Measurement and evaluation of suitable ecological land based on the minimum cumulative resistance model: A case study in Shanghai, China

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Abstract. Driven by rapid urbanization in China, land use change has become one of the most significant factors influencing the provision of ecosystem services. The conversion of ecological land, especially cropland, to the built-up area is the most significant change in the process of urbanization. Measuring the quantity and pattern optimization of urban ecological land is critical to guaranteeing urban ecological security and realizing urban sustainable development. In this study, the Chinese city of Shanghai, a very famous and important megacity in China, was selected as the case study to explore the land use changes from 1995 to 2017 and calculate the suitable amount of ecological land to meet the needs of socioeconomic development of Shanghai. Remote sensing and GIS-based techniques were used to map spatial distribution and changes in ecological land from 1995 to 2017. Results showed a continuing spatial expansion of the built-up area and decline in the ecological land. From 1995 to 2017, the proportion of ecological land in Shanghai dropped from 84.41% to 59.15%. Also we applied the minimum cumulative resistance model (MCRM) to calculate the amount of ecological land for Shanghai. Considering the potential source of ecological land and comparing the current land use status with the model simulation results, we proposed the suitable ecological land area for Shanghai should be no less than 3487.6 km², which is 51.2% of the total area of Shanghai, and is mainly distributed in Chongming County, Changxing Island, Hengsha Island and Jiuduan Island. Our findings suggested that optimal land use strategies should be implemented in the urban construction process. For urban ecological land, further positive protection measures should be implemented. For ecotones between urban built-up area and ecological land, protection should be given priority and spatial expansion of built-up area should be strictly controlled. For built-up area, reasonable land use intensity should be kept to improve the land use efficiency.

1. Introduction
Much of the world is experiencing fast urbanization. By the beginning of the 21st century, half of the population lived in an urban area. Urban population in those developed countries exceeded 70-80% of the total population [1].

Because of the rapid economic development, urbanization has occurred at an unprecedented rate in China since the beginning of the 21st century [2], especially in a few large, highly developed cities, such as Shanghai, Beijing and Guangzhou. With the acceleration of the urbanization process, the rapid expansion of urban built-up area has led to the ecological land decrease, land use imbalance, environmental deterioration and other ecological challenges [3].
Land use in urban areas can be characterized by its physical, ecological, social, and economic attributes. Urban land not only provides a supporting for human economic activities, but also serves as the fundamental basis for ecosystem services[4-5]. However, during the rapid urbanization process, many peri-urban open spaces, such as parks, forest, cropland and wetlands, have been built over, which has resulted in a steep decline of ecosystem services at the municipal and regional levels [6]. The conversion of ecological land, especially cropland, to the built-up area is the most significant change in the process of urbanization [7-8], more than 50% of arable land, most of which is high-yield cropland, has been converted to the built-up area.

Studies in western countries have not put forward the specific terms of “ecological land” as an independent and specialized type of nomenclature, but the concept and related research papers of open space, peri-urban space and non-built-up areas are well recognized [6]. Forest, cropland, parks, grassland, and wetlands, as the main types of ecological land, can provide ecosystem services such as carbon sequestration [9-10], nutrient and sediment retention, storm peak mitigation, biodiversity maintenance, crop pollination [11], and cultural and recreational uses [12-13]. The most difference between the ecological land and the built-up area is that the latter is imperious surface cover, which can weaken ecosystem services.

Researchers in China have mainly studied the definition of ecological land and suitable classification systems [14-15]. Several tools have been developed and applied to assess the ecological process of landscape level, which include habitat suitability index model [16], graph theoretic model [17], network and corridor models [18] and weighted landscape graph model [19]. These models can be a good simulation of landscape connectivity at the landscape scale. However, the computation of these models is quite complex and their data requirements are more stringent [6]. There exist great limitations when these models are applied to ecological land accounting [20-21].

The MCRM was developed by Knaapen et al. [20], originally for the purposes of diffusion process of species. But its application is not limited to a particular specific ecological process. The MCRM is now regarded and accepted as one of the best models in assessing landscape connectivity at the landscape level due to its simple data structure, fast algorithms and visual results [21-22]. In recent years, the MCRM has been applied to determine the urban ecological security pattern and in urban ecological planning [23-24].

