Estimating urban suitable ecological land based on the minimum cumulative resistance model: A case study in Nanjing, China

Y P Ye1,2 and S N Wang1
1 College of Hydrology and Water Resources, Hohai University, Nanjing 210098, China
E-mail: yapingye@hhu.edu.cn

Abstract. Intense transformation and conflicts between different land use types has occurred in the past decades and will still exist in the coming decades in China. Ascertaining the quantity and pattern optimization of urban ecological land is critical to guaranteeing urban ecological security and realizing urban sustainable development. In this study, Nanjing, a very famous city in the Yangtze River Delta in China, was selected as the case study to explore the land use changes from 1995 to 2015 and calculate the suitable amount of ecological land to meet the needs of its socioeconomic development. From 1995 to 2015, the proportion of ecological land in Nanjing dropped from 84.41% to 59.15%. Based on the minimum cumulative resistance model (MCRM), we designed four alternate scenarios to explore the optimal quantity and pattern of ecological land in Nanjing. By comparing the current land use status with the model simulation results, we proposed the suitable ecological land area for Nanjing should be no less than 3963 km², which is 56% of the total area of Nanjing. The land use strategies and the measures to protect ecological land in this study can provide a reliable reference for sustainable development of other highly urbanized regions in China.

1. Introduction
Since the 21st century, due to the rapid economic development, China's urbanization has developed at an unprecedented rate [1]. Urban population density, rapid growth, large consumer demand, consumption and the use of natural resources are strongly consuming land resources [2]. The increasing demand for built-up areas leads to the transformation of ecological land (such as farmland, woodland, grassland and wetland) to built-up areas (such as residential, commercial and industrial land) [3]. Land use changes have significantly influenced the provision of crucial ecosystem services [4], such as food production, carbon sequestration, water flow regulation, and sediment and nutrient retention [5,6].

In 2017, the urbanization rate of China's permanent residents reached 58.52% (national bureau of statistics, 2017), and the spatial expansion of urban land will increasingly become the main feature of China's land use change in the coming decades [7]. The rapid development of cities often encroaches on valuable ecological resources [8]. Due to the reduction of green space, people rely more on ecosystem services. However, the importance of ecosystem services in regional development has not been paid enough attention, which has caused a series of consequences such as environmental degradation and the weakening of ecosystem services [9,10]. The degradation and loss of ecosystem services will threaten people's survival and the security of the earth. In recent years, the research on
ecological land has gradually become a hotspot.

Studies in western countries at the early stage mainly focused on the definition and classification. Host [11], Daily [12] and Turner [13] developed some classification of ecological land and assessment on its impact on different areas. In recent years, studies on ecological land transformed to the relationships and interaction between the ecological land and different landscape types. More attention has been paid to quantitative measurement and classification [14].

At present, Chinese researches on urban ecological land mainly focus on the concept and classification of urban ecological land [15]. This paper defines urban ecological land as an important space providing ecological products and ecosystem functions, which can maintain regional ecological balance, maintain biodiversity, and prevent and mitigate natural disasters. It mainly includes woodland, grassland and water area. Because different land use types provide different ecosystem services, scholars generally believe that the evolution of ecological land use pattern is an important reason for the change of ecosystem functions [16].

In recent years, scholars at home and abroad began to study the impact mechanism of social development, regional economy and natural environment on urban expansion through the process of urban space expansion. Ecological footprint analysis method [17], green accounting method [18], energy value analysis method [19], ecological environmental pressure index method [20] and other indicators and methods are proposed. However, most of these models rely on statistical data, and are inevitably affected by subjective factors in the collection process, affecting the accuracy of data, which has great limitations [21].

The MCR model was proposed by Kannpen in 1992 [22]. It was originally used to study the spread of species. Since this method has the characteristics of landscape geographic information and biological behavior, it not only reflects the ecological process of landscape pattern, but also determines the location and mode of ecological corridor [23,24]. Therefore, it is gradually applied to the study of urban space expansion and the evaluation of land ecological suitability.

