Ecological quality assessment of urban green spaces based on landscape metrics: *A case of Nanjing, China*

Hao Xu *

College of Landscape Architecture, Nanjing Forestry University, Nanjing, China

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Abstract

China's ongoing urbanization is having a profound effect on the environment, and Nanjing, as one of the most important metropolitan areas of the city cluster in China's Yangtze River Delta, is not immune to this development; as such, it is greatly affecting the scale and structure of its urban green spaces. An ecological quality assessment of Nanjing's green spaces is fundamentally significant to appropriate spatial planning and the implementation of sustainable development ideas. This study uses ALOS (Advanced Land Observing Satellite) remote-sensing image data to map the distribution of urban green spaces in Nanjing, and employs various landscape metrics to analyze and evaluate the city's spatial layout and ecological quality. Results of the study reveal that the distribution of urban green spaces in Nanjing is highly uneven, with most located in suburban areas and few within the city's core. Green space within the urban area is highly centralized around the Zijin Mountain woodlands, while green space in the suburbs is highly dispersed and fragmented. A large proportion of Nanjing's green space comprises farmlands, primarily distributed on the outskirts of the city and in the suburbs. The amount of farmland, however, is continuously decreasing, as the land is being used in the ongoing urban development. This is expected to rapidly lower the ecological quality of the region's green spaces. In order to improve the ecological quality here, both recreational and ecologic functions of green space should be considered during the phases of spatial planning. It also is suggested that more core green spaces be built, such as ecological country parks, to increase the ratio of woodlands, enhance the management of ecological spaces in suburban areas, establish ecologic greenways, and strengthen the connectivity of green spaces.

Keywords: Urban green space; Ecological quality; Landscape ecology; Landscape metrics; Remote sensing images; GIS; Nanjing; China

1 Introduction

Urban green space is the land within a city that retains some of its natural characteristics, providing residents with space for recreation and spiritual cultivation, serving as a space in which endemic species can survive and reproduce, and vital to maintaining and improving the urban environment, biodiversity, and sustainable development [1-3]. Human activity and urbanization have a profound impact upon the scale and structure of green space systems, with many regions exhibiting green space tendencies toward isolation and fragmentation, often as a result of urban development activities. Consequently, this reduces the region's ecological quality and results in negative impacts upon the ecological system and biodiversity of the region [4-7]. Therefore, it is necessary to effectively conduct spatial planning and management on urban development and green space systems based on the goals and principles of sustainable development, in order to make better use of green spaces' ecological functions, as well as promoting and raising the ecological quality of both the urban and suburban areas of Nanjing.

Though China is a developing country, it boasts the world's largest population and is undergoing a process of rapid urbanization. This urban development has produced profound effects on the country's natural environment. Since the implementation of an open-market economy in the late-1970s, which resulted in high mobility of production elements and dynamic population immigration, city clusters, such as the Beijing-Tianjin-Hebei Region, Yangtze River Delta, and Pearl River Delta, began to form along the eastern coastal regions of China. With well-built infrastructures and centralized administrative functions, the central cities within these clusters are the key players in China's urbanization and have an amalgamation effect that exhibits rapid population growth and city expansion [8, 9]. The development of these metropolises also produced a great impact upon the scale of local green space and spatial structure, and put a heavy strain on the endemic ecological environment [10].

The spatial pattern of green space is a key element in assessing its ecological quality, functionality, and structure which, under the framework of sustainable development, is paramount to policymaking regarding appropriate spatial planning and management. As an effective analytical tool, landscape metrics (or landscape ecology) have been commonly employed in recent years to analyze the spatial structure and functionality of green spaces as well as to perform ecological quality assessments. Landscape metrics include composition indices and spatial configuration indices that can be

*Corresponding author's E-mail: xuhao3@hotmail.com

utilized to quantitatively evaluate the composition and structure of green space, which is vital to ecological planning and assessment. This study uses Nanjing, one of the central hubs of China's Yangtze River Delta region, as the target area to examine the spatial distribution patterns of green space in the city using various landscape metrics [11-15]. By assessing the city's ecological quality, this study aims to serve as the basis of future spatial planning and strategic management activities.