Most of the studies on urban land use in China still focus on the conversion between built-up area and other land use types, and the assessment of the impacts caused by the expansion of built-up area, while studies on suitable ecological land has just started in China. Since there are no mature methods and guidelines for the determination of ecological land to meet the minimum services to sustain the urban development, we try to choose the MCRM to simulate the expansion process of ecological land and to calculate the suitable amount of ecological land to sustain the urban development because MCRM shows good performance on landscape-level connectivity.

In this paper, Shanghai was chosen as a typical study area to: (1) examine the land use changes and transformation during the rapid urbanization period (from 1995 to 2017); (2) analyze the change in space and function of ecological land during the past 20 years; (3) apply the MCRM model to calculate the area of suitable ecological land needed to balance economic development and ecosystem protection. Evidence from our studies can be used as a basis for policymaking and urban planning to help to find and implement some optimized or harmonized land management strategies and achieve sustainable urbanization in China.

2. Materials and methods

2.1. Study area
Shanghai lies on the west coast of the Pacific Ocean and along the east edge of the Asian continent (between 30°40′-31°53′N, 120°52′-122°12′E) (Figure 1), the municipality covers an area of 6,340 km². Shanghai located at the lowest reaches of the Yangtze River, is a very famous, highly developed and urbanized megacity in China. Driven by rapid economic development, the process of urbanization
has accelerated greatly since the end of the 20th century. By 2017, the urbanization rate of Shanghai has reached 87.6%, much higher than the national average of 58.52% (The Statistical Bulletin on National Economic and Social Development of Peoples’ Republic of China in 2017).

![Figure 1. Location of the study area.](image)

Shanghai is characterized by a subtropical monsoon climate with ample sunshine, for distinct seasons and abundant rainfall. Rivers and lakes within the boundary cover an area of 500 km², accounting for 9-10% of the total area. The total resident population of Shanghai is 24.20 million. It is divided into 16 administrative districts: Jingan (JA), Changning (CN), Putuo (PT), Huangpu (HP), Xuhui (XH), Hongkou (HK), Yangpu (YP), Minhang (MH), Baoshan (BS), Jiading (JD), Jinshan (JS), Songjiang (SJ), Qingpu (QP), Fengxian (FX), Chongming (CM) and Pudong New Area (PD New Area). The urbanization rate was 70.8% in 1995 and increased to 87.6% in 2017.

2.2. Data sources and land use classification
We used Landsat5 TM images of August 12, 1995, July 19, 2004 and Landsat 8 OLI_TIRS images of August 29, 2013 and August 24, 2017 for this study. Using version 4.8 of the ENVI GIS and version 10.3.1 of ArcGIS software, we analyzed the four images and applied supervised classification.

We classified the study area into woodland, cropland, water-covered area and built-up area (Table 1), using the Land Use Classification System (GB/T 21010-2017) enacted by the Ministry of Natural Resources (former Ministry of Land and Resources) of the People’s Republic of China in November 2017. Shanghai Land Use Master Plan (1997-2010) and Shanghai Land Use Master Plan (2006-2020) drafted by the Shanghai Planning and Land Resource Bueau were used as a reference. Other data were from Shanghai Urban Master Plan (2017-2035). As shown in Shanghai Statistical Yearbook, the

![Figure 2. Rate of Cropland, woodland, water-covered area and built-up area of Shanghai, 1995, 2004, 2013 and 2017.](image)
number of gardens in Shanghai is relatively small. In this study, we classified the garden into cropland and residential land, commercial land and transportation land into a built-up area. In this study, the water area of the Yangtze River was not included.

Table 1. Land-use types found within the municipal boundaries of Shanghai [6].

| Type of land use       | Land Descriptions                                                                                         |
|-----------------------|-----------------------------------------------------------------------------------------------------------|
| cropland              | Arable land (irrigated paddy fields, irrigated land, dry land, vegetable farms), gardens(orchards, mulberry trees, tea gardens, other gardens), meadows |
| woodland              | Woodland, shrub land, sparse forest, immature forest, degraded forest, nurseries                          |
| water-covered area    | Rivers, lakes, reservoirs, ponds, reed wetlands, ditches, hydraulic structures (e.g., canals)              |
| built-up area         | Residential and industrial land (urban residential, independent industrial and mining land, special land), transportation land |

To improve the accuracy of the land area in our classification, we also downloaded the communique of the First General Survey of Geographical conditions in Shanghai (October 2017) and Shanghai Statistical Yearbook of the four period for comparison.

