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Identification and Characterization of Production–Living–Ecological Space in a Central Urban Area Based on POI Data: A Case Study for Wuhan, China

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Abstract: Cities are the main carriers of high population agglomeration and socio-economic activities and are also the areas where contradictions among production, living, and ecological space are concentrated. Effective identification of production–living–ecological space is conducive to the balanced and sustainable development of urban space. First, this paper analyzes the formation mechanism and connotation of urban production–living–ecological space and constructs the classification system of point-of-interest (POI) data. Then, it identifies the production–living–ecological space in the central urban area of Wuhan effectively by using the analytic hierarchy process, spatial analysis method, and the quadrat proportion method and verifies the accuracy of production–living–ecological space by the sampling verification method. Last but not least, it adopts spatial auto-correlation analysis and Geo-detector to reveal spatial heterogeneity and its driving factors. The results indicate that: (1) The overall accuracy of the identification accuracy test of production–living–ecological space in Wuhan is 92.86%. (2) There is a significant spatial correlation among production space, living space, and ecological space in the central urban area of Wuhan with living space being the dominant space and production space the secondary space intersected and embedded in the north and south banks of the Yangtze River. (3) Results of the analysis of the driving factor show that elements comprising life services, corporate enterprises, and scenic spots play a leading role in realizing the living space, the production space, and the ecological space, respectively, and the interactions between these elements have a significant driving effect on the three types of space. The results prove that POI big data are more scientific and practical in urban spatial planning, and it can provide a useful reference for the sustainable development of spatial planning.

Keywords: production–living–ecological; POI; sustainable urban planning; Wuhan; China

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1. Introduction

In recent years in China, rapid industrialization and urbanization have put great pressure on agricultural and ecological space and have resulted in intense contradictions between agriculture, ecology, and urbanization with the result that the sustainable development and utilization of available land have been severely impacted [1]. There is clearly an urgent need for optimization of the available land space [2,3]. In this regard, countries, based on their unique situation and conditions, compile sustainable development data on spatial planning to deal with the increasingly competitive human–land contradiction [4]. The ESDP (European Spatial Development Planning) categorizes space according to regional functions, population, and administrative elements [5]; the United Kingdom has compiled spatial planning based on the three dimensions of economy, society, and the environment [6]; the United States has constructed a spatial planning model that consists of a comprehensive framework of “livable communities, human capital, transnational governance, and regional mobility” [7]; Japan has compiled a spatial planning model with economic development at the core, giving attention to changes in the ecological environment and improving people's living standards [8]; Germany has compiled a spatial planning model that includes aspects of the economy, transportation, social services, and sustainable use of resources [9]; China has proposed to promote spatial planning as "the space for production that is used intensively and efficiently; that the living space is livable and appropriate in size, and that the ecological space is unspoiled and beautiful [10]". In other words, some focus is given to the production–living–ecological space whereby the aim is to realize the coordination and optimization of production space, living space, and ecological space. Such a strategy has been widely accepted by academic communities and government departments in China [11]. However, the premise and foundation of spatial planning is spatial identification; thus research on spatial identification is urgently needed.

Research concerning the identification of production–living–ecological space is abundant. At the macro scale, Liu et al. [12] revealed the spatial pattern and evaluation characteristics of production–living–ecological space in China based on land-use classification; Jin et al. [13] discussed the spatial-temporal differentiation pattern, the functional index differentiation, and the motivation for production–living–ecological space in the urban agglomeration of the Fujian Delta region of China by constructing a functional index for the production–living–ecological space. At the meso scale, Cui et al. [14] analyzed the evolution characteristics of the spatial pattern of production–living–ecological space of an urban area in Hubei Province, Central China; Li et al. [15] analyzed the spatial pattern and its relevance to the function of production–living–ecological space in Jiangsu Province. At the micro scale, Li et al. [16] undertook a comprehensive and quantitative assessment of the function of the production–living–ecological space in Tangqi Town, Hangzhou City, from the perspective of land, ecosystem, and landscape functions.

Regarding the research methods for the identification of the production–living–ecological space, there are two methods mainly in use: (1) the merging classification method and (2) the index system measurement algorithm. The former uses land-use type to merge and classify the production–living–ecological functions to obtain the production space, the living space, and the ecological space [17]. This approach is simple and easy to implement and can rapidly identify the number of production–living–ecological functions (i.e., quantity); however, appropriate consideration is not given to the spatial heterogeneity (i.e., quality) and functional complexities of the production–living–ecological space. In contrast, the index system measurement algorithm is based on an authoritative evaluation system such as the suitability evaluation system [18], the resource and environmental carrying capacity evaluation system [19], the multi-regulation integrated evaluation system [20], or the land-use multi-functional evaluation system [21] to identify the production–living–ecological space. This latter method has the advantages of having strong regional pertinence, better reflection of the functional heterogeneity, and composite characteristics, but there are disadvantages such as a diversified evaluation system, difficult data acquisition, functional aggregation, and lack of multi-scale integrated expression. In terms of research on the impact mechanisms, qualitative and quantitative methods have been used to analyze the key factors and the interrelationships of the changes in the spatial pattern of the production–living–ecological space at the macro scale [22], the meso scale [13], and the micro scale [23]. After reviewing the above studies, it is concluded that the above two identification methods do not accurately reflect the "quantity" and "quality" of the production–living–ecological space, and there is insufficient data to describe the complex and dynamic characteristics. In addition, there are few studies on urban centers or built-up areas, and there are few studies on the mechanism whereby production–living–ecological space is influenced at the grid scale.

Geospatial big data represented by point-of-interest (POI) data have been widely used in urban spatial refinement research. The application of big data in the field of e-commerce is also relatively common [24]. The point of interest is a point element, which has the space and attribute information of a real geographical entity [25]. Moreover, POI data can display spatial distribution and constitute a refinement for research on spatial recognition and spatial differentiation in urban central areas [26]. Internationally, applications of the POI concept in urban transportation, disease transmission, social crimes, etc., [27] are common; domestically, such studies are mainly concentrated on topics concerning urban spatial structure [28,29] and identification of functional areas in urban settings [30]. Due to the large sample size and easy access of POI data in the urban center, POI data contain a large amount of production, living, and ecological space information, which provides the possibility to identify accurately the "production–living–ecological" space in the central urban area and explore the mechanisms that influence it. However, to date, POI data have seen limited use for research on production–living–ecological space.

This paper proposes a spatial classification system for urban production–living–ecological space based on POI data, using an analytic hierarchy process, an ArcGIS (Geographic Information System) spatial superposition method, and the quadrat ratio method to identify accurately the production–living–ecological space in the central urban area of Wuhan, China. Using spatial auto-correlation analysis and the geographic detector methods, we reveal the interrelationships and the mechanisms that influence the production–living–ecological space. Based on new findings, policy recommendations are made. Urban space is the main carrier of human production, living, and socio-economic activities [31]. The dynamic balance of urban production, life, and ecology is the inevitable requirement of sustainable urban planning [32], and it is also an important goal to achieve the long-term development of the country and the city [33]. Furthermore, this article explores the scale of the urban center area, explores the spatial laws for production–living–ecological space, and provides a useful reference for sustainable development of urban planning.

2. Materials and Methods

2.1. Research Area and Literature Review

2.1.1. Overview of the Study Area

The central urban areas of Wuhan, China (Jiang'an District, Jianghan District, Qiaokou District, Hanyang District, Wuchang District, Hongshan District, Qingshan District) were selected as the study area (Figure 1). Wuhan is located in Hubei Province, China, in the middle reaches of the Yangtze River; the geographic coordinates are 29°58′~31°22′ N, 113°41′~115°05′ E. With a population of 11.212 million and a GDP of CNY 1.56 trillion in 2020, the city is an important industrial, science, and education base and a comprehensive transportation hub in China. At present, the city is accelerating the construction of a national economic center, a high-level scientific and technological innovation center, a commercial and logistics center, and a center city for international exchange. Therefore, the central area of Wuhan has a wealth of geographical entity elements, which can better represent the relationships between human society and the geographical environment; this situation clearly has great significance in terms of exploring the city's production–living–ecological space.

The base map data come from the geographic information resource catalog service system of China (1:1 million, https://www.webmap.cn/commres.do?method=result100W, accessed on 13 November 2020).

2.1.2. Data Sources and Preprocessing

The POI data involved in this study come from the AMAP (Auto Navigation Map) of Wuhan in 2019. The program is compiled in Python to crawl, and a total of 364,611 items of data were obtained. The data include 8 attributes such as the name, type, address, longitude, latitude, administrative area, address, administrative area code, etc. According to the AMAP classification system, the POI data have three levels of classification. Due to the large number of classifications and the existence of data redundancy and overlap, data preprocessing was adopted, whereby the elements with low public awareness and which are irrelevant to this research were removed.

