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Measuring urban sprawl and exploring the role planning plays: A shanghai case study

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ABSTRACT

Measuring the degree of urban sprawl largely depends on the local context and available data. This research establishes a multidimensional index which combines city expansion, urban compactness and urban form to measure sprawl. Urban planning, as part of the state-led growth approach, has exerted dramatic impact on city growth in China. Recent studies have discussed the role of planning in city growth. However, measuring the impact of planning on sprawl, has not been conducted. Taking Shanghai as a case study, this paper builds a multidimensional index to measure the spatio-temporal characteristics of urban sprawl in Shanghai from 1990 to 2010. It finds that urban sprawl was more serious in 2000s than in the 1990s, and the sprawl also presents spatial heterogeneity within different areas of the city. While quantifying the role of planning in urban sprawl, this study adopts the Geo-Detector based on spatial variation analysis of the geographical strata in order to assess the impact of planning on urban sprawl. It finds that planning is strongly correlated with urban sprawl, in other words, urban sprawl is kind of a "planned sprawl" in Shanghai. The research concludes with future planning policies necessary for a more sustainable and compact development pattern.

1. Introduction

As China has become increasingly urbanized, most of its cities have exhibited high growth rates and fragmented patterns of urban expansion, especially at the city outskirts (Yeh and Wu, 1996; Yu et al., 2007). When first introduced to China in the 1980s, (Fung, 1981), the notion of urban sprawl was often referred to as rapid urban growth (Wu and Yeh, 1997,1999). The concept was then extended to the inefficient spatial development pattern on the urban fringe (Deng and Huang, 2004; Wei and Zhao, 2009). Different from sprawl seen in Western cities, which is mainly driven by lifestyle changes (Squires, 2002), sprawl in China is significantly influenced by the state. In the context of an imperfect land market and decentralization process, local governments have become the de facto facilitator to guide market forces and achieve economic growth (Zhu, 2005). Driven by the incentive to maximize benefits from land leasing and pressure from developers to acquire land, local governments have tended to oversupply land, leading to urban sprawl problems (Tian, 2014).

There has been a wealth of literature documenting the methods for measuring sprawl and comparing the degree of sprawl among a diverse set of cities (Galster et al., 2001; Lopez and Hynes, 2003; Tsai, 2005; Jiang et al., 2007; Schneider and Woodcock, 2008; Bhatta et al., 2010a, 2010b; Zhang et al., 2014). Studies on sprawl have focused primarily on U.S. cities, but recent studies across the globe have emerged, such as in Europe (Antrop, 2004; Kasanko et al., 2006), China (Deng and Huang, 2004; Zhang et al., 2013; Jiang et al., 2016), India (Bhatta et al., 2010b) and Israel (Frenkel, 2004).

Given the varying contexts, indicators measuring sprawl differ from country to country. Direct comparisons among global cities from different geographical settings have also appeared using remotely sensed data and census information (Schneider and Woodcock, 2008). In China, some studies on urban sprawl have examined the spatio-temporal change of landscape based on time-series data (Yu et al., 2007; Jiang et al., 2016; Zhang et al., 2016), but studies on the complexity of sprawl and its driving forces have been fairly scarce (Yue et al., 2007; Zeng et al., 2014; Yue et al., 2016). Moreover, given the difficulty of obtaining sufficient social, economic and land use data, the indicators which are applied in developed countries are not easily applied in developing countries. For instance, in China, information on employment, residential unit, and land use data at the street community (*Jiedao*[1] in Chinese) or township is not available. How planners can design a

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[1] *Jiedao*/township is the smallest geographic unit where census data can be achieved in China, and *Jiedao* is located in the urban area, while township is located in the rural area.

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method to accurately identify the degree of sprawl based on limited data in the local context remains a critical issue.

In China, a city master plan has significant impact on city growth and the real estate market because the arrangement of infrastructure facilities can change land values in certain areas. A city master plan forecasts the size and boundary of a city built-up area and its population over a 20 year period, designates areas for various types of land use, such as residential, commercial, industrial and farmland, and arranges major infrastructure and citywide social amenities (Tian and Shen, 2011). Different from population growth, the growth boundary designated by the master plan has been an essential and tangible tool to guide city growth. During the past three decades, Chinese urbanization took a formal form of industrial zones and planned new towns, and planning was used by local governments to maximize land income or to open up new spaces for growth in order to generate taxes, and was a powerful tool for growth. Therefore, planning contributes to the operation of the local growth machine (Wu, 2015; Tian et al., 2017). To what extent planning has curbed or accelerated urban sprawl is worth further research.

In this research, we select Shanghai as a case study, and three temporal satellite images at 10 years intervals (1990, 2000 and 2010) have been classified to determine urban growth. We develop a multi-dimensional index method combining the evaluation of city expansion, urban compactness, and urban form to measure the degree of urban sprawl at the spatial level of the *Jiedao* or township, and analyze the spatio-temporal characteristics of urban sprawl from 1990 to 2010. Then, we adopt geographical detectors proposed by Wang et al. (2010) based on spatial variation analysis of the geographical strata to assess the impact of planning on urban sprawl.

This paper is organized as follows: the first section reviews literature on methods of measuring urban sprawl and characteristics of Chinese urban sprawl. The following section provides a method for measuring city growth and compares the change of degree of sprawl in Shanghai from 1990 to 2000 and 2000 to 2010. Next, this research applies the Geo-detector to examine the impact of planning on urban sprawl. The paper concludes with future policies necessary for a more sustainable and compact development pattern.

2. Measuring urban sprawl

Urban sprawl is an inefficient spatial pattern of urban expansion, representing one end of the continuum in contrast with the “compact” city form (Ewing, 1997). Despite the ambiguous and controversial definition of urban sprawl, common agreement exists as to its specific characteristics: low density or single-use development; scattered or leapfrog expansion; excessive spatial growth; segregated land use; and auto-dependency (Gordon and Richardson, 1997; Ewing, 1997; Brueckner, 2000; Galster et al., 2001; Lopez and Hynes, 2003). During recent decades, planners have widely studied and documented the socio-economic costs and the negative impact of urban sprawl such as increasing loss of land resources, environmental degradation, and the growing lack of accessibility to jobs, etc. (Burchell et al., 1998; Kahn, 2000; Johnson, 2001). Particularly, the land-consumptive and inefficient nature of sprawl is well acknowledged (Hasse and Lathrop, 2003).