TABLE 1 Size and population of the studied districts

Area of Study	Acronym	Size (km^2)	Population (10,000)	Population density (person/km^2)
Gulou	GL	54.18	130.37	**24,062**
Qinhuai	QH	49.11	100.49	**20,462**
Xuanwu	XW	75.46	63.37	**8,398**
Jianye	JY	81.75	45.40	**5,554**
Yuhuatai	YHT	132.39	35.49	**2,681**
Qixia	QX	395.38	51.60	**1,305**
Jiangning	JN	1,563.33	97.94	**626**
Gulou	GL	54.18	130.37	**24,062**
Qinhuai	**QH**	**49.11**	**100.49**	**20,462**

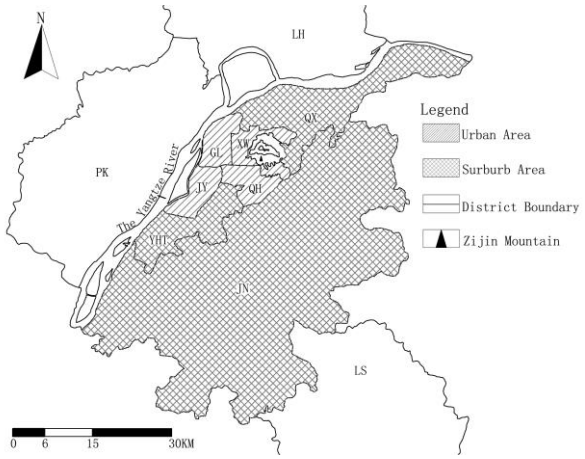

FIGURE 1 The map of Nanjing

2 Target area of study

Located at the lower reach of the Yangtze River, Nanjing is the provincial capital and administrative, cultural, and financial center of Jiangsu, with a total population of 7.39 million (Nanjing Department of Statistics, 2009). Similar to Hangzhou and Shanghai, Nanjing also is a critical, central city in the Yangtze River Delta area. As shown in Figure 1, Nanjing has an area of 6,587 square kilometers, with the Yangtze River flowing through the city from southwest to northeast. South of the river are the districts of Gulou, Qixia, Qinhuai, Jianye, Xuanwu, Jiangning, Gaochun, and Lishui, while the Pukou and Liuhe districts lie north of the river. Nanjing lies within the northern humid subtropical climate zone (i.e., abundant precipitation, flora and fauna), and exhibits four clear seasons, with longer winters and summers and shorter springs and autumns.

Nanjing is surrounded by low-lying hills and dotted with numerous rivers and lakes in the belt of Ningzhen Hills. The Zijin Mountain area in the eastern suburbs, which has become one of the largest multipurpose parks in the city, stretches westward deep into the city's urban region, connecting with the Jiuhua, Beiji, Gulou, Wutai, and Qingliang Mountains. Along the Yangtze River there are the Mufu, Qixia, Xiang, Shi, and Ma'an Mountains, which are also connected to Qingliang Mountain; north of the Yangtze River is the Laoshan Mountain range. Xuanwu Lake, Muochou Lake, and Qinhuai River make up the main water bodies in the city, the latter of which is 110 km long and was once Nanjing's most vital waterway to the city's development and daily lives of its residents.