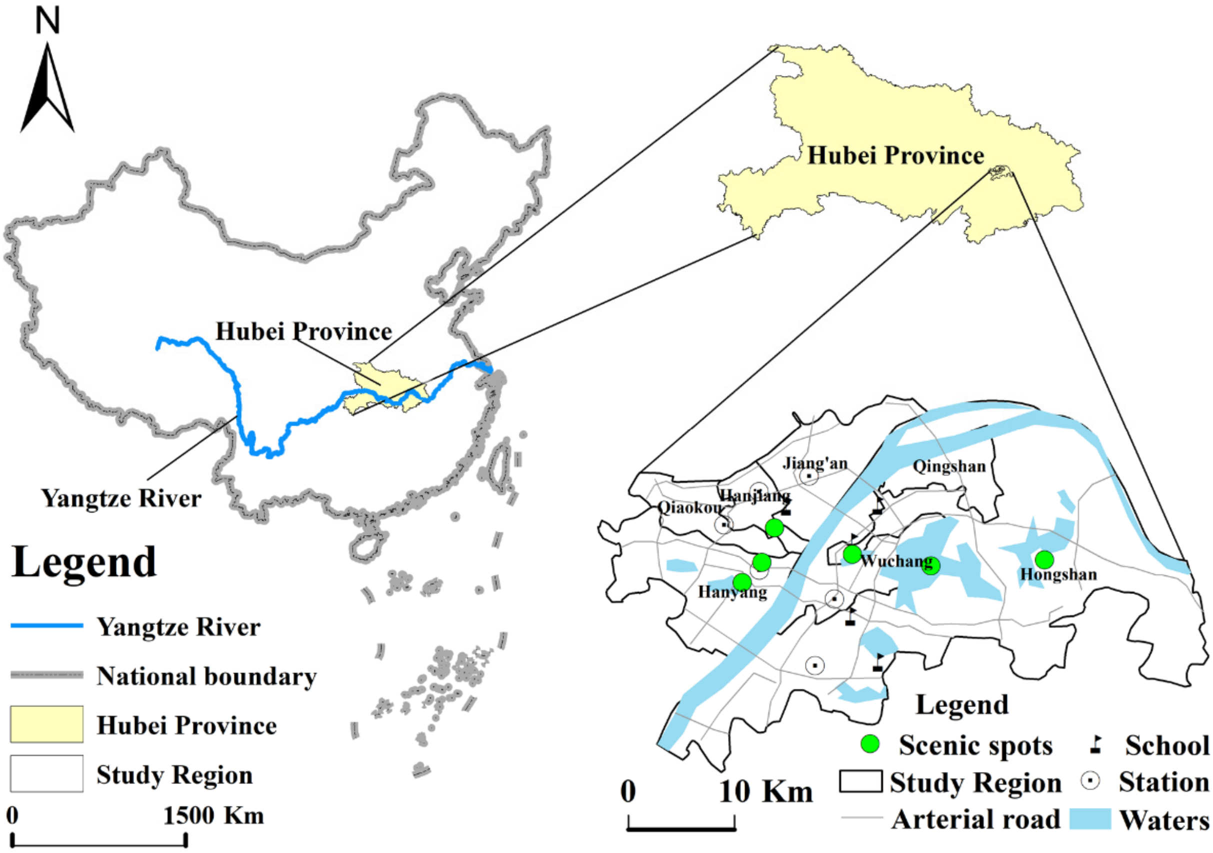

Figure 1. Location map of the study area.

In the study, a grid of 300 m × 300 m was constructed as a research unit for identifying the production–living–ecological space, and a total of 11,224 research units were obtained.

2.2. Mechanism of Formation and Concept of the Production–Living–Ecological Space

The concept of the production–living–ecological space, which originates from human–land couplings [12], is based on the functions of land use (Figure 2). The Sensor project [34] pointed out that multi-function land use includes economic, social, and environmental functions, which can provide corresponding products and services for human beings [35]. Gebhard [36], De Groot [37], and Chen [38] believed that the multi-function aspects of land use can be divided into three functions: the production function, the ecological function, and the living function. Production function refers to the ability to provide the material supply needed for human survival and development; living function refers to the ability to provide material and spiritual support for human living, travel, consumption, entertainment, etc.; ecological function refers to the ability to maintain the ecological balance and meet human basic ecological needs. The multi-function aspects of land use include two main categories, namely, human and land. In early society, human beings searched for food and clothing in nature. At this time, land functions were dominated by ecological functions, and the agglomeration of functions formed an ecological space. In agricultural society, human beings developed and used land to different degrees to derive a stable food source and meet basic survival needs; thereafter, the production function of land was subsequently developed. In areas dominated by the production function, the agglomeration of production functions formed a production space such that the surface landscape with a production function developed and became a geographical entity; this included entities such as farms and workshops. In the production process, human societal, habitat, safety, and other needs gradually emerged, and the living aspects of the land function were developed thus constituting a living space; hence the geographical entity representing living space emerged. In industrial societies, human needs became more diversified, land use and development became more diversified, and the versatility of land use was demonstrated. Different ways of exploiting land use and different intensities of use allowed the land function in a certain area to be divided into primary and secondary functions [39], and the relevant geographic entities also had composite functions, which formed a composite space (Figure 3). From the above analysis, it is clear that the multi-function aspects of land use are driven by human needs. Human behavior is the external manifestation of demand [40], while geographical space embodies the human behavior element, which is represented by the externalization of geographical entities.

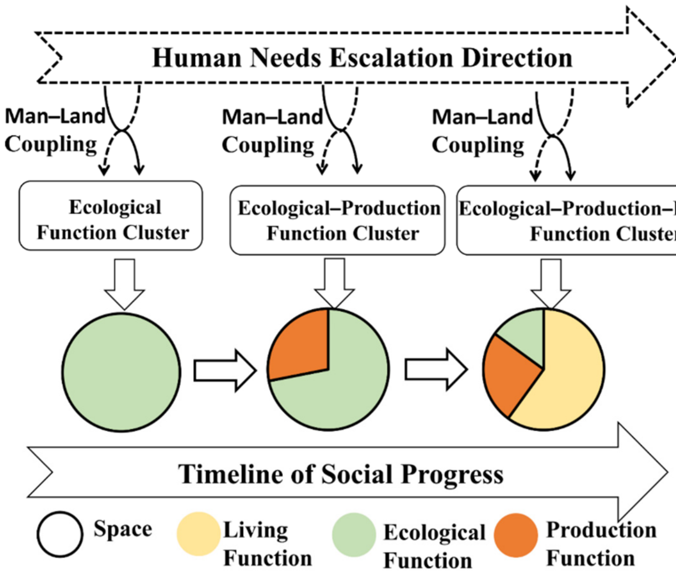

Figure 2. Mechanism of formation for production–living–ecological space.

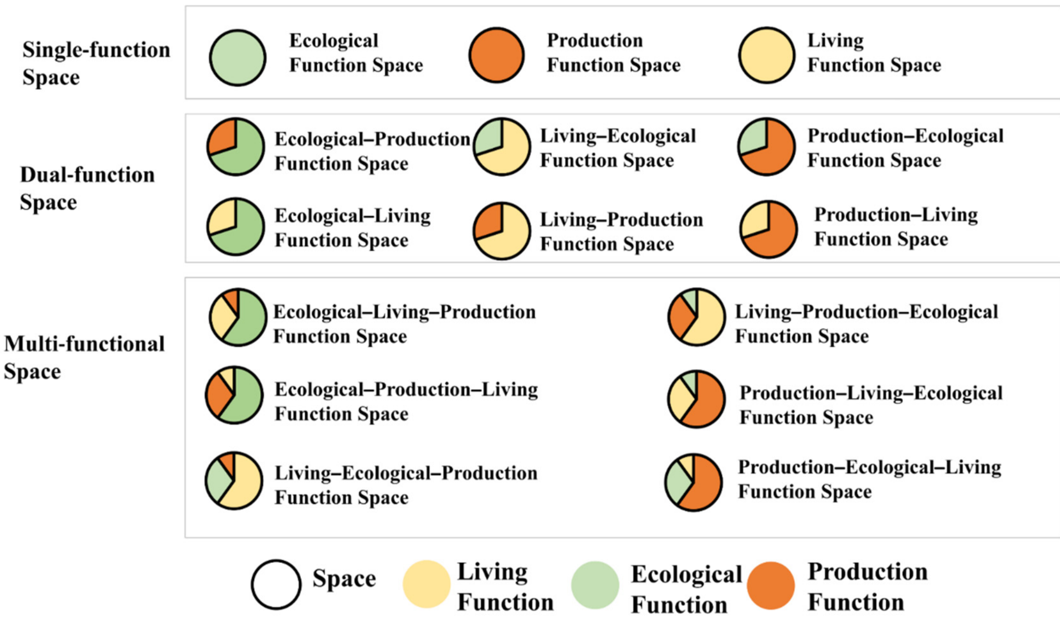

Figure 3. The combination of types of production–living–ecological functional space.

The POI concept expresses in an abstract manner all kinds of geographical entities in the human land system, such as restaurants, shopping malls, companies, etc., and is able to record the spatial location information of social and economic sectors [41] and register the production–living–ecological function information of geographical entities. In addition, traditional land-use data are usually derived from local government and land-related departments and are relatively difficult to obtain, and there usually is a long update cycle. In contrast, POI data are of large sample size, and there is high accuracy, timeliness, and easy access [42]. Therefore, POI data provide the possibility to identify accurately the spatial patterns of the production–living–ecological space [43,44] and reveal the factors and interaction relationships that influence the spatial patterns.

