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Driving Factors and Spatial Heterogeneity Analysis of Ecosystem Services Value

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Abstract: Ecosystem services value pressure has different driving factors and shows differences in different regions. Taking Beijing City as the study area, considering the spatial distance and local spatial connection factors, this paper explores the driving factors and spatial heterogeneity analysis of ecosystem services value based on STIRPAT model. The factors chosen in the paper are population, per capita GDP, green rate, the proportion of the third industry, the total energy consumption per capita and urbanization rate. The result shows that, population, per capita GDP, green rate, the proportion of the third industry, the total energy consumption per capita and urbanization rateare the important driving factors that affect the value of ecosystem services in Beijing City, and the green rate is positive, the other indicators have a negative impact on the per capita ecosystem service value, in which, the influence of the proportion of the third industry and urbanization rateare the maximum two factors. The relationship between ecosystem services value and its driving factors is very complicated, so this paper takes geographical space effects into the STIRPAT model, and the driving factors of each district is gotten, By analyzing the driving factors of the ecosystem services value of each district, the influence of the driving factors in different regions of Beijing is great. Generally speaking, the influence of the urban expansion area and the urban development zone is higher than that of the ecological conservation area. Based on quantitative analysis of the driving factors and spatial heterogeneity analysis, the relevant measures to improve the service value of the ecosystem services in different regions of Beijing were proposed.

Key words: ecosystem services value; STIRPAT model; driving factor; spatial heterogeneity

0 Introduction

Ecosystem service is an important part of ecological assets that contributed to human survival and quality of life, and has great indirect and direct economic value[1-2]. With the deterioration of the environment, the ecosystem service value (ESV) evaluation of land use caused by ecological effects has become a hot research topic[3-5]. In recent years, scholars began paying attention to the value of ecological system service factors. Land use is the most closely link between human and nature, and the resulting land cover change affects the structure and function of ecological system[6-7], resulting in changes in ecosystem service value[8]. There are many researches on the influence[9-15] of LUCC and the corresponding forecast[16-17] on ESV change. Some scholars explored the driving factors and prediction of the future trends of the ecosystem service value from the NPP[18], social economic[19-23] and humanities[24] etc., correlation analysis and regression analysis methods are used in these researches. Overall, the present study mostly focuses on a region and analyzes the regional ESV driving factors. Due to the huge economic and geographical differences in the region, the driving factors of ESV are non-equilibrium or non-stability in the geographical space. STIRPAT model is widely used in the analysis of environmental impact factors[25-27], which has been applied to the analysis of the driving factors of ESV[24], but the spatial difference analysis of the driving factors of ESV is insufficient. This paper chooses Beijing city as the research object, and uses the STIRPAT model to analyze the driving factors of regional ESV, and the

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spatial distance and local spatial connection factors will be considered and spatial effects will be taken into the STIRPAT model framework. Finally, the driving factors and differences of ESV will be analyzed by the geographically weighted regression (GWR).

1 Research method

IPAT model, proposed by the American scholar EHRLICH[28], is used to measure the impact of human factors on the environment, the expression is:

$$I = P \times A \times T \tag{1}$$

In which, I is environmental pressure; P is population quantity; A is wealthy degree; T is technology level.

The model is used to measure the influence of the interaction among populations, wealth and technology on the environment and has been widely used in the field of environmental economics because it is simple and easy to operate. The number of variables is finite in the model and results only reflect the impact on the environment as the linkage effects of the three factors, it is difficult to distinguish the influence of each factor on the environment. So, DIETZ, et al[29], proposed a random regression impact model of population, affluence and technology level (Stochastic impacts by regression on population, affluence and technology, STIRPAT). The model is transformed IPAT into a stochastic model, analyzing the impact of human driving force on the environmental stress, the expression is:

$$I = cP^{\alpha}A^{\beta}T^{\gamma}e \tag{2}$$

In which, c is constant coefficient; e is model error; α, β, γ are elastic coefficients. STIRPAT model is a multivariable nonlinear model, which is obtained from the two sides of the model equation:

$$\ln I = \ln c + \alpha \ln P + \beta \ln A + \gamma \ln T + \ln e \tag{3}$$

The standard STIRPAT model provides a simple decomposition factor of human activities on the environmental impact of causal analysis framework. The driving factors on the environment can be analyzed and humanities and social factors change response can be forecasted[30]. In this paper, we will analyze the driving factors of ESV change based on the extended STIRPAT model according the existing research[27,31]. The value of per capita ecosystem services (E) is chosen to represent the environmental pressure, the population quantity is expressed by the general population(P), wealthy degree is expressed by GDP per capita, and the greening rate (G) reflects the natural environment of the region, changes in the proportion of the tertiary industry (S) in a certain extent can reflect changes in the intensive use of land, thus affecting land ecosystem service function value, so the selection of the tertiary industry added value accounted for the proportion of GDP as the index of industrial structure; Ten thousand Yuan GDP energy consumption and urbanization rate as an index to reflect the social and economic development, can reflect the change of land use, so the urbanization rate(U) and ten thousand Yuan GDP energy consumption(N) are chosen to represent the socio-economic development stage index. The expression is:

$$E = cP^{a_1}A^{a_2}G^{a_3}S^{a_4}N^{a_5}U^{a_6}k \tag{4}$$

In which, k is random variable; a_1, a_2, a_3, a_4, a_5, a_6 are elastic coefficients, respectively, the total population, per capita GDP, greening rate, the proportion of the tertiary industry, ten thousand yuan GDP energy consumption and urbanization rate of 1% per change, will cause the ESV of $\frac{a_1}{100}, \frac{a_2}{100}, \cdots, \frac{a_6}{100}$ changes. To facilitate the use of regression analysis to determine the parameters of the model, the Eq. (4) on both sides of the log,

$$\ln E = \ln c + a_1 \ln P + a_2 \ln A + a_3 \ln G + a_4 \ln S + a_5 \ln N + a_6 \ln U + \ln k \tag{5}$$