At present, the Chinese researches on urban land use mainly focus on land use change, spatial expansion and comprehensive benefit evaluation, but ignore the role of urban spatial ecological demand in urban expansion mechanism [25]. In this paper, we take Nanjing as the research area. Based on the natural environmental conditions of Nanjing and from the perspective of building a livable city, the MCR model is used to simulate the spatial evolution process of important ecological land, and the number of ecological land is calculated to ensure the healthy development of Nanjing.

2. Materials and methods

2.1. Study area

Nanjing, the capital of Jiangsu Province, China, lies in the southwest of the province and the lower reaches of the Yangtze River (between 31°14′--32°37′N, 118°22′ -- 119°14′E) (figure 1). The municipality covers an area of 6,587 km² and has an annual average temperature of 15°C and an annual average precipitation of 1106mm. Nanjing has thirteen administrative districts: Gaochun (GC), Pukou (PK), Luhe (LH), Lishui (LS), Yuhuatai (YHT), Jianye (JY), Qinhuai (QH), Qixia (QX), Xiaguan (XG), Gulow (GL), Xuanwu (XW), Baixia (BX) and Jiangning (JN). In February, 2013, XG was merged into GL District and BX was merged into QH. Nevertheless, for the comparison purposes, the pre-merger zoning was still used in this study. Urbanization rate in Nanjing increased from 49.6% in 1995 to 73.1% in 2005 and 81.4% in 2015 (Statistics, 1996, 2006, 2016), much higher than the national average of 56.1% (China, 2016).
2.2. Data sources

Land use data for 1995, 2005 and 2015 were selected to detect the trends of past land use change. We use Landsat8 image of 2015 and Landsat7 images of 1995 and 2005 for this study and take the city’s administrative map as reference. After pre-processing, such as radiometric calibration, atmospheric correction and geometric correction, and in the study, we divided land use into seven types: built-up area, water body, transportation land, farmland, woodland, grassland, and unused land (figure 2).

2.3. Minimum cumulative resistance model

2.3.1. Model description. The minimum cumulative resistance model represents the sum of the resistance consumed or overcome to reach the target point from the source through different resistance units. The specific expression is as follows:

\[
MCR = f_{\text{min}} \sum_{i=m}^{i=n} D_{ij} \times R_i
\]

Where \( f \) reflects the minimum resistance at any point in the space and the positive correlation between the spatial distance of the two and the characteristics of the landscape base surface when it passes
through the landscape base surface \( i \); \( D_{ij} \) represents the spatial distance of the object from the source \( i \) to the landscape base \( j \); \( R_i \) refers to the resistance of landscape \( I \) to movement. And \( \sum \) means all the distances and the resistances accumulated from the landscape unit \( i \) to the source unit \( j \).

2.3.2. Model assumptions. The study applying the MCRM to suitable ecological land is based on the following assumptions.
- According to the purposes, urban land can be divided into ecological land and non-ecological land. Ecological land refers to the island most suitable for ecological protection, while non-ecological land refers to the land which is most suitable for urban construction.
- The expansion of ecological land is considered to go from the “sources” (e.g., wetlands, rivers, green space) along the “spatial resistance plane” and will be restricted by the non-ecological land.

Under such assumptions, the quantity and layout of ecological land can be determined according to MCR value based on the spatial heterogeneity of land cover and the different resistance in different land units.

2.3.3. Determination of sources. Source is the type of landscape that promotes the development of ecological processes. As the foundation of the whole construction process of landscape ecological security pattern, the accuracy of the identification of urban ecological source area is very important. Since the ecological source area itself has high habitat quality and connectivity, which can protect the biodiversity and maintain the integrity of the ecosystem, the ecological source area in this paper refers to the drinking water source protection area, nature protection area and the area with high vegetation coverage.