In order to quantify the dimension and degree of urban sprawl, several new indices have emerged. They are usually one or two dimensional, focusing on population density (Fulton et al., 2001; Lopez and Hynes, 2003), land expansion (Yu et al., 2007; Burchfield and Overman, 2006) and job accessibility (Weitz and Crawford, 2012). For instance, researchers compare the growth ratio of urban land conversion in conjunction to population change to quantify the relative intensity of sprawl (Fulton et al., 2001; Kasanko et al., 2006). Sprawl has also been measured by the degree of equal distribution of built-up areas, using methods like the relative entropy or Gini coefficient (Tsai, 2005; Bhatta et al., 2010a; Martellozzo and Clarke, 2011; Hu et al., 2015). While these single dimensional measures are easy to calculate with existing available data, they seldom consider the negative social and environmental impact associated with sprawl (Ewing and Hamidi, 2015).

Recently, studies have conceptualized urban sprawl as a multi-dimensional phenomenon (Frenkel and Ashkenazi, 2005), and a number of multidimensional indices have been developed. In general, sprawl measures can be divided into five major independent dimensions which identify different types and extents of sprawl, including growth and change rates, density, spatial-geometry such as fragmentation, accessibility, and land resource loss (Galster et al., 2001; Frenkel and Ashkenazi, 2005; Hasse and Lathrop, 2003; Cutsinger et al., 2005; Tsai, 2005). In the first of the multiple indices, this one developed by Galster et al(2001), sprawl is defined as a pattern of land use that presents low levels in at least one of eight distinct dimensions: density, continuity, concentration, clustering, centrality, nuclearity, mixed use, and proximity. Then, Ewing et al. (2002) extend the indices with a wider degree of variability and use the principal component analysis (PCA) to cluster the sprawl areas. Similarly, Frenkel and Ashkenazi (2005) identify three dimensions of sprawl: density, scatter (or fragmentation), and mix of land-uses. Hasse and Lathrop (2003) developed a series of five indicators to measure the costs and negative externalities of sprawl on land resources.

Despite some drawbacks such as redundant information (Schneider and Woodcock, 2008; Bhatta et al., 2010b), multidimensional measures of sprawl based on pattern metrics are useful to analyze the complex nature of sprawl (Ewing and Hamidi, 2015). In recent studies, many researchers have further updated and refined the original indices and conducted empirical analysis to capture changes in sprawl patterns over time in different areas (Sarzynski et al., 2014; Hamidi and Ewing, 2014). Nevertheless, the main problem associated with sprawl measurement is the failure to define the threshold between sprawling and non-sprawling (Bhatta et al., 2010b). Unfortunately, sprawl is still a relative concept today and its measurements vary from region to region.

3. Chinese urban sprawl and its causes

Chinese urban sprawl presents several similar characteristics with the U.S. context such as dispersed and fragmented development, a main pattern of new development zones and semi-urbanized villages, urbanized areas growing faster than actual population, and a significant loss of critical cultivated and forested land resources (Zhang, 2000; Deng and Huang, 2004; Yu et al., 2007; Tian et al., 2017). The differences, however, are quite apparent. For instance, low-density and commercial strip development are not characteristics of sprawl in most Chinese cities (Zhang, 2000). On the contrary, sprawl is sometimes accompanied with a fairly high population density, especially in some fringe villages (Schneider and Woodcock, 2008; Wei and Zhao, 2009). Additionally, the Chinese central city is still a booming area rather than a declining one as seen in many large U.S. cities. These differences reveal distinct driving forces behind the sprawl pattern in China.

As a result of suburbanization, urban sprawl in Western cities is derived from a combination of both market and government failures (Ewing et al., 2015). Given the externality of land markets, government reactions may aggravate market distortions by providing subsidies for automobiles and establishing land-use regulations to control outcomes (Ewing, 1997). In other words, sprawl is not simply a natural response to market forces, but a product of market imperfections and government actions. Similarly, Chinese urban sprawl is also the result of a combination of market forces and government actions (Zhang, 2000; Yu et al., 2007). Both state-led growth and the bottom-up model have significantly contributed to scattered and fragmented development (Zhu and Hu, 2009; Tian and Zhu, 2013).

Urban sprawl in China takes root in the imperfect and uneven land market reform (Yeh and Wu, 1996; Ding, 2003; Deng and Huang, 2004). Since the land reform in the 1980s, a dual system of land

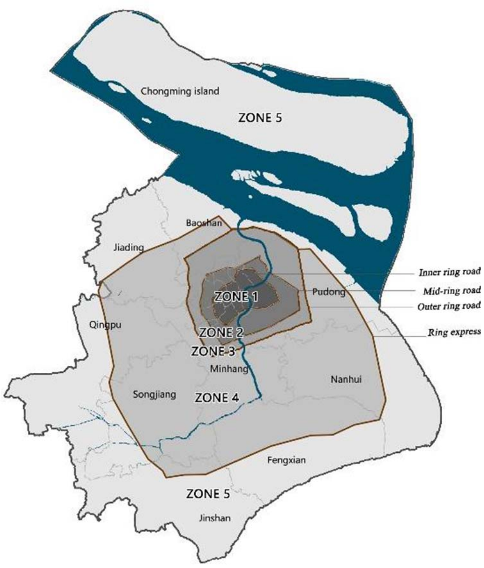

Fig. 1. Identification of zones in Shanghai.

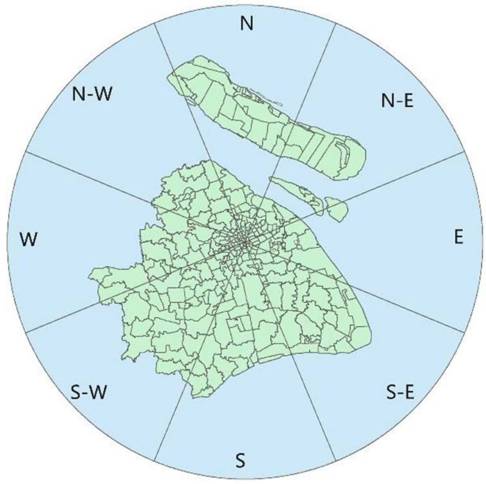

Fig. 2. Identification of sectors in Shanghai.

ownership has been established, with urban and rural land each having a fundamentally different property rights structure. The resulting gap between urban land prices and low compensation standards for acquiring rural land drives local governments to expropriate rural land and develop new urban areas such as the New Development Zones (Yeh and Wu, 1996; Zhang, 2000; Deng and Huang, 2004).

