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Spatial Changes of Suburban Forest Ecological Functions and Their Impact on Ecological Equity in the Process of Urbanization—A Case Study of Jiangning District, Nanjing, China

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Abstract: After the transformation of counties in urban suburbs into districts, the rapid urbanization and industrialization process in China's developed regions had a huge impact on the spatial distribution and equity of the suburban forest ecological functions. Accurately describing this impact could provide an important reference for the construction of suburban forest engineering and for ecological environmental planning. Jiangning District of Nanjing City, China, was selected as the research area, while the forest resource planning and design survey data in 2007 and 2017, together with the demographic data of the study area, were collected as the main information sources. Following the establishment of the forest ecological function evaluation indicators and the analysis of the spatial change of the forest ecological functions, the Gini coefficient was calculated to analyze the changes of the regional ecological function equality. The results showed that: (1) Compared with 2007, the proportion of areas with low forest ecological functions (abbreviated as FEF) in the study area in 2017 showed a downward trend, and the proportion of areas with medium and high FEF showed an increasing trend; (2) Compared with 2007, the forest landscape in the study area in 2017 was severely fragmented, the spatial aggregation of the FEF showed a significant decline, and the FEF developed towards a direction of spatially balanced distribution; (3) During 2007–2017, the sub-compartments with high-value FEF in the study area (hot spots) shifted to the northwest, where the economy was developed and the population density was higher, and the sub-compartments with low-value (cold spots) shifted to the south, where the economy is underdeveloped and with lower population density; (4) From 2007 to 2017, the Gini coefficient of the FEF in the study area decreased, indicating that the regional ecological equity had initially improved. The urbanization and industrialization process of the urban suburbs is a double-edged sword. On the one hand, the process has caused the fragmentation of forest landscape, the decline of the forest area, and the unbalanced spatial distribution of the population. On the other hand, the huge material wealth and human capital accumulated through industrialization have promoted regional ecological equity and improved the living environment of the local residents.

Keywords: urban suburban forest; forest ecological function; ecological equity; Gini coefficient

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1. Introduction

The forest is a terrestrial ecosystem with the largest distribution area, the most complex organizational structure, and the richest biodiversity on the earth. The forest ecological function refers to the ecological environment conditions and the effects formed by the forest ecosystem and its ecological processes that are conducive to human production and development [1,2]. As an important component of the suburban ecosystem, the urban suburban forest is the only green infrastructure in the urban suburbs, providing local residents with water and soil conservation, climate regulation, environmental purification, and other multiple service functions [3,4]. Because the urban suburban forests have efficient and stable self-purification capabilities and continuous and complete ecological service functions, they play an extremely important role in improving the quality of regional human settlement environment [5,6]. Since the beginning of the 21st century, major cities in China's Yangtze River Delta have experienced rapid urbanization. A large number of people have migrated from the remote and impoverished countryside to the urban center [7,8], resulting in not only a sharp increase in the urban population, but also great changes in the regional land use and land cover [9,10]. With the development of modern industrialization, major changes have taken place in the structure of the local land use, and the regional ecosystems have become increasingly fragile [11,12]. Therefore, how to improve the stability of the urban suburban forest ecosystem to give full play to its ecological service functions (abbreviated as FEF) has become an important concern for regional planners.

The comprehensive evaluation of suburban FEF and the analysis of the impact of the urbanization process on ecological equity can quantitatively describe the value of forest ecological service functions in urban suburbs, and provide important guidance for the optimal layout and ecological construction of urban suburban forests. Until now, most studies on the evaluation of FEF have focused on the evaluation of a single or a few ecological functions at the stand and landscape scales [13,14]. A small number of comprehensive evaluations of the forest ecological service functions at the national and regional scales are usually based on the forest resource statistics data and focus on the economic evaluation of the forest service function [15,16]. Existing studies on the evaluation of urban FEF lack the content of spatial analysis, and there are fewer research results on the ecological equity related to the change of population movement.

Ecological equity can be expressed as a measure of the equity of the ecological environment for people to provide ecological well-being, which has received extensive attention in recent years [17]. The current research on ecological equity mainly focuses on the allocation of natural resources and pollutant discharge, and there are few studies on the equity of forest ecological services [18–20]. Due to the unbalanced natural conditions, population density, and economic development levels, the distribution of forests in the urban suburbs is usually irrational, affecting the fair and reasonable enjoyment of forest ecological benefits by residents in these areas. In terms of the evaluation of the equity of the forest distribution in urban suburbs, the per capita index method and spatial accessibility analysis are usually used for evaluation [21,22]. The per capita index method oversimplifies the spatial distribution pattern of suburban forests, while the selection of the influencing factors of the accessibility analysis method is easily influenced by subjective factors, which restricts the wide application of these methods. In recent years, the Gini coefficient has been widely used in the evaluation of ecological equity. Due to the rationality and universality of this indicator, the Gini coefficient can evaluate ecological equity at different scales such as the household scale, city scale, and provincial scale [23–25]. Since the Gini coefficient can be used to evaluate the difference in the allocation of resources or pollutant content between regions, it has become the main indicator of ecological equity evaluation.

