



The improvement of ecological environment index model RSEI

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Abstract

Protecting the ecological environment is an important goal of the world sustainable development. Rapid and quantitative evaluation of regional ecological environment is the technical support and necessary condition for this goal. The ecological environment index model (RSEI) which used to assess ecological environment is the most popular now. But it changed into two completely opposite models in the application. Most researchers choose which model to use based on the desired results. This article concludes the reason by studying the operating mechanism of the model and finds that it is the eigenvector direction in the principal component analysis causes this to happen. Taking Pingyu County as an example, this article calculates RSEI with Landsat 8 images in different periods in Google Earth Engine using the two existing models respectively and finds that two models show two opposite result trends in spatial distribution. Using any model to calculate the same image, the results are also opposite if changing the input order of the indicators. It is the eigenvector direction determines the spatial distribution by comparing and analyzing the eigenvector of each image and its corresponding RSEI. Then, this paper improves the model by fixing the eigenvector direction based on the actual effects on ecological environment of the four indicators, taking absolute values of the eigenvectors of NDVI and Wet which have a positive effect on the ecological environment and the opposite of absolute values of the eigenvectors of LST and NDSI which have a negative effect on the ecological environment, in order to improve the RSEI model. Using the improved model calculate each image, the results are consistently accurate. Furthermore, this paper also proposed a model for users who calculating the principal components through software where the eigenvector direction cannot be altered artificially. This paper proposes the improved model which is suitable for all users whether using software or conducting programming. The improved model is suitable for all images of any input order of the indicators. It provides the possibility of applying remote sensing big data to the ecological environment. At the same time, the study of the mechanism of the model provides a scientific basis for future scholars to calculate in batches.

Keywords RSEI · Principal component · Eigenvector · Eco-environment index

Introduction

In 2015, the 2030 Agenda for Sustainable Development proposes a goal: protect, restore, and promote sustainable use of

terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss (UN 2015). This goal requires analysis and acquisition of ecosystem data. Remote sensing data is an important data source, and rapid quantitative assessment of the ecological environment is the technical support for ecological protection. Early scholars have qualitatively analyzed the regional ecological environment from the aspects of climate, atmosphere, soil, land, water body (Changon and Semonim 1979; Basta and Bower 1982; Guo et al. 1999; Man and Nu 2010), and the direction of land use change (Li et al. 2003). And then scholars usually select some single proxy indicators to evaluate the regional ecological environment. The main indicators are vegetation cover change (Han et al. 2017), heat island effect (Guo et al. 1999), landscape pattern index (Cui and Zang 2013), ecological service value (Du and Huang

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2017; Zhu et al. 2006; Cui 2013; Wang et al. 2017), ecological contribution rate (Man and Nu 2010; Li et al. 2016), carbon emissions (Man and Nu 2010), and normalized vegetation index (Wang et al. 2018). Recently, scholars have been exploring comprehensive and quantitative methods to assess the regional ecological environment, which can be divided into three main categories: (1) the ecological environment index EI (Yue and Zhang 2018; Zhang et al. 2017a, 2017b; Zhao et al. 2018) based on the technical specification for assessment of ecological environment status issued by the Ministry of Environmental Protection of China (State Environmental Protection Administration 2006); (2) the RSEI (remote sensing ecological environment index, RSEI) proposed by Xu Hanqiu (Xu 2013a, 2013b); (3) other ecological environment index models (Jang 2017). The environmental limitation index in the EI relies on the annual environmental report at the county level, therefore results to research scale must be divided by the administrative boundaries. And it goes against the law of natural ecology, more then, some indicators are difficult to obtain. The RSEI model has been widely used as soon as it was proposed for the reason it can break the limitations mentioned above. And it supports any temperature zone and climatic condition such as warm temperate arid climate (Li et al. 2018), temperate arid climate (Zhang et al. 2019), temperate semi-arid climate (Song et al. 2019), cold temperate monsoon climate (Liu et al. 2018a, 2018b), middle temperate semi-arid semi-humid climate (Yang et al. 2018, 2019), and subtropical humid climate (Zhang et al. 2017a, 2017b). However, when applying it to evaluate ecological environment changes, a single image with a long time interval (the shortest is 5 years) is used to represent the ecological environment status of the period (Wang et al. 2018; Xu et al. 2017; Yang et al. 2019; Zheng 2014), which may lose some key changes of the ecological environment. The RSEI model still has some problems in calculating long-time series images for it can results to two opposite results. Thus, another opposite model was derived from the original model when evaluating the regional ecological environment. Some scholars calculate the RSEI according to the original model (Xu 2013a, b; Liu et al. 2015; Zhang et al. 2017a, b; Song and Xue 2016; Li et al. 2018; Zhang et al. 2019; Yu et al. 2018; Liao et al. 2018; Liu et al. 2018a, b), but other scholars directly use PC1 as the regional ecological environment index rather than “1-PC1” during the use of the model (Zhang 2018; Shan et al. 2019; Yang et al. 2019). The reason for this is that scholars simply apply the model with lack of understanding of the operation and model mechanisms. They often choose a model depending on the results they expect. In addition, because model selection requires preliminary results to be seen first, it is only

suitable for a small amount of calculations, not for long-term sequences and batch operations. Regional ecological environment assessment is an important basis for formulating regional economic and social sustainable development plans and ecological environment protection strategies. However, there is no perfect ecological environment assessment model in the existing models that can evaluate the regional ecological environment in a long-term, instant, objective, continuous, and comprehensive manner. The existing models can bring different results because of the non-uniqueness of eigenvector directions in the principal component analysis method. In an actual research, scholars usually directly use the method and few people pay attention to eigenvectors and their directions. This greatly limits the development of remote sensing ecological environment assessment methods. At the same time, blindly applying and improving models due to the lack of research on model mechanisms can sometimes mislead scholars to make erroneous evaluations. Moreover, the original model also limits its suitable conditions to apply. This paper improves the widely used RSEI model by studying its mechanism and revises the model for different users in order to provide a more stable, more accurate, and more scientific model for regional ecological environment assessment, so as to provide a technical support for government decision-making and sustainable development.

Study area and data sources

Study area

Pingyu County (Fig. 1) (within 114° 24'–114° 55' E, 32° 44'–33° 10') is located in the central and western part of Huai River watershed, southeast of Henan province, the junction of two provinces (Henan and Anhui), and three cities (Zhumadian, Zhoukou, and Fuyang). The total area is about 1282 km². Pingyu County is located in the transitional climate zone from subtropical zone to warm temperate zone. And it owns the characteristics of two climatic zones, with warm climate and abundant rainfall. The county is dominated by plain landform with flat terrain, slightly higher in the northwest than in the southeast. According to the land cover classification system LCCS (Di Gregorio and Jansen 2000) of FAO (Food and Agriculture Organization of the United) and UNEP (United Nations Environment Programme), cultivated land and factory or residential land are the main ecosystems in this county, accounting for 97.7% of the total area, of which cultivated land accounts for 83.3%, factory or residential land accounts for 14.4% of the total area. Artificial or natural waterbodies, artificial surfaces and associated areas, and natural and semi-

