Allometric Growth Analysis between Economic Development and Its Environmental Effect in Shandong Peninsula Urban Agglomeration

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Abstract. Rapid urbanization and its interaction with economy and that with environment have been extensively studied, but the spatial relations between city's economic growth and its environmental effects have rarely been reported. Therefore, in this study, the allometric model and long-time series nighttime lighting (NTL) data were employed to analyse the relative growth rates between economic advancing and environmental pollution. The main conclusions of our study are as follows: (1) the tendency of the TNL and that of the MTL maintain the same trend in our study period ;(2) in all levels, the relative growth of industrial pollutant emissions is faster than that of economic growth; (3) in prefectural level, the scaling exponents show obvious spatial agglomeration and spatial differentiation. The most serious air pollution was caused by economic activities in Jinan and its surrounding cities, while the water pollution is mainly distributing along Yellow River.

Keywords-Allometric growth, nighttime light data, economic development, environmental pollution

1. INTRODUCTION

As an important place where human production activities take place, the change of urban land use reflects economic development and iteration of technology. Urban expansion, which shows different phased characteristics and trends under the influence of different socioeconomic and natural geographical conditions, has become a new theme of urban research in various countries. With the rapid globalization and marketization, the industrial structure and economic growth within a city are increasingly affected by the surroundings, showing a trend of regional development. Urban agglomeration has replaced a single city as an important growth pole of region and has become main form of Chinese urbanization. It is the main carrier of regional economic activities and population, which affects the development of regional economy through agglomeration economy, externality and polarization effect. However, the growth of urban agglomeration is often at the cost of certain resource investment and the population gathering further aggravates the conflict between economic advancing and environmental protection. Therefore, a comprehensive understanding of interaction between urban economy and ecological environment is of great significance to the formulation of regional socio-economic development planning.

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Existing studies have significantly addressed the relation between ecosystem service function and urban expansion. The spatial distribution changes of regional resources, biodiversity and ecosystem types caused by land use/cover change are main reason leading to degeneration of terrestrial ecosystem[1-2]. Current research mainly focused on the response of ecosystem service function to land use/cover change[3-5] and the interaction between land use and ecological service system[6]. Others focused on single ecosystem function, such as the assessment of soil and water conservation capacity[7-8], biodiversity[9] and content of soil organic carbon[10].

Another major direction of existing research is the interaction between economic growth and urban expansion. In classical economic theory, the economic growth usually following the adjustment and upgrading of industrial structure, the essence of which is the interdepartmental labor mobility driven by comparative interest, while urbanization describes the transformation from non-agricultural sectors to industrial and tertiary sectors. In other words, economic growth can gradually promote the urbanization process through the optimization of industrial structure. In the economic space, the above process is the transfer of traditional agriculture to non-agricultural sectors while in the geographical space, it is the agglomeration of elements in cities and the transformation from rural areas to cities and towns[11]. This reallocation of labor force in spatial distribution is the development process of urbanization. Empirical study using various models and techniques is used extensively in describing its integrative relationship, such as spatial economic model and Geographic Information System (GIS). Advance in remote sensing technology in recent years has created conditions for obtaining continuous and comparable urban surface information. In particular, the publication of global long-time series night-time lighting (NTL) data has provided great support for studies on spatial and temporal dynamic of human activities in large scale. Due to the matching of NTL data and human activities, the majority of previous studies applied NTL data to the inversion of population or GDP spatial distribution and the extraction of built-up area. However, there are research gaps in the coevolution between economic development and environmental pollution.

The aim of this paper is to present the interrelations between economic growth and industrial pollution from the perspective of allometric growth. And a allometric analysis model is developed from the empirical study of China's Shandong Peninsula urban agglomeration.

2. DATASETS AND RESEARCH METHODS

2.1 Datasets

The data that is used comes from multi-temporal DMSP-OLS and NPP-VIIRS nighttime light (NTL) remote sensing images from 2003 to 2018 provided by NOAA-NGDC which has been calibrated by Zhang et al.[12], and socioeconomic data from the Chinese National Bureau of Statistics (NBS). In addition, free administrative division data from the National Geomatics Center of China are used to determine the boundaries of study area.

