Exploring the Characteristics and Drivers of Expansion in the Shandong Peninsula Urban Agglomeration Based on Nighttime Light Data

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***Abstract*—This study takes 16 cities in the Shandong Peninsula urban agglomeration as the research object. Based on the nighttime lighting data from 2000 to 2020, the enhanced vegetation-adjusted nighttime light index is constructed on a five-year time scale using the statistical data comparison method to extract the urban built-up area boundaries, built-up area expansion index, and spatial form characteristics. The following findings have been drawn: First, the urban expansion rate, intensity, and compactness of the cities in the study area are characterized by a year-on-year decline. Jinan and Qingdao show a double-core pattern of urban expansion. In the first stage, the intensity of built-up area expansion is the strongest, and the compactness also shows a decreasing annually trend from the southwest to the northeast. Second, the highest percentage of sprawl is edge expansion with the main urban areas of cities dominated by edge expansion, while counties have a high percentage of outlying. Third, the northern coastal areas of the city's center of gravity and the cities of southern Lunan show varying degrees of divergent trends. The center of gravity of the cities around Jinan is characterized by local concentration, and the mutual attraction of the cities of Weifang and Qingdao is increasing. Fourth, based on the analysis of the center of gravity-GTWR, the main drivers of speed expansion are fiscal and economic, population education, transportation, and urban facilities construction. The compactness expansion drivers are financial, medical, population, transportation, education, and urban construction. The drivers are characterized by a more pronounced spatiotemporal heterogeneity.**

***Index Terms*—Built-up area expansion, nighttime light (NTL) data, Shandong Peninsula urban agglomeration, the center of gravity-temporally weighted regression (GTWR).**

I. Introduction

URBANIZATION is characterized by population growth and land use change. Since the 1980s in China, the rural population has flocked to cities, and China's urban residents have increased from less than 20% in 1978 to 63.89% in 2020. A vast population has accumulated in city areas, forcing the city to expand its land coverage. New urban encroachment on the existing land destroys its natural state and landscape pattern [1], causes biodiversity loss due to environmental alteration of habitats [2], [3] and destabilizes the original ecosystem [4]. Dense urban populations drive the expansion of urban boundaries outward, compressing rural arable land and leading to food security problems [5], [6]. The growth of city land is attracting more labor from villages into cities; city factories emit gases containing sulfur and nitrogen into the atmosphere, causing severe damage to the environment and water [7], [8]. The ecological carrying capacity of cities is seriously threatened [9]. The city's inner area is mainly covered by impermeable surfaces, which absorb heat and reflect less, inhibiting greenhouse gas discharges and creating an urban heat island phenomenon [10], [11], [12].

Urban boundary expansion is an obvious indicator of urbanization [13]. Currently, there are no uniform standards for defining urban boundaries in China. According to the city boundary defined by Cai and Zhang [14], the first type of urban boundary is the administrative area boundary, a statistical unit in Chinese government statistics. The second type of boundary is the urban center boundary, which is densely populated and where economic activities are well connected. The third type refers to population densities greater than 1500 people/area. In (GB/T50280-98), the urban built-up area is defined as the urban contiguous development within the administrative boundary of a city and refers to the area where the city is developed continuously and where municipal utilities are complete. The boundaries of the built-up area emphasize the natural attributes of the surface and the economic attributes of the above-ground population activities; thus, we choose the built-up area boundary of urban areas as a measure of urbanization.

The two most commonly used datasets are the Defense Meteorological Satellite-Program Operational Linescan System (DMSP-OLS), which has a spatial accuracy of 1000 m but was discontinued in 2013, and the National Polar-Orbiting Partnership-Visible Infrared Imaging Radiometer Suite (NPP-VIIRS), which has a spatial resolution of 500 m and has been operating and recording Earth lighting activity since 2012. Nighttime light (NTL) captures the faint light emitted from the ground, and it serves as a class of remote sensing data that can dynamically detect the luminescence of human activity on the ground over a long time series. Currently, nighttime lighting data are mainly used in analyzing the spatial structure of cities, classifying urban hierarchies, identifying urban agglomerations [15], [16], [17], evaluating the parameters of social indicators, such as population, GDP [18], [19], detecting environmental

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safety [20], and evaluating major emergencies, such as armed conflicts [21], [22]. Sutton et al. [23] first extracted urban areas of different natures after setting different lighting threshold values using DMSP-OLS, after which time NTL was widely used to extract urban areas. Zhang and Su [24] studied 30 metropolitan areas in China using DMSP-OLS to quantitatively analyze the speed and intensity of urban expansion. With the introduction of the NPP-VIIRS, the NTL withdrawal city time frame was extended. Liu et al. [25] fitted DMSP-OLS to NPP-VIIRS to extract urban sprawl dynamics in China and found that the fitted data were more stable. Zhang et al. [26] used a centroid model to plot the range of the urban center of gravity movement for Beijing, Tianjin, and other places to quantitatively visualize the direction of city dilation. Using a landscape sprawl model, Gong [27] found that the three land sprawl models work together to show a spiral urban sprawl process for the sprawl of the Guangzhou conurbation.

In a study of the drivers behind urban sprawl, Liu et al. [28] argued from a qualitative theoretical perspective that urban sprawl in China is closely linked to national land policies and economic development. Deng [29] used an empirical model for quantitative analysis and found that economic booms have a marked influence on urbanization expansion. City sprawl is a geographical phenomenon, and the factors behind the expansion can be explained with relatively little error from a spatial analysis perspective. Müller et al. [30] used the analysis of variance and spatial autocorrelation methods for Sweden and concluded that high-speed junctions have a positive impact on urban sprawl. However, the reality is that urban sprawl drivers change in both time and space [31]. While the analysis of urban sprawl drivers now lacks a common analysis of spatiotemporal dimensions, spatiotemporal geographically weighted regression overcomes the neglect of spatiotemporal consistency in previous studies [32].

This article focuses on the "growing" Shandong Peninsula Cities Cluster and uses NTL to describe built-up areas. The spatiotemporal perspective of the sprawl pattern is used to study its sprawl characteristics, and the center of gravity-temporally weighted regression (GTWR) analysis is used to explore the drivers of built-up area sprawl. The objectives of this article are as follows: First, to map the spatial coverage of the city center of the study region using NTL data; and second, to analyze city growth from time dilation indices and spatial evolution characteristics. For the speed and compactness of urban spreading, the center of gravity-GTWR is used to analyze the driving factors. The research in this article will provide an effective basis for decision making on town planning and land management in the Shandong Peninsula Cities Cluster.

II. Study Area and Data

A. General Information About the Research District

The Shandong Peninsula urban agglomeration (see Fig. 1) is bordered by the North China Plain to the west, the Bohai Sea to the north, and the Yellow Sea to the east. The natural environment within the Shandong Peninsula urban agglomeration is predominantly mountainous and hilly, consisting of four major topographic areas: the Luxibei Plain, the Luzhong Hilly Plain, the Jiaolai Plain, and the Jiaodong Hilly Plain. By the end of 2020, the total number of people in the study area was approximately 101.65 million. Fig. 1 illustrates the structure of the division within the Shandong Peninsula Cities Cluster. According to Zhang and Wang [33], Shandong is divided into Ludong, Luzhong, Luxi, and Lunan based on the geographical location and economic linkages within Shandong cities (see Fig. 1).

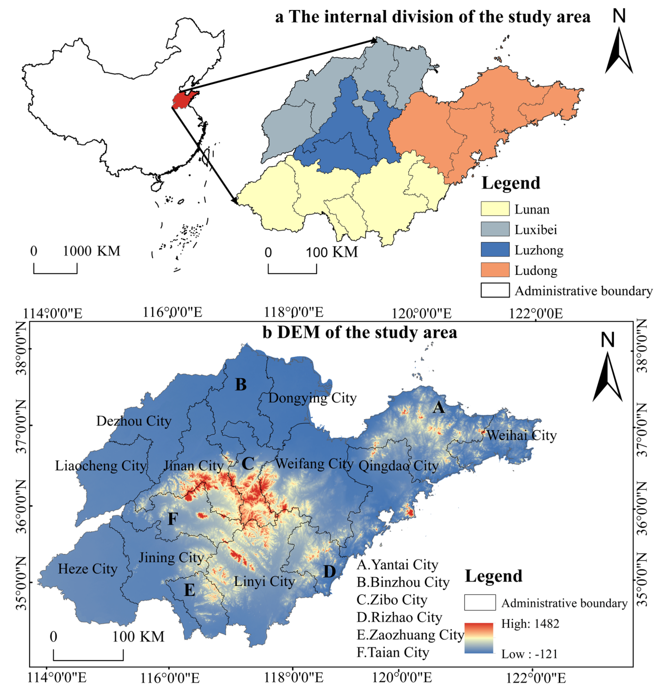

Fig. 1. Information on the location of the research district.