Regarding the concept of production–living–ecological space, researchers have interpreted the concept from different perspectives. Liu et al. [45] interpreted the concept from the perspective that the production–living–ecological space comprises the three functional spaces of ecology, production, and living and is the product of natural and socio-economic systems coupled in a synergistic way; Huang et al. [46] also interpreted the production–living–ecological space from a functional perspective, but more emphasis was given to space as being the dominant function; Zhang et al. [47], and Zhu et al. [48] interpreted the production–living–ecological space from the perspective of the nature of land use, believing that the production space provides space for humans to provide production and management services, and the ecological space provides the environmental background space for human survival and development. The living space is a space that provides for human living, entertainment, and education. From the perspective of ecological civilization, Liu et al. [49] believed that living space is a space that features strong living attributes such as food, clothing, housing, transportation, entertainment, and education. Production space is a space for activities such as the production of goods, and ecological space is a space for life-sustaining activities. Huang et al. [50] considered the mechanism of formation of the production–living–ecological space and believed that the production–living–ecological space is a functional space that provides humans with the corresponding products and services.

This paper attempts to synthesize the definitions of different scholars and combine the principles of the formation of the urban production–living–ecological space. With respect to production space, it is argued that it is a functional space that encompasses the production of goods and services to meet human needs. Production space includes three major categories: business services space, industrial space, and transportation space, which specifically correspond to corporate enterprises, factories, road transportation, warehouses, financial services, etc. With respect to living space, this space is a functional space that provides human habitation, entertainment, medical treatment, culture, shopping, public services, etc., and specifically corresponds to residential buildings, supermarkets, schools, catering services, medical facilities, and leisure facilities. In the case of ecological space, this space is a functional space that provides ecological products and services for human beings and includes parks and green spaces and scenic spots, specifically corresponding to parks, wetlands, scenic spots, green belts, etc.

2.3. Methods

Research was undertaken on the following premises (Figure 4). First, according to the mechanism of formation and the concept of urban production–living–ecological space, the POI classification system of urban production–living–ecological space was constructed (Table 1). Second, the Delphi method, expert scoring, and an analytic hierarchy process were used to calculate the weight of each element in the classification system (that is, the relevance value), and the value was assigned according to the public's cognition of the area of the geographical entity (that is, the influence value). Third, the relevance value was multiplied by the influence value, and the calculated value was used as the comprehensive weight value for each element. Fourth, a 300 m $\times$ 300 m grid was constructed as the basic identification unit to identify the production–living–ecological space, and the number of points of interest that fell into a single grid was counted; thereupon, the comprehensive weight value was multiplied by the POI number to calculate the number of production–living–ecological functions. Fifth, the dominant space and composite space were identified by spatial superposition analysis and the quadrat proportion method. Finally, spatial correlation analysis and the Geo-detector methods were used to analyze the mechanisms whereby the production–living–ecological space was influenced; policy recommendations were then proposed.

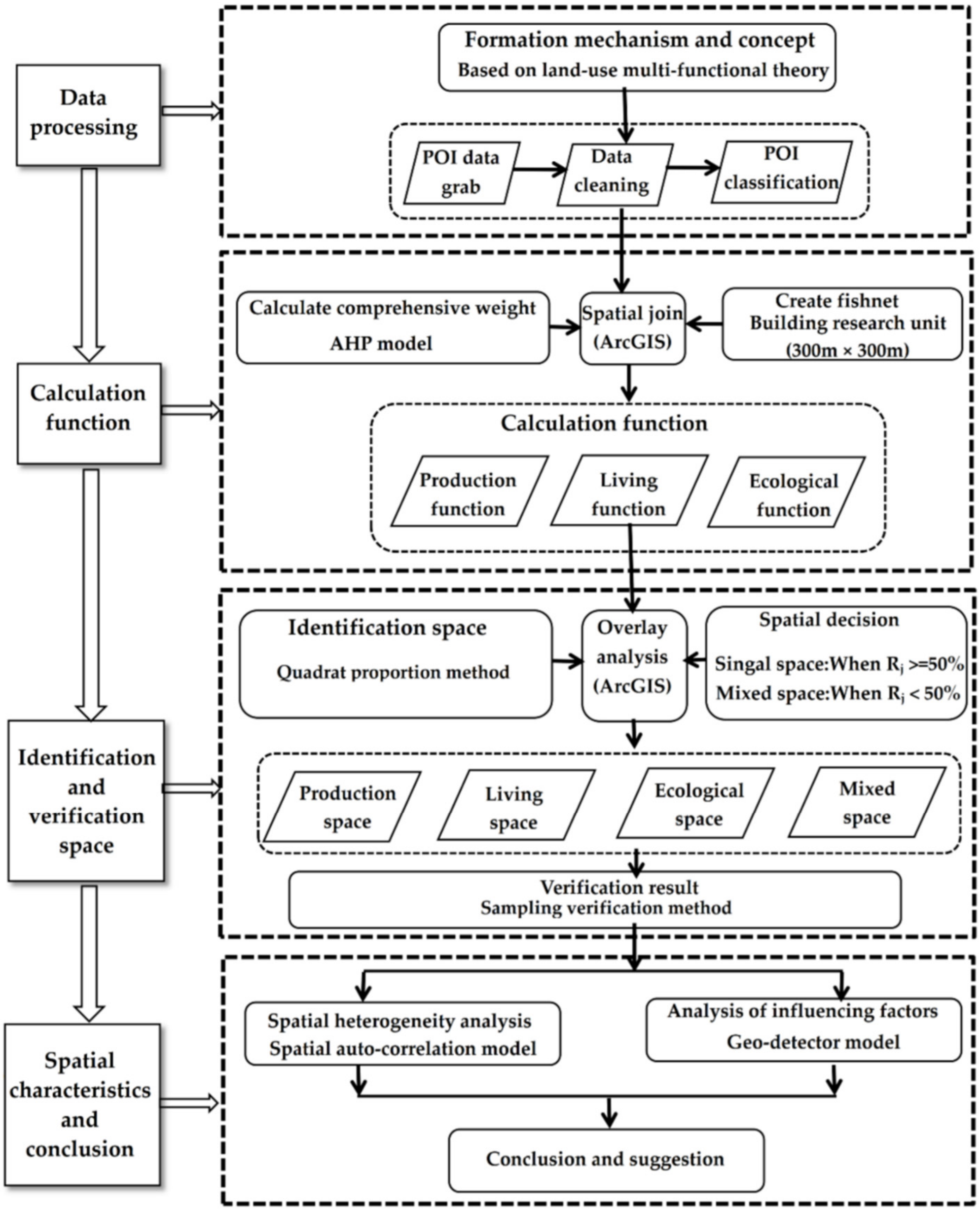

Figure 4. Flowchart of the methods.

Table 1. POI classification system and relevance value (α), influence value (β), and comprehensive weight (W) data.

Target Layer	Criterion Layer	Element Layer	Industrial Classification	Relevance Value (α)	Influence Value (β)	Comprehensive Weight (W)
Production space	Business space	Corporate enterprises	Advertising, decoration, construction companies, etc.	0.2685	20	5.3700
		Financial services	Banks, insurance and securities companies, etc.	0.2028	30	6.0840
	Industrial space	Factory	Factories, workshops, etc.	0.2884	70	20.1880
		Warehousing logistics	Warehouses, logistics, rail stations, etc.	0.0791	50	3.9550
		Auto services	Automobile sales and maintenance companies, etc.	0.0837	40	3.3480
	Transportation space	Transportation	Subway stations, bus stations, parking lots, airports, railway stations, wharfs, etc.	0.0776	30	2.3280
Living space	Habitable space	Residential buildings	Villas, urban residential areas, rural homesteads	0.1507	50	7.5350
	Service space	Retail monopolies	Retail stores, specialty stores, convenience stores, gift shops, etc.	0.0120	10	0.1200
		Supermarket shopping	Comprehensive shopping markets, malls, etc.	0.0793	30	2.3790
		Hotel catering	Casual restaurants, hotels, etc.	0.0689	25	1.7225
	Public space	Life services	Beauty salons, photography shops, funeral facilities, etc.	0.1840	15	2.7600
		Medical treatment	Hospitals, veterinary practices, etc.	0.1209	20	2.4180
		Science and education	Schools, museums, research institutions, etc.	0.1354	40	5.4160
		Sports and leisure	Sports and entertainment venues, etc.	0.0584	20	1.1680
		Communal facilities	Public, toilets, news, kiosks, etc.	0.0349	15	0.5235
		Public squares	Public squares	0.0218	40	0.8720
	Management space	Government agencies	Government agencies, etc.	0.1339	30	4.0170
Ecological space	Green space	Parks and wetlands	Parks, zoos, botanical gardens, wetlands, etc.	0.8000	70	56.0000
		Scenic spots	Scenic spots, temples, etc.	0.2000	60	12.0000

2.3.1. Identification of Production–Living–Ecological Space Based on POI Data

POI Data Classification System

Based on the mechanism of formation and the concept of urban production–living–ecological space (as referred to in the "Urban Land Classification and Planning and Construction Land Standard (GB50137-2011)" and the "2017 National Economic Industry Classification (GB/T 4754-2017)"), and drawing lessons from the study of Hu et al. [51], a POI data classification system of urban production–living–ecological space was constructed, following the principles of consistency and universality of POI data (Table 1) [52].

