Identification of Ecological Space in Nanjing City Based on Forest Ecological Service Functions and Ecological Sensitivity

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Abstract The effective identification and protection of ecological spaces is a fundamental cornerstone for achieving sustainable development and promoting a green society. It plays an indispensable role in ecological protection, resource management, and environmental governance, and is of great significance for the sustainable development of human society. Rapid and scientific identification of ecological spaces provides a scientific foundation for regional ecological protection planning. In this study, we used survey data from the planning and design of forest resources alongside 2017 Landsat 8 OLI remote sensing image to comprehensively analyze forest ecological service functions and ecological sensitivity using the layer-cake model to identify ecological spaces in Nanjing City. The results show that the area of extremely important forest ecological service function zones in Nanjing was 288.57 km^2, accounting for 3.47% of the total area of Nanjing. The area of highly sensitive zones in Nanjing was 464.39 km^2, accounting for 7.05%. Considering both forest ecological service functions and sensitivity, the area of core ecological spaces in Nanjing was 692.86 km^2, accounting for 10.52% of the total area, and the main land use types were woodland and waters. The area of transitional ecological space in Nanjing was the largest, reaching 3 150.29 km^2, accounting for 47.83% of Nanjing's total area. This study provides valuable insights for optimizing the layout of ecological spaces and serves as a reference for related research efforts.

Key words Ecological service functions; Ecological sensitivity; Ecological space; Layer-cake model; Nanjing City

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With the rapid development of urban economy, the protection of urban ecological environment faces increasing challenges. In order to promote the construction of ecological civilization, China has successively issued a series of documents, such as the *Tenth Five-year Plan" for Ecological Environment Protection and Opinions of the Central Committee of the Communist Party of China and the State Council on Comprehensively Promoting the Construction of Beautiful China*. Therefore, it is of great significance to optimize land use planning, promote sustainable land use models, improve the efficiency of land use and promote the harmonious coexistence between man and nature.

Ecological space[1] refers to the spatial range occupied by various organisms and their habitats in an ecological system in a geographical area. It includes not only natural ecosystems (such as forests, wetlands, grasslands, *etc.*), but also the ecological environment under the influence of human activities. The concept of ecological spaces emphasizes the physical space required by biological populations and their interactions, as well as the necessary conditions for maintaining ecological functions (such as water circulation, carbon storage, species habitat, *etc.*). The effective identification and protection of ecological spaces is very important for biodiversity protection, ecological security, sustainable land use and resource management, serves as a vital foundation for achieving sustainable development and promoting a green society, plays an irreplaceable role in ecological protection, resource management and environmental governance, and is of great significance to the sustainable development of human society.

The core of ecological space assessment and decision-making is ecosystem functionality and sensitivity[2]. In most existing studies, an ecological space is delimited based on ecosystem service functions and ecological sensitivity[2–3]. Although Nanjing has a high degree of urbanization, its forest coverage rate ranks first in the province for six consecutive years, and the forest coverage rate reached 31.96% in 2023. Woodland types occupy a more important position in Nanjing. In this study, based on the survey data of planning and design of forest resources and Landsat 8 OLI remote sensing image data in 2017, forest ecological service functions and ecological sensitivity were comprehensively studied based on the layer-cake model to explore the rapid and scientific division method of urban ecological spaces with high urbanization and forest coverage rate, so as to provide scientific basis for regional ecological protection regulations.

1 Data and methods

1.1 General situation of the study area Nanjing (118°22′ – 119°14′ E, 31°14′ – 32°37′ N), the capital of Jiangsu Province, is located in the lower reaches of the Yangtze River in eastern China (Fig. 1). Nanjing borders Shanghai in the east, Anhui in the south, and other cities in Jiangsu in the west. With convenient transportation, Nanjing is an important political, cultural and economic center in East China. Nanjing has a subtropical monsoon climate, with four distinct seasons and an annual precipitation of about 1 100 mm. Nanjing is dominated by subtropical monsoon ev-

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ergreen broad-leaved forests. The rich vegetation types and ecological environment bring diversity to the city's greening. Nanjing has several nature reserves and parks, such as Nanjing Zijinshan and Laoshan National Forest Park, which are home to a variety of plants and animals. The vegetation of Nanjing is lush, and the ecological environment is excellent.

