

Article

Trends in Urban Vegetation Growth in China from 2000 to 2022

Fang-Jie Yu and Li Yan *

School of Geodesy and Geomatics, Wuhan University, Wuhan 430072, China

* Correspondence: liyan@sgg.whu.edu.cn

Abstract: Over the past two decades, urbanization in China has been advancing rapidly. The intricate effects of urbanization on vegetation growth in the urban core have been studied and reported. However, the percentage of impervious surfaces in the urban core, as defined in previous studies, was relatively low, and included some pixels containing farmland and water bodies. Consequently, their results may be affected by urbanization processes, such as the transformation of land types. Hence, this paper extracted 100% impervious surfaces from 2000 to 2022 as urban core areas in China using a 30 m resolution China land cover dataset (CLCD), which completely excluded the effect of urbanization itself on the experimental results, obtaining the trend of vegetation change in the real urban core area. Employing the remote sensing imagery of the Enhanced Vegetation Index (EVI) from 2000 to 2022, we analyzed the growth of vegetation in 1559 urban cores and the surrounding rural areas in China. The study's findings revealed that the majority of the core areas (85.3%) studied in this paper exhibited a significant ($p < 0.05$) increase in vegetation, indicating that the various urban greening policies in China have been effective. However, only about 23.7% (369) of the urban core areas showed a faster increase in vegetation than the rural areas. This suggests that for most urban cores (1190), vegetation increase is not as pronounced as it is in surrounding rural areas. Additionally, the EVI rate of change in the urban cores obtained using CLCD versus MODIS land cover data significantly differed. The latter obtained a less pronounced trend of vegetation growth compared to the former, attributable to the disparity in their spatial resolution and the methodology used to define urban areas. The study underscores the importance of vegetation growth and its distribution in various urban core areas to comprehend the dynamics of urban cores' vegetation growth and to offer insights for the subsequent formulation of greening policies. Moreover, data with different resolutions will significantly impact the results, thus highlighting the necessity of employing high spatial resolution data for more comprehensive research.



Citation: Yu, F.-J.; Yan, L. Trends in Urban Vegetation Growth in China from 2000 to 2022. *Land* **2024**, *13*, 1015. <https://doi.org/10.3390/land13071015>

Academic Editor: Eusebio Cano Carmona

Received: 17 May 2024

Revised: 21 June 2024

Accepted: 5 July 2024

Published: 8 July 2024



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Keywords: urbanization; urban core; rural area; enhanced vegetation index (EVI); remote sensing

1. Introduction

Urbanization is a global phenomenon encompassing various social changes, including the expansion of towns and cities [1]. Since the beginning of the 21st century, China's urbanization process has experienced rapid advancement. Notably, China's newly added built-up area from 2001 to 2018 ranked first globally [2]. Urbanization typically involves the conversion of green spaces into impervious surfaces, i.e., a shift in the land cover type [3,4], which imposes pressure on urban ecosystems and, consequently, diminishes the net primary productivity of vegetation [5], potentially hindering vegetation growth [6,7]. Moreover, increased urbanization leads to higher temperatures and concentrations of carbon dioxide, which may benefit plant growth [8–11]. Additionally, green management initiatives in cities positively influence plant growth. Therefore, the impact of urbanization on vegetation growth is intricate and multifaceted [9,12]. Nevertheless, after the urban core is fully urbanized, changes in the types of land cover there will essentially cease to happen. Therefore, in contrast to the newly built-up urban areas, temperature, carbon dioxide concentration, and urban greening initiatives have a greater impact on vegetation changes in urban cores than does urbanization itself.

Recent studies have indicated that urbanization in China has a dual effect on urban vegetation growth. For peri-urban villages, it has been observed that vegetation responds less to urbanization the farther away it is from the urban core [13–15]. In certain arid areas of China characterized by fragile natural conditions, urbanization significantly benefits vegetation growth [16]. Conversely, in coastal cities in the southeast, which are characterized by abundant precipitation, urbanization has a minimal impact on vegetation growth [17]. Additionally, the impacts of urbanization on vegetation vary during different stages [18]. In the early stages of urbanization, negative effects predominate, whereas in recent stages, positive effects have become more prominent [13].

Urban greening is often suggested as an effective approach to alleviate urban environmental challenges, including air pollution [19–21], noise, and urban heat islands [22], all of which pose significant threats to the health of urban residents. And for the urban core, as the area where political, economic, cultural and other public activities of a city are most concentrated, the greening situation is also closely noticed by people. China has also been committed to sustainable development strategies aimed at enhancing urban greenery. Numerous scholars have previously investigated vegetation changes in various Chinese urban cores [13,15,23–33]. In 2014, Zhou et al. [33] examined the spatial and temporal trends of terrestrial vegetation activities in 32 major Chinese cities along the gradient of urban development intensity, revealing that the impact of urbanization on urban vegetation varied according to the Urban Development Index (UDI) region within each city. In 2017, utilizing cloudless Landsat and other imagery from 2000 to 2014, Chen et al. [24] quantitatively assessed the changes in green space in densely populated urban cores in China during the 21st century. Their results indicated that green space coverage continued to decline in both old and new urban areas in most of the cities studied. In 2019, Du et al. [13] selected 46 representative metropolises in China to investigate the impact of urbanization on vegetation cover in urban core built-up areas over the past 40 years, revealing significant spatial variation in the effects of urbanization on vegetation in China. In 2021, Hong et al. [25] utilized remote sensing data to examine the green changes in China's urban core built-up areas from 2001 to 2018, revealing varied trends of vegetation changes across different stages of built-up areas. And in 2023, Zhang et al. [31] investigated vegetation changes in 315 Chinese cities under the influence of urbanization and meteorological changes, elucidating vegetation growth trends and their relationship with urbanization.

However, most previous studies have treated all pixels with a percentage of impervious surfaces greater than a certain threshold as the urban core. For instance, in their study, Zhou et al. [33] considered all pixels with a UDI greater than 75% as urban cores. In Zhao et al.'s study [32], urban core areas were defined as pixels with a UBI greater than 50%. In their 2023 study, Zhang et al. [31] considered pixels with a percentage of impervious surfaces greater than 50% as the urban core. Zhong et al. [34] defined areas with a UDI greater than 75% as the urban core in their 2024 study. During the urbanization process, some parts of the urban core, in these studies, may transform its land type. As a result, their findings may incorporate the impacts of urbanization itself, including significant reductions in vegetation area due to changes in land cover types. Thus, vegetation in most of the urban cores, in these studies, show a decreasing trend. For instance, the average area-weighted growing season EVI from 2000 to 2012 decreased significantly ($p < 0.05$) with increasing UDI in 28 of the 32 cities studied by Zhou et al. [33]. In Zhang et al.'s study [31], urban vegetation cover and urban vegetation per capita showed a significant decline from 2003 to 2020. The urban vegetation coverage decreased by 0.35% per year, and the urban vegetation per capita decreased by 0.51 m² per year at the national scale. The authors' results include the direct effects of urbanization on urban vegetation, such as sprawl. However, they were unable to obtain information on vegetation changes in areas that were no longer experiencing urban structural changes. In addition, if 50% or 75% is chosen as the threshold, the urban core may contain some water bodies and farmland,

which may lead to some uncertainty. These issues would have a serious impact on the experimental results and must be addressed.

