Study on the Response Mechanism of Ecosystem Services to Urban Land Expansion by Dynamic Equivalent Factor Method: A case of Wuhan, China

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Abstract. A clear insight into the response mechanism of Ecosystem Services (ESs) to urban land expansion can provide references for balancing the relationship between urbanization and ecosystem. Some qualitative studies have looked at the relationship between ESs and urban land expansion, but they can hardly reveal the response mechanism. Thus, we adopted the dynamic equivalent factor method to quantitatively assess each of the Ecosystem Service Values (ESVs) and the total ESVs, then explored the response mechanism through the correlation analysis in Wuhan. The results showed that: (1) During 1990-2015, various ESVs in Wuhan decreased continuously, with the largest decline in the food production, the smallest in hydrology regulation; the ESVs of the whole region showed a downward trend, particularly, in the central region where construction land was concentrated, the ESVs dropped sharply. (2) The demand pressure of ESs brought by population growth was much larger than the direct damage of urban land expansion to ESs. (3) The urban land expansion had the greatest damage to raw material production. This research could deepen the understanding of the relationship between urban land expansion and the decrease of ESVs, but also provide theoretical references for the reasonable expansion of urban land in Wuhan.

Keywords: Ecosystem services value; Urban land expansion; Response mechanism; Wuhan City; Dynamic equivalent factor method.

1. Introduction
Ecosystem services refer to the natural environmental conditions and utility formed by ecosystems and ecological processes, to maintain human survival [1], mainly including provision services, regulation services, support services and cultural services [2]. Ecosystem services could be regarded as an essential foundation for achieving the goal of regional sustainable development. However, The Millennium Ecosystem Assessment Report showed that more than 60% of global ecosystems are being degraded or have been degraded [2]. In the past few decades, the scale of urban land in China has expanded rapidly with the development of the economy. It has a strong impact on the land structure and ecological landscape of the region, changing the original ecological landscape pattern, threatening the regional...
ecological security. Therefore, it resulted in the reduction of biodiversity, environmental pollution\(^{[3]}\), soil erosion, and other ecological problems, but also caused the decline of ecosystem services capacity. Therefore, exploring the response mechanism of ESs to urban land expansion is beneficial to reduce the damage of ecosystem services caused by urban land expansion, and is of great significance to promote the rational expansion of urban land.

Ecosystem Services Value (ESV) is to quantify the values of natural resources or ecosystem services from the perspective of natural ecology by using ecological and economic research methods\(^{[4]}\). At present, the accounting methods of ESVs mainly include material quality evaluation, value evaluation, emergy analysis and ecological model\(^{[5]}\). Among them, Costanzo and their team put forward an evaluation method of material quality, based on the equivalent factor of unit area value\(^{[6]}\) (equivalent factor method). They classified and comprehensively evaluated the global ESV and calculated the global ESV table by summarizing the value of the main ecological process functions and ecosystem benefits. Their achievements are widely recognized and applied in this filed and relevant studies in China. However, the method probably could not be directly applicable to the context of China because of some reasons such as low valuation of cultivated land, high valuation of wetland and high valuation in general.

G.D Xie and his partners developed the Costanzo's method and calculated the equivalent factor table for China's ecosystem services, based on a questionnaire survey of 700 professionals with an ecological background in China in 2008, they then proposed amendments and supplements in 2015\(^{[7, 8]}\). Xie’s method laid a foundation for further study to carry out ESVs assessment for different scales, different regions and different land-use types\(^{[9-11]}\). With the in-depth development of related research in China, dynamic factors are gradually incorporated into the evaluation system, and the dynamic evaluation of equivalent factors is realized\(^{[5]}\). However, the dynamic equivalent factors method is affected by economic factors such as the value of funds and inflation, which can’t accurately reflect the differences of ESs of the same plot in different periods. To solve this problem, relevant scholars adopted GDP\(^{[12]}\) and CPI\(^{[13]}\) to conduct time correction. However, in contrast, the time value of funds has better-reflecting effect and stability\(^{[14]}\).