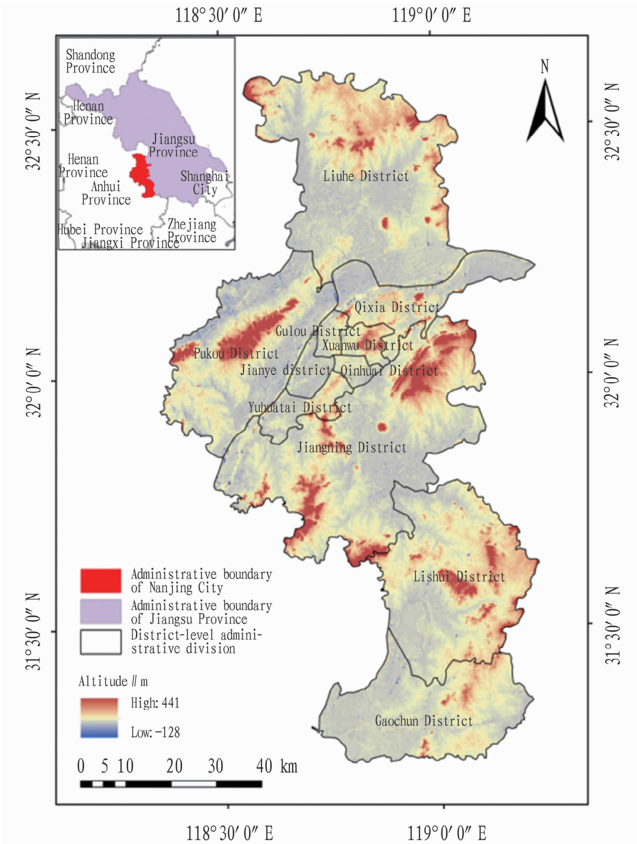

Fig. 1 Location of the study area

1.2 Research data

1.2.1 Survey data of planning and design of forest resources. The survey data of planning and design of forest resources (referred to as second-class survey data) is the survey data of resources for state-owned forestry bureaus (fields), nature reserves, forest parks and other forest management units or county-level administrative regions. Its purpose is to grasp the present situation and dynamic changes of forest resources and provide basic data support for the preparation of forest management plans, overall design, forestry division, planning and design. The main content of second-class survey data mainly includes the dynamic laws of the quantity, quality, growth and extinction of forest resources, and the relationship with the natural environment, economy and management conditions. Based on these data, the sustainability and health status of forest resources can be evaluated to provide services for formulating and adjusting forestry policies, making forestry plans and identifying forest management effects. The methods of obtaining second-class survey data include fixed plot survey, remote sensing technology and geographic information system (GIS). These methods can be used to draw topographic maps, analyze climatic conditions and hydrogeological data, and conduct sample surveys on different types of vegetation community, and obtain data of species composition and quantity, vegetation structure and spatial pattern. In this study, based on the survey data of planning and design of forest resources in Nanjing in 2017, eight factors, such as forest stock volume, forest naturalness, forest community structure, forest tree species structure, total vegetation coverage, canopy density, stand mean height, and thickness of litter layer, were extracted to construct an evaluation system, and the evaluation results of forest ecological service functions were obtained in the study area.

1.2.2 Landsat-8 OLI remote sensing image. Landsat-8 is an earth observation satellite launched by the National Aeronautics and Space Administration (NASA) and the United States Geological Survey (USGS) in February 2013, and it belongs to the eighth satellite in the Landsat series. Landsat-8 is equipped with two main remote sensing instruments, among which the operational land imager (OLI) provides high-quality remote sensing data for environmental monitoring, resource management and land cover classification. OLI, which is a multi-spectral imager, can obtain spectral information from visible light to near infrared and short-wave infrared rays, and is used to monitor various phenomena on the earth's surface. It provides nine spectral bands, including the newly added coastal blue and cloud detection bands. Except the spatial resolution of the 8^{th} band panchromatic band is 15 m × 15 m, that of other bands is 30 m × 30 m. Landsat-8 has a complete global coverage of the earth every 16 d, with a scanning width of 185 km. Its orbital height is 705 km.

In this study, the image data with the cloud amount of less than 5 in the vegetation growing season in 2017 and was retrieved in the geospatial data cloud. Because one image could not cover Nanjing City, two eligible images were finally obtained. The specific information is shown in Table 1. The downloaded images need to be pretreated through radiation calibration, atmospheric correction and mosaic before being used to calculate vegetation index.