Therefore, in this study, we defined the urban core as a collection of pixels with 100% impervious surfaces, excluding those pixels where urban sprawl would have occurred during the study period; based on this, we analyzed trends in vegetation change in the true urban core, which can be used to assess the effectiveness of urban greening policies over the past two decades and to provide a basis for subsequent policy development. We initially extracted the urban component from the China land cover dataset (CLCD). Following resampling, impervious surfaces with a resolution of 250 m were acquired. Subsequently, pixels with 100% impervious surfaces were extracted from the resampled data as urban core areas. Urban core areas from 2000 to 2022 were then used to define the study area, ensuring that our core area did not undergo land type change during the study period and, thus, completely eliminating the potential impacts of urbanization, water bodies, and farmland, such as urban expansion. Considering that the urban core is no longer experiencing land type change and that the vegetation there is mainly affected by indirect factors from urbanization and urban sustainable development policies, the following hypotheses are proposed. (1) In the last two decades, vegetation in most urban cores has shown a significant growth trend. (2) Different land cover data can significantly impact the observed vegetation growth trends in the urban core. We analyzed temporal changes in the Enhanced Vegetation Index (EVI) within 1559 major urban cores in China, along with the surrounding rural areas within a 10 km radius, throughout the urbanization process. Ultimately, we obtained the vegetation growth trend in urban core areas during 2000–2022, aiming to inspire and inform future enhancements in greening policy.

2. Data and Study Area

2.1. Data

2.1.1. CLCD

The CLCD product is created by combining Landsat images with Google Maps. We obtained the CLCD spanning from 2000 to 2022. This dataset boasts a high spatial resolution of 30 m and documents the coverage of nine distinct land types across China. Nine primary land use categories are classified, including cropland, forest, shrub, grassland, water, snow/ice, barren, impervious, and wetland. Based on visually interpreted samples, the CLCD products achieved an overall accuracy of 79.31% [23]. Furthermore, an assessment using test samples from third parties revealed that the overall accuracy of CLCD surpasses that of MCD12Q1, ESACCI_LC, FROM_GLC, and GlobaLand30 [35].

2.1.2. MODIS Land Cover Data

The MODIS Land Cover Type Product (MCD12Q1) maps global land cover at a 500-m spatial resolution at an annual time step for six different land cover legends [36]. These maps are generated through the classification of spectro-temporal features extracted from MODIS data. For this study, images spanning from 2001 to 2021 were utilized to identify urban areas. Ultimately, we examined the disparities between the results obtained from CLCD products and MODIS images.

2.1.3. MODIS Enhanced Vegetation Index (EVI)

In this study, EVI is generated from the remote sensing dataset from the MOD13Q1 (Terra satellite) data portfolios obtained from 2000 to 2022, with a spatial resolution of 250 m and a temporal resolution of 16 days (<https://ladsweb.modaps.eosdis.nasa.gov/search/>) accessed on 14 September 2023. The formula for the EVI is expressed as follows:

$$EVI = 2.5(NIR - R) / (NIR + C_1R - C_2B + L) \quad (1)$$

In the above equation, *NIR*, *R*, and *B* represent reflectance at near-infrared (0.7–1.1 μm), red (0.6–0.7 μm), and blue (0.45–0.52 μm) wavelengths respectively. *L* is the soil condition-

ing parameter, and C_1 and C_2 are the parameters that correct for the atmospheric influence on R through B [37]. Following Justice et al.'s recommendations, $C_1 = 6$, $C_2 = 7.5$, and $L = 1$ were used by default [38]. Compared to NDVI, EVI rectifies errors attributed to atmospheric conditions or surface vegetation and enhances sensitivity in densely vegetated areas [39,40]. Therefore, EVI is extensively employed to monitor changes in vegetation growth and cover [41–45]. In this study, the EVI during the plant's growing season was utilized, representing the average EVI from April to October each year.

2.2. Study Area

The terrain of China exhibits a three-step ladder pattern from west to east [46]. West China experiences a climate that transitions gradually from south to north, spanning from plateau mountains to a temperate continent. Conversely, in East China, the climate shifts from south to north, transitioning from a tropical and subtropical monsoon to a temperate monsoon, resulting in diverse conditions for vegetation growth across cities in eastern and western China [25]. China has experienced rapid urbanization over the past two decades, with its urban population increasing from 482.7 million in 2000 to 901 million in 2020, resulting in urbanization rates ranging from 36% to 64% [15]. The urban cores examined in this study were exclusively from China, totaling 1559 in number (Figure 1). These areas represented sizable regions exceeding 1 km², carefully selected from all urban cores across the nation. The concentration of selected urban cores in eastern China stems from intersecting 23 years of land cover data to obtain urban cores and filtering them by area, thereby excluding urban cores in the northwest.