Nanjing is undoubtedly one of China's most famous historical and cultural centers, as the location saw urban settlement as early as 472 BC with the nation of Yue founding its capital. In 212 AD, during the Three Kingdoms period, King Sun Quan of Dongwu built the Stone City in Nanjing as a fortress for naval and city defense, and in 229 AD, he established the city of Jianye in the same location to serve as his nation's capital. Afterward, Dong Jin Dynasty and the Southern Dynasties (Song, Qi, Liang, and Chen) all continued to use the city as their capital, naming it Jiankang. In 1368, Emperor Zhu Yuanzhang established the Ming Dynasty and selected Nanjing as the state capital. He initiated a large-scale renovation and expansion of the city, which gradually developed Nanjing into the largest city in the entire country at the time, famed for its textile, construction, shipbuilding, and woodblock printing industries. Nanjing was also the political and economic center of Southeast China during the Qing Dynasty (1644–1912), then between 1912 and 1949, the era of the previous Republic of China (prior to the People's Republic of China [PRC]), Nanjing was once again the nation's capital and received additional, extensive development. With the implementation of the first Five-Year Plan in 1953, Nanjing initiated urban planning programs to guide development activities. From the 1960s until the end of the Cultural Revolution in 1976, the city's planning and development stagnated due to political circumstances; however, since the reform and opening-up policies in the late-1970s, Nanjing's urbanization has once again gained momentum. In 1983, the State Council approved the Nanjing City Development Master Plan, which was the first legally binding general planning scheme for Nanjing since the establishment of the PRC. It proposed that city development would radiate in five annular areas outward from the city center core. This general development plan

was adjusted in 2001, at which time the Yangtze River was designated as the main axis, and the city's downtown core as the center of urban development. A multi-centered spatial structure for city development with better land use measures than the original also was put forward. The government of Nanjing has also attempted to address green space development challenges through its own city and land use planning [16, 17].

This study focuses on the following seven administrative districts of Nanjing south of the Yangtze River: Gulou, Qinhuai, Xuanwu, and Jianye as the urban districts, and Yuhuatai, Qixia, and Jiangning as the suburban districts. The total area of the districts is 2351.6 square kilometers, with a resident population of 5.2466 million, which accounts for 71% of Nanjing's total population. Table 1 indicates the size, population, and population density of each district. Historical urban buildings, concentrated human activity, and evident disturbance to green spaces can all be observed in the city[18,19]. Through quantitative index analysis, this study reveals green space characteristics in a high-population-density historical city such as Nanjing; moreover, the evaluation of ecological effects seeks to assist policymaking in regard to green space planning and city management.

TABLE 2 Landscape metrics used in this study and their purpose

Metrics	Usage
CA	Measures the size of the green space
PLAND	Measures the composition of the green space; determines the size ratios and main component
MPS	Measures the dominant type of green space
LPI	Measures the dominant green space patch, type, and level of concentration
NP	Measures landscape heterogeneity
PD	Indicates the degree of fragmentation
TE	Measures the degree of landscape fragmentation and disturbance
ED	Measures the degree of landscape fragmentation and disturbance
MPI	Measures the degree of green space patch fragmentation and dispersion

3 Research Methodology

The ALOS satellite remote-sensing image data of the Nanjing region during November 2008 included the 10m resolution multi-spectrum data and the 2.5m resolution full-wavelength data. The raw remote sensing data underwent image fusion, image geometry correction, and image mosaic processes using the software ENVI 5.0. The Xi'an 85 geographic coordinate system was adopted, and the boundaries between districts were extracted according to the administrative map of Nanjing then saved in the "shapefile" format. Image geometry correction and coordinate conversion were then done for these files using ARCGIS 10.2 software.

In ENVI 5.0, the images were cropped based on the district boundary files, in order to produce respective images for each individual administrative district. With this as the foundation, supervised classification was used to categorize the land use in each image, resulting in five categories: artificial land, water body, woodland, grass and shrub land, and farmland. From this, distribution maps of green spaces (which includes only woodland, grass and shrub land, and farmland) were extracted and converted into "grid" files. These files were finally imported into Fragstat 4.2 to conduct landscape metric analysis.

The landscape metrics chosen for this study were class area (CA), percent of land (PLAND), mean patch size (MPS), largest patch index (LPI), number of patch (NP), patch density (PD), total edge (TE), edge density (ED), mean proximity index (MPI), mean nearest neighbor distance (MNN), and landscape shape index (LSI). Table 2 shows the functions of each landscape metric for the purposes of this study.

4 Composition analysis of green space

The CA index indicates the size of each type of green space. As shown in Figure 2, the CA index for woodland is the highest in Jiangning district, followed by Xuanwu, Qixia, and Yuhuatai, while Gulou, Qinhuai, and Jianye each have a low CA index for woodland. The grass and shrub land CA index is the highest in Jiangning and Qixia. Jiangning also has the highest farmland CA index, followed by Qixia, Jianye, and Yuhuatai (Gulou and Qinhuai districts do not possess farmland areas).

