermal infrared band;  $\rho$  is a fixed variable of  $1.438 \times 10^{-2}$  mK.

In Fig. 2, the higher the correlation between the variable and the RSEI, the closer the value is to 1. The best four parameters are UNVI, NDMI, SI, and LST. Although the long-time ecological sequence is researched, in order to obtain the optimum index for the study area, only the index for any year of the study year is chosen.

It is very interesting to note that the RSEI calculated from NDVI, WET, NDBSI, and LST does not correlate well with its four indices. This indicates that four fixed indices are not suitable for all research areas and also proves the necessity of selecting the suitable index according to the research area.

Wu (2004) found that the change in the spatial granularity and range obviously affects the ecological sensitivity monitoring by the research. Liu et al. (2020a, 2020b) found the assessment results in the RSEI model are obviously different with different spatial granularity by comparing Sentinel-2 with Landsat8. Mei et al. (2019) found that the ecological pattern may be significantly disturbed at different spatial calculation scales. Zhu et al. (2020a, 2020b) believed that the entire research area is regarded as the window for

calculation in RSEI model but the ecological significance is not considered. Thus, it cannot truly reflect the impact of the regional ecological environment.

The concept of regional scale in landscape ecology is introduced to assign the ecological implication to the RSEI model. In this research, the target pixel point is expanded to 2000m as a window according to the relevant provisions of the Technical Guidelines for Environmental Impact Assessment Ecological Impact (Chen et al. 2010), resulting in a window area of  $4000 \times 4000 \text{m}^2$  (about  $133 \times 133$  pixels). The principle of the moving window is shown in Fig. 3.

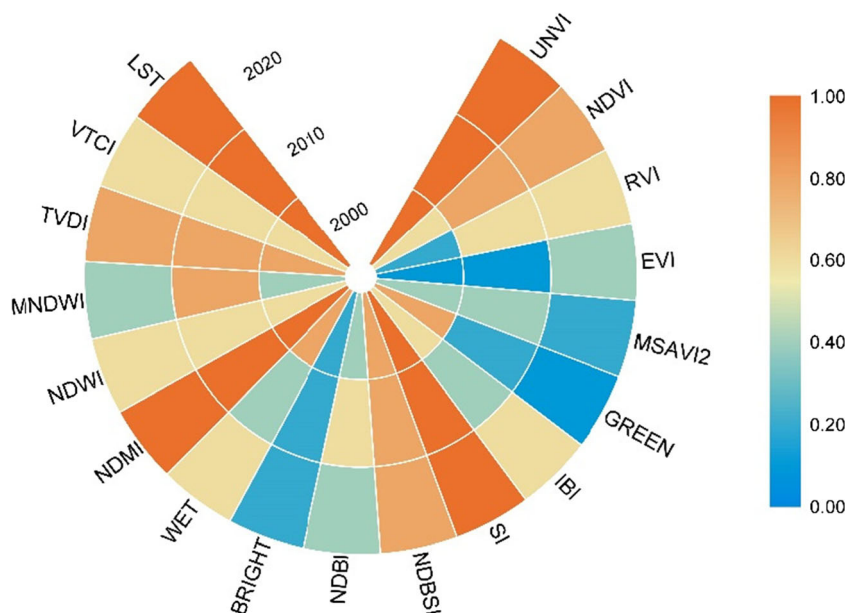
After the principal component analysis is conducted for each window, only the center pixel of the first primary component is reserved to avoid the influence of the area far away from the center pixel on the target pixel and to fully preserve ecological significance. However, this does not solve all the problems, and the arbitrariness of the feature vector direction can lead to completely opposite results of RSEI. As a result, the results calculated in the sliding window are completely out of control.

Xu attempted to use Eq. 3 to solve the problem that the results of the principal component analysis caused by the direction of the eigenvectors are exactly opposite of the expected values. However, there is no scientific basis for adopting Formula 3. It is inadvisable that the unexpected result is only operated according to the direction of subjective expectations and previous knowledge.