Table 1 Information of the images

Image	Strip number	Line number	Time	Cloud amount
1	120	37	2017-07-21	0.91
2	120	38	2017-07-21	1.12

1.2.3 Other data. In this study, the data of altitude, slope, rainfall and soil erosion are also needed for the assessment of eco-environmental sensitivity. Among them, elevation data comes from the ASTER GDEM data set of digital elevation with the resolution of 30 m; slope data was obtained based on elevation data by using the Slope tool of ArcGIS software. The spatial resolution of elevation and slope data is 30 m × 30 m. Rainfall and soil erosion data come from the resource and environmental science data platform, and the spatial resolution of their original data is 1 km × 1 km, and they were resampled to the spatial resolution of 30 m × 30 m by using ArcGIS.

1.3 Research methods

1.3.1 Evaluation method of forest ecological service functions.

The evaluation of forest ecological function service refers to the evaluation of various service functions provided by forest ecosystem, so as to quantify its economic value and ecological and environmental benefits. The evaluation of forest ecological function service mainly includes the evaluation of the benefits of forest in water conservation, soil conservation, carbon fixation and oxygen production, accumulation of nutrients, purification of atmospheric environment, and protection of biodiversity. Based on the survey data of planning and design of forest resources in Nanjing, eight factors, such as forest stock volume, forest naturalness, forest community structure, forest tree species structure, total vegetation coverage, canopy density, stand mean height, and thickness of litter layer, were extracted to construct an evaluation system, and the evaluation results of forest ecological service functions were obtained in the study area[5]. Evaluation factors and weight of forest ecological function are as shown in Table 2.

Table 2 Evaluation factors and weight of forest ecological function

Evaluation factor	Type			Weight
	I	II	III	
Forest biomass // t/hm^2	≥150	50 – 149	<50	0.20
Forest naturalness	1, 2	3, 4	5	0.15
Forest community structure	1	2	3	0.15
Tree species structure	6, 7	3, 4, 5	1, 2	0.15
Total vegetation coverage // %	≥70	50 – 69	<50	0.10
Canopy density	≥0.70	0.40 – 0.69	0.2 – 0.39	0.10
Mean tree height // m	≥15.0	5.0 – 14.9	<5.0	0.10
Grade of the thickness of litter layer	1	2	3	0.05

Forest ecological function index is as follows:

$$K = \frac{1}{\sum_1^8 W_i X_i} \qquad (1)$$

In the formula, W_i represents the weight of each evaluation factor; X_i is the score of each evaluation factor (types I, II and III score 1, 2 and 3 respectively). The index is less than or equal to 1, and the larger the value, the better the forest ecological function.

1.3.2 Evaluation method of eco-environmental sensitivity. Assessment of eco-environmental sensitivity needs to consider water conservation, soil and water conservation, soil erosion and biodiversity. Therefore, modified normalized difference water body index was used to evaluate the water conservation function of the study area, and water erosion modulus, wind erosion modulus, normalized difference built-up index, altitude and slope factors were used to evaluate the water and soil conservation and soil erosion capacity of the study area. Normalized difference vegetation index was used to evaluate the biodiversity function of the study area. Normalized difference water index, normalized difference built-up index and normalized difference vegetation index need to be calculated based on Landsat-8 OLI remote sensing images.

1.3.2.1 Normalized difference vegetation index. Normalized difference vegetation index (NDVI) is used to evaluate the growth and coverage of surface vegetation[6]. NDVI is calculated by the spectral difference between near infrared band (NIR) and red band (Red) reflected by the earth's surface, because healthy vegetation has strong reflection in the near infrared band and weak reflection in the red band. The value of NDVI ranges from −1 to 1. The calculation formula is as follows:

$$NDVI = \frac{NIR - Red}{NIR + Red} \qquad (2)$$

In the formula, NIR is the reflectivity in the near infrared band; Red is the reflectivity in the red band.

1.3.2.2 Normalized difference built-up index. Normalized difference built-up index (NDBI) is mainly used to identify and analyze the distribution of buildings and urban areas[7]. NDBI is calculated based on the reflection difference between near-infrared band (NIR) and short-wave infrared band (SWIR). Buildings and urban areas usually have strong reflection in the short-wave infrared band, but weak reflection in the near-infrared band, so the areas of buildings and human activities can be highlighted by analyzing the reflection difference between short-wave infrared band and near-infrared band. The value of NDBI is usually from −1 to 1, and the larger the value, the higher the building density. The calculation formula is as follows:

$$NDBI = \frac{SWIR - NIR}{SWIR + NIR} \qquad (3)$$

In the formula, SWIR is the reflectivity in the short-wave infrared band; NIR is the emissivity in the near infrared band.

