

## Spatiotemporal Differentiation Characteristics of Ecosystem Service Value in Wuhan City Based on Gradient Analysis (Postprint)

**Authors:** Quan Li, Teng Li, Mingzheng Yang, Wei Ying

**Date:** 2017-04-11T00:00:00+00:00

### Abstract

Based on six scenes of Landsat TM/ETM+ remote sensing imagery covering the Wuhan municipal area from 2000 and 2010 as foundational data, land use types were extracted using the maximum likelihood classification method. Combined with the calculated per-unit-area ecosystem service values for Wuhan, a raster-scale distribution map of ecosystem service values for Wuhan was generated. Gradient analysis methods were introduced, wherein concentric rings were established with the urban center as the origin and sampling strips were configured considering urban development axes. Two indicators—change magnitude and change rate of ecosystem service values—were selected for gradient analysis. The results indicate that Wuhan's total ecosystem service value decreased by 268 million yuan from 2000 to 2010. Concentric ring analysis revealed that the most significant declines in ecosystem service value occurred in northern rings 3-5 (12-30 km from the urban center) and southern rings 3-4 (12-24 km from the city center), while northern ring 8 and southern ring 7 exhibited the most pronounced increases. Strip analysis found that on east-west oriented strips, the ecosystem service value change rate curve displayed a symmetrical 'W' shape, whereas in the north-south direction, the change rate curve could be divided into four segments based on variation magnitude. Additionally, consistent with the pattern observed in the concentric ring change rate curves, the northern region experienced more drastic changes than the southern region.

### Full Text

### Preamble

**Spatiotemporal Variation of Ecosystem Services Value Based on Gradient Analysis in Wuhan: 2000–2010**

**LI Quan<sup>1,2,\*</sup>, LI Teng<sup>1</sup>, YANG Mingzheng<sup>3</sup>, YING Wei<sup>1</sup>**

<sup>1</sup>School of Resources and Environmental Science, Wuhan University; Key Laboratory of Geographic Information System, Ministry of Education, Wuhan 430079, China

<sup>2</sup>College of Global Change and Earth System Science, Beijing Normal University, Beijing 100875, China

**Abstract:** Ecosystems provide a multitude of services that are fundamental to the well-being, livelihood, health, and survival of humans. A comprehensive understanding of the spatiotemporal features of Ecosystem Services Value (ESV) is necessary for appropriate land use and land management in metropolitan areas. Based on this research, methods of quantitative analysis could be considerably improved. Considering Wuhan as an example, we classified Landsat TM/ETM+ images into developed land, unused land, arable land, garden plots, forests, and water by using a maximum likelihood analysis, and calculated the ESV per unit area. Based on spatial distributional maps of ESV, we introduced a gradient analysis and set gradient circles and belt transects to analyze the spatiotemporal features of ESV. The main conclusions were: 1) the amount of ESV decreased by 268 million RMB from 2000 to 2010; 2) based on the gradient circles analysis, ESV decreased within the north 3rd ring road (corresponding to 12–30 km from the urban center) and south 3rd ring and south 7th road (corresponding to 12–24 km from the urban center), whereas ESV increased within the north 8th ring; 3) based on the belt transects analysis, the change rate of ESV showed a symmetrical W-shape pattern latitudinally, whereas longitudinally, it was partitioned into four sections based on the amplitude of the ESV change rate. Overall, northern Wuhan demonstrated more changeability in ESV than the southern area.

**Keywords:** Ecosystem Services Value (ESV); gradient analysis; spatiotemporal variation; Wuhan

Ecosystems are an essential foundation for human survival and development, providing various services and benefits to humanity through their existence and formation processes [1-3]. Ecosystem Services Value (ESV) refers to the monetary valuation of benefits that humans obtain directly or indirectly from ecosystem functions [4]. Both ESV and the distribution of regional natural geographical elements exhibit randomness and structural characteristics in space, resulting in certain spatial autocorrelation of ecosystem service values [2,6]. Studying the spatiotemporal differentiation characteristics of regional ESV is closely related to socioeconomic development status [5] and helps reveal the mechanisms of spatial interaction between research objects, which is significant for guiding ecological city construction and urban sustainable development [7].

