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Analysis of vegetation cover changes in the context of urbanization in Wuhan based on Normalized Difference Vegetation Index

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Abstract:

In this study, the vegetation cover changes in Wuhan city in the context of rapid urbanization were analyzed by calculating the Normalized Difference Vegetation Index (NDVI) using Landsat satellite imagery in 2004, 2015, and 2024. The results of the study revealed a significant decrease in vegetation cover in the fringe areas of Wuhan between 2004 and 2015 due to urban expansion. However, between 2015 and 2024, with the implementation of ecological restoration and greening projects, the vegetation cover was restored and improved in some areas, especially in the new urban areas and ecological construction zones. The NDVI difference analysis showed the spatial distribution characteristics of vegetation degradation and restoration, pointing out the unevenness of vegetation cover changes in the urbanization process. This study highlights the importance of balancing urban development and ecological environmental protection in the process of urbanization and provides a scientific basis for urban ecological planning and sustainable development in Wuhan. Meanwhile, the methodology and findings of this study can serve as a reference for ecological studies in other rapidly urbanizing regions and help to understand and address the ecological challenges posed by urbanization.

Keywords: NDVI; Vegetation cover change; Urban expansion; Ecological governance.

1. Introduction

As global urbanization accelerates, urban ecosystems are facing unprecedented challenges. UN-Habitat predicts that the global urban population will account for 68 per cent of the world's population by 2050, with Asia being one of the regions with the most rapid urban expansion [1].In China, this process is particularly prominent: data from the National Bureau of Statistics (NBS) show that the urbanization rate of China's resident population jumped from 17.9 per cent to 65.2 per cent between 1978 and 2022, and the China Statistical Yearbook 2023 states that in 2022 alone there will be an increase in urban construction land of about 3.9×10^4 km^2 [2]. Such drastic land use changes have been shown to exacerbate urban heat island intensity and lead to a chain of ecological problems, such as regional air quality degradation, soil erosion [3, 4].

Vegetation is an important component of urban ecosystems, which not only provides residents with key ecological services such as purifying air, regulating climate, and conserving soil and water, but also serves as the basis for maintaining urban biodiversity [5]. However, numerous studies have shown that rapid urbanization is often accompanied by fragmentation and loss of natural vegetation patches [6]. For example, Liu found that 35 large cities in China lost an average of 18% of their high-density vegetation areas from 2000-2015, with urban centres being particularly severe [7].

In recent years, remote sensing technology has become a core tool for urban ecological monitoring. Multi-source data such as MODIS, Landsat, and Sentinel provide long time-series, high spatial resolution vegetation information [8]. The Normalized Difference Vegetation Index (NDVI) is widely used to quantify vegetation cover and its dynamics due to its sensitivity to chlorophyll uptake characteristics [9]. Smith's team used Landsat imagery to reveal that the Boston metropolitan area experienced a 12% decline in vegetation cover between 1990 and 2006 due to urban sprawl [10]. Zhang and Guindon showed that a greening project within the fifth ring road in Beijing resulted in an 8.7% rebound in the area of highly vegetated areas between 2010 and 2020 based on NDVI analysis [11]. These studies show that NDVI is an effective tool that can provide a scientific basis for urban ecological planning and management.

This study takes Wuhan as an example to explore the characteristics of vegetation cover and its driving mechanism in the context of urbanization. The study aims to calculate the NDVI and analyze its spatial and temporal change characteristics by examining Landsat image data from 2004, 2015, and 2024. The research analyzes the spatial distribution characteristics of vegetation cover in Wuhan. It also evaluates how vegetation cover has changed over time, including shifts in the mean NDVI and the area covered by different vegetation classes. Another focus is exploring the spatial patterns of these vegetation cover changes and pinpointing areas where vegetation has degraded or recovered. Additionally, the impacts of urban expansion and ecological management on vegetation cover changes are examined. This study is expected to provide a scientific basis for urban ecological planning and sustainable development in Wuhan and serve as a reference for ecological research in other rapidly urbanizing regions.