2.3. Minimum cumulative resistance model

2.3.1. Model description. The minimum cumulative resistance [22] refers to the cost incurred by the main body to overcome resistance generated by different landscape from the source to the destination [25], which reflects the potential accessibility. The modified minimum cumulative resistance formula [26] was: \[ MCR = f_{\min} \sum_{i,j} D_{ij} \times R_{ij} \]

Where MCR is the minimum cumulative resistance value; \( D_{ij} \) is the spatial distance between landscape unit \( i \) to source unit \( j \); \( R_{ij} \) stands for the resistance coefficient that exists in transition from landscape unit \( i \) to source unit \( j \); \( \sum \) denotes all the distances and resistance cumulative transited from landscape unit \( i \) to source unit \( j \); \( f \) is the function of the positive correlation that reflects the relation of the least resistance for any point in space to the distance from any point to any source and the characteristics of the landscape base surface.; \( \min \) connotes the minimum value of cumulative resistance generated in different processes of landscape unit \( i \) transforming into a different source unit \( j \).

First of all, we classified sources into constructing sources and ecological sources and selected the natural, socioeconomic, and policy factors as the resistance evaluation factors. Based on the determination of ecological sources, constructing sources and evaluation factors, we used the tool of ‘cost distance’ in the version10.3 of ArcGIS and ‘grid calculator’ to calculate the resistance processes to obtain two minimum cumulative difference surface (resistance plane) MCREL (minimum cumulative resistance for ecological land) and MCRBA (minimum cumulative resistance for built-up area). Then the difference between these two values was calculated. \( MCR = MCREL - MCRBA \).

When \( \Delta MCR = 0 \), it means that it is suitable for the boundary of ecological land and built-up area; when \( \Delta MCR > 0 \), it indicates stronger resistance for ecological land, which means this land is suitable for the built-up area. On the contrary, when \( \Delta MCR < 0 \), the resistance to the built-up area is high and thus it is suitable for the expansion of ecological land.

2.3.2. Determination of sources. Constructing sources refer to the built-up area, including cities, towns, villages and roads, which generate strong resistances to ecological expansion. Ecological sources refer to the non-built-up areas, such as drinking water source reserves, basic farmland,
biodiversity reserves and high vegetation-covering areas which produce less resistance to ecological expansion.

2.3.3. The setting of resistance factors. In this study, we selected the natural, socioeconomic, and policy factors in Shanghai as the resistance evaluation factors. Land use type was chosen to represent the natural factor, while the distance to the roads and settlements represented the socioeconomic factor and the drinking water reserve and biodiversity reserve was set for the policy factor.

3. Results

3.1. Dynamic changes in ecological land
In this paper, the ecological land area in Shanghai included cropland, woodland and water-covered area, with the wetlands as a part of the water-covered area. Generally, the ecological land in Shanghai has been decreasing. From 1995 to 2004, the ecological land experienced the heaviest loss while the decreasing trend slowed down after 2004 (Figure 2).

![Figure 3](image1.png)  
*Figure 3.* Land use patterns within the municipal boundaries of Shanghai in 1995, 2004, 2013, and 2017.

![Figure 4](image2.png)  
*Figure 4.* Distribution of suitable ecological land in the Shanghai.

The ratio of each land use type in 1995 was cropland > woodland > built-up area > water-covered area. This has changed to the built-up area > woodland > cropland > water-covered area by 2017. Figure 3 shows the spatial distribution of land uses along with a multi-temporal dimension (1995, 2004, 2013 and 2017). It can be seen that cropland in 2013 turned into woodland in 2017, especially in Chongming Island. The change of cropland land into woodland is also an important reason for the decrease of cropland in Shanghai during the four years.
• Cropland area decreased by 19.89% from 1995 to 2004, with an annual reduction of 2.21% (Table 2).
• Woodland area decreased by 25.27% from 1995 to 2004, representing an annual reduction of 2.81%.
• The water-covered area decreased by 2.33% from 2004 to 2013, representing an annual reduction of 0.26%, which made a relatively stable contribution to maintaining the ecological land in Shanghai.
• The built-up area expanded rapidly during the whole study period, with the biggest increase of 99.31% (11.04% per year) occurring from 1995 to 2004 (Table 2).