2.3.4. The setting of resistance factors. In this study, we selected soil erosion, topographic condition, vegetation coverage, landscape type as the ecological factors to analyze the spatial distribution of different factors.
- precipitation erosion factor
  Precipitation erosion factor is an indicator to reflect the potential ability of rainfall to cause soil erosion. The calculation of precipitation erosion factor was first developed by Williams [26] and then modified in 1969.
  \[
  R = \sum_{i=1}^{12} 1.735 \times 10^{(1.5 + 0.96 P/H)} \times (-0.8118)
  \]
  Where \( R \) represents precipitation erosion factor, \( P_i \) represents monthly average rainfall, and \( P \) represent annual rainfall (unit: mm).
  In this study, we used the following empirical formula to calculate P and R (figure 3).
  \[
  P = 24.7856 \times H^{0.4086}
  \]
  Where \( P \) is the annual rainfall and \( H \) is the altitude.
  \[
  R = 0.44488 \times P^{0.96982}
  \]
- soil erodibility factor
  Soil erodibility factor is a parameter representing different soil erosion resistance, mainly reflecting in the difficulty of soil to resist washing and transporting by rainfall and running water. In this paper, the EPIC model proposed by Williams et al [27] is used to calculate soil erodibility (figure 4).
\[ K_{\text{EPIC}} = \left\{ 0.2 + 0.3 \times EPX \left( -0.0256 \times SAN \left( 1 - \frac{SIL}{100} \right) \right) \left( \frac{SIL}{CLA + SIL} \right)^{0.3} \right. \\
\left. * \left( 1 - 0.25 \times \frac{C}{C + EPX(3.72 - 2.95 \times C)} \right) \right. \\
\left. * \left( 1 - 0.7 \times SN \right) \right. \\
\left. \right. \left( SN + EPX(22.9 \times SN - 5.51) \right) \right\} \]

\[ SN = 1 - \frac{SAN}{100} \]

where \( SAN, CLA, SIL \) represent the proportion(%) of sand, clay and silt respectively. \( C \) denotes the proportion (%) of organic carbon.

- slope

Topographic factor has great influence on water conservation function. The slope changes the water conservation service of the region by influencing the surface runoff.

Generally, the higher slope area has weaker water conservation ability than the low slope area because the soil is easy to lose under the faster runoff speed caused the steep slope (figure 5).

2.3.5. The setting of resistance factors. This paper takes the ecological land in Nanjing as the research object and analyzes the accumulated resistance of the ecological land expansion in Nanjing city from the source. Resistance factors considered in this paper mainly include land cover type, distance from road and distance from residential area. Resistance coefficients are set for resistance factors to generate raster data of resistance factors. The data of resistance layer were summed up to calculate the resistance surface data of ecological land expansion.

3. Results

3.1. Land use change from 1995 to 2015 in Nanjing

The results showed that the main land use types in the study area were cultivated land, which accounted for more than 70% of the total area. Figure 6 shows the spatial and temporal distribution of land use (1995, 2005 and 2015). We put transportation land together with built-up area in comparing land use changes in the three periods due to lack of data for certain years. Between 1995 and 2005, grassland experienced the heaviest loss of 24%, followed by woodland and farmland, with a decrease of 4% and 2% respectively. During this same period, built-up areas are growing at the fastest rate with
the increase of 115% while the area of water body remained almost unchanged. Between 2005 and 2015, the largest shrinkage of grassland area was also observed, with a loss of 40%, while woodland and farmland decreased by 6% and 5% respectively. However, as the trend in the last period, the built-up area continued its fastest expansion, increasing by 96% during this period, while water body area kept stable. Overall, during the study period, the land use change was characterized by the shrinkage of grassland, woodland and farmland and the rapid expansion of built-up area. Grassland, woodland and farmland decreased by 54%, 9% and 8%, respectively. Conversely, built-up area increased by 320% over the two decades. Water body area remained relatively stable during the whole study period.

Figure 6. The area of different land use types in different years.

3.2. Resistance plane of ecological land
During the expansion process of ecological land, different landscape type produces different resistance. According to the characteristics and structure of ecological land, the resistance level to the expansion of ecological land in Nanjing is ranked as follows: woodland < water bodies or wetlands < grassland < unused land < farmland < built-up area. The resistance value of different landscape type is between 0 and 500. In addition, roads and settlements also generate resistances to the expansion of ecological land. The closer it is from roads and settlements, the greater the resistance for the expansion of ecological land is. The resistance factors for the expansion of ecological land and the resistance coefficients are listed in table 1. The coefficients are obtained from the experts’ suggestion and some statistical data, which represented the relative resistance but not the absolute data, which reflect the corresponding trend.