2. Study Area and Data Sources

2.1 Study Area

This study focuses on Wuhan, an important city in central China (Figure 1).Located in Hubei Province, China, Wuhan is the geographical centre point of China and the confluence of the Yangtze and Han Rivers, which gives it a unique geographical location and strategic importance. As the capital of Hubei Province, Wuhan is the political, economic, cultural and transportation centre of central China.The city's climate is subtropical monsoon, with four distinct seasons and abundant rainfall, providing good natural conditions for vegetation growth.

Wuhan has a complex urban structure and rapid urbanization, and urban expansion has had a significant impact on the surrounding ecological environment. In recent years, with the acceleration of urbanization, the built-up area of Wuhan has been expanding, and urban green spaces and natural vegetation have been encroached upon and damaged to varying degrees. Therefore, it is important to study the vegetation cover changes in Wuhan to understand the impact of urbanization on the ecological environment.

Figure 1. Study area

2.2 Data sources and pre-processing

The data source used in this study is Landsat series satellite imagery, specifically including image data from 2004,

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2015 and 2024.The images at these three time points were chosen to capture the vegetation cover status of Wuhan at different stages of urbanization.The image data were chosen to be acquired in summer to reduce the influence of seasonal differences on NDVI calculation.

The data acquisition platform is mainly Google Earth Engine (GEE), which is a powerful remote sensing image processing and analysis platform that supports the preprocessing of large-scale remote sensing images and NDVI calculations. The advantage of the GEE is that it is able to process and analyse a large amount of remote sensing data, and at the same time, it provides preprocessing functions, such as cloud coverage culling, image cropping, which greatly improve the efficiency and accuracy of data processing. The efficiency and accuracy of data processing are greatly improved.

The data preprocessing steps include geometric and radiometric corrections to ensure the accuracy and consistency of the image data. In addition, cloud cover is removed using the Fmask algorithm or GEE's built-in cloud mask function to reduce the influence of clouds on NDVI calculations. Finally, the images were cropped according to the administrative boundaries of Wuhan to ensure the accuracy of the study area. Through these preprocessing steps, high-quality remote sensing image data can be obtained, providing a reliable database for the subsequent NDVI calculation and vegetation cover change analysis. These data will help to deeply understand the characteristics of vegetation cover changes in Wuhan in the context of urbanization and provide a scientific basis for urban ecological planning and sustainable development.

In this paper, three special years, 2004, 2015, and 2024, which represent three special stages of Wuhan's early urban construction, rapid urban expansion, and ecological restoration, respectively, will be selected as the research objects, which are of high research significance.

3. Methodology

3.1 NDVI calculation

The Normalized Difference Vegetation Index (NDVI) is an important indicator of vegetation cover status and is calculated as in equation (1):

$$NDVI= (NIR-Red)/(NIR+Red) \tag{1}$$

Where NIR represents the reflectance in the near-infrared band, and Red represents the reflectance in the red light band. In this study, Landsat satellite images were used, and the NIR and Red bands were selected for the calculation. The values of NDVI range from -1 to 1. Positive values usually indicate the presence of vegetation, and the larger the value, the higher the vegetation cover. Negative values may represent water bodies or areas without vegetation.

3.2 NDVI classification

In order to analyse the status of vegetation cover more intuitively, NDVI values were reclassified into four levels following the thresholds widely adopted in urban vegetation studies [11]. The NDVI values are divided into the following four levels. NDVI > 0.6 is a high-density vegetation area, representing good vegetation cover, such as forests, grasslands. $0.3 <$ NDVI ≤ 0.6 is a medium vegetation area, with average vegetation cover, which may include bushes, sparse grasslands. $0.1 <$ NDVI ≤ 0.3 is a sparse vegetation area, with less vegetation cover, which may be green areas in cities, farmlands. NDVI ≤ 0.1 is no vegetation or building land, mainly urban built-up areas, and bare land. This scheme is consistent with the classification systems recommended by Pettorelli for comparative NDVI-based vegetation monitoring and facilitates clear interpretation of spatio-temporal changes in urban vegetation cover [9].