The change of land area, type and pattern caused by Land Use/Cover Change (LUCC) directly affects the value of ecosystem services\(^{[11]}\). Urban land expansion is thought to be the main reason for the decline of ESV\(^{[15]}\). Some scholars have analyzed urban land expansion characteristic and its influencing degree, and discussed the impact degree of urban land expansion on ecosystem services by analyzing LUCC changes and ESV changes\(^{[16, 17]}\). In contrast, others identified the spatial and temporal characteristics of urban land expansion and ESV through quantitative calculation\(^{[18]}\). However, the studies above may fail to reveal the relation of urban land expansion on ESV. For reserving this problem, some scholars have used land-use transfer matrix to quantitatively analyze the relationship between urban land expansion and ESV change\(^{[19]}\). However, due to the short period of the research, the pattern has not be summed up yet. Other scholars have analyzed this relationship through data mining models\(^{[20]}\), and qualitatively revealed the influence of urban land expansion on ESV. However, this research ignored the impacts on ESV caused by urban land expansion, which occupied different land types. Thus, the obtained conclusions are not thorough enough to reveal the inner mechanism. In summary, most existing research on the impacts of urban land expansion on ESVs was limited to the analysis of the impact degree and characteristics of urban land expansion on ESV changes. A few studies qualitatively analyzed the mechanism. However, they failed to reveal the response mechanism of ESs to urban land expansion, and could not provide more accurate scientific decisions for the reasonable expansion of urban land.

We use the dynamic calculation method to quantitatively calculate the ESV in different periods in Wuhan. We make time correction by the time value of funds and regional correction by the yield per unit area of crops, so that the ESV in different time has stronger accuracy and comparability. Based on the different impacts on ESs caused by the differences of land types urban land expansion encroached, this paper quantitatively reveals the response mechanism of ESs to urban land expansion, providing the scientific basis and decision support for the rational expansion of urban land, and also contributing the related research on the impacts of urbanization on the ecosystem.
2. Materials and Methods

2.1. Study area
Wuhan, located in the east of Jianghan Plain, at the intersection of Yangtze River and Han River, its total area reached 8494.41 km². As the capital of Hubei Province, it is also the essential city of Yangtze River Economic Belt and the plan “The Rise of Centre China”. The topography is generally high in the north and low in the south, and the land is alternating with hills and plains. It is rich in water resources, the water area is 2217.6 square kilometers; in addition, it has sufficient wetlands and mineral resources. Construction land in Wuhan has been expending at a high speed. The expansion intensity reached the fourth in China from 2004 to 2008[21]. The disorderly expansion led to the deterioration of the ecological environment in Wuhan and the serious environmental problems.

![Figure1 Location map of Wuhan](image)

2.2. Data collection
The data used in this paper include: the land use data of Wuhan in six periods of 1990, 1995, 2000, 2005, 2010 and 2015, which originated from the Resource and Environment Science and Data Center (http://www.resdc.cn); The sown area of grain in China originated from China Statistical Yearbook. The population and grain output per unit area in Wuhan from 1990 to 2015 were derived from Wuhan Statistical Yearbook.

2.3. Calculating ecosystem services value
Equivalent factor method is one of the ESV calculation methods, the calculation process of which is relatively simple, with less sample size, easier acquisition for researchers and wide application scale. Correcting the original equivalent factor in time and region to realize dynamic evaluation would improve the accuracy of the evaluation result. Therefore, we use the dynamic equivalent factor method to evaluate ESV and correct the equivalent factor in time and area through the Annual Equivalent Rate (AER) and the annual output per unit area of crops.

First, referring the national equivalent factor value of Liu Hai et al [22], we made time correction by the AER [23]:
\[ D_{Tn} = D_n + D_n \times \sum_{m=n}^{2014} \gamma_m \]  

\( D_{Tn} \) is the value of a national standard equivalent factor in the n year after time correction (yuan/hm²); \( D_n \) is the value of one national standard equivalent factor in the n year (yuan/hm²); \( \gamma_m \) is the AER in the m year (%). When m is greater than 2014, \( \sum_{m=n}^{2014} \gamma_m \) is 0.

Then, we made region correction:

\[ D_{Wn} = D_{Tn} \times \frac{P_{wn}}{p_n} \]  

\( D_{Wn} \) refers to the value of ecosystem service of a standard equivalent factor in Wuhan in the n year (yuan/hm²); \( P_n \) is the yield per unit area of main crops in the n year in China (kg/hm²); \( P_{wn} \) is the yield of main crops per unit area (kg/hm²) of Wuhan in the n year.