The classification system consists of three layers, that is, the target layer, the criterion layer, and the element layer. The target layer contains three functional spaces—production, living, and ecological. The criterion layer is a sub-category of the three functional space layers, and there is a total of 8 criterion layers; for instance, different criterion layers are composed of several elements, and there are 19 elements in total. The element layer contains the specific industrial classification of the elements.

Comprehensive Weight Calculation

Given that the POI data are point elements that do not have attributes such as area, it is necessary to calculate the degree of correlation between the POI data and the production–living–ecological space (namely, the relevance value) and to calculate the degree of influence of the area of the geographic entity on the production–living–ecological space (namely, the influence value). This study used the Delphi method, expert scoring, and an analytic hierarchy process to determine the weight value of each element in the element layer of the classification system as the relevance value (α); due to the different sizes of the geographical entities, the number of production–living–ecological functions represented by each element is also different [53]. For this reason, according to the public cognition of the area of the geographical entity and the measurement model of Zhao et al. [54], this paper assigns the value to each element as the influence value (β), with an assignment interval of 0–100. Finally, to more accurately identify the production–living–ecological space, the relevance value (α) and the influence value (β) are multiplied together to calculate the comprehensive weight (W) of each element (Table 1), that is, $W = \alpha \times \beta$.

Quantitative Measurement of the Function of the Production–Living–Ecological Space

ArcGIS is used to spatially connect the POI data in the central urban area of Wuhan with the grid of the study area and to count the number of points of interest that fall into each element in the grid unit. In addition, the following formula is used to calculate the number of production–living–ecological functions in the identification unit:

$$F_i = N_i \times W_i, \quad i = 1, 2, 3, \ldots\ldots, n \tag{1}$$

where F_i is the number of functions of the i type of elements in the identification unit, N_i is the number of POI data of the i type of elements in the identification unit, and W_i is the comprehensive weight of the i type of elements.

The number of functions of each type of element in the identification unit is summed to obtain the total number of ecological functions, production functions, and life functions in the identification unit. The formula is as follows:

$$S = \sum_{i}^{n} N_i \times W_i, \quad i = 1, 2, 3, \ldots\ldots n$$

where S is the sum of the number of functions of all the elements of the target layer in the identification unit, and N_i and W_i are as given in Equation (1) above. The identification results for the ecological function (Figure 5), the production function (Figure 6), and the living function (Figure 7) are presented respectively.

Quantitative Identification of the Production–Living–Ecological Space

The results for the ecological function, production function, and living function obtained by the above calculation are spatially superimposed, and the spatial analysis method and the quadrat ratio method are used [55] to identify the production space, the living space, the ecological space, and the intersecting space (that is, the mixed space). The formula for the quadrat ratio method is as follows:

$$R_j = \frac{S_j}{\sum_j^n S_j}, \quad j = 1, 2, 3$$

where R_j is the value of the proportion of the j type functional element in the cell grid, and S_j is the number of the j type functional element in the cell grid. When R_j is more than 50%, the j type function is considered as the dominant function, and the cell grid is a single function space; when R_j is less than 50%, the cell grid is considered as a mixed functional area, and the cell grid space is considered as a mixed space. The two functional elements with the highest value are selected as the functions of the space [30], such as production–living space, the living–ecological space, or the production–living space.

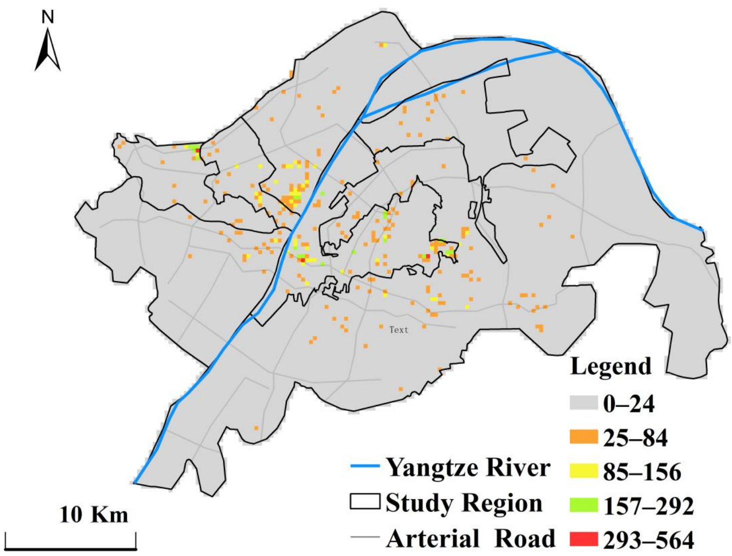

Figure 5. Identification results for the ecological function.

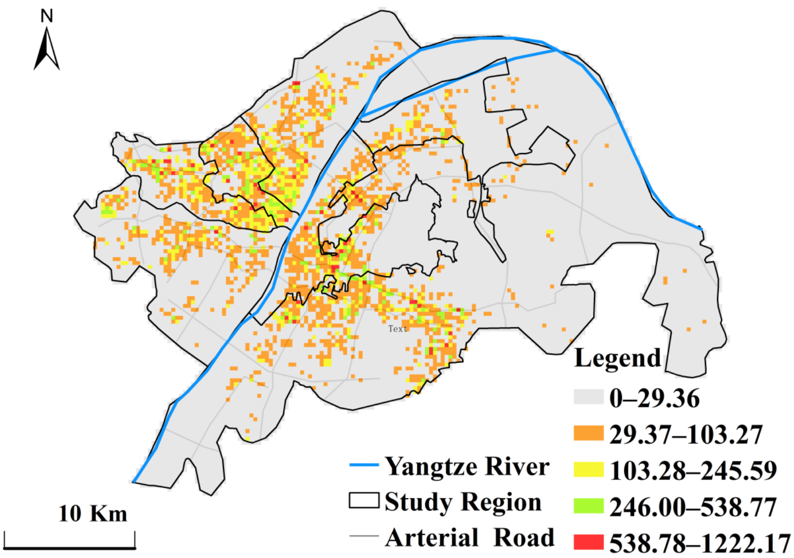

Figure 6. Identification results for the production function.

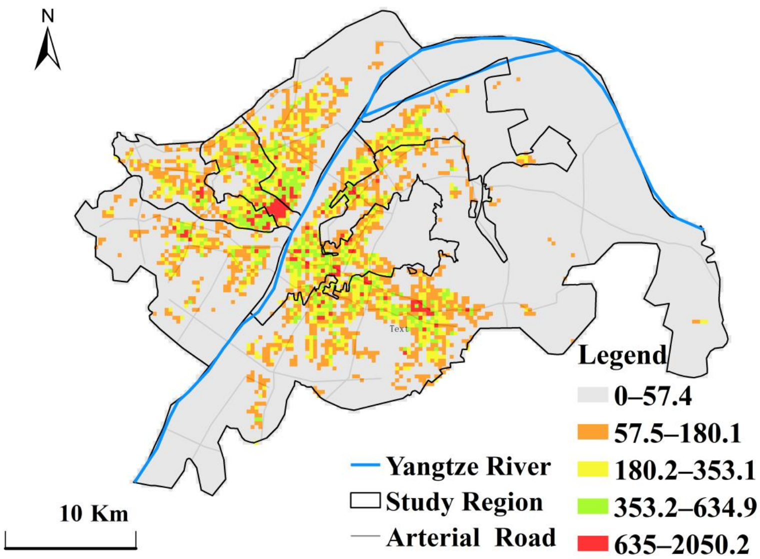

Figure 7. Identification results for the living function.

2.3.2. Spatial Heterogeneity Analysis of Production–Living–Ecological Space

Spatial auto-correlation analysis describes the degree of spatial correlation of a variable or multiple variables and judges quantitatively the degree of spatial distribution interdependence of research objects via the correlation coefficients. Spatial auto-correlation analysis describes the degree of spatial correlation of a variable or multiple variables and judges quantitatively the degree of interdependence of the research object in the spatial distribution via the correlation coefficient. After passing the significance test, the correlation coefficient for $Moran'sI$ value is [–1, 1]. When $0 < Moran'sI < 1$, this indicates that the research object has an agglomeration effect in the spatial distribution, hence showing a significant positive correlation. The larger the value of $Moran'sI$, the greater the degree of correlation; when $Moran'sI = 0$, the spatial distribution of the research object appears random; when $-1 < Moran'sI < 0$, the spatial distribution of the research object has a negative correlation, and the smaller the value of $Moran'sI$, the greater the negative correlation. This paper uses univariate and bivariate spatial auto-correlation methods to study the relational characteristics of the spatial pattern of the production–living–ecological space.