In China, forest resources planning and design survey Level Two Survey has the advantages of many survey factors, high survey precision, and continuous dynamics. The survey content includes multiple factors such as land types, topography, forest species, tree species, soil thickness, forest structure, and stock volume. These factors are closely related to the forest ecological functions and become accurate and reliable data sources for the comprehensive evaluation of FEF at the regional scale [26]. On the basis of establishing a forest survey database, we selected factors closely related to the FEF to construct an ecological function index which could reflect the comprehensive ecological quality of each forest stand (sub-compartment), in order to explore a scientific and applicable method for regional FEF evaluation [27]. Therefore, with the multi-period forest resources planning and design survey data as the main information source, under the support of geographic information (GIS), and combined with the ecological function index, the Gini coefficient, it was possible to analyze the spatial changes of urban suburban FEF and their impact on the ecological equity. The research results could provide a scientific reference for the construction of forest cities and ecological environment planning in the Yangtze River Delta, China.

Jiangning District is located in the middle of Nanjing City, Jiangsu Province, China. Before 2000, it was an agricultural county dominated by the primary industry of rice and wheat planting. After 2000, with the approval of the State Council of China, Jiangning District was withdrawn from the county and turned into a district of Nanjing City, and the focus of its economic development shifted to secondary and tertiary industries such as automobile manufacturing, biopharmaceuticals, logistics and transportation, and software research and development. Since 2017, the gross domestic product (GDP) of Jiangning District has been ranked the first among the eleven districts of Nanjing. At present, Jiangning has become an important national science and education center and innovation base, an important transportation and logistics hub of Yangtze River Delta, and an airport hub in the eastern part of the country [28]. The rapid urban development and industrialization process, the vigorous implementation of landscape greening engineering, and the deepening of the "Green Nanjing" urban forest project, which aims to improve the ecological environment, have had a huge impact on the spatial patterns of the FEF in the study area. Along with the large influx of the immigrant population around the study area and the accelerating movement of the population in various streets within the study area, the equity of the FEF in the study area has also undergone major changes. The forest ecological environment problems encountered in the urbanization process of Nanjing Jiangning District are very common in the Yangtze River Delta. However, there are still insufficient studies on the equity problems of urban forests.

Therefore, in this study, Nanjing Jiangning District was taken as the case study area. The survey data of the forest resources planning and design in 2007 and 2017 were used, and the demographic data of the research area in the same years as the forest survey were collected as the main information source, followed by the analysis of the spatial changes of the forest ecological functions and their impact on equity. The main objectives of this study were as follows: (1) To reveal the spatial change patterns of the FEF in the process of urbanization in the Yangtze River Delta, China; (2) To analyze the impact of the spatial changes of the FEF on the forest etiological equity; (3) To propose suggestions for improving the ecological equity in urban suburbs; (4) To provide scientific reference for the ecological planning for urbanized suburbs in the Yangtze River Delta.

2. Materials and Methods

2.1. Study Area

Jiangning District (31°37′~32°07′ N, 118°28′~119°06′ E) is located on the south bank of the lower reaches of the Yangtze River, in the middle of Nanjing, Jiangsu Province, China, with a total area of 1561 km^2 (Figure 1). Jiangning is part of the hilly mountainous area of Ning-Zhen-Yang, with a complex terrain structure, known as "sixty percent of hilly mountains, ten percent of water and thirty percent of plains". The northeast of the district is in the western section of the Ningzhen Mountain, the southwest is on the northern edge of the Ningwu Faulted Basin, the central part is on the Loess Hill and the Qinhuai River alluvial plain, and the west is on the riverside plain. The regional terrain is high in the north and south and low in the middle, similar to a "saddle". Generally speaking, the terrain of Jiangning is relatively flat, the altitude is mostly below 5 m above sea level (asl), and the highest altitude is about 352 m asl [28].

The study area belongs to the northern subtropical monsoon climate zone, with a humid climate and four distinct seasons. The annual average temperature is 14.60 °C and the annual average precipitation is 1004.60 mm. Due to the favorable natural conditions, Jiangning has abundant forest resources. The local coniferous tree species are mainly Masson pine, black pine, and cypress, while the broad-leaved trees are mainly *Quercus acutissima*, *Sweetgum*, *Maackia amurensis*, *Zelkova serrata*, and *Populus adenopoda*. Since

2007, with the continuous deepening of the urban forest project of "Green Nanjing", the construction of key greening projects such as green road passages, river and lake shelter belts, forest parks, green and beautiful villages, and urban landscape greening in the research area has achieved remarkable achievements, greatly improving the quality of the human living environment.