B. Data Sources and Preprocessing

Table I presents the study data. This includes the name of the data, the source, the access URL, and the accuracy of the data. The NTL data were obtained from the dataset of Wu et al. [34]. The study was corrected with DMSP-OLS and NPP-VIIRS, which then predicted NTL, filled in missing data, and fitted the two types of data. This method showed an improved performance for nighttime lighting data. The enhanced vegetation index (EVI) is a remote sensing data for monitoring vegetation that improves on the normalized difference vegetation index (NDVI), which overcomes the NDVIs susceptibility to saturation and atmospheric and soil disturbances [35]. EVI data source annual average values were downloaded from the Google Earth engine (GEE). GEE has great potential in dealing with data processing in the future [36]. The administrative boundary data source is the National Geographic 1:1 million National Basic Geographic Database. The area of built-up area data is from the Shandong Statistical Yearbook and China Urban Construction Statistical Yearbook. Table II presents basic geographical and economic information on the individual cities of each municipal group. Table II presents the data collected from the 2021 Statistical Yearbook data for each city.

TABLE I
SHANDONG PENINSULA CITY CLUSTER STUDY DATA

Data	Source	Website	Precision
NTL	DMSP-OLS data set(1992-2021)	https://dataverse.harvard.edu/dataset.xhtml?persistentId=doi:10.7910/DVN/GIYGJU	1000
EVI	GEE(Google Earth Engine)	https://earthengine.google.com/	250
Administrative boundaries	National Geographic 1:1 million national basic geographic database	https://earthengine.google.com/	
Area of built-up area	Shandong Provincial Statistical Yearbook and China Urban Construction Statistical Yearbook	http://tjj.shandong.gov.cn/tjnj/nj2021/zk/indexce.htm;https://www.mohurd.gov.cn/index.html	

TABLE II
BASIC GEOGRAPHICAL AND ECONOMIC INFORMATION ON THE SHANDONG PENINSULA URBAN AGGLOMERATION

City	Longitude(E)	Latitude(N)	Altitude(m)	Area(km^2)	GDP(100 million yuan)	Population (10000 people)
Jinan	116°21′~117°93′	36°02′~37°54′	6~1481	10244	10140.91	920.24
Qingdao	119°30′~121°00′	119°30′~121°00	-5~708	11293	12400.56	1007.17
Zibo	117°3′~118°31′	35°55′~37°17′	-1~1045	5965	3673.54	470.56
Zaozhuang	116°48′~117°49′	34°27′~35°19′	28~38	4564	1733.25	385.86
Dongying	118°07′~119°10′	36°55′~38°10′	1~11	8243	2981.19	219.35
Yantai	119°34′~121°57′	36°16′~38°23′	-2~877	13865	7816.42	710.21
Weifang	118°10′~120°01′	35°41′~37°26′	4~168	16167	5872.17	938.67
Jining	115°52′~117°36′	34°26′~35°57′	27~588	11000	4494.31	836.07
Taian	116°20′~117°59′	35°38′~36°28′	20~1481	7762	2766.46	547.85
Weihai	121°11′~122°42′	36°41′~37°3′	-3~402	5800	3017.79	291.46
Rizhao	118°25′~119°39′	35°04′~36°04′	1~706	5359	2006.43	296.84
Linyi	117°24′~119°11′	34°22′~36°13′	-2~1059	17191	4805.25	1102.57
Dezhou	115°45′~117°36′	36°24′~38°0′	7~927	10356	3078.99	561.36
Liaocheng	115°16′~116°32′	35°47′~37°02′	22.6~49	8628	2316.84	595.25
Binzhou	117°15′~118°37′	36°41′~38°16′	1~826	9660	2508.11	393.03
Heze	114°45′~116°25′	114°45′~116°25′	37~68	12239	3483.11	879.9

NTL data and EVI were extracted from the study area using an administrative boundary data mask. The raster calculator of ArcGis was used to remove the pixels with EVI less than 0.01 to avoid interference with the subsequent experiments, which were mainly water body and water body mixed pixels. The NTL dataset and EVI dataset were all projected to WGS-UTM-1984.

III. METHOD

In this article, NTL and EVI are extracted using an administrative boundary data mask to construct the enhanced vegetation-adjusted nighttime light index (EANTLI), built-up area data are collated from the Shandong Statistical Yearbook, and the scope of the EANTLI built-up area is extracted using the dichotomy method. The calculation of urban expansion index and urban space type includes expansion speed, expansion intensity, expansion compactness, urban center of gravity migration, and expansion type. The center of the GTWR model was used to analyze the economic, demographic, and other data from the statistical yearbook to analyze the drivers of the built-up area. The detailed process is shown in Fig. 2.

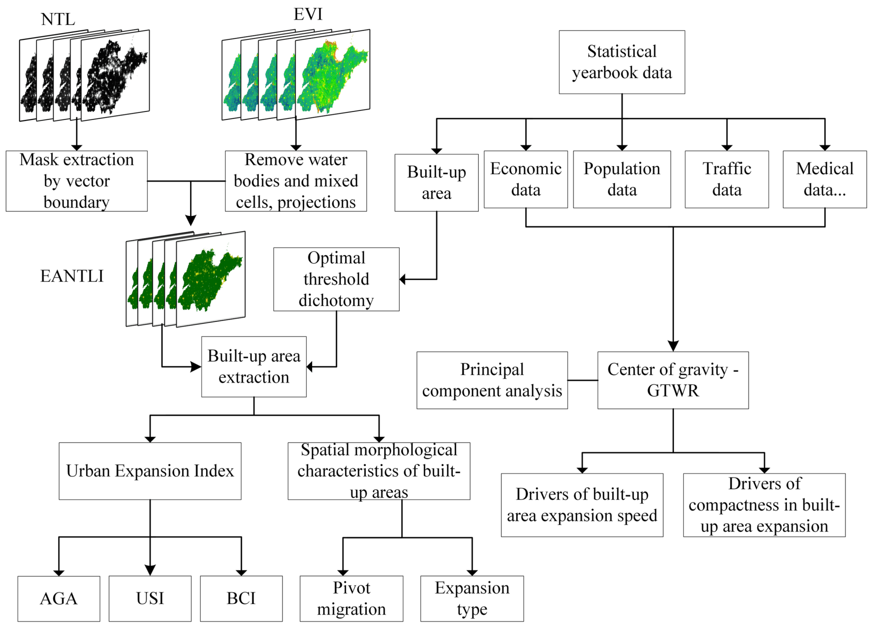

Fig. 2. Technology roadmap.

A. Construction of the EANTLI Index and Build-Up Extraction

1) Construction of the EANTLI Index: The EANTLI was proposed by Zhuo et al. [35] to correct NTL saturation data. The index exploits the decreasing brightness of nighttime lighting data from inner city to suburban areas, which parallels an increase in vegetation, to construct a saturation index to moderate NTL data. The equation is given as follows:

$$\mathrm{EANTLI} = \left[\frac{2}{1-(\mathrm{NTL_{nor}}-\mathrm{EVI})}-1\right] * \mathrm{NTL} \quad (1)$$

$$\mathrm{NTL_{nor}} = \frac{\mathrm{DN}-\min}{\max-\min} \quad (2)$$

where $\mathrm{NTL_{nor}}$ is the normalized nighttime light data and EVI is the enhanced vegetation index (mixed pixels less than 0.01 have been removed).

2) Threshold Method to Extract Built-Up Areas: Built-up areas were extracted utilizing the statistical data comparison method with reference to 2001, 2006, 2011, 2016, and 2021 Shandong Statistical Yearbook data and urban area in the China Urban Statistical Yearbook. This method allows simple and fast extraction of urban areas [37].

B. Urban Expansion Index

1) Speed of Extension of Study District: The urban extension rate indicator was chosen to measure the growth of the city coverage area, reflecting city growth rates. AGA is the ratio of the difference between the urban area of the current period and the urban area of the previous period to the time interval [38]

$$\mathrm{AGA} = \frac{U_{m+n}-U_m}{n} \quad (3)$$

where AGA is the rate of built-up area expansion and U_{m+n} denotes the urban built-up area in year $m+n$. n is the study scale interval in years.

2) Intensity of Study District Expansion: The expansion rate (AGA) cannot quantitatively describe the dynamic level of urbanization. The urban sprawl intensity (USI) is applied to reflect the strength of urbanization, making urbanization comparable across years. USI is the ratio of the incremental built-up area to the base area [39]

$$\mathrm{USI} = \frac{\mathrm{UA}_{n+i}-\mathrm{UA}_n}{n\mathrm{UA}_i} \times 100\% \quad (4)$$

where USI is the urban sprawl intensity, UA_{n+i} is the urban area of the city in year $n+i$ and UA_n is the urban area of the city in year n. n is measured in years as a time interval.