**Table 1** Multi-index merit list

	Index	Calculation formula	References
Greenness	NDVI	$(\rho_{nir} - \rho_{red}) / (\rho_{nir} + \rho_{red})$	Liu et al. (2020b)
	UNVI	$(C_v - aC_s - C_4) / (C_w + C_v + C_s)$	Zhang et al. (2019)
	EVI	$2.5(\rho_{nir} - \rho_{red}) / (\rho_{nir} + C_1\rho_{red} - C_2\rho_{blue} + L)$	Mao et al. (2015)
	RVI	$\rho_{nir} / \rho_{red}$	Schell et al. (1973)
	MSAVI2	$\left( 2 * (\rho_{nir} + 1) - \sqrt{(2\rho_{nir} + 1)^2 - 8(\rho_{nir} - \rho_{red})} \right) / 2$	Zhao et al. (2011)
	Green	$A_2, 1\rho_1 + A_2, 2\rho_2 + A_2, 3\rho_3 + A_2, 4\rho_4$	Shi et al. (2019)
Dryness	IBI	$\frac{(2 * \rho_{swir1} / (\rho_{swir1} + \rho_{nir}) - (\rho_{nir} / (\rho_{nir} + \rho_{red})) + \rho_{green} / (\rho_{green} + \rho_{swir1}))}{(2 * \rho_{swir1} / (\rho_{swir1} + \rho_{nir}) - (\rho_{nir} / (\rho_{nir} + \rho_{green})) + \rho_{green} / (\rho_{green} + \rho_{swir1}))}$	Liu et al. (2020b)
	SI	$((\rho_{swir1} + \rho_{red}) - (\rho_{blue} + \rho_{nir})) / ((\rho_{swir1} + \rho_{red}) + (\rho_{blue} + \rho_{nir}))$	Liu et al. (2020b)
	NDBSI	$(IBI + SI) / 2$	Liu et al. (2020b)
	NDBI	$(\rho_{swir} - \rho_{NIR}) / (\rho_{swir} + \rho_{NIR})$	Xu et al. (2018)
	Bright	$A_3, 1\rho_1 + A_3, 2\rho_2 + A_3, 3\rho_3 + A_3, 4\rho_4$	Shi et al. (2019)
Wetness	NDMI	$(\rho_{nir} - \rho_{swir}) / (\rho_{nir} + \rho_{swir})$	Chen et al. (2020)
	NDWI	$(\rho_{green} - \rho_{nir}) / (\rho_{green} + \rho_{nir})$	Wang et al. (2019a, b)
	MNDWI	$(\rho_{green} - \rho_{swir}) / (\rho_{green} + \rho_{swir})$	Wang et al. (2019a, b)
	WET	$a_1\rho_{blue} + a_2\rho_{green} + a_3\rho_{red} + a_4\rho_{nir} - a_5\rho_{swir1} - a_6\rho_{swir2}$	Liu et al. (2020b)
Heatness	TVDI	$(LST - LST_{MIN}) / (LST_{MAX} - LST_{MIN})$	Li et al. (2020a, b)
	VTCl	$(LST_{N_iMAX} - L_{N_i}) / (LST_{N_iMAX} - LST_{N_iMIN})$	Wang et al. 2017
	LST	$T / (1 + (\lambda T / \rho)) \ln \varepsilon$	Liu et al. (2020b)

**Fig. 2** The optimal ecological factor selection in different years selects the related heat map



Li et al. (2020a, 2020b) found that the non-uniqueness of the eigenvector direction leads to opposite RSEI calculation results according to the mechanism analysis and principal component analysis. In addition, as the input band order changes, the eigenvector direction changes randomly and the corresponding eigenvalue changes as well. The results are correct only when the NDVI and WET eigenvector direction is positive and the LST and NDBSI eigenvector direction is negative. If NDVI and WET eigenvector direction is positive, the result obtained is opposite of the expected result. Thus, the problem can be completely solved in terms of the model mechanism.

$$P = \begin{bmatrix} a_1 & b_1 & c_1 & d_1 \\ a_2 & b_2 & c_2 & d_2 \\ \vdots & \vdots & \vdots & \vdots \\ a_n & b_n & c_n & d_n \end{bmatrix} \tag{4}$$

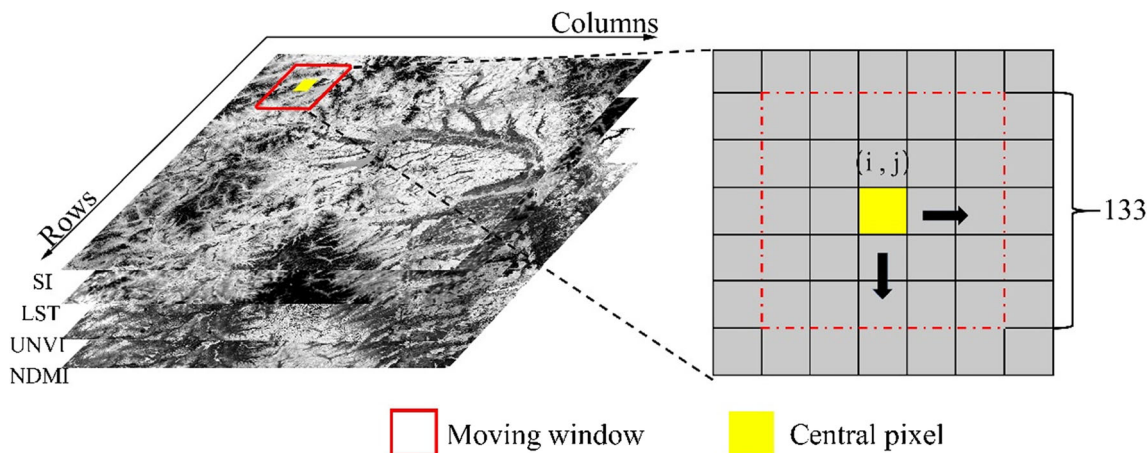
Among them, a, b, c, and d respectively refer to four inputted indices, n refers to all pixels in the entire image, and P refers to a four-dimensional matrix. In the principal component calculation, the covariance matrix of the P matrix is calculated. As the covariance matrix is the positive definite symmetric matrix, there are surely a group of non-negative eigenvalues to meet  $\lambda_1 > \lambda_2 > \dots > \lambda_n > 0$ . The corresponding unit eigenvectors are marked as:

$$\|\alpha l_j\| = |\alpha| \|(l_{1j}, l_{2j}, \dots, l_{nj})^T\|, \alpha \neq 0 \tag{5}$$