1) *Multi-temporal nighttime light data*

The sensor of Defense Meteorological Satellite Program's Operational Linescan System (DMSP-OLS) was initially designed to detect night clouds, so it is not equipped with on-board calibration. When the sky is cloudless, city illumination can be captured and recorded by the sensor. The overpass time of the satellite is between 19:30 and 21:30. However, due to the defects of sensor design, its data keeps changing gain coefficients according to the dynamic scene luminosity. Furthermore, the obvious lighting overflow causes the lit area in the data larger than actual light source area. The annual DMSP-OLS stable light product can be downloaded from the website of National Oceanic and Atmospheric Administration. It is available from 1992 to 2013, with a spatial resolution of 30 arc seconds and digital numbers (DNs) ranging from 0 to 63.

Comparing with DMSP-OLS NTL images, the monthly composite dataset from NPP-VIIRS has improved spatial resolution (~15 arc s, about 500 m) and radiometric sensitivity (~505–890 nm). It equips with a solar diffuser for on-board calibration. Three different gains stages are used to record the ground illumination under different bright conditions. In the processing phase, according to known coefficients, raw data are converted into radiance. In addition, the overflow in the NPP-VIIRS data is effectively reduced by aggregating and deleting stretched pixels.

In this study, a calibrated NTL data that was composited from two different dataset was used to calculate nighttime light indices in study area from 2003 to 2018.

2) Socioeconomic data and auxiliary data

The boundary data of administrative divisions of Shandong Peninsula urban agglomeration, including provincial, and prefectural boundaries, were obtained from the Chinese National Geomatics Center. The NTL image of study area were extracted from the global datasets by using a mask polygon of provincial boundary.

The industrial pollution emission data (volume of industrial waste water discharged, volume of industrial sulphur dioxide discharged and volume of industrial soot and dust discharged) for each prefectural unit were obtained from the China Statistical Yearbook and the China City Statistical Yearbook. All statistics data were manually checked to ensure accuracy.

2.2 Research methods

1) Nighttime light indices

Two different nighttime light indices were calculated to reflect the general situation in study area.

The total nighttime light (TNL) is total DN value of all pixels in the built-up area, which reflects the generally developmental level in built-up area. Further, it properly combines information of urban land area with the intensity of socio-economic activities. The calculated equation is described by:

$$TNL=\sum_{i=1}^{n} x_i \quad (1)$$

where n is number of pixels while x_i represents the DN value of i-th pixel.

The mean nighttime light (MNL) is average DN value of all pixels in the built-up area, which reflects the average level of social and economic activities. The MNL overcome the limitation of judging development of cities only by the size of built-up area:

$$MNL=\frac{\sum_{i=1}^{n} x_i}{n}=\frac{TNL}{n} \quad (2)$$

where n is number of pixels, TNL represents total nighttime light index that we mentioned above.

2) Allometric model

The law of allometric growth originated from biology and was widely used in the study of urban morphological evolution. The so-called allometric growth means that different parts of a system have different relative rates of growth, but the relative growth rate of each part is constant in a certain period of time. If the system follows the law of allometric growth, the relationship between two parts can be described with following function such as:

$$\frac{1}{y}\frac{dy}{dt}=b\frac{1}{x}\frac{dx}{dt} \tag{3}$$

The above equations can be transformed into power equation by mathematical manipulation:

$$y=ax^b \tag{4}$$

Or converted to the following form:

$$lny=b*lnx+lna \tag{5}$$

where x and y refer to measures of different subsystems, respectively. Two parameters, a and b, refer to the proportionality coefficient and scaling exponent, respectively. The scaling exponent b, also known as allometric growth coefficient or allometric growth intensity, is the ratio of relative growth rate.

Under certain conditions, the above formula may degenerate into logarithmic linear relationship:

$$\mathrm{y=a*lnx+b} \tag{6}$$

Or further degenerate into exponential equation below:

$$y=ae^{bx} \tag{7}$$

In some cases, the allometric model may completely degenerate into linear form:

$$y=ax+b \tag{8}$$

Linear correlation is partially addable, but from the perspective of systematology, an optimized system is partially non-additive. Therefore, the orientation of translating into linear form can mirror degradation of system structure.