By the end of 2022, the district had reached a GDP of 300.06 billion yuan. As an important science and education center and innovation base of the country, an important transportation and logistics hub, and an airport hub in the eastern region of the country, the rapid economic development of Jiangning has attracted a large number of immigrants from the surrounding areas, and the regional population growth rate has been accelerating year by year. In 2022, the district had 10 streets, including 136 urban communities and 71 rural communities, with a permanent population of 2.35 million [29].

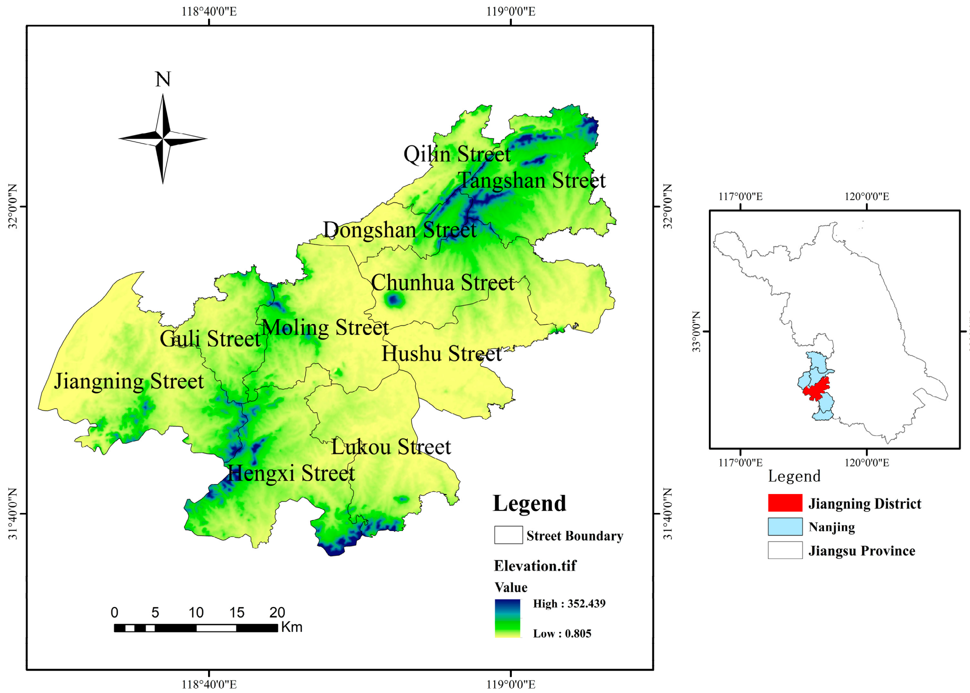

Figure 1. Geographical location of the case study area.

2.2. Research Methods

2.2.1. Data Sources and Preprocessing

There were three major data sources used in this paper: (1) Vectorized sub-compartment data of forest resources planning and design survey (Level Two Survey) in the research area in 2007 and 2017. The number of sub-compartments in 2007 and 2017 was 19,606 and 55,677, respectively, with more than 60 survey factors such as land type, topography, forest species, tree species, soil, forest structure, and stock volume [30–32]. (2) Vector shape files of the street administrative boundaries and the road networks, and the digital elevation model (DEM) of the study area purchased from the Big Map Data Company (http://www.bigemap.com/, accessed on 10 June 2022). The road networks included expressways, national roads, provincial roads, and local secondary roads in 2007 and 2017. The spatial resolution of DEM was 2 m × 2 m. (3) Resident population and household registration population statistical data of each street from the statistical Yearbook of Jiangning District's in 2008 and 2018.

Based on the collected data mentioned above, the Surface tool in the GIS Spatial Analysis Toolbox of ArcGIS 10.2 was used to generate the slope of the study area using the DEM, and the Buffer Tool was used to generate a distance to road raster file.

2.2.2. Construction of Ecological Function Index

From more than 60 sub-compartment attributes, we selected eight factors closely related to the FEF, namely forest canopy closure, total vegetation coverage, forest natural degree, community structure, tree species structure, litter layer thickness, stock volume, and stand average height to construct the forest ecological function index (abbreviated as FEFI) by weighted average according to their relative importance, to comprehensively assess the FEF of each sub-compartment. Each ecological function factor and its weight are shown in Table 1 and the definition and calculation method for each factor are detailed and described in reference [33]. It should be noted that the weights of the eight evaluation factors were directly quoted from Technical Regulations for Forest Resources Planning and Design (DB32/T 2168-2012) promulgated by the Quality and Technical Supervision Bureau of Jiangsu Province in 2012 [34].

Table 1. List of forest ecological function evaluation indicators and their weights.

Evaluation Factor	**Stock Volume**	**Natural Degree**	**Community Structure**	**Tree Species Structure**
Weights	0.20	0.15	0.15	0.15
Evaluation Factor	**Stand Average Height**	**Canopy Closure**	**Total Vegetation Coverage**	**Litter Layer Thickness**
Weights	0.10	0.10	0.10	0.05

In order to eliminate the calculation bias caused by evaluation factors with different measurement levels, each evaluation factor was standardized before the factors were integrated.