3.3 Methods for analysing vegetation change

3.3.1 NDVI difference analysis

Changes in vegetation cover can be visually identified by calculating the difference between NDVI images from different periods. This is done by subtracting the NDVI image of 2024 from the NDVI images of 2015 and 2004, respectively, to obtain a difference plot. Positive values in the difference plot indicate an increase in vegetation cover, and negative values indicate a decrease in vegetation cover. This method can quickly locate areas of vegetation change and provide a basis for subsequent detailed analyses.

3.3.2 NDVI mean value statistics

The mean values of NDVI images were calculated for each period to reflect the overall trend of vegetation cover across the study area. By comparing the NDVI mean values in 2004, 2015, and 2024, the overall change in vegetation cover during urbanization can be understood.

3.3.3 Analysis of area changes

The area of areas with different NDVI classes was counted and analysed to assess the scale and extent of changes in vegetation cover. The specific steps are as follows:

First, based on the preset NDVI classification standard, the remote sensing image data at each time node are graded, and the spatial area of each NDVI grade area is counted separately. Second, based on the results of area statistics, the area change rate of each NDVI grade area is calculated, which is defined by the formula (2):

$$\text{Area change rate} = \frac{latearea - earlyarea}{earlyarea} \times 100\% \qquad (2)$$

Through the above analysis, the dynamic trends of high-density vegetation area, medium vegetation area, sparse vegetation area and no vegetation area can be revealed in depth. This method not only helps to comprehensively grasp the scale and extent of changes in vegetation cover, but also provides a scientific basis for assessing the impact of urbanization on the regional ecological environment.

3.3.4 Spatial distribution analysis

In this study, the spatial distribution characteristics of vegetation cover changes were analysed in detail by combining the NDVI difference map and the results of area change analysis. By comparing the NDVI distribution maps in different periods, regional differences in vegetation cover changes can be observed. For example, urban centre areas may experience a decrease in vegetation cover due to an increase in construction land, while suburban areas or new areas may achieve an increase in vegetation cover through ecological restoration and greening projects. This spatial distribution analysis helps to reveal the patterns and characteristics of vegetation cover changes in the process of urbanization and provides a scientific basis for urban planning and ecological protection.

3.3.5 Data processing and analysis tools

This study mainly uses ArcGIS software for data processing and analysis.ArcGIS is equipped with powerful spatial analysis functions, which can conveniently carry out operations such as NDVI calculation, image classification, difference analysis, and area statistics. In addition, the Google Earth Engine platform will also play an important role in the data preprocessing stage, which supports the preprocessing of large-scale remote sensing images and NDVI calculation, and can improve the efficiency and accuracy of data processing. By combining these two tools, the scientific nature of the research method and the reliability of data processing can be ensured.

4. Results

4.1 Spatial Distribution of NDVI

4.1.1 Spatial distribution characteristics of NDVI in 2004

In 2004, vegetation cover in Wuhan showed significant spatial heterogeneity, with high NDVI values concentrated in mountainous areas, wetlands and lakes around the periphery of the city, such as the East Lake and the South Lake areas (Figure 2). This reflects the fact that there was still a lot of natural vegetation and green space in the early stage of urbanization. In contrast, the NDVI values in the central city were lower, indicating that the expansion of urban buildings and infrastructure has caused some compression of vegetation cover. The urban fringe areas, on the other hand, showed a high to low NDVI gradient, which may be related to the erosion of natural vegetation at the early stage of urban expansion.

