Research Progress of Urban Ecological Evaluation Methods Based on Remote Sensing Indexes

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Abstract. Urbanization and the ecological environment have a long-standing, mutually constraining relationship. A healthy ecological environment is the natural basis for human society's survival and an important indicator of urbanization. Therefore, an accurate assessment of urban ecology is of vital significance. Remote sensing technology has natural advantages over traditional urban ecological quality assessment methods, such as high efficiency, timeliness, and comprehensive coverage. This paper aims to introduce the application of remote sensing technology in urban ecological evaluation, focusing on both single and comprehensive indices. The method for processing remote sensing indices involves combining captured electromagnetic waves with specific bands to form remote sensing indices. These indices are then analyzed to evaluate urban ecological conditions, including monitoring urban vegetation and evaluating urban development. The research trend of optimizing data sources and improving index construction is also discussed. This paper demonstrates the feasibility of using processing method of remote sensing index for urban ecological evaluation. It provides decision makers with valuable information and offers technical support for promoting sustainable urban development.

Keywords: Sustainable urban planning, ecological assessment, remote sensing indices, environmental monitoring.

1. Introduction

Urbanization is an inevitable trend in socio-economic process, while the ecological environment is the natural foundation on which human society depends for survival. Urbanization has both positive and negative impacts on the ecological environment. While the construction of an ecological environment influences the process of urbanization, the latter brings about anthropogenic impacts that can cause changes in the range of the ecological environment. This is the interactive and mutually constraining relationship between the urban and ecological environments, which is known as the mechanism of interactive coupling between urbanization and the ecological environment [1]. Above all, accurately assessing urban ecological quality is vital in guiding the construction of the urban ecological environment and promoting the urbanization process.

However, traditional means of ground observation, such as monitoring stations or mobile observation teams, have limitations, including low efficiency, poor timeliness, and limited coverage when obtaining multi-party data. Remote sensing technology, aided by modern high technology, can provide rapid and real-time information, effectively addressing the limitations of traditional ecological evaluation. It has become a crucial tool for modern urban ecological evaluation [2]. By combining different bands in satellite or aerial images, researchers can calculate indices that reflect the characteristics of features, such as the Normalized Difference Vegetation Index (NDVI) and the Bare Soil Index (BSI). However, these indices have the disadvantage of not providing an objective and comprehensive reflection of urban ecology. By integrating various environmental and ecological data, composite indices offer a more comprehensive environmental quality evaluation. For instance, the Ecological Index (EI) evaluation method, proposed by the General Administration of Environmental Protection of China in 2006, provides a comprehensive environmental evaluation. Furthermore, machine learning methods such as Remote Sensing Ecological Index (RSEI) [3] and NDVI-ML [4] have been utilized to create comprehensive indices based solely on remotely sensed images. These urban ecological evaluation methods have gained increasing attention and are widely employed in assessing urban ecological quality [5].

This paper introduces a processing method of remote sensing index for both single and composite indices. It describes the progress of applying these methods in urban ecological evaluation, with the aim of bridging the gap between urbanization and the ecological environment, which will provide important technical support for the sustainable development of cities.

2. Method

Any natural object has the ability to emit, absorb, and reflect electromagnetic waves. The difference lies in the unique characteristics of each ground object's reflection or emission radiation. For example, using remote sensing to study vegetation requires consideration of the varying shapes, sizes, and chlorophyll contents of canopy leaves. These factors affect the interaction between leaves and electromagnetic waves, resulting in unique reflections or emissions that reveal the physical and biological properties of the studied features.

The method for processing remote sensing indexes is based on using remote sensors to collect, process, and express electromagnetic wave information reflected or emitted by non-contact targets. These electromagnetic waves form remote sensing indexes, and the enhanced spectral characteristics of specific band combinations can be used to acquire indexes of various elements of concern. This achieves the purpose of sensing the corresponding feature characteristics. When considering vegetation, buildings, and other urban ecological components, they can reflect the urban ecology.