3) Compactness of Study District Growth: While sprawling cities result in the waste of vast resources, compact urban development does not spread urban resources too thinly, allowing the ecological economy to maintain a sustainable state of development. In this study, the urban compactness index (BCI) was selected to measure urban compactness [40]

$$\mathrm{BCI} = \frac{2\sqrt{\pi * A}}{P} \quad (5)$$

where BCI is the city density index, A is the area of the build-up area, and P is the perimeter of the build-up area. The BCI index ranges from 0 to 1; if the BCI index is closer to 1, and the built-up area is more compact.

C. Built-Up Area Landscape Expansion Index (LEI)

1) Landscape Expansion Index: The types of urban sprawl proposed by Liu et al. [41] can be classified into three types according to the range of values of the LEI: outlying, infilling, and edge expansion. Outlying is a new urban extension that does not overlap with the original urban extent and is a new patch independent of the original urban patch. Edge expansion means that the new growth overlaps with the existing urban patches and expands outward along the existing urban patches. Infilling

TABLE III
DRIVING FACTOR

Indicator	Variables	Unit	Indicator	Variables	Unit
Resident population	x_1	million people	Road density	x_{11}	km/100 sq.km
Gross regional product	x_2	billion	Road mileage	x_{12}	km
Fiscal expenditure	x_3	billion	Total water supply	x_{13}	million cubic metres
Fiscal revenue	x_4	billion	Length of water supply pipes	x_{14}	km
University students	x_5	million people	Total electricity supply	x_{15}	million kwh
Econdary school students	x_6	million people	Green area	x_{16}	hectares
Primary school students	x_7	million people	Medical institutions	x_{17}	units
Park area	x_8	hectares	Health staff	x_{18}	million people
Road length	x_9	kilometres	Hospital beds	x_{19}	million
Road area	x_{10}	million square metres			

refers to new patches that fill in undeveloped areas within the original city limits within the original urban patches. Research options are used to explore the types of dynamic urban spatial expansion. Its expression is as follows: Patch is the portion of the buffer zone that intersects the original built-up area

A is the difference between the area of the new buffer and the area [43]

$$\text{LEI} = 100 \times \frac{A_M}{A_M + A_N} \tag{6}$$

where LEI is the built-up area patch expansion index. Depending on the value of LEI, different landscape sprawl patterns are classified. If $0 \leq \text{LEI} < 2$, the landscape sprawl pattern is outlying, $2 \leq \text{LEI} < 50$, the landscape sprawl pattern is edge expansion, and $50 \leq \text{LEI} \leq 100$, the landscape sprawl pattern is infilling. Referring to Liu, the buffer area is set to 200.

2) Relocation of the City's Center of Gravity: The term center of gravity is derived from a mechanical concept in physics and refers to the point in space where an object is subjected to forces in all directions and can reach equilibrium. As cities grow, they are affected by natural and human-made factors that can shift the focus of urban development [42]. Computing the center of gravity of the area at different stages of time reflects the direction of the spatial extension of the urban area, its development trajectory, and the distance the center of gravity has moved. The formula for the center of gravity of a city is given as follows:

$$X_t^m = \frac{\sum_{i=1}^{n} (C_i^m \times X_i)}{\sum_{i=1}^{n} C_i^m}, \quad Y_t^m = \frac{\sum_{i=1}^{n} (C_i^m \times X_i)}{\sum_{i=1}^{n} C_i^m} \tag{7}$$

where C_i^m is the area of the urban of space unit *n* in year *m*, and X_i and Y_i are the central latitude and longitude coordinates, respectively, of the urban *i*.

D. Center of Gravity-GTWR Model

GTWR is an extension of GWR [43], introducing a time factor into the spatial analysis, which can explain the driving forces of the evolution of a region with the expression [32]

$$Y_i = \beta (X_i + Y_i + T_i) + \sum \beta_k (X_i + Y_i + T_i) X_{ik} + \varepsilon_i \tag{8}$$

where Y_i is the dependent variable and (X_i, Y_i, T_i) are the constant terms in the GTWR model; $\beta_0(X_I, I, T_i)$ is the regression coefficient at the *i*th sample point; $\beta_k(X_i^m, Y_i^m, T_i)$ is the mean weight of the model function at the space–time coordinates (X_i^t, Y_i^t, T_i); X_{ik} is the result of the standalone variable X_k at point *i*; and ε_i is the random error term at the *i*th sample point.

TABLE IV
DOMINANT FACTORS FOR PRINCIPAL COMPONENT VARIABLES

Classification	Principal components	Principal components	Dominant directions
Phase	F1	X_2、X_3、X_4、	economy
	F2	X_{11}、X_{12}	transport
	F3	X_{17}、X_{19}	health
	F4	X_6、X_7	education
	F5	X_{13}、X_{14}、X_{15}	urbanism
Continuous	F1	X_2、X_3、X_4、X_{17}、X_{18}、X_{19}	economy & health
	F2	X_1、X_6、X_7	population education
	F3	X_{11}、X_{12}	transport
	F4	X_{14}	urbanism

In this study, 19 drivers were selected with reference to relevant studies, mainly in the areas of population, economy, education, healthcare, transport, and urban development (see Table III).

In this research, the speed of city expansion and compactness are chosen as the dependent variables for the center of gravity-GTWR. The speed of expansion degree is a stage-specific independent variable, using the difference between the data from the previous period and the data from the next period. We chose to use the density of urban extension as a continuum to represent the variable and measured it using current year data. To avoid the problem of multicollinearity in the independent variables, principal component analysis was used (see Table IV). Divided into two categories of drivers, phases and persistent drivers. The main components of the phase are F1-Finance,

TABLE V
BUILT-UP AREA EXTRACTION ERROR ANALYSIS

City	2000			2005			2010			2015			2020		
	M/km^2	R/km^2	Re/%	M/km^2	R/km^2	Re/%	M/km^2	R/km^2	Re/%	M/km^2	R/km^2	Re/%	M/km^2	R/km^2	Re/%
Jinan	158.0	157.1	0.6%	325.9	323.4	0.8%	444.6	442.0	0.6%	559.4	557.0	0.4%	800.7	793.7	0.9%
Qingdao	210.1	212.6	-1.2%	367.2	369.0	-0.5%	510.3	507.3	0.6%	769.5	770.0	0	952.7	953.1	-0.1%
Zibo	149.6	146.6	20.0%	191.8	190.3	0.8%	223.9	224.5	-0.3%	269.0	267.0	0.8%	294.2	292.6	0.6%
Zaozhuang	93.5	92.85	0.7%	157.9	154.6	2.1%	164.9	164.7	0.2%	206.2	205.0	0.5%	201.2	200.9	0.1%
Dongying	58.2	58.0	0.3%	85.3	85.1	0.2%	107.3	108.1	-0.7%	118.3	118.7	-0.3%	152.4	153.3	-0.6%
Yantai	201.0	202.0	0.5%	329.0	328.9	0.1%	490.0	490.0	0	561.9	560.5	0.3%	623.9	623.5	0.1%
Weifang	162.4	161.8	0.4%	297.6	299.9	-0.7%	375.9	372.4	0.9%	445.0	451.5	-1.4%	485.1	485.5	-0.1%
Jining	82.6	81.7	1.0%	145.0	144.4	0.5%	182.3	180.9	0.8%	274.0	267.9	2.3%	322.4	321.0	0.4%
Taian	42.3	41.2	2.6%	164.0	162.7	0.80%	201.2	200.9	0.2%	243.5	238.9	1.9%	283.7	280.2	1.3%
Weihai	91.9	92.3	-0.4%	159.9	161.3	-0.9%	247.8	247.5	0.1%	276.8	277.1	-0.1%	292.8	292.7	0.1%
Rizhao	35.1	35.2	-0.4%	58.1	58.3	-0.3%	91.2	89.8	1.5%	101.2	100.8	0.4%	125.2	124.7	0.4%
Linyi	55.2	55.0	0.4%	143.5	139.8	2.7%	166.6	165.7	0.6%	214.8	213.0	0.8%	252.9	258.9	-2.3%
Dezhou	34.3	33.1	3.5%	81.6	81.4	0.3%	119.9	118.3	1.3%	218.6	217.9	0.3%	236.7	235.2	0.7%
Liaocheng	60.5	59.1	2.4%	74.7	73.7	1.3%	91.8	91.7	0.1%	127.1	126.2	0.8%	209.9	205.7	2.0%
Binzhou	21.1	21.3	-1.0%	52.2	51.8	0.8%	85.4	85.5	-0.2%	138.6	138.3	0.2%	198.8	198.8	0
Heze	36.4	35.9	1.3%	51.5	51.2	0.7%	76.8	76.6	0.2%	101.1	99.6	1.5%	208.2	206.8	0.7%

F2-Transport, F3-Health, F4-Education, and F5-Urban Development. The continuous independent variable is made up of four principal components, F1 for economic healthcare, F2 for population education, F3 for transport, and F4 for urban construction. The indicators were divided by the principal component method and analyzed using a geographically weighted regression of the center of gravity to explore the drivers of built-up area expansion.