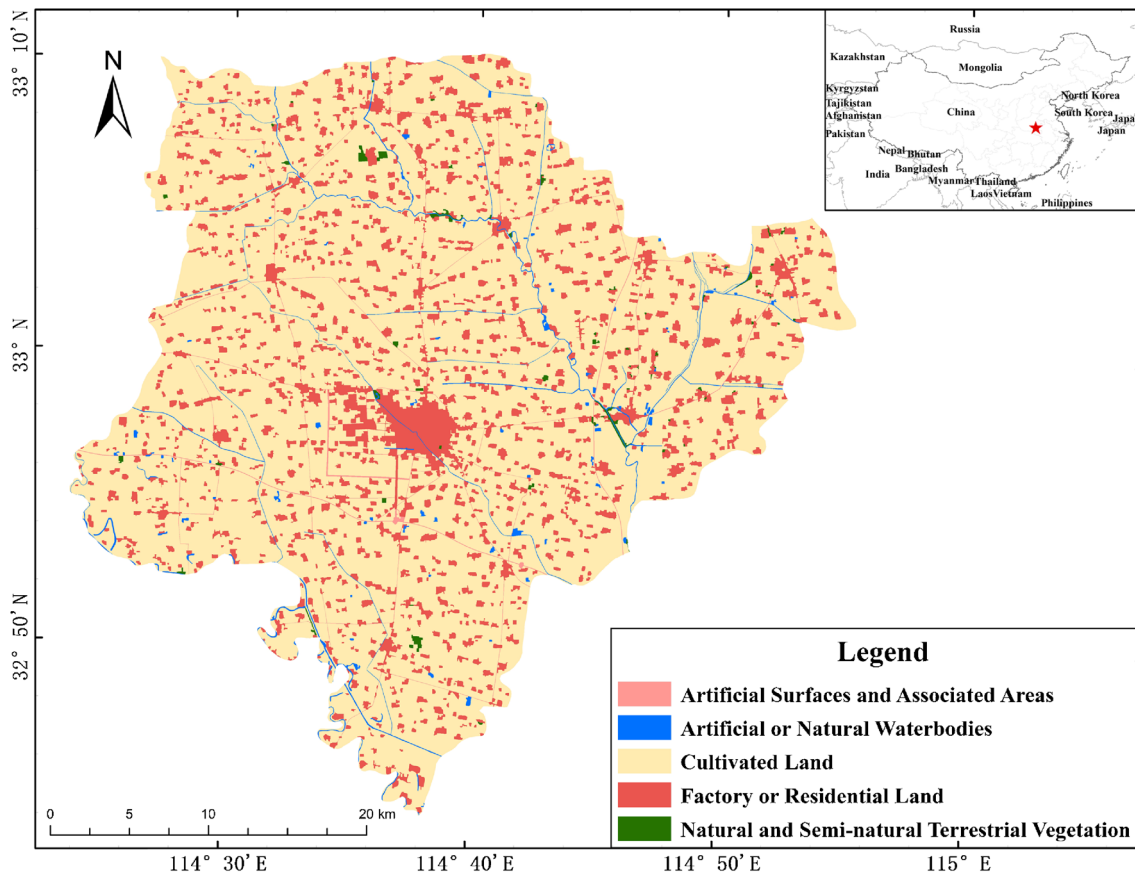


Fig. 1 Study area. Data from Data Center of Lower Yellow River Regions, National Earth System Science Data Sharing Infrastructure, National Science & Technology Infrastructure of China (<http://henu.geodata.cn>)

natural terrestrial vegetation account for 2.3% of the total area of the county.

According to regional geography and climatic characteristics, the four indexes in this article are typical and stable in Pingyu County. Data in this county has little change and the Landsat image series are relatively complete with little cloud. Pingyu County, Henan province, China, where shows appropriate representativeness, is selected as the research area of this paper.

Data sources

The data source in this study is Landsat 8 image of Tier 1 from the United States Geological Survey (USGS), covering all remote sensing images of Pingyu County from 2014 to 2016. All images have been atmospheric correction and geometric correction. We select data via traversing the remote sensing images of Pingyu County from 2014 to 2016 in Google Earth Engine, then 10 periods are selected following the principle of less than 10% cloud cover. This is followed by taking these 10-phase images for example. This paper studies the operation mechanism of the model, and test and calculate step by step to verify the problems in the model. We also

improve and correct the problems to form a stable model that is suitable for all users.

Research methods

Green index

The normalized vegetation index (NDVI) is the proxies of green index in RSEI model (Xu et al. 2017), which can be calculated using the following Equation (1):

$$NDVI = \frac{NIR - Red}{IR + Red} \quad (1)$$

where NIR and Red are near infrared band and red band, which are band 4 and band 3 respectively.

Dry index

The impervious surface (NDSI) is the proxies of the dry index in RSEI model (Xu et al. 2017), which can be calculated using the following Equations (2–4):

$$SI = \frac{(Red + SWIR1) - (NIR + Green)}{(Red + SWIR1) + (NIR + Green)} \tag{2}$$

$$IBI = 2 * \frac{NIR}{NIR + Red} - \left(\frac{\frac{Red}{Red + Green} + \frac{Blue}{Blue + NIR}}{2 * \frac{NIR}{NIR + Red} + \left(\frac{Red}{Red + Green} + \frac{Blue}{Blue + NIR} \right)} \right) \tag{3}$$

$$NDSI = (SI + IBI) / 2 \tag{4}$$

where red means red band; green stands for green band; blue represents blue band, which are band 3, band 2, and band 1 respectively.

Wet index

The wet component of reel cap transformation (Wet) is the proxies of the wet index in RESI model (Xu et al. 2017), which can be calculated using the following Equation (5) (Crist 1985) and Equation (6) (Zhang 2017) based TM and OLI/TIRS sensor respectively:

$$Wet = 0.0315 \times NIR + 0.2021 \times Red + 0.3102 \times Blue + 0.1594 \times Green - 0.6806 \times SWIR1 - 0.6109 \times SWIR2 \tag{5}$$

$$Wet = 0.1511 \times NIR + 0.1973 * Red + 0.3283 \times Blue + 0.3407 \times Green - 0.7117 * SWIR1 - 0.4559 \times SWIR2 \tag{6}$$

where SWIR1 and SWIR2 are medium infrared band 1 and medium infrared band 2 respectively.

LST index

Land surface temperature (LST) is the proxy of heat index in RESI model (Xu et al. 2017). The LST can be derived by the single channel algorithm (Jiménez-Muñoz et al. 2009; Sobrino et al. 2008). The method for LST is described in Equations (7)–(10):

$$LST = \gamma \left[\frac{1}{\varepsilon_i} (\varphi_1 L_i + \varphi_2) + \varphi_3 \right] + \delta \tag{7}$$

$$\gamma \approx \frac{T_i^2}{b_r L_i} \tag{8}$$

$$\delta \approx T_i - \frac{T_i^2}{b_r} \tag{9}$$

$$\begin{bmatrix} \varphi_1 \\ \varphi_2 \\ \varphi_3 \end{bmatrix} = \begin{bmatrix} 0.04019 & 0.02916 & 1.01523 \\ -0.38333 & -1.50294 & 0.20324 \\ 0.00918 & 1.36072 & -0.27514 \end{bmatrix} \begin{bmatrix} w^2 \\ w \\ 1 \end{bmatrix} \tag{10 - 1}$$

when OLI/TIRS sensor are used.

$$\begin{bmatrix} \varphi_1 \\ \varphi_2 \\ \varphi_3 \end{bmatrix} = \begin{bmatrix} 0.06982 & -0.03366 & 1.04896 \\ -0.51041 & -1.20026 & 0.06297 \\ -0.05457 & 1.52631 & -0.32136 \end{bmatrix} \begin{bmatrix} w^2 \\ w \\ 1 \end{bmatrix} \tag{10 - 2}$$

when TM sensor are used.

where ε_i indicates the surface specific emissivity; γ and δ are the correlation coefficient of Planck’s law; b_r can be expressed by $\frac{c_2}{\lambda}$, with $c_2 = 1.4387685$ and λ is the effective wavelength of the thermal infrared band; L_i represents the at-sensor brightness; T_i is the at-sensor brightness temperature; $\varphi_1, \varphi_2, \varphi_3$ are the parameters of atmospheric functions; w indicates atmospheric water vapor content;

Water index

The improved normalized difference water body index (MNDWI) (Xu 2005) is used to mask the water body, and the MNDWI can be calculated using the following Equation (11):

$$MNDWI = \frac{Green - MIR1}{Green + MIR1} \tag{11}$$

Standardization indicators

The dimensions of each index are different. Before calculating the ecological index, we use Equation (12) (Han et al. 2013) to standardize each index.

$$NI_i = (I_i - I_{min}) / (I_{max} - I_{min}) \tag{12}$$

where NI_i is the indicator values after standardization, I_i refers to the index value at pixel i , I_{min} and I_{max} are the maximum and minimum values of the index respectively.