The decentralization process of decision-making since 1994 is another factor necessary for understanding Chinese sprawl (Zhang, 2000; Zhao, 2011). A considerable amount of decision making power, including land use regulation and financial decisions given to local governments allow local governments to dispose of land based on their economic interests (Zhu, 1999; Zhang, 2000). Under this circumstance, land leasing revenue has become the most popular source of fiscal benefits for local governments (Zhang, 2000). To maximize revenue gains and attract investment, local governments eagerly encourage city growth though land leasing, which eventually results in rapid urban expansion and serious urban sprawl (Wu and Yeh, 1999; Deng and Huang, 2004; Tian, 2014). Additionally, the revenue-enhancing development drives local governments to loosen control and management for urban growth, especially in suburban areas (Zhao, 2011). As a consequence, Chinese urban sprawl has been prevalent.

In China, recent studies have quantified the spatial characteristics of sprawl based on single or multi-dimensional indices. For instance, Jiang et al. (2007) select three types, with a total of 13 indicators, including landscape change, city growth efficiency and impacts of growth to measure the urban sprawl of Beijing. Jiang et al. (2016) use structure entropy analysis and kernel density estimation to characterize the spatial-temporal variation of the Beijing sprawl pattern. Yue et al. (2013) adopt a leapfrog development index, population density, sprawl index, landscape metrics, and inconsistency of land use to measure urban sprawl in Hangzhou. In terms of driving forces, Zhang (2000) attributes Chinese urban sprawl to the combination of market forces and government reaction (especially at the local level) to the marketplace, and Tian et al. (2017) argue that state-led growth has played a dominant role in the expansion of non-agricultural land. Overall, multi-dimensional measures of sprawl generated from Western literature are widely accepted by Chinese scholars, but whether some indices can be directly applied to the Chinese context remains debatable (Yue et al., 2016). Meanwhile, the driving forces behind sprawl have not been adequately discussed.

4. Study area, data sources and research methods

4.1. Study area

Shanghai is located at the mouth of the Yangtze River, the longest river in China, and is the economic center of the country. Since the reform opening, Shanghai has witnessed rapid growth in population and economic strength. Its GDP grew from 78.17 billion Yuan in 1990 to 2496.5 billion Yuan in 2015. During this same time period, its population increased from 13.43 million in 1990 to 24.19 million (Shanghai Statistics Bureau, 2016). The Shanghai metropolitan area covers a land area of 6340.5 km^2 and includes 19 districts.

There are four ring roads in Shanghai, consisting of an inner ring road, a mid-ring road, an outer ring road and the ring express. The region within the outer ring road is called the central city, and the region within the inner ring road is the core area of the central city. The region between the outer ring road and ring express is the inner suburban area, and the region outside the ring express is the outer suburban area (Fig. 1). In order to measure urban sprawl throughout Shanghai, we name the area within the inner ring road (Zone 1), inner—middle ring road (Zone 2), middle-outer ring road (Zone 3), outer ring road-ring express (Zone 4), outside the ring express (Zone 5).

Besides the administrative boundary and spatial circles divided by ring roads, we divide Shanghai into eight sectors with the People's Square at the center in order to further analyze the spatial characteristics of urban sprawl in different directions of the city (Fig. 2).

4.2. Data sources

Shanghai land use vector data (1990, 2000 and 2010) is sourced from the national land use database system. The national land use database system was founded in 1996 and is updated every five years. Land use information includes eight classifications, namely cultivated land, grassland, forested land, water area, urban settlement, rural settlement, isolated construction land and unutilized land. The scale of land use vector data is 1:100,000.

The demographic data for Shanghai is from the fourth (1990), fifth (2000) and sixth (2010) National Population Censuses of the People's Republic of China and is based on the spatial unit of *Jiedao* or township. Socio-economic information, including GDP and other social and economic data are cited from statistical yearbooks (1990, 2000, and 2010) and statistical bulletins (1990, 2000 and 2010) of districts and counties

Table 1
Shanghai Urban Sprawl Indices.

	Sub-dimension	Indicator	Positive or Negative	Comprehensive Weight (CW)
City expansion	Construction land growth	Growth of construction land (X1)	Positive	0.2000
Urban efficiency	Availability of public facilities	Number of hospital beds per 1000 persons (X2)	Negative	0.0857
		Number of primary and secondary school students per 1000 persons (X3)	Negative	0.0857
	Density	Permanent population per km^2 of land (X4)	Negative	0.1714
		GDP density per km^2 of land (X5)	Negative	0.0857
	Transportation accessibility	Closest distance between town center and subway stations (X6)	Negative	0.1286
		Sum of the closest distances between the town center and district/municipal centers (X7)	Negative	0.0429
Urban form	Patch density	Number of patches per square kilometer (X8)	Positive	0.0667
	Average patch area	Mean of all of patches (X9)	Negative	0.0667
	Area of leapfrog patches	The sum of leapfrog patch areas (X10)	Positive	0.0667

Note: Consistency of overall hierarchical ranking CI = 0.0000, RI = 0.6571, CR = 0.0000; pass the test.

Table 2
Classification criteria of urban sprawl types.

Types	Range of SI value
Non-sprawl	SI < 0.00
Light sprawl	0 ≤ SI < 0.20
Medium sprawl	0.20 ≤ SI < 0.40
High sprawl	SI ≥ 0.40

Table 3
Classification criteria of urban sprawl change types.

Types	Range of CSI
Sprawl stagnation	CSI < − 0.40
Weakening sprawl	−0.40 ≤ CSI < 0.00
Ascending sprawl	−0.00 ≤ CSI < 0.40
Enhanced sprawl	CSI ≥ 0.40

in Shanghai. Moreover, information on hospital beds is cited from the *Complete Volume of Chinese Hospitals* (1991, 2001 and 2011). The number of primary and secondary school students is derived from the *Directory Database of Chinese Education Institutions 2011* (Secondary School Volume and Primary School Volume).