According to Eq. (5), we can analyze the driving factors of regional ecosystem service value. Due to the complexity and variability of ESV in space, the driving factors of ESV in different regions are different. Therefore, when using the regional ESV cross section data to establish econometric model, it is assumed that the regional ESV is more in line with the reality. This study uses spatial econometric theory and method of geographically weighted regression (Geographical weighted regression model, GWR)[27] to portray the ESV driving factors heterogeneity. GWR can analyze the ESV of different regions along with the spatial interaction mechanism of geographical distance[32], the expression is:

$$\ln E_i = \ln c(u_i, v_i) + a_1(u_i, v_i)\ln P_i + a_2(u_i, v_i)\ln A_i + a_3(u_i, v_i)\ln G_i + a_4(u_i, v_i)\ln S_i + a_5(u_i, v_i)\ln N_i + a_6(u_i, v_i)\ln U_i + e_i \tag{6}$$

In which, i is zone number, (u_i, v_i) is the geographical coordinates of the i-th region.

2 Study area and data

2.1 Study area

Beijing City is located in the northwestern part of the North China Plain, the geographical coordinates is north latitude 39°28′ ~ 41°25′, east longitude 115°25′ ~ 117° 30′, and the north-south long approximately 176 km, east-west width of about 160 km, with a total area of 1 641 054 hm^2. The natural condition of Beijing is superior and the geographical position is extremely important. Beijing has obvious circle distribution characteristics with the clear city′s main functional zoning, named the core area of the capital function, urban function development zone, urban development and ecological conservation in new development zone division four regions. With different regional land use characteristics, the impact on the ESV is also different.

2.2 Data acquisition and processing

In order to avoid the chance of cross section data analysis, this paper selects 5 a average value of 2009—2013 for calculation. The 2009—2013 statistical data of land use of Beijing comes from the department of land and resources, with the land use classification of cultivated land, garden, woodland, grassland, construction land, water and unused land. The total population, per capita GDP, greening rate, the proportion of the tertiary industry, urbanization rate and ten thousand yuan GDP energy consumption data are from the "Beijing Regional Statistical Yearbook (2010—2014)". The land use type of Dongcheng and Xicheng is only construction land, so the study did not involve this two regions. According to the meaning of the model, six variables were taken into natural logarithm and mean centered processing in order to eliminate the multiple co-linearity of the independent variables.

2.3 Ecosystem service value of land use type

On the basis of terrestrial ecosystems per unit area ESV equivalent table in China of XIE[33], basic per unit area ecosystem service value of each land use type in Beijing City is determined based on space and time correction[34] (Tab. 1). Based on the land use data of Beijing City, the total value of ecosystem services and the value of per capita ecosystem services in 2009—2013 were calculated (Tab. 2).

Tab. 1 Basic per unit area ecosystem service value of each land use type in Beijing City Yuan/hm^2

Land use types	Gas condition	Climate regulation	Water conservation	Soil formation and protection	Waste disposal	Biodiversity conservation	Food production	Raw material	Entertainment culture	Total value
Cultivated land	976. 39	1 862. 36	643. 26	2 923. 01	2 369. 92	694. 77	1 768. 85	139. 75	2 790. 84	14 169. 16
Garden	2 507. 13	2 507. 58	2 214. 31	4 204. 73	2 348. 56	2 243. 59	964. 75	1 507. 48	2 149. 67	20 647. 78
Wood land	3 201. 46	2 519. 69	3 004. 11	3 470. 22	1 081. 86	2 981. 92	99. 38	2 587. 35	1 201. 46	20 147. 45
Grass	1 927. 95	1 965. 55	1 435. 16	4 129. 70	2 556. 21	2 040. 43	828. 86	120. 50	98. 23	15 102. 60
Waters	0	828. 57	36 709. 38	18. 01	32 746. 64	4 485. 10	180. 12	18. 01	7 817. 40	82 803. 23
Unused land	0	0	105. 90	70. 60	35. 30	1 200. 23	35. 30	0	35. 30	1 482. 63
Construction land	0	0	0	0	0	0	0	0	0	0

Tab. 2 Total and per ecosystem services value in each district and county from 2009 to 2013 in Beijing City Yuan

Region	ESV	Per ESV	Region	ESV	Per ESV
Chaoyang	3.81×10^8	105. 92	Shunyi	1.77×10^9	1 980. 75
Fengtai	2.90×10^8	137. 01	Changping	2.00×10^9	1 226. 57
Shijingshan	9.20×10^9	146. 00	Daxing	2.34×10^0	1 690. 68
Haidian	5.29×10^8	157. 35	Huairou	5.02×10^9	13 338. 95
Mentougou	2.01×10^9	6 866. 35	Pinggu	2.13×10^0	5 064. 72
Fangshan	3.26×10^9	3 381. 49	Miyun	6.39×10^9	13 615. 09
Tongzhou	3.39×10^9	2 761. 66	Yanqing	4.67×10^9	15 008. 55

Tab. 2 shows that the total and per capita ESV of each districts have a great gap. Overall, the ESV of ecological conservation area was higher than that of the urban expansion area and urban development zone. The total value of Miyun is the highest one and the value is 6.391×10^9, followed by Huairou, Yanqing, Chaoyang, Fengtai and Shijingshan, Shijingshan is only 9.200×10^7 Yuan. Yanqing per capita ESV of the highest, for 15 008.55 Yuan; followed by Miyun and Huairou, Shijingshan, Fengtai, and Chaoyang are the lowest one.