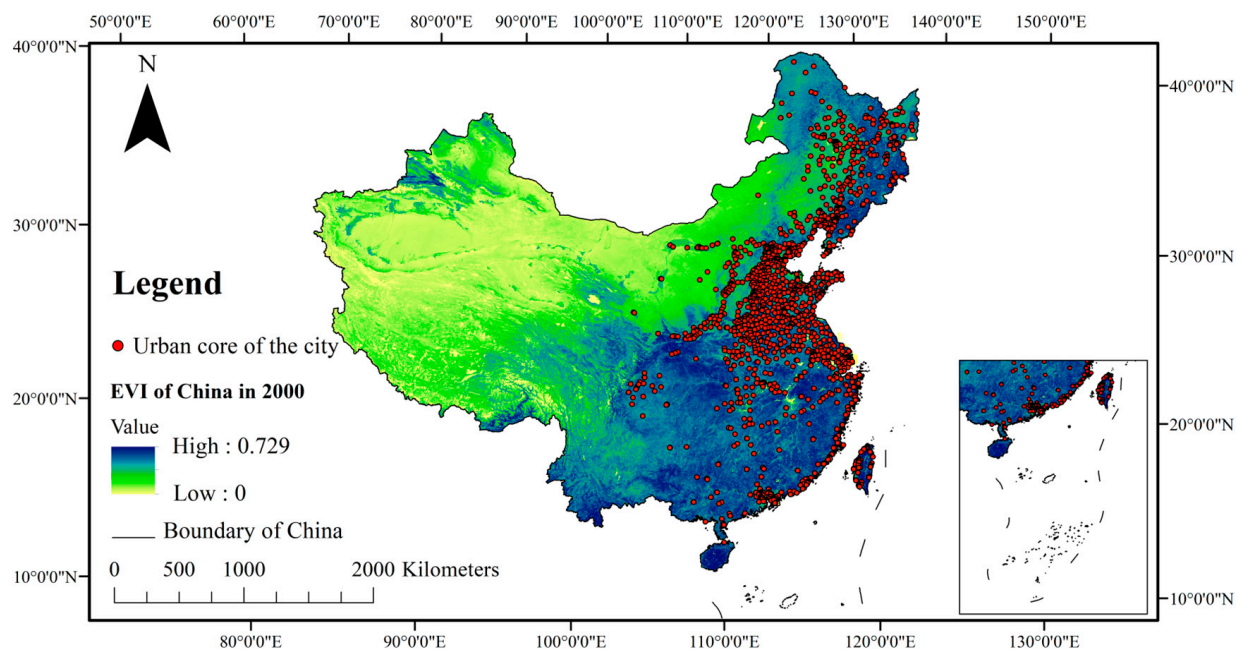


Figure 1. Distribution of urban cores. An MOD13Q1 EVI image of China taken in the 2000 growing season (April–October) serves as the background.

3. Methods

3.1. Urban Core Extraction

In this study, we considered pixels with 100% impervious surfaces from 2000 to 2022 as urban cores and extracted them using ENVI 5.3 software and ArcGIS 10.8.1 software. Initially, utilizing ENVI 5.3, impervious areas and water bodies were extracted from CLCD products (impervious area: pixel with digital number equal to 8; water bodies: pixel with digital number equal to 5). Subsequently, the resulting 30 m resolution impervious surfaces data were resampled to generate a 250 m resolution image of the percentage of impervious surfaces to ensure consistency with the EVI data [47,48]. Additionally,

based on the sampled data, we extracted pixels with 100% impervious surfaces to define urban core areas using decision tree classification in ENVI 5.3, and converted them into vector files. Furthermore, intersection operations in ArcGIS 10.8.1 were conducted on the urban core areas from 2000 to 2022 to obtain the urban cores spanning 23 years, signifying built-up areas over the 23-year period. Subsequently, considering that if the area of the experimental object is too small, it will make the number of pixels of some samples too small, which will, in turn, increase the error of the land cover type of the urban core, areas exceeding 1 km² were selected as our experimental sample, amounting to 1559 urban cores in total. Consequently, our urban cores do not change over time, circumventing the genuine disruptions caused by urbanization, such as the reduction in vegetation area due to urban expansion. This approach helps to accurately describe trends in vegetation change in urban cores independent of urbanization itself, resulting in a more precise portrayal of vegetation growth in urban cores. As for MODIS images, most processing steps are similar to those for CLCD. However, unlike CLCD, there is no need to extract 100% impervious surfaces after resampling the MODIS data, as the data already include urban areas that can be directly extracted (urban area: pixel with digital number equal to 13 [36]).

3.2. Rural Area Extraction

We conducted a buffer analysis on the urban core to create circular buffer zones with a radius of 10 km. These areas were considered rural areas surrounding the urban cores. To eliminate the influence of water on the analysis results, we excluded water bodies from the buffer zones to focus solely on the land areas [47,49]. Furthermore, other urban areas (pixels with greater than 0% impervious surfaces) were removed from the buffer to prevent interference from adjacent urban regions.

3.3. Variation Trend Judgement and Percentage Increase for per City

We processed the EVI data spanning 23 years from 2000 to 2022 to calculate the average EVI for each city during the annual plant growing season (April–October). Subsequently, linear regression analysis based on EVI was employed to determine the slope, thereby revealing the trend of vegetation change in both urban cores and rural areas from 2000 to 2022, and the results were tested for significance level. In terms of the variation in EVI, a slope > 0 indicates an increase in vegetation, while a slope < 0 indicates a decrease in vegetation. A $p < 0.05$ indicates that the result is significant.

Furthermore, we computed the area of vegetation growth and reduction as a percentage of the total area separately for each urban core and rural area [13]. Ultimately, the vegetation growth status of each urban core and the surrounding rural area was analyzed over the 23-year period.

3.4. Difference between Urban Core and Rural Area in Vegetation Change

Consistent with previous research, this study computed the EVI for both the urban core and the rural area, determining the difference between them to examine changes in vegetation between the urban core and the rural area [13,15,50]. Differences in the urban–rural vegetation indices are expressed as ΔEVI :

$$\Delta EVI = EVI_{urban} - EVI_{rural} \quad (2)$$

In the equation above, EVI_{urban} and EVI_{rural} represent the EVI in urban and rural areas (spatial average), respectively. Subsequently, the slope is computed based on ΔEVI and tested for significance level.

4. Results

4.1. Temporal Trends of Vegetation Coverage in Urban Cores Using CLCD

The temporal trend of EVI in major urban cores across China from 2000 to 2022 is depicted in Figure 2. It is evident that there was a general increasing trend in EVI across these urban cores. Approximately 91.9% (1433) of the urban cores showed an increasing

trend in EVI, with 85.3% (1330) demonstrating a significant increase ($p < 0.05$). The urban core with the fastest-growing vegetation exhibited an EVI increase with a slope of 0.118 per decade. Conversely, only 8.1% of urban cores (126) exhibited a decrease in EVI, with 60 samples displaying a significant ($p < 0.05$) decline (3.8%). These findings confirm our first hypothesis that the vast majority of urban cores exhibited a positive trend in vegetation growth, with vegetation degradation observed in only a small number of urban cores.