1.3.2.3 Modified normalized difference water index. Normalized difference water index (NDWI) is used to detect water by analyzing the reflection differences between water and other surface features (such as vegetation and buildings) in different bands[8]. Based on the reflectivity difference between green band and near infrared band, NDWI can effectively improve the identification accuracy of water. Because the original NDWI index may confuse some buildings and vegetation with water, modified normalized difference water index (MNDWI) is proposed, and short-wave infrared band (SWIR) is used to replace near infrared band to improve the detection accuracy of water. MNDWI can better suppress the interference of buildings and vegetation and enhance the detection effect of water. The value of MNDWI ranges from −1 to 1. When MNDWI is greater than 0, it usually indicates the water area. The higher the MNDWI value, the more obvious the water characteristics in this area, because water has low reflectivity in the short-wave infrared band (SWIR) and high reflectivity in the green band. As MNDWI is less than 0, it usually represents non-water areas, such as vegetation, buildings, exposed ground, *etc.*, because the reflectivity of ground features such as vegetation and buildings is high in the short-wave infrared band. The specific calculation formula is as follows:

$$MNDWI = \frac{Green - SWIR}{Green + SWIR} \qquad (4)$$

In the formula, Green is the reflectivity in the green band; SWIR is the reflectivity in the short-wave infrared band.

1.3.2.4 Principal component analysis. Principal component analysis (PCA) is a statistical method, and aims to transform multiple indicators into a few comprehensive indicators by using the idea of dimensionality reduction. The principle of PCA is to project high-dimensional data into low-dimensional space through linear transformation, so as to maximize the variance of the projected data on the new coordinate axis. This is achieved by finding the principal component of the data (namely the main changing direction of the data). The goal of PCA is to find a low-dimensional subspace, so that the projection of data on this subspace can best preserve the characteristics of the original data. This can be achieved by maximizing the variance of projection data or minimizing the sum of squares of projection errors[9].

PCA is widely used in many fields. For instance, it can reduce the dimension of data set and maintain the important characteristics of data; in terms of data compression, it can reduce the storage and processing requirements of data on the premise of maintaining the important characteristics of data. Seen from feature extraction, it can extract useful features from the original data and remove redundant information. It can be used in data visualization, namely projecting high-dimensional data into two-dimensional or three-dimensional space for visual analysis.

In this study, based on the data of altitude, slope, precipitation and soil erosion, as well as NDVI, NDBI and MNDWI extracted from Landsat-8 OLI remote sensing images, PCA was conducted to obtain the evaluation results of eco-environmental sensitivity in the study area.

1.3.3 Layered model. Layered model, which is an ecological planning method, emphasizes landscape planning on the basis of respecting natural laws and inherent values of nature[10]. This model was put forward by Macharg of the University of Pennsylvania, who elaborated this idea in his book Design with Nature. Layered model regards landscape as an interrelated whole including decisive factors such as geology, topography, hydrology, land use, plants, wildlife and climate, and emphasizes the continuity of vertical ecological processes of these factors.

The core idea of layered model lies in multi-level planning of landscape through factor hierarchical analysis and map overlay technology. This method not only considers all aspects of the natural environment, but also ensures the rationality and sustainability of the planning through scientific analysis. Macharg believes that landscape planning should follow the inherent value and natural process of nature, and build an artificial ecosystem that can be shared with people, so that landscape change and land use can be applied to ecological ways. In this study, layered model was used to superimpose the results of forest ecological service function evaluation and eco-environmental sensitivity evaluation to get the results of ecological space identification in Nanjing City.

2 Results and analysis

2.1 Results of forest ecological function evaluation Based on the evaluation factors of forest ecological function, the ecological service functions of the study area was calculated, and it was divided into four grades by natural classification method, including extremely important, important, moderately important and generally important areas according to their forest ecological function (Fig. 2). Extremely important zones were mainly distributed in mountainous areas such as Zijin Mountain, Laoshan National Forest Park and Qixia Mountain. Important zones were mainly located around extremely important zones. Moderately important zones were widely distributed, including mountainous areas such as Baota Mountain and Jinque Mountain in the west of the study area, Xinjizhou area in the Yangtze River basin, and Gaochun Wetland Park in the south of the study area.