3 Result

3.1 Overall driving factor analysis

The STIRPAT model was used to analyze the driving factors of the per capita ESV, and the results were shown in Tab. 3.

Tab. 3 OLS estimation results of STIRPAT model

Variable	Coefficient	Standard error	*T* statistic
E	7.415	0.160	46.466
ln*P*	−0.621	0.300	−2.068
ln*A*	−0.433	0.549	−0.789
ln*G*	0.161	1.209	2.651
ln*S*	−3.188	1.048	−3.043
ln*N*	−1.119	0.430	−2.601
ln*U*	−3.029	0.841	−3.601
R^2	0.942		
F	18.946		

The function heterozygosity per capita ESV is 94.2%, and the whole model proposed the 1% level of significance test, population (ln*P*), per capita GDP (ln*A*), greening rate (ln*G*), the proportion of the tertiary industry (ln*S*), ten thousand Yuan GDP energy consumption (ln*N*) and urbanization rate (ln*U*) all proposed the 1% level of significance test. The results show that the number of population, per capita GDP, greening rate, the proportion of the tertiary industry, ten thousand Yuan GDP energy consumption and urbanization rate are all the important driving factors of the value of ESV in Beijing City, in addition to the greening rate, other indicators have a negative impact on the value of ESV. From the elastic coefficient, every 1% increase in population will bring per capita ecological system service value decreased by 0.621%; per capita GDP for every 1% increase will bring decrease by 0.433% of per capita ESV; greening rate increases by 1% each, it will bring 0.161% per capita ESV value added; each 1% increase in the proportion of the tertiary industry, will bring per capita ESV decreased by 3.188%; Yuan GDP energy consumption for every 1% increase in will bring per capita ESV decreased by 1.119%; urbanization rate increases by 1% each, it will bring a per capita ESV decreased by 3.029%.

3.2 Analysis of regional driving factors

The driving factors of the ESV can be analyzed based on the STIRPAT model, and the results has important significance for the analysis of the entire ecosystem service value of Beijing, but the methods have certain limitation to reveal the difference of the ESV of Beijing City. Therefore, this study uses the weighted least squares (WLS) in the geographical weighted regression model (GWR) to simulate the impact model of the ESV of STIRPAT Eq. (6). According to this, the differences elasticity of driving factors in different areas are calculated, the results are shown in Tab. 4. The results of *F*-test of the model and *t*-test on the explanatory variable shows that, the equation model passes the 1% level of significance test, explanatory variables in regression coefficient pass the 1% level of significance test. Considering the spatial difference, the influence factors of the ESV in different regions are not consistent.

Tab. 4 GWR estimation results of STIRPAT model

District	*E*	ln*P*	ln*A*	ln*G*	ln*S*	ln*N*	ln*U*	R^2	Standard error	Standardized residual
Chaoyang	7.326	−0.261	−0.002	0.072	−5.250	−1.417	−2.524	0.967	0.291	0.324
Fengtai	7.631	−0.706	−0.097	2.657	−5.150	−1.837	−2.967	0.969	0.272	−0.398
Shijingshan	7.665	−0.728	−0.193	0.716	−4.941	−1.831	−3.188	0.974	0.153	−1.174
Haidian	7.649	−0.719	−0.273	0.033	−4.708	−1.794	−3.280	0.975	0.253	−0.404
Mentougou	7.702	−0.729	−0.316	5.017	−4.698	−1.781	−3.414	0.979	0.102	1.851
Fangshan	7.699	−0.748	−0.155	4.001	−5.060	−1.862	−3.213	0.976	0.158	0.540
Tongzhou	7.148	−0.377	0.056	0.106	−4.864	−0.960	−2.781	0.971	0.263	−0.437
Shunyi	7.231	−0.292	−0.269	0.448	−3.280	−1.060	−3.598	0.965	0.052	0.846
Changping	7.540	−0.727	−0.637	0.105	−3.494	−1.621	−3.517	0.981	0.161	0.315
Daxing	7.505	−0.554	0.041	1.484	−5.522	−1.752	−2.427	0.960	0.324	1.441
Huairou	7.303	−0.609	−0.804	0.089	−2.123	−1.560	−3.004	0.965	0.160	0.955
Pinggu	7.212	−0.245	−0.045	0.087	−3.543	−0.999	−3.543	0.956	0.330	−1.828
Miyun	7.278	−0.607	−0.403	0.011	−2.728	−1.247	−3.267	0.952	0.348	0.288
Yanqing	7.382	−0.918	−0.996	0.104	−2.221	−1.012	−3.258	0.988	0.051	1.081