Table 1. Resistance factor for the expansion of ecological land and resistance coefficients.

| Resistance factor | Classification and grading | Resistance coefficient |
|-------------------|---------------------------|------------------------|
| Landscape type    |                           |                        |
| woodland          |                           | 10                     |
| Water body        |                           | 1                      |
| Grassland         |                           | 20                     |
| Farmland          |                           | 200                    |
| Unused land       |                           | 100                    |
| Built-up area     |                           | 500                    |
| Transportation land|                           | 500                    |
| Distance to roads |                           |                        |
| <50m              |                           | 500                    |
| 50-200m           |                           | 300                    |
| 200-500m          |                           | 200                    |
| 500-1000m         |                           | 100                    |
| >1000m            |                           | 10                     |
| Distance to settlements |                 |                        |
| <100m             |                           | 500                    |
| 100-500m          |                           | 300                    |
| 500-1000m         |                           | 100                    |
| >1000m            |                           | 10                     |
3.3. Alternate scenarios for expansion of ecological land in Nanjing

Based on the spatial distribution data of ecological land in Nanjing and the resistance data (figure 7), we used the "cost distance" tool and "grid calculator" in ArcGIS10.3 to calculate the spatial expansion resistance of ecological land (figure 8).

![Figure 7. Spatial distribution of resistance factors of ecological land.](image1)

![Figure 8. Spatial distribution of resistance coefficient of ecological land expansion.](image2)

![Figure 9. Cumulative resistance value of ecological land.](image3)

Generally, the resistance value of woodland in the hilly area in Nanjing is low, indicating a weak resistance to ecological land expansion (figure 9). Based on the analysis results of resistance to ecological land and frequency statistics of grid data of cumulative resistance value for the important ecological sources, we designed three scenarios for ecological land expansion in Nanjing.

3.4. Evaluation on ecological services for the alternative scenarios

The resistance value reflects the difficulty degree of ecological land expansion. Based on the threshold division of cumulative resistance value, three values of 1000, 20000 and 50000 are set as the threshold value of three scenarios, among which resistance value 50000 indicates that the proportion of ecological land is the biggest and thus the ecosystem services can be guaranteed to the full extent (figure 10 Scenario 3).  

![Figure 10. Distribution of ecological land under three scenarios.](image4)

Then we conducted superposition analysis of ecological land distribution under three scenarios with the current built-up area distribution and obtained the guarantee degree of ecosystem services.
The results are listed in table 2.

Table 2. Comparison of three scenarios of ecological land expansion.

| Scenario   | Area of ecological land | Proportion of ecological land (%) | Guarantee degree of ecosystem services (%) | Area in conflicts with current built-up area |
|------------|-------------------------|-----------------------------------|-------------------------------------------|---------------------------------------------|
| Scenario 1 | 2252Km²                 | 34                                | 62                                        | 64Km²                                      |
| Scenario 2 | 3963Km²                 | 56                                | 91                                        | 856Km²                                     |
| Scenario 3 | 4594Km²                 | 69                                | 100                                       | 1336Km²                                    |

3.5. The suitable quantity and layout of ecological land in Nanjing

Figure 10 shows that the scale of ecological land in mountainous area is large while the scale and distribution pattern of ecological land in plain area are different. Ecological land area under scenario 1 is small, especially in plain area, thus no effective separation zone is formed though the conflict area with the existing built-up area is small. Under this scenario, ecological land is unable to give full play to ecological services and to control urban sprawl effectively due to its poor landscape connectivity. Scenario 2 performs better than Scenario 1, which has a bigger ecological land area, especially in plain area where obvious ecological land corridors and ecological separation zones has occurred around the built-up areas. The scale and pattern of ecological land can guarantee the provision of ecosystem services. Scenario 3 has the biggest ecological land area and thus has the best landscape connectivity and highest security of ecosystem services. However, the conflict between large areas of ecological land with the existing built-up area is obvious. In addition, it occupies large amount of farmland of Luhe, Pukou, Gaochun and Lishui districts, which is against the objectives of protections for arable land and basic farmland in Land and Resources Protection and Utilization Planning for Nanjing in the thirteenth ‘five-year’ plan. Considering the present situation urban land use, food security and other socioeconomic development factors, we concluded that this scenario is not the best plan for Nanjing’s future development though it’s the best for ecological land expansion.