Because  $\|l_j\| = 1$ , therefore:

$$\alpha = \pm 1 \tag{6}$$

This also explains why the eigenvectors are opposite and the RSEI model result is completely opposite of the expected



**Fig. 3** Construction principle of comprehensive index of the moving window



result. However, the eigenvector directions of NDVI, WET, NDBSI, and LST are not always consistent. Li obtained the calculated result based on 10 phases of image data in this premise. However, the test was only conducted ten times and is of no statistical significance.

As most scholars have conducted the principal component analysis based on packaged software such as Arcgis, ENVI, and ERDAS, it is difficult to observe the problem in the variable in the calculation process. Therefore, we calculate the principal component of four indices and traverse the images pixel by pixel in the moving window in Python. In addition, we calculate the contributions of four indices to the first principal component in all windows and record the eigenvectors of four indices relying on Spyder development environment.

If the entire image is traversed by the moving window, this means that the principal component is calculated millions of times and millions or even tens of millions of statistical samples are generated statistically. With the visual approach, the problem can be visualized. In Fig. 4a, the eigenvector contribution directions of the first principal component of the four fixed indices in the RSEI model are reflected. We can find that NDBSI and LST are consistent in the eigenvector contribution direction, but there is a large difference between NDVI and WET eigenvector contribution. This implies that the NDVI, WET, NDBSI, and LST are not consistent in the eigenvector direction. Thus, the research conclusion of small samples made by Li et al. (2020a, 2020b) is specific to the study area. In Fig. 4b, the eigenvector contribution direction of the first principal component is reflected after index selection. In terms of spatial distribution, UNVI, NDMI, SI, and LST eigenvector contribution direction is consistent, which makes it possible to

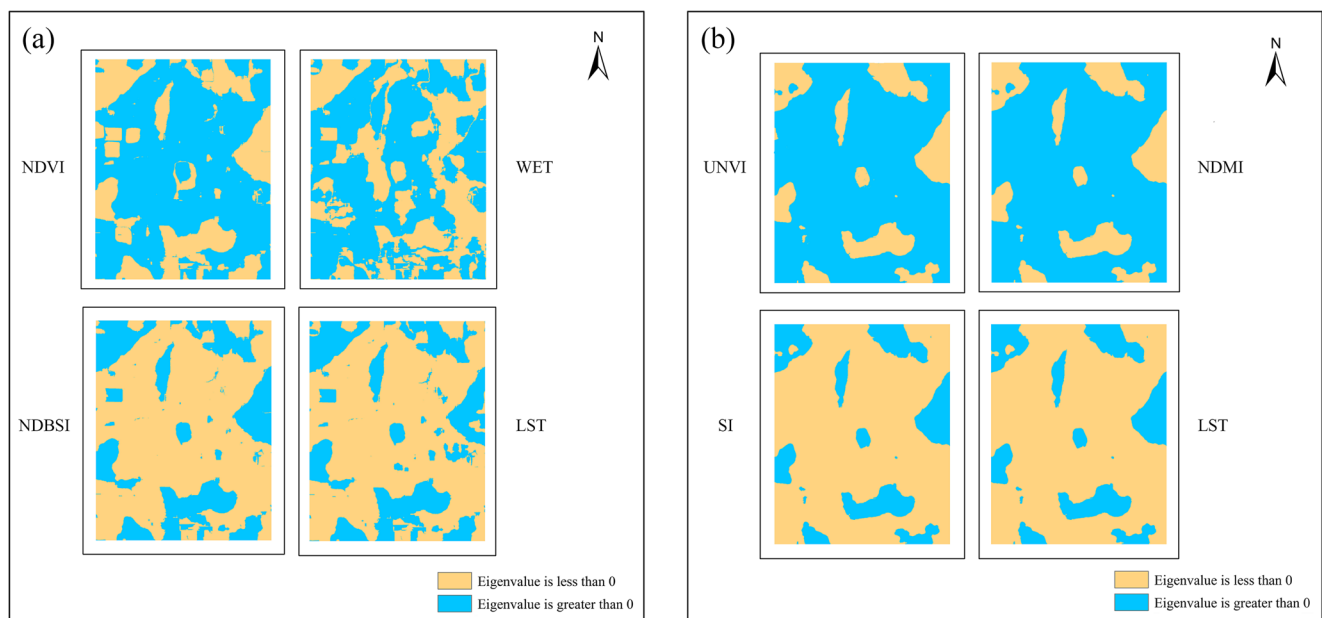
calculate the remote sensing ecological index in the moving window. If the greenness (UNVI) and humidity (NDMI) contribution values are negative and the dryness (SI) and land surface temperature (LST) contribution values are positive, the result is opposite of what would be expected. The image is processed with Formula 3.