ESV driving factors shows large differences in different districts due to the process of regional economic development in consideration of spatial effect and regional differences. Tab. 4 shows that the elasticity coefficients of all the population factors are negative, indicating that the declined population will reduce regional per capita ESV, and the elasticity coefficient of Fengtai, Shijingshan, Haidian, Mentougou, Fangshan, Changping, Yanqing are more than average, indicating that these districts can be brought to bear on the population growth of ESV caused by the greater pressure. The per capita GDP elasticity coefficients of Daxing, Tongzhou are positive, indicating that the GDP increase did not bring the per capita ESV reduced, there is an increase in a certain degree of that description of Tongzhou and Daxing in the process of economic development phase because of more attention to the protection of the ecological environment, and the elasticity coefficient is higher than the average in Changping, Huairou and Yanqing, indicating that there are more pressure on ESV caused by the economic development. The elasticity coefficient of green coverage rate in all area is positive, indicating that the green coverage rate promotes the regional per capita ecological system service value increased. Among them, the elastic coefficients of the Daxing, Fangshan, Mentougou, Fengtai are higher than the mean of 0. 161. Therefore, these areas could improve effect on ESV more obviously by increasing the rate of greening. The elasticity coefficient of proportion of the tertiary industry is negative in all areas, indicating that the increase of the tertiary industry will cause the ESV reduced, the elasticity of the Chaoyang, Fengtai, Shijingshan, Haidian, Mentougou, Fangshan, Tongzhou are higher than the average, these regions have heavy pressure on the ESV than the others. All of the district's elasticity coefficient of ten thousand Yuan GDP energy consumption are negative, indicating that the increased energy consumption will cause the per capita ESV decreased, which the elastic coefficient of the Chaoyang, Fengtai, Shijingshan, Haidian, Mentougou, Fangshan, Changping, Daxing and Huairou are higher than the average, indicating that these regions are under greater pressure on ESV caused by energy consumption growth. The district's elasticity coefficient of the urbanization rate is negative, indicating that the urbanization rate will cause the per capita ESV decreased, while the elasticity coefficients of Shijingshan, Haidian, Mentougou, Fangshan, Shunyi, Changping, Pinggu, Miyun and Yanqing are higher than the average, indicating that these regions are under greater pressure on ESV caused by urbanization.

4 Conclusions

(1) ESV driving factors can be quantitatively analyzed by STIRPAT model, but it has certain restrictions for the analysis of the spatial difference of different regions. Combined with the geographical weighted regression model, regional internal driving factors and control measures can be explored in accordance with different regions. Based on the STIRPAT model, the ESV driving factors in Beijing are analyzed, the result shows that the proportion of the population, per capita GDP, the rate of greening, the tertiary industry and urbanization rate and ten thousand Yuan GDP energy consumption are all the important driving factors influence Beijing, in which, greening rate has a positive impact, the other five indicators of ESV have negative impact, while the negative impact of proportion of the third industry and urbanization rate are larger than others. Combined with the geographical weighted regression model, the driving factors of the ESV are analyzed and the influence degree of driving factors in different regions is found.

(3) It is an important measure to increasing the greening rate for the improvement of ESV in Beijing City, and the most important negative factor is the proportion of the third industry and urbanization rate, the proportion of the tertiary industry and urbanization rate increases by 1% each, per capita ESV will decrease to more than 3%, indicating that the third industrial development and urban expansion occupied the ecological land, reducing the function value of ESV, so it is urgent to improve the land intensive use level. Ten thousand Yuan GDP energy consumption can also affect the ESV. Ten thousand Yuan GDP energy consumption amounts for every 1% increase, the per capita ESV will reduce amplitude 1. 119%, so the improvement of the level of industrial technology and reducing of industrial energy consumption will promote the regional ecological environment.

Population increase also causes a decrease of ESV, indicating that population increase would encroach on the ecological land, resulting in less per capita ecosystem service function value. Therefore, Beijing should pay attention to the improvement of ecological environment and ecological land use protection in the process of urbanization, in order to make the urban population and ecology coordinated development. GDP increase can cause reduction of the per capita ESV, indicating that the economic development has negative impact to the regional ecological environment and causes some impact.

(4) The analysis of the influencing factors of the ESV in different districts in Beijing shows that between the influence degree of various factors, the city function expansion area and the development of the new city is higher than that of ecological conservation development areas, illustrating driving factors vary in different levels of development and different regions. The development of city function expansion area and new city's rapid economic area is quicker than other areas, and the population, the economic development, the proportion of the industry, the rate of energy consumption are higher than that of the city and ecological conservation area. Therefore, these areas must pay attention to population control and improvement of the level of technology, economical and intensive utilization of land, green area increase. It has an important role in supporting ecological conservation area of Beijing in ecological security and the construction of livable cities, so these areas should continue to increase the green area and the development of green industry, and maintain a good ecological environment.

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生态系统服务价值驱动因素与空间异质性分析

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摘要：以北京市为例，采用STIRPAT模型和地理加权回归模型分析了区域生态系统服务价值的驱动因素及空间差异。结果显示，人口数量、人均GDP、绿化率、第三产业比重、万元GDP能耗和城市化率都是影响北京市生态系统服务价值的重要驱动因素，其中绿化率是正向影响，其他5个指标对生态系统服务价值有负面影响，其中第三产业比重和城市化率的负面影响最大。加入空间距离和局域空间联系因素，对分区的生态系统服务价值驱动因素进行分析发现，北京市不同区的驱动因素的影响程度不同，各个驱动因素中，城市功能扩展区和城市发展新区的影响要高于生态涵养发展区。通过对驱动因素的定量测算及分区空间异质性分析，提出了北京市不同区域的提高生态系统服务价值的相关措施。