In this study, the dimensions of NTL data and statistical data are equivalent, so the threshold of scaling exponent b in the above formulas is 1. If $b> 1$, the relative growth of y is faster than that of x (positive allometry); if $b<1$, the relative growth of y is slower than that of x (negative allometry); if $b= 1$, the relative growth of y is the same as that of x (isometry).

In addition, two kinds of power function regression models with $a=1$ and $a\neq1$ (Eq. 4) were employed to analyze the annual TNL and industrial waste water emission of each prefectural unit from 2003 to 2018, and the coefficient of determination (R^2) of different regression models were compared. The fitting accuracy of the model with $a=1$ is optimal, as shown in Table 1.

TABLE 1. COEFFICIENT OF DETERMINATION OF DIFFERENT MODELS.

City name	R^2 of model ($a \neq 1$)	R^2 of model ($a=1$)	ΔR^2
Jinan	0.557	0.997	0.44
Qingdao	0.501	0.989	0.488
Zibo	0.145	0.971	0.826
Zaozhuang	0.175	0.994	0.819
Dongying	0.462	0.999	0.537
Yantai	0.362	0.995	0.633
Weifang	0.409	0.996	0.587
Jining	0.482	0.993	0.511
Taian	0.241	0.997	0.756
Weihai	0.054	0.985	0.931
Rizhao	0.655	0.998	0.343
Laiwu	0.05	0.986	0.936
Linyi	0.736	0.997	0.261
Dezhou	0.13	0.988	0.858
Liaocheng	0.443	0.996	0.553
Binzhou	0.459	0.996	0.537
Heze	0.585	0.996	0.411

3. RESULTS AND DISCUSSION

3.1 Trend of Nighttime light indices of study area

Using the spatial analysis tools in ArcGIS and the calibrated nighttime light dataset, total nighttime light index (TNL) and mean nighttime light index (MNL) of Shandong Peninsula urban agglomeration were calculated by Eq.1 and Eq.2 to characterize the trend of regional development, as shown in Table 2.

TABLE 2. TOTAL NIGHTTIME LIGHT (TNL) AND MEAN NIGHTTIME LIGHT (MNL)IN SHANDONG PENINSULA URBAN AGGLOMERATION.

Year	Total nighttime light (TNL)	Mean nighttime light (TNL)
2003	17674.31	0.13
2004	19570.60	0.14
2005	18315.55	0.15
2006	21619.54	0.16
2007	22059.00	0.16
2008	22640.37	0.17
2009	23570.11	0.18
2010	27134.76	0.21
2011	23925.92	0.18
2012	25544.83	0.20
2013	28965.51	0.23

2014	22812.67	0.16
2015	23147.40	0.16
2016	22973.70	0.16
2017	25907.84	0.18
2018	27008.34	0.19
2003	17674.31	0.13

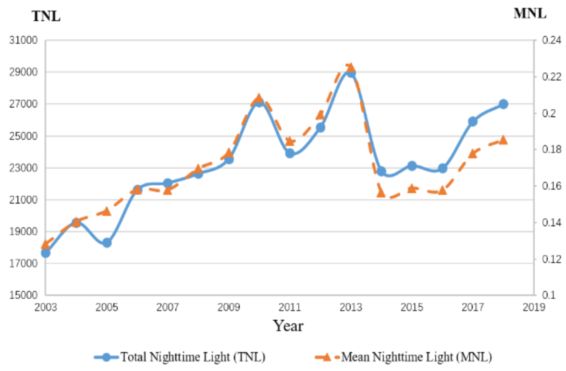

Figure 1. Tendency of TNL and MNL in study area.

Generally speaking, the tendency of the TNL and that of the MTL maintain the same trend in our study (see Fig.1). In addition, compared with initial period (2003), the TNL and MTL at the end of study (2018) increased by 52.8 % and 44.6 %, respectively.