For the evaluation factors where the larger is better:

$$r_{ij} = \frac{x_{ij} - \underset{j}{min}\{x_{ij}\}}{\underset{j}{max}\{x_{ij}\} - \underset{j}{min}\{x_{ij}\}} \tag{1}$$

For evaluation factors where the smaller is superior:

$$r_{ij} = \frac{\underset{j}{max}\{x_{ij}\} - x_{ij}}{\underset{j}{max}\{x_{ij}\} - \underset{j}{min}\{x_{ij}\}} \tag{2}$$

where r_{ij} is the standardized value of the i-th ecological function factor of the j-th sub-compartment; x_{ij} is the investigation value of i-th ecological function factor of the j-th sub-compartment; $\underset{j}{min}x_{ij}$ is the minimum value of the i-th ecological function factor of all the sub-compartments; and $\underset{j}{max}x_{ij}$ is the maximum value of the i-th ecological function factor of all the sub-compartments.

2.2.3. Spatial Analysis of Forest Ecological Functions

We used Moran I and Z, which are two indices of geo-statistics, to analyze the changes of spatial aggregation of the FEFI. Four pattern indexes including patch density (PD), patch size (MPS), shape index (MSI), and fractal dimension (FD) were used to analyze the spatial pattern change of the forest landscape in the study area [35,36]. Spatial clustering was used to extract high ecological function sub-compartments (hot spots) and low ecological function sub-compartments (cold spots). Change analysis of the geographical distribution center of the hot spots and cold spots was carried out to reveal the regional FEFI distribution changes [37]. The spatial changes of the forest landscape in the study area from 2007 to 2017 were analyzed by calculating the four landscape pattern indexes.

If Moran's I > 0 and ∣Z∣ > 1.96, the value of the FEFI of forest sub-compartment is similar to its neighboring, and the FEFI shows an aggregated spatial distribution; if Moran's I < 0 and ∣Z∣ < 1.96, the FEFI shows a discrete spatial distribution; if Moran's I = 0 and ∣Z∣ = 1.96, the forest ecological function index shows a random distribution. The calculation of the landscape pattern index was performed through Patch Analyst, a plug-in of ArcGIS 10.2. The patch density (PD) and patch size (MPS) can reflect the fragmentation degree of patches, the shape index (MSI) and the fractional dimension (FD) can reflect the complexity of patches. The spatial clustering analysis was realized by using the aggregation and special case analysis tools in the ArcGIS 10.2 spatial statistics toolbox. When the statistical value $p = 0.05$, through spatial clustering, the forest sub-compartments were divided into four types according to the level of the FEFI: high-value sub-compartments (hot spots, HH), low-value sub-compartments (cold spots, LL), high-value special sub-compartments surrounded by low-value sub-compartments (HL), and low-value special sub-compartments surrounded by high-value sub-compartments (LH). The purpose of spatial geographic distribution center (Mean Center) analysis was to identify the geographical distribution center of the FEFI by calculating the average value of the geographic coordinates from all the sub-compartments in the study area.

2.2.4. Ecological Equity Evaluation

The Gini index is a common indicator used internationally to measure the income gap between residents of a country or region [38]. Since the Gini index can be used to evaluate the degree of difference in the amount of resources or pollutants between regions, it has become the main indicator for the evaluation of the equity of forest ecological functions. The maximum Gini coefficient is 1 and the minimum is equal to 0. The closer the Gini coefficient is to 0, the more the distribution of the FEF tends to be equal. According to the regulations of international organizations such as the United Nations Program, a Gini coefficient below 0.2 is regarded as absolutely equity, 0.2–0.3 is regarded as relatively equity; 0.3–0.4 is regarded as relatively reasonable; and 0.4–0.5 is regarded as a large gap; when the Gini coefficient reaches 0.5 or above, it means that the gap is huge.

The equity evaluation of urban FEF is mainly based on the population distribution data. After obtaining the urban FEFI value of each administrative region, the Gini coefficient was applied to calculate the equity index of the urban FEF. Many Chinese scholars have explored the specific calculation method of the Gini coefficient and put forward more than ten different calculation formulas. Referring to the research results of Boyce et al. in 2016, the Gini coefficient of the FEFI is calculated as follows [18]:

$$Gini = 1 + \left(\frac{1}{n}\right) - [\frac{2}{Meanpop \times n^2}]\sum_{i=1}^{n}[(n-i+1) \times popula_i] \quad (3)$$

where *Meanpop* is the average of the ecological function index of all streets, $popula_i$ is the FEFI of street i, and n is the number of streets.