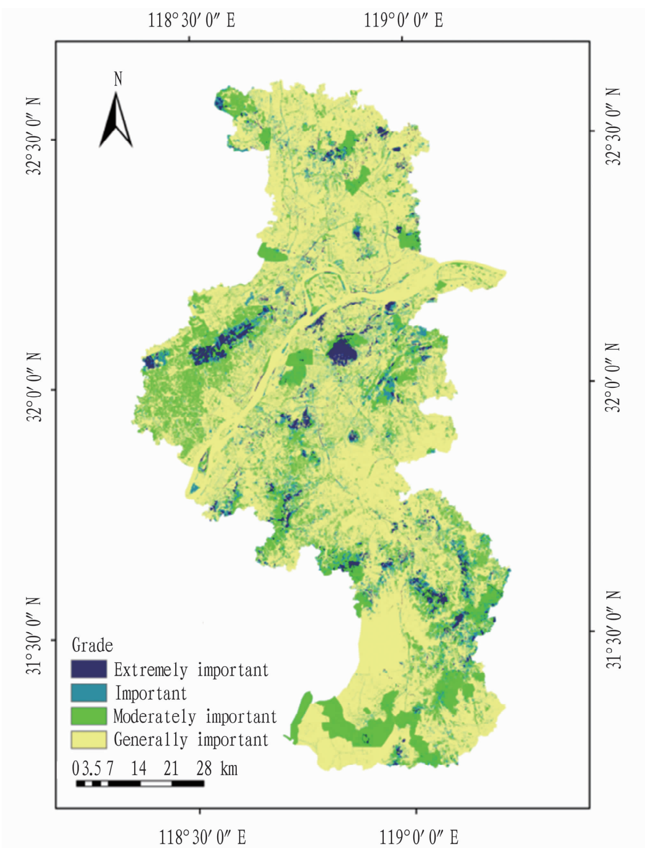

Fig. 2 Spatial distribution of forest ecological function evaluation grades

The area of four kinds of forest ecological function was calculated, in which the area of extremely important, important, moderately important and generally important zones accounted for 3.47%, 7.30%, 19.24%, and 69.99%, respectively (Table 3).

Table 3 Area and proportion of four kinds of forest ecological function

Grade	Forest ecological function	
	Area//km²	Proportion//%
Extremely important	228.57	3.47
Important	480.85	7.30
Moderately important	1 267.34	19.24
Generally important	4 610.27	69.99

2.2 Results of ecological sensitivity evaluation Based on Landsat-8 OLI, NDVI, NDBI and MNDWI were calculated, and the spatial resolution of rainfall, water erosion modulus data, wind erosion modulus data, DEM and Slope data was unified to 30 m (Fig. 3).