E. Accuracy Evaluation

This study will use the optimal threshold method to extract the built-up area values for error analysis with the statistical yearbook data [44]

$$R_e = \frac{M - R}{M} \tag{9}$$

where *M* is the built-up area extracted at the optimal threshold, *R* is the built-up area in the statistical yearbook, and R_e is the relative error.

IV. ANALYSIS OF RESULTS

A. EVI Reduces the Saturation of DMSP-OLS

The EVI distribution is a reflection of the vegetation cover on the ground, while the NTL is a reflection of the area of human activity. The distribution of EVI is negatively correlated with the distribution of NTL and this relationship is used to reduce the saturation of light at night using EVI.

A vertical profile of NTL from Qingdao city from west to east through Jiaozhou, Chengyang District, and Laoshan District is shown in Fig. 3. Overall, the curves for NTL without saturation and NTL with saturation follow essentially the same trend. The DN value of the NTL with the saturation curve remains at 63 in the city, showing high saturation, while in the suburban or rural vicinity, the DN value is largely below 63. The NTL without saturation addresses this flaw. In the urban high-value area showing richer spatial detail within the city, the corrected nighttime lighting data rise from west to east, from the outskirts of Jiaozhou to a pixel value of 1000 in the city center, drops to 150 in the outskirts of Chengyang, and shows a fluctuating rise in the city center of Chengyang, first to 500 and then down by approximately 50 units of pixel value, with the DN rising again to 800 and then to 1000, accompanied by a steady decline in the DN away from the city center. The DMSP-OLS saturation problem is improved.

B. Built-Up Area Extraction and Extended Feature Analysis

1) Built-Up Area Extraction and Accuracy Verification: Table V presents the relative error between the results of the built-up areas extracted from the Shandong Peninsula Urban Agglomeration and the results of the Statistical Yearbook from 2000 to 2020. The largest relative error is 3.5% in Dezhou in 2000, 60 relative errors are within 1%, and only 8 relative errors are over 2%. Overall, it is feasible to extract built-up areas using NTLs with EVI correction.

Since 2000, the research area has undergone dramatic changes. The built-up area of Shandong Province increased by more than 1000 km^2 every five years over 2000–2020, with the exception of 2005–2010, when an additional 899.1 km^2 were added, and the first phase of the increase was as high as

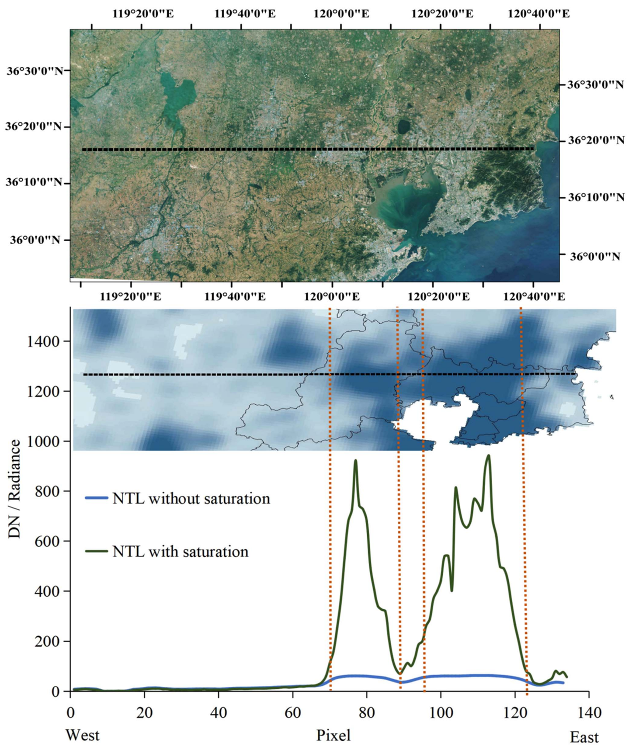

Fig. 3. Analysis of latitudinal samples of NTL with a resolution of 1000 m.

TABLE VI
BUILT-UP AREA EXPANSION DATA AT VARIOUS TIMES

Pirod	Added area(km^2)	AGA	USI	Pirod	BCI
2000-2005	1295.60	16.13	24%	2000	0.41
2005-2010	899.10	11.21	7%	2005	0.35
2010-2015	1032.39	12.84	6%	2010	0.26
2015-2020	1048.91	13.05	6%	2015	0.31
				2020	0.24

1295.6 km^2 (see Fig. 4) and Table VI presents the overall area of new built-up area in the study area over different periods of time, AGA, USI, and BCI.

2) Analysis of Spatial Differences in Expansion Indices by City:

a) During the period 2000–2005, the average rate of city expansion reached 16.13. The intensity of town sprawl was 24%, and the average compactness of city expansion decreased from 0.41 to 0.35. Between 2005 and 2010, the rate of city expansion fell by 4.92% to 11.21. The intensity of urban expansion is around one-third less in the current phase than in the previous phase, at 7%. The compactness of urban expansion decreased by 0.06 compared with the previous period. Between 2010 and 2015, the speed of urban expansion increased slowly by 1.63–12.84. The intensity of city expansion decreased by 1%. The BCI increases by 0.05–0.31 at this stage. Between 2015 and 2020, the rate of urban expansion showed a small increase to 13.05, the intensity of expansion remained at 6%, and the compactness decreased to 0.24 (see Table VI).

b) Table VII presents the rate, intensity, and compactness of urban sprawl in cities in Shandong Province at five-year intervals. The AGA, USI, and BCI vary from one city to another due to different natural conditions, economic bases, and governmental development orientations. Fig. 5 shows the spatial distribution of morphological expansion in built-up areas. The rate of spatial expansion in Qingdao and Jinan is characterized by a dual-core spatial layout, with the average rate of expansion of the two cities reaching 30%, mainly because Jinan is the political center of Shandong Province, which attracts the provincial workforce by bringing together political and economic factors, and due to the proximity of Qingdao to Japan and South Korea and the development of foreign investment and trade. It is easier to promote urban outward expansion. In contrast, the extension rate in the northwestern part of Lunan is lower and has a tendency to slow year by year. Among them, Rizhao and Dongying are expanding at a rate of only approximately 4%. These regions have little foreign trade investment, a relatively weak industrial base, and a serious outflow of labor [45].

c) The intensity of expansion of the cities in 2000–2005 was generally higher than that in the last three phases. The expansion intensity of Jining and Taian cities in this phase reached 60%, while that of Zibo city reached 3.72%. Zibo city is a traditional industrial city, facing some difficult problems of industrial transformation, and the city development drive is insufficient. Dongying is a sensitive ecological zone in the Yellow River Delta to the north and has the smallest population of any of the 16 cities, with just over 2 million people in the city. As a result, Dongying's expansion has been slow.

d) The level of urban compactness decreases from cities in the southwest to cities in the northeast of the study area. The various USIs show a general downward trend over the past 20 years. Qingdao and Yantai have lower average compactness levels of 0.18 and 0.2, respectively. Qingdao has a low compactness level of 0.2 because of topographic constraints and the excessive pace of urban development, which has resulted in a more fragmented built-up area. Urban growth is more dispersed because of the topographical constraints of Qingdao and Yantai and the rapid rate of urban expansion.