In order to keep the principal component analysis result in all windows consistent with the numerical range and ratio in the original window, the images within the window range can be normalized, flipped, and mapped with the method in Fig. 5. Sometimes, due to the presence of some anomalies, the level of values of the points included in the mapping results is abnormal. In order to solve the problem, confidence interval is needed to eliminate these points when calculating the exponent (2 to 98% in the study).

## 4. Experimental results and analysis

### 4.1 Feature contribution weight

After the entire image is traversed with RO-RSEI, the first principal component contributed 50–97% of the results with a mean value of over 83% in all windows for the three time periods 2000, 2010, and 2020, respectively. Numerically, most of the information of four indices is concentrated on the first principal component to reflect the ecological environmental features. Table 2 shows the results of the PCA calculations for RO-RSEI and RSEI in 2020. From the table, it can be seen that there is a clear positive and negative relationship between RSEI and all ecological indices. The greenness and humidity are negative, while dryness and surface temperature



**Fig. 4** Eigenvector contribution direction. **a** RSEI four indexes and **b** index preferred selection

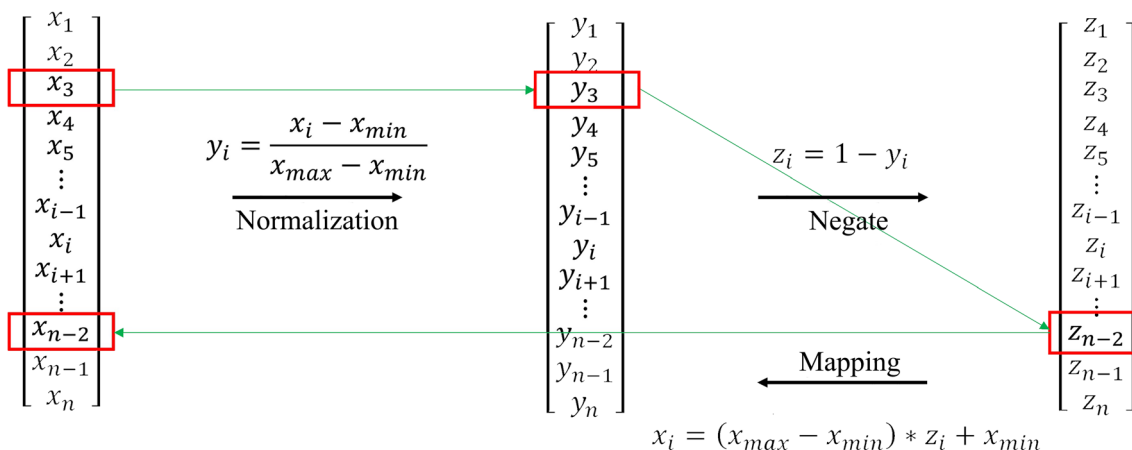


Fig. 5 Spatial numerical conversion method in the moving window

are positive, which are completely opposite of the expected result. As the absolute value of humidity is minimum and the dryness is maximum, it indicates that dryness is an important factor affecting the ecosystem in RSEI model. However, in terms of the regional optimized result in the RO-RSEI model, the contribution to each index is not consistent with the Li research result. This therefore suggests that all regions have a positive contribution in terms of greenness, humidity, dryness, and surface temperature. The absolute value of humidity in the research area is maximum and the surface temperature is minimum. The conclusion is fully opposite of RSEI result.

### 4.2 Difference of spatial and temporal distribution in RSEI and RO-RSEI

For the statistical analysis, the spatial difference of the results calculated with different calculation methods is visually presented with the visualization method. In Fig. 6, the results of the RSEI and RO-RSEI for 2020 are compared. We get a clear spatial difference between the results of the RO-RSEI method and those of RSEI by obtaining the center pixel of the first principal component in the window. We use the section line to get the specific difference.

In Fig. 7, there is a clear difference between the results of the RSI and RO-RSEI for the main urban area. The value of RO-RSEI is higher compared to the results of RSI. This is due to the fact that the eastern part of the urban area is highly covered by vegetation, which certainly has a positive impact

on the ecology in the regional ecological assessment. Although the large floor area and increased dryness can have an ecological impact, the apparent ecological quality does not break off spatially as a “cliff.” Obviously, this is the outcome of the RSEI.

In fact, the ecological impact on the target unit is considered in the entire research area in RSEI model. Then, the ecological impact on the area surrounding the target unit is not fully considered by axis rotation in the mathematical dimension reduction but the entire research area is considered (Marden 1999). The direction of PCA variance projection will therefore affect ecologically pleasing places. It can be seen that if the research area is ecologically unpleasant, the result obtained in the RSEI model is not accurate.