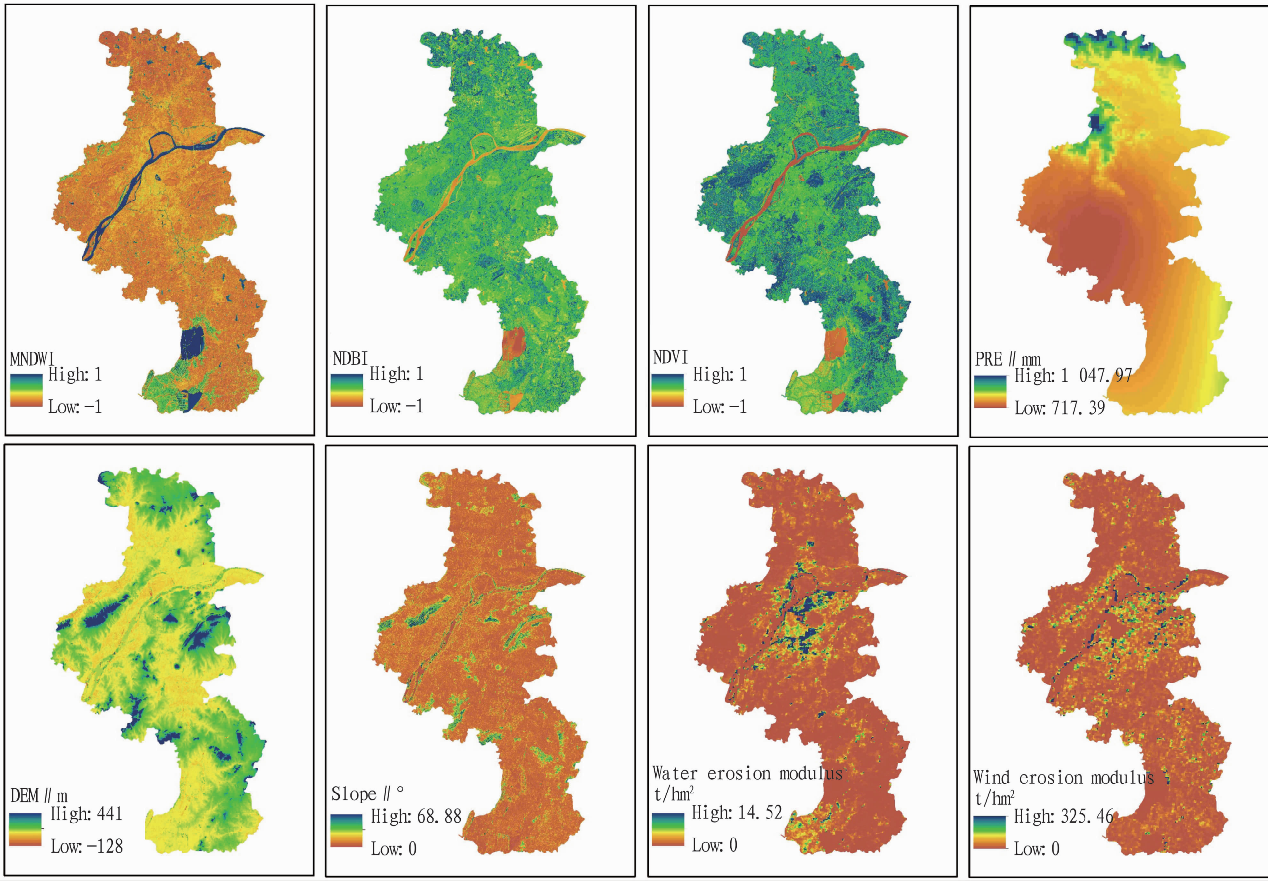

Fig. 3 Evaluation factors of eco-environmental sensitivity

Based on eight evaluation factors of eco-environmental sensitivity, PCA was used to get the eco-environmental sensitivity of the study area. By using the natural classification method, the study area was divided into extremely sensitive, sensitive, moderately sensitive and generally sensitive zones, and the spatial distribution is shown in Fig. 4. Extremely sensitive zones mainly included the Yangtze River basin and its tributaries and Shijiu Lake. Sensitive zones were mainly distributed in the densely populated areas in the central and western parts of the study area. Moderately sensitive zones were widely distributed, and the area had a high proportion. Generally sensitive zones were mainly distributed in mountainous areas in the north and southeast of the study area.

In the study, the area of extremely sensitive zones was 464.39 km^2, accounting for 7.05%. The area of sensitive zones was 1 603.29 km^2, accounting for 24.34%. The area of moderately sensitive zones was the largest, accounting for 3 103.81 km^2 (47.12%). The area of general sensitive zones was 1 415.55 km^2, accounting for 21.49%.

Table 4 Area and proportion of eco-environmental sensitivity grades

Grade	Eco-environmental sensitivity	
	Area // km^2	Proportion // %
Extremely sensitive	464.39	7.05
Sensitive	1 603.29	24.34
Moderately sensitive	3 103.81	47.12
Generally sensitive	1 415.55	21.49