Figure 3 shows the green space PLAND index of the target area, indicating the size ratio of each green space type within the total area of the targeted districts. The highest woodland PLAND index is observed in Xuanwu, followed by Jiangning and Yuhuatai. Grass and shrub land PLAND index is the lowest in Gulou, while no major difference is seen among the other districts. Jiangning shows the highest farmland PLAND index, followed by Qixia, Jianye, and Yuhuatai. By comparing the green space composition within each district, the proportion of woodland is greater in Gulou and Xuanwu, and the proportion of grass and shrub land is the greatest in Qixia, Jianye, Yuhuatai, and Qinhuai, while in Jiangning, farmland takes up the largest proportion of green space.

Figure 4 shows the MPS index of green space in the studied areas, which indicates the average size of various types of green space patches. The highest woodland MPS index is found in Xuanwu, leading other districts by a remarkable margin, while the lowest is found in Qinhuai and Jianye. Grass and shrub land MPS is highest in Qixia and Xuanwu, and lowest in Gulou. In terms of internal comparison, the woodland MPS indexes for Gulou and Xuanwu are substantially higher than their corresponding

grassland and farmland indexes. The farmland indexes for Jiangning and Qixia Districts are much higher than their corresponding woodland and grass and shrub land indexes. Grass and shrub land MPS indexes in Qinhuai, Yuhuatai, and Jianye districts are slightly higher than the woodland and farmland indexes in the same districts.

Figure 5 shows the green space LPI index distribution, denoting the size ratio of the largest green space patch within each administrative district; for example, the woodland LPI is greater in Gulou and Xuanwu and, likewise, the farmland LPI in Jiangning. In addition, the highest woodland LPI occurs in Xuanwu, which is much higher than the LPI indexes of other green space types in this district. The grass and shrub land LPI in Jiangning and the farmland LPI in Yuhuatai are significantly lower than those in other regions that contain these types.

According to the above green space composition metrics, the total area of green space within the urban districts (Gulou, Qinhuai, Xuanwu, and Jianye) is very limited, with the largest part concentrated in Xuanwu district and least in Gulou. Green space area is significantly higher in the suburban districts (Qixia, Yuhuatai, and Jiangning) compared to urban districts; therefore, the suburbs comprise the main body of green space within Nanjing's entire system. Of these suburbs, Jiangning district has the greatest area of green space, far greater than even the sum of the six other districts studied. Among the urban districts, Xuanwu has a higher green space ratio; whereas the green space ratios in Gulou and Qinhuai are both very low.

Among the urban districts, Xuanwu possesses abundant and concentrated woodland resources. This type of green space also serves as the main type in the urban districts overall. Grass and shrub land, however, is the prevalent type of suburban green space, while the main green space body in Jiangning district in particular is farmland.

5 Spatial configuration analysis of green space

Figure 6 indicates the NP index of green space, referring to the number of green space patches in each district. The woodland, grass and shrub land, and farmland NP indexes in Jiangning are significantly greater than all the other districts, while the overall green space NPs of Xuanwu and Qinhuai are the lowest. Green space NP index is much greater in the suburbs than in the urban areas. Other than in Qinhuai, the grass and shrub land NPs are all significantly higher than the woodland and farmland NPs in all districts studied. With the exception of Qixia, where the farmland NP is much higher than the woodland NP, all other districts have relatively equal farmland NP and woodland NP.

Figure 7 shows the green space PD index distribution of the research area, indicating the density of green space patches. Generally, the grass and shrub land PD values are significantly higher than those of woodland and farmland. The woodland PD indexes are the highest in Qinhuai, followed by Yuhuatai, Jianye, and Jiangning, whereas in Qixia, Gulou, and Xuanwu districts the woodland PD indexes are very low. The grass and shrub land PD indexes are higher in Gulou, Jiangning, Yuhuatai, and Jianye, while Xuanwu, Qixia, and Qinhuai show relatively lower values. The farmland PD index is the highest in Jianye, while the lowest in Xuanwu.