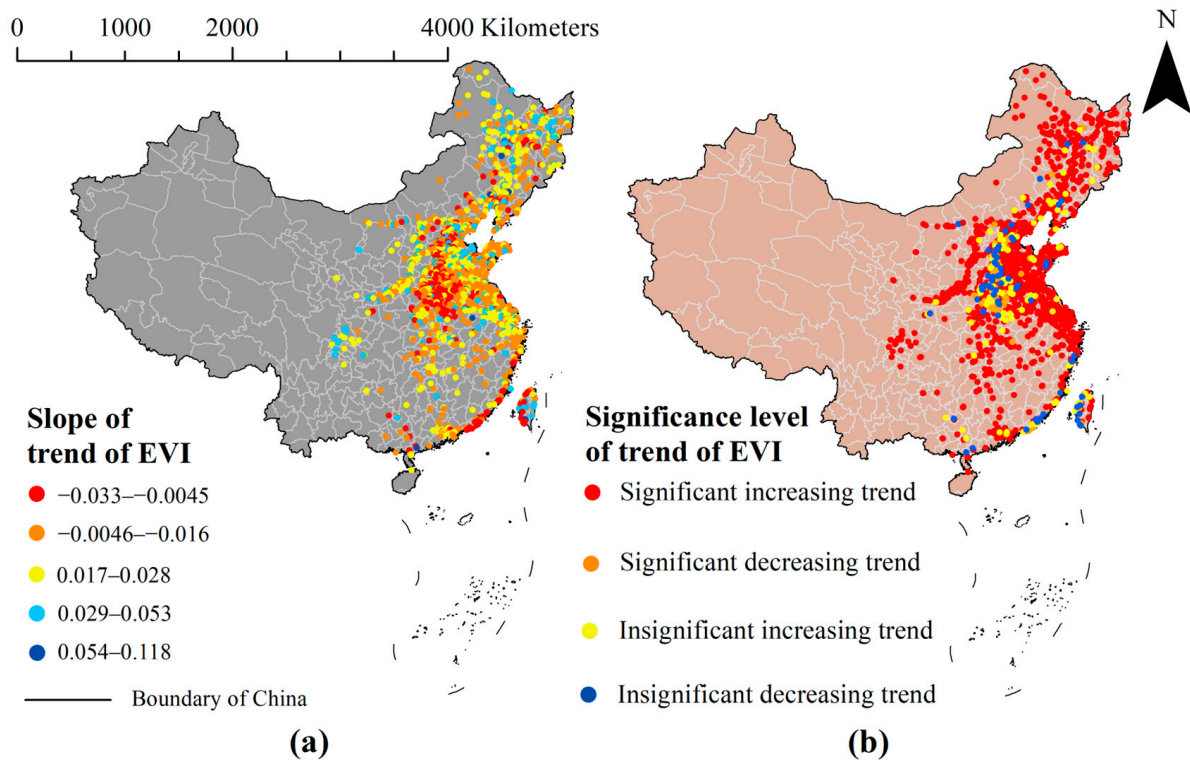


Figure 2. Slope and significance level of EVI in 1559 urban cores. Data were obtained from MOD13Q1 EVI images of China taken during 2000–2022. (a) Temporal trends in EVI in 1559 urban cores. (b) Significance level of EVI changes in 1559 urban cores.

Figure 3 illustrates the percentage of the area with increased EVI in the urban cores. We computed the extent of EVI increase for each urban core and conducted further statistical analysis. Subsequently, the percentage of the area within each urban core experiencing an increase or decrease in EVI was determined. Among the urban cores, 950 (60.9%) had an EVI increase covering 80% or more of their area. Conversely, only 16 urban cores (1%) had less than 20% of their area experiencing vegetation growth. The urban cores with a relatively low percentage (less than 40%) of the area experiencing vegetation growth are concentrated in the northern regions of China, which is closely related to climatic and soil conditions. These findings are closely associated with the sustainable development strategy formulated by the country.

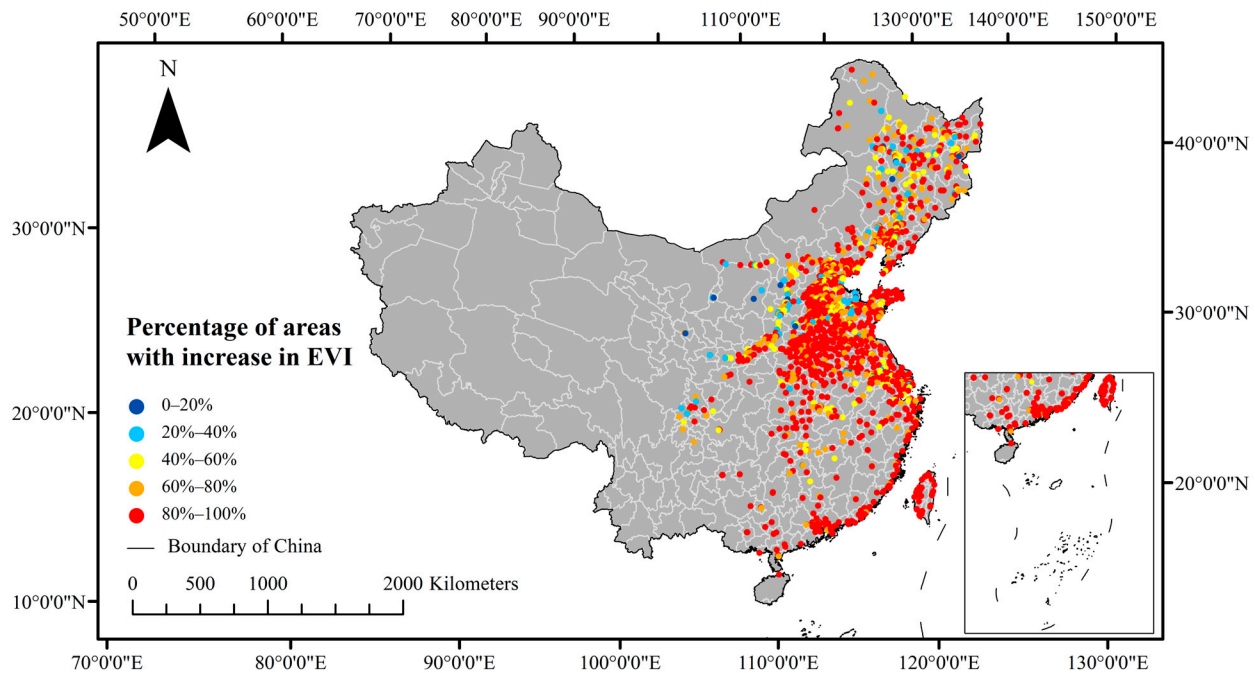


Figure 3. Percentage of areas with EVI increase in 1559 urban cores. Data were obtained from MOD13Q1 EVI images of China taken during 2000–2022.

4.2. Changes in Urban Core and Rural EVI Differences in CLCD

The EVIs of the urban core and rural areas were processed separately, revealing the temporal trend of the EVI difference between the urban core and the corresponding rural buffer zone (Figure 4). Approximately 23.7% (369) of the ΔEVI decreased. Additionally, 12.9% of the ΔEVI between the urban and rural areas showed a significant decrease ($p < 0.05$). Nonetheless, there were still 1190 instances where the ΔEVI between the urban core and its surroundings widened, with 903 showing significant increases ($p < 0.05$), accounting for approximately 57.9% of the 1559 urban cores. The maximum slope of the increase in ΔEVI is 0.083 (per decade). These findings suggest that vegetation growth in approximately three quarters of the urban cores lags behind that in the surrounding rural areas, indicating a widening difference in greening between urban and rural areas.