Model analysis and improvement

Existing model

The existing ecological environment index models applied by researchers can be expressed by Equation (13)–(14):

$$RSEI_0 = 1 - PC1[f(NDVI_s, NDSI_s, Wet_s, LST_s)] \tag{13}$$

$$RSEI_0 = PC1[f(NDVI_s, NDSI_s, Wet_s, LST_s)] \tag{13 - 1}$$

$$RSEI = \frac{RSEI_0 - RSEI_{min}}{RSEI_{max} - RSEI_{min}} \tag{14}$$

where $RSEI_0$ indicates the ecological environment index before standardization; $RSEI$ indicates the ecological environment index after standardization; $NDVI_s, NDSI_s, Wet_s,$

and LST_s are the four standardized indexes in RSEI model; $PC1[f(NDVI_s, NDSI_s, Wet_s, LST_s)]$ indicates the first principal component; $RSEI_{min}$ and $RSEI_{max}$ are the minimum and maximum values of $RSEI_0$, respectively.

Equation (13) is the earliest RSEI model proposed by Xu (2013a, 2013b). Equation (13-1) emerges during the application of Equation (13). Later scholars randomly select models based on their expected outcomes.

Model analysis

For any image, we calculate the ecological environment index using formulas 13 and 13-1 respectively, the results are all opposite. The eigenvalue contribution rate of PC1 obtained by both models is 86.58%, indicating that the four indexes of the model can explain most of the samples. However, there results are completely opposite in spatial distribution. The eigenvalues obtained by two models are the same but the directions are completely opposite by researching the process of model running. Then, we use the same model to calculate the same image by changing the input order of the four indicators, and the results are also opposite along with the opposite eigenvector direction. There are some rules about eigenvector direction:

- (1) The input index order affects the direction of the eigenvector. When calculating the ecological environment index of the same image and the same region, the eigenvector direction changes with the input order of four indexes in the principal component analysis. Taking the image of Pingyu County of Henan province in China on January 23, 2014 as an example, we calculate the RSEI value of the County using Equation (13) together with (14). There are many orders about the four indexes, taking the order of NDVI, Wet, LST, and NDSI and the order of LST, NDSI, NDVI, and Wet as examples. When fixing the input order of the four indexes of the principal component analysis as NDVI, Wet, LST, and NDSI, and the results of the eigenvectors and RSEI are shown in Table 1. In this case, the contribution direction of NDVI and Wet to the ecological environment is positive, while that of LST and NDSI is negative. Changing the input order of the four indexes to LST, NDSI, NDVI, and Wet, then the eigenvectors and RSEI results are shown in Table 2. The contribution direction of NDVI and Wet to ecological environment is negative, while that of LST and NDSI is positive. It can be seen from Tables 1 and 2 that with the different index input order:
 - ① the contribution rates of eigenvalues are the same;
 - ② the absolute values are equal of each index in the same component;
 - ③ the directions of the eigenvectors are opposite;
 - ④ when the eigenvector's direction changes, the RSEI result changes.
- (2) The eigenvector direction is random, and the result changes along with it. When calculating the RSEI of all the ten images selected before by the two models, and the spatial distribution of results turn out to be random. As shown in Table 3, NDVI and Wet in a, e, f, and j contribute positively to the ecological environment, while LST and NDSI contribute negatively to the ecological environment. On the contrary, NDVI and Wet in b, c, d, g, h, and i have a negative impact on the ecological environment, while LST and NDSI have a positive impact on the ecological environment. And the results change, we simply follow the direction of the eigenvector by each model. Figure 2 shows that the RSEI values of a, e, f, J, and b, c, d, g, h, and i are oppositely to each other in spatial distribution. The high RSEI values of a, e, f, and J are low in b, c, d, g, h, and i, and vice versa. According to common sense, the ecological environment of urban construction land is worse than woodland and farmland. So, it is only when the eigenvector direction of NDVI and Wet are negative and the LST and NDSI are positive in PC1 can get the right result by Equation (13), and the opposite by Equation (13-1). However, all the eigenvalue contribution rates in PC1 of the ten images are more than 80% by any model, indicating that PC1 has concentrated more than 80% of the characteristics of the four indexes. So, we infer that the eigenvectors and its direction determine the result and its spatial distribution.
- (3) The values of eigenvectors still have some rules. As Table 3 shows, no matter what the eigenvector direction is, the direction of NDVI and Wet is always same in the PC1 of all the ten images, and the same to the direction of LST and NDSI. But in the other principal components such as PC2, PC3, and PC4, the eigenvector directions of each index are irregular, and their eigenvalue contribution rates are all small.
- (4) There is no scientific basis to use 1 minus the value of the PC1 as the result as Equation (13) expressed. Equations (13) and (13-1) are two completely opposite models leading to two opposite results. Figures 2 and 3 are the results calculated by the two models, and it is not difficult to see that the results spatial distribute are reverse based on the same image. The peak value region in a model is the valley value region, and vice versa. However, the two models are both used to calculate the RSEI, which model to choose simply rely on the result should be for the early researchers during the application of them. There is no reasonable explanation for this.

In conclusion, the original RSEI model can well characterize the ecological environment only when the direction of NDVI and Wet are positive in PC1. Otherwise, the result will

Table 1 Principal component analysis with the input order of NDVI, Wet, LST, and NDSI

Date	Index	PC1	PC2	PC3	PC4
2014.01.23	NDVI	0.747	0.138	0.612	- 0.219
	Wet	0.096	- 0.114	- 0.414	- 0.898
	LST	- 0.015	0.977	- 0.213	- 0.028
	NDSI	- 0.657	0.119	0.640	- 0.380
	EV	0.039	0.005	0.001	0.000
	CROEV (%)	86.58	11.19	2.04	0.2

EV indicates eigenvalue; CROEV indicates the contribution of eigenvalue

be wrong. Although the original model can satisfy the needs of research, due to the randomness of the eigenvector direction, the original model has many restricted conditions. It is only suitable for cases where the data is calculated one by one if a researcher expects and gets the right result. For batch calculation, the results are completely uncontrollable so that cannot get right results as shown in Figs. 2 and 3.

Model improvement and discussion

As mentioned above, the main problem of the RSEI model is caused by the direction of the eigenvector. In order to study the reason why the eigenvector direction is uncertain, the mechanism and process of principal component analysis has been studied first. Each 30-m grid of the remote sensing image is a sample in principal component analysis. There are 1,424,444 samples in our study region. The first step of principal component analysis is to average the four indicators to make the 4 indicators dimensionless. The method is to subtract the average value of each index value. Then the averaged 4 indexes will form a $4 \times 1,424,444$ -dimensional matrix U .