C. Urban Spatial Expansion Patterns

1) Built-Up Area LEI: Table VIII shows the percentage of the three types of expansion in the built-up areas of Shandong Province over the time interval studied. Over the study period, the overall trend of outlying shares has been upward, then downward, and finally fluctuating upward again. In the second period, it rose from 24.18% to 28.66%, then fell back to 9.32% overall

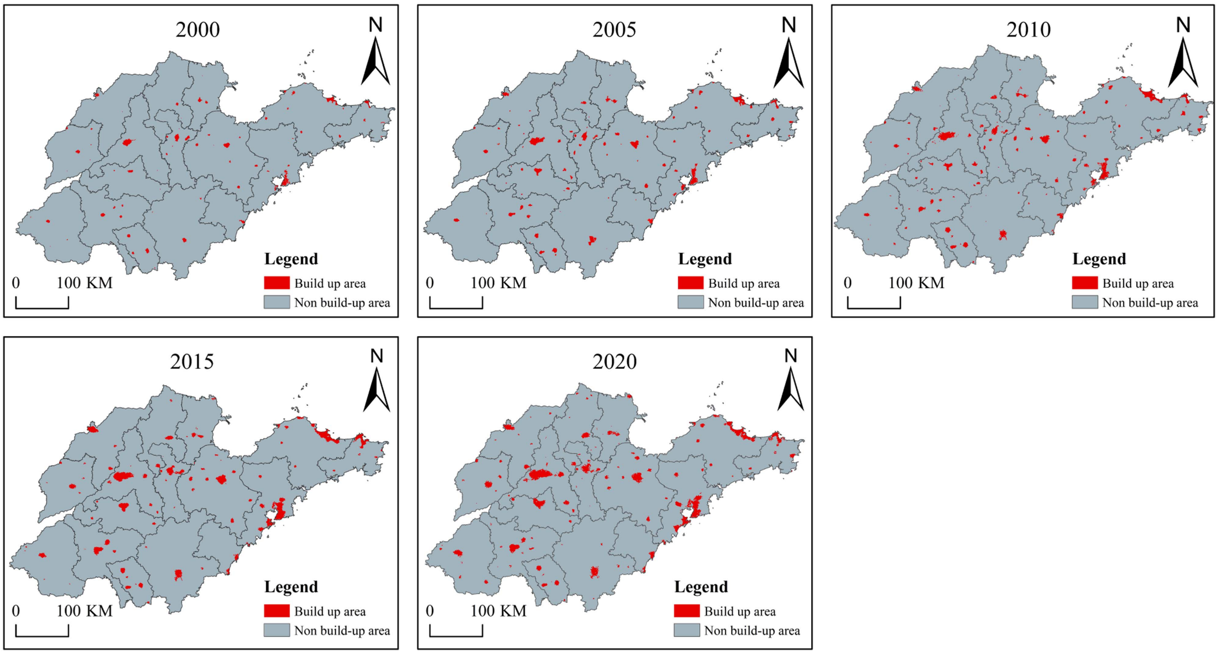

Fig. 4. Spatial mapping of urban areas by period.

TABLE VII
URBAN EXPANSION INDEX WITHIN THE SHANDONG PENINSULA URBAN AGGLOMERATION

City	AGA				USI				BCI				
	2000-2005	2005-2010	2010-2015	2015-2020	2000-2005	2005-2010	2010-2015	2015-2020	2000	2005	2010	2015	2020
Jinan	33.4	23.6	22.8	48.0	21.3%	7.3%	5.2%	8.6%	0.46	0.31	0.24	0.29	0.20
Qingdao	31.4	28.6	51.8	36.6	15.0%	7.8%	10.2%	4.8%	0.19	0.22	0.16	0.19	0.14
Zibo	8.4	6.4	9.0	5.0	5.6%	3.4%	4.0%	1.9%	0.34	0.27	0.23	0.27	0.18
Zaozhuang	16.7	2.0	8.1	3.2	23.5%	1.3%	4.9%	1.6%	0.44	0.36	0.31	0.34	0.30
Dongying	6.6	4.2	2.0	6.8	12.0%	4.8%	1.8%	5.7%	0.34	0.34	0.26	0.28	0.24
Yantai	25.6	32.2	14.4	12.4	12.7%	9.8%	2.9%	2.2%	0.23	0.21	0.20	0.22	0.17
Weifang	27.0	15.6	13.8	8.0	16.7%	5.3%	3.7%	1.8%	0.30	0.28	0.21	0.24	0.19
Jining	21.6	7.4	16.4	11.6	60.0%	5.1%	9.1%	4.4%	0.43	0.35	0.25	0.39	0.25
Taian	24.4	7.6	7.6	8.2	59.5%	4.7%	3.8%	3.4%	0.49	0.34	0.28	0.41	0.34
Weihai	13.6	17.6	5.8	3.2	14.8%	11.0%	2.3%	1.2%	0.25	0.26	0.23	0.23	0.20
Rizhao	4.6	6.6	2.0	4.8	13.1%	11.4%	2.2%	4.8%	0.55	0.45	0.29	0.31	0.31
Linyi	17.6	5.0	9.6	7.8	32.9%	3.6%	5.8%	3.7%	0.47	0.38	0.26	0.28	0.21
Dezhou	9.6	7.4	20.0	3.4	29.1%	9.1%	16.9%	1.6%	0.57	0.40	0.30	0.40	0.25
Liaocheng	8.4	3.6	7.0	16.0	27.1%	4.9%	7.7%	12.7%	0.49	0.39	0.31	0.30	0.25
Binzhou	6.2	6.6	10.6	12.2	29.5%	12.7%	12.5%	8.8%	0.58	0.40	0.34	0.37	0.26
Heze	3.0	5.0	4.6	21.6	8.3%	9.8%	6.1%	21.8%	0.48	0.60	0.34	0.38	0.27

between 2010 and 2015, before fluctuating slightly upward to 12.84% in the final period. The trend in edge expansion was the opposite of enclave expansion, falling, then rising, and finally falling. It declined from 74.65% to 69.74% between 2005 and 2010, then increased to 89.66% in the following five years, before falling to 85.19% in the final period. The share of infilling fluctuates at only approximately 1%.

In the early 2000s and 2005s, outlying development dominated in some urban centers and county-level city centers, such as in Luzhong. In contrast, urban centers in the Ludong, Lunan, and Luxibei regions were dominated by edge expansion, while county-level cities were dominated by outlying. Between 2005 and 2010, the vast majority of cities focused on peripheral development, with only the city center of Dezhou exhibiting outlying, while other urban county centers experienced sporadic outlying. From 2010 to 2015, outlying occurred in the Qingdao, Weihai, and Zibo city centers, with edge expansion in all other areas. From 2015 to 2020, all urban centers were developed at their edges. In most of the county-level centers, edge expansion became the main type of expansion. Infilling occurred only in Liaocheng and Zibo (see Fig. 6).

2) Urban Center of Gravity Shift and Influencing Factors: The center of gravity of cities generally expands to areas with a high level of economic development and areas with a high rate

TABLE VIII
TYPE OF CITY EXTENSIONS AT DIFFERENT STAGES

Period	2000-2005	2005-2010	2010-2015	2015-2020
Outflying	24.18%	28.66%	9.32%	12.84%
Edge-expansion	74.65%	69.74%	89.66%	85.19%
Infilling	1.17%	1.60%	1.02%	1.97%

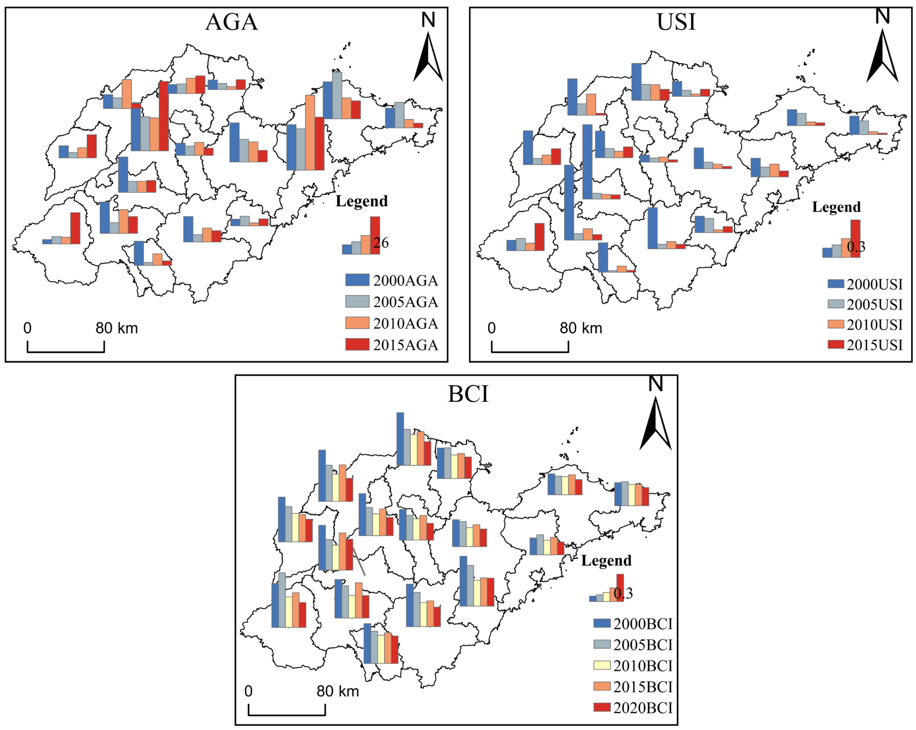

Fig. 5. Spatial distribution characteristics of city expansion indices within the Shandong Peninsula City cluster.

of urban development. The study of the urban center of gravity migration reflects the direction of urbanization and provides a guarantee for scientific urban planning.