Additionally, we calculated the percentage of the area experiencing increased EVI in rural areas and subtracted it from the corresponding percentage in urban cores (Figure 5). This calculation aimed to determine the disparity in the area percentage of increased EVI between urban and rural areas. The findings revealed that only 527 (33.8%) of the urban core areas exhibited a higher percentage of the area experiencing EVI growth compared to rural areas, and these urban cores are distributed relatively evenly across the spatial domain. Conversely, the remaining 1032 (66.2%) of urban cores displayed a lower percentage of the area experiencing EVI growth compared to rural areas, with a maximum difference of 92.2%. This finding further implies that vegetation growth in the majority of urban cores lags behind that in rural areas. This result may be attributed to the different climatic conditions and human activities in urban and rural areas, leading to distinct patterns of vegetation growth in the two regions. Generally, rural areas offer a more conducive environment for vegetation growth compared to urban cores [51–53].

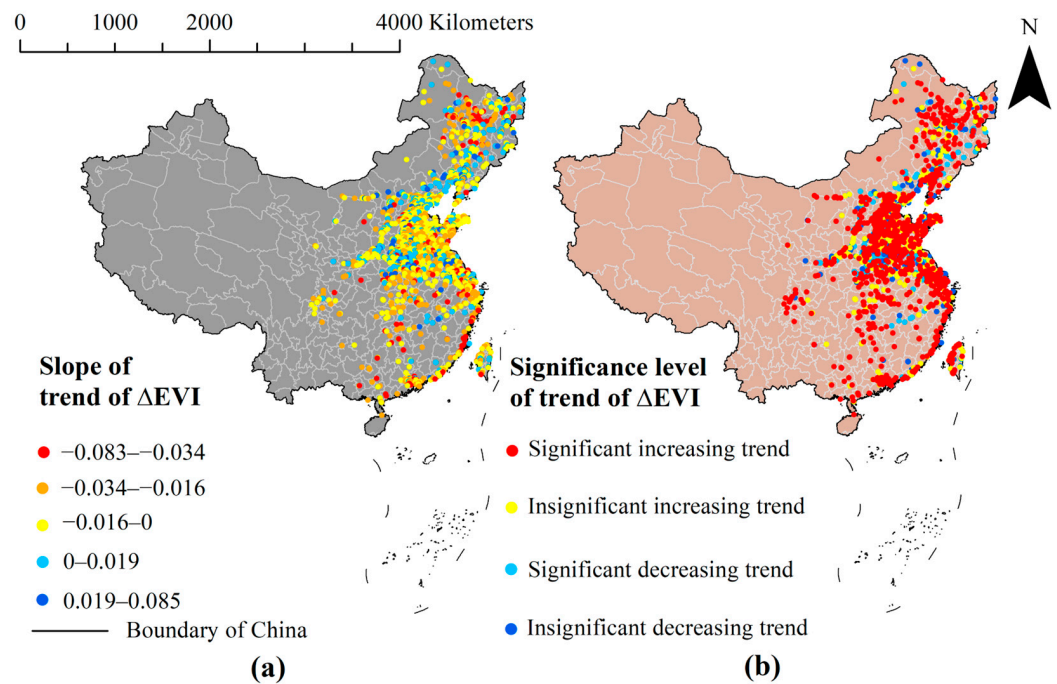


Figure 4. Trends of the difference in EVI between urban cores and rural areas. Data were obtained from MOD13Q1 EVI images of China taken during 2000–2022. (a) Temporal trends in ΔEVI . (b) Significance level of ΔEVI changes.

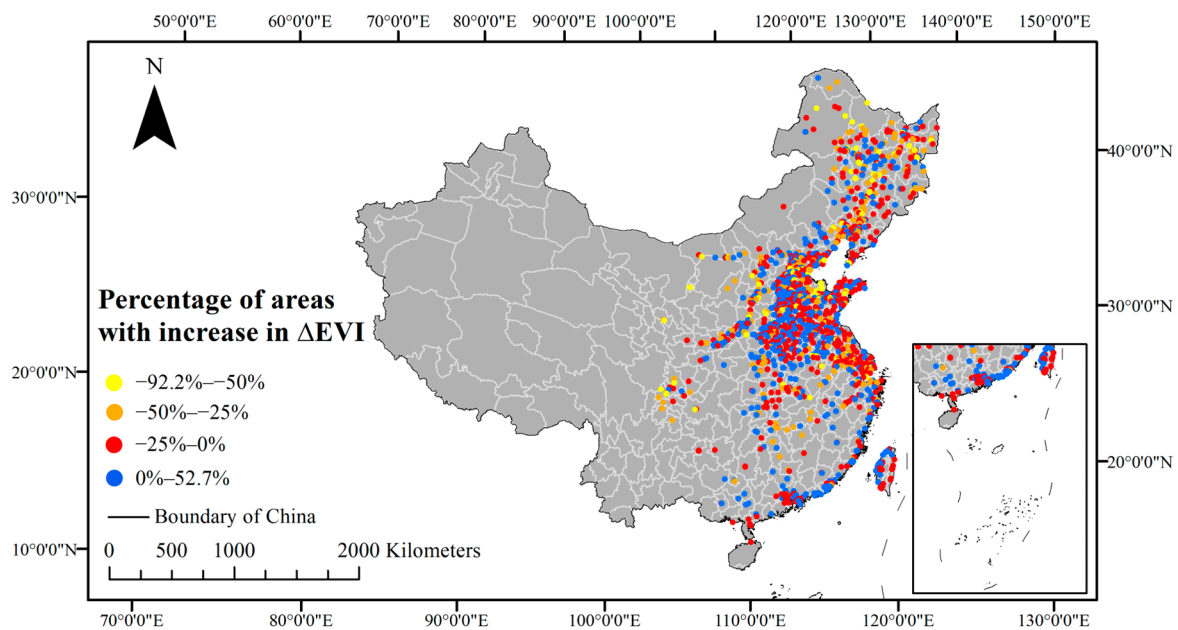


Figure 5. Difference between urban and rural EVI growth shares. Data were obtained from MOD13Q1 EVI images of China taken from 2000 to 2022.

4.3. Difference between Results Obtained from CLCD and MODIS Data

We processed CLCD and MODIS data using identical methods. The growth shares of urban and rural vegetation in the two images were obtained separately. However, due to the difference in image resolution, we obtained different results, which are in line with our expectations.

Only 1029 urban cores, comprising 66% of those obtained from MODIS images, exhibited an increase in EVI, indicating a significant 25.9% decrease compared to the CLCD

images, a substantial deviation (Figure 6). Additionally, the number of urban cores with significant EVI growth ($p < 0.05$) was merely 914, accounting for 58.6%, which also represented a notable reduction compared to the 85.3% of CLCD images. These differences confirm our second hypothesis that different land cover data can have a significant impact on the results.