Table 2 Principal component analysis with the input order of LST, NDSI, NDVI, and Wet

Date	Index	PC1	PC2	PC3	PC4
2014.01.23	NDVI	- 0.747	- 0.138	- 0.612	- 0.219
	Wet	- 0.096	0.114	0.414	- 0.898
	LST	0.015	- 0.977	0.213	- 0.028
	NDSI	0.657	- 0.119	- 0.640	- 0.380
	EV	0.039	0.005	0.001	0.000
	CROEV (%)	86.58	11.19	2.04	0.2

EV indicates eigenvalue; CROEV indicates the contribution of eigenvalue

$$U = \begin{bmatrix} x_1 & y_1 & z_1 & w_1 \\ \dots & \dots & \dots & \dots \\ \dots & \dots & \dots & \dots \\ x_p & y_p & z_p & w_p \end{bmatrix}$$

where p is 1,424,444, the $x, y, z,$ and w is NDVI, Wet, NDSI, and LST respectively. The covariance matrix contains two parts of information: one is the information on the diagonal, that is, the variance of each indicator, reflects the variation of each indicator, and the other is the information outside the diagonal, that is, the covariance between the indicators which is the interaction between indicators.

Since the covariance matrix is a positive definite symmetric matrix, it has non-negative eigenvalues $\lambda_1 > \lambda_2 > \dots > \lambda_p > 0$. And the unit eigenvectors corresponding to the eigenvalues are written as l_1, l_2, \dots, l_p , where $l_j = (l_{1j}, l_{2j}, \dots, l_{pj})^T$. Since l_j is an unit vector, its length is 1. That is, $\|l_j\|=1$. It can be known from the matrix theory that for any eigenvalue λ_j , each corresponding eigenvector can be expressed as follows:

$$\alpha l_j = (\alpha l_{1j}, \alpha l_{2j}, \dots, \alpha l_{pj})^T, \alpha \neq 0$$

According to the characteristics of the unit eigenvector,

$$\|\alpha l_j\| = |\alpha| \|l_j\| = 1.$$

have known

$$\|l_j\| = 1,$$

So

$$\alpha = \pm 1.$$

That is to say, for any eigenvalue λ_j , the unit eigenvectors are $\pm l_j$. This explains why the eigenvectors have opposite directions in the principal component analysis of the RSEI model. Although the eigenvalues and their contribution rates are not affected by the direction of the eigenvectors, there are great differences in the application of sample comprehensive evaluation. Principal component analysis is often used to reduce the dimensionality of indicators, but in this paper, it is used to fit indexes for sample evaluation. So the eigenvector direction is quite important.

It has been proved that there are some rules about the eigenvector although its direction is uncertain above. The direction of NDVI and Wet is always same, and the direction of NDSI and LST is always same in PC1. What is more, their directions are always different. We also find that although the input order of the four indexes can change the directions of the eigenvectors, the absolute values of eigenvectors and the contribution rates do not change. Because NDVI and Wet have a positive contribution on the ecological environment, and

Table 3 Principal component analysis of 10 images

Date	Index	PC1	PC2	PC3	PC4
a 2014.01.23	NDVI	0.747	0.138	0.612	-0.219
	Wet	0.096	-0.114	-0.414	-0.898
	LST	-0.015	0.977	-0.213	-0.028
	NDSI	-0.657	0.119	0.640	-0.380
	EV	0.039	0.005	0.001	0.000
	CROEV (%)	86.58	11.19	2.04	0.2
b 2015.01.10	NDVI	-0.687	-0.140	0.603	-0.380
	Wet	-0.174	0.168	-0.626	-0.741
	LST	0.036	-0.975	-0.214	-0.048
	NDSI	0.704	-0.044	0.445	-0.552
	EV	0.046	0.004	0.001	0.000
	CROEV (%)	88.60	8.58	2.50	0.32
c 2015.04.16	NDVI	-0.686	-0.454	0.455	-0.340
	Wet	-0.257	0.286	-0.616	-0.688
	LST	0.242	-0.842	-0.483	-0.009
	NDSI	0.636	-0.055	0.426	-0.642
	EV	0.045	0.002	0.001	0.000
	CROEV (%)	93.86	3.97	2.03	0.15
d 2016.04.18	NDVI	-0.599	-0.258	0.745	-0.138
	Wet	-0.120	-0.024	-0.281	-0.952
	LST	0.384	-0.923	-0.015	-0.021
	NDSI	0.692	0.285	0.604	-0.273
	EV	0.044	0.002	0.001	0.000
	CROEV (%)	94.55	3.54	1.83	0.08
e 2014.04.29	NDVI	0.732	0.310	0.603	-0.068
	Wet	0.089	0.058	-0.246	-0.963
	LST	-0.447	0.891	0.084	-0.009
	NDSI	-0.506	-0.328	0.754	-0.259
	EV	0.037	0.001	0.001	0.000
	CROEV (%)	95.57	2.82	1.56	0.04
f 2016.05.04	NDVI	0.706	-0.346	-0.599	-0.150
	Wet	0.137	-0.024	0.403	-0.905
	LST	-0.399	-0.915	0.060	-0.009
	NDSI	-0.568	0.206	-0.690	-0.399
	EV	0.037	0.004	0.001	0.000
	CROEV (%)	87.78	10.25	1.87	0.09
g 2016.07.23	NDVI	-0.564	-0.468	0.647	-0.212
	Wet	-0.111	-0.089	-0.449	-0.882
	LST	0.625	-0.780	-0.016	0.009
	NDSI	0.528	0.406	0.616	-0.421
	EV	0.012	0.001	0.001	0.000
	CROEV (%)	87.77	7.94	3.98	0.31
h 2015.08.22	NDVI	-0.715	0.418	0.533	-0.170
	Wet	-0.117	-0.014	-0.432	-0.894
	LST	0.471	0.878	-0.069	-0.041
	NDSI	0.502	-0.232	0.724	-0.412
	EV	0.023	0.001	0.001	0.000
	CROEV (%)	90.39	5.57	3.71	0.32
i 2014.09.04	NDVI	-0.696	-0.220	-0.622	-0.284
	Wet	-0.246	-0.002	0.617	-0.748
	LST	0.291	-0.954	0.040	-0.060
	NDSI	0.609	0.203	-0.480	-0.597
	EV	0.014	0.001	0.001	0.000
	CROEV (%)	85.22	8.02	5.91	0.84
j 2014.12.25	NDVI	0.772	-0.069	-0.585	0.238
	Wet	0.088	0.102	0.461	0.877
	LST	-0.009	-0.991	0.126	0.050
	NDSI	-0.629	-0.056	-0.655	0.414
	EV	0.039	0.006	0.003	0.000
	CROEV (%)	81.15	11.73	6.89	0.23