Between 2000 and 2020, the centers of gravity of the cities changed in different directions, and the attractiveness of the cities was characterized by localized agglomeration. Under the influence of the provincial capital Jinan, the surrounding Taian Liaocheng, Dezhou, and Zibo City, the direction of urban expansion is close to Jinan and Qingdao and Weifang city centers of gravity move in the opposite directions, indicating that the mutual attraction between the two cities is increasing. Driven by the central plains economic circle, the center of gravity of the cities of Heze and Jining migrates to the southwest, while the centers of gravity of the northern coastal cities of Yantai, Weihai, and Dongying all migrate to the north within their respective administrative boundaries. Rizhao, Linyi, and Zaozhuang in southern Lu are cities with changing centers of gravity to the east (see Fig. 7).

D. *Drivers of City Expansion*

Analyzing the drivers of city extension can better explain the reasons for changes in urban spatial expansion and help urban planners provide decision-making support. The stage factors of cities' dilation rate and compactness can be used as independent variables. The gravity-GTWR was used for the drive analysis, and the correlation coefficient results were applied to the ArcGIS method of natural breaking points to classify them into five classes, where a higher value indicates a greater influence of the driver on urban expansion and a positive or negative value indicates a positive or negative driver. The correlation coefficient and city extension velocity and compactness are shown in Figs. 8 and 9.

1) Analysis of Drivers of Expansion Velocity in Built-Up Areas: The drivers of the rate of city growth in the study area are characterized by significant migration and agglomeration during the same period (see Fig. 8).

From 2000 to 2005, the increasingly sprawling city of Luxibei was strongly influenced by the economy (F1), transportation (F2), and medical (F3) influences, which are concentrated in northwest Lu and Zibo cities. The education (F4) regression coefficient in Ludong area, Binzhou, Dongying, Rizhao, and Zibo was positive, indicating that F4 promotes the sprawl rate of the region. The urban construction (F5) coefficient was positive in the high-value areas in Weifang, Rizhao, Binzhou, and Dongying.

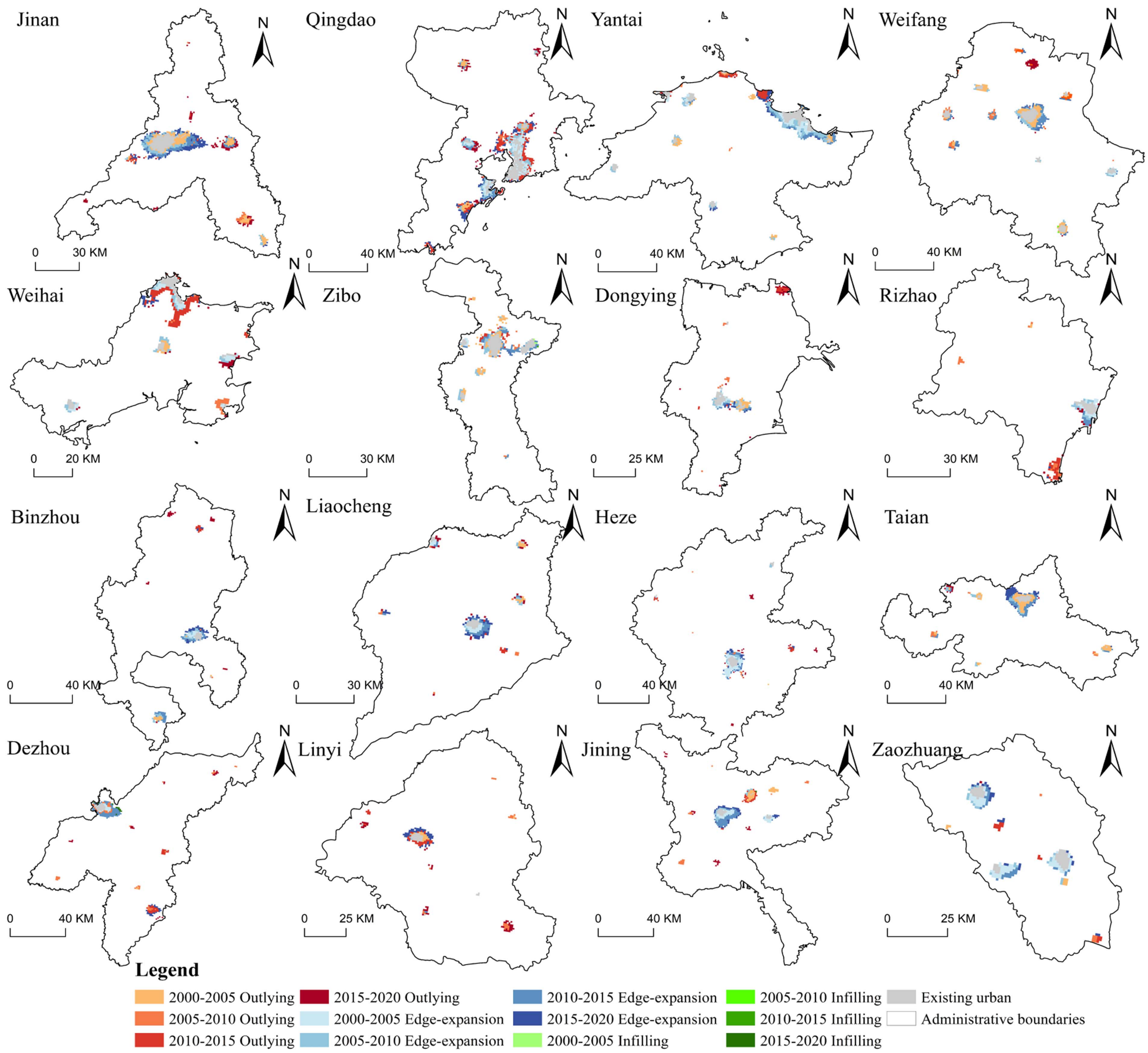

Fig. 6. Spatial distribution of the types of city extensions.

From 2005 to 2010, the areas with positive high values for the economic (F1) coefficient were all distributed at the outer margins of the research zones. F1 had a strong positive influence on the Yanwei region. The intensity of the traffic (F2) coefficient compared with the economic (F1) effect increased gradually from the external to the internal edge of the research region, especially in Jinan and Taian. The F3 coefficient had a dampening effect on the rate of extension of the study district at this stage, with negative high-value areas clustered in the Ludong region. The rates of expansion in parts of Luzhong, Lunan, and Luxibei were strongly influenced by the role of F4. F5 was based on the influence of education (F4), which moved west to east.

Between 2010 and 2015, the vast majority of the Shandong Peninsula urban agglomeration was positively driven by F1 with negative driving forces only in Yantai City. F2 negative inhibition was distributed in Ludong, Binzhou, and Dongying. The F3 area of influence migrated westward to Luzhong, eastern Lunan, and Luxibei. F4 positive high-value areas were in Dongying, Zibo, Weifang, Rizhao, and Yantai. F5 had a reduced area of influence compared with F4 only in the Yanwei region and Heze City.

In 2015–2020, all the study areas in Rizhao city, except Linyi, received a positive economic (F1) drive, indicating that the growth rate of the above areas received a significant economic (F1) influence. The positive impact of transport (F2) was reduced to the cities of Lunan, Qingdao, and Weihai. Medical F3 had a positive effect only on Qingdao. Both Liaocheng and Heze experienced a positive shift in the education (F4) and urban construction (F5) coefficients.

2) Compactness Drivers for Research Region Growth: The range of urban sprawl compactness influenced by the same driver was characterized by significant spatial migration over time (see Fig. 9).