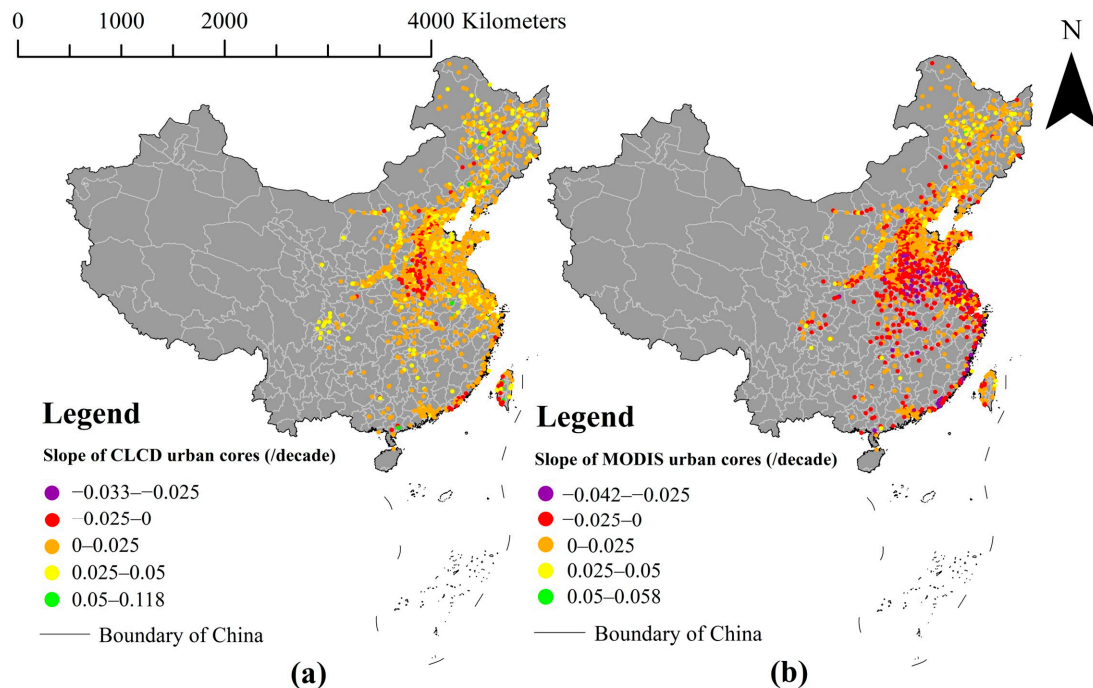


Figure 6. The comparison between CLCD urban cores and MODIS urban cores. Data were obtained from MOD13Q1 EVI images of China taken from 2000 to 2022. (a) Temporal trends in EVI in CLCD urban cores. (b) Temporal trends in EVI in MODIS urban cores.

Meanwhile, we observed that the growth rate of EVI in the urban core area captured by MODIS images is generally lower than that in CLCD images. For instance, the urban core with the most rapid vegetation growth achieved an EVI slope of 0.118 (per decade) using CLCD products; in contrast, the highest value obtained from MODIS images is merely 0.058 (per decade), roughly half as much. Furthermore, the disparities in the EVI slopes of the urban cores derived from the two images exhibited significant spatial heterogeneity. Urban cores with substantial variations were concentrated in the North China Plain and the south, with relatively minor variations in the northern urban cores. This discrepancy strongly correlates with the disparity between CLCD and MODIS images. The fundamental issue is that the two have different criteria and results for classifying land cover types (Figure 7). For instance, in MODIS images, pixels with greater than 30% impervious surfaces are classified as urban areas [36], whereas in the CLCD, only pixels with 100% impervious surfaces are categorized as 'Impervious'. Consequently, our urban core delineation from MODIS images extends further than CLCD and encompasses many pixels with less than 100% impervious surfaces (Figure 8). These areas have experienced urbanization effects since 2000, resulting in a reduction in vegetated areas. Consequently, the results we obtained with MODIS images were significantly different from those obtained with CLCD (Figure 9). The former yielded significantly lower vegetation growth trends than the latter, both in the urban cores and in the rural areas.

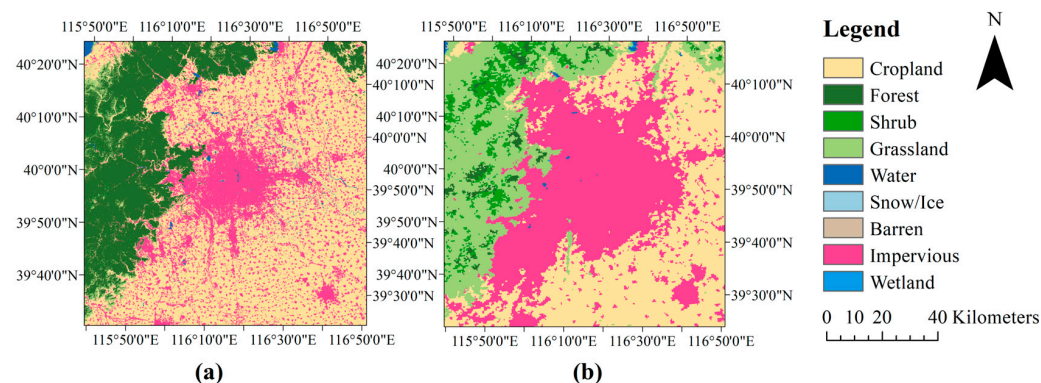


Figure 7. Different classification results of land cover types from CLCD and MODIS images. (a) Classification result of land cover types from CLCD in 2001. (b) Classification result of land cover types from a MODIS image in 2001.

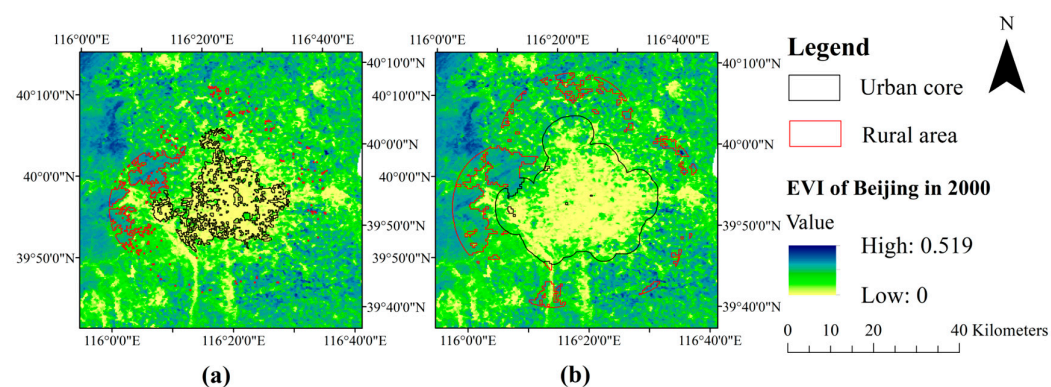


Figure 8. Different urban core and rural area in Beijing from CLCD and MODIS images. (a) Urban core and rural area from CLCD. (b) Urban core and rural area from MODIS images.