EV indicates eigenvalue; CROEV indicates the contribution of eigenvalue

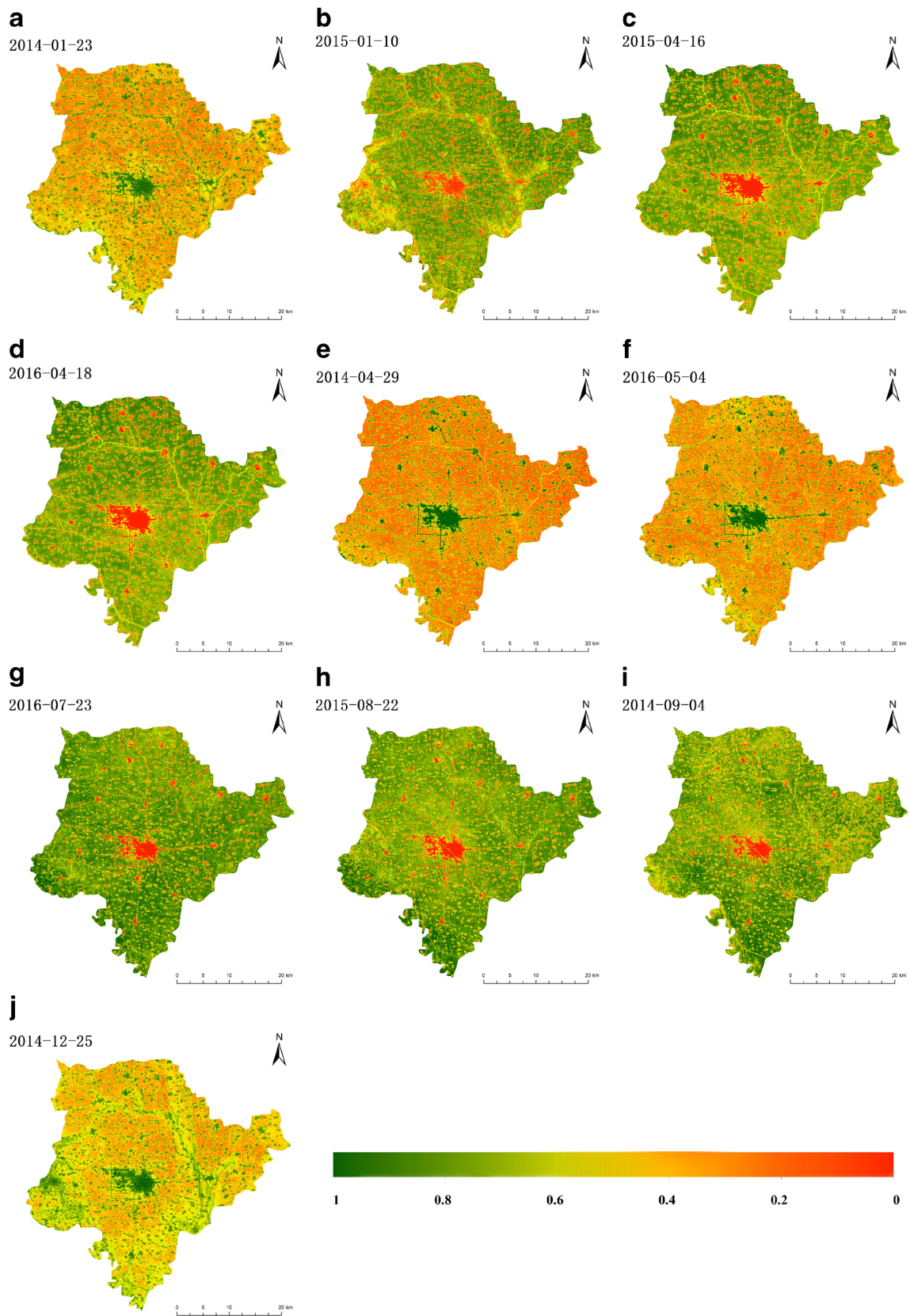


Fig. 2 RSEI of Pingyu County by model of Equation 13 together with 14

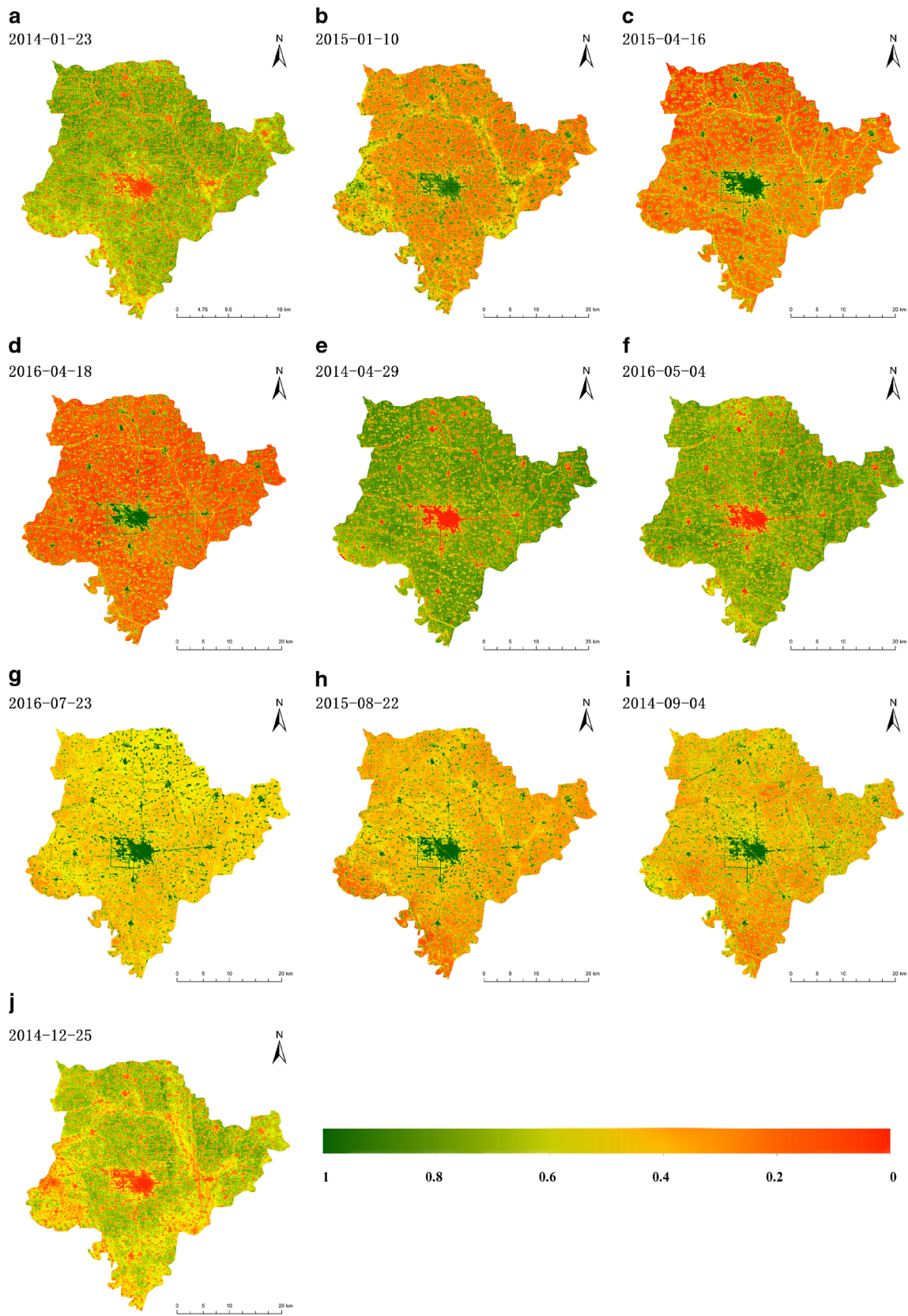


Fig. 3 RSEI of Pingyu County by model of Equation 13-1 together with 14

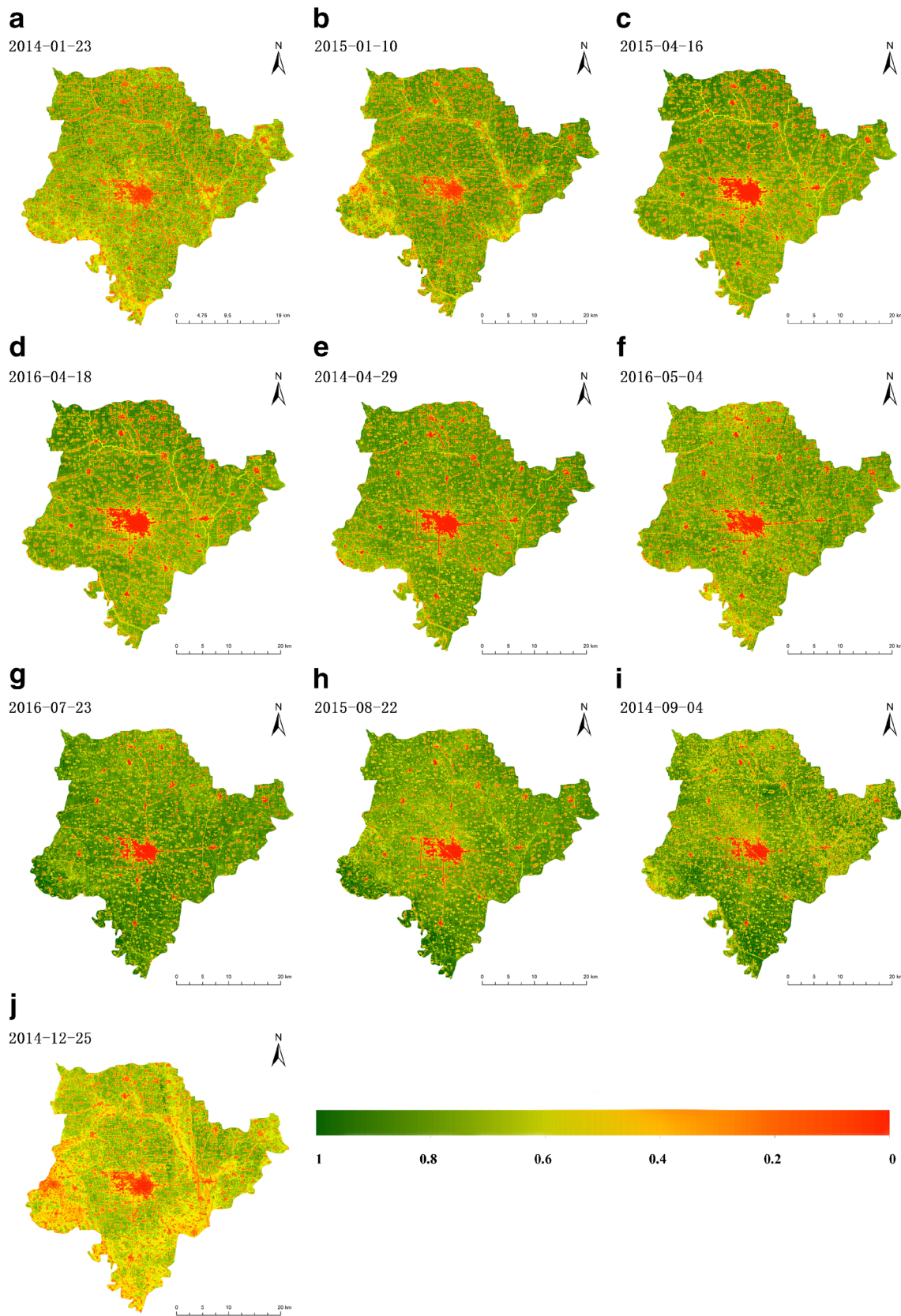


Fig. 4 RSEI of Pingyu County by Improved RSEI Model of Equation 15 together with 16

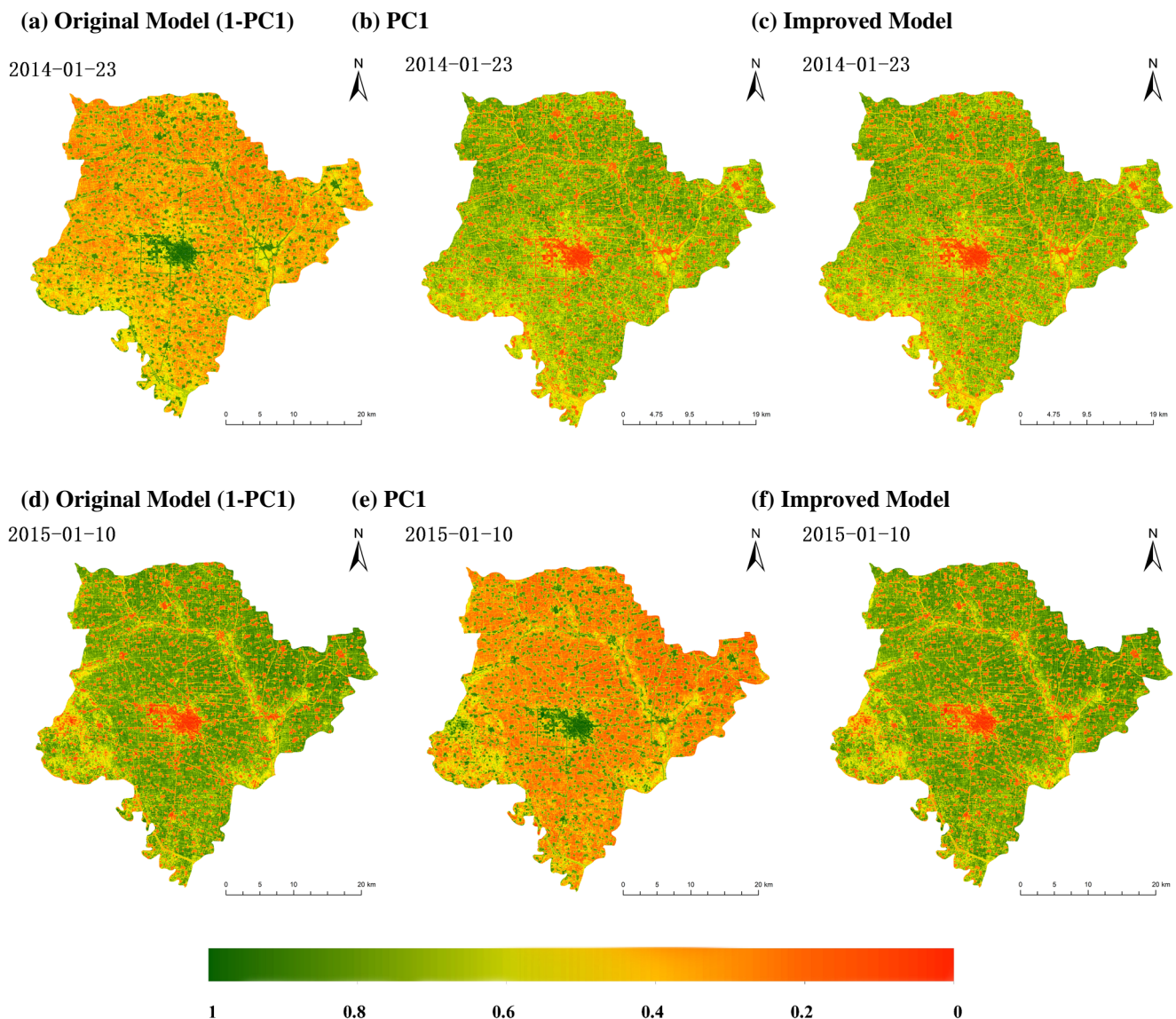


Fig. 5 Comparisons of calculation results of different models. **a** Original model (1-PC1). **b** PC1. **c**. Improved model. **e** Original model (1-PC1). **f** PC1. **g** Improved model

NDSI and LST have a negative impact on the ecological environment, and because the rules mentioned in “Model analysis” above only emerge in PC1, the eigenvector direction of each index in other principal components is random with no rules. There is no basis to choose which eigenvector ($\pm I_j$) to use in other principal components scientifically. Moreover, the low contribution rate of other principal components may be caused by image noise. Although some researchers improve the model by using the cumulative contribution instead of the contribution of PC1 (Song et al. 2019), it is not suitable to calculate the ecological environment quality index for the uncertainty of other principal components may cause the model deformation thus reduce the model quality. We modify the eigenvector direction of PC1 artificially according to the actual impact of each index on the ecological environment

during principal component analysis. We take the absolute values of the eigenvectors of NDVI and Wet, and take the opposite absolute values of NDSI and LST. At the same time, we use PC1 instead of “1-PC1” to calculate the eco-environment quality index. The improved model is expressed as follows in Equations (15) and (16):

$$RSEI_0 = PC1 \left[f(NDVI, Wet, NDSI, LST)_{(|V_{NDVI}| \cdot |V_{Wet}| - |V_{NDSI}| \cdot |V_{LST}|)} \right] \tag{15}$$

$$RESI = \frac{RESI_{0_{max}} - RESI_{0_{min}}}{RESI_{0_{max}} - RESI_{0_{min}}} \tag{16}$$

where V_{NDVI} , V_{Wet} , V_{NDSI} , V_{LST} indicate the eigenvector of the NDVI, Wet, NDSI, and LST respectively.