Global spatial auto-correlation [56] describes the spatial distribution of living, production, and ecological space and can test whether agglomeration occurs. The formula is as follows:

$$Moran's\ I = \frac{n\sum_{i=1}^{n}\sum_{j=1}^{n} W_{ij}(x_i - \overline{x})(x_j - \overline{x})}{(\sum_{i=1}^{n}\sum_{j=1}^{n} W_{ij})\sum_{i=1}^{n}(x_i - \overline{x})^2},\ (i \neq j)$$

where, x_i, y_j are the point element densities of the research units i and j in the research area, respectively; n is the number of research units in the research area; W_{ij} is the spatial weight (in this paper, Queen contiguity is used to construct the spatial weight [57]; $\overline{x}$ is the average density.

Bivariate spatial auto-correlation describes the spatial correlation characteristics of multiple variables in the study area; hence the degree of correlation between the production, living, and ecological space elements for the study area may be calculated. The formula [58] is as follows:

$$Moran's\ I_{z\ y}^{a} = \frac{X_y^a - \overline{X}_y}{d_y} \times \sum_{c=1}^{n} W_{ac} \times \frac{X_z^c - \overline{X}_z}{d_z},\ (a \neq c)$$

where y and z represent two optional variables in the research area; X_y^a is the value of variable y in research unit a; X_z^c is the value of variable z in research unit c; $\overline{X_y}$ and $\overline{X_z}$

are the average values of the variables y and z, respectively; d_y and d_z are the variances of the variables y and z, respectively; n is the number of research units in the research area; and W_{ij} is the spatial weight (in this paper, Queen contiguity is used to construct the spatial weight).

2.3.3. Identification of Influencing Factors Based on the Geo-Detector Method

Spatial differentiation concerns the spatial manifestation of the interaction processes between nature and the social economy. The Geo-detector method is a statistical method used to detect spatial differentiation and to reveal the driving factors underpinning spatial differentiation [59]. The core idea is that if an independent variable has an important influence on the dependent variable, then the spatial distribution of the independent variable and the dependent variable are similar [60,61]. Geographic detectors include 4 categories of detectors, that is, factor detectors, interaction detectors, risk detectors, and ecological detectors. This article uses factor detectors and interactive detectors to detect the spatial differentiation of the production–living–ecological space and the factors that influence the differentiation. The model is as follows:

$$q = 1 - \frac{\sum_{h=1}^{L} N_h \sigma_h^2}{N\sigma^2}$$

where L is the stratification of factor X, that is, the classification or partition, N_h and N are the number of units in layer h and the whole region, σ_h^2 and σ^2 are the variances of layer h and the whole region Y, respectively, q is the explanatory power, and its range is [0, 1]; the larger the value of q, the stronger the explanatory power of factor X to Y.

The interaction detector explains whether the evaluation factors X_1 and X_2 will work together to enhance or weaken the explanatory power of the single evaluation factor to the dependent variable or whether the impact of the evaluation factor on the dependent variable is independent of each other. The two factors (X_1 and X_2) interact in the following categories (Table 2).

Table 2. Detection of interaction.

Interaction	Result
$q(X_1 \cap X_2) < Min(q(X_1), q(X_2))$	Non-linear attenuation
$Min(q(X_1), q(X_2)) < q(X_1 \cap X_2) < Max(q(X_1), q(X_2))$	Single-factor non-linear attenuation
$q(X_1 \cap X_2) > Max(q(X_1), q(X_2))$	Two-factor enhancement
$q(X_1 \cap X_2) = q(X_1) + q(X_2)$	Independent
$q(X_1 \cap X_2) > q(X_1) + q(X_2)$	Non-linear enhancement

$q(X_1)$, $q(X_2)$ are the q values for the influence of factors X_1 and X_2 on Y, respectively. $Max(q(X_1), q(X_2))$ means that the maximum value is taken; $Min(q(X_1), q(X_2))$ means that the minimum value is taken; $q(X_1) + q(X_2)$ means the sum of the q values for the two factors; $q(X_1 \cap X_2)$ refers to the interaction effect of the factors X_1 and X_2.

3. Results

3.1. Identification Results and Verification

3.1.1. Identification Results

The identification results for the production–living–ecological space based on the POI data are presented in Figure 8. There are 234 identification units in the ecological space (total area 21.06 km^2), 1514 identification units in the production space (total area 136.26 km^2), 4006 identification units in the living space (total area 360.54 km^2), and 70 in the mixed space identification unit (total area 6.3 km^2). Among them, there are 6 identification units in the production–ecological space (total area 0.54 km^2), 36 identification units in the ecological–living space (total area 3.24 km^2), and 28 identification units in the production–living space (total area 2.52 km^2). It can be seen from the above that the living space in the central urban area of Wuhan occupies a dominant position, followed by the production space.

3.1.2. Spatial Distribution Pattern for the Production–Living–Ecological Space

The average nearest neighbor index method is used to analyze the production–living–ecological space and to assess quantitatively the spatial aggregation. The results show that the nearest neighbor index for production space is 0.81, and the production space presents an aggregated distribution; the nearest neighbor index for living space is 1.074, and the living space is randomly distributed; the nearest neighbor index for ecological space is 0.626, and the ecological space presents an aggregated distribution; the nearest neighbor index for mixed space is 0.862, and the mixed space presents an aggregated distribution.

The respective identification results for the production space, living space, and ecological space are converted into point elements, and nuclear density analysis is performed to explore the respective spatial distribution patterns. The distribution patterns for the production–living–ecological space are presented in Figure 9. The living space (Figure 9a) is concentrated on the north and south banks of the Yangtze River and is also distributed inland. The living space around Zhongshan Park in Jianghan District on the north bank of the Yangtze River, Tangjiadun in Jiang'an District, and Miaoli Road are the most concentrated, followed by Hanxi Station in Qiaokou District, the Wangjiawan Central Living Area in Hanyang District, Shuixianli Community, and the living space near Zhongjia Village, these distributions appearing as dots; the Yellow Crane Tower Park, Dadongmen Interchange, and Chu, the living space near the Cai community, is more concentrated and contiguous, while the living space in Hongshan District and Qingshan District is scattered, such as in the case of Xiongchu Avenue Elevated, near the Linjiang Community. The overall distribution of production space (Figure 9b) has a dot pattern and is concentrated in Qiaokou District, Hanyang District, and Jianghan District on the north bank of the Yangtze River and Wuchang District on the south bank of the Yangtze River and the southeast of Hongshan District. Observing the distribution of production space, it is found that production space is, in general, distributed near traffic arteries, such as the Qiaokou District (which is located near the west section of Changfeng Avenue), Jianghan District (which is located near Qingnian Road, Huaihai Road, and Changqing Overpass), Hanyang District (which is located in Mi near the Liangshan Interchange and Qintai Avenue), Wuchang District (which is located near Dadongmen Interchange, Zhongbei Road, Chuhan Road, and Wuhan Avenue), and Hongshan District (which is located near Baishazhou Viaduct and Xiongchu Avenue Viaduct). Regarding the distribution pattern for ecological space (Figure 9c), the ecological space is mainly distributed in natural settings and near scenic spots. The overall distribution pattern is beaded, such as for the Donghu Scenic Area and Moshan Scenic Area in Hongshan District, the Yellow Crane Tower Park in Wuchang District, the Garden Expo Park in Qiaokou District, and Guqintai in Jiang'an District. Regarding the distribution pattern for mixed space (Figure 9d), the distribution of mixed space is relatively concentrated, being mainly in Jiang'an District and Hanyang District situated along the Yangtze River and Canglang Pavilion in Wuchang District. These areas are mainly in the old part of the city and where a large number of commercial, office, and living areas are located. This area also contains service facilities and residential land; thus the area enjoys a strong mix of functions.

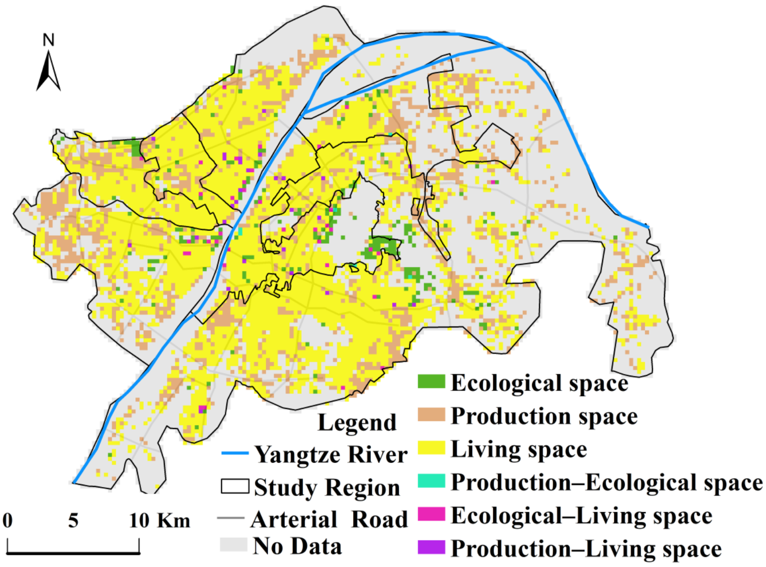

Figure 8. Identification results for the production–living–ecological space.