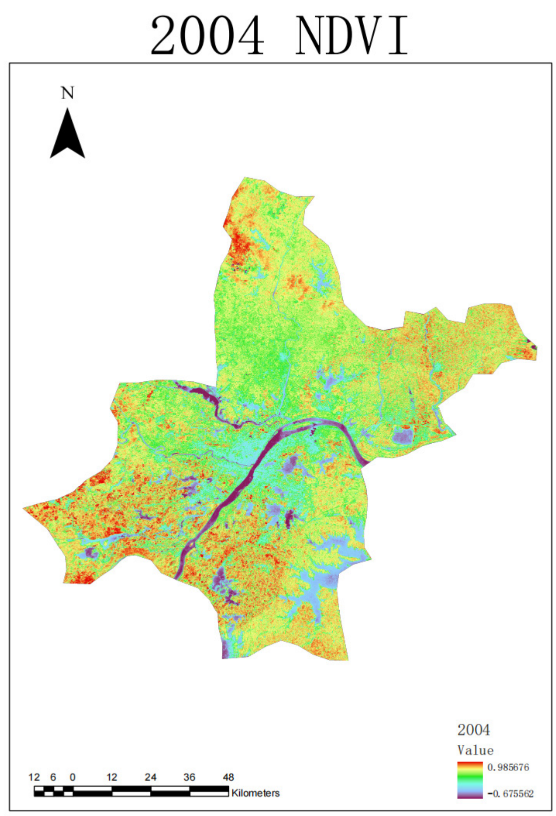

Figure 2. Wuhan NDVI 2004

4.1.2 Characteristics of NDVI spatial distribution in 2015

In 2015, along with the acceleration of urbanization, the NDVI image showed significant changes in vegetation cover (Figure 3). The NDVI values in the central area of the city increased, probably thanks to the greening project and the construction of the green space system. However, areas with high NDVI values in the periphery of the city, especially in the urban-rural interface of Hannan, Jiangxia, and Huangpi, showed a significant shrinkage and a significant decrease in NDVI values, reflecting the encroachment of urban expansion on the peripheral green space. The construction of new urban areas also led to the disappearance of some green areas, making the high

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NDVI value area further reduced.

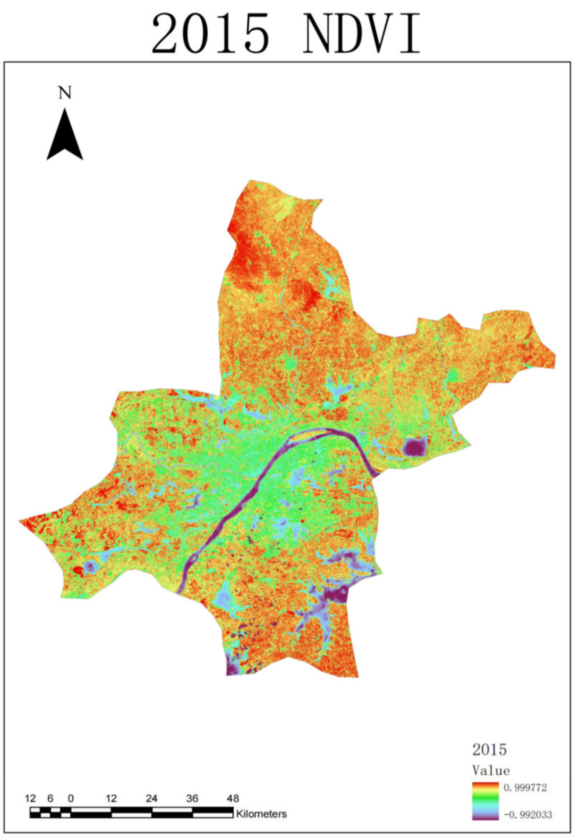

Figure 3. Wuhan NDVI 2015

4.1.3 Characteristics of the spatial distribution of NDVI in 2024

By 2024, the vegetation cover in Wuhan had recovered (Figure 4). The NDVI values in suburban areas such as Guanggu and Jiangxia have improved, indicating that the vegetation cover in these areas has improved, which may be related to the continuous promotion of urban ecological restoration and greening projects. The NDVI value in the city centre area, although still low, has improved compared to 2015, which may reflect the effectiveness of green space system construction in the centre area. Overall, the NDVI image in 2024 shows a shift in the spatial distribution of vegetation cover from “centralised distribution” to “localised restoration” and “decentralised improvement”, suggesting that although the city is still in the middle of the urban area. This indicates that despite the pressure of urban expansion, ecological restoration measures have contributed to the recovery and improvement of vegetation cover in some areas.