The green space TE index is an expression of the edge length of green space patches. As demonstrated in Figure 8, the suburban green space TE values are much higher than those in urban areas; for example, Jiangning has the highest TE value while Gulou has the lowest. Judging from the TE indexes of each green space type, the grass and shrub land indexes are higher than those of woodland and farmland in Gulou, Xuanwu, Yuhuatai, and Jianye. In Jiangning, the grass and shrub land TE index is lower than farmland but higher than woodland. In Qinhuai, the woodland TE index is higher than that of grass and shrub land.

Shown in Figure 9 is the green space ED index of each research district, which indicates the patch edge length per unit area. The suburban green space ED indexes are higher than those of the urban districts; In particular, Yuhuatai and Jiangning have the highest values, while Gulou and Xuanwu have the lowest. Other than in Qinhuai and Jiangning, the grass and shrub land ED index in each of the five other districts is higher than both the farmland and woodland ED indexes combined. The farmland ED index is higher in Jiangning than the combined grass and shrub land and woodland ED indexes.

Figure 10 lists the MPI index for each type of green space. The farmland MPI in Jiangning is far greater than any other type, and it is also the highest MPI in Qixia. The woodland MPI index in Xuanwu and Jiangning all show significantly higher MPI values, while the overall green space MPIs for Gulou, Qinhuai, and Jianye are extremely low.

Figure 11 demonstrates the green space MNN index, which reveals the degree of dispersion of the green spaces. The woodland MNNs are higher in Gulou and Qixia, but lower in Qinhuai and Yuhuatai. The grass and shrub land MNNs are significantly higher in the city core area than in the outskirts. The highest farmland MNN is seen in Xuanwu District, and other than Xuanwu and Qinhuai, the woodland MNNs in the other districts are much greater than their farmland and grass and shrub land MNNs.

Shown in Figure 12 is the green space LSI index, which measures shape complexity. The LSI value of Jiangning is the highest in the entire research area, though overall the LSI values for the suburban areas are generally higher than those for the urban districts. With the exception of Qinhuai, the grass and shrub land LSI values are generally higher and the woodland LSIs are generally lower in all districts.

Judging from the landscape structure and vast area, the suburban areas have a larger number of green space patches and a higher edge density than their urban

counterparts. This therefore implies greater landscape heterogeneity as well as a higher degree of disturbance within the suburban districts. In particular, Jiangning has the highest levels of heterogeneity and disturbance among all seven districts studied. Farmland is the dominant green space type in Jiangning and Qixia, whereas in Xuanwu, woodland is the dominant type. The woodlands generally show a high level of isolation, weak connectivity to other green space types, and a relatively low degree of disturbance. In addition, the level of fragmentation and disturbance of the grass and shrub lands is relatively higher than farmlands.