### Table 2. Land use changes, rates of change per study period, and annual rates of change for the land-use types found within the municipal boundaries of Shanghai, 1995–2017.

| Table of land use | Percentage of total area (%) | The rate of change in proportion (%) | The annual rate of change (%) |
|------------------|-----------------------------|--------------------------------------|-------------------------------|
|                  | 1995 | 2004 | 2013 | 2017 | 1995-2004 | 2004-2013 | 1995-2004 | 2004-2013 | 2013-2017 |
| cropland         | 45.78 | 36.68 | 33.46 | 25.31 | -19.89 | -7.73 | -2.21 | -0.86 | -6.07 |
| woodland         | 22.43 | 16.76 | 14.55 | 19.66 | -25.27 | -12.19 | -2.81 | -1.35 | 8.82 |
| water-covered    | 16.20 | 15.49 | 14.96 | 14.18 | -4.37 | -2.33 | -0.49 | -0.26 | -1.26 |
| built-up area    | 15.59 | 31.08 | 37.03 | 40.85 | 99.31 | 20.49 | 11.04 | 2.28 | 2.61 |

Since 1995, the built-up area expanded outwards from the central urban area. Ecological land, especially cropland, was gradually replaced by built-up areas. In 1995, the most predominant land use type in the study area was cropland, which occupied more than 45.78% of the total area. The area of cropland was three times that of built-up area. However, the proportion of cropland area dropped to only 25.31% of the total area in 2017. The built-up area exceeded cropland area ever since 2013.

### 3.2. Calculation of suitable ecological land

#### 3.2.1. Resistance plane
Resistance values of ecological land and evaluation factors are listed in Table 3; the values of the built-up area are the contrast.

The resistance plane of ecological land or built-up area reflects the minimum cumulative resistance value for each land unit transforming into its source ecological land or built-up area. As the resistance value increases, the likelihood of successful expansion from original land into its source land decreases; in contrast, a smaller resistance value increases the likelihood of successful transformation. The resistance of various elements of different types of land varies with the type of land. We used 1-5 to represent the different levels of resistance, with 1 being lowest and 5 being highest [21].

#### 3.2.2. Distribution characteristics of the suitable ecological land
Based on the above calculation, we choose that area with ΔMCR < 0 as the ecological land which should be kept for the future development of Shanghai while the area with ΔMCR > 0 is suitable for future expansion in a built-up area (Figure 4).

The land with high values of resistance, which indicate an advanced level of urban construction, is mainly distributed in the middle and northern part along the Huangpu River, which is the old city area, with higher economic development level. Hence, it is less likely to transform into the ecological land.
This part of Shanghai is suitable for the development of the built-up area and has little space for the expansion of ecological land.

**Table 3.** The value system for resistance factors to constructed land.

| Primary indices | Factors                  | Resistance of ecological land |
|-----------------|--------------------------|-------------------------------|
|                 |                          | 1  | 2  | 3  | 4  | 5  |
| Natural factors | Landscape type           | woodland and water-covered area | cropland | —  | Barren and settlement | built-up area |
| Socio-economic factors | Distance from road /km | >10 | 5-10 | 2-5 | 1-2 | 0.5-1 |
|                  | Distance from settlement /km | >20 | 15-20 | 10-15 | 5-10 | 0-5 |
| Policy factors   | Water conservation       | first-grade protection zones | second-grade protection zones | prospective reserve | buffer zones | others |
|                  | Environment resource patch | core zones | 1-2km-buffer zones | 3km-buffer zones | 4-5km-buffer zones | others |
|                  | Biodiversity conservation area | conservatio n area | prospective reserve | 1km-buffer zones | —  | —  |

The total area of suitable ecological land in Shanghai is 3487.6 km², which accounts for 51.2% of the total land area of the municipality. The suitable ecological land is mainly located in Chongming County, Changxing Island, Hengsha Island, Jiuduan Island, Jinshan District, Fengxian District, the southeastern area of Qingpu District and the southeastern part of Pudong New District.

The municipal government has realized the significance of ecological land in its sustainable development. In its new round of urban planning, the government is now implementing some protection measures to improve its sustainability. Green land, cropland, woodland and wetlands will be further protected to vitalize the city and improve its competitiveness [27]. To achieve this, suitable ecological land should be reserved. The percentage of ecological land in Shanghai in 2017 is 59.15% of the total land area. Based on the demand for ecosystem services and combined with the trends home and abroad [6], the percentage of ecological land in Shanghai should be maintained at 60% or more in future growth in order to keep the balance between the economic development and ecological protection, maintaining a reasonable urban landscape pattern and ecological security.