We use the improved model recalculate the eco-environment quality index and the RSEI values of 10 images are highly consistent in spatial distribution. The ecological environment quality index of urban ecosystem is the lowest, and the ecological environment quality index of forest and farmland ecosystem is the highest. There are differences in different images of different time phases. But the over trend of the values is convincing and valid. Furthermore, when change the input order of the indexes, the result will not be affected, which prove that the improved model is stable and reliable (Fig. 4).

There are three models mentioned above. They include the original model proposed by Xu (Equations 13 and 14), model directly used the PC1 (Equations 13-1 and 14), which is opposite to the original model as the eco-environment quality index and improved model in our study (Equations 15 and 16). In order to find the relationship between the three models, this paper chooses two images of the same month with opposite eigenvector direction to calculate the eco-environment quality index by the three models respectively. The dates of two images are 2014/1/23 and 2015/1/10. The results are shown as Fig. 5. Panels a and e in Fig. 5 are calculated by the original model, b and f are calculated by the opposite original model, and c and g are by the improved model in this paper. It is easy to find that the spatial distribution of the eco-environment quality indexes is fallacious in a and f. The results of the first two models are both half right and half wrong. And only the results by the model improved in this paper are always true and effective. Results by the improved model are compared with the results (Chang and Qin 2017) by the method in Technical Specification for Assessment of Ecological Environment Status issued by Ministry of Environmental Protection of China. And two results are highly consistent which verifies the validity of the model. The spatial distribution of the eco-environment quality index is same in result b and c, and so is e and g, indicating the result of the image on date 2015/1/10 is right under the first model, and the result of the image on date 2015/1/10 is right under the second model.

In this paper, all the calculations are run in Google Earth Engine with codes, during which the direction of eigenvector can be determined or modified manually. So it is easy to apply the improved model through modifying codes. However, some researchers conduct principal component analysis with the software such as ENVI, ERDAS, and ArcMap whose codes have been encapsulated and cannot be modified customized. So an improved model for software users is proposed in this paper. Although the direction of eigenvector cannot be modified, it is visible. Also as Fig. 5 shows that no matter what the directions of the eigenvectors are, there is always one model whose calculate results are the same as the improved model. So this paper improves the model based on the initial direction of the eigenvector of the PC1. The model can be expressed by Equations (17) and (18):

$$RSEI_0 = \begin{cases} PC1[f(NDVI, Wet, NDSI, LST)], & V_{NDVI}, V_{Wet} > 0 \\ 1-PC1[f(NDVI, Wet, NDSI, LST)], & V_{NDVI}, V_{Wet} < 0 \end{cases} \quad (17)$$

$$RESI = \frac{RESI_{0_j} - RESI_{0_{min}}}{RESI_{0_{max}} - RESI_{0_{min}}} \quad (18)$$

where V_{NDVI} and V_{Wet} indicate the eigenvector value of NDVI and Wet in PC1. When the two values are greater than 0, we choose the upper model in Equation (17) to calculate the eco-environment quality index, otherwise we choose the lower model in Equation (17).

Conclusion

Protecting the ecological environment is a worldwide problem. Economic development cannot be achieved at the cost of ecological environment, so regional comprehensive ecological environment assessment plays a crucial role during national development. However, existing evaluation models always have various problems, so they cannot give a comprehensive, objective, scientific, and accurate evaluation of the regional ecological environment. This article studies the process and mechanism of the most popular RSEI model at present, and analyzes and improves it according to the phenomenon of inconsistency. Taking Pingyu County as an example, this paper calculates RSEI in different time phases by using two existing RSEI models in Google Earth Engine. The results show that the direction of eigenvectors of principal component analysis in the model influences the results of spatial distribution, and the reason is that the eigenvector directions of principal component analysis are not unique. According to the contribution (positive and negative) of the four indexes to the ecological environment and the model mechanism, the directions of the eigenvectors are modified artificially. Then, recalculating the RSEI using the improved model and the results show that:

- (1) RSEI index can calculate the impact of multiple factors on ecology quantitatively, and the calculated ecological index can reflect the regional ecological environment, which is widely used by the academic community. But the original RSEI models cannot always calculate the ecological environment index correctly. The eigenvector directions of the original RSEI model are random and lack a scientific basis, and thus the calculation results will vary. The ecological environment index calculated by the original RSEI model formed by Equations (13) and (14) is correct only when the eigenvectors of NDVI and Wet are negative, and the eigenvectors of NDSI and LST are positive. And model formed with Equations (13-1) and (14) can get the right result only when the

direction of eigenvectors of NDVI and Wet is positive and NDSI and LST is negative.

- (2) The modified RSEI model has a scientific basis and the calculated results are deterministic, which can better reflect the contribution of regional ecological conditions and parameters. The direction of the eigenvector has no effect on the eigenvalues and contribution rates in principal component analysis, so it has no effect on the results when used to reduce the dimensionality of complex indexes. However, it plays a decisive role when used to fit indexes. Nevertheless, the existing models do not explain nor define the direction of eigenvectors, which is just the reason why the current models are confusing in the application. Among the four calculation parameters, NDVI and Wet represent the benign condition of the ecological environment, so the improved model takes positive values. NDSI and LST represent the malignant state of the ecological environment, so the improved model takes negative values. Therefore, the calculated results by model calculates can better reflect the ecological environment. The improved RSEI model can always calculate the ecological environment index correctly. The improved RSEI model formed by Equations (15) and (16) modifies the eigenvector direction based on the actual influence direction on ecological environment of four indexes and the rules mentioned above. And the results of all images by the improved model are correct and consistent. Regardless of the direction of the eigenvectors of the four indicators, the ecological environment index calculated by the improved RSEI model is always correct which can better assess regional ecological environment. The improved RSEI model defines the direction of the eigenvector, and solves the problem of reverse result caused by the index sequence and time phase in the calculation of the existing model.
- (3) The modified models with stable and reasonable characters solve the problem of batch calculation of ecological environment index and are suitable for all users. The emergence of remote sensing big data requires the batch calculation of ecological environment index. The model provides technical possibilities for further quarterly and annual studies. When using program to calculate principal component analysis, the eco-environment index can be calculated through modifying the eigenvector direction by taking the absolute values of the eigenvectors of NDVI and Wet and the opposite numbers of absolute values of NDSI and LST. When principal component analysis is carried out by software, the directions of eigenvectors cannot be controlled manually. In this case, researchers must get the first principal component and its eigenvector first and then choose a proper model to calculate the eco-environment quality index according to the direction of the eigenvector. If the values of the

eigenvectors of NDVI and Wet eigenvectors are positive or the values of the eigenvectors of NDSI and LST are negative, the upper model in Equations (17) and (18) are selected. And if the values of eigenvectors of NDVI and Wet are negative or the eigenvector values of NDSI and LST are positive, using lower equation in Equations (17) and (18) to calculate the ecological environment index.