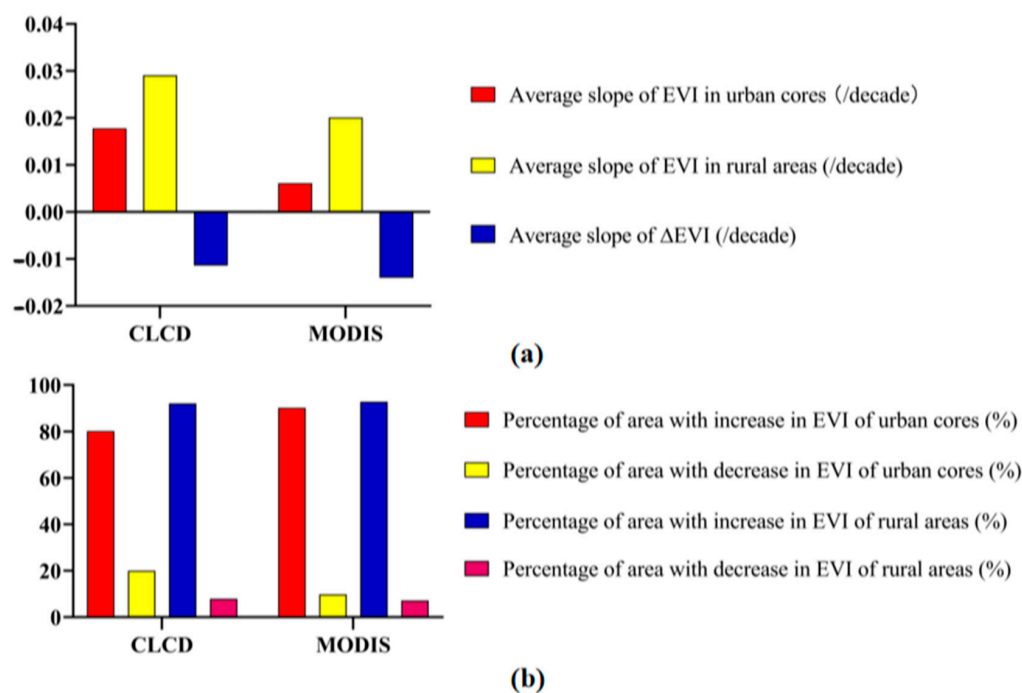


Figure 9. Different results obtained using CLCD versus MODIS images. (a) Differences in the average slope of EVI. (b) Average area percentage of increase and decrease in EVI.

5. Discussion

5.1. Trend of Vegetation Growth in Urban Core and Rural Area

The findings of this study indicate favorable vegetation growth trends in most urban cores, with 85.3% exhibiting a significant increase ($p < 0.05$) in EVI. This finding is inconsistent with previous studies [12,31,32], where vegetation growth trends in urban cores tended to decline. For instance, Zhang et al. [31] found that over 90% of urban cores showed declining vegetation trends from 2003 to 2020. Zhou et al. [12] found that the NDVI of urban areas has generally declined over the past 30 years due to the construction of newly urbanized areas, and that only some older urban areas have improved their vegetation cover. The difference stems from the methodological variations in defining the urban core. Previous studies commonly used pixels with impervious surfaces percentages above a threshold as the urban core (e.g., a threshold of 50% [31]), and their analyses typically considered direct factors related to urbanization, such as urban expansion. However, our study focused on vegetation change in the true urban core, i.e., in areas where no change in land type has occurred. Therefore, only pixels with 100% impervious surfaces were selected as the urban core to exclude direct factors such as urbanization's impact on vegetation reduction. In addition, prior studies included some areas of farmland, water bodies, etc., which have influenced the results. Our method mitigates some of the uncertainties in previous studies, aiding in the understanding of vegetation growth patterns in urban cores, the assessment of the effectiveness of urban greening policy implementation over the past decades, and subsequent policy formulation.

Moreover, we found that the areas with a small percentage of vegetation growth (less than 40%) are mainly concentrated in northern China, which may be related to the difference in climate and soil conditions between the north and the south. Southern China has a warm and humid climate with ample precipitation, making it more suitable for plant growth. Northern China, being an arid and semi-arid region, has vegetation growth largely limited by precipitation [54]; In addition, the average temperature in northern cities is lower and the heat supply is less adequate compared to southern cities, further limiting vegetation growth in urban cores [55]. Moreover, differences in climate and soils have led to variations in the effectiveness of greening policy implementation in urban cores in the south and the north. Vegetation in southern urban cores responds more quickly to greening policies and grows better than in northern urban cores [56].

Additionally, our analysis showed that approximately three quarters of urban cores exhibited declining EVI trends compared to surrounding rural areas, consistent with prior research findings [57]. There are several main reasons for this result. (1) There are differences in greening policy. The greening of the urban core is strengthened by the construction of green spaces, while rural areas have enhanced vegetation through extensive afforestation since the late 1990s to combat soil erosion and desertification [11,58]. In contrast, rural afforestation projects are larger in scale and contribute more to greening. (2) There are differences in land use and building density. The urban core is characterized by high building densities and land application for largely non-vegetated uses. Vegetation areas in urban cores are very limited compared to rural areas. Additionally, urban cores often suffer from soil compaction and surface sealing due to high building density, harming plant roots and thus limiting healthy vegetation growth [59]. On the other hand, more tall buildings in the urban core tend to reduce light on plants and slow down their growth [60]. (3) There is pressure from human activities, environmental pollution, and climate problems. High human activity in the urban core constantly pressures vegetation, e.g., high density of people, and high traffic flow. Meanwhile, these factors cause high levels of air pollution, hindering healthy vegetation growth. However, rural areas have relatively little human activity, favoring continued vegetation growth [31,59]. Moreover, air temperature and precipitation significantly impact urban vegetation change due to differences in meteorological factors between urban and rural areas, such as the severe urban heat island effect (or ultra-high temperatures), which further harms urban vegetation [59,61,62]. (4) There are differences in the use of water resources. Vegetation in the urban core requires more

water due to the heat island effect [63]. Groundwater resources are less available in the urban core than in rural areas. Although irrigation can help, prolonged water shortages can damage plant roots and limit vegetation growth [64,65]. Moreover, rural vegetation growth is negatively correlated with distance from the urban core, with areas further away from urban boundaries experiencing better vegetation growth, as they are less affected by the urban cores [15].