关键词：生态系统服务价值；STIRPAT模型；驱动因素；空间异质性

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Driving Factors and Spatial Heterogeneity Analysis of Ecosystem Services Value

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Abstract: Ecosystem services value pressure has different driving factors and shows differences in different regions. Taking Beijing City as the study area, considering the spatial distance and local spatial connection factors, this paper explores the driving factors and spatial heterogeneity analysis of ecosystem services value based on STIRPAT model. The factors chosen in the paper are population, per capita GDP, green rate, the proportion of the third industry, the total energy consumption per capita and urbanization rate. The result shows that, population, per capita GDP, green rate, the proportion of the third industry, the total energy consumption per capita and urbanization rateare the important driving factors that affect the value of ecosystem services in Beijing City, and the green rate is positive, the other indicators have a negative impact on the per capita ecosystem service value, in which, the influence of the proportion of the third industry and urbanization rateare the maximum two factors. The relationship between ecosystem services value and its driving factors is very complicated, so this paper takes geographical space effects into the STIRPAT model, and the driving factors of each district is gotten, By analyzing the driving factors of the ecosystem services value of each district, the influence of the driving factors in different regions of Beijing is great. Generally speaking, the influence of the urban expansion area and the urban development zone is higher than that of the ecological conservation area. Based on quantitative analysis of the driving factors and spatial heterogeneity analysis, the relevant measures to improve the service value of the ecosystem services in different regions of Beijing were proposed.

Key words: ecosystem services value; STIRPAT model; driving factor; spatial heterogeneity

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引言

生态系统服务是指对人类生存及生活质量有贡献的生态系统产品和生态系统功能，具有巨大的间接和直接经济价值，是生态资产重要组成部分[1-2]。随着环境问题的恶化，利用生态系统服务价值定量评估土地利用引起的生态效应已成为研究热点[3-5]。近年来，学者们开始关注生态系统服务价值的影响因素，土地利用是人与自然交叉最为密切的环节，土地利用以及由此导致的土地覆被变化影响着生态系统的结构和功能[6-7]，从而导致生态系统服务价值的变化[8]。目前研究中关于土地利用/覆被变化对生态系统服务价值变化的影响方面的研究较多[9-15]。还有学者基于土地利用/覆被变化，对生态系统服务价值的变化进行了相应的预测研究[16-17]。也有学者从其他方面探究生态系统服务价值的驱动因素，如从 NPP[18]、社会经济[19-23]和人文[24]等方面展开研究，采用相关性分析与回归分析等方法定量研究生态系统服务价值的驱动因子及其影响程度，并对生态系统服务价值的未来变化趋势进行预测。总体而言，目前的研究多针对某一区域，对区域的生态系统服务价值驱动因子进行总体分析，然而区域内部的经济地理差异巨大，生态系统服务价值的驱动因素在地理空间上存在非均衡性或非稳定性。STIRPAT 模型广泛应用于环境影响因素分析中[25-27]，有学者将其应用到生态系统服务价值的驱动因素分析中[24]，但对生态系统服务价值的驱动因素中的空间差异分析不足。本文选择北京市为研究对象，采用 STIRPAT 模型对区域生态系统服务价值的驱动因素进行总体分析，考虑空间距离和局域空间联系因素，将地理空间效应纳入 STIRPAT 模型框架中，通过地理加权回归方法（GWR）分析驱动因素的空间差异，以期探索生态系统服务价值的分区域驱动因素及其差异。

1　研究思路

IPAT 模型由美国学者 EHRLICH 提出[28]，用来测度人文因素对环境影响，其表达式为

$$I = P \times A \times T \tag{1}$$

式中　I——环境压力　　P——人口数量

A——富裕度　　T——技术水平

该模型用来度量人口、财富和技术三者之间相互作用对环境的影响。由于该模型简单、易操作，其在环境经济领域中得到了广泛应用，但该模型考虑的变量数目有限，而且所能得到的结果反映为三者的联动影响，难以区分每个因素对环境的影响。DIETZ 等[29]提出了人口数量、富裕度和技术水平的随机回归影响模型（Stochastic impacts by regression on population, affluence and technology, STIRPAT），该模型是将 IPAT 模型转换成一种随机模型来分析人类驱动力对环境压力的影响，STIRPAT 模型具体表示为

$$I = cP^{\alpha}A^{\beta}T^{\gamma}e \tag{2}$$

式中　c——常系数　　e——模型误差

α、β、γ——弹性系数

STIRPAT 模型是一个多变量非线性模型，对模型等式两边取对数得到

$$\ln I = \ln c + \alpha \ln P + \beta \ln A + \gamma \ln T + \ln e \tag{3}$$

标准的 STIRPAT 模型提供了一个简单的分解人类活动因子对环境影响的因果分析框架，据此可以分析驱动因素对环境影响的作用，还可以预测环境对人口数量和富裕度等人文社会因素变化的响应[30]。本文参考已有研究[27,31]，采用拓展的 STIRPAT 模型进行生态系统服务功能价值变化的驱动力因素分析。以人均生态系统服务功能价值（E）作为环境压力；人口数量采用总人口表示；富裕度采用人均 GDP 表示，绿化率（G）反映了区域的自然环境状况，可以影响生态系统服务价值；第三产业比重（S）的变化在一定程度上可以反映土地集约利用的变化，从而影响土地生态系统服务功能价值，因此选择第三产业增加值占生产总值的比重作为产业结构化指标；万元 GDP 能耗（N）和城市化率（U）作为反映社会经济发展的指标，在一定程度上也能反映土地利用方式的变化，因此选择城市化率和万元 GDP 能耗作为社会经济发展阶段指标。