The estimation model of Wuhan ecosystem service values:

\[ ESV_j = \sum_{i=1}^{n} (S_i \times VC_{ij}) \]  

\( ESV_j \) represents the value of the type j service; \( S_i \) is the area of the type i land use in Wuhan (hm²); \( VC_{ij} \) means the equivalent factor value of the type j service of the land use type i (yuan/hm²).

2.4. Analyzing the impact of urban land expansion on ecosystem services

The negative impacts of urban land expansion on ESs could be direct and indirect. Direct impact refers to changing other land types into construction land through land-use change, causing damage on regional ESs. The damage value of urban expansion damage (formulas (4)) and the damage value per unit area(formulas (5)) can be used to reflect the direct impact.

\[ ESV_s = \sum_{i=1}^{n} (SC_i \times VC_i) \]  

\[ ESV_x = \frac{ESV_{st}}{SC_{st}} \]  

\( ESV_s \) is the value of city expansion damage (ten thousand yuan); \( SC_i \) is the area of type i land use occupied by urban land expansion in Wuhan (hm²); \( ESV_x \) is the damage value caused by urban land expansion per unit area in a certain period (yuan/hm²); \( ESV_{st} \) is the damage value of urban land expansion in a certain period (ten thousand yuan); \( SC_{st} \) is the expansion area of urban land in a certain period.

Indirect impact is the population growth accompanied by urban land expansion [24-26], causes greater demand pressure on ecosystem services so that affects regional ecosystem service level. We represented the indirect impacts by the loss value of ESV per capita in Wuhan.

2.5. Linear regression analysis

Linear Regression analysis is one method in mathematical statistics used to analyze and quantitatively describe the relationship between multiple factors. On the basis of quantitatively expressed the area and process of urban land expansion and the ESV, we used Multifactor Linear Regression of SPSS 22.0 quantitatively analyzing the relationship between urban expansion and the decline of regional ESV, explore the response mechanism of ESs to urban land expansion.

The total value of each service is different, the loss of the same value has different destructiveness to each service. Therefore, in order to judge the destructiveness of urban expansion to different ecosystem services, we modified the coefficients (hereinafter referred to as "destruction coefficients"): 

\[ D_{Tn} = D_n + D_n \times \sum_{m=n}^{2014} \gamma_m \]
In the formula, $\mu_{jk}$ and $\tau_{jk}$ are the revised and pre-revised coefficient of the $k$th independent variable in the type $j$ ecosystem service change model respectively.

3. Results

3.1. The time trend analysis of ESV

The value of equivalent factor of Wuhan in Table 1 was obtained by time and region correction through formulas (1) and (2). The modified value of equivalent factor increased slightly from 2000 to 2005, while the others decreased. The results are similar to Zhao et al.’s GDP revision[12]. Through the China Statistical Yearbook, it is found that the proportion of the total value of the primary industry decreased sharply from 1990 to 2000, from 26.6% to 14.7%, and the revised equivalent factor also dropped sharply from 724.70 yuan to 567.93 yuan. From 2000 to 2010, the proportion of the gross value of the primary industry decreased slowly, and the equivalent factor after time collection also dropped slowly. Because the development speed of agriculture was only slightly lower than that of economy from 2000 to 2010.

Table 1 Equivalent values per unit equivalent factor in Wuhan

| Years | Nation | Time  | Region | Wuhan |
|-------|--------|-------|--------|-------|
| 1990  | 356.74 | 770.95| 724.70 | 724.70|
| 1995  | 383.24 | 654.38| 682.34 | 682.34|
| 2000  | 404.8  | 567.93| 644.20 | 644.20|
| 2005  | 449.1  | 579.29| 650.52 | 650.52|
| 2010  | 481.19 | 550.96| 609.29 | 609.29|
| 2015  | 530.46 | 530.46| 597.77 | 597.77|

The ESV in each stage of Wuhan can be calculated through formula (3). The ESVs in Wuhan has decreased from 11.665 billion yuan to 8.63 billion yuan in the past 25 years, with a significant decrease. As far as each stage is concerned, ESV shows a linear decline process overall, with the largest reduction in 2005-2010 and the smallest in 2000-2005. The decreases are 7.47%, 6.87%, 0.28%, 9.08% and 5.3%, respectively, indicating that ESV experienced a "fast-slow-fast-slow" process (Figure 2).