In fact, the RSEI model may underestimate ecological quality in the urban area and some sparse shrub area. NDVI in RSEI model is highly sensitive in the area with medium vegetation coverage. If the surface vegetation coverage is too low or high, the NDVI index is not sensitive. As a result, the RSEI model cannot correctly monitor the regional ecological environmental quality, and it is technically difficult to take targeted ecological protection measures.

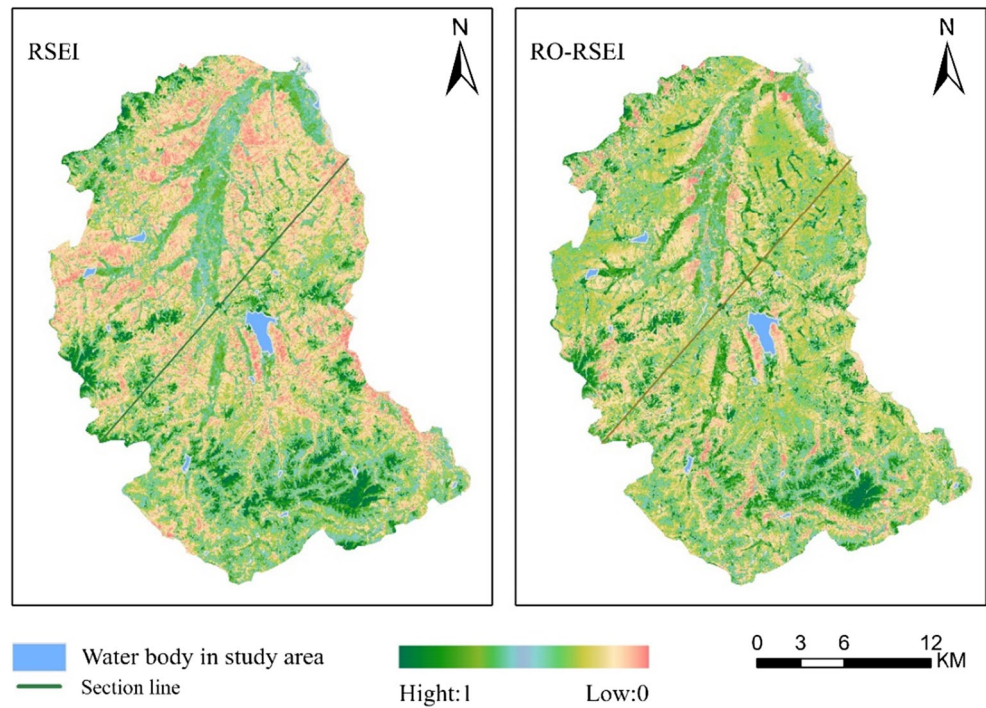
The ecological monitoring results of the RSEI are very unstable over time scales. The results show that the ecological quality is overestimated or underestimated. The aggregation of the ecological environment in space can be visualized in the violin and box plots (Fig. 8). The ecological change carries on slowly, and the ecological environment of Shuangyang

Table 2 Statistics of contribution of all indexes to the first principal index

Model		Greenness	Wetness	Dryness	Heatness
RSEI	Value	-0.52734	-0.19351	0.66653	0.49012
RO-RSEI	Value_min	-0.818034	-0.829838	-0.637461	-0.596323
	Value_max	0.8100123	0.8258523	0.6163028	0.597732
	Value_mean	0.299551	0.3613595	-0.335751	-0.171706



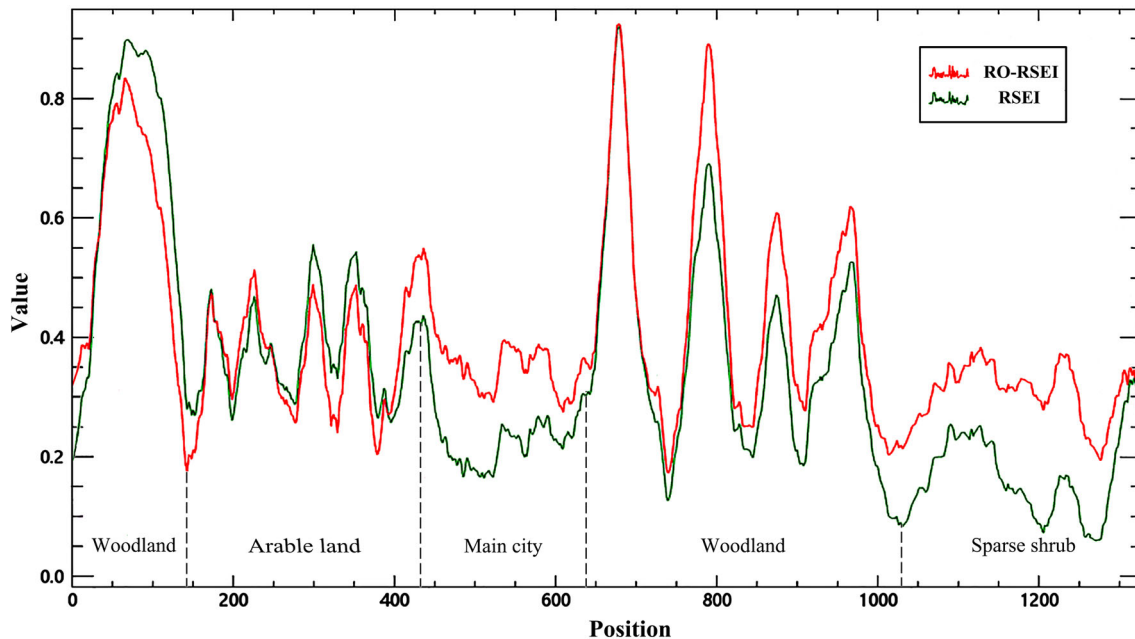
**Fig. 6** Difference of spatial distribution in RSEI and RO-RSEI in 2020