3. Results and Analysis

3.1. Dynamic Changes in FEFI

Eight FEF factors of each sub-compartment in 2007 and 2017, namely, forest canopy closure, total vegetation coverage, natural degree, community structure, tree species structure, litter layer thickness, stock volume, and stand average height, were extracted. Based on the standardization of the ecological function factors, the FEFI of the study area in 2007 and 2017 were generated by weighted average according to the weights of 0.20, 0.15, 0.15, 0.15, 0.15, 0.10, 0.10, and 0.05. The FEFI was graded according to the criteria of low (<0.3), medium (0.3–0.6), and high (>0.6), and the spatial distribution maps of the FEFI in the study area in 2007 and 2017 were produced (Figure 2), and the change table of the FEFI from 2007 to 2017 was generated (Table 2).

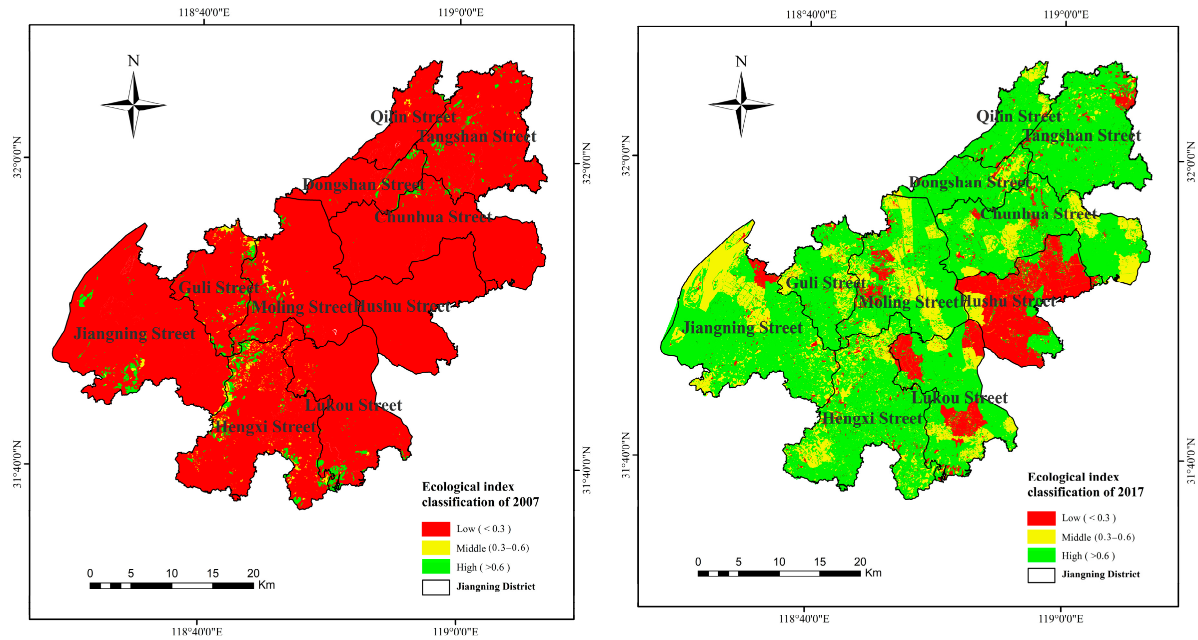

Figure 2. Spatial distribution of FEIF in 2007 and 2017.

Table 2. Changes in FEFI from 2007 to 2017.

Time	Average Value	Standard Deviation	Proportion of Different Levels of Ecological Index (EI) (%)		
			Low (<0.3)	Medium (0.3–0.6)	High (>0.6)
2007	0.369	0.299	81.168	2.067	16.765
2017	0.589	0.174	15.039	49.646	35.315
Change	0.221	−0.125	−66.129	47.579	18.550

It can be seen from Figure 2 that in 2007, the sub-compartments with high FEFI were mainly distributed in the three state-owned forest farms of Qinglong Mountain, Tang Mountain, and Dongshan Bridge in the northeastern mountainous area and southwest basin of the study area. In the vast middle hills and plains, except for Fang Mountain, Niushou Mountain, Jiangjun Mountain, and other scenic spots, the FEFI values of the forest sub-compartments were at a low level. Under the dual effects of the urbanization process and the urban forest project of Greening Nanjing, the spatial distribution of the FEFI in the study area in 2017 showed a completely different pattern from that in 2007: the sub-compartments with low FEFI were mainly concentrated in Hushu Street, which is underdeveloped and far away from the urban downtown area, then in the streets with large population density and relatively developed economy including Jiangning Street, Lukou Street, and Moling Street. In 2017, the sub-compartments with high and medium FEFI were located in the remaining six streets, namely Guli, Dongshan, Chunhua, Qilin, Tangshan, and Hengxi.