4.3. Research methods

Given the availability of economic and demographic data, we use the township/*Jiedao* as the spatial unit to establish urban sprawl indices. The research time framework is divided into two periods: 1990s (from 1990 to 2000), and 2000s (from 2000 to 2010).

As mentioned above, urban sprawl is a type of inefficient expansion characterized by low density, poor accessibility, and lack of sufficient public facilities. In this study, we define three dimensional indicators, namely, city expansion, urban compactness and urban form to measure urban sprawl during the two time periods in our research framework. City expansion includes growth of construction land; while urban compactness involves four sub-dimensions: availability of public facilities, population density, GDP density and access to transportation. Urban form includes three sub-dimensions: patch density, average patch area and area of leapfrog patches. Table 1 gives a brief description of the urban sprawl evaluation index system.

(1) Defining city expansion

The growth of construction land of a township/*Jiedao* is adopted as the proxy indicator of city expansion. Defining urban compactness

① Availability of public facilities: public facilities, particularly schools and hospitals, are critical for efficient land use. The lack of sufficient public facilities is often regarded as one of the characteristics of sprawl (Jiang et al., 2007). Therefore, this research uses the availability of elementary and high schools and hospitals as two indicators to characterize urban compactness; ② Density: Density is the most widely used indicator of sprawl (Galster et al., 2001; Ewing et al., 2002; Cutsinger et al., 2005). It is expressed here as the population density and GDP density within a township/Jiedao. Generally, the higher population and GDP density, the more compact the land use; ③ Transportation accessibility: Land with high accessibility is usually regarded as being more efficient than land with poor accessibility. Based on data availability, we select two indicators to represent transportation accessibility: one is accessibility to metro stations: A transit-oriented development (TOD) can maximize access to public transport, and a well-planned TOD strategy is essential for compact land development (Cabanatuan, 2016). A TOD neighborhood typically has a center with a transit station or stop. Here, we use the inverse of minimum distance to a metro station as an indicator of transportation accessibility; the other is accessibility to the city center or the district center in an urban area. Decentralization of urban areas is often cited as a cause for longer travel distances and inefficiencies in land use (Galster et al., 2001).

(2) Defining urban form

One of the major characteristics of urban sprawl is fragmentation (Galster et al., 2001). We use three indicators to measure fragmentation of urban form: patch density, average patch area, and area of leapfrog patches. Usually the higher patch density and area of leapfrog patches, the more fragmented urban form is; the larger the average patch area, the more compact urban form is. Defining urban sprawl is best done using a multi-dimensional index method.

How to weight different dimensional indicators to produce an overall score for each spatial unit remains a question. While Galster et al. (2001) weights each of the dimensions equally in calculating the index, Jiang et al. (2009) recomputed the aggregate score by granting the indicators different weights, however, they did not explain their weighting schemes. In reality, it is difficult to identify which indicator has more or less weight than others.

Weighting for indexes is a key issue for a multi-dimensional index method. This research adopts an analytic hierarchy process (AHP) to weight multiple indices of urban sprawl. AHP is a simple and flexible multi-criteria decision-making method proposed by Saaty in the 1970s. It is widely applied in the fields of sociology, economics and management science. In this research, AHP computation is completed in a DPS data processing system (advanced version, v16.05). The comprehensive

Table 4
Urban sprawl based on boundary of township/*Jiedao* in Shanghai.

	1990–2000			2000–2010		
	Township (Number)	*Jiedaos* (Number)	Land area, km^2 (percentage)	Township (Number)	*Jiedaos* (Number)	Land area, km^2 (percentage)
Non-sprawl	53	47	2962.59 (43.77%)	37	66	1381.57 (20.41%)
Light sprawl	49	40	2940.49 (43.44%)	27	29	1791.74 (26.47%)
Medium sprawl	15	19	623.81 (9.22%)	51	13	3229.48 (47.71%)
High sprawl	2	5	242.29 (3.58%)	4	3	366.39 (5.41%)

weight value of each indicator is calculated as shown in Table 1.

Based on the weight value of indexes, the calculation formula of the urban sprawl index is as follows:

$$SI = 0.2 \times 1 + 0.0857 \times 2 + 0.0857 \times 3 + 0.1714 \times 4 + 0.0857 \times 5 + 0.1286 \times 6 + 0.0429 \times 7 + 0.0667 \times 8 + 0.0667 \times 9 + 0.0667 \times 10 \quad (1)$$

Where SI represents the urban sprawl index, and X1, X2, X3 …, X10 represent indicators as shown in Table 1.

According to Formula (1), sprawl indices of townships/Jiedaos in the 1990s and 2000s are calculated and changes of urban sprawl are compared during the two decades.

(3) Classification of urban sprawl types

According to Formula (1), we calculate the sprawl index of each township/*Jiedao* in Shanghai, and analyze the numerical distribution of sprawl indices. We then refer to the results with two different classifications i.e., Natural Break Jenks and Geometrical Interval, each provided by GIS, and define the criteria for classification. The criteria are identical for both periods, making sure the results for the two periods are comparable. Based on the values of SI, we classify urban sprawl into four types: non-sprawl, light sprawl, medium sprawl, and high sprawl, as shown in Table 2.

From the 1990s to 2000s, Shanghai's urban sprawl underwent dramatic changes. In order to accurately analyze the changes of urban sprawl during these two periods, we subtract the sprawl indices of one unit in each period and then classify the change of sprawl index (CSI) into four types: sprawl stagnation, weakening sprawl, ascending sprawl and enhanced sprawl (Table 3). The classification is based on the objective distribution law of numerical value, referring to Jenks' Natural Breaks Classification Method, which can achieve maximum difference between groups and minimum difference within groups. We try to examine whether the sprawl of these townships/*Jiedao* were weakened or enhanced in the 2000s compared with the 1990s through the establishment of CSI.