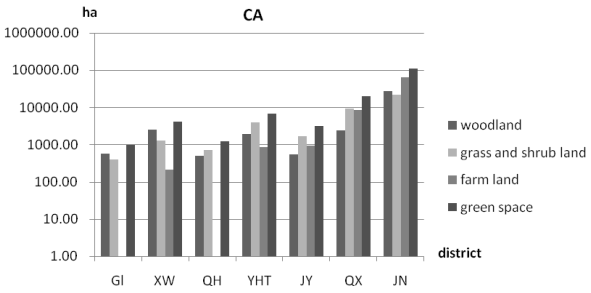

FIGURE 2 The CA of the green space in the study area

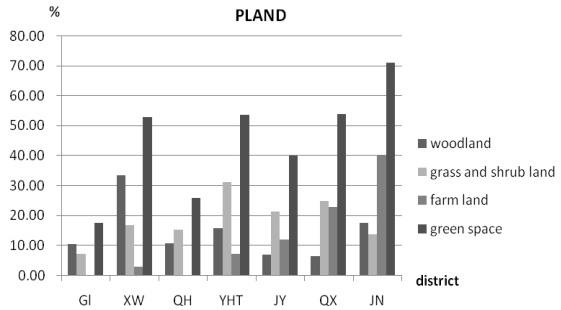

FIGURE 3 The PLAND of the green space in the study area

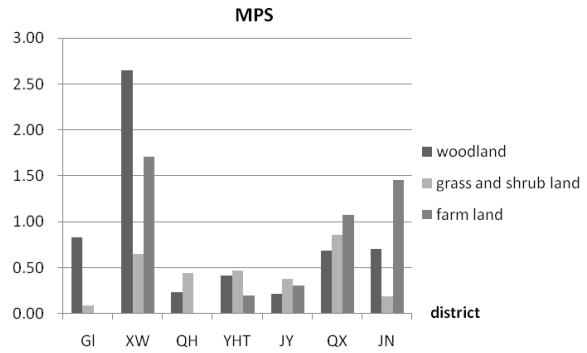

FIGURE 4 The MPS of the green space in the study area

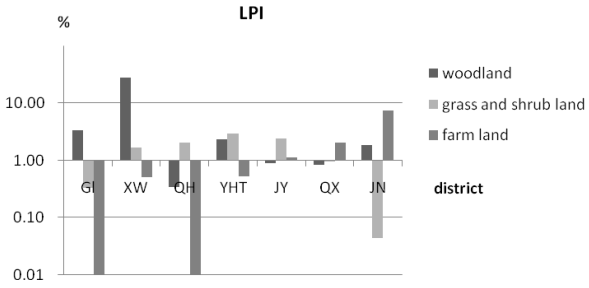

FIGURE 5 The LPI of the green space in the study area

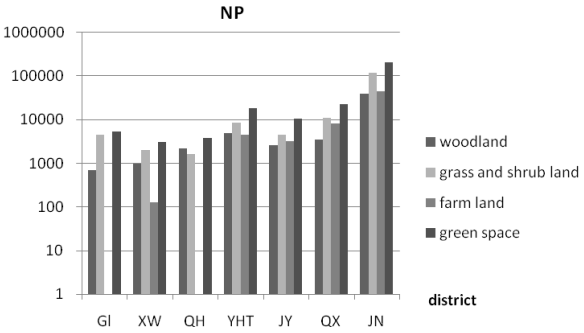

FIGURE 6 The NP of the green space in the study area

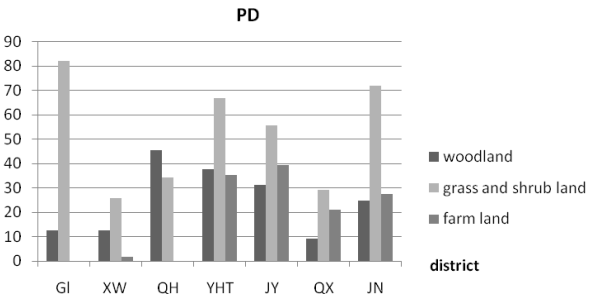

FIGURE 7 The PD of the green space in the study area

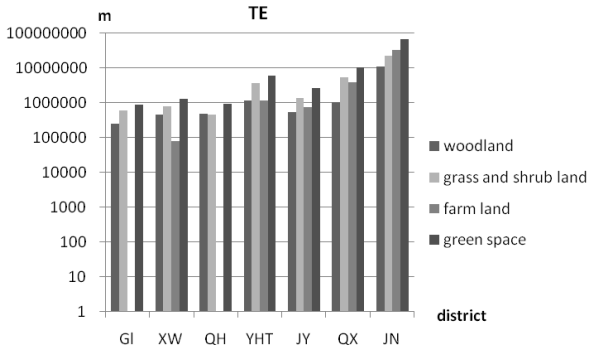

FIGURE 8 The TE of the green space in the study area

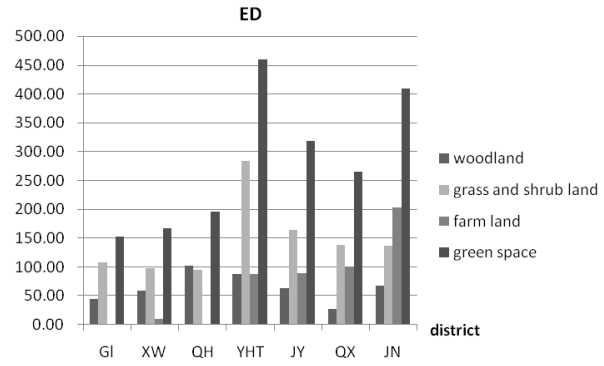

FIGURE 9 The ED of the green space in the study area

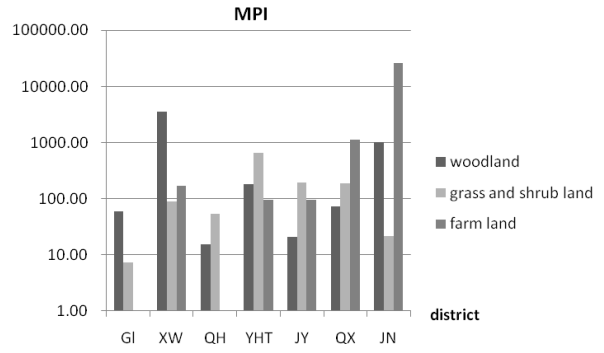

FIGURE 10 The MPI of the green space in the study area

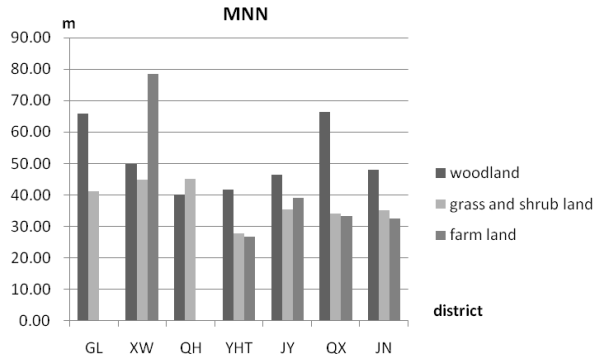

FIGURE 11 The MNN of the green space in the study area

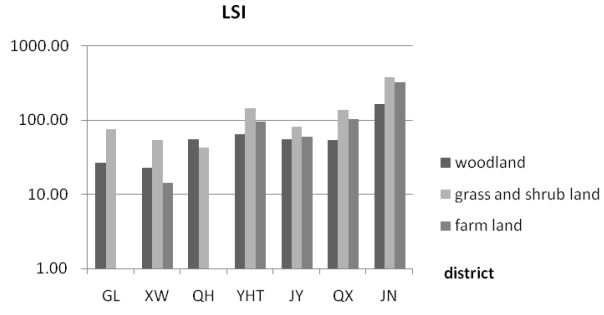

FIGURE 12 The LSI of the green space in the study area

6 Conclusions

Gulou, Qinhuai, Xuanwu, and Jianye are all densely populated urban districts, with limited available land and a high level of development. Gulou District has the highest population density and the least total area of green space. The green space that does exist in Gulou consists mainly of woodlands and grass and shrub lands, with woodlands taking a slightly greater proportion, primarily concentrated around the hills of Qingliang Mountain Park, Gulin Park, and Shitoucheng Park on the banks of the Qinhuai River. Woodland patches are relatively concentrated within each district, and their average size is far larger than that of grass and shrub land patches. The shapes of these woodland patches also are observed to be minimally disturbed. The grass and shrub land in Gulou experiences a high degree of fragmentation and has a small average size and a complicated shape distribution. In addition, it is greatly affected by artificial environments such as road networks, and is highly dispersed with weak connectivity between patches.

Qinhuai District is the center of Nanjing's Old Town, and home to the royal palace of the Ming Dynasty. It has deep historical roots as well as highly developed business activities. With a slightly lower population density than Gulou, this district also has a slightly larger green space area. The woodlands in Qinhuai, highly fragmented and disturbed, are less prominent than grass and shrub lands and show a complex patch shape distribution. Therefore, woodland is considered as a secondary green space type in this district.