$$E = cP^{a_1}A^{a_2}G^{a_3}S^{a_4}N^{a_5}U^{a_6}k \tag{4}$$

模型中，k 为随机变量；a_1、a_2、a_3、a_4、a_5、a_6 为弹性系数，分别表示总人口、人均 GDP、绿化率、第三产业比重、万元 GDP 能耗和城市化率每变化 1%，将分别引起生态系统服务价值$\frac{a_1}{100}, \frac{a_2}{100}, \cdots, \frac{a_6}{100}$的变化量。为了方便运用回归分析确定模型中的参数，对式（4）两边取对数得

$$\ln E = \ln c + a_1 \ln P + a_2 \ln A + a_3 \ln G + a_4 \ln S + a_5 \ln N + a_6 \ln U + \ln k \tag{5}$$

根据式（5），可以分析区域生态系统服务价值的驱动因素。但由于生态系统服务价值在空间上具有复杂性和变异性的特点，使得各地区生态系统服务价值的驱动因素的地理空间效应差异较大。因此，使用区域生态系统服务价值截面数据建立计量经济学模型时，假定区域生态系统服务价值在空间上具有异质性更符合现实情况。本研究采用空间计

量经济学理论方法中的地理加权回归模型(Geographical weighted regression, GWR)[27],对生态系统服务价值驱动因素的异质性特征进行刻画。GWR能够分析不同区域的生态系统服务价值随着地理距离变化的空间作用机制[32],有

$$\ln E_i = \ln c(u_i,v_i) + a_1(u_i,v_i)\ln P_i + a_2(u_i,v_i)\ln A_i + a_3(u_i,v_i)\ln G_i + a_4(u_i,v_i)\ln S_i + a_5(u_i,v_i)\ln N_i + a_6(u_i,v_i)\ln U_i + e_i \quad (6)$$

式中 i——区域序号 (u_i,v_i)——i 区的地理坐标

2 研究区域概况与数据获取

2.1 研究区域概况

北京市位于华北平原的西北部,地理坐标为北纬39°28′~41°25′,东经115°25~117°30′,南北长约176 km,东西宽约160 km,总面积1 641 054 hm²,北京市傍山面海,腹地辽阔,自然条件优越,地理位置极为重要。北京市土地利用呈现明显的圈层分布特点,已经明确了城市主体功能区划,划分为首都功能核心区、城市功能拓展区、城市发展新区和生态涵养发展区4个区域。不同区域用地特点不同,对生态系统服务价值的影响也有所不同。

2.2 数据获取与处理

为了避免截面数据分析可能造成的偶然性,本文选用2009—2013年5 a平均值进行模型计算。北京市各区土地利用数据来源于2009—2013年北京市国土资源部门统计数据,土地利用类型划分为耕地、园地、林地、草地、城镇村及工矿用地、交通运输用地、水域及水利设施用地和其他土地。各地区总人口、人均GDP、绿化率、第三产业比重、城市化率和万元GDP能耗数据均来源于2010—2014年《北京市区域统计年鉴》。由于土地利用统计数据中,东城区和西城区的土地利用类型统计类型全部为建设用地,因此该研究中未涉及这两个区域,只进行了其他14个区的研究。根据模型含义,首先对6个变量值取自然对数,其次为了消除多重共线性对自变量进行均值中心化处理。

2.3 土地利用类型生态系统服务价值

本研究结合谢高地的中国陆地生态系统单位面积生态系统服务价值当量表[33],基于已有研究进行时间空间校正后[34],确定了各土地利用现状用地及其生态系统服务基准价值(表1)。结合北京市土地利用统计数据,计算2009—2013年各区生态系统服务总价值及人均生态系统服务价值(表2)。

由表2可知,北京市各区的生态系统服务总价值和人均生态系统价值差距较大,总体而言,生态涵养区的生态系统服务总价值高于城市扩展区和城市发展新区。密云区总价值最高,为 6.391×10^9 元;其次是怀柔区、延庆区;朝阳区、丰台区和石景山区最低,其中,石景山区仅有 9.200×10^7 元。延庆区人均生态系统服务价值最高,为15 008.55元/人;其次是密云区和怀柔区,石景山区、丰台区和朝阳区最低。

表1 北京市各土地利用类型的单位面积生态系统服务价值

Tab.1 Basic per unit area ecosystem service value of each land use type in Beijing City 元/hm²

用地类型	气体调节	气候调节	水源涵养	土壤形成与保护	废物处理	生物多样性保护	食物生产	原材料	娱乐文化	总价值
耕地	976.39	1 862.36	643.26	2 923.01	2 369.92	694.77	1 768.85	139.75	2 790.84	14 169.16
园地	2 507.13	2 507.58	2 214.31	4 204.73	2 348.56	2 243.59	964.75	1 507.48	2 149.67	20 647.78
林地	3 201.46	2 519.69	3 004.11	3 470.22	1 081.86	2 981.92	99.38	2 587.35	1 201.46	20 147.45
草地	1 927.95	1 965.55	1 435.16	4 129.70	2 556.21	2 040.43	828.86	120.50	98.23	15 102.60
水域	0	828.57	36 709.38	18.01	32 746.64	4 485.10	180.12	18.01	7 817.40	82 803.23
未利用地	0	0	105.90	70.60	35.30	1 200.23	35.30	0	35.30	1 482.63
建设用地	0	0	0	0	0	0	0	0	0	0