The positive impact of BCI on the fiscal (F1) urban expansion in 2000 was mainly distributed in the cities of Zaozhuang and Qingdao. This suggests that financial factors contributed to the growth of cities in these areas. In 2005, the positive impact area

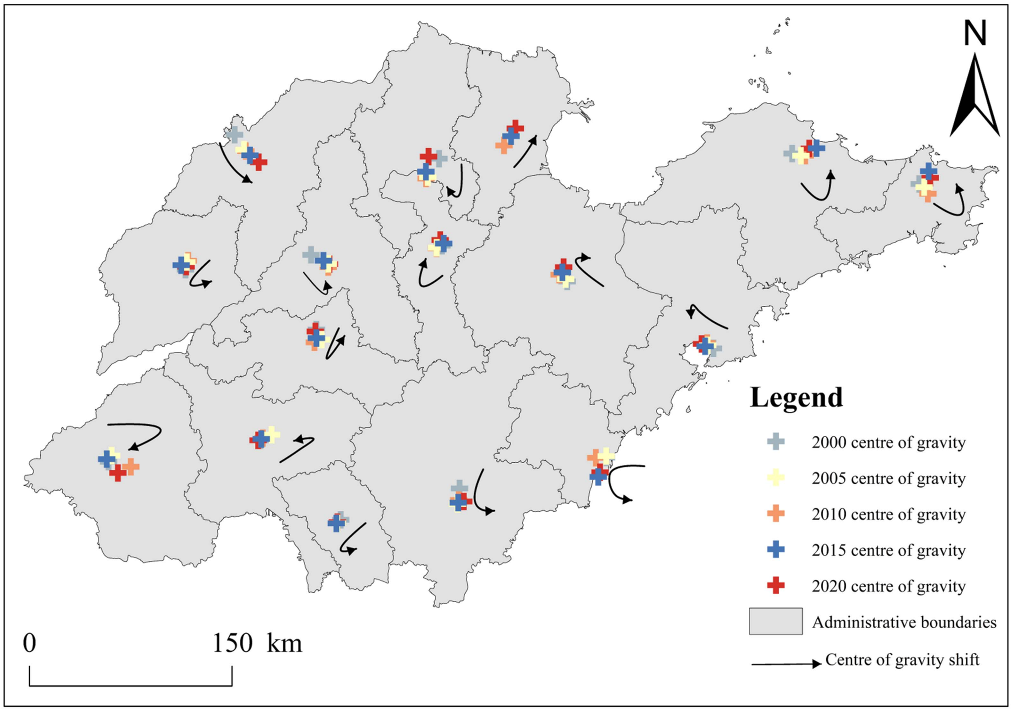

Fig. 7. Shift of the barycenter in the study area.

shifted to Yanwei district, while the negative high-value area was still concentrated in Luxibei and Zibo. Fiscal (F1) 2010 had a marked effect on some urban areas in Lunan and Luxibei. In 2015, the positive impact area expanded to the east, while the negative impact region was concentrated in Luzhong. In 2020, the fiscal-dependent areas shifted from the coastal cities of Ludong to the inland cities of Luzhong and Luxibei. This indicates that the economy had a high driving influence on inland cities in 2020, while it had a negative influence on the Yanwei region.

Population education (F2) played a positive role for Heze and Rizhao from 2000 to 2010 and a hindering role for the areas at the intersection of Ludong, Lunan, and Luzhong, with Weifang, Qingdao, and Zibo having the most significant negative effect in 2005. The negative impact shifted to Luxibei in 2010. The year 2015 had the most significant positive impact for Heze, with high negative correlation coefficient areas concentrated in Luxibei and Luzhong and the weakest correlation between Yanwei region compactness and F2. In 2020, the Yanwei region was positively correlated with F2, while for the cities in Lunan and Luxibei, compactness was less correlated with F2.

For transport (F3), the main impact areas were relatively dispersed in 2000, mainly in some cities in Lunan, Binzhou, and Qingdao. Clustering occurred in 2005 in Luxibei and northern Luzhong, but the impact was also strong in Qingdao and Heze. In 2010, the impact area shifted to Luzhong, with a clumped distribution in Lubei. In 2015, the impact areas were mainly concentrated at the junction of Ludong, Lubei, and Luzhong. The main impact areas in 2020 were scattered in the marginal areas of Shandong Province, such as the Yanwei region, Liaocheng, and Heze.

Urban construction (F4) had a significant impact on cities in the Ludong–Luzhong–Lunan region in 2000, and the 2005 impact drive extended to four cities in Luzhog, the border between Lubei and Ludong. In 2010, the F4 area of influence was narrowed to Luxibei and Dezhou. In 2015, the impact of the former continued to be extended to Jinan Binzhou, with a more significant impact on the city of Jinan. In 2020, the impact continued to extend to all cities in Luzhong and was most pronounced in Binzhou.

V. Discussion

A. Built-Up Area Expansion Study

NTL has the disadvantage of blooming and saturation effects, which leads the extracted results to regularly be larger than reality [46]. At the scale of small- and medium-scale studies, most research on the exploitation of built-up areas considers the need to first correct for the saturation of NTL [47]. However, regarding urban agglomerations, the problem of high saturation of lights at night is ignored on a national scale [48]. In this study, the EVI index was introduced into NTL. The EANTLI constructed by utilizing the characteristics of the EVI index reflecting the difference in surface vegetation cover between urban and nonurban areas will be close to the DN value of 63, which will be increased to 1000 by correction. The problem of NTL saturation will be alleviated.

Most studies of urban built-up area expansion have focused on economically developed urban agglomerations, such as Beijing–Tianjin–Hebei [48] and the Yangtze River Delta [49]. Less research has been done on the “growing” Shandong Peninsula

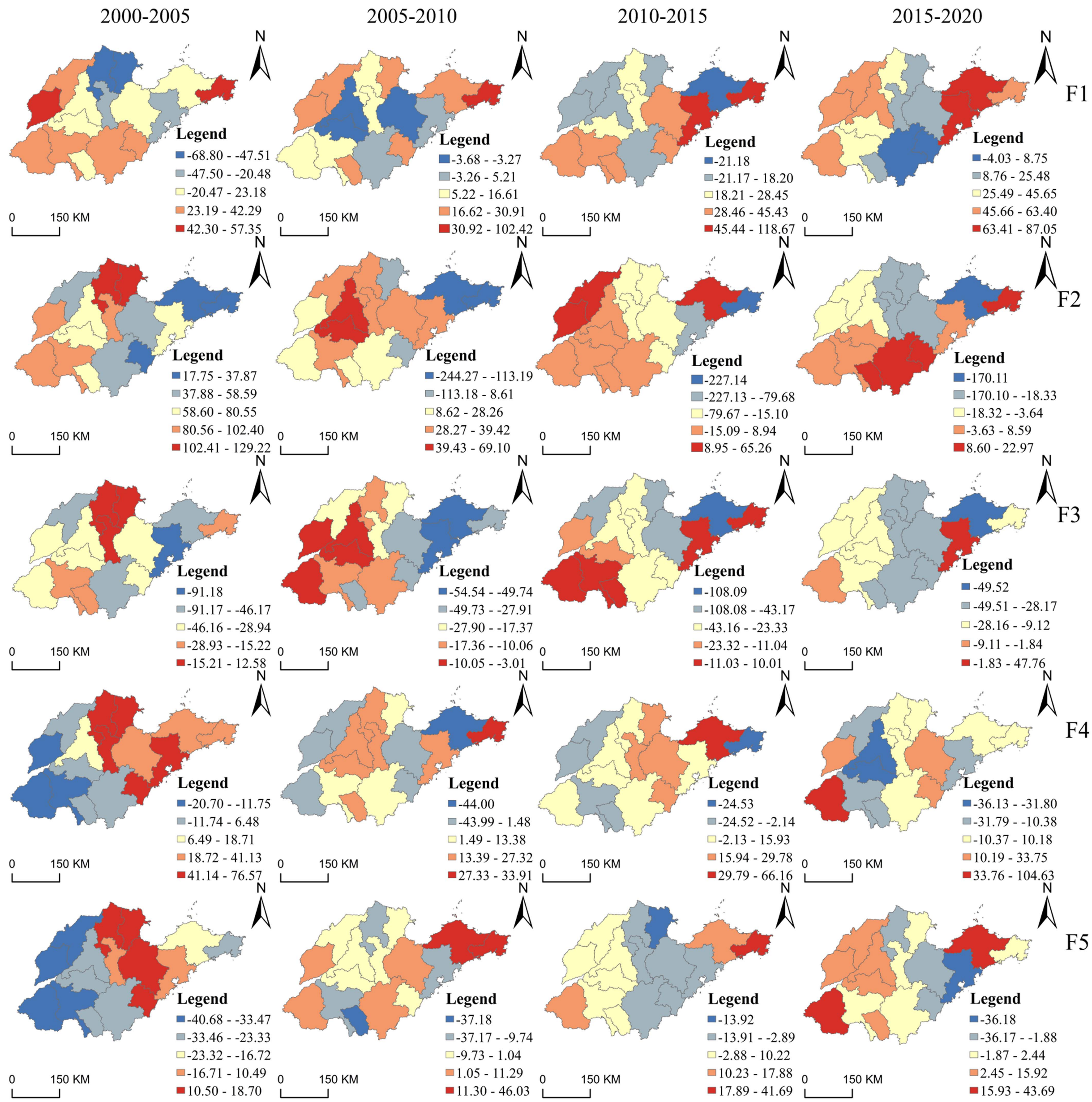

Fig. 8. Analysis of the drivers of the rate of extension of cities in the research region.