Remote sensing indexes that characterize ecology can be divided into single indexes and comprehensive indices based on the constituent elements. A single index is constructed using mathematical relationships between a single or a pair of specific bands to detect specific types of surface features or conditions. A comprehensive index is a mathematical model that combines multiple single indices. It is designed to provide more comprehensive information by combining multiple surface characteristics. Due to their simplicity and ease of calculation, single indices are more useful in specific applications such as vegetation monitoring and agricultural assessment. Composite indices, on the other hand, are more suitable for urban planning, environmental monitoring, and other scenarios where multiple surface characteristics need to be integrated because they provide more comprehensive information.

2.1. Single index

Table 1. Common single index

Name of index	Meaning	Focus element
NDVI	Measures the density and health of vegetation	Greenness
RVI	Assesses the condition of vegetation, especially in areas with low shrub and sparse vegetation cover	
EVI	Improved vegetation index with better resistance to soil background and atmospheric conditions	
MSAVI	Suppression of soil background, improved vegetation signal	
UNVI	Vegetation monitoring for different vegetation cover levels	
IBI	Assessment of the dryness of built-up land in urbanized areas	Dryness
SI	Assessment of the distribution of bare soil areas, reflecting land degradation	
NDBSI	Identify and assess the distribution of bare soil areas	
NDWI	Monitoring the distribution and changes in surface water bodies Humidity	Humidity
Wet	Moisture component based on the K-T transform, reflecting the moisture status of soil and vegetation	
MNDWI	Improved water monitoring index with reduced sensitivity to vegetation and buildings	
VTCI	Based on Ts-NDVI eigenspace extraction for monitoring vegetation condition in arid zones Heat	Heat
LST	Reflects temperature conditions at the surface	
TVDI	Combines temperature and vegetation information to assess drought conditions	

In urban ecology, greenness, humidity, heat, and dryness are crucial indicators closely linked to human survival. They are also significant factors for humans to intuitively assess the ecological conditions and, therefore, frequently used to evaluate ecosystems [3].

Table 1 shows the primary single exponents of these four important indicators. NDVI is one of the commonly used indices to characterize greenness. The reflectance of healthy green vegetation in the near-infrared (NIR) and infrared (IR) bands differs significantly due to the strong absorption of the IR band for green plants and the high reflectivity and transmissivity of the NIR. Therefore, the NDVI value is directly proportional to the difference between the reflectance of the NIR and IR bands, indicating the vegetation growth and ecology conditions.

2.2. Composite index

Relying on a single index is insufficient to comprehensively and objectively reveal the complexity of urban ecosystems. Evaluation tools that combine multiple indices for comprehensive consideration have emerged, making urban ecological evaluation more objective. The mainstream comprehensive index construction methods include weighted superposition analysis, principal component analysis, and machine learning algorithms.

EI is a result of weighted superposition analysis. This method integrates various environmental and ecological data to comprehensively evaluate environmental quality. While this method has shown promise in applied research for environmental protection and ecological evaluation, it is not widely used due to shortcomings such as subjective interference in the process of indicator selection and weight assignment [6].

For example, the RSEI, using the principal component analysis (PCA) method, follows the specific calculation steps shown in Figure 1. Hanqiu Xu provides an efficient and intuitive environmental monitoring and urban planning tool based on the composite index of remote sensing images. The tool uses four indicators: humidity, greenness, heat, and dryness, combined with PCA. The Remote Sensing Ecological Index (RSEI) synthesizes information from multiple indicators to generate an index that reflects the city's ecological health, similar to the EI index.

As shown in Fig. 1, the construction of composite index with PCA, using RSEI as an example, is mainly divided into three steps: image preprocessing, single index calculation and principal component analysis.