In terms of changing trend, the value of each ecosystem service showed a downward trend as a whole. Except for the slight increase of hydrology regulation, waste treatment and aesthetic landscape provision from 2000 to 2005, the value of other services showed a linear downward trend, and the changes in each stage were consistent with the overall change trend of ESV. The changing trend of hydrology regulation and waste treatment was basically the same, showing the process of "rapid decline, slow rise, rapid decline and slow decline".

As for the range of changing, generally speaking, the food production decreased the largest (33.34%), the smallest decrease was hydrology regulation (23.23%). For each stage, the maximum decline (12.12%) was food production in 2005-2010 and the minimum (1.03%) was biodiversity in 2000-2005. Except for the increase in 2000-2005, the decline in Hydrology regulation, waste treatment and aesthetic landscape provision were lower than other services in other periods.

The sharp decline in food production was due to the extensive encroachment on cultivated land by the urban land expansion in Wuhan. The area of agricultural land decreased by 22.75% during the study period and reached the highest level in 2005-2010. The area of agricultural land decreased by 34063hm², a decrease of 7.27% in 2005-2010. Wuhan has a broad water area, which is the main place to provide hydrology regulation and waste treatment services. In recent years, Wuhan has always emphasized water area protection, formulated strict lake protection policies, and curbed lake landfills [27, 28]. Therefore, the decrease of hydrology regulation is lower than that of other ecosystem services. Because the
equivalent factor in 2005 was larger than that in 2000, hydrology regulation increased slightly in 2000-2005, which was also the main reason for the decrease of other ecosystem services in 2000-2005.

Abbreviations: FP-food production; RM-raw material; GR-gas regulation; CR-climate regulation; HR-hydrology regulating; WT-waste regulation; SC-soil conservation; BM-biodiversity maintenance; ALP-aesthetic landscape provision.

The value of each ecosystem service in Wuhan per capita is shown in Figure 3. On the whole, except that the hydrology regulation, waste treatment and aesthetic landscape provision service decreased slightly from 2000 to 2005, the change trend of other ecosystem services per capita is basically consistent with the direct change of each ecosystem service. But the change range per capita is significantly larger than the direct change of each ecosystem service, on the whole, the decline rate of each service was more than 50%, food production per capita declined the most (56.62%), while hydrology regulation per capita declined the smallest (50.04%); in terms of each stage, the maximum decline was 22.94% for food production per capita from 2005 to 2010, and the minimum was 5.39% for
per capita hydrological regulation from 2000 to 2005. These indicated that the rapidly increasing population in Wuhan has caused great demand pressure on ecosystem services.

3.2. The spatial trend analysis of ESV

We made the ESV distribution map of Wuhan by ArcGIS 10.2 (Figure 4). The distribution of ESV in Wuhan was complex, areas with extremely high and low ESV were staggered distributed in the central and western region. Southern region’s ESV was generally high. Northern region’s ESV was generally low except the northernmost place. Among them, the high ESV areas were mainly distributed in the water, wetland, northwest and northeast forest of Wuhan. The middle ESV areas were mainly distributed in the agricultural land throughout the city. Low ESV areas were mainly distributed in urban, rural residential areas and other areas with high intensity of construction and development, concentrated in the central region. From the changing trend, the ESV in Wuhan showed a downward trend in the whole city from 1990 to 2015, except in 2000-2005. The proportion of high value area decreased from 33.42% in 1990 to 24.65% in 2015, and the proportion of middle value area decreased from 61.34% in 1990 to 6.89%. The former was mainly caused by the decrease of water service value, while the latter was mainly due to the decline of farmland service value. The decrease of ESV in the surrounding areas of urban and rural construction land was most significant. The low value areas in the eastern region, the northern region and the northeast region increased rapidly, and the median area continued to decrease, indicating that the expansion of urban and rural construction land has a great negative impact on ecosystem services.