gradually changes from “diamond” to “bottle.” From the RSEI results, we can find that from 2010 to 2020, the minimum value of the ecological environment decreases from 0.26742 to 0.06377, a median decrease of 20%. Although the ecological environmental quality obviously becomes very poor, the value in RO-RSEI is only reduced by 6.541%. In fact, it can be seen from the Shuangyang District Government Report and Bai (2019) and other researchers’ studies that the built-up land area increased by 33.725 km<sup>2</sup> and the forest

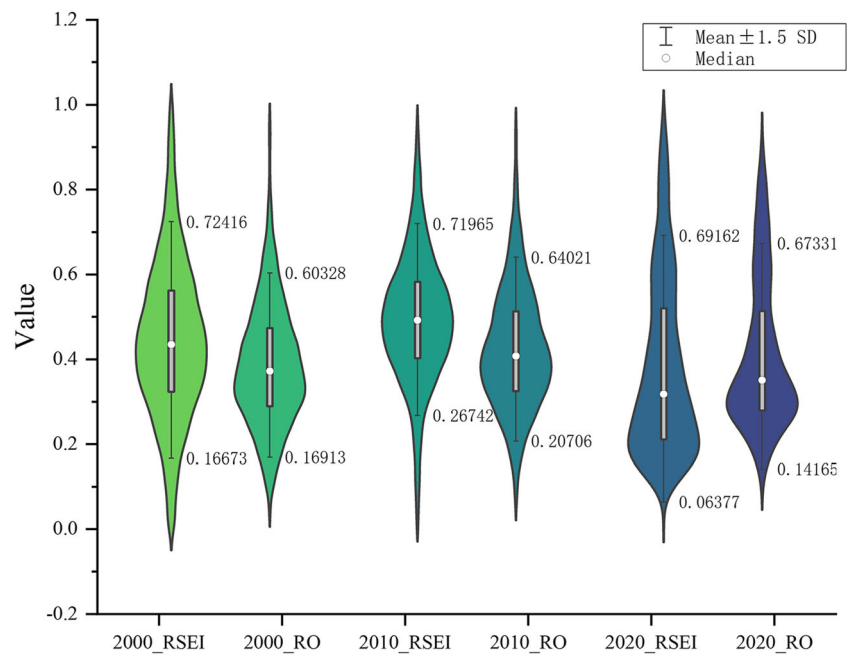
cover increased by 20 km<sup>2</sup> from 2010 to 2020. The ecological quality in Shuangyang District is deleveld but the RSEI monitored results are significantly different, contrary to the fact.

The RSEI and RO-RSEI are normalized and the values are divided into five intervals at intervals of 0.2. The larger the number, the better the quality. In order to show the spatial difference in the results between RSEI and RO-RSEI, the arithmetic of subtraction is conducted (Fig. 9). As a whole, the difference in assessment levels between the two models is



**Fig. 7** Profile changes in RSEI and RO-RSEI in 2020

**Fig. 8** Distribution of ecological quality on Phase III



almost zero in areas where the difference is too large or too small, while the difference in variation is mostly between 1 and -1. This means that there is no great difference in the assessment result levels in two models for the same target unit, and the difference is mainly presented in the ecological level transition zone. Two sample blocks with positive (Fig. 9a) and negative contribution (Fig. 9b) in the grading distribution map are respectively selected. In Fig. 9a, the urban area in Shuangyang District is surrounded by farmland and forest and the level of ecological assessment in the RSEI model is lower than that of the RO-RSEI. According to Fig. 6, it can be seen that the urban area is at the lowest level in the RSEI model. However, the assessment level in RO-RSEI model is higher than the former, which is consistent with the actual surface coverage. In Fig. 9b, the ecological contrast is conducted in the eastern part of the study area where it interacts with forest and bare ground. The value in RO-RSEI is lower than the value in RSEI because of the large area and the use of pixel ecological monitoring in the RSEI model. Thus, if the ecological value in areas of high vegetation coverage is greater, then the ecological value is less in areas of bare soil. The comprehensive influence in the regional environment is considered in the RO-RSEI model. Therefore, the center pixel value of the rectangular box in b region with high vegetation coverage is similar to the RSEI result. The values outside the bare soil extent in the RSEI model are larger than those in the RO-RSEI.