Furthermore, two significant declining points can be located in 2010 and 2013, which is consistent with the policy changes of agglomeration during this period. In 2010, the implementation of *Main Functional Areas Planning in Shandong Province* and its corresponding supporting regulations has resulted in a temporary decline of two nighttime light indices. Similarly, a series of environmental protection and urbanization plans, such as *Air Pollution Control Planning in Shandong Province (2013 – 2020)*, have curbed the upward trend of indices once again and stabilized them in the next few years. However, in 2016, the establishment of Shandong Peninsula Urban Agglomeration has propeled TNL and MTL into a new growth cycle. The gap in decline between TNL and MTL reflects the dramatic sprawl of built-up area in the region after 2016.

3.2 Environmental effects of economic growth

Variables such as GDP per capita and population are wildely used to characterize social and economic conditions of a country or a region. As China's official GDP data has always been aggrated implicitly, the NTL datasets, due to its highly positive correlation with the related production activitiies, are commonly employed to reveal the real economic development level in a region. Therefore, our study uses the annual TNL (explanatory variable) as substitution of the socio-economic development level in the study area. After combining with the volume of main industrial pollutants (explained variables) in the corresponding period, these variable pairs were used to measure the impact of socio-economic activities on the environment. The scaling exponents of collectivity are shown as follows:

TABLE 3. SCALING EXPONENT(B) OF COLLECTIVITY.

Year	b_1*	b_2**	b_3***
2003	1.264	1.618	1.432
2004	1.263	1.625	1.448
2005	1.283	1.657	1.469
2006	1.257	1.614	1.403
2007	1.271	1.602	1.374
2008	1.272	1.586	1.365
2009	1.272	1.571	1.356
2010	1.267	1.539	1.317
2011	1.278	1.588	1.439
2012	1.263	1.566	1.401
2013	1.245	1.5	1.381
2014	1.282	1.572	1.505
2015	1.281	1.557	1.481
2016	1.263	1.49	1.443
2017	1.226	1.389	1.336
2018	1.217	1.32	1.25

* scaling exponent between TNL and industrial waste water emission

** scaling exponent between TNL and industrial sulphur dioxide emission

*** scaling exponent between TNL and industrial soot and dust emission

According to Table 2, there is a sustainly positive allometry among all variable pairs of Shandong Peninsula

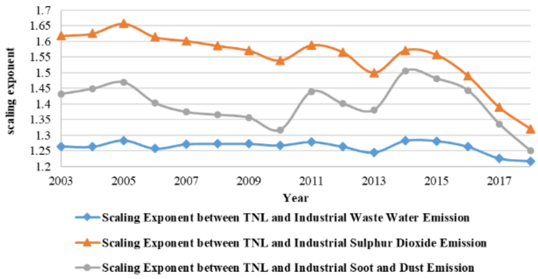

Figure 2. Tendency of scaling exponents between TNL and industrial pollutant emissions.

urban agglomeration. In another words, the relative growth of industrial pollutant emission is faster than that of ni-ghttime light, which indicates that the regional economic activities have brought strongly environmental effects. In terms of different emission types, the scaling exponent of industrial pollutants discharged with exhaust gas (i.e. sulphur dioxide and dust) share analogous trend that both scaling exponents are declining in volatility, meaning that the relation between economic activities and enviro-nmental pollution tends to be coordinated. Furthermore, as b_1 is only slightly higher than the threshold (b = 1), water body is less polluted than air.

The trendencies of all exponents showed in Fig.2 have an obvious periodic characteristic, which is closely related to policy. In stage I (2003-2014), the scaling exp-onents of exhaust gas (b_2 and b_3) showed a U-shaped va-riation, while the undulation of b_2 was not obvious. After2014, with the implementation of *New Urbanization Planning (2014-2020)*, atmospheric pollution control and water resources protection has become a focal point in S-hangdong province. As a result, scaling exponents between TNL and industrial pollutant emissions droped sharply, which means the conflict between economic enh-ancing and environmental pollution was alleviated by rigorous ecological protection measures. The damages to environment caused by urban economic activities are weakening after that.

To further verify the spatial differentiation of economic-environmental allometric growth among prefectural units in study area, the same power functional model based on time series of each city was applied to analyse the allometry at prefectural level. As shown in Table 4, the raletive growth rates of prefectural units (b_1, b_2 and b_3) are higher than threshold, indicating that those variables are keeping positively allometric ralation. In this case, a higher scaling exponent reveals a worst environmental damage.