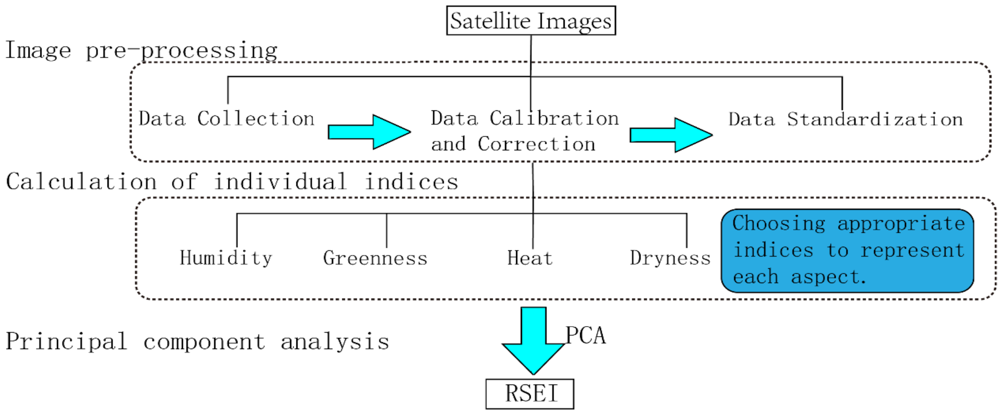

Figure 1. Composite Index Construction Flowchart

First, image preprocessing is required. Preprocessing includes three parts: data acquisition, data calibration and correction, and data normalization. The data collection aspect requires that the images contain low cloudiness, the time phases are the same, and the maximum difference in time phases is less than half a month. This ensures that the data quality and the collected features have similar status. Data calibration and correction includes calibration, geometric correction, radiometric correction, etc., which can ensure the accuracy and consistency of the data. The final normalization can eliminate the differences between different data due to differences in terrain, light, and atmosphere, etc., and ensure that the indicators are comparable when integrating calculations.

In addition, a suitable index needs to be selected for calculation. The RSEI first used the dimensions of Wet, NDVI, LST and NDBSI, representing humidity, greenness, heat and dryness respectively.

Finally, PCA was used to extract the main components and concentrate the main information on the first 1-2 principal components to realize the single variable representing multiple variables. RESI can be expressed as a function of the four indicators:

$$RESI = f(G, W, T, D) \tag{1}$$

Where G for greenness, W for humidity, T for heat, and D for dryness.

The results indicate that RSEI is more consistent with EI [7], simplifying the complexity of data collection and processing. The proposal of RESI facilitates the rapid evaluation of ecological quality based solely on remotely sensed data, which is favored by many scholars [8]. It provides a new objective, fast, and simple perspective on monitoring and evaluating urban ecological quality.

In recent years, index fusion has undergone significant development due to machine learning methods, as well as in the field of remote sensing. Machine learning, particularly deep learning techniques, has proven to be efficient and flexible in extracting information from complex remote sensing data, making it more accurate and feasible. Machine learning methods, such as convolutional neural networks (CNN) and recursive neural networks (RNN), can improve feature extraction and data fusion strategies, leading to higher quality and efficiency in remote sensing data parsing. These methods have demonstrated unique advantages in processing multi-temporal, multi-spectral, and multi-resolution remote sensing data [9, 10].

However, it is worth noting that machine learning is primarily focused on prediction rather than information extraction. Additionally, model training often requires a significant amount of data, computational resources, and time to avoid overfitting. In contrast, PCA can extract the data's main features and reduce data complexity while retaining as much variability as possible from the original data. In remote sensing index synthesis, PCA can effectively identify and extract significant signals from remote sensing data while reducing redundancy and noise, and this is particularly important for monitoring surface features.

3. Application

Remote sensing technology has a unique advantage in the ecological evaluation of cities due to its strong temporal sequence, wide coverage area, low cost, and good dynamics. It provides data on surface cover, vegetation status, and land use changes, among other aspects, in response to the needs of urban ecological evaluation. The use of processing method of remote sensing index in urban ecological evaluation enhances our understanding of ecology during urbanization. It provides decision-makers with new perspectives on existing cities' main ecological evaluation issues.