表2 2009—2013年北京市各区生态系统服务总价值及人均生态系统服务价值

Tab.2 Total and per ecosystem services value in each district and county from 2009 to 2013 in Beijing City 元

区域	生态系统服务总价值	人均生态系统服务价值	区域	生态系统服务总价值	人均生态系统服务价值
朝阳区	3.810×10^8	105.92	顺义区	1.767×10^9	1 980.75
丰台区	2.900×10^8	137.01	昌平区	1.997×10^9	1 226.57
石景山区	9.200×10^7	146.00	大兴区	2.343×10^9	1 690.68
海淀区	5.290×10^8	157.35	怀柔区	5.023×10^9	13 338.95
门头沟区	2.012×10^9	6 866.35	平谷区	2.130×10^9	5 064.72
房山区	3.260×10^9	3 381.49	密云区	6.391×10^9	13 615.09
通州区	3.394×10^9	2 761.66	延庆区	4.674×10^9	15 008.55

3　结果分析

3.1　总体驱动因素分析

采用 STIRPAT 模型,对人均生态系统服务价值的驱动因素进行总体分析,结果如表 3 所示。

表 3　STIRPAT 模型 OLS 估计结果

Tab.3　OLS estimation results of STIRPAT model

变量	系数	标准误差	T 统计量
E	7.415	0.160	46.466
$\ln P$	−0.621	0.300	−2.068
$\ln A$	−0.433	0.549	−0.789
$\ln G$	0.161	1.209	2.651
$\ln S$	−3.188	1.048	−3.043
$\ln N$	−1.119	0.430	−2.601
$\ln U$	−3.029	0.841	−3.601
R^2	0.942		
F	18.946		

人均生态系统服务价值函数拟合度为 94.2%,模型整体上通过了 1% 水平的显著性检验,人口数量($\ln P$)、人均 GDP($\ln A$)和绿化率($\ln G$)、第三产业比重($\ln S$)、万元 GDP 能耗($\ln N$)、城市化率($\ln U$)均通过了 1% 水平的显著性检验。结果显示,人口数量、人均 GDP、绿化率、第三产业比重、万元 GDP 能耗和城市化率在影响北京市生态系统服务价值的驱动因素中,都是重要因素。除了绿化率,其他指标都对生态系统服务价值有负面影响。从弹性系数看,人口每增加 1%,会带来人均生态系统服务价值减少 0.621%;人均 GDP 每增加 1%,会带来人均生态系统服务价值减少 0.433%;绿化率每增加 1%,会带来人均生态系统服务价值增加 0.161%;第三产业比重每增加 1%,会带来人均生态系统服务价值减少 3.188%;万元 GDP 能耗每增加 1%,会带来人均生态系统服务价值减少 1.119%;城市化率每增加 1%,会带来人均生态系统服务价值减少 3.029%。

3.2　分区域驱动因素分析

通过 STIRPAT 模型可以分析出生态系统服务价值的驱动因素,并对其进行定量化分析,结果对于分析整个北京市的生态系统服务价值驱动因素具有重要意义。但以上方法对于揭示北京市各区内部的生态系统服务价值的差异有一定的局限性,因此,本研究采用地理加权回归模型(GWR)中的加权最小二乘法(WLS)对 STIRPAT 生态系统服务价值影响模型进行模拟(式(6)),并依此来计算北京市不同区生态系统服务价值驱动因素弹性的差异,结果如表 4 所示。通过对模型的 F 检验和对解释变量的 t 检验的结果表明,方程模型整体上通过了 1% 水平的显著性检验,各个解释变量回归系数均通过了 1% 水平的显著性检验。考虑空间差异影响后,不同区域生态系统服务价值的影响因素弹性系数不一致。

表 4　STIRPAT 模型的 GWR 估计结果(弹性系数)

Tab.4　GWR estimation results of STIRPAT model

区域	E	$\ln P$	$\ln A$	$\ln G$	$\ln S$	$\ln N$	$\ln U$	R^2	标准误差	标准残差
朝阳区	7.326	−0.261	−0.002	0.072	−5.250	−1.417	−2.524	0.967	0.291	0.324
丰台区	7.631	−0.706	−0.097	2.657	−5.150	−1.837	−2.967	0.969	0.272	−0.398
石景山区	7.665	−0.728	−0.193	0.716	−4.941	−1.831	−3.188	0.974	0.153	−1.174
海淀区	7.649	−0.719	−0.273	0.033	−4.708	−1.794	−3.280	0.975	0.253	−0.404
门头沟区	7.702	−0.729	−0.316	5.017	−4.698	−1.781	−3.414	0.979	0.102	1.851
房山区	7.699	−0.748	−0.155	4.001	−5.060	−1.862	−3.213	0.976	0.158	0.540
通州区	7.148	−0.377	0.056	0.106	−4.864	−0.960	−2.781	0.971	0.263	−0.437
顺义区	7.231	−0.292	−0.269	0.448	−3.280	−1.060	−3.598	0.965	0.052	0.846
昌平区	7.540	−0.727	−0.637	0.105	−3.494	−1.621	−3.517	0.981	0.161	0.315
大兴区	7.505	−0.554	0.041	1.484	−5.522	−1.752	−2.427	0.960	0.324	1.441
怀柔区	7.303	−0.609	−0.804	0.089	−2.123	−1.560	−3.004	0.965	0.160	0.955
平谷区	7.212	−0.245	−0.045	0.087	−3.543	−0.999	−3.543	0.956	0.330	−1.828
密云区	7.278	−0.607	−0.403	0.011	−2.728	−1.247	−3.267	0.952	0.348	0.288
延庆区	7.382	−0.918	−0.996	0.104	−2.221	−1.012	−3.258	0.988	0.051	1.081