4. Discussion

With the continuous development of society, people's demand for ecological environment is increasing. How to coordinate the relationship between urban construction land growth and urban ecological space protection is particularly important. Urban ecological land is not only a barrier to protect and develop the city's natural ecosystem, but also a place for local residents to relax, socialize and have fun. It is an important guarantee to improve the quality of life. However, the development intensity of Nanjing is relatively large, and the contradiction between urban growth and the development of ecosystem services is prominent. Compared with other cities in developed countries, the distribution of green space in parks in Nanjing is not balanced and the gap of green space in cities is large. The total forest resources in the plain area are insufficient, and the forest integrity, connectivity and biodiversity are insufficient compared with the developed cities [28].

Based on the above problems, this paper puts forward the following suggestions. (i) Protect the ecological resources of the central city of Nanjing, protect the nature reserves and scenic spots around Nanjing, and give full play to its important ecological barrier function and leisure space function. (ii) Strict control of development activities near ecological sources to ensure connectivity of ecological corridors. (iii) To control the growth rate of urban construction land and increase the number of green land in urban built-up areas.(iv) Improve the quantity and quality of urban parks, and reserve enough urban public ecological space. With the Qinhuai River, Xuanwu Lake and other urban canal landscape as the core, it highlights the regional cultural characteristics of Nanjing, highlights the urban symbols and historical context, integrates the urban river landscape, connects the county, and provides the public with a place for visual and spiritual enjoyment

This paper has many shortcomings and limitations. In this study, the resolution of remote sensing images affects the classification accuracy of land use types, and the selection of resistance factors is subjective. In future studies, we should pay more attention to objectivity and consider other factors.
affecting ecological diffusion.

5. Conclusions
During the study period, the land use change was characterized by the shrinkage of grassland, woodland and farmland and the rapid expansion of built-up area. Grassland, woodland and farmland decreased by 54%, 9% and 8%, respectively, while built-up area increased by 320% over the two decades.

We applied the MCRM to select landscape type, distance from the road, distance to the settlements to extract the suitable ecological land for Nanjing. Our results showed that suitable ecological land in Nanjing should be no less than 3963 km$^2$, accounting for 56% of the total land area of the city. It is mainly distributed in Gaocun, Lishui, Luhe and Pukou districts, while protection for basic farmland in these districts should also be taken into account. Ecological land in city areas is mainly distributed in mountainous areas, such as the Purple Mountain, Qingliang Mountain and Niushou Mountain, and water bodies such as the Yangtze River, Qinhuaui River and Mochou Lake. Ecological land in these areas will form the green belt around Nanjing, providing multiple ecosystem services for the municipal development.