3.1. Multiple indices

Single indices are easy to calculate and have various urban applications, such as monitoring urban vegetation, studying the urban heat island effect, and monitoring the urbanization process. There is a growing trend towards integrating them with the spatial analysis techniques of Geographic Information Systems (GIS).

The urban heat island effect is the phenomenon where surface and air temperatures in the city center and surrounding areas are significantly higher than those in distant suburbs. Zhang Zhaoming et al. analyzed the spatial distribution characteristics, influencing factors, and seasonal characteristics of the heat island in Beijing using a universal single-channel algorithm to invert the land surface temperature [10]. Hu Hualang et al. took into account the concept of landscape ecology 'thermal landscape' to establish a set of research methods and an evaluation indicators system to study the urban thermal environment by combining remote sensing technology and GIS [11]. The analysis of the results reveals the factors that affect the heat island, which can guide effective urban planning and design mitigation strategies.

To evaluate building sites, the NDBI values obtained from remote sensing images can analyzed to reveal the spatial distribution pattern and change trend of urban building sites [12]. Figure 2 shows the results of a study that evaluated the distribution characteristics of building sites in the main urban area of Chongqing. The study classified NDBI through thresholds to obtain the number structure and spatial distribution characteristics of NDBI in the area. These findings can serve as a valuable data source for urban planning evaluation.

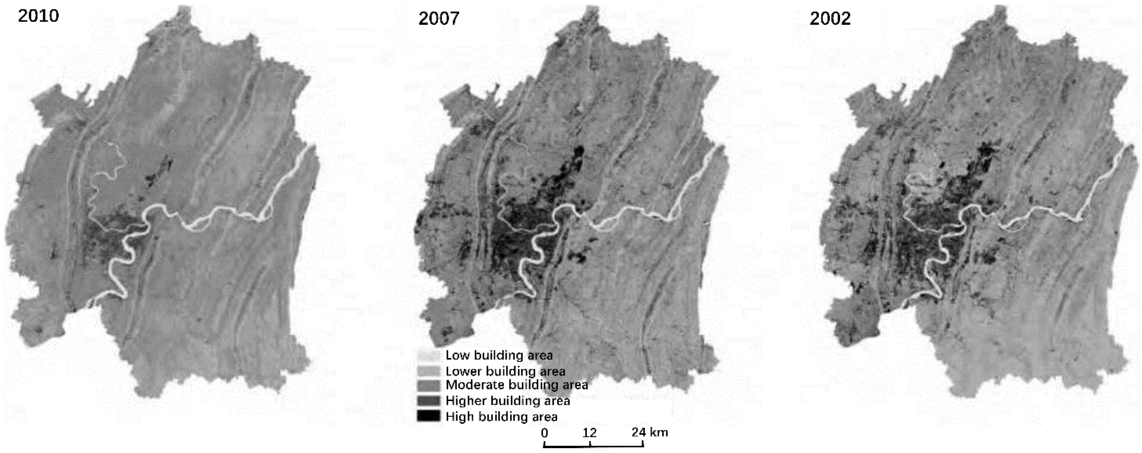

Figure 2. Spatial Distribution of NDBI in Chongqing Metropolitan Area [12]

3.2. Multiple indices

Comprehensive indices are intricate and suitable for detailed analysis. They are used in urban planning to support various tasks, such as assessing the quality of urban development, exploring the urban environment, and monitoring and guiding sustainable urban development strategies.

The combination of remote sensing indices can be achieved through machine learning algorithms. Algorithms like decision trees, random forests, and support vector machines can be combined with various remote sensing indices, such as NDVI, EVI, and atmospheric resistance vegetation index (ARVI), to accurately classify forest species [13]. The NDVI-ML method, which combines NDVI with computer vision and machine learning techniques, can also improve vegetation detection accuracy and efficiency.