### 4.3 Comparison of RSEI and RO-RSEI with ecological indices

The ecological environment index (EI) is an evaluation index of ecological environment quality officially proposed by the

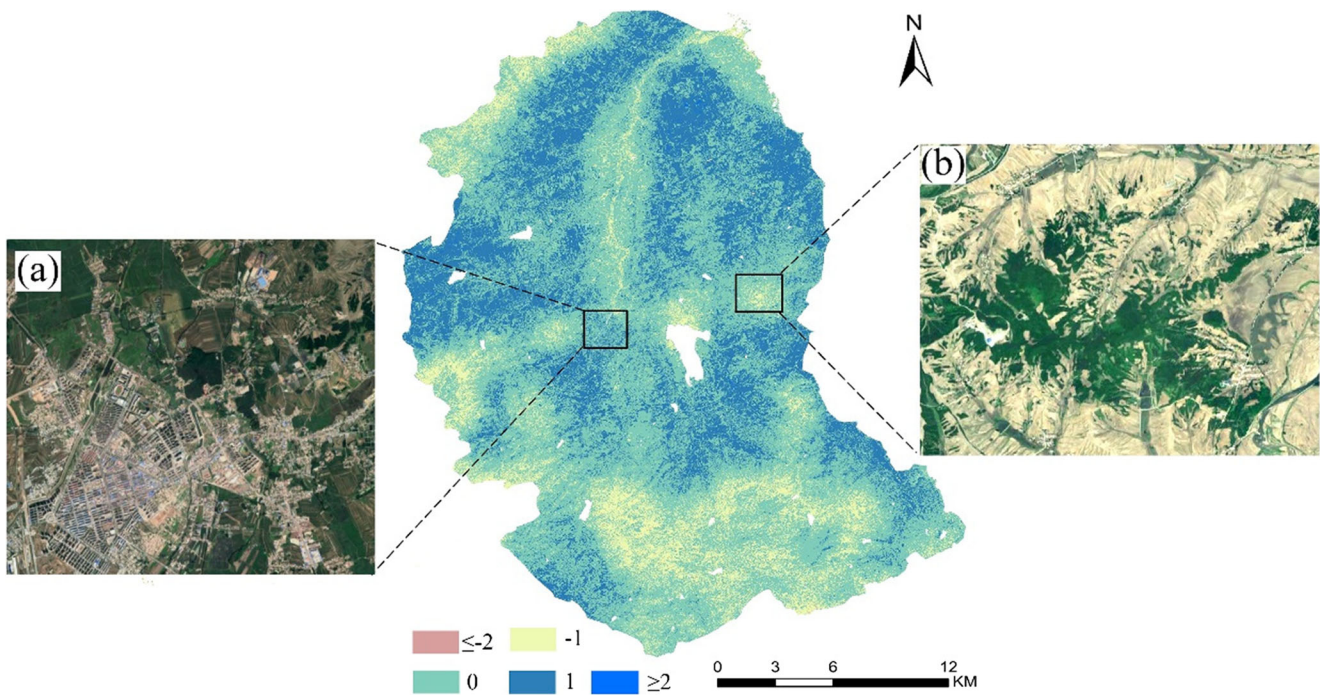
Ministry of Environmental Protection (MEP) of China. The coupled EI is a comprehensive ecological environment evaluation index constructed by coupling parameters such as biological abundance, vegetation coverage, pollution index, and water network density. The official EI index is classified as 5 levels with values ranging from 0 to 100. Therefore, EI is comparable with RSEI and RO-RSEI.

According to Table 3, it can be found that although the coupling variables of the EI model and RO-RSEI are different, the classification results of RO-RSEI are closer to the officially published EI model than those of RSEI. Numerically, the absolute maximum and minimum deviations of RO-RSEI and EI are 0.02247 and 0.00372, respectively; the absolute maximum and minimum deviations of RSEI and EI are 0.052745 and 0.0335, respectively. The average offset of RSEI is 6.41 times that of RO-RSEI.

## 5. Discussion

In recent years, the construction of composite index based on remote sensing has gradually attracted people’s attention (Healey et al. 2005; Mildrexler et al. 2009). The index construction method mainly uses experts’ grading method and linear weighted method to determine the weight (Tiner 2004; Rhee et al. 2010). In order to avoid the influence of subjective experience on the weight, the RSEI uses a covariance-based principal component analysis to determine the weight of each factor. Comparing RSEI with the EI model proposed by the MEP, the result is good (Xu 2013a, 2013b).