各区的生态系统服务价值在考虑了空间效应和地区差异后,由于各区域经济发展进程不同和区域环境差异,生态系统服务价值的驱动因素显示出较大差异。由表 4 可知,人口影响因素方面,所有区人口因素的弹性系数都是负值,说明人口增加会降低区域人均生态系统服务价值,而丰台区、石景山区、海淀区、门头沟区、房山区、昌平区、延庆区的弹性系数大于平均值,说明这些地区所承受的人口增长对

生态系统服务价值造成的压力更大；经济发展影响方面，通州区和大兴区的弹性系数为正值，说明通州区和大兴区的 GDP 增加没有带来人均生态系统服务价值的减少，反而有一定程度的增加，说明通州区和大兴区在经济发展过程中相对更注重生态环境保护，而昌平区、怀柔区和延庆区的弹性系数高于平均值，说明这些区域的经济发展对生态系统服务价值造成的压力更大；绿化率影响方面，所有区绿化覆盖率的弹性系数都是正值，说明绿化覆盖率的提高促进了区域人均生态系统服务价值的增加，其中，大兴区、房山区、门头沟区、丰台区的弹性系数高于均值 0.161，因此，这些区域通过增加绿化率，对生态系统服务价值的提高效果更明显；第三产业比重影响方面，所有区的弹性系数都是负值，说明第三产业增加会造成生态系统服务价值的减少，朝阳区、丰台区、石景山区、海淀区、门头沟区、房山区、通州区的弹性系数都高于均值，这些区域第三产业比重增长对生态系统服务价值造成的压力更大；万元 GDP 能源消耗方面，所有区的弹性系数都是负值，说明增加能源消耗都会造成人均生态系统服务价值的减少，其中，朝阳区、丰台区、石景山区、海淀区、门头沟区、房山区、昌平区、大兴区和怀柔区的弹性系数都高于均值，说明这些区域所承受的万元 GDP 能源消耗增长对生态系统服务价值造成的压力更大；城市化率方面，所有区的弹性系数都是负值，说明城市化率提高会造成人均生态系统服务价值的减少，其中，石景山区、海淀区、门头沟区、房山区、顺义区、昌平区、平谷区、密云区和延庆区的弹性系数都高于均值，说明这些区域所承受的万元 GDP 能源消耗增长对生态系统服务价值造成的压力更大。

4 结论

（1）STIRPAT 模型能较好地对生态系统服务价值的驱动因素进行分析，并可以定量化驱动因素的影响程度，但对于分析不同区域的空间差异有一定的限制，而结合地理加权回归模型，可以揭示区域内部驱动因素差异，从而可以提出符合不同区域的调控措施。

（2）利用 STIRPAT 模型对北京市的生态系统服务价值驱动因素进行分析，人口数量、人均 GDP、绿化率、第三产业比重、城市化率和万元 GDP 能耗都是影响北京市生态系统服务价值的重要驱动因素，其中绿化率是正向影响，其他 5 个指标对生态系统服务价值都是负面影响，而其中第三产业比重和城市化率的负面影响最大。结合地理加权回归模型对分区的生态系统服务价值驱动因素进行分析，发现不同地区驱动因素的影响程度不同。

（3）对于北京市总体而言，增加绿化率是提高生态系统服务价值的重要措施，将来的城市建设要不断提高绿化率；影响生态系统服务价值最重要的负面因素是第三产业比重和城市化率，北京市第三产业比重和城市化率每增加 1%，人均生态系统服务价值减少幅度都要高于 3%，说明将来北京市第三产业的发展和城市扩张侵占了生态用地，而导致生态系统服务功能价值减少，因此北京市在将来要提高对土地的集约化利用水平；万元 GDP 能耗量也是影响生态系统服务价值的重要因素，万元 GDP 能耗量每增加 1%，人均生态系统服务价值减少幅度为 1.119%，说明提高产业技术水平、降低产业能耗对于促进区域生态环境有重要意义；人口增加对生态系统服务价值也造成一定减少，说明人口增加会侵占生态用地，而导致人均生态系统服务功能价值减少，因此，北京市在人口增加的同时，应注重生态环境的改善，在城市化过程中注重对生态用地的保护，使得城市人口与生态协调发展；GDP 增加造成人均生态系统服务价值减少，说明在经济发展的同时，也对区域生态环境造成了一定的影响。

（4）对北京市不同区的生态系统服务价值的影响因素进行分析发现，各个因素的影响程度中，城市功能扩展区和城市发展新区的影响要高于生态涵养发展区，说明不同区域的发展水平不同，驱动因素有所差异。城市功能扩展区和城市发展新区的经济发展速度较快，其人口数量、经济发展、第三产业比重、城市化率和能耗要高于生态涵养区。因此，这些区域更要重视控制人口规模、提高技术水平，节约集约利用土地、增加绿地面积，而生态涵养区对北京市的生态安全和宜居城市建设起到了非常重要的支撑作用，这些区域应继续增加区域绿地面积，发展绿色生态产业，维护自身良好的生态环境。

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