Xuanwu is the urban district with the lowest population density, exhibiting an abundance of natural, cultural, and historical resources. Its Zijin Mountain and Xuanwu Lake form the backbone of Nanjing's natural landscape bodies. Concentrated within the hills of Zijin Mountain, woodlands in Xuanwu comprise 70% of the entire district's green space. There also exists a large-scale grass and shrub land in the southern part of Zijin Mountain, which is an important recreational site in Nanjing. Generally, Xuanwu is the urban district with the most abundant green space that shows the lowest degrees of disturbance and fragmentation.

Jianye is located at the southwest part of the city center, close to the Yangtze River. With undeveloped land in its central and southern parts, Jianye is the new center of Nanjing's urban development, and currently has the lowest population density among all the urban districts studied. The area of woodland within Jianye is comparable to that of Gulou, (i.e., sparsely distributed, highly separated, and poorly connected). The main type of green space in Jianye is grass and shrub land, widely distributed in the underdeveloped areas of the district. Large-scale patches of farmland are also observed in its southern part. The shape distribution of the green space patches in this district is somewhat complicated, indicating a high level of disturbance from human activities.

Yuhuatai is located in the southern part of Nanjing, and has the highest population density among the city's suburban districts. Green space area in this district is relatively large, with the primary type being grass and shrub land, which is widely distributed, with close proximity and good connectivity, but revealing complicated shapes that denote high disturbance by human interference. Woodland is mostly found within the Yuhuatai Scenic Area. A small amount of farmland is still preserved in this district.

With a relatively low population density, Qixia District is located north of the city center, touching the Yangtze River at its most western part. This district is Nanjing's industrial production base and, as such, has many factories. The ratio of woodland in the region is the smallest among the districts studied, mostly concentrated in the Qixia and Mufu mountain ranges, with patches that are highly dispersed. Farmland and grass and shrub land comprise a larger proportion, and thereby are the primary green space types. Farmland is concentrated in the eastern part that has not seen much urbanization, with high proximity and good connectivity to other green spaces. Grass and shrub land in the district show high levels of interference and relatively complex shape distribution.

The suburban district of Jiangning has the largest area and lowest population density, and its scale of the total green spaces is also the largest among all districts studied. Farmland takes up approximately half of the district's total green space, exhibiting a large average patch area and a high degree of concentration. Woodlands in Jiangning account for 85% of the total woodland area within the suburban districts studied, and they are mainly located on the mountains and hills. Large-scale, concentrated woodlands are not frequently observed in Jiangning, but the connectivity between patches is average. The largest patches of green space in the district are grass and shrub land, but their spatial configuration is complex, with much interference and high levels of fragmentation and dispersion. This indicates that although Jiangning possess a great area of green spaces, they suffer strong disturbance from human activities.

In general, the green space distribution in Nanjing is highly uneven, with most located in the suburbs and few in the urban areas. Green space in the urban districts is clearly centralized, showing concentration around the Zijin Mountain area. In the suburbs, the green space is scattered, with high levels of fragmentation. This indicates that the urbanization of the suburban areas is intense and lacks strict spatial management. Farmland accounts for approximately half of the total green space, located mostly in the suburbs, particularly in the Jiangning District. As urbanization and development continues, the amount of farmland is expected to decrease, as this type of green space is gradually being eradicated for use in city development and construction. This is expected to pose a significantly adverse impact to the ecological quality of Nanjing's green spaces[20].

The ecological quality conditions of green space are the guiding reference for urban planning and sustainable development. However, it is difficult to build more large-scale urban green spaces within the city's core; therefore, the focus of green space development should be on increasing the proportion of woodland, improving the connectivity between green spaces, and forming more ecologically beneficial structures. The abundant green spaces in the suburban areas are the main body of Nanjing's overall green space. Due to the pressure of continuing urbanization, it is more crucial to employ ecological principles and concepts in the planning of suburban areas.

Acknowledgments

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Author

Hao Xu, 1973.11,Nanjing City, Jiangsu Province, P.R. China

Current position, grades: Associate Professor at Nanjing Forestry University.
Scientific interest: GIS, RS and landscape analysis
Publications: 34