![Figure 4 Spatial distribution of ESVs in Wuhan in 1995-2015](image)

3.3. The analysis of urban land expansion.

From the change of the area and value of urban land expansion during 1990–2015 (Figure 5), it can be found that: From the aspect of urban expansion area, the construction land in Wuhan expanded rapidly in the past 25 years, with the rise of 1.47 times. From the development stage, Wuhan urban expansion has shown an increasing trend, with a slight decline in 2010-2015; the increase rate reached maximum in 2005-2010 and changed little from 1990 to 2000, indicating that urban expansion has experienced a "slow-rapid-deceleration" expansion process. From the point of view of the damage value of urban expansion, the overall growth rate increased linearly, with little change from 1990 to 2010 and a slight decreased in 2010-2015. As for the damage value per unit area, it showed a fluctuating downward trend on the whole, and experienced the decline process of "slow decline, slow rise, rapid decline and slow decline". This decline process reflected the change of the proportion of urban land expansion encroaching on land types with high ESV in Wuhan during the study period, which was the largest in 2000-2005, and the smallest in 2005 - 2010; meanwhile, it reflected that the government of Wuhan had
carried out a process of "control-relaxation-strict control-relaxation" for the expansion of construction land in the study period.

3.4. The analysis of ESV’s response mechanism.

The damage coefficients to each ecosystem service value and total ESV caused by urban land expansion area and urban expansion destruction value was presented by Multifactor Linear Regression analyzing and the damage coefficient was further modified through formula (6) (Table2). With the increase of the area of the urban land expansion by 1 hm², the per capita value of food production, raw material production, gas regulation, climate regulation, hydrology regulation, waste treatment, soil conservation, biodiversity, aesthetic landscape provision and total ESVs decreased by 0.001 yuan, 0.001 yuan, 0.002 yuan, 0.001 yuan, 0.002 yuan, 0.009 yuan, 0.008 yuan, 0.002 yuan, 0.003 yuan, 0.002 yuan and 0.028 yuan.

When the damage value of urban expansion increased by 1 million yuan, each ESVs and the total ESVs increased by 0.2 yuan, 0.1 yuan, 0.2 yuan, 0.3 yuan, 1.3 yuan, 1.1 yuan, 0.4 yuan, 0.3 yuan and 4.2 yuan, respectively. Under the condition that the expansion area of urban land remains was controlled, the decrease of the ESVs per capita decreased with the increase of the proportion of waters, wetlands and forests occupied by the expansion of urban land. This was because the waters, wetlands and forests occupied by the expansion of urban land in Wuhan were usually developed into high-grade residential and amusement areas[29]. It can neither carry a large population nor attract a foreign population, which has an extremely low impact on population growth and has a low indirect impact on ecosystem services. Grassland and farmland with low ecological value have convenient transportation, excellent topography and low development costs, most of which were developed into commercial districts, residential areas and development zones[29]. It can carry a large population, resulting indirect impact of population growth on ESs more than the direct impact of land use change on ecosystem.

Figure 5 Changes of urban land expansion and damage values in Wuhan in 1990-2015
Table 2 ESV damage coefficient correction

| Service | Original coefficient | Modified coefficient | Damage values of urban land expansion | Original coefficient | Modified coefficient |
|---------|----------------------|----------------------|---------------------------------------|----------------------|----------------------|
|         | Urban expansion areas|                      |                                       |                      |                      |
| FP      | 0.001*               | 0.025                | -0.002*                               | -0.050               |
| RM      | 0.001**              | 0.035                | -0.001**                              | -0.035               |
| GR      | 0.001**              | 0.021                | -0.002**                              | -0.042               |
| CR      | 0.002**              | 0.026                | -0.003**                              | -0.038               |
| HR      | 0.009*               | 0.030                | -0.013**                              | -0.043               |
| WT      | 0.008*               | 0.031                | -0.011**                              | -0.042               |
| SC      | 0.002*               | 0.030                | -0.003*                               | -0.044               |
| BM      | 0.003**              | 0.031                | -0.004**                              | -0.041               |
| ALP     | 0.002*               | 0.026                | -0.003**                              | -0.039               |
| ESVs    | 0.028*               | 0.028                | -0.042**                              | -0.042               |

Annotation: * Represents that the coefficient is significant at the level of 0.05, ** Represents that the coefficient is significant at the level of 0.01. Some data was supplemented by interpolation method.