5. Results and discussion

5.1. Spatio-temporal characteristics of urban sprawl of the township/Jiedao

Table 4 reveals the spatio-temporal characteristics of urban sprawl of the township/*Jiedao* in Shanghai. In the 1990s, there were 53 non-sprawling townships and 47 *Jiedaos* which comprised 43.77% of the total metropolitan area. There were only two high sprawling townships and five *Jiedaos* accounting for 3.58% of the total. In terms of spatial characteristics, non-sprawling townships/*Jiedaos* were mainly located at the urban fringe, particularly Chongming Island, Qingpu and the Nanhui district. The sprawl types of most townships/*Jiedaos* is light sprawl in most areas of Shanghai except Chongming. Medium sprawling townships/*Jiedaos* were concentrated in the south of Jiading district, and high sprawling areas were distributed in the north of Fengxian district and the middle and east of Chongming Island. Moreover, an overwhelming majority of the high and medium sprawling townships/*Jiedaos* were located west of Huangpu river, and only two were east of Huangpu river (Pudong); due to the fact that Pudong was opened not long ago and is still at the early stage of construction. It is apparent that the 1990s saw mild urban sprawl in Shanghai. Although the urban space was expanding in Shanghai, its growth was based on a fairly compact pattern.

In the 2000s, the city had a total of 37 non-sprawling townships and 66 *Jiedaos.* The area of these 103 townships and *Jiedaos* accounted for 20.41% of the city's total area. The city had 27 medium sprawling townships and 29 *Jiedaos*. Their land area accounted for 26.47% of the city's total area. In total, the areas of high and medium sprawling townships/*Jiedaos* reached 53.12% of the city, indicating Shanghai sprawl had significantly intensified.

Compared with the 1990s, the area of non-sprawl townships/*Jiedaos*

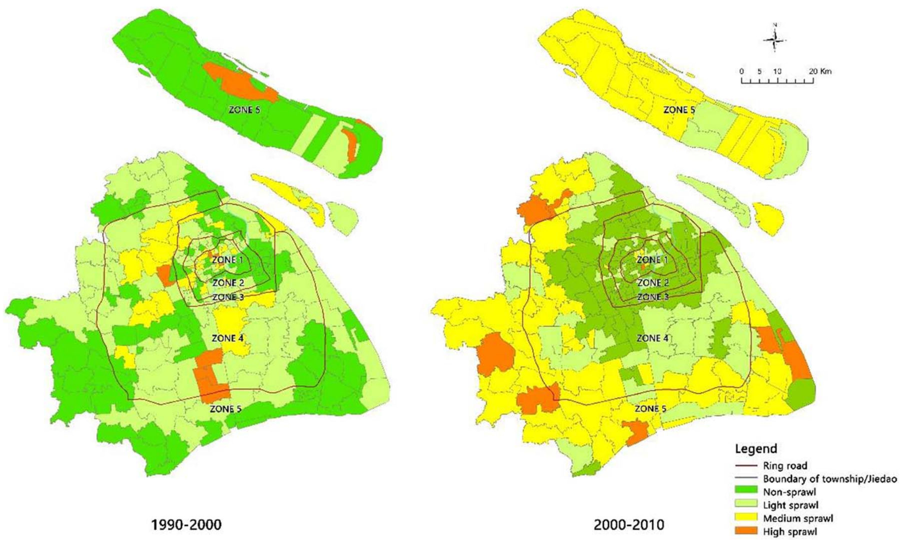

Fig. 3. Urban sprawl of township/Jiedao in Shanghai from 1990 to 2010.

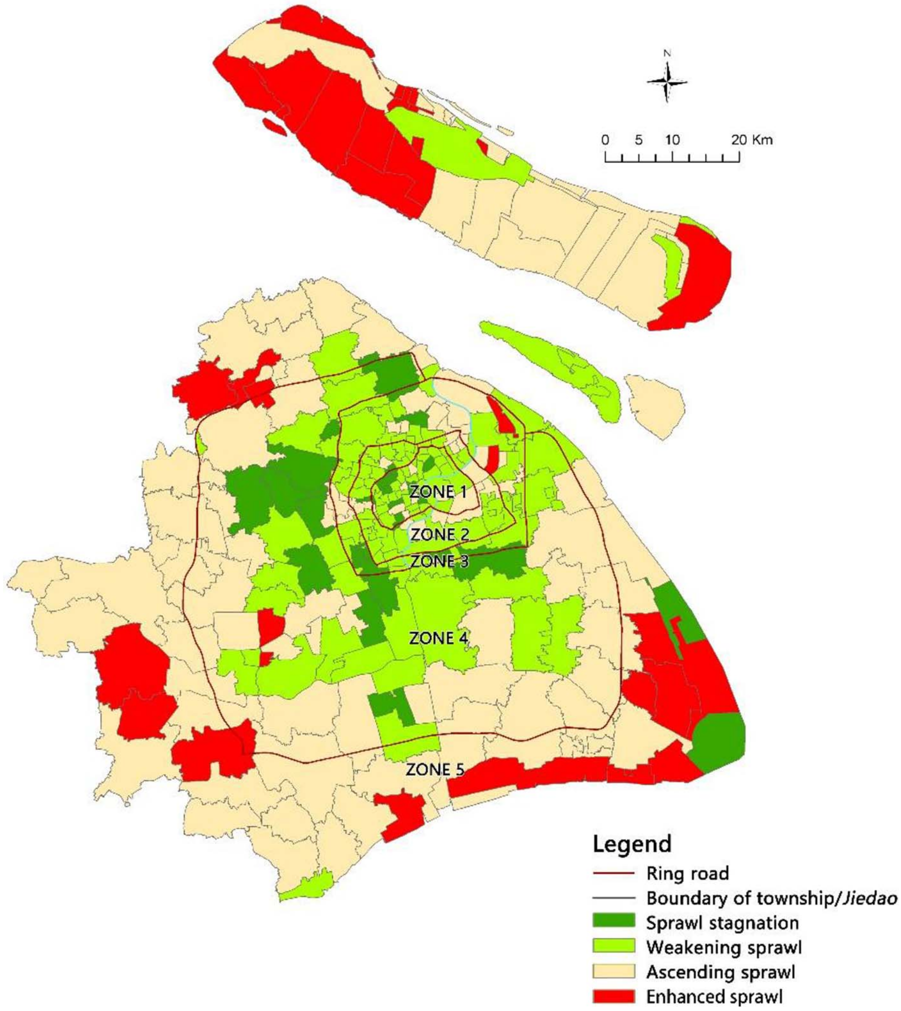

Fig. 4. Urban sprawl types based on CSI from 1990s to 2000s.

decreased by 1581 km^2, and the proportion decreased by 23.36%. The amount of light sprawling townships/*Jiedaos* fell by 16.97% in the 2000s. In contrast, the proportion of medium sprawling townships/*Jiedaos* rose by 1.83%. The growth in area of medium sprawling townships/*Jiedaos* was fastest, while the area of non-sprawl and lightly sprawling townships/*Jiedaos* declined rapidly. In general, the 2000s witnessed much faster sprawl compared with the 1990s.