Since Costanza published “The Value of the World’s Ecosystem Services and Natural Capital” in *Nature*, the quantitative assessment of global ecosystem services value and natural capital has become a hotspot in international sustainable development research, triggering numerous studies on ESV theory, accounting methods, and applications by scholars worldwide [8]. In existing research, the analysis of ESV distribution spatial patterns constitutes an important compo-

ment. Some studies have zoned research areas according to ESV levels for comparative analysis of changes [9], while others have analyzed the sensitivity between land use structure changes and ESV [10]. However, most spatiotemporal differentiation analyses of ESV are based on geostatistical methods. For example, Hu and Bing calculated global and local spatial autocorrelation coefficients within watersheds [11]; Peng Baofa performed Kriging interpolation on discrete ESV raster data [12]; and Zhao Liang conducted hotspot and coldspot analyses of spatial changes in the Raoli River Basin [13]. Zhang Xiaonan et al. studied spatial heterogeneity of ESV in different directions [14]; Li et al. analyzed China at the macro-region level [15]; and Wang et al. examined the impact of land use changes on ESV in Chongming Island, Hangzhou, and Shenzhen [16,18,19]. Zhao [17] studied the spatiotemporal differentiation of ESV in response to land use changes. However, quantitative research on the spatial distribution patterns of ESV itself remains limited, and methodological approaches are insufficient.

Gradient analysis, which refers to the spatial characteristic of landscape features changing systematically along a particular direction [20], was first applied to vegetation distribution. McDonnell and Pickett [21] sampled ecosystem services along urbanization gradients in the UK; Radford et al. [22] studied changes in ecosystem service values along a rural-urban gradient in Greater Manchester; and Kroll et al. [23] examined the spatiotemporal dynamics of ecosystem service supply and demand relationships in East Germany since reunification, identifying population as the most important driver of changes in ecosystem service demand. Although gradient analysis has become an effective method widely applied in studying spatiotemporal differentiation characteristics of geographical elements, current research has mainly focused on landscape structural features.

To reveal the spatiotemporal variation characteristics of ESV and its spatial patterns at different distances from the urban center, this paper builds upon the research of Costanza and Xie Gaodi, combines remote sensing and geographic information system technologies, introduces gradient analysis, and systematically analyzes the spatial distribution patterns and spatiotemporal change processes of the research object.

## 1. Study Area

Wuhan is located in the eastern part of the Jiangnan Plain, at the confluence of the Yangtze and Han Rivers (113°41'–115°05' E, 29°58'–31°22' N). It is the largest city in Hubei Province and serves as the political, economic, educational, and cultural center of central China. The city has a subtropical monsoon climate with abundant water resources and a total area of 8,467.11 km<sup>2</sup>. Wuhan has experienced rapid urbanization, with the current urban population exceeding 10 million and GDP surpassing 1 trillion RMB. The occupation of cultivated land by construction land has caused drastic changes in land use types, leading to fluctuations in Wuhan's ecosystem services value.

## 2. Land Use Classification

Using ERDAS IMAGINE 9.2 software, we processed Landsat TM/ETM+ images from 2000 and 2010 (bands 4, 3, 2) as the primary data. After destriping ETM+ images, we performed geometric correction using Wuhan topographic maps as reference, applied image enhancement, and conducted fusion and other preprocessing operations. Vector polygon clipping was then performed to obtain remote sensing images covering the Wuhan municipal area. Based on the current Land Use Status Classification Standard (GB/T 21010–2007) and using maximum likelihood classification, we interpreted the images. Individual obviously misclassified patches were corrected through field observations. We extracted six land use types: forest land, arable land, garden land, water bodies, construction land, and unused land. The overall classification accuracies for the two-phase images were 81.2% and 87.3%, respectively, with Kappa coefficients of 0.7935 and 0.8476. Producer's and user's accuracies for all categories exceeded the required classification accuracy threshold.