Furthermore, vegetation growth conditions in urban cores notably differed between the MODIS images and CLCD products we utilized. EVI slopes derived from MODIS images generally showed lower values compared to CLCD, especially in southern China's urban cores. This difference arises from two primary factors. (1) There is variation in the spatial resolution between CLCD and MODIS images. CLCD boasts higher spatial resolution, enabling more precise land cover classification. Compared to MODIS images, CLCD can greatly improve the accuracy of urban vegetation mapping and provide accurate spatial and temporal information on vegetation at the urban scale. (2) There is variation in the extent of the urban area delineated between CLCD and MODIS images. In this study, the "Impervious" category in the CLCD product is considered as the urban extent. Therefore, the urban area from the CLCD product contains pixels with 100% impervious surfaces. However, in the MODIS product, pixels with greater than 30% impervious surfaces are considered as urban areas. The study area delineated using MODIS imagery includes many other categories of land such as 'Grasslands'. Vegetation in these other land categories is severely degraded due to urbanization, leading to a slower apparent vegetation growth rate. (3) There is variation in methodologies for processing CLCD and MODIS images. For the CLCD product, we extracted 100% impervious surfaces after resampling it for the study, while this step was not done for the MODIS data. This disparity further leads to differences in the final urban core extent obtained using CLCD versus MODIS, indirectly resulting in differences in the final vegetation growth rates.

5.2. Urban Greening Policy

Over the past 23 years, urban core areas in the majority of Chinese cities have consistently experienced an upward trend in EVI. During this period of urbanization, green planning and sustainable development strategies in Chinese cities have aimed to strike a balance between urban expansion and vegetation enhancement [9]. For instance, in 1997, China defined the sustainable development strategy as "a strategy that must be implemented in modernization". In 2001, the State Council of China issued a directive aimed at enhancing urban greening initiatives, advocating for the integration of the Urban Green Space System Plan into urban planning frameworks [66]. The issuance of the Technical Guideline for the Delineation of the Ecological Protection Red Line in 2014 marked a significant advancement in ecological land regulation [67]. In 2017, the Ministry of Housing and Urban–Rural Development issued the Guidance on Strengthening Ecological Restoration and Urban Repair Work, which includes important ecological protection measures such as accelerating the ecological restoration of landscape spaces, restoring and utilizing abandoned land, and increasing green public spaces [68]. Over the last two decades, these policies have been effectively implemented in China. Furthermore, urbanization may lead to increased carbon dioxide concentrations and surface temperatures, significant factors contributing to vegetation growth in urban cores [8,10,69]. Consequently, vegetation greenness has increased, leading to a rise in average EVI. Policies aimed at urban sustainable development and environmental protection have played a pivotal role in fostering vegetation growth within urban core areas.

5.3. Uncertainty and Future Outlook

Uncertainties persist in the results of this analysis for several reasons. Firstly, the analysis relies on delineating urban core areas in remote sensing images as the primary unit of study, rather than considering each city as an individual unit. This approach may lead to situations where each city contains multiple urban core areas. Secondly, utilizing EVI as an

indicator of vegetation growth in this study introduces a level of uncertainty. Changes in EVI detected in urban cores via remotely sensed images may be attributed to alterations in species composition within the pixel rather than actual vegetation growth [70]. Thirdly, quantifying the impact of specific urban sustainability policies on vegetation growth in core areas poses challenges, as our analysis encompasses the combined effects of various policies. Fourthly, defining the urban core solely in terms of 100% impervious surfaces may cause us to miss important green spaces within the urban core, such as some large parks. However, we also found that lowering the threshold to 95% or 90% still results in missing large green spaces within the core. Despite these uncertainties, our study confirms that vegetation in the urban core has exhibited robust growth and the implementation of urban greening policies has been effective. Furthermore, further research is needed to quantify the specific positive and negative effects of distinct greening policies on urban core vegetation. Additionally, alternative metrics, such as leaf area index (LAI) and solar-induced fluorescence (SIF), warrant consideration in future studies [15,71]. Multiple criteria can also be used to define the urban core and accurately analyze all vegetation within it.

6. Conclusions

China has experienced rapid urbanization over the past several decades. During the process of urbanization, the trends of vegetation changes in the urban cores are complex due to the impact of temperature, the concentration of carbon dioxide, and urban greening policies. Therefore, obtaining the real vegetation change trend is of great significance in analyzing the effects of urban greening policies and subsequent policy formulation. Different from previous studies, in order to explore the trends of vegetation in real urban cores, we defined urban cores as collections of pixels with 100% impervious surfaces, excluding factors such as urban sprawl, and analyzed the EVI of urban cores. Our research focuses on fixed urban core areas that do not change over time, thereby avoiding uncertainties associated with urbanization and mitigating the impact of extensive vegetation degradation caused by urban expansion. Results show that the vast majority exhibited positive vegetation growth, with approximately 83.3% demonstrating significant increases ($p < 0.05$), with a maximum growth rate of 0.118 (per decade). These findings suggest that China's urban greening policies have yielded positive outcomes over the past two decades, facilitating vegetation growth in urban cores amidst rapid urbanization. However, our results also show that vegetation growth in 76.3% of urban cores remained lower than that in the surrounding rural areas, with 57.9% experiencing a significant widening of the urban–rural disparity ($p < 0.05$). Among them, the ΔEVI between urban cores and rural areas widened at a maximum rate of 0.083 (per decade). This indicates that our country still suffers from uncoordinated growth of vegetation in urban and rural areas and large differences in the rate of vegetation change. In the following years, effective policies need to be developed to promote the coordinated growth of urban and rural vegetation cover. These policies need to be targeted, taking full account of the differences in climate, soils, and other factors between urban cores and rural areas. Additionally, urban greening policies must be consistently implemented and tailored to the local context. This involves considering the specificities of urban cores in different regions in terms of climate, soil, and level of development, to develop a truly unique greening policy for each city. Furthermore, some large green spaces may be excluded due to our method of defining the urban core, which has a minor impact on the results. Subsequently, multiple criteria can be explored to extract the extent of the urban core area and accurately analyze all the vegetation within the core area.

Furthermore, the study revealed that vegetation growth trends in urban cores derived from MODIS images were lower compared to those derived from CLCD, which shows spatial heterogeneity. This proves that higher spatial resolution satellite imagery can more accurately depict urban vegetation distribution and record changes in vegetation dynamics, providing valuable insights for future research on vegetation dynamics within urban core areas. Subsequently, high spatial resolution data can be utilized to quantitatively explore the impact of various greening management policies on vegetation growth, enabling more

targeted and effective greening policies and providing strong support for improving the detailed aspects of sustainable development policies.

Author Contributions: F.-J.Y.: writing—review and editing. L.Y.: Conceptualization. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: This research did not involve any human participants or animals.

Informed Consent Statement: As this study did not involve any human participants, informed consent was not applicable.

Data Availability Statement: The data that support the findings of this study are openly available in ScienceDB at <https://doi.org/10.57760/sciencedb.16979>.

Conflicts of Interest: The authors declare no conflict of interest.

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