In terms of change of sprawl index (CSI), there were 11 towns and 15 *Jiedaos* of the sprawl stagnation type, with an area of 457 km^2, accounting for 6.75% of the total area of the city. There were 34 towns and 57 *Jiedaos* of weakening sprawl, with an area of 1491 km^2 equal to 22% of the total area. As a whole, the area of ascending sprawl townships/*Jiedaos* and of enhanced sprawl, accounted for 71% of the total area of the city, much larger than that of sprawl stagnation and weakening sprawl. This again indicates that urban sprawl in the 2000s was much stronger than the 1990s.

5.2. Spatio-temporal characteristics of urban sprawl along ring roads

In terms of the circle layers formed by urban ring roads (Fig. 3), non-sprawling townships/*Jiedaos* were concentrated in Zones 2 and 5. Townships/*Jiedaos* with light sprawl were widely distributed rather than concentrated in any circle layers, and medium sprawling ones were mainly located in the area of Zones 1 and 4, except for a few which were scattered in Zones 2 and 3. Highly sprawling townships were distributed in Chongming Island and Zone 4, and such *Jiedaos* were alsodistributed in the downtown area within the inner ring road. In general, urban sprawl was fairly mild and there was no strong sprawl along ring roads in the 1990s, basically because the ring express was not put into operation until 2000, and the growth of urban space had not begun yet.

Different from the 1990s, sprawl along ring roads was obvious during the 2000s. Non-sprawling townships/*Jiedaos* were mainly located in the central city area (Zones 1, 2, 3 and part of Zone 4), and another several non-sprawling towns were distributed sporadically in peripheral Nanhui and Jinshan districts. Townships/*Jiedaos* with light sprawl were mainly located in Zone 4. Medium sprawling townships/*Jiedaos* were concentrated in the western and southern parts of the city and most areas of Chongming Island, and highly sprawling towns were mainly located along the ring express.

Fig. 4 shows the distribution of CSI, and we see that the sprawl stagnation type areas included *Jiedao* in the central city area (Zones 1, 2 and 3) and towns outside the outer ring road (Zone 4) and; the weakening sprawl areas were concentrated in the central city area and Zone 4. The ascending sprawl areas were mainly in the outer suburbs along the ring express. The enhanced sprawl areas were mainly located outside the ring express, including Chongming Island. On the whole, sprawl along ring roads is clearly seen. From 1990 to 2010, CSI gradually intensified from the central city to the outer suburban zone. For example, the enhanced sprawl towns were concentrated in Zone 5. The results show that during the 2000s, urban sprawl had shifted from the central city to the outer suburbs.

5.3. Spatio-temporal characteristics of urban sprawl in different sectors

As shown in Table 5 and Fig. 5, in the 1990s, the percentage of non-

Table 5
Urban sprawl in eight sectors of Shanghai.

	1990–2000 (Percentage of land area)				2000–2010 (Percentage of land area)			
	Non-sprawl	Light sprawl	Medium sprawl	High sprawl	Non-sprawl	Light sprawl	Medium sprawl	High sprawl
N	11.87	0.90	0.25	1.50	2.19	1.64	10.69	0.00
NE	4.61	3.68	1.42	0.34	1.20	5.15	3.70	0.00
E	1.95	3.74	0.06	0.01	2.56	2.52	0.68	0.00
SE	7.00	8.50	0.79	0.01	3.48	5.53	5.86	1.42
S	4.19	8.29	1.44	1.40	2.73	5.01	7.10	0.48
SW	10.18	6.74	1.86	0.03	3.00	2.82	10.50	2.50
W	2.24	6.60	2.02	0.25	3.33	1.48	6.17	0.14
NW	1.72	4.99	1.37	0.04	1.91	2.32	3.00	0.87
Total	100				100			

sprawling areas was highest in the north sector (11.87%), as was the proportion of high-sprawl areas (1.5%). The share of light sprawl was highest in the southeast sector, and that of medium sprawl was highest in the western sector. Generally speaking, sprawl in the south, southeast and southwest was stronger than in the north, northeast and northwest from 1990 to 2000 (Table 6).

In the 2000s, sprawl in the south was higher than in the north, although the share of medium sprawl in the north significantly increased compared with that in the 1990s. The share of non-sprawling areas was similar among all eight sectors, and light sprawl units were mainly located in the northeast and southeast. Medium sprawl units were concentrated in the north and southeast and high sprawl units were mainly located in the southeast and southwest sectors.

Fig. 6 presents the CSI in the eight sectors from the 1990s to 2000s. The sprawl stagnation areas were mainly concentrated in the southeast and the west, with area proportions of 1.91% and 2.08%, respectively. The spatial distribution of the weakening sprawl areas was relatively balanced, with the southern area having the highest area proportion (4.45%) and the western area having the lowest area proportion (1.11%). In terms of ascending sprawl areas, the area proportion of the southwest area was the highest (10.68%). The enhanced sprawl areas were concentrated in the northern, southeast and southwest district, with area proportions of 5.58%, 3.87% and 3.43%, respectively. Overall, the spatial distribution of all four sprawl type areas was spatially unbalanced in different sectors, for driving forces vary from region to region. The following part will select several typical townships/*Jiedaos* with dramatic changes in sprawl index to further analyze underlying causes of sprawl.