It can be seen from Table 2 that the FEFI of the study area in 2007 and 2017 were generally at a lower–middle level, which is consistent with the natural and socio-economic conditions of the study area. After 2000, the research area was converted from a county to a district. With the accelerating process of urbanization and industrialization, the land development intensity of the state-owned forest farms such as Tang Mountain, Dongshan Bridge, and Qinglong Mountain, and forest parks such as Jiangjun Mountain, Fang Mountain, and Niushou Mountain, continued to increase, leading to a decrease in the forest area in the study area. Compared with 2007, the FEFI in the study area rose from 0.3686 to 0.5893 in 2017, with an increase of 0.2207. In 2007, the proportion of the forest area with low FEFI in the study area was as high as 81.168%, followed by the proportion of the area with high FEFI (16.765%), and the proportion of the area with medium FEFI (2.067%). Driven by the urban forest project of Beautiful Nanjing from 2007 to 2017, key greening projects such as green passages, river and lake shelter belts, forest parks, beautiful and green villages, and urban landscape greening in the plain hillock areas with low forest coverage in the study area have achieved remarkable results. In 2017, the proportion of areas with a low FEFI in the study area decreased from 81.168% in 2007 to 15.039%, with a drop of 66.129%. On the contrary, the proportion of areas with a medium FEFI and a high FEFI increased from 2.067% and 16.765% in 2007 to 49.646% and 35.315% in 2017, respectively, with an increase of 47.579% and 18.550%.

3.2. Spatial Change of Forest Ecological Function Index

3.2.1. Changes in the Pattern of Forest Ecological Function Index

First, with the Feature to Point Tool of ArcGIS 10.2(Environmental Systems Research Institute, Inc. (Esri) was founded in 1969 and is headquartered in RedLands, California, USA), the polygonal vector files of the sub-compartments were converted into point vector files, and the Moran I and Z values of the FEFI of the sub-compartments in the study area were calculated using the Spatial Autocorrelation Tool in the Spatial Statistical Analysis Toolbox. The ArcGIS 10.2 plug-in tool of Patch Analyst was used to calculate the landscape pattern index of the study area in 2007 and 2017. The calculation results are shown in Table 3.

Table 3. Changes in the spatial pattern of forest sub-compartments from 2007–2017.

Time	Spatial Aggregation of FEFI		Fragmentation Index		Shape Index	
	Moran's I	Z	Patch Density (PD)	Plaque Size (MPS)	Shape Index (MSI)	Fractional Dimension (FD)
2007	0.150	90.288	12.570	7.955	1.5619	1.375
2017	0.073	67.666	35.603	2.801	1.917	1.452
Changes	−0.078	−22.622	23.033	−5.154	0.3551	0.077

It can be seen from Table 3 that the FEFI in the study area from 2007 to 2017 showed a spatial aggregation distribution pattern. Compared with 2007, the spatial aggregation of the FEFI in the study area showed a significant decline in 2017. The Moran I coefficient decreased from 0.150 to 0.073, and the Z value decreased from 90.288 to 67.666, decreasing by 0.078 and 22.622, respectively. It can be seen from Table 3 that from 2007 to 2017, the fragmentation of the forest patches in the study area increased significantly, and the shape of the forest sub-compartments tended to become more complicated. From 2007 to 2017, large-scale constructions projects of beautiful villages, traffic road greening, and street landscape greening were carried out. The forest coverage rate and forest ecological functions of hilly and plain areas with low ecological functions increased, resulting in the improvement of the EI in the study area. As a result, the gap of the FEFI in different places of the study area was reduced, and the spatial aggregation of the FEFI was also weakened. From 2007 to 2017, due to the rapid development of urbanization and industrialization in the study area, the forests planted in the process of the urban forest construction projects of Green Nanjing were mainly small area plantations, resulting in the fragmentation of the forest landscape and the more complicated shape of the sub-compartments.

3.2.2. Changes in Cold and Hot Spots of FEFI

After the spatial aggregation analysis of the FEFI of the sub-compartments in the study area, the dynamic changes of the environmental factors such as the topography and human disturbance in the sub-compartments with high FEFI (hot spots, HH) and low FEFI (cold spots, LL) during 2007–2017 were analyzed. The Multi Values To Points tool in the Spatial Analysis Toolbox of ArcGIS 10.2 was used to extract three ecological environmental factors (Table 4): the altitude, slope, and distance from the main road to the hot spot and cold spot (road distance). It can be seen from Table 4 that in 2007, the sub-compartments with a high FEFI (hot spots) in the study area were mainly distributed in the mountains and hills with high altitudes, steep slopes, and far away from main roads, while the sub-compartments with a low FEFI (cold spots) were mainly located in the plains with low altitude, gentle slopes, and close to main roads. From 2007 to 2017, the environmental differences between the sub-compartments with a high FEFI and the sub-compartments with a low FEFI had been greatly reduced, leading to a homogeneous spatial pattern of the ecological environment factors between the hot spots and cold spots. This change was closely related to the large-scale greening projects between 2007 and 2017 in the plain and hillock streets which occupy 88% of the land area of Jiangning District.