## 3. Ecosystem Services Value Calculation

Based on the 2000 and 2010 Wuhan land use type maps and referencing Xie Gaodi et al.'s method for calculating the economic value of ecosystem service equivalent factors [24], we calculated the economic value of ecosystem service value factors for Wuhan based on grain production benefits. Arable land corresponds to farmland ecosystems, forest land to forest ecosystems, garden land to forest and grassland ecosystems, water bodies to river/lake ecosystems, and unused land to desert ecosystems. Using grain output value and cultivated area data from the Wuhan Statistical Yearbook, we calculated that the average total benefit per unit area of grain production in Wuhan from 2000–2010 was 13,625.252 RMB/hm<sup>2</sup>. According to Wuhan Price Bureau data on agricultural product costs and benefits, the total input per unit area was 2,534.252 RMB/hm<sup>2</sup>. Based on Hu Ruifa and Leng Yan's research [25], the shadow rent for national grain production was approximately 7,126.3 RMB/hm<sup>2</sup>. Comparing these estimates, Wuhan's shadow rent for grain production was about 11,149.2 RMB/hm<sup>2</sup>. Using this value multiplied by each ecosystem service equivalent value, we obtained ecosystem function service value coefficients (i.e., the service value per unit area). The unit area ESV values for Wuhan in 2000 and 2010 were: forest land 71,263 RMB/hm<sup>2</sup>, arable land 20,021 RMB/hm<sup>2</sup>, garden land 45,642 RMB/hm<sup>2</sup>, water bodies 114,928 RMB/hm<sup>2</sup>, construction land 0 RMB/hm<sup>2</sup>, and unused land 1,064 RMB/hm<sup>2</sup>.

Following Costanza's ESV calculation formula, we calculated Wuhan's ecosystem services value:

$$ESV_k = A_k \times VC_k$$

where  $ESV_k$  represents the ecosystem service value of land use type  $k$ ,  $A_k$  rep-

resents the area of land use type  $k$ , and  $VC_k$  represents the ecosystem service value coefficient of land use type  $k$ .  $ESV$  represents the total regional ecosystem service value.

#### 4. Gradient Analysis

To investigate the spatial distribution characteristics of Wuhan' s ecosystem services value, we introduced gradient analysis. Using Wuhan' s urban center as the origin, we established concentric rings with radius increasing by 6 km increments—8 rings in the northern region and 7 rings in the southern region—and calculated the ESV within each ring. Considering the east-west development axis along the Yangtze River and the north-south transportation development axis, we established sampling belt transects. Each transect used  $9 \text{ km} \times 3 \text{ km}$  rectangular quadrats, with 13 quadrats on the east-west transect and 14 quadrats on the north-south transect. The sampling frames slid sequentially from south to north and from west to east.

To quantify and compare changes in Wuhan' s ESV between 2000 and 2010, we defined two indicators: change amount and change rate. The change amount formula is:

$$V_j = V_{j2010} - V_{j2000}$$

where  $V_j$  represents the change amount of ecosystem service value in unit  $j$  between 2000-2010, and  $V_{j2010}$  and  $V_{j2000}$  represent the ESV in unit  $j$  for 2010 and 2000, respectively.  $j$  represents different gradient rings or quadrats on transects ( $j = 1, 2, 3, \dots$ ).

The change rate formula is:

$$R_j = \frac{V_{j2010} - V_{j2000}}{V_{j2000}} \times 100\%$$

where  $R_j$  represents the change rate of ecosystem service value in unit  $j$  between 2000-2010, and other variables have the same meaning as in formula (3).

[Figure 1: see original paper] The gradient torus and belt transects in study area

[Figure 2: see original paper] The coding of gradient circles

[Figure 3: see original paper] The coding of belt transects

### 1. Analysis of Total Ecosystem Services Value Composition and Change

Based on statistics from land use type maps, we multiplied the area of each land use type by its corresponding unit area ESV to obtain the ecosystem service

values and their proportions in the total value for each type (Table 1). The results show that Wuhan's total ESV was 28.139 billion RMB in 2000 and 27.871 billion RMB in 2010. In terms of composition, arable land has the largest area and thus contributes the most to total ESV despite its relatively low unit value. Water bodies, despite covering less than 16-17% of the total area, contribute over 32% to total ESV due to their extremely high ecological value. Forest land's area and unit value fall between water bodies and arable land, contributing about 32% to total value. Garden land, construction land, and unused land together account for about 35% of the total area but contribute less than 3% to total value due to either small area or low unit value.

From 2000 to 2010, Wuhan's total ecosystem service value decreased by 268 million RMB, accounting for approximately 1% of the total value. Among the six land use types, all showed varying degrees of decline except garden land, which increased in value. The decline was most severe for water bodies, accounting for 52.27% of the total reduction, followed by forest land at 35.19%. The increase in garden land value is likely related to the conversion of some farmland to orchards in suburban areas such as Caidian and Huangpi.