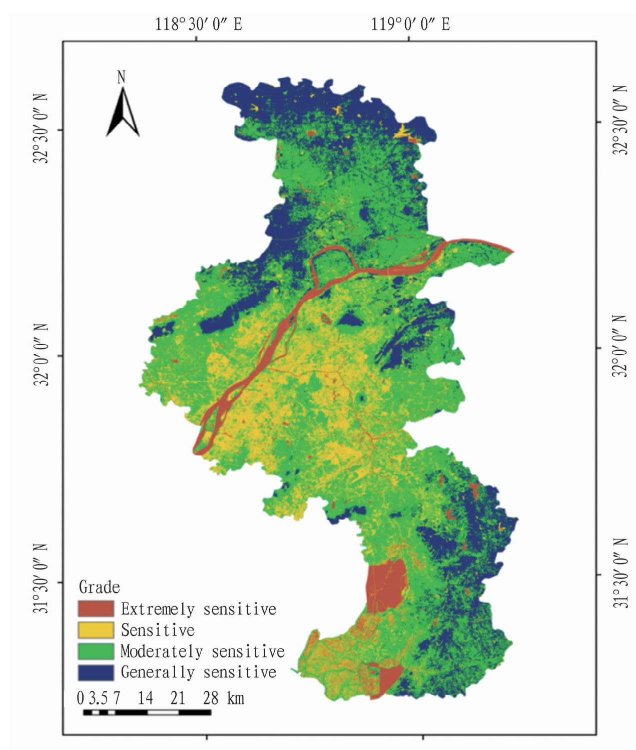

Fig. 4 Spatial distribution of eco-environmental sensitivity evaluation grades

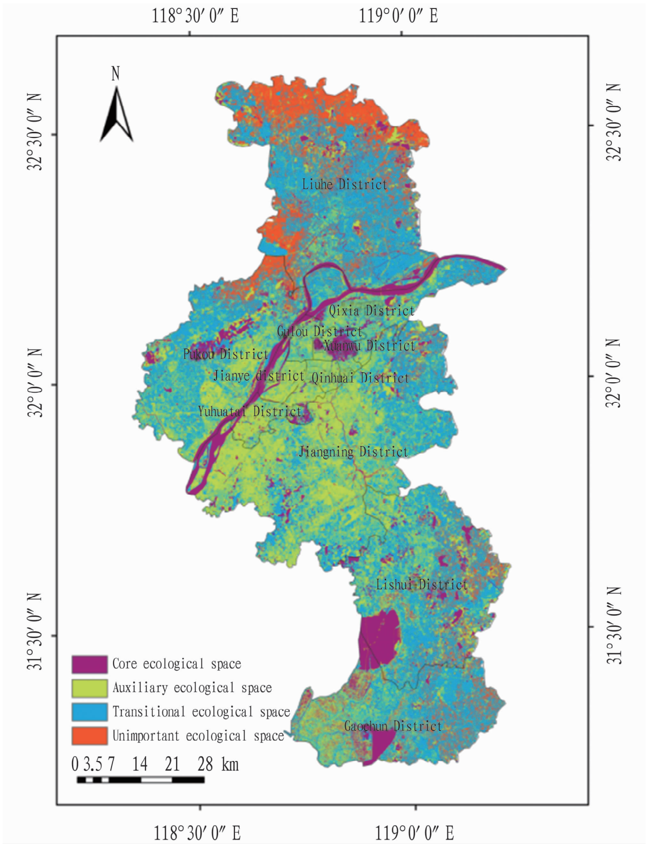

Fig. 5 Distribution of ecological spaces in the study area

2.3 Results of ecological space identification The identification of ecological spaces is based on the layer-cake model, as well as the results of forest ecological service functions and ecological sensitivity evaluation. Firstly, extremely important and extremely sensitive zones were classified as core ecological space; secondly, important and sensitive zones were classified as auxiliary ecological space; thirdly, moderately important and moderately sensitive areas were classified as transitional ecological space; finally, generally important and generally sensitive areas were classified as unimportant ecological space. The specific distribution is shown in Fig. 5. Core ecological space was mainly distributed in Xuanwu District, Pukou District, Lishui District and Gaochun District of Nanjing City. Auxiliary ecological space was mainly distributed in Gulou District, Jianye District, Qinhuai District, Yuhuatai District and Jiangning District. Transitional ecological space was distributed in all districts. Unimportant ecological space was mainly located in the north of Pukou District and Liuhe District.

As shown in Fig. 6, the area of transitional ecological space was the largest, up to 3 150.29 km^2, accounting for 47.83% of total area of the study area; the area of auxiliary ecological space was 1 995.53 km^2, accounting for 30.29%. The area of unimportant ecological space was close to that of core ecological space, in which the area of the former was 748.36 km^2, and that of the latter was 69.83 km^2.