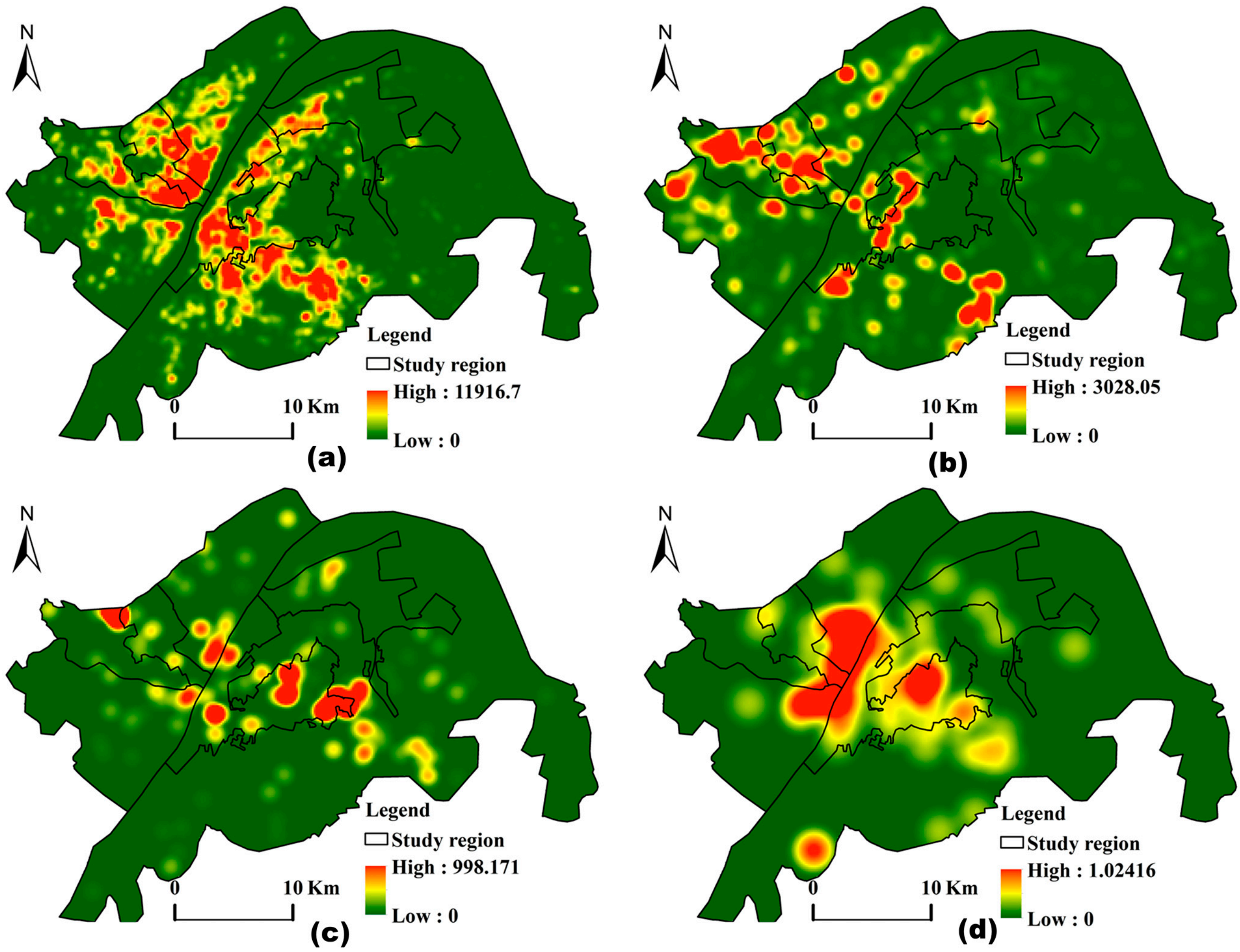

Figure 9. Kernel density analysis of production–living–ecological space. (**a**) Kernel density analysis of living space; (**b**) Kernel density analysis of production space; (**c**) Kernel density analysis of ecological space; (**d**) Kernel density analysis of mixed space.

3.1.3. Verification of Identification Results of Production–Living–Ecological Space

The study selected 28 areas at random for verification, each having an area of 1000 m $\times$ 1000 m. Comparing the identification results of production–living–ecological space with the planning map of Wuhan's main urban area (2010–2020), the results are shown in Figure 10 and Table 3. The verification results show that the number of areas that were consistent/basically consistent with the planning chart reached 26 (20 consistent; 6 basically consistent), accounting for 92.86% of the total. There were two verification areas that were inconsistent with the planning map, which is the reason why there were no POI data for mountains, forests, and waters. For example, the verification area numbered 11 is forested mountains. It can be seen from the verification that the method of identifying the production–living–ecological space in the central city area based on POI data has certain accuracy and operability.

Table 3. Verification of identification results for production–living–ecological space.

Verification Area	Space Type	Land-Use Status	Validation Results
1	Living–production space	Industrial land, warehousing land, residential land	Consistent
2	Living–production space	Education and research land, residential land	Basically consistent
3	Living space	Business and financial land Education and research land	Basically consistent
4	Living–production space	Residential land	Basically consistent
5	Living space	Residential land Education and research land	Consistent
6	Living space	Residential land Education and research land	Consistent
7	Ecological space	Mountains and scenic spots	Consistent
8	Living–production space	Business and financial land Education and research land Residential land	Consistent
9	Living space	Residential land	Consistent
10	Living space	Residential land	Consistent
11	Living space	Green space, scenic spots	Inconsistent
12	Living–ecological space	Education and research land Residential land, green space	Consistent
13	Living–production space	Residential land Business and financial land	Consistent
14	Living–production space	Business and financial land Education and research land Residential land	Consistent
15	Living–production space	Business and financial land Residential land	Consistent

Table 3. *Cont.*

Verification Area	Space Type	Land-Use Status	Validation Results
16	Production–living–ecological space	Business and financial land	Consistent
		Residential land	
		Management land	
		Green space	
17	Living–production space	Industrial land	Basically consistent
18	Ecological–living–production space	Business and financial land	Consistent
		Residential land	
		Management land	
		Green space	
19	Living–production space	Green space, residential land	Consistent
20	Living–production space	Business and financial land	Consistent
		Residential land	
		Education research land	
		Medical land	
21	Living–production space	Residential land	Basically consistent
		Green space	
		Municipal land	
22	Living–production space	Residential land	Consistent
		Management land	
		Cultural land	
		Entertainment land	
		Business and financial land	
23	Living–production space	Residential land	Consistent
		Transportation land	
		Business and financial land	
24	Ecological space	Residential land	Inconsistent
		Business and financial land	
		Green space	
25	Living space	Residential land	Basically consistent
		Roads	
26	Living–production space	Residential land	Consistent
		Business and financial land	
		Hospitals and clinics	
27	Production space	Industrial land	Consistent
28	Production space	Industrial land	Consistent

Description: Consistent means that the content of the field "Space Type" is the same as that of the field "Land-Use Status". Basically consistent means that the field "Space Type" and the field "Land-Use Status" are mostly the same. Inconsistent means that the field "Space Type" and the field "Land-Use Status" are mostly different.