ESV of various ecosystem types and their proportion in the total value in 2000 and 2010 (10,000 RMB, %)

## 2. Analysis of ESV Change Based on Concentric Rings

Through overlay analysis of Wuhan's 2000 and 2010 ESV data, negative change values within a ring indicate ESV decline, while positive values indicate increase. The results were rendered as change amount maps and change rate curves for each ring. The innermost ring (Ring 1) represents the urban core, showing slight ESV increase during 2000-2010. Moving outward from the city center, both north and south directions show significant ESV decline, primarily occurring in Rings 2-4 (6-24 km from city center), with the northern region exceeding the southern region in both extent and magnitude. Beyond this zone, ESV shows varying degrees of increase again, particularly in Rings 6-8 (30-48 km from city center), with southern growth significantly higher than northern growth.

[Figure 4: see original paper] Classification result of land use

[Figure 5: see original paper] Variation of ESV with respect to circles, 2000-2010

[Figure 6: see original paper] Change rate of ESV with respect to belt transects, 2000-2010

The reasons for this pattern are as follows: The central urban area is fully developed with little new construction, so its slight ESV increase mainly results from interannual variations in Yangtze River water area and increased green space. Areas with severe ESV decline concentrate in the urban periphery, corresponding to zones with the most rapid urbanization. According to Wuhan's master plan (1996-2020), Rings 3-5 in the north, where decline was most pronounced, are locations of new towns or town clusters such as Wujiashan and Beihu. Ring 3 in the south is where the rapidly developing Jiangxia District is

located. In the outermost rings representing rural areas beyond 30 km, farmland still dominates. With the implementation of returning farmland to forest and grassland policies, ESV shows an upward trend, particularly notable in the northwest Mulan Mountain Scenic Area and southeast Liangzi Lake protection zone.

### 3. Analysis of ESV Change Based on Belt Transects

Similar to the concentric ring analysis, the east-west transect shows a symmetrical W-shaped change rate curve from center to periphery, partitioned into four sections based on change amplitude: slight increase, significant decrease, slight increase, and significant increase. In the left half (C0-C6), substantial conversion of arable land to construction land along the Han River upstream development zone caused more dramatic changes. In the right half (C9-C13), the decline mainly came from East Lake area, while the increase, like in the central urban area, relates mainly to interannual variations in Yangtze River width.

The north-south transect change rate curve can be divided into four sections: R1-R7 (southern suburbs, mainly arable land) shows significant ESV increase; R8-R12 (southern near-urban and urban areas, mixed construction and farmland) shows basically unchanged ESV; R13-R20 (northern urban and near-urban areas) shows significant ESV decrease; and R21-R29 (northern suburbs and Mulan Mountain Scenic Area) shows dramatic ESV increase. Consistent with the concentric ring pattern, the north shows more dramatic changes than the south.

[Figure 7: see original paper] Change rate of ESV with respect to W-E belt transects

[Figure 8: see original paper] Change rate of ESV with respect to S-N belt transects

## 1. Conclusions

This paper calculated Wuhan's unit area ecosystem service value and introduced gradient analysis to examine spatiotemporal differentiation characteristics of ESV resulting from land use changes between 2000 and 2010. The main findings are: (1) Wuhan's total ESV decreased by 268 million RMB from 2000-2010, with water area shrinkage causing the most severe decline; (2) Based on concentric ring analysis, ESV decline was most significant within 12-30 km north of the city center and 12-24 km south, while Rings 6-8 showed the most obvious increase; (3) Based on belt transect analysis, the east-west change rate curve showed a symmetrical W-shape, while the north-south curve could be divided into four sections: significant decline, slight decline, slight increase, and dramatic increase. Consistent with the concentric ring pattern, the north showed more dramatic changes than the south.

## 2. Discussion

This assessment and analysis enhance understanding of ESV spatial patterns and spatiotemporal differentiation laws, providing macro-level reference for urban planning, land use, and urban management decision-making departments. ESV assessment involves multiple disciplines including resource economics, environmental economics, demography, and economics. As this paper focused on spatial pattern analysis of ESV, the estimation of ecosystem service values was not sufficiently detailed or comprehensive, only calculating total ESV for land use types without considering specific ecosystem services within each type. Future research should collect more urbanization-related socioeconomic data to further analyze urbanization impacts on ESV in combination with urbanization levels.