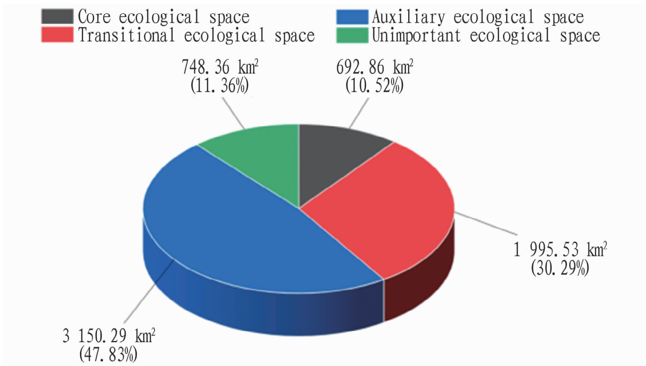

Fig. 6 Proportion of the area of ecological spaces in the study area

Land use in different types of ecological spaces was further analyzed. In the core ecological space, the area of waters accounted for 62.81% of the total area of this space, followed by woodland (16.12%), while the proportion of buildings was the lowest, only 4.51%. In the auxiliary ecological space, except for other types of land, the proportion of buildings was the highest, accounting for 34.16%, and the proportion of woodland was the lowest (6.13%). In the transitional ecological space, the proportion of other types of land was the highest proportion (75.97%), followed by buildings (16.21%). In the unimportant ecological space, the situation of land use was similar to that of transitional ecological space, and the proportion of buildings and other types of land was the highest, while that of woodland and waters was the lowest. According to the situation of land use, woodland and waters occupied an important position in the core ecological space of Nanjing City and need to be protected.

Table 5 Statistics of land types of ecological spaces

Ecological space	Woodland		Buildings		Waters		Others	
	Area//km^2	Proportion//%	Area//km^2	Proportion//%	Area//km^2	Proportion//%	Area//km^2	Proportion//%
Core ecological space	111.70	16.12	31.26	4.51	435.18	62.81	114.72	16.56
Auxiliary ecological space	122.32	6.13	681.77	34.16	221.46	11.10	969.98	48.61
Transitional ecological space	151.78	4.82	510.78	16.21	94.51	3.00	2 393.22	75.97
Unimportant ecological space	21.15	2.83	81.47	10.89	12.25	1.64	633.49	84.65

3 Conclusions

In this study, layer-cake model was used to identify ecological spaces in Nanjing based on the evaluation of forest ecological service functions and eco-environmental sensitivity. The evaluation results of forest ecological service functions in Nanjing show that the area of extremely important zones was 228.57 km^2. The evaluation results of ecological sensitivity reveal that the area of extremely sensitive zones was 464.39 km^2. In Nanjing, the proportion of transitional ecological space was the highest, up to 47.83%. The area of core ecological space was 692.86 km^2, accounting for only 10.52%, and it was the smallest among the four types of ecological space. In the core ecological space, the proportion of the area of waters and woodland was large, while the proportion of buildings was the lowest. There was a certain conflict between building land and ecological space, and the proportion of building land was high, which would have a certain impact on the protection of ecological security. The results of this study show that the ecological situation in Nanjing was relatively good. Building land was mainly concentrated in the auxiliary and transitional ecological space. Strictly controlling the urban development boundary (namely limiting the expansion of the city into the scope of ecological space) and increasing the area of artificial green space (such as parks and green belts) in cities and towns can effectively reduce the proportion of construction land in ecological spaces and then the impact on ecological security and protect the ecological environment.

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radiometer was 300 m, and the spatial and temporal variation of water vapor was the most significant within 100 m near the ground, so there was a certain difference. At the three moments on June 9, there was rain. It can be seen that there was a significant difference between the temperature profiles of the two, and it reached 10-15 K. The values of RH were very close, so it was close to 100%. In the rainfall process from July 11 to 15, similar differences also appeared. That is, before the rainfall, the difference between the two in temperature was small, and there was a certain difference in RH. During the rainfall, the difference in temperature was significant, and atmospheric vapour was almost saturated. As shown in Fig. 9, the average temperature detected by the microwave radiometer was 2.5 ℃ lower than that of the tower when there was no rain, and the mean square error was 1.2 ℃. As there was rain, it was 10.8 ℃ lower, and the mean square error was 4.1 ℃.

3 Conclusions

Based on the measurement principle of bright temperature by microwave radiometer, a set of quality control process of bright temperature data was proposed, in which the effect of water film on the microwave radiometer was corrected. Through the analysis of data at Xianghe Station, the temperature and humidity profiles of the microwave radiometer after quality control was consistent with the data obtained by the 102-meter observation tower when there was no rain.

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