References
[1] Tao Y, Li F, Crittenden J C, Lu Z M and Sun X 2016 Environmental impacts of China's urbanization from 2000 to 2010 and management implications Environ Manag 57 498-507
[2] Bohnet I and Pert P 2010 Patterns, drivers and impacts of urban growth-a study from Cairns, Queensland, Australia from 1952 to 2031 Landsc Urban Plan. 97 239-48
[3] Li F, Ye Y P, Song B W and Wang R S 2015 Evaluation of urban suitable ecological land based on the minimumcumulative resistance model: A case study from Changzhou, China Ecol Model 318 194-203
[4] Deng X, Liu J and Ma E 2015 Impact assessments on water and heat fluxes of terrestrial ecosystem due to land use change Impacts of Land-Use Change on Ecosystem Services Zhan J ed. (Heidelberg, Berlin: Springer Berlin Heidelberg) pp 149-209
[5] Liu S, Deng L, Dong S, Zhao Q, Yang J and Wang C 2014 Landscape connectivitydynamics based on network analysis in the Xishuangbanna Nature Reserve, China Acta Ecol 55 66-77
[6] Stockmann U, Adams M A, Crawford J W and Zimmermann M 2015 The knowns, known unknowns and unknowns of sequestration of soil organic carbon Agric Ecosyst Environ 164 80-99
[7] Seto K C, Güneralp B and Hutyra L R 2012 Global forecasts of urban expansion to anddirect impacts on biodiversity and carbon pools Proc. Natl Acad Sci USA 109 16083-8
[8] Foley J A et al 2005 Global consequences of land use Science 309 570-4
[9] Li F, Wang R, Paulussen J and Liu X 2005 Comprehensive concept planning of urbangreening based on ecological principles: A case study in Beijing, China Landsc. Urban Plan 72 325-36
[10] Qiu J , Turner M G . Spatial interactions among ecosystem services in an urbanizing agricultural watershed[J]. Proc Natl Acad Sci USA, 2013, 110(29):12149-154.
[11] Host G E 1996 A quantitative approach to developing regional ecosystem classification Ecol Appl 6 608-18
[12] Daily G C 1997 Natures Services, Societal Dependence on Natural Eco-systems (Washington DC: Island Press)
[13] Turner M G and Gardener R H 1991 Quantitative Methods in Landscape Ecology (Springer-Verlag New York Inc.)
[14] Sherrouse B C and Semmens D J 2012 Social values for ecosystem service, Version2.0: cumentation and user manual Appl Geogr 35 84-94
[15] Deng X W, Sun Y C and Han S J 2005 General principles of urban ecological landclassification and planning Chin. J. Appl. Ecol. 16 2003-6 (in Chinese)
[16] Li F, Ye Y P, Song B W, Wang R S and Tao Y 2014 Assessing the changes in land use and ecosystem services in Changzhou municipality, People’s Republic of China, 1991–2006 *Ecol Indic* **42** 95-103

[17] Singh N J, Yoccoz N G, Bhatnagar Y V and Fox J L 2009 Using habitat suitability models to sample rare species in high-altitude ecosystems: a case study with Tibetan argali *Biodivers. Conserv.* **18** 2893-908

[18] Wang Y H, Yang K C, Bridgman C L, et al 2008 Habitat suitability modelling to correlate gene flow with landscape connectivity *Landscape Ecol.* **23**(8) 989-1000.

[19] Jordan F, Baldi A, Orci K M, Racz I and Varga Z 2003 Characterizing the importance of habitat patches and corridors in maintaining the landscape connectivity of a Pholidoptera transsylvanica (Orthoptera) metapopulation *Landscape Ecol* **18** 83-92

[20] Nikolakaki P 2004 A GIS site-selection process for habitat creation: estimating connectivity of habitat patches *Landscape Urban Plann* **68** 77-94

[21] Saura S 2010 Measuring connectivity in habitat mosaics: The equivalence of two existing network indices and progress beyond them *Community Ecol* **11** 217-22

[22] Knaapen J P, Scheffer M and Harms B 1992 Estimating habitat isolation in landscape planning *Landsc Urban Plan* **23** 1-16

[23] Wu C G, Zhou Z X and Wang P C 2009 Evaluation of landscape connectivity based on least-cost model *Chin. J. Appl. Ecol* **20** 2042-8 (in Chinese)

[24] Adriaensen F, Chardon J P, De Blust G, Swinnen E, Villalba S, Gulinck H and Matthysen E 2003 The application of ‘least-cost’ modelling as a functional landscape model *Landscape Urban Plann.* **64** 233-47

[25] Yu K J 1999 Landscape ecological security patterns in biological conservation *Actacol. Sin* **19** 8-15

[26] Williams J R 1990 The erosion-productivity impact calculator (EPIC) model: A case history *Philos T R Soc B* **329** 421-8

[27] Wischmeier W H 1959 A rainfall erosion index for a universal soil-loss equation *Proc Soil Science Society of America* **23** 246-9

[28] Li F, Liu X S, Zhao D, Wang B B, Jin J S and Hu D 2011 Evaluating and modeling ecosystem service loss of coal mining: A case study of Mentougou district of Beijing, China *Ecol Complex* **8** 139-43