The Mean Center Tool in the spatial analysis toolbox of ArcGIS 10.2 was applied to generate the geographical distribution centers of the cold spots and hot spots in the study area in 2007 and 2017, respectively (Figure 3). It can be seen from Figure 3 that from 2007 to 2017, the centers of the hot spots with a high FEFI shifted to the north of Moling Town, which has a developed economy and a large amount of immigrants, while the center of the cold spots with a low FEFI shifted towards Lukou Street, where the traffic is less developed and where a large amount of local residents emigrate. The change of the geographical distribution centers of the cold and hot spots was closely related to the location, economic level, and population migration direction of each street in the study area. Among the ten streets in Jiangning District, Moling, Guli, and Dongshan Streets are close to the downtown area of Nanjing, and Dongshan Street is the place of the district government. The above four streets all have a high level of economic development and a large number of immigrants. On the contrary, Hengxi, Lukou, and Hushu streets are far from the downtown area of Nanjing, their economic level is relatively low, and are areas where a large number of local people emigrate. Therefore, in terms of manpower, material resources, and financial resources for afforestation, the northern streets in the study area close to the downtown area of Nanjing had obvious advantages over the southern streets which are far away from the downtown area, resulting in major changes in the geographical distribution centers of the cold spots and hot spots from 2007 to 2017.

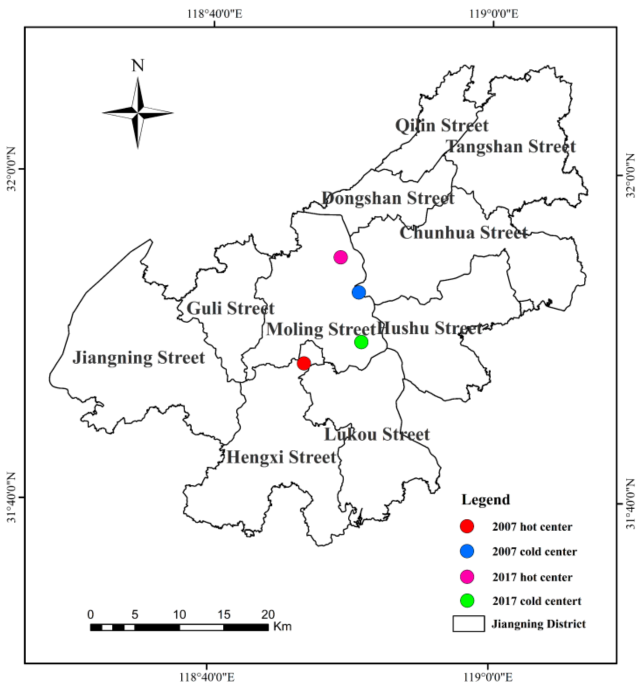

Figure 3. Distribution of mean centers of cold and hot spots in 2007 and 2017.

Table 4. Environment changes of cold and hot spots from 2007 to 2017.

Time	Hot Spots			Cold Spots		
	Elevation	Slope	Road Distance	Elevation	Slope	Road Distance
2007	65.026	4.911	444.673	245.09	1.429	199.339
2017	29.446	2.123	183.080	31.788	1.932	273.019
Changes	−35.58	−2.788	−261.593	−213.302	0.503	73.68

3.3. Analysis of Dynamic Changes in the Equity of FEFI

The Zonal Statistics tool in the Spatial Statistics Toolbox of ArcGIS 10.2 was used to calculate the average FEFI of each street in 2007 and 2017. Then, the average FEFI was multiplied by the area of each street and divided by the population of each street in 2007 and 2017. Finally, the average FEFI of each street by population was obtained (Table 5). It should be noted that due to the large differences in the economic development level of the various streets, and the large gaps in the direction and quantity of population flow, the phenomenon of inconsistency between the registered population and the resident population was serious in the study area. Moling, Dongshan, and other streets in the north of the research area, which are close to the downtown area of Nanjing, had a high level of economic development, a large net inflow of population, and the number of resident populations was far greater than the registered population. On the contrary, in the southern streets of Hushu and Chunhua, which are far away from the downtown area, the resident population was smaller than the registered population. In order to ensure the accuracy of the calculation results, the resident population instead of the registered population of each street was adopted in the calculation of the Gini coefficient of the FEFI.

Table 5. Changes in EI by streets in Jiangning from 2007 to 2017.

Street Name	Area (hm^2)	FEFI in 2007		FEFI in 2007	
		Street Average	FEFI by Population	Street Average	FEFI by Population
Chunhua	20,068.9	0.4447	0.1891	0.4601	0.1491
Dongshan	6914.6	0.4157	0.0192	0.4933	0.0173
Guli	9177.2	0.5534	0.1006	0.4969	0.0689
Hengxi	21,413.0	0.5324	0.1868	0.4413	0.1180
Hushu	14,863.0	0.4500	0.1029	0.4183	0.0729
Jiangning	26,293.8	0.4934	0.1720	0.4929	0.1309
Lukou	16,388.5	0.4690	0.1080	0.4669	0.0820
Moling	18,028.9	0.4414	0.0248	0.4855	0.0208
Qilin	6135.8	0.4239	0.0501	0.5061	0.0456
Tangshan	17,128.4	0.5163	0.1518	0.4787	0.1073