urban agglomeration. The only studies that have identified built-up area characteristics have been limited to a single perspective of urban time dilation indices or spatial dilation characteristics. Liu et al. [50] chose to analyze the characteristics of built-up area expansion in terms of urban expansion speed and intensity. The authors in [51] and [52] only used the landscape pattern index or LEI to analyze the characteristics of urban sprawl in the Shandong Province, and it is clear that these understandings of urban agglomerations lack comprehensiveness. On this basis, this study analyses the temporal expansion characteristics of the study area using the indicators of urban expansion speed, intensity, and compactness. Jinan and Qingdao cities in Shandong Province are expanding at a rate of 30, characterized by a dual-core spatial layout. The two core cities have a significant driving effect on the rate of expansion of neighboring cities. The rate of urban expansion in the northwest of the country and in the south of the country is developing very slowly, and local economic development should be promoted in the northwest of the country. The local government should do a good job of attracting investment and improve the construction of air, land, and sea transport facilities, and build a multitype transport network. The revitalization of the Lunan Economic Circle enabled resource sharing among the cities of Rizhao, Linyi, Zaozhuang, Jining, and Heze, and the strengthening of regional cooperation links. Only from the urban time, the expansion index cannot show the morphological changes in urban space. This article adds the type of urban expansion on this basis, and it can be found that county urban sprawl outlying dominates 2015–2020, so county governments at all levels of the Shandong Peninsula Urban Agglomeration should promote the construction of municipal

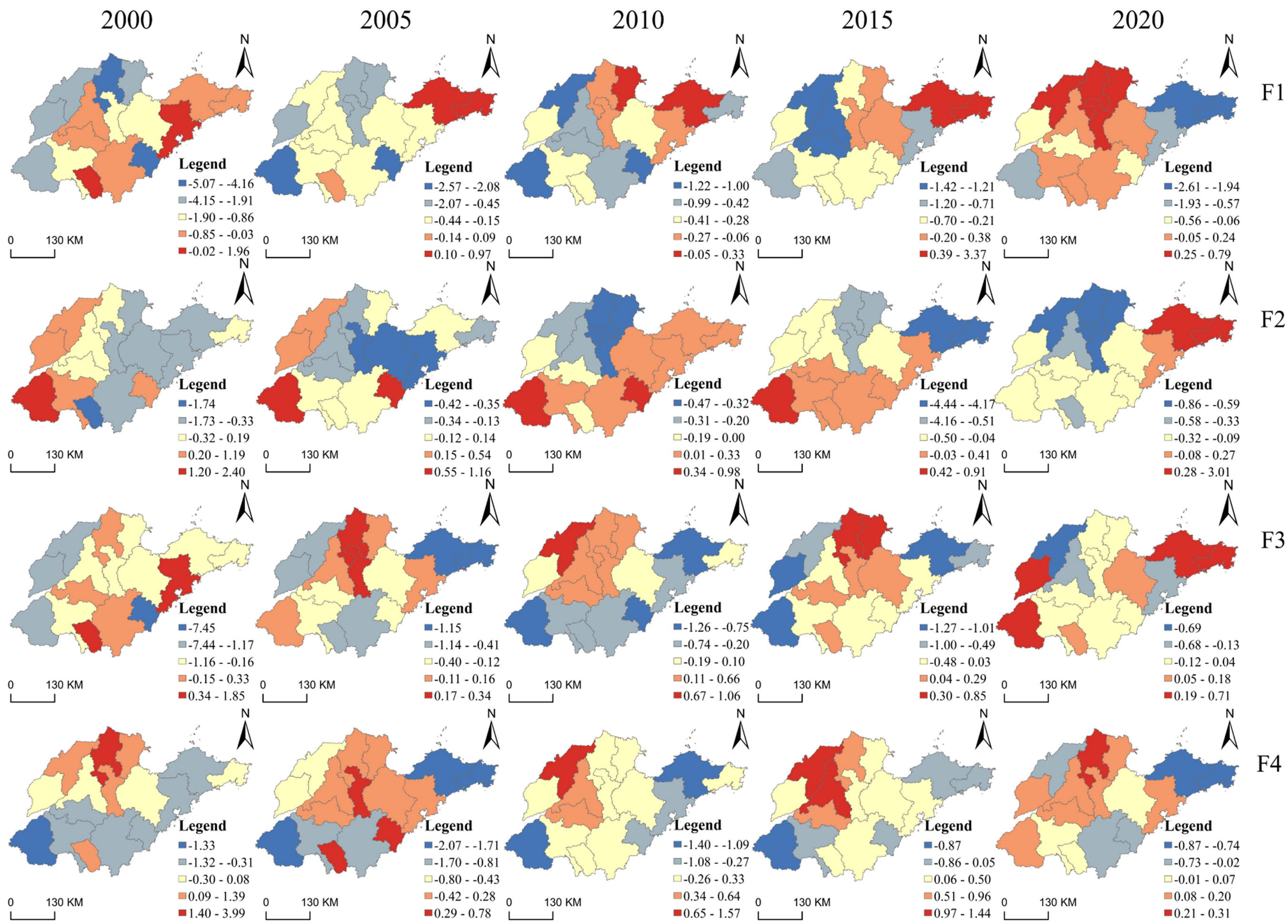

Fig. 9. Analysis of the drivers of BCI expansion in the study area.

infrastructures at the county and city levels, accelerate new urbanization, and correspondingly improve the development of the transport network.

Due to the differences in natural geographic conditions and socioeconomic levels, the expansion of the Shandong Peninsula urban agglomeration shows phases and differences. Therefore, the future planning process should focus on the coordination of spatial development within Shandong cities. Shandong Peninsula city cluster, in China's city cluster planning strategy, has an important position; this study identifies the urban built-up area and analyzes the built-up dynamic expansion characteristics and the driving factors behind it. This study identifies the urban built-up areas, analyzes the characteristics of built-up dynamic expansion and the driving factors behind it, and has great reference value for the future planning and construction of the Shandong Peninsula city cluster.

B. Choice of Center of GRWR Method

Previous research methods on the drivers of urban sprawl have used linear regression analysis, such as correlation analysis, gray correlation [53], and logistic models [54]. With the development of multidisciplinary cross fertilization, some studies have considered the spatial correlation characteristics of the drivers and combined the logistic model with the GWR model to derive the logistic GWR [55]. However, these research methods ignore the effect of time on variables. The innovation of this article couples the center of gravity migration model with the GTWR. The study delineates five years as a time node, within which all specific driver spatial characteristics can be derived, addressing the previously neglected problem of nonsmoothness in the city extension time, thus allowing the studies of spatiotemporal consistency to be independent of the drivers of urban expansion in the district.

C. Constraints and Future Developments

There are some limitations in this study, from which innovations can be made in future studies. The first one is that the urban built-up area of Shandong Peninsula urban agglomeration is expanding very fast, and using five years as a time study period cannot detect the expansion characteristics of urban built-up area boundaries meticulously. The second, the spatial resolution of the NTL data used in the study is very low, 1000 m, which can only roughly make a determination of the city boundary. To address these limitations, future research should shorten the time interval of the study to get more detailed urbanization characteristics of the study area. In the future, if the NTL is corrected by adding POI, social media data, and road network data, not only the spatial resolution of the NTL can be improved but also the detailed urban spatial expansion characteristics of the study area can be obtained.

VI. Conclusion

This study uses NTL and EVI data to determine the built-up region from 2000 to 2020, using 16 cities in the Shandong Peninsula cities cluster as the research object and conducts morphological analysis. The center of gravity-GTWR model was used to analyze the strength of city expansion and the drivers of compactness. The relevant findings are as follows.

1) The construction of the EANTLI alleviates NTL saturation and has richer variation characteristics in the city center area.
2) The rate and intensity of urban growth were greatest from 2000 to 2005, with urban compactness declining each year from 2000 onward. Spatial differences in expansion indices within cities are evident, with cities in the Ludong and Luzhong regions expanding at a greater rate than other regions. The intensity of city growth is generally greater than during the remaining phases, and urban compactness tends to decrease from the southwest to the northeast.
3) Characteristics of urban spatial patterns: types of urban sprawl are dominated by edge expansion, with a fluctuating and decreasing share of outlying and a very small share of infilling. Outlying dominates in areas, such as county-level cities, with a high proportion of edge expansion in the main urban areas and other locations.
4) The northern coastal area and the cities in southern Shandong show different degrees of dispersion and change trends. The center of gravity of the cities around Jinan is characterized by local concentration, and the mutual attraction of the cities of Weifang and Qingdao is increasing.
5) Using the center of gravity-GTWR method of analysis, the major drivers of the expansion rate of urban growth are financial and economic, population education, transport, and urban facilities construction. The main drivers of the urban expansion's compactness include financial and medical, population, transport, education, and urban construction. The drivers are characterized by a more pronounced temporal heterogeneity.

The research analyses in depth the features and driving mechanisms of urban expansion to provide a basis for urban planning and sustainable development.

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