The RSEI-based method for quantifying urban ecological health represents the PCA method for generating a comprehensive index. It widely applies to monitoring urban expansion and its impact on the ecological environment. Xu et al. proposed and refined the RSEI methodology to objectively assess the ecological impacts of urban development and population growth. For instance, statistical modeling was used to predict the relationship between the population, the increase of impervious surface (IS), and their impacts on the RSEI, by combining the feature inversion technique and the improved RSEI [14]. Xiongan New Area was chosen as the study area. The study introduced the concept of IS area-related population density (IPD) and found that the ecological quality of the new area is related to IPD rather than traditional population density. This finding provides a new perspective for the regional master planning of the new area. Additionally, the RSEI was improved by introducing sharpened LST and implementing the change vector analysis (CVA) method [15]. This improved method was applied to quantify and detect ecological changes in Fujian Province from 2002 to 2017. The results revealed an overall improvement in ecological conditions in Fujian Province during the study period but also identified ecological degradation in the eastern coastal areas. It serves as a foundation for implementing specific ecological restoration actions.

4. Discussion

The remote sensing index is one of the most direct products of remote sensors, effectively solving the optical features multi-scale effects and other issues. Higher social demand for remote sensing index has gradually emerged, mainly reflected in the optimization of data sources and the improvement of index construction in two aspects.

The lack of a universally accepted index is a major challenge. Using RSEI as an example, the original author selected NDVI, NDBSI, LST, and Wet as indices but did not provide a basis for their selection. Furthermore, several indices have limitations. For instance, the NDVI exhibits lower sensitivity in areas with high vegetation. Zhang Yaqiu et al. conducted an exploratory study based on analyzing multiple indices and examining their correlation, and they selected a set of indices that more accurately reflect the ecological environment status of the study area [7]. However, index construction still needs improvement.

Additionally, the innovative fusion algorithm optimizes data sources. When processing remote sensing data, algorithms such as STARFM can be used to fuse high spatial resolution and high temporal resolution images, resulting in significantly improved image accuracy [16]. The use of fusion algorithms can effectively address the issue of low accuracy in data sources. This is significant for fine monitoring and assessment of ecological changes, enabling researchers to more accurately capture the nuances of environmental changes and support the process of environmental management and decision-making.

Finally, attention has been given to the progress made in the application of light quantum polarization remote sensing technology. To address the issue of quantitative remote sensing in atmospheric transmission, optical quantum polarization remote sensing technology can improve the accuracy of surface vegetation inversion models, reduce the error assessment of atmospheric impacts, and enhance the spatial and spectral resolution of optical remote sensing systems [17]. This advancement offers a new perspective on the processing method of remote sensing indices for urban ecological evaluation. It also allows overcoming the uncertainty of remote sensing irradiance calibration.

5. Conclusion

The processing method of remote sensing indices has great potential for development in urban ecological evaluation and has garnered increasing attention from researchers. This paper introduces both single and comprehensive indices and provides examples of the progress made in applying processing method of remote sensing index to urban ecological evaluation.

The single index is easy to compute and can be used to monitor specific elements of the city, such as urban vegetation, the urban heat island effect, and the urbanization process. Composite indices are advantageous for detailed and comprehensive analysis, such as assessing the quality of urban development, exploring the urban environment, guiding the sustainable development of cities, and other multidimensional functions. In the composite indices part, this paper introduces and compares mainstream weighted superposition analysis, principal component analysis, and machine learning algorithms for the multi-source remote sensing index combination method. It concludes that traditional weighted superposition analysis has shortcomings in index selection and human interference in weight assignment, machine learning focuses more on prediction, and PCA focuses more on information extraction. Finally, this paper points out the development trends of optimizing data sources and improving index construction.

The processing method for remote sensing indices bridges urbanization and the ecological environment, providing crucial technical support for the sustainable development of cities, enabling scientific and efficient urban planning and enhancing the ability to monitor and respond to environmental conditions.