After the correction of the damage coefficient, the coefficient of raw material production was the largest among the coefficients of urban land expansion area, exceeding the coefficient of ESVs (overall coefficient). It revealed that the urban land expansion in Wuhan had a big destruction to the production capacity of raw materials. In addition, the coefficients of hydrology regulation, waste treatment, soil conservation and biodiversity were slightly higher than the overall coefficient. The coefficients of food production, gas regulation, climate regulation, aesthetic landscape provision and other services were all lower than the overall coefficients, indicating that the expansion of urban land in Wuhan had a small destruction to these services. For the coefficients of damage value of urban expansion, due to the indirect influence of population, all of them are negative. All ESs would benefit from improving the damage value of urban expansion. The coefficients of food production, soil conservation and hydrology regulation were less than the overall level, and the beneficial degree was large; the coefficients of gas regulation and waste treatment were equal to the overall level, and the beneficial degree was moderate; others were smaller than the overall level, and the beneficial degree was small. The beneficial degree of food production was much greater than other ecosystem services. The reason was that only food production would benefit with the increase of urban expansion damage value, given the current level of urban land expansion and destruction.

4. Discussion

This paper recognized the different impacts on the ecosystem caused by the encroachment on different land types of urban land expansion, quantitatively analyzed the relationship between urban land expansion and ESs, and preliminarily revealed the response mechanism of ESs to urban land expansion. It provides a theoretical foundation for the rational expansion of urban land in Wuhan in the choice of encroaching land types and gives a reference for the study of the influence of LUCC on ESV. However, the urban expansion damage value can only roughly be used to analyze the proportion change of urban expansion encroaching on high ecological value land, but can not be able to quantitatively judge the specific area and proportion of local types of change. The expansion of urban land is a complex process of land change, which has different characteristics in expansion scale, fractal characteristics, expansion model and spatial distribution [30], whether these factors will affect the ESs remains to be studied.

For the research method, this paper adopts the dynamic calculation method of time correction and avoids the problem of inconsistent results under economical influence of the economy, so that it improves the accuracy and comparability of ecosystem service evaluation across the time. The research provides a reference for the study of ESV time comparison. However, only one-year regular bank interest rates are used to calculate. It is still needed to verify whether other interest rates are more suitable for time correction. As far as the correction results are concerned, the revised results in this paper are
similar with Zhao et al who used GDP correction \[12\], but different to the results modified by CPI indicator from Wang et al \[13\]. The AER, GDP and CPI can reflect inflation to a certain extent \[14\], but the correction method which can reflect the real value of ESV at different time needs to be further discussed.

5. Conclusions
This paper used the dynamic equivalent factor method and added a modification through the time value of money. To calculate the ESV of Wuhan in different periods, we explored the direct and indirect influence mechanism of urban land expansion on the regional ESs. The results show that:

Except for hydrology regulation, waste treatment and aesthetic landscape provision, the value of other ESs and total ESV showed a downward trend in 2000-2005. Among them, the decline of food production was the largest, followed by soil conservation, and the decrease of hydrology regulation was the smallest. The ESVs per capita of hydrology regulation, waste treatment and aesthetic landscape provision showed a trend of the first rise then declined from 2000 to 2005, while the other ESs per capita declined with a similar law with that of direct decline. However, the per capita decline was significantly greater than the direct decline.

The expansion rate of urban land in Wuhan increased in 1990-2010, but decreased only in 2010-2015. Urban expansion encroaches on a large number of high-quality farmlands, which is significantly detrimental to food production. A large number of landfill lakes reduce the area of water and increase the degree of lake fragmentation, much endangering hydrological regulation and biodiversity.

In the past 25 years, the population growth brought about by the expansion of Wuhan has driven the city to expand to the land with good terrain like farmland. When the urban expansion area is fixed, the expansion to farmland reduces the direct damage to the ecosystem caused by urban land expansion. However, the demand for ESs increases with population growth. Therefore, the traditional urban expansion model of encroaching farmland in exchange for ecological land protection can’t reduce the impacts of urban land expansion on the regional ecosystem.

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