6. Examining the role of planning in urban sprawl

With rapid and large-scale city construction, local governments need to enhance their control over urban development. Local planning is a major tool to serve that purpose (Tian, 2014). Under a state-led growth approach, planning is not a tool of "prevention of sprawl", but becomes a tool for serving the needs of growth. The fundamental driving forces of city growth are social and economic factors such as population growth, investment, transportation, and planning policy. The sprawl index has already considered the factors of population and transportation, but data for investment in individual Townships/*Jiedaos* is not available. Therefore, this research mainly studies the impact of a city master plan on sprawl. Plans have proved to be a vital instrument of urban policy and a catalyst for urban change. Physical plans put forth graphic images of the future that can rally stakeholders to act. In China, the formulation of a city master plan is top-down by nature and lacks social and financial considerations (Tian and Shen, 2011). Planning is also used by local governments to maximize land income or to open up new spaces for growth in order to generate taxes. Tian et al. (2017) attribute this type of city growth to "planned sprawl." To what extent planning has contributed to sprawl, however, has not been evaluated.

In this research, we adopt geographical detectors to assess the impact of planning on urban sprawl. The principle of Geo-Detector is based on spatial heterogeneity, which refers to uneven distribution of traits, events, their relationship across a region or simply, spatial variation of attributes (Wang et al., 2016). If the spatial distribution of a factor (X) presents similar characteristic as that of sprawl index (Y), it means that Y is significantly correlated with X.

Geo-Detector is available as a free download from www.geodetector.org.[2] Users prepare data in an Excel file: the first column stores sample data (Y), the second and following columns store strata (X, denotes the stratum of a sample unit belonging to a nominal variable) of a stratification, the rows are records. Download the software, read data and run the program, a worksheet "Factor detector" is created where the q-statistic and its p-value are present. We adopt the "Factor detector" and "Interaction detector" produced by Geo-Detector to measure the impact of planning on sprawl. The factor detector identifies factors that are responsible for the sprawl, and a q-statistic method is used to measure the degree of spatial stratified heterogeneity and to test its significance. There is no definite definition for the value of q, like R^2 in linear regression. The physical meaning of the q value is that the independent variable x interprets the dependent variable y of 100 × q%. Moreover, if the q value is not statistically significant, it still has a clear physical meaning, but does not have to do the assumption of normal distribution. The q value is within [0,1] (0 if a spatial stratification of heterogeneity is not significant, and 1 if there is a perfect spatial stratification of heterogeneity) (Wang et al., 2016). The interaction detector reveals whether the factors interact or lead to sprawl independently. In other words, whether the interaction of factor X1 and X2 enhances or weakens impacts on sprawl Y, or a factor leads to sprawl independently.

The Shanghai City Master Plan (1999–2020) was approved by the central government in 2001, and is a statutory plan to guide city development in the 2000s. In China, a city master plan has three key planning elements that reveal the intention of the local government and are critical for guiding city growth: newly added construction land, land use control (particularly land for public facilities) and transportation network (Tian and Shen, 2011). Therefore, we select four variables as surrogates of planning, namely, area of newly added construction land in the master plan (X1), land for public facilities (X2), number of highways (X3), and score of metro stations[3] (X4) and evaluate their impact on sprawl in 230 *Jiedao*/townships. Geo-Detector results reveal that the q value of X1 is 0.4329, and that of X4 is 0.2348. The p-value of X1 is significant (less than 0.05), and those of X2, X3 and X4 are not significant. The q values of X2 (0.01) and X3(0.0362) are much less than X1 and X2. Moreover, we examine the impact of interaction factors on sprawl. The results show the impact of interaction of the leading factor, X1, and other factors on sprawl. The q value of X1∩X2 is 0.4966, and that of X1∩X4 is 0.8228. In other words, newly added construction land and the number of metro stations in the city master plan can largely explain the sprawl in 230 *Jiedaos*/townships. Therefore, we conclude that the city master plan has played a key role in contributing to urban sprawl, and newly added construction land and metro stations are key factors correlated with urban sprawl.

Looking at the details of the Shanghai City Master Plan (1999–2020), we can confirm that the state-led growth model has contributed to urban sprawl. One major planning concept, "One City, Nine Towns" is a development strategy to alleviate the city from the enormous pressure of spatial growth and to promote development of

[2] The readers who are interested in Geo-detector can refer to Wang, J., Zhang, T., & Fu, B. (2016). A measure of spatial stratified heterogeneity. *Ecological Indicators* 67(2016): 250–256 for more details.

[3] If a metro station is located within the *Jiedao*/township boundary, we assign the *Jiedao*/township highest score, 3. A *Jiedao*/township within the buffer zone of 500 m of a metro station is assigned the score of 2, and a *Jiedao*/township within the buffer zone of 1000 m of metro station is assigned the score of 1.

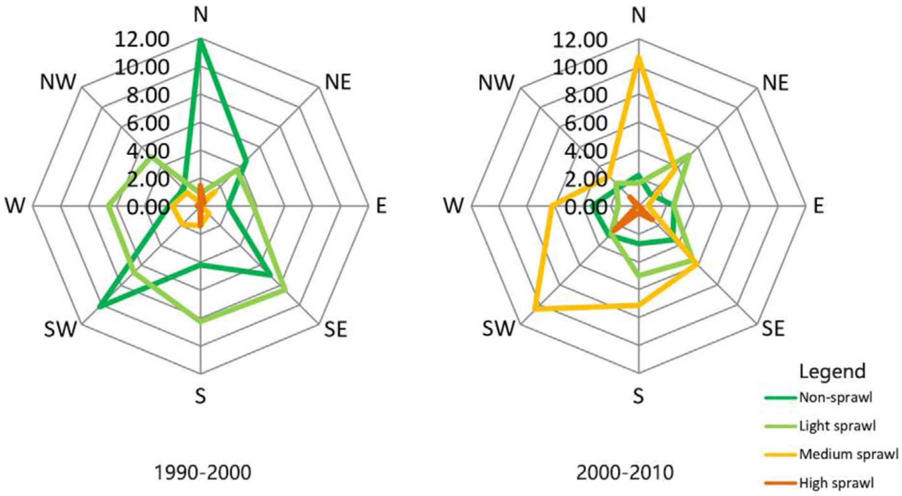

Fig. 5. Urban sprawl in different sectors in Shanghai from 1990 to 2010.

Table 6
Results of factor detector and interaction detector analysis in 230 *Jiedao*/townships[a].