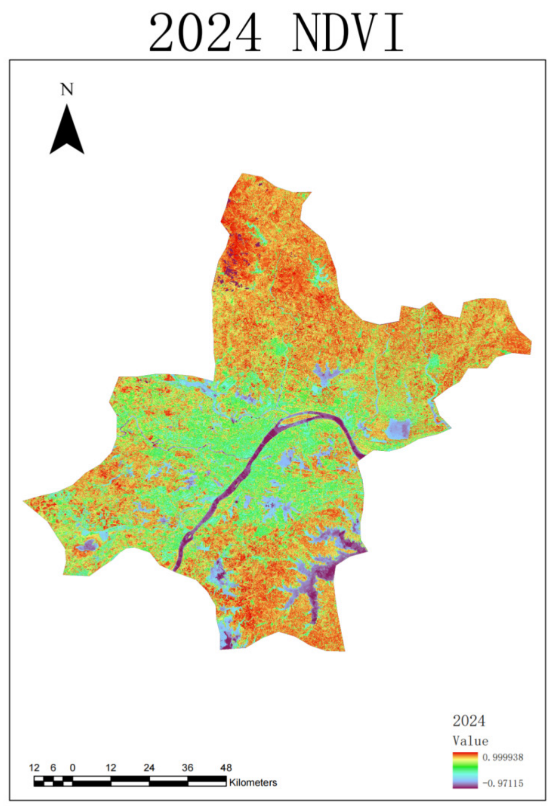

Figure 4. Wuhan NDVI 2024

4.2 Vegetation degradation and restoration

4.2.1 Spatial patterns of vegetation degradation and restoration

Based on the NDVI difference map, the areas of vegetation degradation in Wuhan during the study period can be identified (Figure 5). The figure shows that the areas with significant NDVI degradation are mainly concentrated in the urban fringe expansion zones, such as the urban-rural interface of Hannan, Jiangxia, and Huangpi. These areas experienced rapid expansion of construction land during the urbanization process, destroying the original natural vegetation, a decrease in NDVI values, and a significant reduction in vegetation cover. In addition, the urban centre area also showed a certain degree of decline in NDVI values. Despite improvements in the region between 2015 and 2024, there are still signs of vegetation degradation compared to 2004, which is mainly attributed to the replacement of green space by buildings and other infrastructure under high-density development.

In contrast, the NDVI difference map also reveals the areas of vegetation recovery in Wuhan during the same period. The vegetation restoration areas are mainly concentrated in new urban areas, such as the Guanggu ecological construction area and the Wuhan greenway coverage area. These areas received more ecological attention and investment during urbanization. The increase in vegetation cover was effectively promoted through ecological restoration and greening projects. In particular, in the Guanggu area, as a high-tech industrial development zone in Wuhan, a series of ecological restoration projects (including afforestation, wetland restoration, etc.) implemented in recent years have significantly increased the NDVI value of the area and promoted the restoration and growth of vegetation cover.