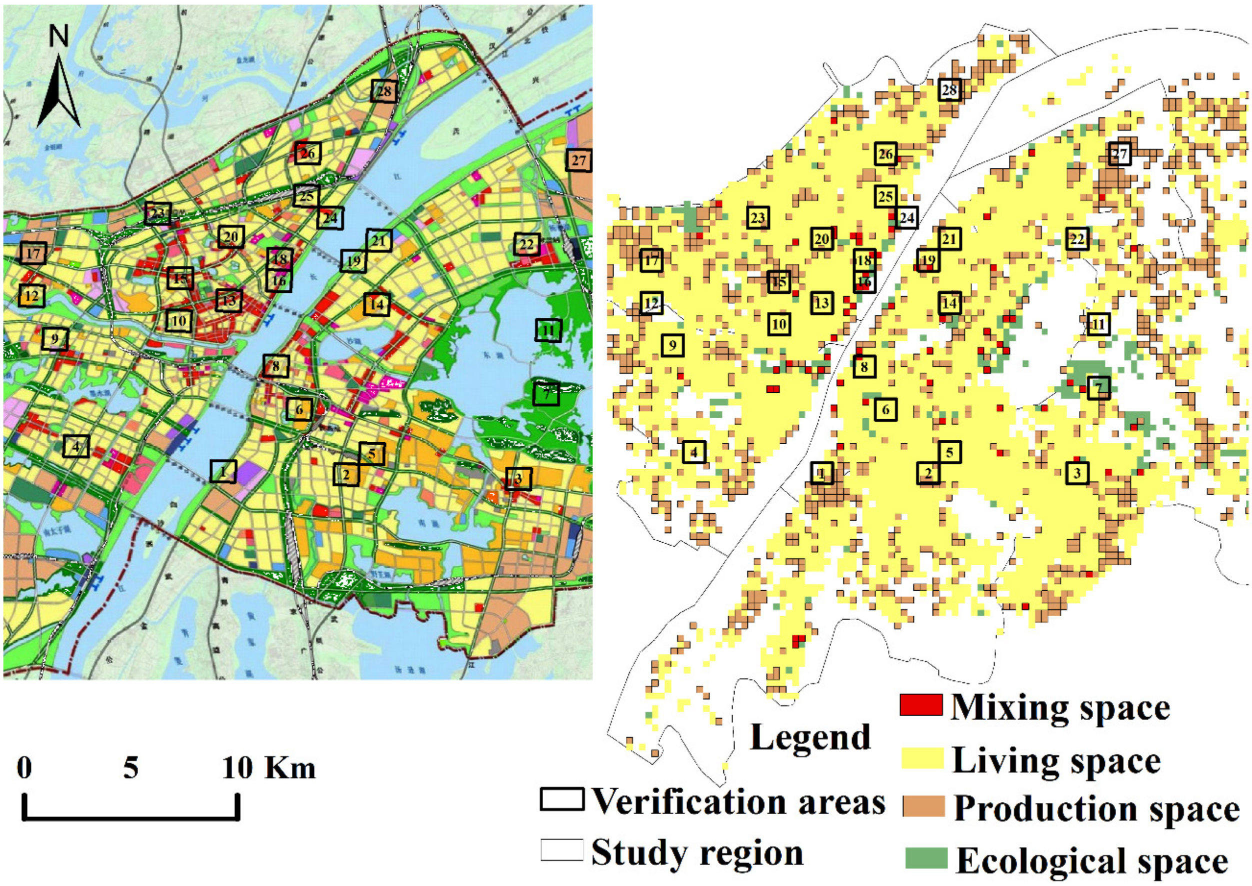

Figure 10. Verification results for the production–living–ecological space identification results. Description: (**a**) the planning map of Wuhan's main urban area (2010–2020); (**b**) the identification results of production–living–ecological space.

3.2. Correlations of the Distribution Characteristics for Production–Living–Ecological Space

The spatial auto-correlation method was used to analyze the production–living–ecological space and to explore the spatial agglomeration rules among the constituent elements of the production–living–ecological space. A 300 m × 300 m grid unit was constructed, and then the GeoDa software was used to establish the space weights according to Queen contiguity; global auto-correlation analysis was then performed on the production space, living space, and ecological space. The analysis results passed the 0.01 significance test, and the $Moran's\ I$ values were 0.379, 0.649, and 0.292, respectively. The results indicate that there was clear spatial auto-correlation in the production, living, and ecological space, and there were significant agglomeration characteristics in space; in particular, the living space had the highest degree of agglomeration. To further explore the interrelationships between production, living, and ecological space, a bivariate global auto-correlation analysis was carried out. The analysis results are shown in Table 4, and the data passed the 0.001 significance level test. It can be seen from Table 4 that the correlation between the living space and the production space was the highest, with an i value of 0.386, followed by the correlation between the ecology space and the living space, which had an i value of 0.128. The lowest correlation was between the ecological space and the production space, which had an i value of 0.07. These results show that the urban production and living spaces complemented each other and provided development support and opportunities for each other [20]. The ecological space and the production space had a low correlation, and this is related to the extensive production and development processes that have an adverse impact on the ecological environment.

Table 4. Spatial auto-correlation results for the production–living–ecological space (univariate and bivariate).

	Ecological	**Living**	**Production**
Ecological	0.292	0.128	0.07
Living		0.649	0.386
Production			0.379

A univariate global spatial auto-correlation analysis was performed on the constituent elements of the production–living–ecological space (Table 5). The analysis results all passed the 0.01 significance test, indicating that there was a significant agglomeration feature. For the living space, the range for the $Moran's\ I$ values (from high to low) was as follows: life services (0.585) > residential buildings (0.478) > medical treatment (0.46) > government agencies (0.458) > hotel catering (0.451) > science and education (0.443) > retail monopolies (0.437) > sports and leisure (0.38) > supermarket shopping (0.377) > communal facilities (0.32) > public squares (0.07). The concentration of living services and residential elements was the highest. For the production space, the range for the $Moran's\ I$ values (from high to low) was as follows: transportation (0.594) > financial services (0.346) > corporate enterprises (0.319) > factories (0.222) > auto services (0.177) > warehousing logistics (−0.001). The degree of agglomeration of transportation facilities was the highest, which is a reflection of the high degree of convenience of transportation in the central part of Wuhan. This was followed by financial services and then corporate enterprises. Warehousing logistics presented negative correlation characteristics and was relatively scattered, which is consistent with the actual geographic distribution of warehousing logistics. With respect to the ecological space, the $Moran's\ I$ value for scenic spots was 0.365, and the $Moran's\ I$ value for parks and wetlands was 0.052, which indicates that the spatial concentration of scenic spots was higher than that of parks and wetlands.

Table 5. Spatial auto-correlation $Moran's\ I$ values for the elements of living space (univariate and bivariate).

	101	**102**	**103**	**104**	**105**	**106**	**107**	**108**	**109**	**110**	**111**
101	0.458	0.092	0.302	0.345	0.320	0.404	0.461	0.373	0.229	0.342	0.313
102		0.07	0.09	0.091	0.125	0.086	0.108	0.107	0.034	0.08	0.085
103			0.32	0.276	0.256	0.286	0.343	0.307	0.181	0.304	0.211
104				0.38	0.333	0.365	0.446	0.391	0.195	0.331	0.312
105					0.443	0.318	0.388	0.35	0.153	0.276	0.335
106						0.46	0.485	0.383	0.214	0.332	0.332
107							0.585	0.484	0.283	0.441	0.388
108								0.451	0.218	0.376	0.334
109									0.377	0.265	0.165
110										0.437	0.267
111											0.478

Description: government agencies (101), public squares (102), communal facilities (103), sports and leisure (104), science and education (105), medical treatment (106), life services (107), hotel catering (108), supermarket shopping (109), retail monopolies (110), residential buildings (111).

A bivariate global spatial auto-correlation analysis was carried out on the constituent elements of the production–living–ecological space (Table 6); the analysis results show that all passed the 0.01 level significance test, which indicates that there is a certain spatial correlation among the constituent elements of the production–living–ecological space. With respect to the living space, if the $Moran's\ I$ value is greater than 0.35, then it is considered that the spatial correlation between the elements is high. According to the above rules, the following conclusions were made. The elements closely related to residential buildings were life services (0.388); the elements closely related to the retail monopolies were life services (0.441) and hotel catering (0.376); the elements closely related to hotel catering were government agencies (0.373), sports and leisure (0.391), science and education (0.35), medical treatment (0.383), and life services (0.484); the elements closely related to life services were government agencies (0.461), sports and leisure (0.446), science and education (0.388), and medical treatment (0.485); the elements closely related to medical treatment were government agencies (0.404) and sports and leisure (0.365). It can be seen from the above findings that life services are closely related to the other constituent elements. Thus, around the life services facilities which are concentrated in the central part of Wuhan, the other elements tend to agglomerate. Public squares had the lowest correlation with the other components. The univariate and bivariate spatial auto-correlation analysis values were low, the spatial distribution was relatively scattered, and the spatial correlation with other elements was extremely low; with respect to production space, transportation and financial services and corporate enterprises had the highest degree of relevance with $Moran's\ I$ values of 0.413 and 0.347, respectively, indicating that around transportation, corporate enterprises and financial services tended to agglomerate as a result of convenient access to the transportation network. The degree of correlation between financial services and corporate enterprises (0.281) was relatively high; in the ecological space, the value of parks and wetlands and scenic spots was 0.037, which is low.

Table 6. Spatial auto-correlation for the $Moran's\ I$ values for the production space elements (univariate and bivariate).

	201	**202**	**203**	**204**	**205**	**206**
201	0.594	0.051	0.072	0.347	0.413	0.007
202		0.177	0.046	0.064	0.036	0.01
203			0.222	0.11	0.04	0.018
204				0.319	0.281	0.02
205					0.346	0.013
206						−0.001

Description: transportation (201), auto services (202), factories (203), corporate enterprises (204), financial services (205), warehousing logistics (206).

3.3. Analysis of Impact Factors

The results for detection of the factors affecting living space are presented in Table 7. The respective q values are as follows: life services (0.771) > hotel catering (0.707) > retail monopolies (0.663) > residential buildings (0.551) > medical treatment (0.531) > sports and leisure (0.525) > science and education (0.505) > supermarket shopping (0.460) > government agencies (0.411) > communal facilities (0.232) > public squares (0.028). It can be seen that the life services elements play a leading role in the formation of living space; hotel catering also has a considerable impact on the living space. The interactive detector method reveals that the q value for any two factors is greater than the q value for a single factor, which means that the interaction of any two factors has a stronger impact on living space than that of a single factor. Among them, the interactions between the life service elements and other elements play a leading role, the average q value being 0.799; this is followed by the interactions between hotel catering and the other elements, which play a secondary role, the average value being 0.757.

Table 7. q Values for the living space elements.