The FEFI by population of each street in Table 4 was put into Formula (3) to calculate the Gini coefficient of the FEFI in the study area in 2007 and 2017. The Gini coefficient in 2007 was 0.3104, which was a relatively reasonable level. The Gini coefficient in 2017 was 0.2906, which was at a relatively equitable level. It can be seen that from 2007 to 2017, with the development of multiple ecological projects such as beautiful villages, traffic road greening, and street landscape greening in the study area, the differences in the FEFI between the streets had gradually narrowed. As a result, the Gini coefficient of the FEFI in the study area had improved from a relatively reasonable level to relatively equity.

4. Discussion

Since the beginning of the 21st century, China's economically developed Yangtze River Delta region entered the period of rapid urbanization and industrialization. With the transformation of land-use types and population migration, the spatial distribution and equity of the FEF in urban suburbs have undergone tremendous changes. Accurately depicting this change could provide scientific reference for urban forest engineering construction and ecological environment planning.

From 2007 to 2017, the EI in the study area was generally at a low–middle level. Compared with 2007, the proportion of the areas with a low FEFI in the study area in 2017 decreased, and the proportions of areas with medium and high FEFIs increased by 47.579% and 18.550%, respectively. From 2007 to 2017, the forest landscape in the study area was severely fragmented, the spatial aggregation of the FEFI showed a significant decline, and the spatial pattern of the FEFI developed towards a balanced distribution. In the study area, the high FEFI value sub-compartments (hot spots) shifted to the northwest where the economy was more developed and the population density was higher, while the low FEFI value sub-compartments (cold spots) shifted to the south where the economy was underdeveloped and the population density was lower. With the development of multiple ecological projects such as beautiful villages, traffic road greening, and street landscape greening, the differences in the FEFI between the streets had gradually narrowed. From 2007 to 2017, the Gini coefficient of the FEFI in the study area had dropped from 0.3104 to 0.2906, and the ecological equity had been initially improved.

From 2007 to 2017, the general forest ecological functions in the study area have been gradually improving, which is similar to the research results of the evaluation of urban FEF in Nanjing [39]. Though started late, studies conducted by other scholars on the ecological service functions of urban forests (FEF) in China have shown an overall trend of improvement in recent years, similar to the findings from this paper [40]. The city managers in some countries in the Americas [41] and Europe [42] have also gradually realized the importance of the ecological service functions of urban forests, and they are making efforts to improve the functions of urban forests. However, there are still cities where the ecological functions of forests are showing a declining trend, such as Iran [43]. Among the areas we studied, there were also some areas where the FEF has remained unchanged or declined. For example, the high FEFI sub-compartments of state-owned forest farms such as Qinglong Mountain and Tang Mountain in the northeast have remained basically unchanged, while the high EI sub-compartments in Fang Mountain, Jiangjun Mountain, and Niushou Mountain, which are located in the central part of the study area, together with the high EI sub-compartments in Dongshan Bridge State-owned Forest Farm, which is on the edge of the south and southwest basin, were transformed into medium EI forest stands. Most of these forest stands with declined EI belong to provincial and municipal ecological public welfare forests. The reduction of the EI in such areas was mostly related to the encroachment of forest land caused by land development, and the negligence in forest management caused by the low economic benefits of public welfare forests. In the process of rapid urbanization and industrialization, how to protect the ecological public welfare forests by delineating ecological red lines and improving ecological compensation standards [44] is an urgent task facing urban forest managers.

Based on the survey data of forest resource planning and design, this paper constructed the evaluation index of FEF, and used the Gini coefficient to evaluate the changes in equity of the FEF under the background of urbanization. Our research results filled the gap of the impact of spatial dynamic changes of the FEF on the ecological equity in the existing forest ecological function evaluation research. Restricted by the investigation factors of forest resource planning and design survey, the forest ecological function evaluation factors did not include such forest ecological functions such as vacuuming and sterilization, temperature regulation, and forest recreation.

5. Conclusions

The process of urbanization in the urban suburbs is a double-edged sword. While developing the economy and improving the living standards of residents, it causes the reduction of forest land and the fragmentation of forest landscapes. With the implementation of multiple ecological projects, the ecological functions in the study area are gradually improving, the degree of forest landscape fragmentation and the spatial concentration of ecological functions are greatly reduced, and the ecological equity is gradually improving. It can be seen that while vigorously adjusting the urban industrial structure and developing the local economy, the importance of ecological equity for the regional harmonious development and urban ecological planning cannot be ignored. In future research, we will combine the Level Two Survey data with the ecological environment factors (such as surface temperature, air quality, and population density) extracted from remote sensing, and the long-term positioning observation data of urban FEF in order to completely describe the spatial-temporal change of the forest ecological functions in urban suburbs and its impact on ecological equity.

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