Factor detector				
	X1	X2	X3	X4
q statistic	0.4329	0.0100	0.0362	0.2348
p value	0.0439	0.7041	0.1837	0.7779
Interaction detector				
	X1	X2	X3	X4
X1	0.4329			
X2	0.4966	0.0100		
X3	0.6114	0.0743	0.0362	
X4	0.8228	0.3270	0.4607	0.2348

[a] Note: X1 = newly added construction land, land for public facilities (X2), number of highways (X3), and score of metro stations (X4).

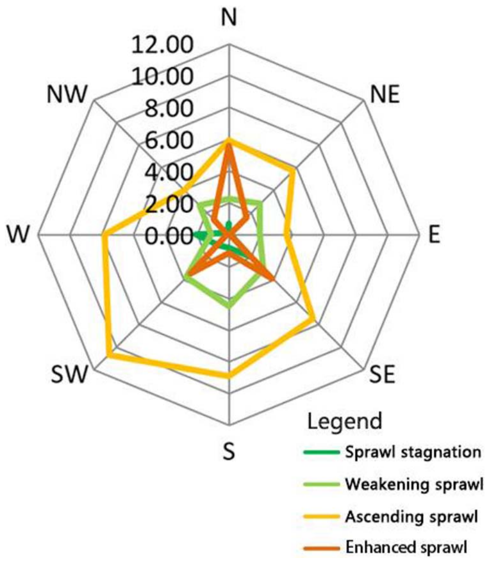

Fig.6. CSI in eight urban sectors from 1990s to 2000s.

suburban areas. "One city" means a "central city" and the nine new towns included three medium-sized towns with a projected population of 800,000 to one million each. Moreover, the expansion of Shanghai has also been driven by many functional zones invested in by the government such as industrial parks, university towns and large affordable housing areas (Fig. 7).

Since the early 2000s, there have been 104 planned industrial parks which covered a land area of 602 km^2 and a total of nine university towns, four old towns in the central city, and five new towns in the suburban area, covering a land area of 21.3 km^2. Moreover, in order to alleviate pressures caused by rapidly rising housing prices, the Shanghai government has designated 31 large affordable housing areas within the suburban areas. The land area of these housing projects reached a total of 131.23 km^2 (Tian et al., 2017).

7. Conclusions

"Sprawl" is a relative concept, in other words, it is not a categorical, wholesale transformation of the landscape, but a matter of degree (Schneider and Woodcock, 2008). By combining dimensions of city expansion, urban compactness and urban form, this research establishes a multi-dimensional index method to measure sprawl under the rapid urbanizing context of China. The index method is suitable for Chinese cities where census data, economic information, land use, and public facilities information is available. This type of data is readily available for most Chinese cities. This research also reveals the need for refinements. Limited by data availability, several key indicators, such as employment data, is missing in this method. Moreover, the Landsat TM image cannot differentiate various land use types, and thus indicators of mixed use are absent. Generally speaking, more work and data are needed to define an appropriate measuring method for fast growing Chinese cities.

The current Chinese planning model is top-down, administratively dominated, and land-driven development and its primary goals are economic growth and city image (Wu, 2015). To what extent urban planning has contributed to urban sprawl has been an under-researched topic. In this research, we apply the Geo-Detector to quantify the impact of planning on urban sprawl. The results reveal that the city master plan has played a key role in promoting city growth and contributed to urban sprawl in Shanghai.

From 2000 to 2015, urban construction land increased by 124.8%, more than doubling the urban population growth rate of 55.4% (Source: China City Construction Statistics Yearbook, 2015). As a consequence, many "ghost towns" with numerous modern high rise buildings and few inhabitants emerged in China. Uncontrolled urban sprawl also puts heavy pressure on the environment. Recent social and economic changes in China call for a transition from a land centered strategy to a human-oriented strategy. The evaluation of urban sprawl can help policy-makers monitor the efficiency of city growth. A greener, more sustainable and inclusive development pattern is expected to

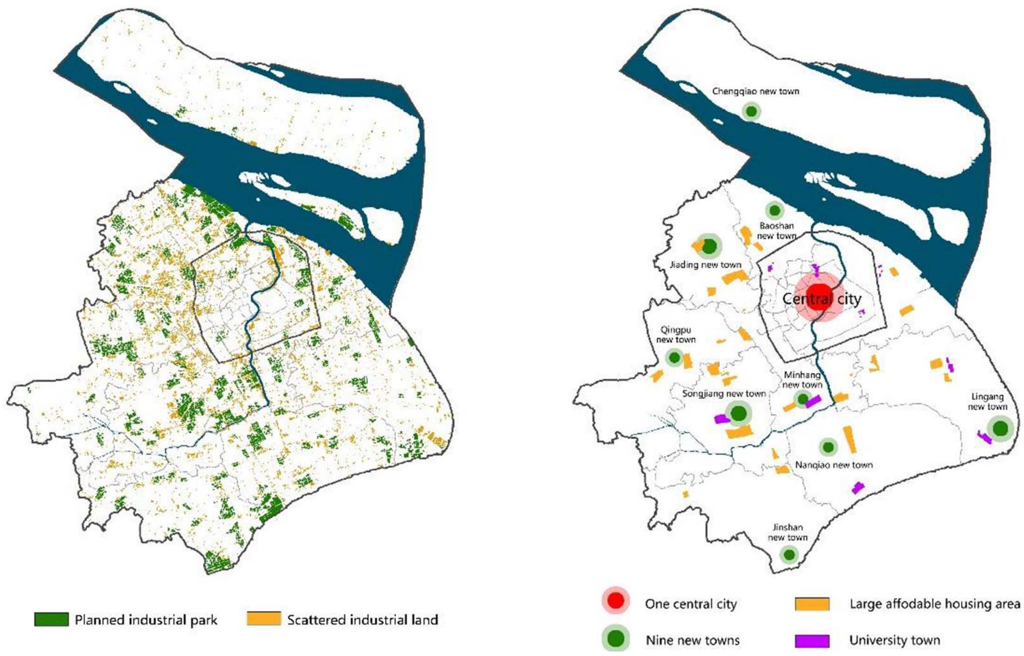

Fig. 7. "One city and nine towns" plan and Industrial land use in Shanghai Source: Tian et al., 2017.

replace the traditional city growth model. Consequently, the transition from growth-oriented physical planning to a comprehensive planning approach involving social, economic and spatial aspects is imperative.

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