	101	**102**	**103**	**104**	**105**	**106**	**107**	**108**	**109**	**110**	**111**
101	0.411										
102	0.428	0.028									
103	0.486	0.249	0.232								
104	0.654	0.530	0.584	0.525							
105	0.629	0.511	0.584	0.664	0.505						
106	0.627	0.543	0.594	0.679	0.703	0.531					
107	0.806	0.776	0.788	0.803	0.834	0.787	0.771				
108	0.775	0.712	0.727	0.756	0.790	0.760	0.828	0.707			
109	0.632	0.478	0.545	0.704	0.745	0.677	0.836	0.801	0.460		
110	0.735	0.670	0.691	0.749	0.783	0.737	0.820	0.788	0.708	0.663	
111	0.643	0.562	0.629	0.715	0.710	0.697	0.841	0.812	0.735	0.807	0.551

Description: government agencies (101), public squares (102), communal facilities (103), sports and leisure (104), science and education (105), medical treatment (106), life services (107), hotel catering (108), supermarket shopping (109), retail monopolies (110), residential buildings (111).

The detection results for the production space elements are shown in Table 8. The respective q values are as follows: corporate enterprises (0.846) > financial services (0.475) > transportation facilities (0.346) > factories (0.167) > auto services (0.109) > warehousing logistics (0.004). It can be seen that corporate enterprises play a leading role in the formation of production space, followed by financial services. The detection results show that the interaction of any two elements has a stronger impact on the production space than that of a single element; that is, an enhancement effect is realized for the former. Among them, the interactions between the transportation facilities and warehousing logistics, auto services and warehousing logistics, and factories and warehousing logistics show a non-linear enhancement effect, and the others show a two-factor enhancement effect, indicating that transportation facilities, auto services, and warehousing logistics play an important role in the distribution of production space. It is worth noting also that the interactions between the corporate enterprises and other elements are the most prominent, with a mean q value of 0.881, which shows that the interactions between the corporate enterprises and other elements play a leading role in the impact of production space. The second most prominent interactions are the interactions between financial services and other elements, with an average q value of 0.648, again showing that financial services play an important role in the development of production industries.

Table 8. q Values for the production space elements.

	201	**202**	**203**	**204**	**205**	**206**
201	0.346					
202	0.427	0.109				
203	0.467	0.257	0.167			
204	0.884	0.880	0.879	0.846		
205	0.539	0.559	0.608	0.884	0.475	
206	0.362	0.113	0.172	0.848	0.477	0.004

Description: transportation (201), auto services (202), factories (203) corporate enterprises (204), financial services (205), warehousing logistics (206).

The detection results for the ecological space elements are presented in Table 9. The respective q values are as follows: scenic spots (0.686) > parks and wetlands (0.329). Clearly, scenic spots play a major role in the distribution of ecological space, followed by park and wetlands. Given that the parks and wetlands are, in the main, formed naturally, the formation process is relatively slow, and they are typically some distance from the urban center; thus the impact on the ecological space is also a gradual process. Most of the scenic spots are constructed artificially; hence such scenic spots or artificial green spaces with a limited area are formed over a short time scale. With improvement in people's material lifestyles, the demand for scenic spots is increasing, and the construction of scenic spots is gradually speeding up. The detection results reveal that the q values for the interactions between the scenic spots and the parks and wetlands were 0.929, thus showing a significant two-factor enhancement effect and indicating that the interactions between scenic spots and the parks and wetland play a leading role in the formation and distribution of the ecological space. Therefore, it is recommended that the construction of scenic spots should be integrated with the development of parks and wetlands so that the synergistic effect of the two elements may be exploited.

Table 9. q Values for the ecological space elements.

	301	**302**
301	0.686	
302	0.929	0.329

Description: scenic spots (301), parks and wetlands (302).

4. Discussion

This paper found that compared with other methods, POI data can go deeper into the central urban area level and identify the production–living–ecological space of the central urban area in a simpler and more precise way. At the same time, they can also distinguish functional space combination and analyze the evolution law of production–living–ecological spatial pattern and their mutual relations in grid scale, laying a foundation for improving space optimizing theory and enriching the regulation and control strategies in the central urban area which makes it convenient for government departments to make more scientific decisions on the urban planning and orientation because POI data show the distribution pattern and utilization intensity of human activity space in point-line—an area data structure that can better analyze the human–environment interaction mechanism.

Although POI data can effectively represent geographic information, there are still some shortcomings. Given that POI data are essentially point elements, it is difficult to express accurately area information of geographical entities over a large area (e.g., airports), which can result in inaccurate expression of the spatial distribution of the elements of interest. Ultimately, it is necessary to combine the analysis of land-use data and the public's recognition of the area of the geographic entity and take the area information into more careful consideration in order to measure the "quantity" and "quality" of the production–living–ecological functions more accurately. In addition, the POI classification system for production–living–ecological space does not yet constitute a unified standard, which is to be improved. Further research is to be conducted in fields such as POI classification system construction and integration of POI data and other data (the traditional socio-economic data, remote sensing data, and so on) so as to contribute to the sustainable development of spatial planning themed "green and beautiful ecological space, intensive and efficient production space and livable and moderate living space".

Drawing on the above research, an optimization strategy concerning the production–living–ecological space in a central urban area should pay attention to the following issues. First, the essence of sustainable use of spatial planning is the coordination and optimization of the production, living, and ecological functions. More attention should be paid to ecological space, and there should be better coordination with regard to the relationship between production and ecological space; in particular, there is a need to avoid any deterioration of ecological space at the expense of growth in the production space. Second, around the nodes of the living space, rational plans and arrangements should be made to develop the space of the living service industries, improve the living support facilities including social security, and ensure that the living space created is attractive and comfortable. Third, as a priority, there should be rational planning with respect to the spatial distribution of the corporate and financial services elements of companies; a comprehensive and efficient transportation network should also be developed, as well as specialized functional clusters in selected industries such that an intensive and efficient production space is generated. Fourth, there should be systematic planning for element spaces such as ecological green space, ecological scenic spots including parks and wetlands, landscape enhancement, and increased supply of ecological land supply in order to create an agglomeration effect of ecological functions.

5. Conclusions

The rapid advancement of industrialization and urbanization has also brought unprecedented impact and shock to the rational distribution and development of the urban space. Using the central urban area of Wuhan as a case study, and according to the formation mechanism and definition of urban production–living–ecological space, Python was used to crawl urban POI data and construct a classification system for production–living–ecological space. On this basis, the analytic hierarchy process, the GIS spatial analysis method, the quadrate proportion method, and other methods were used to identify the production–living–ecological space in the central area of Wuhan; moreover, the mechanisms that influence the production–living–ecological space were explored using the spatial auto-correlation analysis method and the Geo-detector method. The results show that: (1) The identification method based on the POI data can better identify the production–living–ecological space in the central area of Wuhan, the identification accuracy being 92.86%. The identification method is practical, is based on sound scientific principles, and provides a theoretical and methodological basis for exploration of urban spatial planning. (2) In terms of the spatial distribution pattern, the central urban area of Wuhan is dominated by living space, followed by production space and, finally, ecological space. The living space is distributed randomly along the north and south banks of the Yangtze River, showing distinct distribution patterns along the river banks and inland from the river; the production space is concentrated and distributed on the north and south banks of the Yangtze River, and the spatial pattern is beaded and dotted; the distribution pattern is mainly associated with closeness to the main traffic routes. The ecological space is clustered and distributed around natural scenery and around the scenic spots on the north and south banks of the Yangtze River, again presenting a beaded distribution pattern. Mixed spaces are clustered and distributed along the north and south banks of the Yangtze River and are embedded in the living space, the production space, and the ecological space. (3) Life services elements and their interactions with other elements play a leading role in the distribution of living space. Corporate enterprises play a leading role in the distribution of production space. Interactions between the various elements have a linear enhancement effect on the distribution of production space. The interactions between transportation facilities and other elements play key roles with respect to the production space. The presence of scenic spots plays a leading role in the distribution of ecological space, and the synergistic effect of scenic spots on parks and wetlands far exceeds the effect of the single elements on their own on the ecological space. (4) There is a significant spatial auto-correlation of production–living–ecological space, among which the concentration of the degree of living space is the most significant. The living space is closely related to the production space and is interlaced and inlaid with respect to the respective spatial distributions. With respect to the living space, the degree of concentration of the life service elements and the elements of residential buildings is the highest, and the correlation with other elements of the living space is strong, highlighting the importance of life services and residential buildings elements in urban spatial planning. With respect to production space, the transportation facilities element shows significant agglomeration, and correlation with other elements in the production space is also clear. It can be seen that transportation facilities play a leading role in the planning of production space. In addition, corporate enterprises and financial services readily form in clusters and are linked to convenient transportation networks as evidenced by the correlations between them. With respect to the ecological space, the correlation between scenic spots is relatively high, but the correlation between scenic spots and parks and wetlands is not significant in the context of ecological space.

The research proves that the method in this paper is simpler and more precise to identify the production–living–ecological space in the central urban area, which is also more scientific and practical, and provides useful exploration for the sustainable development of urban spatial planning. The rise of geographic big data (such as POI data) provides new opportunities and perspectives for the realization of the simulation and inference of geographic systems and the exploration of the development rules and trends of complex urban space. Researchers should make full use of spatial statistical analysis methods and continuous exploration in geographical big data analysis methods and mathematical models, strengthen regional empirical research, and build a disciplinary collaborative research system to embrace the new opportunities of research in urban planning brought by geographical big data.

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