Aiming at the problem that the ecological significance of RSEI model is not obvious, this paper introduces the concept



**Fig. 9** RO-RSEI grade change distribution

of “regional scale” in ecology, and solves it through the moving window method (Fig. 3). However, random fluctuations in the direction of the eigenvectors of the principal component analysis method can cause disorderly changes in the final ecological monitoring results (Fig. 4). We have solved this phenomenon by selecting the optimal index method. In the end, we modify the direction of the ecological monitoring results by the spatial mapping method using the direction of the contribution of the optimized optimal parameters to the first principal component as a reference (Fig. 5) to obtain the RO-RSEI model. The result shows that:

- (1) The findings that NDVI, WET, NDBSI, and LST are identical to L1 greenness, humidity, dryness, and surface temperature are not entirely consistent, as implied by the calculation of PCA traversing pixels calculation window in the moving window in the eigenvector direction. However, there is great difference in the eigenvector

contribution direction after millions of calculations. The eigenvector results after index optimization turn out to be good, with all windows conforming to the “same direction” theory. Thus, RO-RSEI model is universally applicable;

- (2) If NDVI and WET contribution is positive and NDBSI and LST contribution is negative, the results are calculated correctly only in RSEI model. If NDVI and WET contribution is negative and NDBSI and LST contribution is positive, it is necessary to normalize and negate the results manually. As a result, a lot of work has been added. If PCA is calculated in the moving window for millions or tens of millions of times, the method will not be adopted. The PCA calculated in each window is normalized, negated, and mapped according to the index’s eigenvector direction, keeping the same proportion as the value in the original window without manual intervention;
- (3) Ecological effect is considered in the RO-RSEI model and the assessment level is continuous spatially, making the ecological monitoring results more accurate especially in urban areas and areas with sparse vegetation cover; compared with the monitoring result in RSEI model, the result in RO-RSEI model is more stable, which matches the current situation, and is more consistent with physical “diffusion model”;
- (4) RO-RSEI is calculated without manual intervention to solve the problem of batched calculation of remote sensing ecological quality monitoring. The remote sensing ecological quality needs to be calculated in batches with

**Table 3** Comparison between EI, RSEI, and RO-RSEI results

		2000	2010	2020
EI	Value	0.3927	0.4461	0.4112
	Level	2	3	3
RSEI	Value	0.445445	0.493534	0.377696
	Level	3	3	2
RO-RSEI	Value	0.386205	0.423634	0.407483
	Level	2	3	3



the remote sensing big data. The proposed model provides technical possibilities for the multi-seasonal and multi-temporal research of remote sensing ecological quality monitoring. In the calculation in RO-RSEI model, no modification is made when the direction of the eigenvectors of greenness and humidity is positive. In addition, when the dryness and surface temperature eigenvector direction is negative, it is only necessary to flip and map the results in the window.

In addition, we found that the amount of ecological information concentrated in RO-RSEI is more than 10% higher compared to that in RSI. RO-RSEI has more advantages in measuring the quality of the ecological environment in a refined manner. Comparing RO-RSEI with RSEI and EI models, RO-RSEI has better similarity with the official EI index. Taking into account the rationality of the index and the ecological significance, RO-RSEI is more reliable, especially in the zone of interaction between aquatic and terrestrial ecosystems (Fig. 9). The RSEI model excludes water bodies in advance and does not take into account the impact of water bodies on the terrestrial ecological environment. RO-RSEI performs better on the ecological environment quality under the interaction between adjacent ecosystems, and has better temporal and spatial continuity.

OR-RSEI is designed to measure the quality of the ecological environment in general and is therefore not applicable to studies of biological diversity and species habitats. Landscape ecology believes that different spatial amplitudes and spatial granularity have a greater impact on the results of ecological environmental quality monitoring. Therefore, it is very important and necessary to discuss the scale effect of ecological environment quality under different spatial and spatiotemporal resolutions. Using different elements, the coupled coordination between surface ecological environment and atmospheric environment, human environment, and social economy is explored. This will be the focus of our future work.

## 6. Conclusion

The regional scale effectively confers the ecological effect on the remote sensing ecological environmental quality assessment. At present, the theoretical exploration and mechanism analysis have been carried out in some aspects in the popular RSEI model, such as model application, index selection, non-unique eigenvector direction, and insufficient ecological significance. On the basis of regional-scale optimization and the RSEI model, a new index for regional ecological assessment, the RO-RSEI model, is proposed with Shuangyang District proposed as an example. The sliding window is realized in Python after index optimization, and the optimized index is

combined with normalization, flipping, and mapping methods.

Compared with RSEI, RO-RSEI improves the information richness of ecological monitoring results. The findings are supported by the EI index but are more meaningful. RO-RSEI provides not only an ecological value, but also a visible ecological image that considers the interactive effects of complex ecosystems. RO-RSEI does not need to consider the stochastic effects of eigenvector direction and is therefore more suitable for bulk monitoring of ecological environment quality.

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**Data availability** The data sources used in the current research are all public data (the data sources are listed in the first section of the article).

## Declarations

**Ethics approval** Ethics approval was not required for this research.

**Consent to participate** The authors declare consent to participate.

**Consent to publish** The authors declare consent to publish.

**Conflict of interest** The authors declare no competing interests.

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