From the ecological point of view, the more the amount of ecological area we maintain, the more stable and sustainable the development for the city will be. However, each city needs development, especially for the international megacity of Shanghai, the responsibility of creating economic value requires the city to develop continuously. Therefore, as long as the suitable ecological land is maintained, the foundation of the city is guaranteed. It is not necessary to overstate the role of ecological land.

**4. Discussions**

As the most intense interaction between human society and the natural environment, the natural ecosystem in the city area is experiencing more and more disturbance from human activities. As
shown in the process of the rapid urbanization in Shanghai, the increasing demand for the built-up area has led to continuous encroachment into woodland, water-covered area and cropland. The degradation and reduction of ecological land inside municipal boundaries weaken urban ecosystem services[5]. Accompanied the acceleration of urbanization process, intense transformation and conflicts will still exist for a long time among different land use types. Therefore, insights into the relationships and balances between spatial changes in municipal land use illustrate the kind of scientific approach that will support decision-making to strengthen regional ecosystem services, manage urban and rural land use and promote the likelihood of sustainable urban development.

In this study, urban ecological land refers to a land use type that provides ecosystem services to the area as a whole and to the urban core in particular, which includes non-built-up areas such as cropland, woodland and water-covered area. Urban ecological land plays a significant role in maintaining regional ecological balance, ecological security, protecting biodiversity, preventing and mitigating natural disasters. Studies on urban land use patterns and dynamic changes will not only explore the land use alteration but the intensity of urban ecosystem services. Measurement and evaluation of the spatial range of ecological land needed to meet the minimum requirements of a healthy urban environment will provide the basis for decision-makers and urban planners to resolve the conflicts between urban development and protection of ecological land in order to maintain a stable urban ecosystem.

For the suitable built-up area, rational development should be implemented. A certain number of green corridors should be constructed to maintain the connectivity between ecological reserves because the continuity of ecological patches is of great significance in the construction of urban natural ecosystem [12] & [28]. According to the experience of some international metropolises, some of the ecological land in most cities is above 50%, and most of them are above 60%, when cropland is added as the ecological land.

To meet the requirement of the ecosystem services and economic development between urban ecological land and built-up area, we recommend the following specific advices: (i) To avoid decline in ecosystem services, enough ecological space, such as forest and wetlands should be protected. In addition, ecological corridors are highly needed to be constructed to promote the connectivity between ecological spaces. This will not only effectively connects the natural resources but also improves ecosystem services within the regions and helps to control the large disordered expansion of construction space. (ii) The rigid control over expansion speed and improvement in built-up area utilization efficiency are also highly needed. Green land with a suitable scale is also needed to be constructed within the densely developed built-up area. (iii) Taking Huangpu River as the axis, establishing buffer green belts along both sides of the river and building green corridors along the urban expressway and main roads. (iv) Public participation and government regulation also need to be promoted.

Some uncertainties and limitations exist in this study. In this study, the use of Landsat TM images with a 30-m resolution affected the accuracy of the classification of land-use categories and extraction of the suitable ecological land. Supervision classification also resulted in errors to some extent. In addition, the six factors selected in applying MCRM have certain representativeness, however, some other factors with impact on the ecological land in Shanghai may still be ignored because of the limitations of information and data collection in Shanghai. Standardization of basic terms, definitions and classification of ecological land needs to be established.

5. Conclusions
Shanghai municipality has evolved from a landscape pattern dominated by cropland to one dominated by built-up areas. From 1995 to 2017, the proportion of the total municipal area consisting of ecological land in Shanghai has declined from 84.41% in 1995 to 59.15% in 2017. From 1995 to 2004, the ecological land area experienced the heaviest loss. After 2004, the declining rate became stable. The proportion of cropland and water-covered area were continuously decreasing during the twenty
two-year study period. Woodland area had been in a state of decline, but after 2013 the government paid more attention to the protection of forest and the proportion of woodland has increased until 2017.

We applied the MCRM to select landscape type, distance from the road, distance to the settlements, drinking water source reserve, seed patch, biodiversity reserve in Shanghai as the six factors to extract the suitable ecological land for Shanghai. Our results showed that suitable ecological land in Shanghai accounts for 51.2% of the total land area of the city. To coordinate the development of between the urban economy and ecology, at least 55% of the total land area of the city should be maintained. For suitable ecological land, protection measures should be taken to protect the land and to restrict the disorder expansion of the built-up area. For the suitable built-up area, rational development intensity is needed and urban green space need to be constructed to ensuring landscape connectivity with the ecological land.

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