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References

- Basta JD, Bower TB (1982) Analyzing natural systems. A research paper from resources for the future. The Johns Hopkins University Press, Baltimore
- Chang ZB, Qin F (2017) Dynamic evaluation of eco-environmental quality in He'nan province based on RS and GIS. *Water Soil Conserv Bull* 037.004(2017):132–137
- Changon SA, Semonim RG (1979) Impact of man upon local and regional weather. *Rev Geophys Space Phys* 17:1891–1900
- Crist EP (1985) A TM tasseled cap equivalent transformation for reflectance factor data. *Remote Sens Environ* 17:301–306
- Cui F (2013) Land use change and eco-environmental response in urban fringe. Nanjing Agricultural University
- Cui J, Zang SW (2013) Ecological environment effect of land use change in Hadaqi industrial corridor. *Geogr Res* 2:848–856
- Di Gregorio A, Jansen LJM (2000) Land cover classification system (LCCS): classification concepts and user manual. <http://www.fao.org/3/y7220e/y7220e00.htm>
- Du X, Huang Z (2017) Ecological and environmental effects of land use change in rapid urbanization: the case of Hangzhou, China. *Ecol Indic* 8:243–251
- Guo XD, Chen LD, Fu BJ (1999) Impact of land use/land cover change on regional ecological environment. *Environ Eng* 6:66–75
- Han W, Cui JQ, Bin C (2013) Analysis of wetland dynamics and its influencing factors in Northeast China. *J Basic Sci Eng* 21:214–223
- Han RD, Zhang L, Zheng Y et al (2017) Eco-environmental effects of urban expansion in Bangkok. *Acta Zool* 37:6322–6334
- Jang H (2017) Study on land use change and its eco-environmental effects in Xijiang River basin of Guangxi. Guangxi Normal University
- Jiménez-Muñoz JC, Cristóbal J, Sobrino JA et al (2009) Revision of the single-channel algorithm for land surface temperature retrieval from Landsat thermal-infrared data. *IEEE Trans Geosci Remote Sens* 47: 339–349
- Li XW, Fang JY, Piao SL (2003) Land use change and its ecological environment effect in the lower reaches of the Yangtze River in recent 10 years. *J Geogr* 58:659–667
- Liu ZC, Xu HQ, Li L (2015) Urban ecological change in Hangzhou city based on remote sensing ecology index. *J Appl Basic Eng Sci* 4: 728–739
- Li CH et al (2016) Land use and cover change (LUCC) in traditional agricultural areas and its eco-environmental effects. *J Southwest Univ (Nat Sci Ed)* 38:139–145
- Li QY, Wang ZX, Cui J (2018) Study on RSEI classification of eco-environmental quality index of Aksu city based on TM data. *Tianjin Agric Sci* 24(67-71):90

- Liao LH, Dai WY, Huang HF (2018) Coupling and coordination analysis of urbanization and eco-environment based on DMSP/OLS and Landsat data. *J Fujian Norm Univ (Nat Sci Ed)* 34:99–108
- Liu P, Ren CY, Wang ZM (2018a) Remote sensing evaluation of ecological environment quality in Nanwenghe Nature Reserve. *J Appl Ecol* 29:191–200
- Liu Y, Yue H, Meng JX, Zhang F, Cui QP (2018b) Remote sensing assessment of the ecological environment of major cities in China section of the Silk Road economic belt. *Environ Monit Manag Technol* 30:35–39+48
- Man S, Nu Y (2010) Oasis cultivated land change and river hydrological effect in Tarim river basin. *Geogr Res* 25(12):2251–2260
- Shan W, Jin XB, Meng XS (2019) Dynamic monitoring of ecological environment quality in land improvement based on multi-source remote sensing data. *J Agric Eng* 35:242–250
- Sobrino JA, Jiménez-Muñoz JC, Sòria G et al (2008) Land surface emissivity retrieval from different VNIR and TIR sensors. *IEEE Trans Geosci Remote Sens* 46:316–327
- Song HM, Xue L (2016) Dynamic monitoring and analysis of ecological environment quality in Weinan city based on remote sensing ecological index model. *J Appl Ecol* 27:3913–3919
- Song MJ, Luo YY, Duan LM (2019) Evaluation of ecological environment in the Xilin Gol steppe based on modified remote sensing ecological index model. *Arid Zone Res* 6:1521–1527
- State Environmental Protection Administration. Environmental Protection Industry Standards of the People's Republic of China (Trial Implementation). HJ/T192-2006
- UN (2015) *Transforming Our World: The 2030 Agenda for Sustainable Development*. United Nations, New York
- Wang H, Qin F, Zhu J, Zhang CC (2017) Impact of land use and landscape patterns evolution on ecosystem service Value. *Acta Zool* 3: 1286–1296
- Wang JH, Liang L, Huang T et al (2018) Land use change and its ecological environment effects in Xuzhou City. *Bull Soil Water Conserv*
- Xu HQ (2005) Study on extracting water information by improved normalized difference water index (MNDWI). *J Remote Sens* 9:589–595
- Xu HQ (2013a) Establishment and application of urban remote sensing ecological index. *J Ecol* 33:7853–7862
- Xu HQ (2013b) Remote sensing evaluation index of regional eco-environmental change. *Environ Sci China* 33:889–897
- Xu HQ, Shi TT, Wang MY (2017) Prediction of land cover change and ecological response to new area planning in Xiongan new area. *J Ecol* 37:6289–6301
- Yang FH, Song JJ, Zhao YR (2018) Remote sensing dynamic monitoring of ecological environment in black soil erosion area of Northeast China. *Environ Sci Res*:1580–1587
- Yang JY, Wu T, Pan XY, Du HT, Li JL, Zhang L, Men MX, Chen Y (2019) Ecological quality assessment of Xiongan new area based on remote sensing ecological index. *J Appl Ecol* 11:1–12
- Yu JSD, Chen YJ, Tong RJ (2018) The calculation and application of remote sensing ecological index based on Web interoperability. *J Guizhou Univ (Nat Sci Ed)* 35:47–53
- Yue A, Zhang Z (2018) Analysis and research on ecological situation change based on EI value. *Green Sci Technol* 14:182–184
- Zhang H (2017) Ecological change analysis of Nanjing city based on remote sensing ecological index. *Geospatial Information*
- Zhang BW (2018) Eco-environmental quality evaluation and system design based on RSEI model. Zhengzhou University
- Zhang Y, Wang ZF, Chen N et al (2017a) Spatial and temporal variation characteristics and influencing factors of ecological environment in Hubei Province. *Environ Sci Technol* S2
- Zhang H, Du PJ, Luo JQ (2017b) Ecological change analysis of Nanjing city based on remote sensing eco-index. *Geospatial Information*
- Zhang NM, Chen DH, Xing F (2019) Ecological change analysis of Bole city in arid region of Xinjiang based on remote sensing eco-index. *Soil Water Conserv Bull* 39:154–159 166
- Zhao CP, Gong JG, Wang H et al (2018) Evaluation of ecological environment in Huangshui basin based on remote sensing. *Rural Water Resources and Hydropower in China*
- Zheng Y (2014) Extraction and change analysis of eco-environmental index based on TM data. Nanjing Forestry University
- Zhu HX, Jia Y, Hou HP (2006) Impact of land use change on ecosystem service value: a case study of Xuzhou. *Sci Technol Manag Land Res* 23:97–99