Fig.3 shows the spatial differentiation of all scaling exponents. It is claerly that all of the scaling exponents in the area have obvious spatial agglomeration feature. Moreover, the values of scaling exponents of Tai'an, Laiwu, Zibo, Binzhou, Dezhou, Zaozhuag and Rizhao are significantly higher than others (see Fig.3), meaning that these cities are much more incoordinated in allometric growth. In another words, the per unit GDP growth of these cities has to pay more environmental cost than others.

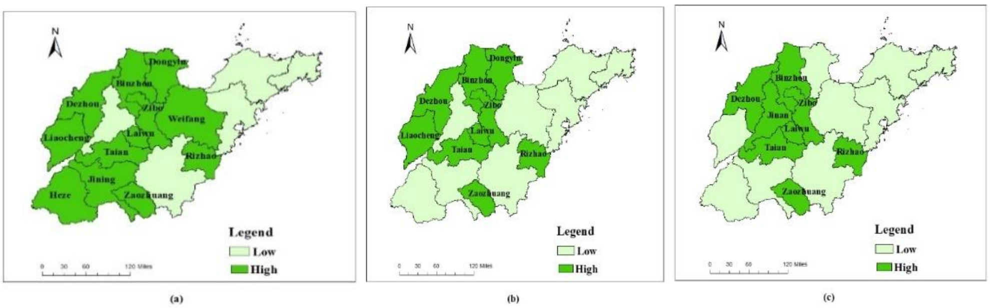

Figure 3. Spatial differentiation of scaling exponents between TNL and industrial waste water, sulphur dioxide and dust emission (a, b and c) in prefectural level.

TABLE 4. SCALING EXPONENT(B) OF PREFECTURAL UNITS.

City name	b_1^*	b_2^{**}	b_3^{***}
Jinan	1.178	1.48	1.402
Qingdao	1.18	1.407	1.275
Zibo	1.353	1.679	1.535
Zaozhuang	1.396	1.644	1.47
Dongying	1.287	1.558	1.265

Yantai	1.184	1.466	1.299
Weifang	1.26	1.465	1.324
Jining	1.28	1.523	1.386
Taian	1.254	1.564	1.414
Weihai	1.145	1.522	1.325
Rizhao	1.356	1.616	1.493
Laiwu	1.255	1.857	1.775
Linyi	1.18	1.464	1.372
Dezhou	1.312	1.598	1.44
Liaocheng	1.335	1.554	1.386
Binzhou	1.328	1.597	1.417
Heze	1.243	1.508	1.393

* scaling exponent between TNL and industrial waste water emission

** scaling exponent between TNL and industrial sulphur dioxide emission

*** scaling exponent between TNL and industrial soot and dust emission

As shown in Fig.3b and Fig.3c, the spatial distributions of b_2 and b_3 are convergent. The air pollution caused by economic activities in Jinan and its surrounding cities (such as Dezhou, Binzhou, Zibo and Laiwu) is significantly higher than that in other cities. Comparing with b_2 and b_3, the lower value of b_1 suggests a better condition that the allometric relation between the increasing rate of wastewater emission and that of economy is more coordinated. Although the value of b_1 is lower, its distribution range of high-value area is apparently wider, effecting the majority of cities. More importantly, the high value area mainly distribute along Yellow River.

4. CONCLUSION

Given the rapid urbanization China has experienced during 21st century， the rapidly increasing intensity of human activities and subsequent pollutant emissions have caused a severe impact on ecological environment around cities. Thus, our study attempts to utilize the relevance between time series nighttime light (NTL) and human economic activities to explore the relative growth rate of different environmental-economical variable pairs. In this way, we can largely avoid possible errors caused by methods that use statistical data only. As an extension of previous research, we firstly analysed general situation in whole study area via caculating the total nighttime light (TNL) and the mean nighttime light (MNL). Then, allometric model was employed to reveal the allometric relations of different environmental-economical variable pairs.

Our results pointed to the existence of a highly positive allometry in both provincial and prefectural level. Particularly, there is a remarkable spatial agglomeration and spatial differentiation in prefectural-level scaling exponent.

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