References

[1] Huang Huangchuan, Fang Chuanglin. Analysis of the interactive coupling mechanism and regularity of urbanization and ecological environment. Geographic Research, 2003, (02): 211-220.

[2] Zhao Shaohua, Liu Sihan, Liu Qinqin, et al. Current status and development trends of remote sensing monitoring of urban ecological environment in China. Journal of Ecology and Environment, 2019, 28 (06): 1261-1271.

[3] Xu Hanqiu. Creation and application of urban remote sensing ecological index. Acta Ecologica Sinica, 2013, 33 (24): 7853-7862.

[4] Ayhan B, Kwan C, Budavari B, Kwan L, Lu Y, Perez D, Li J, Skarlatos D, Vlachos M. Vegetation Detection Using Deep Learning and Conventional Methods. Remote Sensing, 2020, 12 (15): 2502.

[5] Wang Lichun, Jiao Li, Laifeng Bing, et al. Evaluation of ecological changes in Xinjiang Manas Lake wetland based on remote sensing ecological index. Acta Ecologica Sinica, 2019, 39 (08): 2963-2972.

[6] Wen Xiaole, Chen Xu, Xu Hanqiu. Urban ecological evaluation in the southern suburbs of Beijing based on remote sensing ecological index - taking Zhuozhou City and Gu'an County as examples. Journal of Fuzhou University (Natural Science Edition), 2022, 50 (02): 286-292.

[7] Zhang Yaqiu, Jiang Fang, Ji Mengda, et al. District and county-level ecological environment assessment based on remote sensing indices. Arid Area Research, 2020, 37 (06): 1598-1605.

[8] Zhang Can, Xu Hanqiu, Zhang Hao, et al. Vegetation coverage changes and ecological effect assessment in typical soil erosion areas of southern red soil - taking Changting County, Fujian Province as an example. Journal of Natural Resources, 2015, 30 (06): 917-928.

[9] Chergui, Nabila, Yasmina Saker and Yousra Belayat. “Forest Tree Species Classification Using Machine Learning and Satellite Images.” 2023 International Conference on Earth Observation and Geo-Spatial Information (ICEOGI) (2023): 1-5.

[10] Zhang Zhaoming, He Guojin, Xiao Rongbo, Wang Wei, Ouyang Zhiyun. Research on heat island in Beijing based on RS and GIS. Journal of Earth Science and Environment, 2007, 29 (1): 107-110

[11] Hu Hualang, Chen Yunhao, Gong Adu. Research progress on remote sensing of urban heat islands. Remote Sensing of Land and Resources, 2005, 17 (3): 5-913.

[12] Zhang Xiaoyuan, Zhou Qigang. Research on the distribution characteristics of NDBI in the main urban area of Chongqing based on GIS and RS. Soil and Water Conservation Research, 2014, 21 (05): 111-115.

[13] Meta-analysis of deep neural networks in remote sensing: A comparative study of mono-temporal classification to support vector machines. ISPRS Journal of Photogrammetry and Remote Sensing, 2019, 152: 192–210.

[14] Xu H, Wang M, Shi T, Guan H, Fang C, Lin Z. Prediction of ecological effects of potential population and impervious surface increases using a remote sensing based ecological index (RSEI). Ecological Indicators, 2018, 93: 730–740.

[15] Xu H, Wang Y, Guan H, Shi T, Hu X. Detecting Ecological Changes with a Remote Sensing Based Ecological Index (RSEI) Produced Time Series and Change Vector Analysis. Remote Sensing, 2019, 11 (20)): 2345.

[16] Liu Jianbo, Ma Yong, Wu Yitian, et al. Research progress and application status of high spatial and temporal fusion methods in remote sensing. Journal of Remote Sensing, 2016, 20 (05): 1038-1049.

[17] Yan Lei, Gu Xingfa, Chu Junhao, et al. Polarized light effect of high-resolution quantitative remote sensing and new fields of polarization remote sensing. Journal of Remote Sensing, 2018, 22 (06): 901-916.