## References (References):

- [1] 生态系统服务与自然资本价值评估, 2001, 21(11): 1918-1926.
- [2] Daily G C. *Nature's Services: Societal Dependence on Natural Ecosystems*. Washington DC: Island Press, 1997: 100-110.
- [3] Cairns Jr J. Protecting the delivery of ecosystem services. *Ecosystem Health*, 1997, 3(3): 185-194.
- [4] Costanza R, d' Arge R, De Groot R, Farber S, Grasso M, Hannon B, Limburg K, Naeem S, O' Neill R V, Paruelo J, Raskin R G, Sutton P, Van Den Belt M. The value of the world's ecosystem services and natural capital. *Ecological Economics*, 1998, 25(1): 3-15.
- [5] 生态系统服务的供给、消费和价值化, 2008, 30(1): 93-99.
- [6] 湖北省潜江市生态系统服务功能价值空间特征, 2011, 31(24): 7379-7387.
- [7] 中国陆地生态系统服务功能及其生态经济价值的初步研究, 1999, 19(5): 607-613.
- [8] 武汉市土地利用与生态系统服务价值的时空变化分析, 2006, 20(4): 170-174.
- [9] 广州市生态系统服务价值时空变化遥感监测, 2012, 39(15): 196-201.
- [10] 中国超大城市土地利用状况及其生态系统服务动态演变, 2011, 31(20): 6194-6203.
- [11] 城市化流域生态系统服务价值时空分异特征及其对土地利用程度的响应, 2013, 33(8): 2565-2576.
- [12] 常德市土地覆被的生态服务价值空间变异分析, 2012, 32(1): 141-145.
- [13] 基于地统计学的区域生态服务价值空间分异规律研究, 2013, 33(10): 3169-3176.
- [14] 年挠力河流域生态系统服务价值时空变化, 2012, 19(6): 168-171, 175-175.
- [15] Li G D, Fang C L, Wang S J. Exploring spatiotemporal changes in ecosystem-service values and hotspots in China. *Science of the Total Environment*, 2016, 545-546: 609-620.
- [16] Wang W J, Guo H C, Chuai X W, Dai C, Lai L, Zhang M. The impact of land use change on the temporspatial variations of ecosystems services value in China and an optimized land use solution. *Environmental Science & Policy*, 2014, 44: 62-72.
- [17] Zhao B, Kreuter U, Li B, Ma Z J, Chen J K, Nakagoshi N. An ecosystem service value assessment of land-use change on Chongming Island, China. *Land Use Policy*, 2004, 21(2): 139-148.

- [18] Li T H, Li W K, Qian Z H. Variations in ecosystem service value in response to land use changes in Shenzhen. *Ecological Economics*, 2010, 69(7): 1427-1435.
- [19] Wu K Y, Ye X Y, Qi Z F, Zhang H. Impacts of land use/land cover change and socioeconomic development on regional ecosystem services: the case of fast-growing Hangzhou metropolitan area, China. *Cities*, 2013, 31: 276-284.
- [20] 景观生态学的原理及应用, 2000.
- [21] McDonnell M J, Pickett S T A, Groffman P, Bohlen P, Pouyat R V, Zipperer W C, Parmelee R W, Carreiro M M, Medley K. Ecosystem processes along an urban-to-rural gradient. *Urban Ecosystems*, 1997, 1(1): 21-36.
- [22] Radford K G, James P. Changes in the value of ecosystem services along a rural-urban gradient: a case study of Greater Manchester, UK. *Landscape and Urban Planning*, 2013, 109(1): 117-127.
- [23] Kroll F, Müller F, Haase D, Fohrer N. Rural-urban gradient analysis of ecosystem services supply and demand dynamics. *Land Use Policy*, 2012, 29(3): 521-535.
- [24] 一个基于专家知识的生态系统服务价值化方法, 2008, 23(5): 911-919.
- [25] 中国主要粮食作物的投入与产出研究, 2006, (3): 2-8.

*Note: Figure translations are in progress. See original paper for figures.*

*Source: ChinaXiv – Machine translation. Verify with original.*