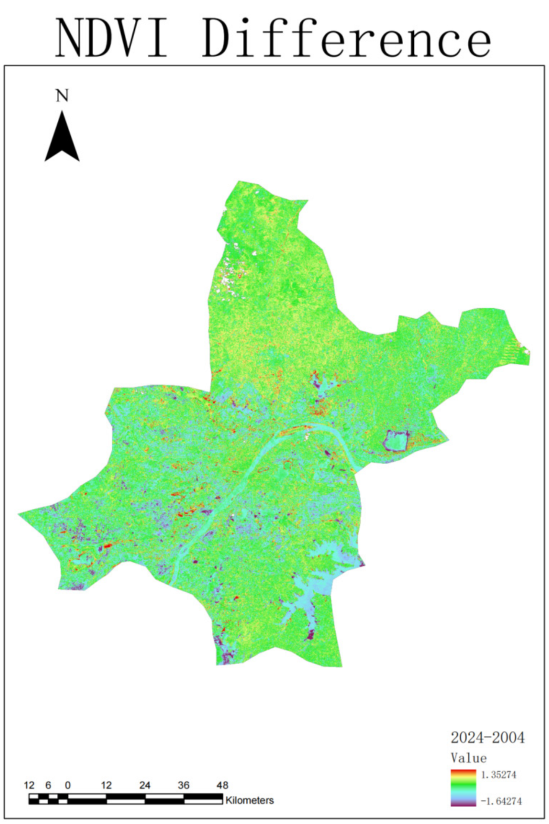

Figure 5. 2004-2024 NDVI variance

4.2.2 Urban Expansion and Ecological Governance Effectiveness

The above pattern of spatial change deeply reflects the internal logic of urban expansion and the effectiveness of its ecological management. Urban expansion inevitably increases the amount of land for construction, which puts significant pressure on the surrounding ecological environment, especially in the urban periphery. However, with increased awareness of ecological management and effective implementation of relevant policies, Wuhan has achieved vegetation restoration and localised improvement in specific areas. It should be noted that there is an obvious imbalance between vegetation degradation and restoration: constructive ecological interventions (e.g., greening projects, ecological restoration projects) can effectively improve NDVI values in localised areas, but due to the limitations of their spatial coverage, they have not yet been able to benefit all areas of the city. It is clear that although urbanization has had an overall negative impact on vegetation cover, it can be mitigated and restored at a limited spatial scale through targeted ecological management measures.

5. Conclusion

In this study, the dynamic changes of vegetation cover in the context of rapid urbanization in Wuhan were systematically analysed using the NDVI based on Landsat satellite images in 2004, 2015, and 2024. Through the comparative analysis of multi-temporal NDVI images, the spatial and temporal evolution of vegetation cover in Wuhan during the study period was revealed. The results show that the vegetation cover in Wuhan experienced significant degradation between 2004 and 2015, which is mainly attributed to the rapid increase of construction land due to urban expansion. However, between 2015 and 2024, the vegetation cover in some areas (especially in the new urban areas and key ecological construction zones) has been effectively restored and improved by ecological restoration and greening projects, and the NDVI difference analysis further highlights the unevenness of the spatial distribution of vegetation degradation and restoration. Although the level of vegetation cover in the city centre is still relatively low, the recovery of vegetation in the suburbs and new areas strongly confirms the positive effects of the ecological management measures.

The core conclusion of this study emphasises the importance of balancing urban development and ecological protection in the process of urbanization. The case of Wuhan has demonstrated that scientific and rational urban planning and effective ecological management measures can, to a certain extent, moderate the negative pressure on vegetation cover caused by urban expansion, and thus promote sustainable urban development. In the future, urban planning should pay more attention to the construction of green space system networks and the continuous implementation of ecological restoration projects, so as to comprehensively improve the ecological service function of the city and the quality of life of the residents.

In addition, the methodological system and the main findings of this study can provide a useful reference for the study of vegetation cover changes in other areas facing the challenges of rapid urbanization. Dynamic monitoring and assessment using remote sensing technology and NDVI is an effective scientific way to understand the impact of

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urbanization on vegetation cover and to support urban ecological planning and management. As the global urbanization process continues, continuous monitoring and in-depth analyses of such ecological changes are essential to effectively address the ecological challenges posed by urbanization.

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